# DIVING FOR SCIENCE...1990

FLORIDA SEA GRANT COLLEGE PROGRAM

FLORIDA MARINE RESEARCH INSTITUTE

AMERICAN ACADEMY OF UNDERWATER SCIENCES

PROCEEDINGS OF THE

AMERICAN ACADEMY OF UNDERWATER SCIENCES
TENTH ANNUAL SCIENTIFIC DIVING SYMPOSIUM

October 4 - October 7, 1990
University of South Florida
St. Petersburg, Florida

WALTER C. JAAP
EDITOR

American Academy of Underwater Sciences
947 Newhall Street, Costa Mesa, California 92627 USA

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Proceedings of the
American Academy of Underwater Sciences
Tenth Annual Scientific Diving Symposium
*"Diving for Science... 1990"*



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# INTRODUCTION

The *Proceedings of the Tenth Annual DIVING FOR SCIENCE. . .1990* contains 40 papers presented at the American Academy of Underwater Sciences Symposium, October 4–7, 1990, St. Petersburg, Florida. The Academy hosts these symposia to disseminate information and to stimulate discussion on the advancement of undersea science and technology. Diving safety is also an important research and operational criterion of the Academy.

The American Academy of Underwater Sciences is recognized as an authority on scientific diving and undersea technology. As such, it has a responsibility to disseminate new information in a published format. The Academy's publications include the proceedings of the annual symposia; special workshop proceedings; *Diving Computers* (1988); *Safe Ascents* (1989); technical manuals; diving standards; and a newsletter, the SLATE. In 1991 the Academy will sponsor a special workshop on multiple-day repetitive diving, and the papers and recommendations will be published in a "proceedings" format. The aforementioned publications are marketed through the American Academy of Underwater Sciences and other commercial vendors; and the publications list may be obtained from AAUS, 947 Newhall Street, Costa Mesa, CA 92627. This *Proceedings* contains papers on diving, scientific results, human impacts, archaeology, and physiology. We are pleased that several presenters this year traveled from outside the United States to attend the symposium.

The symposium was hosted by the Diving Program at the Florida Marine Research Institute with assistance from the Florida Institute of Oceanography, the U.S. Geological Survey, and the Committee (AAUS) for Southeast Region Scientific Diving Coordination. Special thanks to the coordinating team: Hector Cruz-Lopez, Kelly Boomer Donnelly, Dan Marelli, Jeanne Hoyt, Jerry Fountain, Jennifer Wheaton, and E.A. Shinn. Principal proceedings editor was Walter Jaap. The session editors included Joe Kimmel, Edwin Hayashi, Steve Gittings, Dennis Hanisak, Dan Marelli, Wilburn Cockrell, and Gregg Stanton. Word processing was done by Marjorie Myers. Gerry Bruger was instrumental in resolving computer-disk incompatibility problems. We are grateful to the University of South Florida for their gracious hospitality in allowing us to use their facilities, and we especially thank Sudsy Tschiderer, Dean Winston Bridges, and Herm Brames. We thank the Florida Marine Research Institute for generously supporting the program. For time, talent, and treasure, we thank Tom Perkins and Karen Steidinger. We appreciate the support given by Florida Sea Grant in publishing these Proceedings, and we especially thank William Seaman and Lorri Kell for their interest and help.

Walter C. Jaap
for the Coordinating Committee

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# DAN ANALYSIS OF RECREATIONAL DIVE ACCIDENTS FOR 1988

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*The Divers Alert Network is approaching the end of its first decade of service to the SCUBA diving public and medicine community. One of DAN's primary goals is the collection of SCUBA injury statistics. The last few years have seen increased efforts to collect more information on the causes of injury.*

## METHODS

In 1988, 553 diving accidents were reported from hyperbaric treatment facilities and from divers who contacted DAN on both the emergency and non-emergency lines. Accident Report Forms are filled out by the injured divers and by hyperbaric facility staff. Hyperbaric staff provide information on treatment while the divers provide information concerning the dive profile and personal data such as medical history. For clarification and confirmation, personnel at DAN central contact the treatment facilities and divers by letter and telephone. By June of 1989, 419 Accident Reports were received.

Of the 419 cases received, 111 were not recreational and 40 were incomplete. Thus, 268 recreational dive accident cases were analyzed.

## DIVER AGE

The mean age of an accident victim was 34 years with the range being 11-61 years. Table 1 gives a frequency of age distribution.

**Table 1. Distribution of Age of Dive Accident Victims**

| AGE | Frequency | Percent |
|---|---|---|
| 10-14 | 2 | 0.7 |
| 15-19 | 4 | 1.5 |
| 20-24 | 27 | 10.1 |
| 25-29 | 62 | 23.1 |
| 30-34 | 64 | 23.9 |
| 35-39 | 39 | 14.6 |
| 40-44 | 35 | 13.1 |
| 45-49 | 19 | 7.1 |
| 50-54 | 11 | 4.1 |
| 55-59 | 2 | 0.7 |
| 60-64 | 3 | 1.1 |
| TOTAL | 268 | 100.0 |

## SEX

Men were involved in diving accidents more than three times as often as women. This probably indicates a larger male diving population but it could reflect higher risk diving habits for men. Table 2 gives the sex of the accident victim.

**Table 2. Sex of the accident victim**

| SEX | Frequency | Percent |
|---|---|---|
| Female divers | 58 | 21.6 |
| Male divers | 210 | 78.4 |
| Total | 268 | 100.0 |

## CERTIFICATION/EXPERIENCE

Forty-nine percent (131 of 268) of the injured divers were beginning level (basic or open water) SCUBA certified. The majority (60 of 78) of new diver (divers with one year or less experience) injuries occurred in the more serious severity codes, indicating central nervous system DCS and/or gas embolism. New diver profiles indicate 75% dived 20 times or less, 61% were diving at or deeper than 80 feet, 50% were diving repetitively, 41% had a rapid ascent and 31% were outside the USN dive tables.

In the 78 divers who had been diving one year or less there were 25 gas embolisms. Of the 25 new diver embolisms, 16 had rapid ascents. These 25 cases represent 32% of all new divers (78) but it represents 69% of all embolism cases (46) analyzed which could suggest that lack of experience may contribute to the risk of AGE.

## CASE BREAKDOWN

Of the 268 analyzed cases, 46 were AGE, 60 were DCS Type I, and 162 were DCS Type II.

## CONCLUSIONS

Accidents do not just happen. The 500-600 dive injuries which occur each year can be attributed to no specific cause, but they are frequently a product of a series of events. While these events can be different for each diver, similarities do exist. Certain conditions or behaviors, in particular, are associated with injury, these include: fatigue, inexperience, and/or drinking alcohol on the preceding night. Deep diving and repetitive diving are also strongly linked to decompression sickness. Inexperience is a major predisposing factor for both decompression sickness and air embolism. New divers are less knowledgeable about diving safety and may have a tendency to go along with more experienced divers doing higher risk diving.

# CHARACTERISTICS AND ASSESSMENT OF DREDGE RELATED MECHANICAL IMPACT TO HARD-BOTTOM REEF AREAS OFF NORTHERN DADE COUNTY, FLORIDA

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*Beach erosion control measures have become a necessity along the south Florida coast due to the continued erosional loss of protective beach and dune areas. The primary method to date, for beach reconstruction in south Florida involves dredging of sand from an offshore "borrow area" and pumping the sand to the shoreline. Although the method results in a "new" beach with greatly enhanced erosion protection and recreational use, it is often not without impacts (both unavoidable and avoidable impacts) to the environment. In the summer of 1988, Dade County sponsored a beach erosion control project to renourish a 2.5 mile segment of northern Dade County shoreline. Near the time of completion of the project, areas of mechanical impacts to the reef adjacent to the borrow area were discovered. The physical characteristics of the impact indicated it was associated with the dredging operations. A subsequent survey of the reefs bordering the borrow area identified nine sites of impact. At each site physical evidence was found consistent with the dredging equipment making contact with and scraping the reef. Two of the nine locations exhibited substantial (i.e., orders of magnitude greater in size) and severe impact. These sites were chosen for detailed assessment. The assessment involved mapping the extent and magnitude of the impacted area via evenly spaced transects which were evaluated by biologists using scuba. The assessed impact at the two sites was spread over an area of 2.2 acres. Approximately 1.5 acres of benthic hard-bottom communities within the impacted area were destroyed (destruction of 75-100% of the benthic organisms). It was estimated that over 25,000 hard coral colonies, 24,000 soft coral colonies and over 2,000 barrel sponges were among the organisms destroyed by the dredging equipment. This destruction represents a significant impact to the hard-bottom community within the region by reducing habitat quality, density of organisms, reef structural complexity and the overall productivity of the area.*

## INTRODUCTION

Dade County, Florida has approximately 21 miles of ocean shoreline. Severe erosion along the shoreline, has resulted in reduced storm protection and loss of a recreational and economic resource. Metropolitan Dade County is committed to enhancing, restoring and revitalizing the coastal beach and dune systems, to provide enhanced storm protection for barrier island residents and recreational opportunities for county residents and visitors. The County's beach projects are administered through the Department of Environmental Resources Management (DC-DERM). To date, 15.4 miles of eroded beach front have been restored. Unfortunately, the restoration of the County's beaches has not been without impact to the nearshore habitats (Marszalek 1981, Goldberg 1989). Of specific concern to this report is the impact caused by physical contact of dredging equipment with the hard-bottom (live-bottom) reef areas adjacent to the dredging site (e.g., borrow area). Although other modes of impact can occur and can be of equivalent or greater concern, only the effects of the mechanical impacts will be discussed here.

During the summer (June through early October) of 1988 DC-DERM served as the local sponsor for a federally funded beach restoration project along 2.5 miles of shoreline in Sunny Isles (Figure 1). The dredging method employed utilizes a "hopper dredge". This type of dredge has arms mounted on the sides of the dredge. The dredging end of the arm is lowered to the bottom where the material (i.e., sand) is suctioned up the arm and into the "hoppers" on the dredge. The ship moves along within the borrow area, dragging the suction arm or "drag head" on the bottom (Figure 2). On August 25, 1988, DC-DERM personnel noted mechanical impact to a portion of the third reef, adjacent to the borrow area. The location and characteristics of the impact indicated that it had been caused by the contact of the hopper dredge's (Hopper Dredge LONG ISLAND) drag head(s) with the reef. Subsequently, a survey of the reefs surrounding the borrow area was conducted by DC-DERM biologists to determine the extent and degree of the impact. Nine separate areas of impact were identified. This report details the location of the areas, characteristics of the impact and method used to quantify the area of hard bottom impacted at two of the nine locations.

The general geological and biological features of the reefs found off the southeastern coast of Florida have been described by Goldberg (1973), Jaap (1984) and Shinn (1988). The geological and biological features of the reefs off northeastern Dade County are similar to those described by the above cited authors, but differ with respect to the depth of formations, and, to a lesser degree, with the biotic components of the reef. A brief summary of the specific features found off Sunny Isles is presented here, outlining the pertinent topographic features and biotic communities.

<u>Geology.</u> Three distinct reef platforms, or terraces, are found between 0.5 and 2.0 miles off the Dade County coast (Figure 1). The reefs are formed of pleistocene reef rock with a "cap", up to eight feet thick, of geologically recent coral reef (Shinn 1988). Shoreward of the first (westernmost) reef is a large sand area with scattered patch reefs. The first reef is a low profile, non-continuous reef believed to be formed by the convergent growth of smaller patch reefs (Goldberg 1973). The second reef is relatively narrow (125-200 m wide), and crests

at 11 to 13 m. The western edge of the second reef shows a mild relief of 1 to 1.5 m, rising out of a sand plain at a depth of 14 to 15 m. The eastern edge shows a greater and steeper relief dropping 1 to 3.5 m to a depth of 17 m onto a sand plain which makes up the borrow area. The western edge of the third reef, adjacent to the borrow area, has a relief of 1.5 to 3 m, rising from between 18 and 19 m to approximately 16.5 m. The eastern edge of the third reef forms the outer reef slope, sloping to +60 m (Figure 3).

Hard bottom communities. A diverse and abundant assemblage of benthic plants, hard corals, soft corals, sponges and fish is found on the offshore reefs in northern Dade County. These communities have been, in part, described by Blair and Flynn (1989). The communities on the second and third reefs are of specific concern as they are the reefs that sustained mechanical impact from the dredge's drag head. The most abundant organisms are the soft corals (i.e., *Eunicea* spp., *Pseudopterogorgia* spp., *Plexaura* spp.) with numerous massive hard coral colonies (i.e., *Dichocoenia stokesii, Siderastrea siderea, Agaricia* spp., *Montastrea* spp., *Stephanocoenia michelini*) ranging in size from 2 cm to 1.5 m in diameter. Goldberg (1973) categorized this community as the "Offshore Reef Platform" assemblage.

Information collected from DC-DERM biological monitoring stations located around the borrow area show 28 species of hard corals and over 130 species of pelagic fish exist in the immediate region. Also, numerous species of sponges (i.e., *Xestospongia muta* [barrel sponge], *Cliona* spp. [boring sponge], *Callyspongia* spp. [tube and vase sponges], *Ircinia* spp. [tube and cannonball sponges], *Haliclona* spp. [finger sponges]), anemones (i.e., *Palythoa caribbea, Bartholomea annulata, Ricordia florida*) and algae (i.e., *Halimeda* spp., *Dictyota* spp., *Sargassum* spp., *Peyssonnelia* spp., *Hydrolithon* spp.) cover the bottom.

## METHODS

Study Area. Between the reef terraces found off the northern Dade County community of Sunny Isles are deposits of carbonate sand. Specific regions of the sand deposits have been identified as "borrow areas" (by the U.S. Army Corps of Engineers) for use in beach renourishment or restoration projects. The borrow area used for the 1988 summer project (Sunny Isles Beach Renourishment Project) was located between the second and third reefs, between 2700 and 3000 meters (~9000 and 10000 feet) offshore, with approximate bordering latitudes and longitudes of 25°57.50'N, 80°05.75'W and 25°55.25'N, 80°05.25' W) (Figure 1). The areas of mechanical impact are located on the eastern edge of the second reef and the western edge of the third reef.

Assessment methods: Perimeter survey. The reefs adjacent to the borrow area were examined for signs of impact (i.e., denuded area of the bottom; overturned, broken or loose hard corals, soft corals or sponges; areas of rubble or large overturned boulders) by DC-DERM biologists, using scuba. The survey began on the eastern edge of the second reef and continued on the western edge of the third reef, until the entire reef edge adjacent to the perimeter of the borrow area had been examined. Swimming side-by-side and approximately

3 to 5 meters above the bottom, two divers were able to scan a 20 to 30 meter path of the reef. When an area of possible impact was noted, the divers descended and examined the bottom for indications of contact by the dredge's drag head with the reef. If the area showed markings characteristic of such impact, the area was marked with a buoy and the position noted. Impact locations were noted with combinations of "line-ups" (alignment of fixed shore points) and fathometer profiles.

Impact assessment: Two areas (impact sites 2 and 3) were quantitatively assessed to determine the area impacted and destroyed. These areas were chosen due to the size (minimally two orders of magnitude larger than the combined areas of the remaining sites). At each site, using a compass and following the bearing of the impact path, a metered tape or a 10-meter line, was stretched along the bottom within an impact tract. At 10-meter intervals (5-meter intervals for impact site 2), a second metered line was extended perpendicular to the first, from the western most point of impact to the edge of the reef. The second line was, therefore, perpendicular to the impact tracts. A DC-DERM diver then swam along the perpendicular transect line noting, on an underwater slate, the beginning and end points (i.e., width) of any impact tracts and the relative degree of impact within each tract. Destruction was categorized into one of five levels: 0% (no impact), 0–25% (slight), 25–50% (moderate), 50–75% (heavy), 75–100% (severe impact).

It is recognized that this methodology can have multiple sources of error. For example, the subjective placement of a region with 25% impact into the 0–25% or the 25–50% category can vary between individuals conducting the assessment and the perception of the degree of impact can vary. Further, the diver's familiarity with the specific area or habitat can affect how he may perceive the degree of impact. Steps were taken to minimize these sources of error. All the assessments were conducted by two DC-DERM biologists with extensive experience with coral reef communities. Specifically, the biologists conducting the assessments are responsible for conducting the biological monitoring programs associated with beach restoration and renourishment projects (including the Sunny Isles project) and are familiar with the areas in question. The specific diver's ability to determine levels of impact was verified using photogrammetric techniques. As a matter of procedure, areas showing borderline levels of impact (i.e., 25, 50 or 75% impact) were placed into the lower of the possible categories. Areas were assessed as mechanical impact attributable to the drag head only if characteristic scrapes or gouges, described below, were present. Specific areas adjacent to heavily or severely impacted areas may have been assessed a slight impact level (0–25%) due to the impact of rubble, generated by the scraping action of the drag head on the benthic organisms.

## RESULTS AND DISCUSSION

A total of nine areas of impact were identified on the reefs. Two sites were on the eastern edge of the second reef, and seven sites on the western edge of the third reef. The most severely impacted sites were sites 2 and 3, on the east side of the second reef. The approximate location of the impact sites relative to the borrow area are shown in Figure 4.

**Characteristics of the impact**: At each area of impact, DERM divers noted marks, scrapes, or tracts indicative of the dredge's drag head coming in contact with the reefs. Gouges were characterized by smoothed, compressed, flat areas approximately 8 to 10 cm wide which cut vertically 0.5 to 5.0 cm into the carbonate rock. The gouged, compressed areas were often seen side-by-side (Figure 5) and correspond precisely to the size and placement of metal "wear pads" (steel plates placed on the edges of the wear head to prevent wearing away of the metal drag head via abrasion) on the underside of the dredge's drag head. Scraped areas appeared as flattened surfaces on the higher points of the reef along a impacted tract. The scraped surfaces also showed obvious compression, reflecting the considerable weight of the object creating the impact. In the more severely impacted areas (i.e., sites 2 and 3), swathes (multiple tracts) of impact could be seen traversing the reef. The full width of a single tract (i.e., one pass of the drag head over the reef) measured 2.5 to 3 m, which is equivalent to the width of the dredge's drag head. At sites 2 and 3, due to repeated incidences of the drag head being pulled across the reef, the width of the impact tract was as wide as 20 m. Within the areas of multiple passes, virtually all benthic organisms (i.e., soft corals, hard corals, sponges and algae) were destroyed (Figure 6). Along specific tracts within impact site 2 and 3, all sediment and rubble were removed from the crevasses and gullies within the impact tract, indicating the barge was actively dredging while pulling the drag head across the reef.

In slightly and moderately impacted areas (e.g., sites 1,4-9), the impact was intermittent and limited to the highest points of the reef. In these areas it appeared as though the drag head of the dredge was suspended, or partially raised, and held at a constant depth in the water column. The drag head, therefore, only made contact with the portions of the reef that were shallower than the depth at which the drag head was held. Although these areas of impact were not as apparent as the severely impacted areas, the characteristic scrape marks were present indicating that the destruction was caused by the drag head. In the areas of partial impact, fractured live bottom, coral heads, injured soft corals and sponges were often found (Figures 7 and 8).

**Description of impact at each site.** Brief descriptions of the location and the impact at the sites are given below, followed by the quantitative assessments of Sites 2 and 3.

**Site 1.** The first impact site was found on the western edge of the third reef and crossed over DC-DERM's biological monitoring station "H". The damage is along two converging paths, indicating multiple incidences of contact. The tracts are 50-75 m long and involve slight (0–25%) destruction of the hard bottom. At this specific site, two large *Montastrea annularis* coral heads were destroyed (Figure 10), along with a number of smaller colonies of *Dichocoenia stokesii* and *Meandrina meandrites*. The heading of the tracts were approximately 350–0/170–180°.

**Site 2.** Impact site 2 is located on the eastern edge of the second reef, approximately 50 m north of DC-DERM's biological monitoring station "I". Numerous tracts of impact were found, causing considerable destruction. The damage is detailed later in this report (see Assessed impact sites).

<u>Site 3</u>. Site 3 is located on the eastern edge of second reef, where the reef projects eastward towards the borrow area, forming an irregularity or notch in the general rectangular shape of the borrow area (Figure 4). As at site 2, the impact at this location consisted of numerous tracts of impact. This site had the greatest magnitude of impacted area and degree of destruction. The impact is detailed later in this report (see <u>Assessed impact sites</u>).

<u>Site 4</u>. The fourth area of impact is located on the western shore of the third reef adjacent to the northeastern most point of the borrow area (Figure 4). This is the region where the dredge turned out of (on northerly passes) or into (on southerly passes) the borrow area. A single impact tract was present, approximately 2.5 to 3 m wide and 20 m long, within which an estimated 50 to 75% of the benthic organisms were destroyed. Bearing of the impact path was approximately 45/225°.

<u>Site 5</u>. Site 5 is on the western edge of the third reef, southeast of the "elbow" in the north end of the borrow area (Figure 4). Four tracts of impact were observed, each 0.5 to 2.5 m wide and 20 to 30 m long. An estimated 25 to 50% of the benthic organisms were destroyed within the impact tracts. The bearing of the impact was approximately 35-45/215-225°.

<u>Sites 6, 7, 8 & 9</u>. The remaining sites were located on the western edge of the third reef (Figure 4). Each area consisted of a single impact tract, 0.5 to 2.5 m wide and 20 to 30 m long, within which 0 to 25% or 25 to 50% of the organisms were destroyed. The bearings of the impact tracts were 350-0/170-180°.

<u>Assessed impact sites</u>: In contrast to the impact at sites 1, 4, 5, 6, 7, 8 and 9, the impact seen at sites 2 and 3 was of greater severity (mostly 50-75% or 75-100%) and involved a much larger area. The width of specific portions of the impacted area indicated that the drag head was pulled over the reef numerous times (Figure 9 ). The bottom was severely scraped and fractured, producing considerable amounts of rubble. Only very small organisms, that had settled in various small depressions, survived.

<u>Site 2</u>. An area of 1,466 $m^2$ (15,780 $ft^2$) was surveyed at site 2. Impact was documented along a 115 m path. Within that area destruction varied between 0 and 75–100%, with the latter being most common. Impact to the reef, attributable to the drag head, was found as far away as 23.8 m from the eastern edge of the reef. The areas of slight or no impact represent either sandy areas, low lying areas or regions of irregular contour, which limited the contact of the drag head with the reef. Furrows in the sand adjacent to the reef, caused by dredging action, could be followed out of the sand and onto the reef.

Within site 2 a total area of 938 $m^2$ (10,096 $ft^2$) was impacted, of which 663.1 $m^2$ (7,137.5 $ft^2$) was destroyed. This is believed to be a conservative estimate of the area of destruction, as the regions assessed at 75–100% damage were most often completely denuded of epibenthic, cryptic and endolithic organisms. The true percentage of destruction was 100 %. With the procedures used, however, the relative assessed loss would be calculated at a level of 87.5% (.875; Table 1). This procedure, in light of the degree and extent of impact, errs on the conservative side for the estimates of area destroyed. Figure 9 is a mosaic, generated from the calculated areas of impact and associated degree of destruction. It is apparent from the width of the area, numerous incidences of pulling the drag head over the reef had to have occurred to cause the amount and pattern of impact documented.

<u>Site 3.</u> Site 3 showed the largest amount of impact. An area of 11,997 $m^2$ (129,135 $ft^2$) was surveyed at this site. Varying levels of impact were documented along a total length of 580 m. The impact tract was interrupted at the 470 meter mark by a large sand area. The tract continued approximately 150 m south of the point of interruption, and continued for an additional 110 m (e.g., a total of 580 m). The total area impacted at site 3 was 7,979 $m^2$ (85,885 $ft^2$) within which 5,343.0 $m^2$ (57,511.6 $ft^2$) was destroyed. Along the main path of damage, impacted areas were documented on the reef as far as 47 m from the edge of the reef (Figure 10). It is obvious from the extent and intensity of the damage represented in Figure 10, that repeated incidences of pulling the dredge's drag head(s) over the reef occurred in this area. Further, some of the damage tracts had all rubble and sand removed from the crevices in the bottom. This indicates that the barge was actively dredging while pulling the drag head over the reef and not merely holding the drag head at an inappropriate depth.

**Table 1. The decimal equivalents of the mean values for the percent impact categories.**

| % Damage | | Decimal Equivalent |
|---|---|---|
| 0 - 25 | = | .125 |
| 25 - 50 | = | .375 |
| 50 - 75 | = | .625 |
| 75 - 100 | = | .875 |

(1) Area Impacted = Width Of Damage Path X Distance Between Assessments.
(2) Area Destroyed = Area Impacted X Decimal Equivalent of Damage.

The total area impacted at sites 2 and 3 was 8,917 $m^2$ (95,982 $ft^2$) or 2.203 acres. Of that impacted area, 6,006.1 $m^2$ (64,649.1 $ft^2$) or 1.484 acres was destroyed. It should be reiterated that these values do not include the impact associated with sites 1, 4, 5, 6, 7, 8 and 9. A summary of the impact documented at sites 2 and 3 is given in Table 2.

**Table 2. Summary of the area extent of impact and impact at sites 2 and 3.**

| Site | Unit Equivalents | Area Surveyed | Area Impacted | Area Destroyed |
|---|---|---|---|---|
| | ($m^2$) | 1,466 | 938 | 663.1 |
| 2 | ($ft^2$) | 15,780 | 10,096 | 7,137.5 |
| | (acres) | 0.362 | 0.232 | 0.164 |

(Continued)

**Table 2 Continued.**

| Site | Unit Equivalents | Area Surveyed | Area Impacted | Area Destroyed |
|---|---|---|---|---|
| | $(m^2)$ | 11,997 | 7,979 | 5,343.0 |
| 3 | $(ft^2)$ | 129,135 | 85,885 | 7,511.6 |
| | (acres) | 2,965 | 1,972 | 1.320 |
| | $(m^2)$ | 13,463 | 8,917 | 6,006.1 |
| TOTALS | $(ft^2)$ | 144,915 | 95,982 | 64,649.1 |
| | (acres) | 3.327 | 2,203 | 1.484 |

## POLICY IMPLICATIONS

Although smaller in scale than the impacts reported here, other instances of mechanical or physical impact to reefs have been documented during beach restoration activities in southeast Florida (Britt and Associates, 1979, Marszalek, 1981, Barry et al. 1989). The cumulative effect of these occurrences, as well as other secondary stresses placed on the reef systems during these projects, may ultimately change the development and implementation of long-term beach restoration policies in Florida.

The most immediate changes in project planning and implementation may be affected through the regulatory process and the criteria used in permitting beach nourishment projects. Numerous safeguards intended to protect reef areas from direct and indirect dredging impacts are presently incorporated into State permits and contract specifications issued for beach nourishment activities. These conditions address such factors as maintaining minimal buffer zones between reef and dredging areas, monitoring the water quality and the physical and biological effects of the dredging activities. A pattern of continued reef impacts associated with beach nourishment projects, despite specific safeguards to prevent them, could lead to policy decisions involving modification of permitting criteria. The modification could result in more stringent permit conditions, requirements for mitigation, utilization of alternative sand sources or shoreline stabilization technology, and delays or possible denial of permits for projects where a probability, or history, of significant resource impacts exist.

In many areas even minor changes in the permitting requirements could have a major effect on the decision to implement large-scale beach nourishment programs. An increase in the minimal buffer zone, for example, from the current 150 to 200 feet, to a more conservative 400 feet would greatly reduce both the siltation effects on surrounding reef areas and the likelihood of mechanical impacts to the reef. The need to provide a wide buffer zone on each side of an already narrow borrow site, however, may greatly reduce, or eliminate the sand quantity available for a project. Changes of this type will greatly affect the economics and viability of nourishment projects as the increased costs of using limited offshore, or more expensive off-site (i.e., Bahamian aragonite or upland sources) materials are weighed against alternative shore protection measures.

Within the last decade, increased governmental and public awareness of the sensitivity and fragility of our reef habitats has greatly reduced the attitude of acceptance of natural resource impacts and resulted in a more aggressive movement toward prosecution and subsequent recovery of damages for these impacts. Past damages awards have often been associated with "high profile" areas or habitats and shipping accidents (i.e., grounding of the freighter WELLWOOD, Key Largo National Marine Sanctuary, Florida, August 1988; grounding and oil spill of the EXXON VALDEZ, Prince William Sound, Alaska, March 1989-damages not yet determined). Recent awards, however, have involved reef impacts associated with dredging activities in hard bottom habitats. Damages of $1.0 million, for example, were recently agreed upon in response to a joint suit filed by the Florida Department of Environmental Regulation and the Dade County Department of Environmental Resources Management against the contractor responsible for the reef impacts described in this report. The funds will be used by the State and County to restore and enhance the impacted reef resources. A similar, though smaller, suit brought an equivalent (on a per meter-square basis) settlement of damages for reef impacts sustained during a 1988 beach restoration in a Boca Raton, Florida. The precedent established by these settlements will certainly be considered by contractors when contemplating bidding on projects utilizing borrow sites in close proximity to reef areas.

The implication of past reef impacts and associated damages can be numerous. There may be a higher cost, for example, for nourishment projects with borrow areas adjacent to valuable or sensitive resources; permitting agencies may initiate implementation of more stringent environmental safeguards or require mitigation commitment (i.e., mitigation bond) through the regulatory process; water quality standards which do not appear to adequately protect living resources may be reassessed or revised; and there may be reevaluation of beach nourishment as the preferred beach protection strategy. The resultant changes in beach nourishment permitting and implementation will not necessarily all be negative. The increased emphasis on protecting these resources may accelerate the development of alternative sand sources and/or technologies which will reduce the frequency of renourishment episodes or will allow beach nourishment activities to occur in an environmentally compatible manner.

## SUMMARY

Nine areas of mechanical impact by the hopper dredge's drag head were identified on the reefs adjacent to the borrow area. Seven impact sites (1, 4, 5, 6, 7, 8 and 9), showed slight to moderate impact (0–25% or 25–50%) paths, which were short in length and involved one (usually) to four incidences of the drag head contacting the reef. Two sites (2 and 3) had large areas of severe impact. A total of 8,917 m$^2$ (95,982 ft$^2$), or 2.203 acres, of impacted area was documented at sites 2 and 3 (938 m$^2$ [10,096 ft2] at site 2 and 7,979 m$^2$ [85,885 ft$^2$] at site 3). A total of 6,006.1 m$^2$ (64,649.1 ft$^2$), or 1.484 acres, of the impacted area was destroyed (663.1 m2 [7,137.5 ft$^2$] at site 2 and 5,343.0 m$^2$ [57,511.6 ft$^2$] at site 3). Damage to the reef was found as far away as 23.8 m (78 ft) at site 2 and 47 m (154 ft) at site 3, from the edge of the reef. The magnitude of impact documented could only have resulted from repeatedly pulling the drag head(s) of the hopper dredge across the reef. This level of destruction represents a significant impact to the hard-bottom community within the region by reducing habitat quality, density of organisms, reef structural complexity and the overall productivity of the area. Possible ramifications of these impacts are increased cost of future beach nourishment projects in regions with sensitive habitats in close proximity; more stringent regulations for beach nourishment projects; and renewed intensity forward finding alternative methods of beach nourishment and stabilization.

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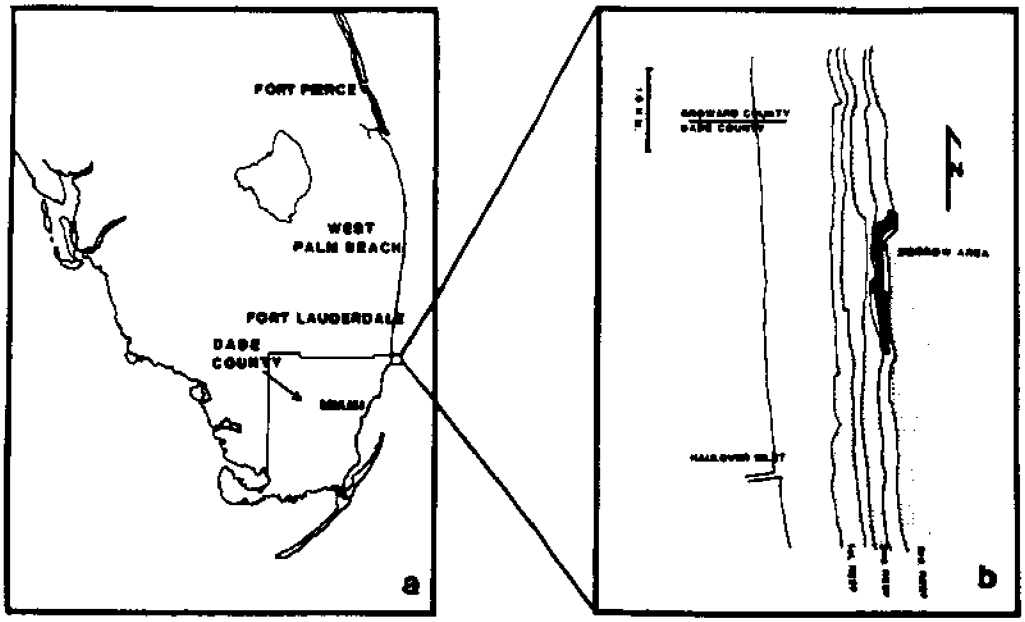


**Figure 1. Regional map showing area of Dade County where the project took place, and the relative location of the borrow area to the offshore reef terraces.**

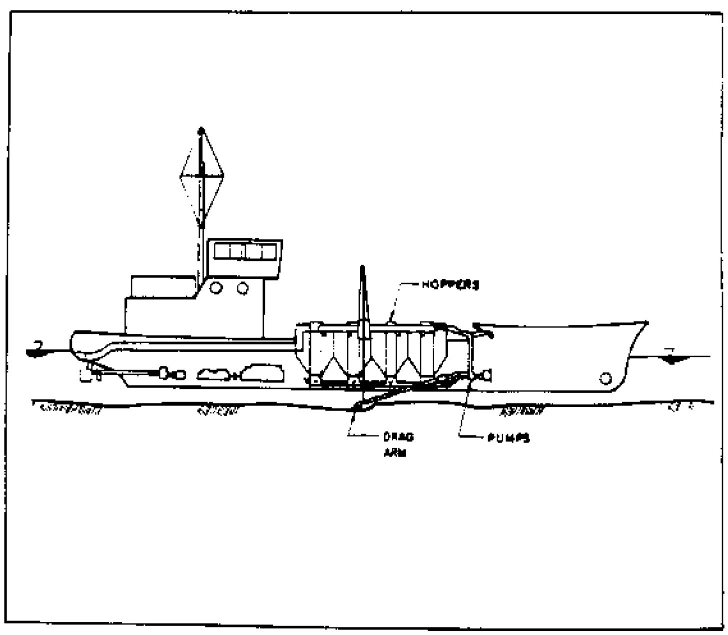


**Figure 2. Schematic of a hopper barge illustrating how such a dredge operates. The "drag head" is located at the end of the "Drag Arm".**

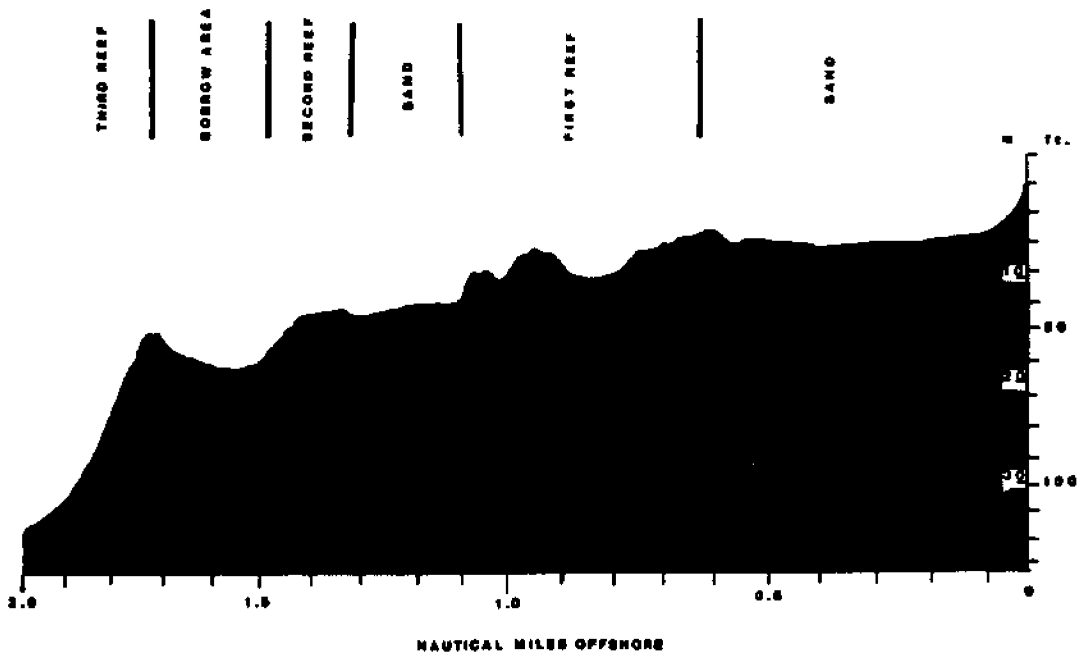


**Figure 3. Nearshore bottom profile found off Northern Dade County.**

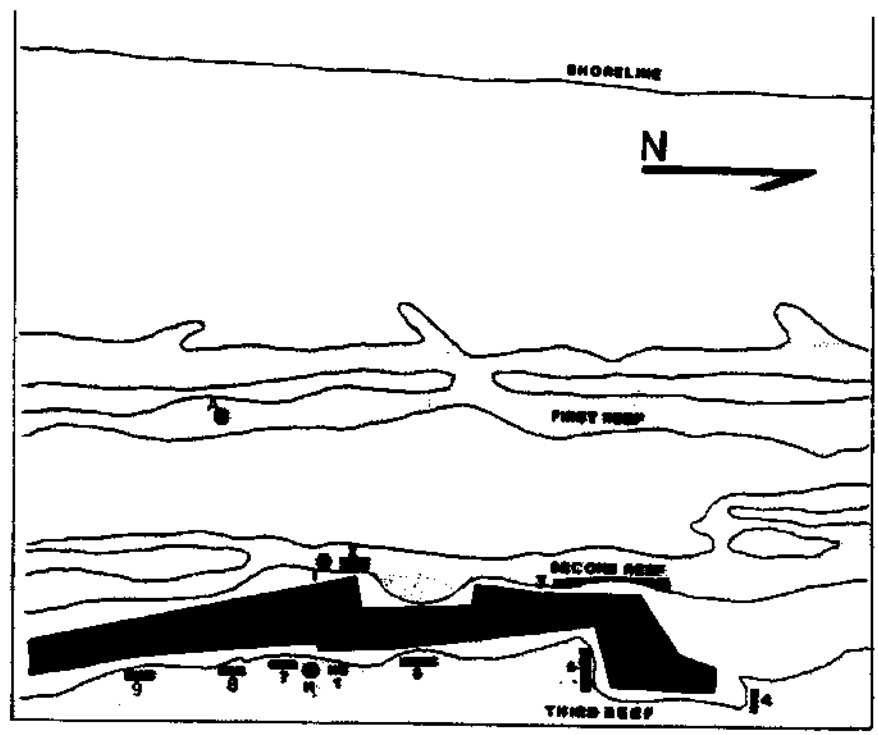


**Figure 4. Locations of the impact areas around the borrow area (1-9) and the biological monitoring stations (A, H, I).**

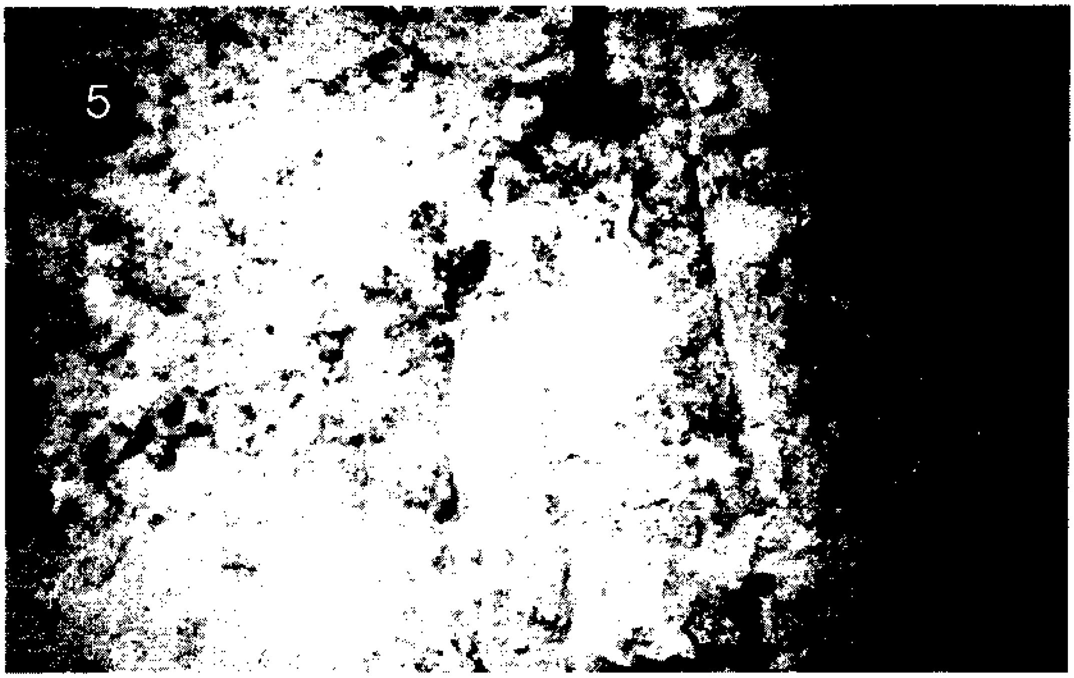


**Figure 5. Parallel scrape marks left by the wear pads of the drag head. Note the vertical gouging of the rock.**


**Figure 6. An impact corridor produced by multiple incidences of the drag head being pulled across the reef. Note the normal growth of soft corals and sponges to the right of the corridor.**


**Figure 7. A fractured *Montastrea annularis* coral head adjacent to biological monitoring station H. The white areas on the rock are areas of the coral head killed by the impact and subsequent inversion.**


**Figure 8. A *Xestospongia muta* barrel sponge cut by the drag head. The sponge remained attached after the impact.**

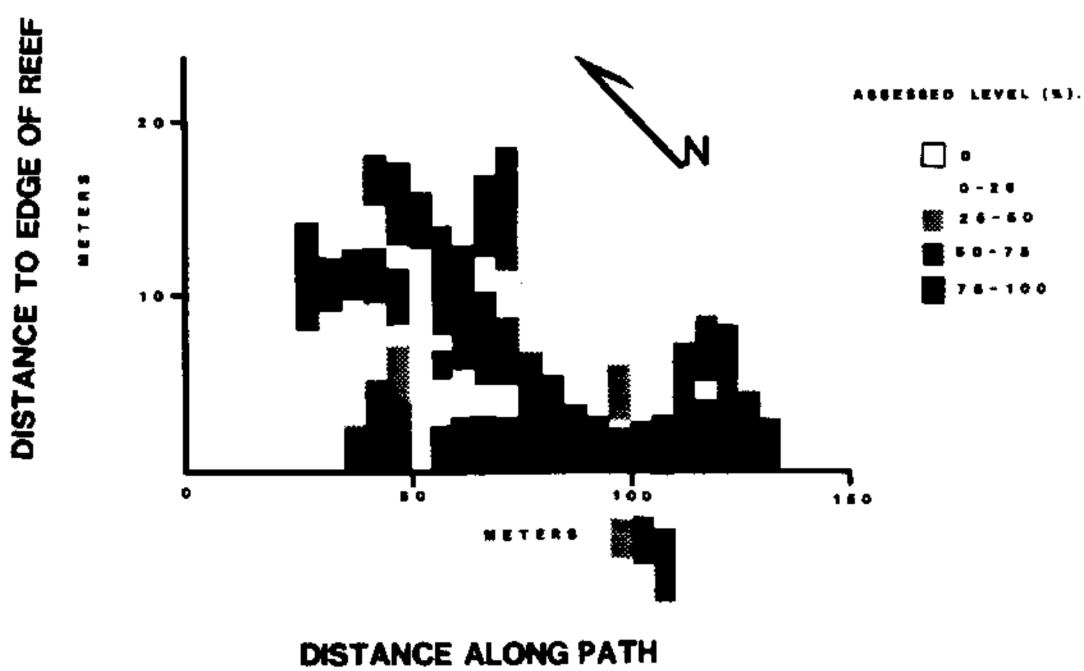


**Figure 9. A mosaic of the impact at site 2 generated from the measured areas of impact and their associated degree of destruction.**


**Figure 10. A mosaic of the impact at site 3 generated from the measured areas of impact and their associated degree of destruction.**

# MECHANISMS OF OUTER CONTINENTAL SHELF (OCS) OIL AND GAS PLATFORMS AS ARTIFICIAL REEFS IN THE GULF OF MEXICO

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*A study of the fish and biofouling communities at two artificial reef sites was conducted in the Gulf of Mexico. South Timbalier Block 128 Platform A (ST 128-A) had been detonated and toppled in place nine months previously. South Timbalier Block 86 Platform A (ST 86-A) had been blown over during a hurricane four years previously. The predominance of immature fish and the paucity of adults of those same species on ST 128-A indicate that this artificial reef has acted as a recruitment site for reef-dependent species. Observations on ST 86-A indicate that the majority of structure-related fish species were full-grown adults. Finfish surveillance, observation of invertebrates, and the presence of two scleractinian coral species at ST 86-A, and not at ST 128-A, suggest that the biotic communities may be more diverse and extensive at ST 86-A. These differences could be due to the manner by which each structure was toppled and/or possibly due to the length of time each has remained undisturbed.*

## INTRODUCTION

There are approximately 3,700 oil and gas production platforms in Federal waters of the Gulf of Mexico. Production platforms are set in place by driving steel support legs deep into the seafloor. Working machinery and personnel sit above the water supported by a steel network that is intentionally overbuilt and remarkably secure (Gallaway and Lewbel, 1982). However, offshore structures are not intended to be permanent.

When production ceases, the company operating the structure must then determine the means of its disposal. The platform may be relocated for use in the industry, removed and scrapped, or used as an artificial reef. In the last few years the practice of converting obsolete offshore platforms to artificial reefs has gathered broad public and private interest. For example, both Louisiana and Texas have legislated State programs to convert obsolete offshore production platforms to artificial reefs.

Despite the rather extensive use of dedicated artificial reefs on the southeastern United States OCS, opinions regarding their use and effects remain divided. Do artificial reefs result in an actual biomass increase, or do they simply redistribute fish populations in those areas where they are established? If artificial reefs serve mainly as aggregators, concentrating otherwise naturally dispersed fish stocks, extensive reef deployment coupled with unmanaged fishing could lower fisheries production. However, if artificial reefs serve as habitat in space-limited situations, extensive reef development could stabilize and/or increase fisheries production.

It is likely that the platforms in the north-central Gulf of Mexico are in some manner influencing fishery resources in the Gulf. However, information and understanding are woefully inadequate as to the extent of the influence, its nature, and whether it is negative or positive, or both. Conclusive evidence and quantitative data are scant. Since there are few natural reefs in the north-central Gulf of Mexico, the controversy regarding natural versus artificial reefs may not be germane to the issue. However, basic knowledge is also lacking on the mechanisms of standing platforms as *de facto* reefs or on obsolete platforms used as artificial reef materials, and little is known concerning interactive effects of platforms as artificial reefs and any nearby natural reef communities.

The over 3,700 platforms of various ages, at various locations in the north-central Gulf of Mexico, present numerous, repetitive opportunities for study. Many platforms are operated by responsible companies willing to assist in research efforts. All platforms have electrical power, refuge from weather, a stable deck, an established supply network, and are secure both above and below the surface (Bull, 1989).

It would require decades and billions of dollars to establish the study opportunities now present in the north- central Gulf of Mexico. To our knowledge, there is but one study planned to acquire basic information concerning standing platforms as *de facto* reefs. It is hoped the study will begin by 1991 and will last two to three years. Until quantitative studies of repetitive regularity are performed, information regarding communities associated with any platforms or artificial reefs will be of a qualitative nature, reporting observed phenomena but unable to quantify what is observed. That is the case with the present paper.

Over a 2-day period in August 1989, we had the opportunity to observe and record the fish and biofouling communities in the Gulf of Mexico at two sites approximately seven miles apart in distance and four years apart in submergence. Both structures included the entire above- and below-water sections of previously standing production platforms. These submerged platforms, now accepted as dedicated artificial reefs by the Louisiana Artificial Reef Program (LARP), had quite different histories in becoming reefs (Figure 1).

In September 1988, after 20 years of active production, South Timbalier Block 128 Platform A (ST 128-A) was retired, severed by use of explosives 16 ft below the seafloor, and toppled in place. In late October 1985, completely shut down during the 20th year of active production, South Timbalier Block 86 Platform A (ST 86-A) was knocked over during

Hurricane Juan. The objective of this study was to compare the fish and biofouling communities at the two sites.

## METHODS

A qualitative study of the fish and biofouling communities at ST 128-A and ST 86-A was conducted using a stationary visual census technique for fish (Bohnsack and Bannerot, 1986) and macrophotography for invertebrates. Fish surveying was performed with the diver remaining stationary while listing and then counting the fish within a clear horizontal range of vision. Additional information noted during fish identification included depth, temperature, approximate lifestage, and behavior. The macrophotography set up consisted of a Nikonos IV-A underwater camera and 35 mm lens, an Oceanic Model 2000 underwater strobe, and a 1:2 extension tube complete with framer (Figure 2).

### South Timbalier Block 128 Platform A:

Data concerning fish and invertebrate distributions, densities, and diversities were gathered during two dives made at this site. During the first dive, a qualitative survey of fish was performed around the deck area and from the deck area to the bottom of the platform (Figure 3). During the second dive, a concerted effort was made to survey fish and invertebrates along the entire length of a single inner leg of the platform reef. This was the first attempt to observe and record the biota on this artificial reef since it was toppled in place.

### South Timbalier Block 86 Platform A:

Two dives were made at this site. Recording of fish and hydrographic information was minimal on the first dive due to the need to record structural measurements (Figure 4). However, macrophotography and a qualitative survey of the fish were performed during the second dive.

## RESULTS AND DISCUSSION

Fish and biofouling communities were present for 20 years prior to the designation of these structures as artificial reefs. While both fish and biofouling communities were undoubtedly beyond the initial phases of recruitment and colonization when the structures where last standing, the communities were likely in vastly different conditions when the platforms were designated as reefs.

In the case of ST 128-A, the use of explosives fatally concussed most of the adult fish and certainly all of the demersal species associated with the platform (Figure 5). Vibration from the blasts ran upward through the support legs and was sufficient to dislodge most of the biofouling and sessile organisms as well (David Bull, pers. comm.). In the case of ST 86-A, sinking from the force of a hurricane was no doubt disturbing, but it was also relatively slow and not massively destructive.

Invertebrate Biofouling Communities and Biotic Interactions:

The biofouling communities typical of offshore structures in the Gulf of Mexico have been described by Gallaway *et al.* (1979). In the coastal waters (0-100 ft) of Louisiana, they are dominated from the surface to a depth of about 24 ft small acorn barnacles *(Balanas amphitrite* and *B. improvisus)*. This almost continuous mat of barnacles is then, in turn, covered by a "secondary" mat of macroalgae, hydroids, bryozoans, and encrusting sponges. The actual species composition of this secondary mat depends largely upon turbidity and the season. At deeper depths ( >24 ft), and often more turbid waters, hydroids dominate (Gallaway, 1981).

The most conspicuous component of both the ST 128-A and ST 86-A biofouling communities was barnacles (Figure 6); however, a significant proportion of these were dead. While the cause of the mortality can only be speculated, the clearance of ST 128-A and ST 86-A was 54 and 41 ft, respectively. These depths are somewhat greater than that suggested for a community dominated by barnacles (Gallaway et al., 1979). As such, the histories of these structures suggest the "drowned" remnants of barnacle communities growing at shallower depths when the structures were intact. These remnant barnacle communities now function as shelters for many small, motile or semimotile animals living on or within them (Figure 7). Many motile (e.g., blennies) and semimotile (e.g., sea urchins) animals depend upon these refuges for protection from strong currents, protection from predators, and for reliable areas where detritus and other food materials may settle out (Gallaway and Lewbel, 1982).

Barnacles are also an important food source. Gallaway and Martin (1980) identified barnacle molts as a dominant food source of the crested blenny, *Hypleurochilus geminatus*. Barnacles may also become available when bits of flesh are left attached to the crushed plates as a result of the feeding of large grazers (Gallaway and Lewbel, 1982).

The biofouling communities of ST 128-A and ST 86-A can be discussed in terms of the sequences of reef development (Schuhmacher, 1977). The encrustations of barnacles, bryozoans, colonial tunicates, and filamentous algae found in abundance on both structures may be considered remnants of the initial stages of reef development: the rapid and homogeneous colonization by predominantly noncalcareous fouling organisms. The second stage of reef development is the settling of mollusks, calcareous red algae, and foraminiferans not affected by grazing organisms, which often largely consume the initial settlers and subsequently attaching larvae. The colonizing organisms may include oysters, calcareous algae, and foraminiferans. Atlantic winged oysters, *Pteria colymbus*, were observed at ST 128-A (Table 1), and calcareous algae were widely abundant at both ST 128-A and ST 86-A.

The growth of scleractinian and hydro-corals on the remains of attached shells, or on other places often inaccessible to grazers, characterizes the third stage in this sequence. Colonies of the flower coral, *Eusmilia fastigiata* (Figure 8), and the orange tube coral, *Tubastrea coccinea*, were found at ST 86-A. *T. coccinea* is known to colonize and thrive in "shady" areas (Kaplan, 1982). This behavior is partially the result of their lack, or independence from, zooxanthellae, the endosymbiotic dinoflagellate algae upon which hermatypic (reef-building) corals depend.

What may be considered the dominant organism associated with this third developmental stage at ST 128-A and ST 86-A are colonies of the "soft corals," *Telesto riisei* (Figure 9). While the order Telestacea is of minor importance in comparison to the five (5) other orders of the Octocorallia, *T. riisei* may have particular significance in the Gulf of Mexico because colonies may reach over 12 in (Colin, 1978). Colonies as large as 12 in were observed at both structures, particularly at ST 86-A.

The final stage of reef development is characterized by dead coral colonies overgrown by calcareous foraminiferans, algae, and bryozoans consolidating the coralline structures by their deposits. These are often followed by the recruitment and growth of more massive hermatypic coral species. While hermatypic corals (e.g., brain corals) have been documented growing on offshore structures, particularly on the outer shelf (David Bull, pers. comm.), the water quality of coastal Louisiana, which includes the South Timbalier area, is not conducive to their development. This area is heavily influenced by the discharge of the Mississippi River, resulting in high primary productivity and high zooplankton consumption, frequent periods of high turbidity, and even fluctuations of the physicochemical parameters.

Corals are relatively sensitive to many environmental perturbations (Jaap, 1979; Loya and Rinkevich, 1980). The effects of turbidity have been widely studied and have been implicated as a prime cause of decreased growth (e.g., Aller and Dodge, 1974; Loya, 1976; Kendall *et al.*, 1985; and others). However, in the Caribbean, the octocoral *T. riisei* is known to grow readily on pilings in many harbor areas and may be the only octocoral of any significance as a fouling organism. Where it is found growing on reefs, it is usually in more turbid environments (Colin, 1978). These conditions are not unlike those encountered at ST 128-A and ST 86-A.

The skeleton of the octocoral *T. riisei* is a rather rigid structure composed of spicules of calcium carbonate imbedded in a horny material. This skeleton is then often colonized by a variety of other organisms. This additional relief can then be utilized as habitat by a host of other organisms as was clearly evident at both ST 128-A and ST 86-A. These other organisms included several varieties of Caribbean tropical fishes such as cocoa damselfish *(Pomacentrus variabilis)*, spotfin butterflyfish *(Chaetodon ocellatus)*, angelfishes (e.g., *Pomacanthus paru)*, several species of blennies (e.g., *Hypsoblennius invemar* and *Hypleurochilus geminatus)*, and a diverse assemblage of invertebrates such as sea urchins *(Arbacia* sp.*)*, arrow crabs *(Stenorhynchus* sp.*)*, and sponges *(Haliclona* sp.*)* (Figure 10).

The organisms associated with the skeleton of *T. riisei* may be involved in various biotic interactions similar to those reported for coral reef environments. While this analogy may seem extreme to some, it is a convenient starting point for analyzing the community composition and interactions occurring on these artificial reef structures. For example, the establishment of algal patches by damselfish, at the expense of hermatypic corals, is a common occurrence on coral reefs (Kendall and Bright, 1989, and references therein). The lush communities of algae are believed to suppress the growth of corals through a reduction in available free space for recruitment and expansion. Coral mortality within these algal patches may also result from algal overgrowth, increased sedimentation, and a persistent biting by the resident damselfish (Potts, 1977).

Fish Communities and Artificial Reef Interactions:

The most striking observation was that the majority of the fish at ST 128-A were young of the year (YOY), immatures, or young adults (Tables 1 and 2). Except for immature cocoa damsels and blennies, which were present at both ST 128-A and ST 86-A, all fish observed during dives at ST 86-A were adult. ST 128-A was exceptional in that numerous immature grouper and snapper were present. In addition, of those adult finfish observed on ST 128-A, no immatures of the same species were observed with the exception of blennies.

At least one pair of adult cocoa damsels was observed on ST 86-A. Adult cocoa damsels require a minimum territorial space that contains attached, small macroalgae. While damselfish territories may develop at the expense of other organisms (notably corals), they do function as centers of primary productivity (Brawley and Adey, 1977). They also provide infaunal organisms safe refuge and protection from carnivores. The diversity and abundance of small motile invertebrates have been found to be significantly greater in such patches than in nearby nonalgal areas (Lobel, 1980, and references therein). At the same time, however, the consumption of noncalcareous algae by grazers, such as the damselfish, butterflyfish, and sea urchins, have been implicated in the successful recruitment of coral to new substrata (Dart, 1972; Potts, 1977; Sammarco, 1982).

Blennies brood their eggs inside barnacle shells in the late spring and protect their young for a short period after hatching. It is noteworthy that fewer immature blennies were observed at ST 86-A than at ST 128-A. It was unexpected, that on ST 128-A, barnacles and blennies would be living at depths of 55-58 ft when they normally occupy the top 20 ft under a standing platform (Gallaway *et al.*, 1979).

There are several factors that are important for artificial reefs to successfully attract fish and/or increase local fishery biomass. It is well known that fish have an innate, positive attraction to underwater structures (thigmotropism). Reef-dependent species (e.g., snapper, grouper, damselfish) recruited to artificial reefs will become residents. Ocean pelagic species (e.g., amberjack, cobia, mackerel) use the vertical relief of artificial reefs as a visual cue for their transient movements (Gallaway and Lewbel, 1982) (Figure 11).

Bohnsack (1989) concluded that the presence of artificial reefs is more important for reef-dependent species in locations more isolated from natural reef habitats. Both ST 128-A and ST 86-A are over 100 miles from natural reef habitats. However, they are not far from standing platforms that are likely acting as established artificial reefs (Scarborough-Bull, 1989).

Stone *et al.* (1979) determined that an artificial reef in close proximity to an established reef initially attracts only the juveniles of reef-dependent species from the nearby established reef. Further, they observed that transient species begin to key on an artificial reef as soon as the artificial structure is emplaced. They concluded that artificial reefs did not diminish the resident population of nearby natural reefs by attracting adult reef-dependent species to the new habitat.

## CONCLUSIONS

Conclusions are based on very little data and are thus qualitative. The observations and data that were collected, however, suggest that continued monitoring of both structures on a regular basis could yield quantitative data concerning artificial reefs.

<u>Fish Communities</u>:

ST 128-A was set in place in 1968 and toppled in place 20 years later by multiple explosive charges that severed all but two legs. It is assumed that the toppling activity and explosives removed most of the adult fish. It is known from real-time video surveys that blennies originally within 20 ft of the surface were alive after the platform was toppled (David Bull, pers. comm.). Whether those same blennies continued to live or remain on ST 128-A is unknown.

The presence of a mixture of species, the predominance of immature fish of those species, and the paucity of adults of those same species lead to the conclusion that ST 128-A has acted as a recruitment site for reef-dependent related species. In addition, the presence of several viable finfish nests and gastropod egg cases indicates that this artificial reef is providing acceptable conditions that will increase biomass.

ST 86-A was set in place in 1965 then knocked over during Hurricane Juan 20 years later. ST 86-A had been down nearly four years at the time of the survey. To the associated marine community, being blown over by a hurricane must have been a great disturbance at the time. However, the event was certainly no more destructive than the explosives used at ST 128-A. Qualitative observations indicate that the structure-related species were full-grown adults. Many of the grouper species (e.g., hinds, coneys) were as large or larger than any individuals observed during many years of diving under platforms in the Gulf of Mexico. Since the platforms were approximately the same age, and the exact time of platform submergence is known, quantitative monitoring on a regular basis may elucidate the carrying capacity of the structure and the turn-over rates of the populations.

Invertebrate Biofouling Communities:

Ultimately, whether or not there will be further recruitment to, and development of, the biofouling communities of ST 128-A and ST 86-A will depend upon a number of environmental, biological, and chemical parameters acting synergistically. Site selection by the larvae, tolerance of the turbidity (nepheloid layer), hypoxic events, susceptibility to predation, competition for space, and resistance to biological disturbances caused by grazing activities and other biotic disturbances will have direct and indirect influences.

The abundance of the soft coral *T. riisei* and its associated epifauna and infauna, damselfish, and a variety of associated fish and invertebrates, suggests similar biotic interactions at ST 128- A and ST 86-A. Studies examining the relationships between these components may provide information invaluable in predicting the developmental stages, community structure, and possibly the productivity of these biofouling communities. A more detailed discussion of the research potential of offshore platforms may be found in Bull (1989).

While both ST 128-A and ST 86-A retained remnants of what may have been very similar biofouling communities prior to submergence, subtle differences between their communities were evident. General observations and the presence of two scleractinian coral species at ST 86-A, and not at ST 128-A, suggest that the biotic communities may be more diverse and extensive at ST 86-A. As suggested in the conclusions for fish communities, these differences could be due to the manner in which each structure became an artificial reef and/or possibly due to the length of time each had remained undisturbed.

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DIVE VESSEL M/V Peter C. DATE 8/25/89 TIME 10 AM LOCATION Snapper Reef (Rig-to-Reef) ST-128 Structure A

| DEPTH | FISHES TYPE | AGE | INVERTEBRATES ATTACHED | INVERTEBRATES MOTILE | APP No. | BEHAVIOR | REMARKS |
|---|---|---|---|---|---|---|---|
| [illegible] ft | tomtates | (1+ yr) immature | | | 30-40 | schooling close to deck section of structure | |
| [illegible]-65 | red snapper | " | | | 30-40 | schooling with tomtates | |
| [illegible] | | (1 inch) immature | Atlantic winged oyster | | hundreds | side by side under an overhang | |
| 60 | butterfly fish | adult pair | | | 2 | | not timid or shy |
| 60 | butterfly fish | (1+ yr) immature | | | 2 | staying with adults | |
| 45 | french ange fish | young adult | | | 2 | | timid and shy |
| 45 | sergeant majors | " | | | 12-15 | males guarding nests dark blue color schooling interplay among others | |
| | | | | | | four nests positive 10 in corners and generally in close proximity | |
| 100 | black Drum | old adult | | | 1 | living in 32 in diameter leg on bottom | |
| 45 | mangrove snapper | adult | | | 3 | ?territorial activity ?spawning not moving from area of decking | |
| 60 | red snapper | young adult | | | 10 | schooling | |
| 50-80 | trigger fish | young adult | | | 50-70 | schooling and being obnoxious | |
| 10-25 | barracuda | adult | | | 3 | 1 was about 6 ft 2 were about 4 ft | hanging around |
| 60-80 | cobia | young adult | | | 12 | schooling and curious | |
| 10-60 | blue runners | young adult | | | 50-75 | schooling fast swimming through | |
| 62 | | (2-3 inch) young | | stone crabs | 2 | backing up into crevices | |
| 62-65 | white-spotted filefish | young adult | | | 2 | feeding on barnacles | |
| 50-60 | spadefish | young adult | | | 25 | slow schooling | |
| 50-60 | wrasse bass | young adult | | | 5 | on leg member that was horizontal territorial over a small area | |
| 50-60 | belted sand bass | young adult | | | 2 | hiding in octocoral *Telesto riisii* | |
| 80 | sheepshead | old adult | | | 4 | milling about | |
| 55-58 | | | barnacles | | 100's | some were feeding; probably Tintinnabulum sp. | |

**Table 1. Observations performed during first dive on ST 128-A.**

DIVE
VESSEL M/V Peter C. DATE 8/29/89 TIME 1300 LOCATION Snapper Reef (Rig-to-Reef) ST-128 Structure A

INNER LEG

| DEPTH | FISHES TYPE | FISHES AGE | INVERTEBRATES ATTACHED | INVERTEBRATES MOTILE | APP NO. | BEHAVIOR | REMARKS |
|---|---|---|---|---|---|---|---|
| 56 ft | blue runner | young adult | | | 50 | schooling | Temp. 85-86 F |
| 56 | trigger, ocean | young adult | | | 12 | singular looking for food | |
| 55-57 | calico grouper | YOY or 1+ | | | 4-6 | staying close to growth & crevices | |
| 56-58 | gag grouper | YOY or 1+ | | | 3 | " " | " " " |
| 56 | barracuda | adult | | | 2 | 1 4ft, 1 6ft | hanging around |
| 56 | crested blennies | adults, YOY or 1+ | | | 40 | several species wherever any large barnacles are | |
| 56 | | | colonial tunicate | | | | the orange species |
| 56 | | | *Aptasia sp.* anemones | | 2 sq ft | | |
| 56-60 | | | bushy octocoral | (*Telesto riisei*) | | begins around 56 ft gets very thick and dies out by 71 ft | |
| 56-58 | mixed species blennies | YOY or 1+ | | | lots | again near large barnacles | |
| 62 | | small | | arrow crabs | 4-6 | | |
| 62 | lookdown | adult | | | 7 | schooling, swimming through | |
| 62 | spadefish | young adult | | | 19 | " | " " |
| 62 | red spotted hawkfish | young adult | | | 2 | hiding in octocoral | |
| 70 | white spotted file fish | young adult | | | 1 | feeding on barnacles | |
| 61 | scamp grouper | YOY or 1+ | | | 2 | staying close to growth & crevices | |
| 62 | | | gastropod egg cases | | | | |
| 62 | | | | *Arbacia sp.* sea urchins | lots | mostly in the corners and hidden | |
| 57 | amberjack | young adults | | | 12 | schooling and swimming through | |
| 55 | French angel | adult | | | 1 | by mooring anchor looking for food | |
| 56-60 | cocoa damsels | YOY and 1+ | | | too many | everywhere on structure with growth, some territorial | |
| 55 | soapfish | young adult | | | 1 | in crevice | |
| 70 | sheepshead | adults | | | 3 | milling about | |
| 56 | spotfin butterfly fish | pair of adults | | | 2 | feeding on lavender encrusting sponge | |

**Table 2. Observations performed during second dive on ST 128-A.**

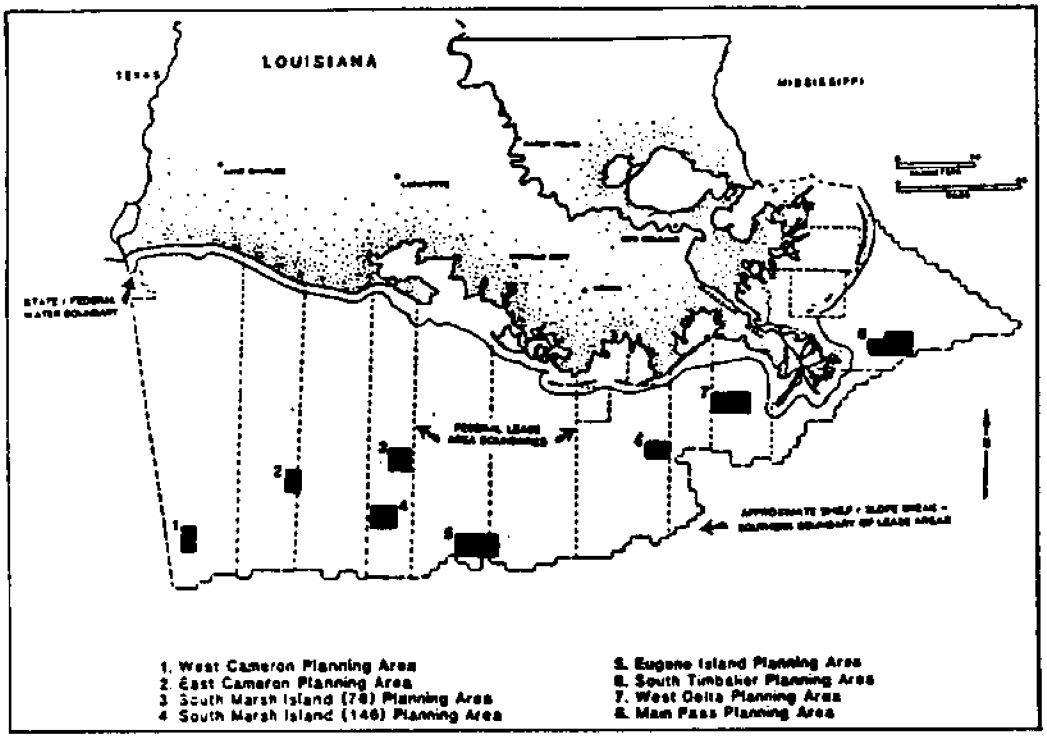


**Figure 1. Louisiana offshore artificial reef planning areas. South Timbalier, site 6, was the study location.**

**Figure 2. Recording data at ST 128-A. (c) David Bull.**

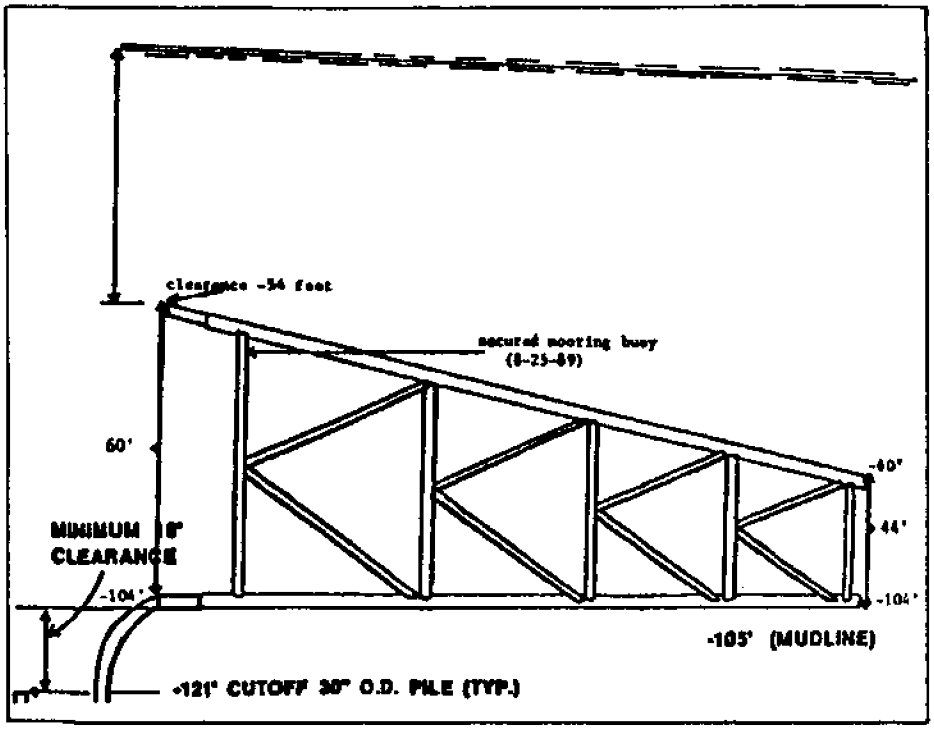


**Figure 3. Schematic of toppled platform ST 128-A (courtesy of Chevron U.S.A., Inc.).**

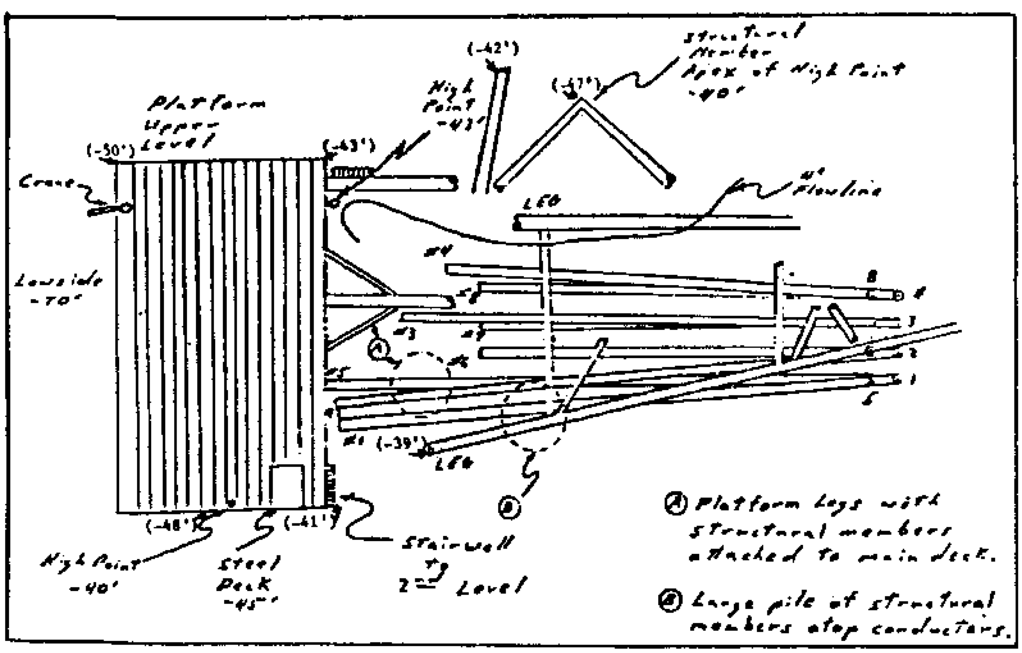


**Figure 4. Schematic of sunken platform ST 86-A (courtesy of ODECO Oil and Gas Co.).**

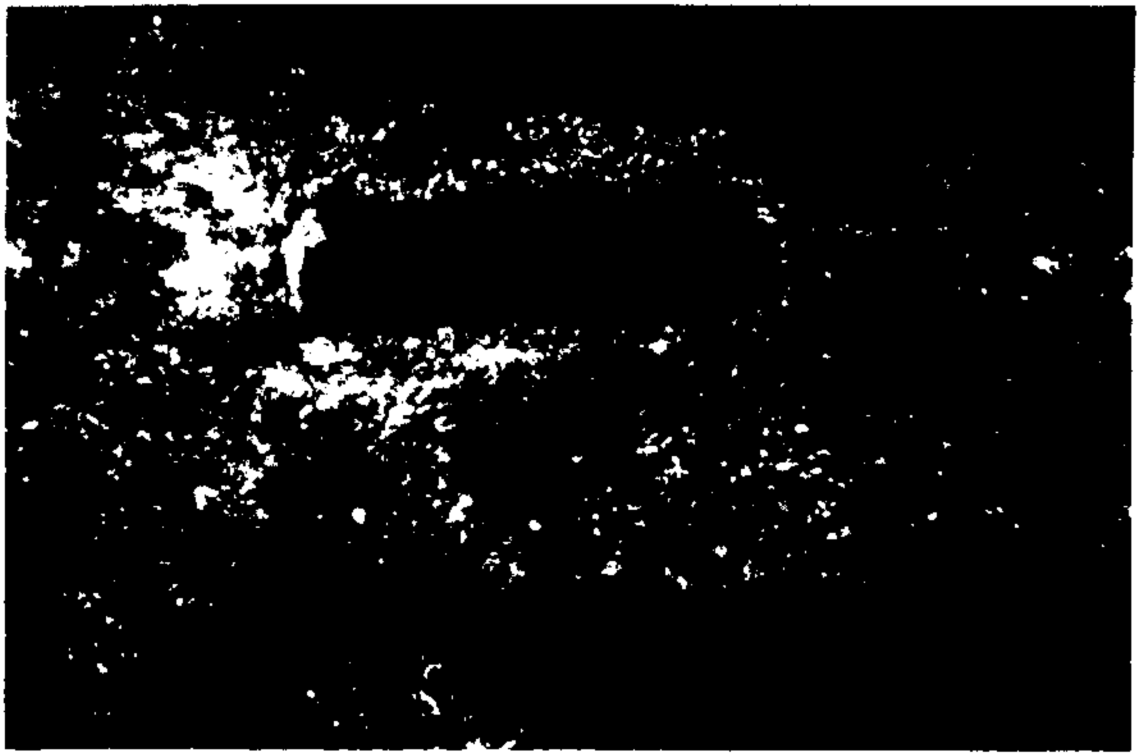

**Figure 5. Through this "window," cut into a leg of platform ST 128-A, explosive charges were lowered to 16 ft below the seafloor before detonation. (c) David Bull.**

**Figure 6. ST 86-A area of submerged deck showing heavy growth of barnacles and encrusting sponges. (c) David Bull.**

**Figure 7. Detail of dead barnacles on ST 128-A: home to a crested blenny, *Hypleurochilus geminatus*, and spongy tunicate, *Didemnun conchyliatum*. (c) James Kendall.**

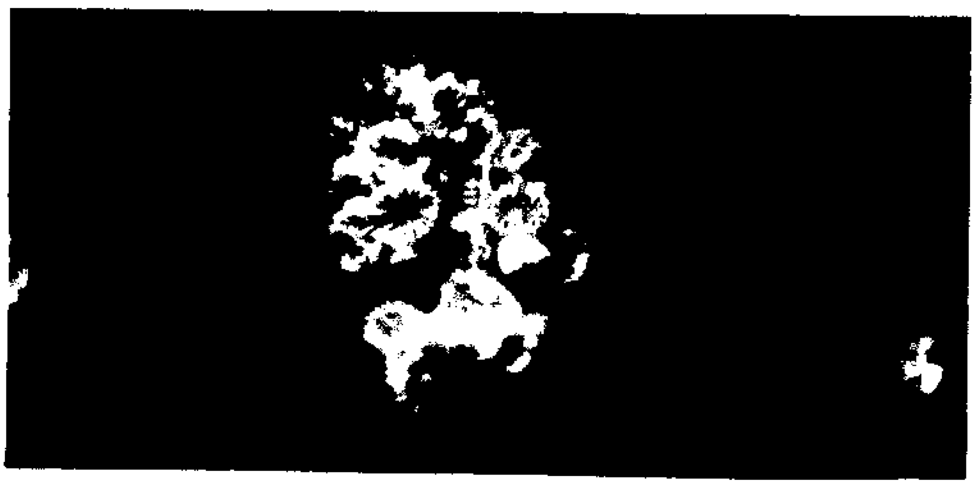

**Figure 8. Detail of flower coral, *Eusmilia fastigiata*, on ST 86-A. (c) James Kendall.**

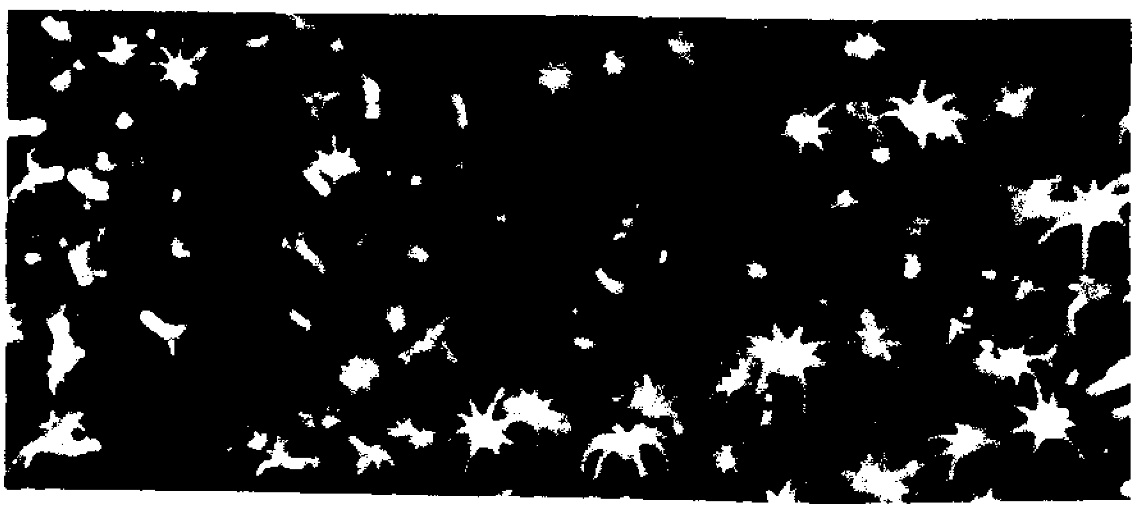

**Figure 9. Detail of octocoral, *Telesto risei*, on ST 86-A. (c) James Kendall.**

**Figure 10. Detail of community associated with octocoral; immature cocoa damselfish, *Pomacentrus variabilis*, sponges, and sea urchin, *Arbacia* sp., on ST 128-A. (c) James Kendall.**

**Figure 11. Ocean pelagics, cobia, *Rachycentron canadum*, above ST 128-A. (c) David Bull.**

# "LIVE BOTTOMS" IN THE CONTINENTAL SHELF ECOSYSTEM: A MISCONCEPTION?

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*The term "live bottom" has been used to denote areas of hard bottom with broken relief that have large associated populations of sessile invertebrates and fishes. "Live bottom" communities have been described in U.S. continental shelf waters primarily from North Carolina to Texas. "Live bottom" habitats are considered by several federal regulatory agencies to be areas of biological importance.*

*We question the use of the term "live bottom" because it suggests that other kinds of bottom habitats, especially soft bottom habitats, are unproductive and uninteresting. Our research shows that soft bottoms support large, productive populations of benthic microalgae, demersal zooplankton, and epifauna. We have also found that fishes associated with "live bottom" habitats frequently obtain a substantial portion of their diets from soft bottom habitats, either by off-reef foraging or import of soft bottom-derived food items.*

*We suggest that the term "live bottom" be replaced by the term "hard bottom community".*

## INTRODUCTION

Struhsaker (1969) first used the term "live bottom" to denote portions of the sea bottom in southeastern U.S. continental shelf waters of broken relief with rich populations of sessile invertebrates and relatively dense aggregations of commercially exploitable fishes. He differentiated "live bottoms" from four other bottom types: coastal habitat, open shelf habitat, shelf-edge habitat, and lower shelf habitat. Others have subsequently distinguished between "live bottoms" and coral reefs, e.g., Rezak et al. (1985). Furthermore, it is important to note that not all hard bottom habitats in continental shelf waters support "live bottom" communities (Kirby-Smith and Ustach, 1986).

Hard bottom areas in a broad area of the U.S. continental shelf have been designated or referred to as "live bottoms". The term has been used frequently in reference to hard bottom communities in the South Atlantic Bight (the continental shelf between Cape Hatteras and

Cape Canaveral; Struhsaker, 1969; Huntsman and Manooch, 1978; Miller and Richards, 1979; Powles and Barans, 1980; Van Dolah and Burrel, 1981; Parker et al., 1983; Hales, 1987). Hard bottom habitats that are not coral reefs have also been identified as "live bottoms" in Florida waters, particularly off the west coast of Florida (Gettleson, 1981; Gettleson et al., 1983; Minerals Management Service, 1986; Derrenbacker and Lewis, 1985). "Live bottom" habitats have also been identified off the coast of Texas (Bright, 1981; Rezak et al., 1985). Hard grounds off the California coast have also been identified as "live bottoms" (Lissner, 1981).

Several distinct and well-known hard bottom areas have been termed "live bottom" habitats. Gray's Reef off Georgia and the Flower Garden Banks off Texas have both been designated or proposed as National Marine Sanctuaries, and are often referred to as "live bottom" areas (Rezak et al., 1985; Fallon and Hopkinson, 1986). An area referred to as "Ten Fathom Ledge" off Cape Lookout, North Carolina, has been proposed as a National Marine Sanctuary, and is also frequently identified as a "live bottom" area (Mobil Oil Company, 1989). The Florida Middle Grounds, an area of hard bottoms in the west Florida shelf with high relief that is heavily fished, also fits the common definition of "live bottom" habitat (Parker et al., 1983).

"Live bottoms" are easily identified and biologically significant habitats. The geological and biological architecture of these habitats confers on them a three dimensional character that is absent in other habitats, and which provides important shelter and substrate for numerous species of many taxa. "Live bottoms" support important commercial and recreational fisheries for reef fishes and other species (e.g., spiny lobster). The hard substrate typical of "live bottoms" supports many species that require firm attachment to resist natural physical perturbations. Many of these species are autotrophs, such as macroalgae or some corals with symbiotic zooxanthellae, while others are important suspension feeders that trap and retain materials. Partly as a result of the physical stability of these communities through time numerous biological interactions, such as symbioses, have evolved. Unfortunately, "live bottom" communities are particularly vulnerable to such human activities as dredging, spoil disposal, and accidental groundings.

The distinctiveness and apparent importance of "live bottom" habitats has led to their identification as areas of special concern to government agencies with responsibility for management of outer continental shelf (OCS) resources and impacts resulting from exploitation of these resources. The Minerals Management Service (MMS), formerly the Bureau of Land Management (BLM), is charged with managing development of OCS resources, and has commissioned several studies of the OCS environment that focus on "live bottom" habitats (Center for Natural Areas, 1979; Duke University Marine Laboratory, 1982; Marine Resources Research Institute, 1982; Rezak et al., 1985). The National Oceanic and Atmospheric Administration (NOAA), through its Sanctuary Programs Division, has funded studies of "live bottom" habitats in National Marine Sanctuaries, such as Gray's Reef, e.g., Fallon and Hopkinson (1986), as has the National Marine Fisheries Service, e.g., Harris (1978a, b). The Environmental Protection Agency and the Corps of Engineers also use the term "live bottom" to distinguish productive hard bottom habitats (T. Nifong, pers. comm.). It must be noted, however, that the term "live bottom" is not defined by statute or in the Code of Federal

Regulations, and so is used by these agencies only as a descriptive term (T. Nifong, pers. comm.).

Designation by federal agencies of "live bottoms" as areas of special biological interest has led to special consideration of these habitats in environmental impact statements and related assessments of environmental effects of exploration/exploitation proposals by OCS leaseholders (T. Nifong, pers. comm.). Furthermore, "live bottom" habitats are accorded special protection under MMS regulations and lease rules. Thus, the "live bottom" concept has acquired at least semi-legal status and is used practically in the context of OCS development.

The term "live bottom" suggests that other substrates are "dead bottoms" that are unproductive and biologically as well as physically separate. The absence of "live bottom" habitats in some areas where development activities are underway or proposed is beginning to be used as justification for claims that no harm to living resources will occur as a result of these activities. The results of our research, and that of others, lead us to question this attitude and the use of the term "live bottom".

**Soft Bottom Productivity**

A key distinguishing feature of "live bottom" communities is their apparently high productivity, supposedly in marked contrast to that of other bottom types. This high productivity is manifested as high standing crops of macroalgae, sessile invertebrates, and/or associated fishes. However, it is important to realize that these organisms are easily detected and quantified by the two principal techniques used in sea bottom surveys, still and video photography, e.g., Parker et al. (1983), and dredge and trawl sampling methods, e.g., Cerame-Vivas and Grey (1966), Schneider (1976). These methods are biased toward sampling macroflora and macrofauna.

A substantial body of evidence now exists to show that soft bottom habitats are also quite productive. However, the organisms responsible for this productivity are generally small and difficult to sample by the methods named above. Furthermore, soft bottom habitats are easily and frequently disturbed by physical processes, often preventing the establishment of high standing crops of even the more obvious soft bottom flora and fauna. Nevertheless, small or cryptic populations in this habitat type are still quite productive.

Benthic microalgal biomass and production have been measured in soft bottom habitats on the North Carolina continental shelf (Cahoon, 1987, 1989; Cahoon et al., in press). Benthic microalgae associated with the siliceous sands of the Carolina shelf are primarily pennate diatoms; other forms of benthic microalgae, perhaps cyanobacteria, dominate the carbonate sands of shelf habitats off southern Florida (Cahoon, pers. obs.). The biomass of benthic microalgae in shelf sediments can equal or exceed phytoplankton biomass integrated through the overlying water column in continental shelf waters For example, mean benthic microalgal biomass measured in 1984 and 1985 at 17 stations in Onslow Bay, N.C. was 20.4 mg chl<u>a</u> $m^{-2}$

(s.e. = 2.77), and mean integrated phytoplankton biomass at the same stations was 5.92 mg chl<u>a</u> $m^{-2}$ (s.e. = 0.70) (Cahoon et al., unpublished).

Microalgal biomass accumulates at the sediment-water interface as a result of production <u>in situ</u>. Measurements of benthic microalgal production in shelf habitats show that production at the sediment-water interface can approach integrated phytoplankton production in shelf waters. For example, benthic primary production measured at seven sites in Onslow Bay, North Carolina from 1985-1989 averaged 23.3 mg C $m^{-2}$ $h^{-1}$ (s.e. = 3.08, n = 26), and water column primary production measured concurrently averaged 27.6 mg C $m^{-2}$ $h^{-1}$ (s.e. = 5.26, n = 15) (Cahoon, 1987, 1989, unpublished data). Thus, soft bottom habitats support substantial primary production that is concentrated at the sediment-water interface.

Soft bottoms harbor a diverse community of small animals including interstitial meiofauna resident among sediment particles, and demersal zooplankton, which alternately enter and leave the substrate. Although these are distinct groups, their memberships overlap somewhat; both groups appear to be dominated by harpacticoid copepods and nematodes (Coull, 1971; Schwinghammer, 1981; Tronzo, 1989). Studies of the abundance of demersal zooplankton associated with soft bottom sediments in continental shelf waters by Tronzo (1989) and Cahoon and Tronzo (1989) have shown that densities of these animals can reach 20,000 and 33,000 individuals $m^{-2}$ in siliceous and carbonate sediments, respectively. These densities can equal or exceed the densities of zooplankton in the overlying water column (Tronzo, 1989; Table 1).

Table 1. Comparison of average total water column zooplankton (collected by vertical hauls with a 150 um net, 0.5 m diam) vs. average total demersal zooplankton (collected by reentry trapping) in Onslow Bay, North Carolina. Five most abundant taxa listed in decreasing order of frequency (Tronzo, 1989).

| Water Column Zooplankton (# animals $m^{-2}$) | Demersal Zooplankton (# animals $m^{-2}$) |
|---|---|
| 17,705 | 20,364 |
| Calanoida | Harpacticoida |
| Cyclopoida | Nematoda |
| Appendicularia | *Amphioxus* |
| Chaetognatha | Cyclopoida |
| (nauplii) | Cumacea |

Soft bottoms also support substantial populations of larger epifauna, including several species with commercial value. The latter include calico scallops, flounders, and penaeid shrimps (Schwartz and Porter, 1977; Kruczynski, 1974). Other epifaunal organisms found in soft bottom habitats include a variety of demersal fishes, echinoderms, bivalves, gastropods, and numerous crabs and shrimps (authors, pers. obs.).

**Imported Materials**

Many of the organisms typical of "live bottom" communities are planktivorous. Sponges, bryozoans, tunicates, and many tube-dwelling polychaetes feed on very small suspended particles, primarily phytoplankton, while hydrozoans, anthozoans, and planktivorous fish (e.g., Hales, 1987) associated with "live bottoms" consume zooplankton. Some of this planktonic food is probably derived from nearby soft bottoms as suspended benthic microalgae and demersal zooplankton carried by currents into "live bottom" habitats. All of these planktonic forms represent food imported to the "live bottom" community from other communities.

**Off-reef Foraging**

Studies of reef-associated fishes have shown that many of the smaller fishes that feed on invertebrates (as opposed to the primarily piscivorous game fishes) are obtaining a major fraction of their diets from soft bottom habitats. Bolden (1990) found that tomtate *(Haemulon aurolineatum)*, a common reef-associated fish, move over soft bottoms at night, presumably to feed. Approximately 80 and 20% (as dry weight) of the diets of tomtates associated with an artificial reef and a nearby natural ledge in Onslow Bay, North Carolina, respectively, were soft bottom organisms. Although tomtates consumed some macroalgae, their gut contents did not include the sessile invertebrates characteristic of "live bottom" habitats, i.e., sponges, tunicates, and coral polyps. Burk (1990) found that black sea bass *(Centropristis striata)* associated with the same reefs included various crabs, shrimps, peracaridan crustaceans, and molluscs typical of soft bottom habitats in their diets. Black sea bass also did not appear to consume sponges or corals. Harris (1979) found that cubbyu *(Pareques umbrosus)* are associated with hard substrate habitats, but include many soft bottom species in their diets, a finding confirmed by Lindquist et al.(in preparation). Studies of reef-associated fishes by Steimle and Ogren (1982) and Sedberry (1985, 1988) also show that these fishes obtain food from soft bottom habitats.

**Community Heterotrophy**

Fallon and Hopkinson (1986) measured benthic respiratory and photosynthetic rates at Gray's Reef National Marine Sanctuary, a "live bottom" habitat off the coast of Georgia. They showed that respiration exceeded production by 32%, and inferred that this "live bottom" community was heterotrophic, that is, it depends on imported organic material to sustain it. Our studies of another hard bottom community (23-mile rock) in Onslow Bay, North Carolina, similarly suggest that the biomass and productivity of macroalgae on the hard substrate are inadequate to support the reef-associated consumer community we quantified (authors, unpubl. data).

## CONCLUSIONS

Our objections to the term "live bottom" center around two points. First, we have shown that other bottom types, particularly soft bottoms, are productive and support important populations of organisms that directly and indirectly support species of economic value. Much of the productivity of soft bottoms, however, is that of microscopic or slightly larger organisms, which conventional sampling techniques have overlooked. Second, we have shown that "live bottom" communities must be linked trophically with other bottom types, and are not self sufficient. Thus, a "live bottom" community depends on the surrounding habitats; its productivity and economic value are partly a function of this external subsidy.

The unfortunate connotation of the term "live bottom", that other areas are "not live", has helped to focus attention away from biologically productive, but visually unimpressive habitats, and has focused the attention of industry and regulatory agencies involved in developing OCS resources on "live bottoms", even when this attention is not appropriate. As a recent example, the MMS has directed Mobil Oil Company to include consideration of "live bottom" habitats in its environmental assessment of an area of the continental slope off Cape Hatteras, North Carolina, in which Mobil and other companies propose to explore for natural gas (30 CFR 250.33(b)(12); Lease OCS-A 0236, Stipulation No.2). As part of its claim that no significant biological damage will result from this exploration, Mobil has stated that no "live bottom" habitats were found in this area, even though Mobil's survey did find very large populations of soft bottom organisms at the site (Mobil Oil Company, 1989).

We advocate the replacement of the term "live bottom" with the term "hard bottom community". The latter term connotes the essential geological and biological features used to define the former term, but does not imply that other habitats or bottom types are unproductive, uninteresting, or not worth protecting.

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# BIOLOGICAL ASSESSMENTS OF DAMAGE TO CORAL REEFS FOLLOWING PHYSICAL IMPACTS RESULTING FROM VARIOUS SOURCES, INCLUDING BOAT AND SHIP GROUNDINGS

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*Wise management of coral reef environments requires that all impacts and stresses to the coral reef ecosystem be identified, and minimized whenever possible. The effects of natural environmental perturbations are more difficult to identify and manage than those impacts resulting from human activity. Obviously, this increases the need for managers of coral reef habitats to recognize those forms of stress and impacts that can be minimized through application of management strategies.*

*Physical damage to coral reefs from boat and ship groundings has been identified as a major impact to the coral reefs of the Key Largo and Looe Key National Marine Sanctuaries. Sanctuary regulations prohibit vessels from operating in such a manner as to strike or otherwise cause damage to the natural features of the sanctuary. Currently, the primary deterrent for this source of reef damage has been through civil procedures and penalties for vessel grounding cases. Litigation to recover damages to natural resources is also pursued in the case of large scale groundings. This legal process requires that the area impacted, or damaged, be accurately assessed for both biological damage and physical evidence to support the litigation. Methods for conducting such assessments are presented in this paper, along with recommendations on what observations are considered important. A review of assessment techniques and application of the information gathered during the assessment process are presented. Some of the criteria used to establish civil penalties for damages to the coral reef resources are discussed in this paper.*

## INTRODUCTION

Reports on the threats to coral reefs are continually appearing in popular periodicals (Lapointe,1989; Lapointe,1989; Shinn,1989; Bunkley-Williams and Williams, 1990; Stone,1990; Hallock-Muller,1990; Cole,1990; and Ward,1990). While some of these reports emphasize one form of stress as being more detrimental to the coral reef environment than others, the obvious concern is that the health of coral reefs is deteriorating throughout the Caribbean, and possibly around the circum-tropical belt of the globe (Stone,1990). The specific causes for these declines are not known, but from all indications, man's activities appear to be the major culprit. Aside from the human impacts, are the environmental perturbations that continually affect the health and success of coral reef environments. These forms of stress present the greatest challenge to scientists and coral reef managers alike, in terms of quantifying and qualifying their impact. On the other hand, the direct physical human impacts that reefs receive are easier to quantify and qualify, thus serving to make litigation and mitigation useful tools in coral reef management.

## DISCUSSION

Wise management of coral reef resources requires that the resource managers identify as many forms of natural and humanly induced stress as possible, and eliminate or reduce those that are within managements' capability of addressing. When an area first comes under some management program, the obvious strategy is to begin by addressing the most conspicuous and harmful impacts, and then determine the other perturbations that are having a deleterious effect on the resources of the area. Clearly, the goal for management is to eliminate as many forms of stress as possible and see that the resources are enhanced, while not unduly restricting the activities of those who want to enjoy and use the area.

This management approach is used at the Looe Key and Key Largo National Marine Sanctuaries (LKNMS & KLNMS) in the Florida Keys where regulations have been established that protect the coral reef resources from a wide range of physical impacts. Law enforcement surveillance, civil penalties, and the threat of natural resource damage actions serve as deterrents to sanctuary violations.

A specific regulation in the two sanctuaries (among others) prohibits the "removal or damaging of distinctive natural features." Although this regulation generally protects all of the natural and historical resources of the sanctuaries from a wide variety of impacts, the regulation has been most useful in prohibiting the taking or harvesting of stony corals and octocorals. Additionally, the sanctuary regulations prohibit anchoring on coral in the Fore Reef at LKNMS and generally prohibit the anchoring on coral throughout the KLNMS. Vessels operating in the sanctuaries shall not be operated in such a manner as to strike or otherwise cause damage to the natural features of the sanctuary (15CFR, 929.7, (6), (i) and 15CFR,937.6, (2), (iii). Although both sanctuaries have other regulations that help in their management, the regulations given above specifically serve to protect the coral reef resources from direct physical impact.

The enforcement program in the Florida sanctuaries has made it possible to use surveillance and litigation as a deterrent to the poaching, or taking of stony corals and octocorals by visitors to the area. Certainly, education has also aided in reducing this impact to the reefs. The installation of 180 mooring buoys at LKNMS and KLNMS has served to reduce the amount of anchor damage to the coral reefs of both sanctuaries. Also, underwater patrols and surveillance have been used to enforce sanctuary regulations that prohibit the physical contact with corals by divers and snorkelers. All of these are but a few of the management strategies that have been used in the sanctuaries to reduce as much of the direct human impact as possible, while giving the reefs an opportunity to combat the problems of water degradation from excessive nutrients, sedimentation, pollution from run-off, and a variety of other problems (Lapointe, 1989; Shinn,1989; Ward,1990; and Cole,1990).

The reefs of the Florida Keys are already under a considerable amount of natural stress simply because of their location at the northern extent of their zoogeographic range. For that reason alone, it makes wise management sense that coral reef managers eliminate as many physical impacts to coral reefs as possible, enabling them to be more capable of combating natural forms of stress, as well as the stress brought on by deteriorating water quality.

## VESSEL GROUNDINGS

Small boat and ship groundings on the reefs of the Florida Keys have been recognized as a major source of direct human impact to the coral reef resources for a number of years (Jaap, 1984; Dustan and Halas, 1987; Tilmant, 1987; and Miller, 1988). Over 225 recorded vessel groundings have occurred in the Key Largo N.M.S. since 1980 and another 33 have occurred at Looe Key N.M.S. since 1981.

Although mooring buoys have served to reduce the amount of anchor damage in the sanctuaries, and law enforcement efforts have been helpful in reducing the incidence of other resource depleting or damaging activities, vessel groundings continue to adversely affect the coral reef resources (Hudson and Diaz, 1988). Regulations in both of the sanctuaries strictly prohibit this type of impact, yet they continue. For that reason, it has become increasingly important that this form of resource damage be firmly addressed by both coral reef resource managers and law enforcement staff alike.

Sanctuary Officers investigate all reported and witnessed vessel groundings in the sanctuaries and enforce the regulations that prohibit damage to the natural features of the sanctuaries. Citations are written for boats running aground in all habitats, including sea grass beds, fossilized rubble bottom, hardbottom communities, and of course, coral reef communities. In the earlier days of the active enforcement programs at the two sites (1982-1983) it was common to encounter a captain that had run aground, and who was surprised to receive a citation for the damages that his vessel had done to the coral reef resources. This was probably because attention to boat groundings in the past (prior to sanctuary enforcement) had focused on the unfortunate mishap for the captain and the resultant damage to his vessel. Today, when Sanctuary Officers respond to groundings, visitor safety remains a top priority, but attention is focused quickly on the damages to the resources and the methods to get the vessel free of the reef without causing any additional, or unnecessary damage to the resources.

## BIOLOGICAL DAMAGE ASSESSMENTS

With over 250 recorded groundings in the sanctuaries in less than 10 years, investigations of grounding cases has consumed a considerable amount of staff time over the years. The extensive time and effort spent on these cases has resulted in an established procedure by which the boat grounding cases are investigated by the sanctuary staff. A major portion of the investigation is an underwater biological assessment of damages to the coral reef resources resulting from the incident (i.e., boat and ship groundings).

The biological damage assessment is prepared by the Sanctuary Biologist or other qualified person, and must attempt to quantify and qualify the damages to the coral reef resources resulting from the incident. Additionally, the assessment must serve to substantiate, or refute the description of events (or circumstances) as they were given to the investigating Sanctuary Officer by the violator. Therefore, the damage assessment is divided into a biological section and a physical section and the following information is collected:

### BIOLOGICAL SECTION

(1) A description of the habitat impacted (i.e. coral reef, sea grasses, coral rubble, sand, etc.).

(2) Dimensions and calculations of the total extent of area affected (i.e., length and width of grounding tract).

(3) Calculation of the extent of resources totally destroyed.

(4) Calculation of the extent of resources partially destroyed.

(5) Calculation of the percent living coral vs. dead fossilized coral in the impacted area.

(6) Species list of the organisms affected by the incident.

(7) Quantification of biota damaged or destroyed, based partially on a survey of the surrounding unaffected areas and partially on actual damage observed inside the impacted area.

### PHYSICAL SECTION

(1) Course of the vessel (direction of travel) at the time of the impact as it can be determined from physical evidence gathered at the grounding site.

(2) Approximate speed at which the vessel was traveling when it ran aground.

(3) Tides at the time of the grounding.

(4) Depth at the forward-most point of progress by the vessel; and depth at the stern resting position of the vessel.

(5) Recording and collection of any physical evidence (i.e., bottom paint, wood, fiberglass, or other substantiating material) present at the grounding site. This is particularly important if the vessel has left the scene, or was not observed aground by the enforcement staff.

It is not within the scope of this paper to specifically describe the various methods that are currently in use for completing biological damage assessments. Regardless of the method or technique used, the important objective is to get the information necessary to precisely describe and quantify the extent of damages to the natural resources resulting from an unnatural event. Consistency and repeatability are important components of any biological damage assessment technique and are criteria that must not be compromised. The following is not an attempt to describe all the various techniques, but simply a brief description of the kind of information needed to successfully prosecute an administrative penalty case.

Initially, the biological damage assessment must include a description of the habitat(s) impacted by the grounding or other type of impact. Sanctuary regulations state that "watercraft shall not be operated in such a manner as to strike or otherwise cause damage to the natural features of the Sanctuary." Therefore, boat grounding investigations and biological damage assessments are not limited to the coral reef habitat, but may include all of the major communities that help to comprise the coral reef ecosystem. Underwater photodocumentation of the impacted habitats and the unaffected areas surrounding the grounding site is an extremely important part of this phase of the assessment. The most commonly used methods are 35 mm photographs and underwater videos.

The second phase of the assessment is to completely determine the extent of damaged area, and to accurately survey the total area impacted by the grounding (or other form of physical impact). The total length of the grounding tract and all the other dimensions that are necessary to help calculate the total size of the area impacted must be carefully measured and surveyed. Open-reel, fiberglass surveyor tapes are ideal for taking underwater measurements and determining dimensions. Copper-clad surveyor stakes are helpful in semi-permanently marking various points of importance along the grounding tract (i.e., beginning and end of tract). The final figure (dimension) of area damaged or impacted by the grounding that is sought by the assessor (surveyor) should include the following: all areas scraped clean by the vessel; areas partially damaged; areas buried by fall-out rubble debris from prop-wash; reef framework damage (Hudson and Diaz, 1988); and any other discernable damage to the reef resources from the impact. Photodocumentation is an important tool in this phase of the biological damage assessment.

After the extent of damages (impact) has been calculated the next step is to determine how much of the coral and coral related organisms have been totally (100%) destroyed by the grounding. NOAA's Office of General Counsel determines a monetary penalty based on the extent of damage and whether the corals were completely or partially destroyed. Clearly, if the coral colony is completely destroyed, or fragmented to the point that recovery is not possible, then the assessor declares it 100% destroyed. This assessment is particularly easy to make in areas that have been scraped clean of all biota. Individual techniques for measuring, or estimating the size of the area impacted vary, but generally, the use of 1 $m^2$, 10 $m^2$, or larger quadrates is a standard method in making this kind of determination. The frequency at which the quadrates are deployed in an area, and the methods of recording the data observed inside the quadrates may vary between assessors. However, the final figure of percent area impacted and the severity of the impact is what needs to be determined for the assessing a civil penalty. The calculation of the area of partial damage is accomplished in much the same manner.

For purposes of assessing a civil penalty, the percent of barren fossil coral substrate is currently calculated in the vicinity of the grounding. The use of quadrates is once again the simplest technique for determining this figure. The reason for making this calculation is that the area of barren substrate (% barren or fossil substrate) is deleted from the total area impacted by the grounding. Some argue that 100% of the substrate is covered with living organisms, whether it be algae, diatoms, etc., and the percent barren substrate should not be deleted from the total calculation of area damaged. This poses a good argument, and revisions to the penalty assessment may be considered. However, to date the biological assessments in the sanctuaries have continued the practice of subtracting the amount of barren substrate from the total area damaged.

A species list, and a quantification of the organisms affected by the grounding, is compiled by the assessor. This list may be extensive in some biological zones, or very limited in others such as seagrass beds. Biological damage to corals and coral-related organisms are given higher assessed penalties than are impacts to seagrass or rubble habitats. Although the sanctuary regulations address damage to all "natural features" of the sanctuary resulting from boat groundings, relatively speaking, there has been a tendency to give higher fines for damages to corals (and coral-related organisms) than for damages to other reef inhabitants.

## PENALTY ASSESSMENT

Following the field investigation and biological assessment, the procedure for processing grounding cases in the National Marine Sanctuaries and assessing a penalty (fine) begins with submitting the case to the NOAA Office of General Counsel. The biological assessment (including all supporting evidence such as photographs and videos), is submitted along with the investigative report that is completed by a Sanctuary Law Enforcement Officer. The Sanctuary Officer's investigative report includes a complete investigation and documentation of the incident, as per the procedures established by NOAA for successfully prosecuting an administrative penalty case.

The Office of the General Counsel uses the information from the Sanctuary Officer's investigative report, combined with the biological (resource) damage assessment, to establish a penalty for the infraction. The consistency by which these assessments have been conducted over the years in the Looe Key and Key Largo National Marine Sanctuaries has resulted in a procedure by which the NOAA attorneys can establish a civil penalty for boat groundings with impressive congruity. In summary, the information that is collected by the assessor includes, but is not limited to, the following:

(1) Estimate of biota affected (area impacted)
  (a) coral totally destroyed
  (b) coral partially destroyed

(2) Estimate of percent coral cover vs. barren substrate

(3) Circumstances of the violation [attenuating circumstances (e.i., adverse weather); negligence; etc]

Title III of the Marine Protection, Research, and Sanctuaries Act of 1972 specifies that a civil penalty of up to $50,000.00 can be assessed per violation for each day that sanctuary regulations are violated. The civil penalty that is assessed for impacts to the natural resources of the sanctuary resulting from boat groundings is a fine for a violation(s) of sanctuary regulations as they are published in 15 CFR, Part 929 (KLNMS) and Part 937 (LKNMS).

The amount of the penalty assessed for individual boat grounding cases varies significantly depending on the extent of damages to the natural resources and the circumstances surrounding the incident. Sanctuary Officers issue citations for groundings as minor as boats striking, or bumping bottom, to as devastating as major ship groundings. The level of concern that vessel groundings has posed for management of the National Marine Sanctuaries in the Florida Keys has led to a demand that each incident be firmly addressed through litigation. It is difficult to determine how much of a deterrent this staunch approach has had regarding boat groundings in the sanctuaries. Although the number of cases seem to be on the rise in both sanctuaries, so is the increase in boating traffic. Also, the level of awareness has been increased in the regular visitors (charter boat captains) to the sanctuary regarding the sanctuary's concern for boat groundings and more incidents are being reported to the sanctuary staff. It is anticipated that strict enforcement of the sanctuary regulations regarding boat groundings will serve in an educational manner to point out that this kind of unnecessary impact to the coral reef resources can no longer be tolerated.

## CONCLUSIONS

In recent years there has been numerous assaults on coral reefs throughout south Florida resulting in thousands of square meters of damage to coral reef habitat. These physical impacts on the coral reef inhabitants have not all been the result of vessel groundings. Off

Boca Raton, Florida a steel cable scoured acres of coral reef habitat, and in the Miami area a dredge, involved in a beach renourishment project, destroyed acres of reef habitat. The frequent occurrence of these kinds of unnatural damages to coral reefs has brought to the attention of scientists and resource managers at all levels of management, the need to firmly address these unnecessary forms of reef damage. As a result, several individuals, representing a variety of state, county, and federal agencies have been involved in completing biological assessments on damages to coral reefs, resulting from a variety of physical impacts to coral reef habitats. By way of this paper, I am announcing a joint publication that will be compiled by Walter Jaap and myself, that will deal with the specifics of a wide variety of biological assessment projects that have been completed as a result of these various incidents. A completion date has not been projected, but some of the preliminary discussions have taken place, and several commitments to contributions have been received.

Among the objectives of the "treatise" will be to familiarize the scientific community and resource managers around the world, with the techniques for conducting biological assessments of physical impacts to coral reef communities. It is anticipated that the project will be completed within the next year.

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## DISCLAIMER

(1) The author of this paper is employed by the Florida Department of Natural Resources, Division of Marine Resources, Bureau of Sanctuaries and Research Reserves and in no way, or manner, is representing the views of the National Oceanic and Atmospheric Administration (NOAA). This is not an official NOAA publication and its contents are the sole thoughts and responsibility of the author.

(2) This article focuses solely on administrative penalties as opposed to natural resource damage actions filed in U.S. District Court. The article refers only to assessments relative to administrative penalties, as opposed to natural resource damage action filed in U.S. District Courts which are (along with civil forfeiture of offending vessels) authorized by the Marine Protection, Research, and Sanctuaries Act of 1972.

The biological and physical assessments for natural resource damage action may have a more detailed focus than those assessments done solely for the purpose of administrative penalty.

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# POPULATION STRUCTURE OF HERBIVOROUS REEFFISHES FROM THE SOUTHWESTERN COAST OF PUERTO RICO

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*Densities of three families (Acanthuridae, Pomacentridae and Scaridae) were estimated by means of transect counts. The relative abundances of juveniles and adults were compared in three inshore and two offshore (shelf-edge) reefs. Scarids were the most abundant group of fishes in all reefs, comprising 30 to 47 percent of the total number of individuals counted in inshore reefs and more that 70 percent of fish counted in shelf-edge reefs. Juvenile acanthurids were observed only in inshore reefs. Juvenile scarids were observed in all reefs, but were more abundant in inshore reefs. Greater adult densities in offshore reefs suggest that these shelf-edge reefs are optimal for spawning. Overall herbivore densities obtained in this study for Puerto Rico (18 to 49 fish per 100 $m^2$) compared favorably with densities from other tropical regions.*

## INTRODUCTION

Herbivorous fishes are important members of coral reef communities. On Caribbean reefs these fishes dominate in number as well as biomass (Randall, 1963). The role of herbivorous fishes in structuring coral reef communities was first suggested by Bakus (1964; 1966; 1969). Experimental work suggests that fish grazing limits algal growth and may result in an increased algal species diversity (Randall, 1961b; 1965; Earle, 1972; Vine, 1974; Adey and Vassar, 1975; Brock, 1979).

Quantitative studies emphasizing herbivorous fishes are scarce, particularly on Caribbean reefs. Barlow (1975) described the distribution of herbivorous fishes on two reefs from Puerto Rico, but his study was limited in time. Robertson and Warner (1978) compared relative abundances of scarids from different habitats in Panama. Several researchers have obtained coral reef fish densities, including herbivorous fishes, from various geographical areas (Odum and Odum, 1955; Bardach, 1959; Randall, 1963; Clark et al., 1968; Bradbury and Goeden, 1974; Jones and Chase, 1975). Robertson et al. (1979) compared the distribution of herbivorous fishes from Aldabra Island in the Indian Ocean, while Bouchon-Navaro and

Harmelin-Vivien (1981) quantified herbivorous fishes from the Red Sea. This latter study presented the distribution of juveniles and adults in different reef habitats.

The present study examined the distribution and abundance of herbivorous fishes (families Scaridae, Acanthuridae, and Pomacentridae) at different reef sites on the southwestern coast of Puerto Rico. The relative abundances of juveniles and adults were compared. For practical reasons, emphasis was placed on the density and population structure of the scarid *Sparisoma aurofrenatum*, i.e., the distributions of juveniles, females, and males of this species were carefully quantified. This scarid could readily be identified in the field at all sizes and phases.

## MATERIALS AND METHODS

Herbivorous fishes were counted at five reefs: La Gata patch, Pinnacles patch, Turrumote forereef, and two offshore reefs (Salinas and Buoy) located at the edge of the insular platform or shelf-edge (Fig. 1). Herbivorous fishes were generally counted along a transect line varying in length from 35 to 150 m depending on the study site. A transect line was placed permanently on the bottom, in a north-to-south direction, at four of the study sites. This orientation provided a way to sample different habitats at each study site. One study site, La Gata patch, presented difficulties with the line transect method since the bottom was obscured by heavy gorgonian growth. Four counts were made on this patch reef using an imaginary line, i.e., by swimming either a north or south compass course from end to end of the reef. One additional count was made by swimming along the perimeter of the patch reef using the edge as a line. Fish were counted at depths of 5 to 15 m at the three inshore sites and at a depth of approximately 18 m at the offshore sites (Fig. 2). All the herbivorous fishes observed within an estimated two meters to one side of the line were counted while swimming one to two meters above the transect line. The resulting counts included areas varying from 70 to 400 $m^2$ depending on the study site. All counts were made during the morning or early afternoon.

All scarids and acanthurids as well as adult pomacentrids (*Pomacentrus* spp. and *Microspathodon chrysurus*) were counted; the ubiquitous *P. partitus* was not counted since this fish feeds on benthic algae only as a juvenile (Emery, 1973). The number of juvenile and adult scarids and acanthurids were recorded during each count. In addition, the number of initial phase or drab-colored individuals and the number of terminal phase or brightly-colored males were recorded for *S. aurofrenatum*. These categories were readily differentiated by coloration. Some species, such as *S. aurofrenatum*, possess juveniles that differ in coloration from adults and can be readily distinguished from other scarids. In all other species, individuals smaller than approximately 90 mm TL (total length) were considered to be juveniles. Often, juvenile scarids could not be identified to the species level.

Counts were repeated a minimum of four times approximately two times per month at each site from January to February, 1978. Repeated long-term counts, i.e., from February, 1978, to October, 1979, were made only at the Buoy shelf-edge reef. Quantitative comparisons among or between sites were made during the same months of the year whenever possible.

## RESULTS

Herbivorous fishes were either solitary, or were found in groups with fewer than six individuals. The resulting counts were therefore very accurate since small groups could be counted readily in the field while large groups would have necessitated estimating total numbers. The relative abundances of herbivorous fishes, i.e., the proportion of individuals in the three families (scarids, acanthurids, and pomacentrids) differed significantly among the five sites (Table 1; $X^2 = 1{,}555$, df $= 8$, $P < 0.05$). Paired comparisons of the proportions of herbivores between sites showed that only the two shelf-edge sites (Buoy and Salinas) did not differ significantly from each other ($X^2 = 4.50$ df $= 2$, $P > 0.05$). Scarids made up more than 70 percent of the total number of herbivorous fishes at the two shelf-edge sites, but less than 50 percent of the total number at inshore sites. Four species comprised more than 90 percent of scarids at all study sites: *Sparisoma aurofrenatum*, *S. viride*, *Scarus iserti* and *S. taeniopterus*. The percentages of juvenile and adult pomacentrids were very high inshore compared to offshore sites. The distribution of acanthurids did not follow an inshore-offshore pattern, although juvenile *Acanthurus coeruleus* were observed only at inshore sites. Juvenile scarids were observed at all sites, but were more abundant at inshore sites. Juveniles of certain *Scarus* spp. (possessing yellow snouts and lightly colored stripes) were observed almost exclusively in inshore sites.

Median densities of *S. aurofrenatum* juveniles, initial phase individuals, and terminal phase males were compared at the five study sites (Table 2). Individuals smaller than approximately 90 mm TL possessed the juvenile coloration and markings. Juvenile densities did not differ significantly at the five study sites (Kruskal-Wallis Analysis of Variance; $H = 3.56$, $P > 0.05$). However, the densities of initial phase individuals and terminal phase males differed significantly at the five study sites (Kruskal-Wallis Analysis of Variance; $H_1 = 23.03$, $H_2 = 28.14$; $P < 0.01$). Significantly higher densities of initial phase individuals were found on Turrumote forereef and the two shelf-edge sites (Buoy and Salinas) than at the two other inshore sites (Mann-Whitney U-Test; $U_1 = 16$, $U_2 = 16$, $U_3 = 1{,}356$; $P < 0.05$; two-tailed). The densities of terminal phase males and initial phase individuals were not significantly different at the two patch reefs, La Gata and Pinnacles (Mann-Whitney U-Test; $U_1 = 19$; $U_2 = 52.5$; $P > 0.05$; two-tailed). Terminal phase male densities were significantly higher at both Salinas and the Buoy when compared to Turrumote (Mann-Whitney U-Test; $U_1 = 34$; $U_2 = 306$; $P < 0.05$; two-tailed) and did not differ between the two shelf-edge sites (Mann-Whitney U-Test; $U = 80$; $P > 0.05$; two-tailed). Although terminal phase males were not counted in transects, they were observed occasionally at the inshore sites. Ratios of initial phase individuals to terminal phase males averaged 2.4 to 1 at offshore sites and 6.0 to 1 at inshore sites.

Total herbivore densities ranged from 18 to 49 fishes per 100 $m^2$ with the lowest density at La Gata and the highest at Turrumote. Herbivore densities at the Buoy, Salinas, and

Pinnacles were 24, 20, an 27 fishes per 100 $m^2$, respectively. Total scarid densities were 5, 12, 14, 19, and 22 fishes per 100 $m^2$ at La Gata, Pinnacles, Salinas, Buoy, and Turrumote, respectively.

## DISCUSSION

Total herbivore and scarid densities obtained during the present study are compared to those found in reefs from various geographical areas (Table 3). Variations in herbivore densities are large, fluctuating from 4 to 148 fishes per 100 $m^2$, and are due in part to differences in the habitats sampled. Barlow (1975) and Bouchon-Navaro and Harmelin-Vivien (1981) found greater concentrations of scarids on reef fronts than in other reef habitats. In the present study, the highest scarid density occurred at Turrumote forereef (22 individuals per 100 $m^2$).

Young acanthurids are known to concentrate in shallow waters (Randall, 1961a; Robertson et al., 1979; Bouchon-Navaro and Harmelin-Vivien, 1981). Juvenile acanthurids were not found at offshore reefs during the present study and their absence from these reefs may be related to a preference for shallow water, since offshore sites were deeper (18 m) than inshore sites (5-15 m).

In the present study, the density of *S. aurofrenatum* was higher at offshore than at inshore sites. This distribution could be related to the abundance of pomacentrids in shallow inshore sites. *Pomacentrus planifrons*, a highly aggressive herbivorous damselfish known to defend territories from other fishes, particularly herbivores (Thresher, 1976), was almost exclusively restricted in distribution to inshore sites. This fish may competitively exclude scarids, especially juveniles, from food resources in inshore areas. However, Barlow (1975) found large numbers of *S. aurofrenatum* and pomacentrids, including *P. planifrons*, on a reef in Puerto Rico. Thus, the two species can occasionally coexist in the same habitat. Robertson and Warner (1978) found approximately equal relative densities of *S. aurofrenatum* on reefs varying in depth from 3 to 18 m. Offshore areas in Puerto Rico may be attractive to *S. aurofrenatum* for reasons that are not related to food resources or depth.

Equal densities of juvenile *S. aurofrenatum* were found at all sites investigated during the present study. This indicates that juveniles show no preference in depth and larvae may settle at random on reefs. However, no data were obtained on mortality rates of larvae or juveniles and differential predation may affect larval settling rates and juvenile densities. Since adult densities in two of three inshore reefs were low compared to offshore sites, there must have been either greater mortality of fish on inshore reefs, or active migration of adults to offshore reefs. Information on adult natural or fishing mortality was not available, but inshore sites were fished more regularly by local fishermen using non-selective gear (fish traps). It is also not unreasonable to assume that adults can travel from inshore to offshore reefs. Migrations covering from 0.3 to approximately 3 km have been documented in scarids (Randall and Randall, 1963; Winn et al., 1964; Ogden and Buckman, 1973; Colin, 1978; Dubin, 1980; Dubin and Baker, 1982; Clavijo, 1982a; 1982b).

The densities of terminal phase males were higher at offshore sites than at inshore sites. Assuming equal predation rates on males at all sites, either: (1) males were actively migrating offshore, or (2) since *S. aurofrenatum* is a monandric protogynous hermaphrodite and all males are derived from females through sex reversal (Reinboth, 1968; Robertson and Warner, 1978; Clavijo, 1982b), a larger number of females changed sex at offshore than at inshore sites. Initial phase males are either rare or entirely absent in *S. aurofrenatum* (Robertson and Warner, 1978; Clavijo, 1982b) and therefore, the initial phase individuals counted visually during the present study include mostly females. The ratios of females to males were higher at inshore sites than at offshore sites, so inshore sites may have an excess of females capable of changing sex and moving offshore.

The question that remains is why do adult *S. aurofrenatum* concentrate at offshore reefs located close to the shelf-edge. Johannes (1978) suggested that coral reef fishes which produce planktonic eggs and larvae prefer to spawn close to reef edges since currents will then carry their gametes away from reef predators. Barlow (1981) proposed the hypothesis that dispersion is the primary selective force determining the reproductive pattern of coral reef fishes with planktonic propagules. Thus, pelagic or broadcast spawners may be able to maintain a selective advantage by spawning primarily in areas close to shelf-edges where ocean currents facilitate the transportation of larvae. Several scarids actively migrate to reef edges to spawn. *Sparisoma rubripinne* gather at a downcurrent reef edge in order to spawn in groups (Randall and Randall, 1963). *Scarus iserti* also spawn in groups at a reef-edge (Colin, 1978). *Scarus vetula* migrate to the edge of one of the shelf-reefs investigated during the present study in order to pair spawn (Clavijo, 1982a). Thus, it is not unreasonable to conclude that offshore sites represent better spawning areas than inshore sites.

## ACKNOWLEDGEMENTS

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**Table 1. Relative abundances of herbivorous fishes at five study sites.**

| | TOTAL NUMBER OF FISHES | NUMBER OF TRANSECT COUNTS | PERCENTAGE COMPOSITION | | |
|---|---|---|---|---|---|
| | | | SCARIDS | ACANTHURIDS | POMACENTRIDS |
| LA GATA PATCH | 217 | 5 | 30 | 18 | 52 |
| PINNACLES PATCH | 244 | 9 | 47 | 25 | 28 |
| TURRUMOTE FOREREEF | 311 | 9 | 44 | 6 | 50 |
| SHELF-EDGE SALINAS | 158 | 4 | 71 | 28 | 1 |
| SHELF-EDGE BUOY | 2,770 | 38 | 76 | 23 | 1 |

**Table 2. Median densities of *S. aurofrenatum* juvenile (JUV), initial phase (IP), and terminal phase (TP) individuals at five study sites.**

| | TOTAL NUMBER OF FISH | NUMBER OF TRANSECT COUNTS | AREA PER TRANSECT ($m^2$) | DENSITY (NUMBER PER 100 $m^2$) | | |
|---|---|---|---|---|---|---|
| | | | | JUV | IP | TP |
| LA GATA PATCH | 25 | 4<br>1 | 200<br>400 | 1.0 | 1.0 | 0 |
| PINNACLES PATCH | 22 | 9 | 100 | 1.0 | 1.0 | 0 |
| TURRUMOTE FOREREEF | 40 | 9 | 70 | 1.4 | 1.4 | 0 |
| SHELF-EDGE SALINAS | 58 | 4 | 200 | 0.8 | 4.5 | 1.8 |
| SHELF-EDGE BUOY | 779 | 38 | 300 | 1.0 | 3.7 | 1.7 |

**Table 3. Comparison of densities of scarids and total herbivores from coral reefs in various geographical areas.**

| AREA AND SOURCE | DENSITY (NUMBER PER 100 $m^2$) | |
|---|---|---|
| | SCARIDS | HERBIVORES |
| ATLANTIC OCEAN | | |
| BERMUDA (BARDACH, 1959) | 0.5 | 72 |
| VIRGIN ISLANDS (RANDALL, 1963) | 7 | 43 |
| PUERTO RICO (BARLOW, 1975) | 10–14 | 12–32 |
| PUERTO RICO (PRESENT STUDY) | 5–22 | 18–49 |
| RED SEA | | |
| DAHLAK ARCHIPELAGO (CLARK ET AL., 1968) | 6 | 61 |
| GULF OF AQABA (BOUCHON-NAVARO AND HARMELIN-VIVIEN, 1981) | 2–9 | 4–23 |
| INDIAN OCEAN | | |
| ALDABRA (ROBERTSON ET AL., 1979) | 12 | 62 |
| PACIFIC OCEAN | | |
| ENEWETAK ATOLL (ODUM AND ODUM, 1955) | 1.4 | 10.5 |
| GREAT BARRIER REEF (BRADBURY AND GOEDEN, 1974) | 9 | 86 |
| GUAM (JONES AND CHASE, 1975) | 3–30 | 21–148 |
| HAWAII (BROCK, 1979) | 110 | – |

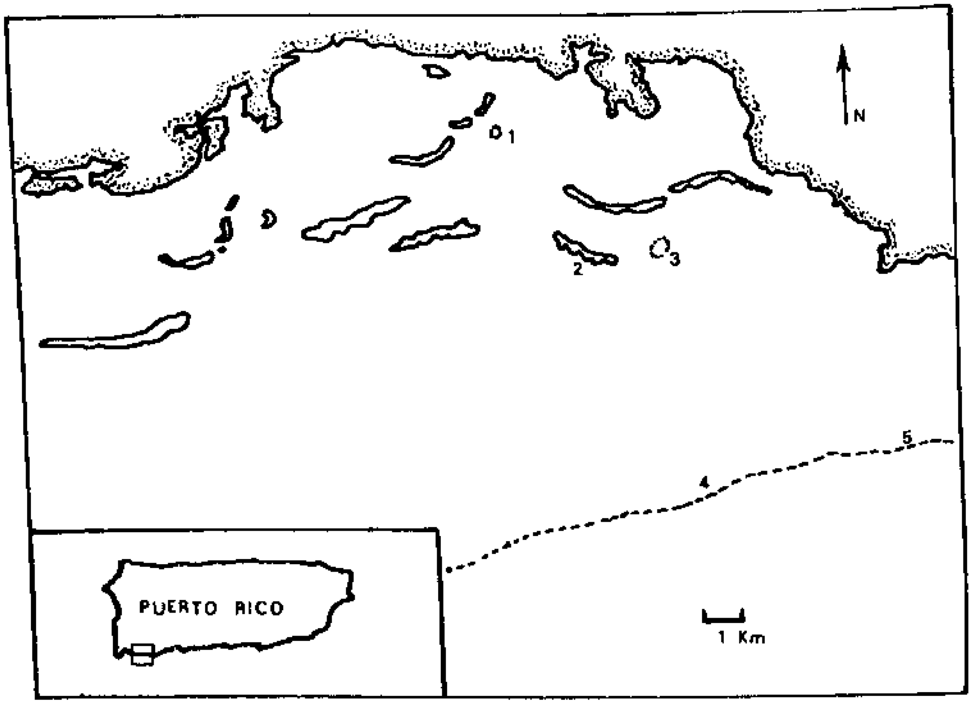


**Figure 1. Map showing study sites: 1 = La Gata Patch Reef, 2 = Turrumote Forereef, 3 = Pinnacles Patch Reef, 4 = Buoy Shelf-edge Reef, 5 = Salinas Shelf-edge Reef.**

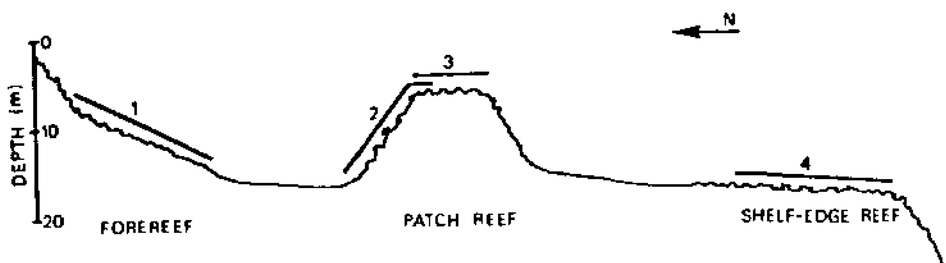


**Figure 2. Depth and orientation of line transects used in counts at study reefs: 1 = Turrumote Forereef, 2 = Pinnacles Patch, 3 = La Gata Patch, 4 = Buoy and Salinas Shelf-edge Reefs.**

# ARCHAEOLOGICAL RESEARCH AT WARM MINERAL SPRINGS, FLORIDA

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*The Warm Mineral Springs archaeological site is comprised of terrestrial and underwater deposits in and around an anaerobic spring-fed 70m deep sinkhole in Sarasota County, Florida. Interdisciplinary research during the past eighteen years has produced a wealth of data about human activity and environmental change over the past 11,000 radiocarbon years. Analysis of the current field season's recoveries has added significantly to existing knowledge of the site and to an understanding of its place in the archaeological record.*

## ENVIRONMENTAL AND PALEOENVIRONMENTAL BACKGROUND

Warm Mineral Springs is a significant archaeological site, not only for the scientific data that it has produced over the past two decades, but also for the technological applications that have been developed and the approaches to method that have been refined there. Aside from questions of technique and method, however, the site provides a look through time back through the last approximately 30,000 years. An understanding of the cultural aspects of Warm Mineral Springs must have as its background an understanding of the physical aspects of Warm Mineral Springs, including the geology, hydrology, and the paleoenvironmental data.

Geologically, Warm Mineral Springs is a solution hole in a karst plateau. Peninsular Florida is underlain by highly porous limestone and many areas are characterized by sinkholes, most of which are shallower in nature (1 to 4 m deep). In the area of Warm Mineral Springs the karst topographic manifestations are quite distinctive, and an aerial view will demonstrate hundreds of shallow and seasonally dry sinkholes that opened up in a time of lowered water table, associated with a lowered sea level. Today in Florida sinkholes are opening up in central Florida where the ground water is being depleted, but in prehistoric times they would open up at times of extreme drought or, principally, through a lowering of sea level. It is hypothesized that Warm Mineral Springs and Little Salt Spring (only 4 km away) opened up at a time of lowered sea level during the terminal Pleistocene, perhaps as early as 30,000 years BP, but certainly by approximately 11,000 BP (Cockrell, 1989).

At Warm Mineral Springs, the cavity itself is today 72 m across (from bank to bank) and is filled with spring-fed water (Figure 1). At 30 m below the surface of today's water, it is only 36 m wide. At the base of the cavity, some 70 m below the surface, it is approximately 70 m wide. Stratigraphically the surrounding terrestrial column from the surface, at approximately 3 meters above sea level, begins with 1 - 2 m post-Pleistocene deposited sand. Underlying the sand is a marine shell marl, the Caloosahatchee Marl, which is approximately 1 m thick and dates from the middle Pleistocene. There is underneath the Caloosahatchee Marl an unconformity from the early Pleistocene back to the Miocene, with the Pliocene being completely absent. The top of the Miocene is the well known Hawthorn Formation, and the Hawthorn Formation occurs all the way through the remainder of the column; it is highly porous and eroded in the walls of the *cenoté*.

The areas above 30 m below the present day water surface were dry for a sufficiently long period of time to allow for the growth of a number of large dripstone formations, principally stalactites and stalagmites, although we also have flowstone occurring as well. The lowest of these dripstones is at 30 m below the surface. We see no speleothem evidence deeper than 30 m below surface to indicate that the water level was ever any lower than that. It is estimated that some of the formations in the band about 13 m below the surface would have taken thousands of years to form by the mechanism of fresh water seep springs dripping down the walls, depositing calcium carbonate over the millennia. In addition to the dripstone formations, there is another significant mineral deposit at Warm Mineral Springs, called tufa, which grows underwater as a result of precipitation of calcium carbonate out of calcium carbonate-charged water that has come into contact with bubbles of trapped CO2. The tufa formations grow principally on the 13 m ledge, in and above the dry deposited sediments, and are a factor to be considered during excavation.

The hydrology of Warm Mineral Springs is critical to understanding the human utilization of the springs in past times as well as the preservation of the materials up to this time. The water in Warm Mineral Springs occurs in three zones today (Cockrell, 1988). The upper zone, or Zone I, extends from the surface down to 7 m below the surface and is generally between 30 to 31 degrees C. It contains a large supply of dissolved oxygen due to the occurrence of aquatic weeds and algaes down to the 7m below surface depth. Zone II of the water extends from 7 m below the surface down to 58 m below the surface. This Zone II normally maintains a temperature of 30 degrees C and is essentially anaerobic in nature. Although there is an oxygen gradient, there is insufficient oxygen in Zone II to allow for any aquatic weeds or marine life to exist. Zone III occurs from 58 m down to the base at 70+m. This water is normally 31 to 33 degrees C and emanates from a cave at the north side of the springs, which goes approximately 30 m toward the north, being only about 3 m wide and 1 m high. The principal water source for Warm Mineral Springs is this cave which terminates at a small crack at the rear of the cave; it is from the crack that the approximately 20 million gallons of anaerobic saline mineralized water a day find their way into Warm Mineral Springs. There are multiple water sources at Warm Mineral Springs - this 20 million gallon a day water source is the principal one (Rosenau *et al.*, 1977). There is a smaller cool fresh water spring on the northeast side that has not been measured as to volume, and there are numerous small seep springs all around the base of the circumference of the diameter of the springs, over the top of the cone of debris on the bottom, and there are fresh water seep springs around the shallower part of Warm Mineral Springs approximately 3 m below surface, primarily as a result of rain water runoff. Additionally, at various places around the wall from 3 m below surface down to 30 m there is clear evidence of interchange with the surrounding ground water. Indeed, given the fact that there is in excess of 20 million gallons a day coming in and only 5 to 8 million gallons a day flowing out the overflow at the southwestern edge of the pool, it is clearly evident that the remaining gallons are seeping out into the highly permeable Miocene limestone that is the matrix of Warm Mineral Springs.

The hydrological column in the surrounding terrestrial strata consists of the surface and ground water which is perched atop the Caloosahatchee Marl, then continues down wherever there are cavities in the limestone to approximately 1,000 meters. At 300 to 1,000 m below surface, the upper zone of the Floridan Aquifer, the water is fresh. Below approximately 1,000 m lies the Boulder Zone of the Floridan Aquifer, and the Boulder Zone contains geothermally heated mineral water. The Boulder Zone produces the approximately 20 million gallons a day of warm saline water that flows into the Springs, and the upper portion of the Floridan Aquifer produces the fresher water, and as noted, the groundwater and rainwater also mixes in. The principal waters, those from the Boulder Zone, contain virtually no dissolved oxygen. The lack of oxygen denies access to aerobic bacteria, and this is the major contributing factor to the unusual preservation of submerged organic remains in the springs. Studies by USGS hydrologist Fran Kohout in the 1970's also demonstrated that no traces of radiocarbon activity could be found in this Boulder Zone water, leading him to estimate that this water had been trapped underneath the earth for more than 60,000 years (Kohout, personal communication).

There are two principal theories as to the origin of this geothermally heated water. One theory is that this water is connate water, ancient sea water that was trapped beneath the Miocene deposits, which would therefore be older than 30,000,000 to 35,000,000 years (Stringfield, 1966). A more recent theory holds that, while the water is indeed ancient, the aquifer is being recharged from far off-shore in the Gulf of Mexico and in the Atlantic Ocean, and that the sea water is migrating laterally to underneath the Florida peninsula; then geothermal heating and great pressure cause the water to rise to the surface through fissures (Kohout *et al.*, 1977). Regardless of origin, the water is essentially anaerobic and this anaerobic condition has led to the preservation of the paleoenvironmental remains, the archaeological remains, and even the dripstone formations in principally the areas below Zone I of the water, or what is today 7 m below the present water surface.

An understanding of sea level change at the end of the Pleistocene is critical to understanding Warm Mineral Springs, as the piezometric surface is directly related to the sea level. As sea level rises, so does the piezometric surface; as sea level falls, so does the piezometric surface. With the dripstone formations demonstrating that the water in Warm Mineral Springs was down at least 30 m below present surface it is possible to speculate that the low stand of the sinkhole's water would relate to the low stand of the sea level during the Pleistocene, and that the rising of the post-Pleistocene sea level to its present day status at approximately 6,000 BP would have positively correlated with the rise of the water in Warm

Mineral Springs, to cause the water to flow over the top at an estimated 6,000 BP (Cockrell, 1989).

Florida is a highly porous limestone peninsula. Today, the surface pores, or sinkholes, when they occur near sea level, tend to be water-filled. During a time of lowered sea level, peninsular Florida would have been topographically much like today's peninsular Yucatan, with virtually no surface drainage; all drainage would be sub-surface. Additionally, it is important to remember that whereas today Warm Mineral Springs is only 20 km from the seacoast, in a time of lowered sea level the Gulf coast would have been approximately 200 km further west. So, Warm Mineral Springs, at the time of lowest sea level stand in the Pleistocene, would have been in the center of the Florida peninsula instead of near the coast, and would have been approximately 100 m above sea level rather than 3 m above sea level. This would not only have resulted in surficial topographic changes, but would have also quite probably contributed to shifts in wind pattern and other climatological events. Other aspects of environmental change would of course relate to the poorly understood causes of the glaciations themselves.

When viewed grossly the sea level change curve seems to be somewhat smooth, but of course it was not smooth at all. Any minor or major fluctuations in sea level, given the porosity of the limestones of the Florida peninsula, would have directly or indirectly correlated with rises and falls of the water in Warm Mineral Springs.

An understanding of the paleohydrological situation when the first humans arrived at Warm Mineral Springs is important. As the people and the plant and animal remains we have recovered would have required at least some fresh water, it is evident that some fresh water was available. The principal water source at Warm Mineral Springs today is not considered potable due to the high concentration of minerals in it. However, in past times, assuming the saline inflow still occurred, the water that was coming in flowed out the porous walls of Warm Mineral Springs, rather than overflowing as it does today (Kohout, personal communication). The fact that this could have occurred is again demonstrated by the fact that nearly 20 million gallons of saline mineral water a day come in, but only 5 to 8 million flow over the top. The surrounding matrix is obviously highly porous and can absorb and diffuse millions of gallons of water a day. At a time of lowered sea level the porous strata around Warm Mineral Springs could have easily absorbed and diffused the entire 20 million gallons a day. The fact that the water was not flowing out of the top is again witnessed by the yet undated dripstone formations and the dated dry-deposited paleoenvironmental remains, as well as the dated intentional human burial on the 13 m ledge. It is clear that the water level was down.

It becomes increasingly obvious, as a result of the interdisciplinary studies we are doing, that there was a fresh water lens in Warm Mineral Springs. Bullfrog bones are found extensively in the 13 m ledge deposits, and no modern bullfrogs can live in saline water; it is assumed that such was the case at the end of the Pleistocene. I believe that when the water level was below the rim of the *cenoté* there was a lens of lighter fresh water overlying the denser saline water. The fact is that we do have bullfrog bones on the 13 m ledge in the 7,000 to 11,000 BP strata and there are no bullfrogs at Warm Mineral Springs today.

Kohout insisted that the inflow of the saline water would have been somewhat constant through time, given the recharge mechanism. The origin of the fresh water, as it is commonly held that the Florida peninsula was arid at this time, is a problem. The dripstone formations are *prima facie* evidence that there was fresh water dripping down at a time of lower water table. Additionally, work by paleobotanists at the Springs demonstrates unquestionably that there were eastern deciduous forest elements present at the Springs at the terminal Pleistocene. There are also deep (40m to 70m) fresh water springs at the bottom of the sinkhole; these springs originate in the upper layers of the Floridan Aquifer, *ca.* 300m down.The 7m to 10m below present surface dripstone formations, which may have taken thousands of years to grow, were formed by the mechanism of fresh water dripping down the walls. This water would have come primarily from rainfall. As noted in the comment on stratigraphic column, the Caloosahatchee Marl occurs about 2 m below the surface. The Caloosahatchee Marl is impermeable, and any rainfall at all would have remained perched on top of the marl, and would have found its way into the Springs. This water would have been principally responsible for the formation of the dripstone formations in the 7m to 10m area. The deepest dripstones are at ca. 30m below surface, and are also undated (an attempt was made to date a dripstone formation through McMaster University in the 1970's, but the formation was too porous to be dated).

The fact is that there was fresh water on the surface of Warm Mineral Springs when the water level in the Springs was lower in past millennia, and there was probably fresh water inflowing at the bottom; additionally, fresh water formed the dripstones. This is critical to understanding the attraction that this site would have had for humans and human food resources. At a time of lowered sea level, when there were no surface rivers, and when there was very little surface water aside from that in deep sinks and caves, this area would have been a source of plant and animal food, as well as fresh water, for these prehistoric peoples. This would have been so even if the era was as arid as some have proposed, although the existence of the 7 to 11 thousand year old well-preserved oak and hickory remains implies considerable available water.

Geohydrological events would have allowed the fresh water lens to continue to float on the saline waters from Paleo-Indian times throughout most of the Archaic, but the fresh water would have ceased being available to both humans and animals once the sea level reached its present day optimum, at about 6,000 years before present. At approximately 6,000 years before present, then, given the interrelationship of the water level at Warm Mineral Springs and sea level, it can be postulated that Warm Mineral Springs waters started flowing over the top. At that time the fresh water lens on the surface would have disappeared and the water at Warm Mineral Springs would have ceased being potable. Interestingly enough, we find very few remains from the Formative Stage, which begins approximately 3000 BP.

In a terminal Pleistocene landscape then, Warm Mineral Springs and the adjacent Little Salt Spring would have been oases of fresh water. Paleoenvironmental studies suggest that at the terminus of the Pleistocene, at approximately the time the first humans came to Warm Mineral Springs, Florida was somewhat more arid than it is today and that there would have been large areas of grasslands. Warm Mineral Springs, as witnessed by the paleoenvironmental data, was surrounded by oak and hickory trees, remnants of an eastern deciduous forest; this does not mean that the entire area was covered by eastern deciduous forest. Warm Mineral Springs may have been an oasis surrounded by a small pocket of eastern deciduous forest. These sites, Warm Mineral Springs and Little Salt Spring, as seen by the remains recovered, were frequented by a wide spectrum of Pleistocene fauna, and the terminal Pleistocene flora is well represented.

The vertebrate paleontological studies and zooarchaeological analyses have demonstrated the existence of Pleistocene fauna at Warm Mineral Springs (McDonald, this volume). Recovered faunal remains include proboscideans, llama, saber cat, giant ground sloth, wolf, deer, panther, raccoon, opossum, fox, numerous rodents, reptiles, amphibians, and invertebrates.

Botanical studies both from macrobotanical and pollen remains have demonstrated that Warm Mineral Springs at the earlier human horizons was surrounded by oak and hickory, as well as a number of other plant species. The topography and environment at Warm Mineral Springs influenced the decision of early scattered small bands, or simply nuclear families, to utilize the site, probably for subsistence at first, and at some point these early peoples began using the site for interment as well.

## ARCHAEOLOGICAL RESEARCH

Archaeologically speaking, the earliest radiocarbon date of human material, an isolated mandible, from Warm Mineral Springs is in a stratum dated at 10,980 +/- 40 BP from the Zone 3 area on the ledge. There has been intermittent human utilization of the site from at least that early through to the present. Prehistorically, Warm Mineral Springs should be viewed as a three-component site. The earliest component, the Paleo-Indian component, thus far has as its early date the 10,980 BP date from the Zone 3 ledge deposits, from which a human mandible was recovered in 1976. Over the years we have found archaeological evidence dating through time up through the Archaic Stage, which at Warm Mineral Springs we are estimating to begin at *ca.* 7,000 BP, and then upward to the Formative Stage, where we recently recovered a bone awl, or possibly a fid, from sediments dated at 2,200 BP. Additionally, we have material on up through the historic period, and into modern times. Material has been falling in Warm Mineral Springs daily for an estimated 30,000 years: on most days, of course, the material falling in would be pollen, which rains constantly down on the surface and then sinks; on other days, Pleistocene megafauna, perhaps even humans, fell into the *cenoté* and were unable to get out.

The estimated age of the opening is based upon information about past sea level changes as well as an estimate that the 30 m thick deposition on the bottom of Warm Mineral Springs is deposited at the rate of about 1,000 years per meter, based on recent radiocarbon analysis of materials from the sediments.

The site contains material from the time of some of the earliest Native American entries into Florida through to modern times. In addition to the three cultural stages, the site has three physical components; that is, the surrounding land area that consists of sandy, acidic well-drained soil that contains very little in the way of preserved material. On land excavations surrounding Warm Mineral Springs we have found *débitage* and a stone tool estimated to be from the Paleo-Indian Stage, along with fossil remains of horse and llama. We have additionally on the land surface found Archaic Stage remains, again consisting of *débitage* and a broken Archaic triangular stemmed point, similar to the Newnan type. We have found no Formative Stage archaeological remains on the surface, but our site records contain a mention that a geologist from the University of Florida collected a piece of pottery from there in the 1950's; this would probably not pre-date 3,000BP. The fact is that there is some scattered cultural material on the surface, but poor preservation has left very little in the way of remains.

The second physical component of the site is that of the 13 m below surface ledge. This 13 m ledge was dry from at least 11,000 BP to approximately 7,200 years BP as witnessed by radiocarbon dating of the dry laid sediments on the ledge. These sediments have produced cultural materials dating around 10,000 to 11,000 BP thus far.

The third physical component of the site is the debris cone on the bottom of the hourglass-shaped sinkhole. The debris cone is estimated to be approximately 30 m in thickness and is approximately 70 + m in diameter. This cone at the bottom of the *cenoté* has been built up by material falling in over the millennia. It is not known at this time whether the actual base of the *cenoté* itself is concave, flat or convex. This debris cone is being excavated currently with the technology described in other papers in this volume. The debris cone has produced human skeletal material, artifacts, and a wealth of paleoenvironmental data. Excavations thus far have proceeded down to 3.3 m in depth, and the deposits are found to be accumulating at approximately 1 m every thousand years.

Human utilization of the site during the Paleo-Indian Stage was, as noted earlier, apparently for subsistence and burial by early gatherer-hunters. Burial Number One, which was radiocarbon dated at 10,240 +/- 80 years BP, was found to contain a spearthrower spur made of carved shell. It is unfortunate that the actual spearthrower itself was not found, but the interment had occurred at 10,240 +/- and the rising springs water did not cover that area until approximately 7200 BP. It can be seen that there was an approximately 3,000 year time period for decomposition to occur and for small rodents to disrupt the area. The burial site was protected by a rockfall from the surface which was dated to *ca.* 8,000 BP. The rockfall created a situation in which three boulders sealed off the burial area until it was opened up in 1972. These early gatherer-hunters, on the land component, had left *débitage* and a tool made from a type of fossil coral which occurs around the Tampa Bay area. There was no cortex material associated with it, indicating that blanks had been brought to this area from elsewhere. An earlier human was found in the 11,000 year old strata, but this time only represented by a male mandible, and it is uncertain as to how it was deposited there, whether intentionally or not, but it was clearly from the *ca.* 11,000 BP stratum. A recently recovered human calcaneum on the 13 m ledge has been dated to 10,260 +/- 70 BP. Untrained collectors since the 1950's have uncovered uncounted numbers of burials, but we were only able to account for about a score of burials by working with one of the people who had extensively looted the site. I have excavated remains of portions of several other individuals over the past two decades. The 13 m below surface ledge was clearly used for disposal of the dead. Burial Number One was intentionally interred in a crevice and sealed with broken dripstones.

The past field season produced two significant artifacts from the ledge, but there is no evidence that they were associated with burial ceremonialism. A worked split fossil shark's tooth was dated at 10,550 +/- 80 BP, and a nearby finely worked bone pin was dated at 10,340 +/- 70 BP.

Additionally, in the 1970's I recovered a human long bone from stratified deposits of organic layered materials in an erosion gully in the debris cone some 60 m below present day surface. There are a number of erosion gullies in the debris cone as a result of sand being dumped in by the truckload over the last three decades in order to provide wading beaches for the bathers; the constant moving of the present day bathers in the water causes the sand to precipitate over the edge and it forms grooves in the limestone walls and erosion channels in the debris cone at the base. One such channel exposed human remains. It is quite possible that the debris cone contains a number of humans who were disposed of by dropping in the sinkhole. This is not an unknown type of burial practice in the southeast. While a student research assistant at the Alabama Museum of Natural History in 1962, I was part of a team that examined a collection of some approximately 200 skeletons that had been cast down a sinkhole, which had a pool of water at the bottom, during the Archaic Stage in the Tennessee River Valley; the practice of casting bodies into cavities in the earth is not unknown in the southeastern United States. Of course, the remains we found on the bottom of Warm Mineral Springs could have possibly been the remains of drowning victims, but I feel that once excavations proceed on the debris cone, there is a great possibility that we will encounter Archaic and Paleo-Indian dead deposited there.

## RESEARCH POTENTIAL

The paleotopography, the general paleoenvironment, and the cultural decisions made by Paleo-Indian, Archaic, and Formative Stage peoples would have governed and regulated the materials that we find in the archaeological record. An understanding of past topography and other past environmental conditions factored in with current understanding of human behavior at these various stages will allow us to postulate where other areas may be examined, where other potential site locations might be found, and where within those loci we would look to find the cultural materials.

A study based on Warm Mineral Springs, Little Salt Spring, and other possible sites, and negative data from other sinkholes which do not have cultural components, will allow the development of a predictive model for predicting other similar related sites either on-shore or off-shore, and the development of a model for the exploration, excavation and study of these sites. In order to construct and test such a model it will be necessary to examine cultural data about particularly settlement and subsistence behavior. It will be necessary to compare the three archaeological stages with which we are concerned here against specific archaeological data from specifically known sites, and then compare those data to provide an indication of where to look for further such sites. Sites such as this can provide invaluably significant data on little known aspects of human prehistory. We know very little about Paleo-Indian behavior, particularly coastal Paleo-Indian behavior in the Florida area; we know virtually nothing about early and middle Archaic coastal behavior in the Florida area. This is primarily because these sites have been drowned and with rare exception have never been located. The utilization of existing data from the preserved sites such as Warm Mineral Springs will provide information for locating these. These sites would be submerged, thus more protected from looters, and protected in some degree from biological destruction as well as weathering and erosion. They would provide a class of data hitherto unavailable, particularly about Paleo-Indian and Archaic Stage peoples.

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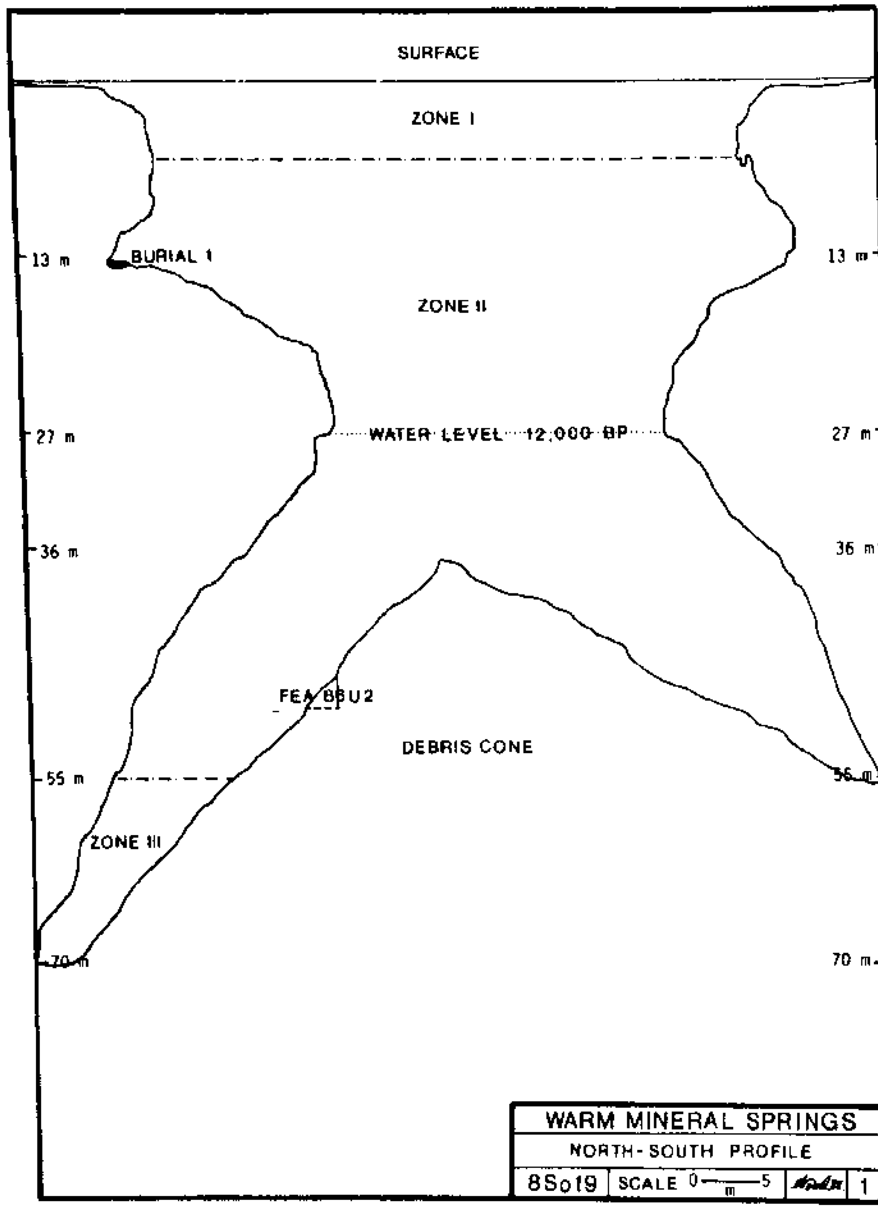
SURFACE
ZONE I
13 m
BURIAL 1
13 m
ZONE II
27 m
WATER LEVEL 12,000 BP
27 m
36 m
36 m
FEA 85U2
DEBRIS CONE
55 m
56 m
ZONE III
70 m
70 m
WARM MINERAL SPRINGS
NORTH-SOUTH PROFILE
8So19
SCALE 0 m 5
1

**Figure 1.**

# SOVIET-AMERICAN-VIETNAM EXPEDITION TO THE SEYCHELLES: SCIENCE DIVING WITH THE RUSSIANS

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*The Soviet-American-Vietnamese Expedition (SAV89) to the Seychelles originated with a request from the Seychelles Government to the Academy of Sciences of the U.S.S.R. for a study of the distribution of marine algae and seagrass resources in the Seychelle Islands. Commercially important species of algae were of particular importance as they might contribute to the economy of the Republic of the Seychelles. The actual goals of the expedition were quite broad but centered on questions dealing with the abundance and distribution of marine organisms and the photophysiology of algae, seagrasses, phytoplankton, and hard and soft corals. SAV89, with over two months of field investigations, was probably the most extensive marine biological research cruise to ever visit the Seychelles.*

*In addition to its scientific importance, SAV89 marked the first time that American marine biologists sailed together with their Soviet colleagues aboard a Soviet research vessel during a marine biology research cruise. The ship, the* Akademic Alexsandr Nesmeyanov, *was 7000 ton displacement, 111 m long, 17m beam, 6.3m draft, and carried a complement of 120 persons, evenly divided between ship's crew and scientific personnel, including 27 certified divers.*

*American participation in SAV89 was the result of perestroika, and a desire for bilateral scientific exchange. To me, it was an opportunity to find out what my Soviet colleagues were really like: what kind of equipment they used, what their underwater research techniques were like, and most importantly, what kinds of scientfic questions were being addressed.*

*The spirit of collaboration and cooperation was stretched to its technical and human limits when two of the Russian divers developed bends symptoms after a series of repetitive dives. The U.S. Embassy arranged for communication with the U.S. Navy Experimental Diving Unit in Panama City, FL and for a U.S. Navy chamber team to fly in. Together with the ship's crew, divers, and scientists, we worked around the clock for four days to save the lives of the two divers. Afterwards, a U.S. Embassy official remarked that he had never seen such close cooperation between Soviet and American embassies anywhere in the world, and that although a tragic situation had brought them all together, some lasting good had been accomplished. The two divers returned to Russia where they have virtually completely recovered from their barotrauma.*

# A REVIEW OF SUDDEN DEATH IN DIVING

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*Sudden loss of consciousness in diving is often followed by sudden death in divers. This paper will review variables that appear to be important to the understanding of this phenomenon. It is clear that risk factors such as age, level of fitness, water temperature and workload can mitigate susceptibility. Less clear are predisposing factors such as fluid balance, psychologic stress, effects of drugs including alcohol and a series of chronic and acute factors identified in the pathogenisis of the onset of sudden death. As the trend toward less frequent physical exams progresses it will be important that the divers improve their ability to assess their individual readiness to participate in specific diving operations.*

Concern regarding sudden unexplained loss of consciousness and sudden death has resulted in considerable literature on the subject. Historically, the evidence marking the precipitation of a sudden loss of consciousness followed by sudden death has centered upon coronary heart disease and myocardial ischemia. Fisch (1985), and his co-workers identified that 90% of sudden deaths are associated with, and most likely related to, coronary heart disease and more specifically to myocardial ischemia. They also state that in 20-25 % of the patients who die suddenly, this event is the first manifestation of their clinical coronary artery disease. They further observed that the major therapeutic effort in controlling sudden death should be directed toward preventing ischemia. The prevention of ischemia represents a challenge for the diving population since there are a number of acute and chronic factors which can be related to ischemia.

James (1985), has provided a partial listing of these factors in his work on sudden death and the following factors are taken from his listing and provided as examples. Acutely, platelete aggregations, coronary spasm, myocarditus, fright, sepsis, hypertension, sudden hypotension, arrythmias, hypoxia, acidosis or alkalosis, fever, dehydration,physical stress and various drugs are known to be factors. Chronically, left ventricular hypertrophy, atherosclerosis, grief, sustained hypertension, some drugs, ethanol, malnutrition, tobbaco smoking, obesity, climatic changes and a variety of heart defects can also contribute to sudden death.

These variables are often difficult to quantify individually and they may be present in a variety of combinations. Physical exams might be of value in the identification of the presence of many of these variables but unfortunately, the exam may not be very helpful as predictor of sudden death since it cannot look ahead to the events which may precipitate such an accident. It appears that the most we can expect from a given physical exam is a fair appraisal of the condition of the organism on the day of the test. In a sense, the exam gives us a type of informed consent based upon our willingness to impose limits on ourselves based upon the nature of the calculated risk we are facing. As often as the concept of knowing ones own limitations has been reiterated in the field of diving, it appears that many of us do not have a perspective that enables us to appreciate the impact of many of the above mentioned variables. It appears that we must learn to evaluate our fitness to perform a particular dive in the context of our ability to handle the demands of the dive without developing stress levels that can trigger a sudden loss control of our physiologic or neurologic equilibrium.

It is quite probable that minimizing emotional stress in diving would reduce the incidence of unexplained sudden death. The autonomic nervous system which regulates the activity of cardiac muscle, smooth muscle and glands plays a key role in this issue. It is a fact that most reasonable individuals know when stress levels begin to rise during an exercise. Where we appear to lack sensitivity is in regard to the level of stress we will tolerate before we take corrective action to reduce the stress level. Increasing the awareness to the warning signs associated with stress may be one of the more important skills that a diver can develop. Eldridge (1979) and Bachrach (1984) have discussed the problems associated with cardiovascular stress and psychologic stress respectively. Both identify psychological stress as a significant factor in the development of cardiovascular stresses which can lead to a sudden cardiac failure. Bachrach (1984) further points out that arrythmias may be induced by cold, fatigue, exercise and emotional stress and can be identified as trigger mechanisms for cardiac disruption. He further postulates that diving accidents cannot occur until control is lost and the demands of the task at hand exceed the performance level of the individual. This viewpoint would argue for an increase in those skills which would operate to provide an early reduction in stress levels regardless of the source. This would require that our training programs focus additional energy upon continual fine tuning of skills that would result in well controlled performance throughout all phases of the dive.

Most effective divers recognize that a loss of self control during dive is extremely dangerous and is usually followed by what I have identified as an "avalanching" phenomenon in which a series of otherwise minor problems become cumulative in their effect. It is under these types of circumstances that the psychophysiologic stressors exceed the individuals ability to exert control. The loss of control precipitates even greater stress loadings and arrythmias are an expected outcome.

Let us, for a moment consider some of the risk factors in sudden death as they might relate to divers. It is important to recognize that divers are subject to all of the risk factors present in the normal population and that, as a result of specific demands on the phsychophsiologic status of the individual divers have additional or emphasized risks. Foremost among these are risks associated with cold. Bachrach (1984) has provided a detailed review of the problem which points out that hypothermia is a major factor in causing disorganized heart rhythm. The electromechanics of heart function can be effected resulting in inefficient pumping action. The increase in oxygen metabolism necessary to maintain core temperature in concert with diving bradycardia and reduced blood flow may contribute significantly to myocardial ischemia. It is expected that variation in tolerance as a result of individual fitness levels will play a significant role in susceptability.

Although a strong correlation appears to exist between sudden death and the individuals fitness level there is some question regarding the ability to predict susceptibility from exercise test. McHenry (1985) has concluded that the prognostic information gained from asymptomatic patients seems to be minimal, probably because the risk for subsequent cardiac mortality is determined in large part by the severity of underlying coronary artery disease and left ventricular dysfunction. He further observed that neither simple nor complex exercise-induced ventricular arrythmias are predictive of subsequent cardiac event in presumably healthy men. This would indicate that testing to rule out existing cardiovascular problems is valid for identifying risk in those who have cardiovascular disorders but not in those who are healthy.

Wolf (1968) looked at neural mechanisms involving vagal effects on the heart as a causative factor in sudden death. He suggests that the hearts connections with the central nervous system may, under certain circumstances result in the heart being permanently "turned off". He noted that the heart rate changes with the rhythm of respiration and that a respiratory-heart rate reflex can induce sinus arrythmia. These observations link the brain to events which are suspect in sudden death. Wolf even postulates that our oxygen conserving reflex could lead to serious arrythmias, cardiac arrest and even death. Distractions and harassment were used in his studies to overcome such events as the diving bradycardia which normally occurs when we submerge our face in cold water. His data showed that the oxygen conserving reflex could be elicited by other stimuli such as fearful experiences in which there was no palpable threat of oxygen deprivation thus, protective reaction patterns can be stimulated with inappropriate regulatory patterns that may aggravate the development of ischemia. It would appear that maintaining higher levels of self control would be worthwhile as a training objective in diving training in order to mitigate the potential for an ischemia producing response to stress or the development of inappropriate neural responses. Surawicz (1985) has stated that ventricular fibrillation, the most common mechanism of sudden unexpected death can be prevented or delayed by adaptation, that is, reduced psychologic stress. He also points out that the threshold for ventricular fibrillation is decreased by acute metabolic acidosis and increased by metabolic alkylosis thus arguing for the avoidance of metabolic acidosis during diving. The avoidance of metabolic acidosis is difficult during exercise since the exercise state produces CO2 and lactic acid and both contribute to a change in pH toward the acid side of the ledger. Strenuous exercise of short duration under anaerobic conditions is a particularly effective acidifier. Increasing exercise tolerance through the improvement of the circulatory capacity and maintaining adequate fluid levels in the body can serve to mitigate this problem.

An intriguing study of cardiac arrythmia as a precursor to drowning accidents was conducted by McDonough and his co-workers (1989). In this study 20 healthy scuba divers were monitored on a 24 hour Holter monitor electrocardiograph on the day of a dive into Puget Sound. He used a classification of premature supraventricular contractions, premature ventricular contractions and complex premature ventricular arrythmias in order to determine their frquency during a predive and dive sequence of activity. His results showed significant increases in all categories during the dives. The totals were 0.13 events during no dive periods of 1 hour and 6.88 events during dive periods for 1 hour. These results were significant at the .001 level. Thus the frequency of all arrythmias was 22 times greater during diving activity periods than non diving periods. He tested the divers at rest and during exercise on an electrocardiograph and found the tests to be insensitive to prediction of arrythmias during the dive. He then tested the divers with ECG during a breathhold, face immersion in 5 degree Centigrade water and was able to detect the majority of those who later developed arrythmias while diving. The results of this study would certainly argue for an increased concern for cold water exposures.

The prospects for the prevention of sudden death do not appear to be forthcoming at this time. The ability to mitigate against its occurrence appear to lie in the identification of pre-existing evidence of cardiovascular instability and disease, maintainance of a high degree of adaptation to the diving conditions, minimizing cold exposure and minimizing psychologic stress during dive. All of these mitigating efforts lie within the control of the individual diver and should be stressed as part of continuing diver education in addition to the basic training.

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# FLORIDA APPROACHES TO MARINE MONITORING

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The Florida Institute of Oceanography (FIO) is an administrative umbrella organization of the State University System of Florida representing the geographically dispersed marine science research community in Florida. The consortium members are the nine public universities, the private University of Miami, Florida Department of Natural Resources, and the Florida Sea Grant College. The Institute provides a forum for initiating and coordinating research vital to the State's responsible conservation and management of the marine environment utilizing the wealth of expertise of its membership and other educational and research organizations. In fulfilling its mission the Institute has long recognized the value of sustained ecological research. This research is necessary for understanding the functioning of ecosystems and for distinguishing natural variability from man-induced impacts. This research must be done on a time and geographic scale appropriate to the ecosystem in question. Funding cycles rarely encompass the time course of natural phenomena such as storms, diseases, and oceanographic-atmospheric events such as ENSO and processes such as global warming trends and sea level rise. Additionally, research at a single site cannot be extrapolated to draw conclusions about the broader system as a whole.

These considerations of scale lead to an integrating concept in Florida. This concept is based on the design of Florida's water management districts which were determined by hydrological zones. The goal of this design was to manage water resources in a manner appropriate to the geographic scale of the resource. The Institute proposes to extend this concept to coastal ocean management with management zones based on biological and physical factors allowing for common research methodology and a coordinated management strategy (Figure 1).

In initiating this plan the FIO has targeted two areas in Florida for pilot studies - the West Florida Shelf and the Florida Keys reef tract. The West Florida Shelf program is in the preliminary stages of development and is not yet funded. However, the need is apparent when one considers the high productivity of the region (including periodic red tides with major ecosystem impact), its great areal extent, and the relative paucity of information available. The major studies in the region were funded by Minerals Management Service to evaluate potential environmental impacts of oil and gas exploration and production activities in the region. These studies were primarily descriptive in nature and not process oriented. In addition, there was no linkage between the water column and the benthos.

The Institute has received funding for the program in the Florida Keys from the John D. and Catharine T. MacArthur Foundation. The program will focus on the reasons for the decline in live coral coverage along the reef tract in the past ten years, keeping in mind that the reef tract is the down stream element in a mosaic of ecosystems commencing at Lake Okeechobee. At least four hypotheses have been advanced to date to account for the decline of live coral and are as follows:

1. nutrification due to agricultural runoff and increased population
2. input of trace metals and pesticides from the same sources
3. stress from the coral bleaching events in 1983 and 1987
4. some combination of the above

The research team has designed a program taking into account the time and geographic scales necessary to evaluate these various hypotheses. The establishment of five core research sites is central to the program (Figure 2). Initial plans are to utilize the NOAA Marine Sanctuary system and other protected areas where possible. The sites selected are Fowey Rocks, Key Largo Marine Sanctuary, Sombrero Reef, Sand Key, and Fort Jefferson National Monument. Each of these sites will be subject to long term continuous monitoring of environmental parameters such as incident and submarine irradiance, air temperature, wind speed, tide and wave height, water temperature at several depths, fluorescence (chlorophyll a), turbidity, and conductivity. These monitoring stations will be automated and data transferred by satellite transmission to the main support facility, the Florida Keys Regional Marine Laboratory on Long Key, roughly midway in the chain of islands. The data will be used to establish long term trends along the geographic scope of the reef tract and as support information for the more site specific studies designed to fill in known data gaps.

Four site specific studies are planned to fill these data gaps and are as follows:

1) Water circulation and transport (N. Smith, Harbor Branch Oceanographic Institution).

The water circulation and transport studies will focus on quantifying water exchange (tidal and non-tidal) between Florida Bay and the reef tract. Secondarily, net transport from the island chain to the reefs will be determined.

2) Coral reef dynamics (J. Porter, University of Georgia; W. Jaap, Florida Department of Natural Resources).

The coral dynamics portion will use photographic recording of quadrates to determine long term changes in coral coverage and growth. This will build on an existing five year library for Key Largo and Looe Key, Key West, Dry Tortugas, Biscayne National Park. The process will be automated to make it more suitable for management purposes.

3) Ecological and physiological indicators of coral health (A. Szmant, University of Miami).

This portion of the program will evaluate a variety of factors influencing coral growth such as incidence of disease, biomass of zooxanthellae, and recruitment. Coral growth will be measured directly using Alizarin Red techniques.

4) Nutrient dynamics (A. Szmant, University of Miami).

The integrated effect of increased nutrients will be assessed using settling tiles (caged and uncaged) to determine the growth of macroalgae. Additionally, macroalgae will be plotted in selected quadrates at the core sites and assessed quarterly to determine seasonal and longer term trends.

While the environmental monitoring stations and site specific studies will provide much needed information to develop effective management strategies for the Florida Keys reef tract, none of these strategies will be effective without broad based public support. It is quite likely that any effective management will involve further restriction of activities on the reef. Therefore, we have incorporated in this program a means of public education via a videotape explaining the relationship of the reef to the larger seascape and how man's activities affect this ecosystem.

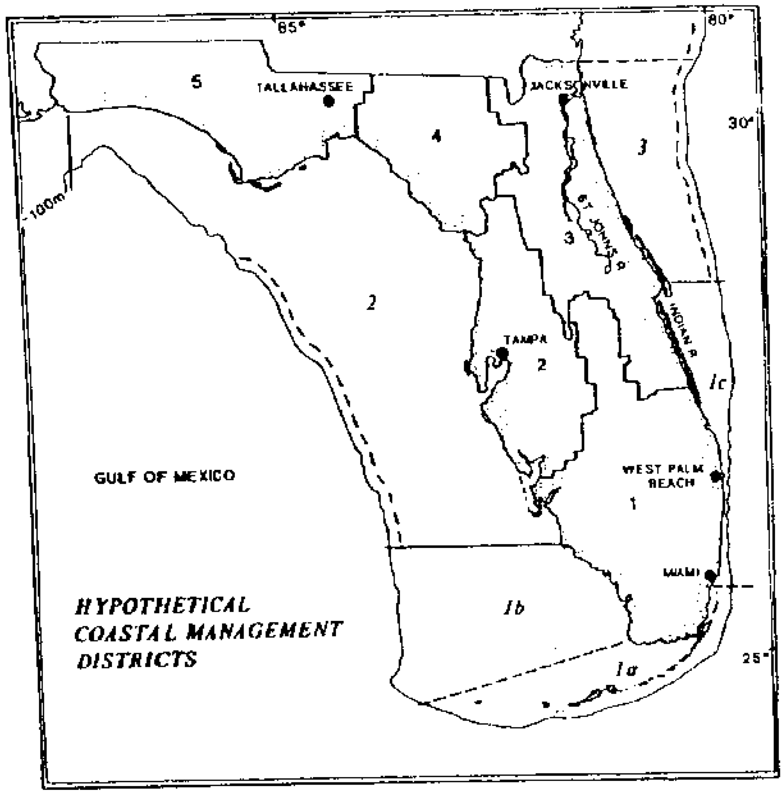
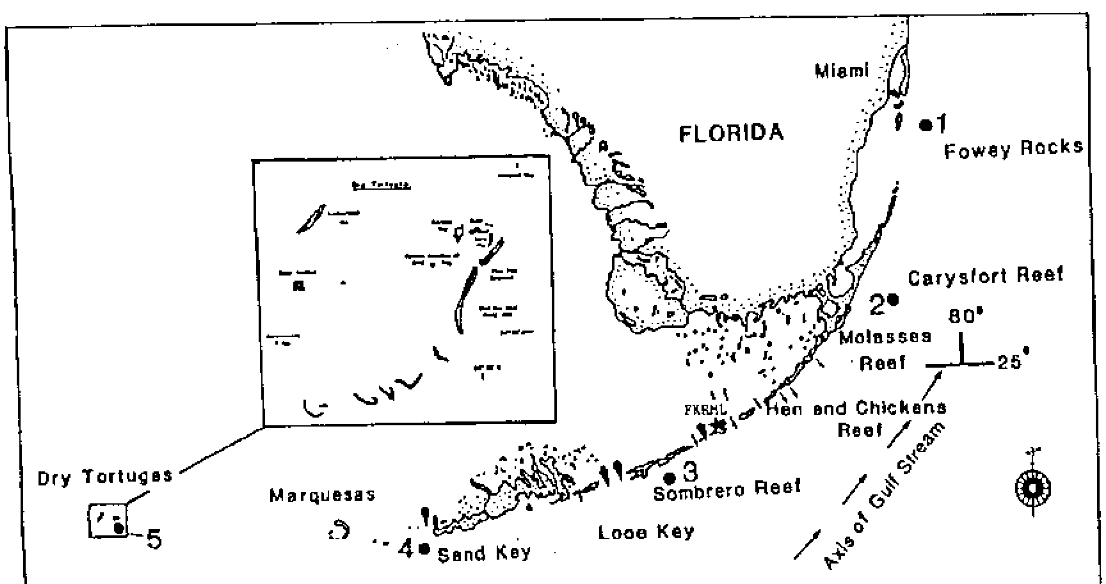



**Figure 1. Hypothetical coastal management districts.**




5. Fort Jefferson National Monument | 4. Sand Key | 3. Sombrero Reef | 2. Key Largo National Marine Sanctuary | 1. Fowey Rocks

**Figure 2. General locations of Core Sites along the Florida Keys reef tract. Water flow from Florida Bay out toward the reef tract is shown by the arrows. The size of the arrows denotes the relative volume of the flow.**

# FIVE YEARS OF CORAL RECOVERY FOLLOWING A FREIGHTER GROUNDING IN THE FLORIDA KEYS

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*Coral community recovery has been followed for five years since the destruction of a portion of Molasses Reef, Key Largo National Marine Sanctuary, by a 122 meter freighter, which ran aground in August 1984. Underwater repetitive and random photographic methods, visual counts, and artificial substrates were used between 1984 and 1989 to assess coral populations, cover, recruitment, and the fate of coral colonies damaged by the grounding. We report here on data and results from random photographic methods and underwater visual censuses. Coral abundances had redeveloped in 1989 from virtually 0% in an area of major impact to a level approximating 65-78% of supposed pre-impact populations though colonies were very small. Cover of hard corals in 1989 was 22% of pre-impact cover, and gorgonian cover approximately 40% of pre-impact cover and tend to have high rates of recruitment. Coral recruitment has been dominated by species which brood larvae. These species are also numerical dominants in mature surrounding communities. Though recovery would occur naturally over an extended period of time, transplantation could be used as a way to increase the relative abundance of species which only rarely have been found as coral recruits. These include primarily the large massive corals conspicuous in typical mature reef communities. Most of these species are broadcast spawners, which have long planktonic stages, low recruitment rates, and low relative abundances in mature communities. Transplantation also restores the habitat complexity essential to the development of the associated invertebrate and fish assemblages characteristic of these diverse ecosystems.*

## INTRODUCTION

In the early morning of 4 August 1984, the 122 m freighter M/V Wellwood ran aground on Molasses Reef, near the southern boundary of the Key Largo National Marine Sanctuary (Figure 1). The damage caused by the grounding was documented by Bright and Andryszak (1984), and Curtis (1985). Some coral population recovery over a 27 month period following the grounding was reported by Bright *et al.* (1987), Gittings and Bright (1988), Gittings (1988) and Gittings *et al.* (1988). Gittings and Bright (1988) reported three categories of mechanical damage on Molasses Reef: damage caused by initial contact, damage by the grounding itself, and damage during ship salvage. In the area of initial ship contact (approximately 8 m depth), large corals along the inbound path protruding substantially above the bottom were abraded, toppled or fractured (within and near Area BS in Figure 2). The *grounding site* itself (6-8 m depth) was the most heavily impacted portion of the reef. In the area under the bow and amidships (Area BB in Figure 2), the broad tops of forereef spurs were ground flat by the ship hull, and linear piles of boulders were formed by the plowing of the port side of the ship as it pivoted on the reef. Nearly all corals were destroyed in an area approximately 1500 $m^2$ which was flattened by the ship. Many corals in depressions survived, but were shaded during the 12 days the ship remained aground, and lost zooxanthellae (symbiotic algae necessary for vigorous growth). This also occurred in corals toppled during the grounding. Significant tissue loss and some mortality occurred as a result of this "bleaching". During *ship salvage,* many corals and large barrel sponges seaward of the grounding site were damaged by tug cables used to pull the vessel off the reef (especially in Area C in Figure 2).

The information presented here represents a portion of work conducted between 1984 and 1989 on coral community assessments at Molasses Reef. Though data were collected from four areas of the accident site between 1984 and 1986 (two damage and two control areas), data presented here are from coral populations in only two areas (one damaged and one undamaged), since the other areas were not sampled after 1986. Also, we present data from underwater counts of small individual corals in square meter quadrats in an area denuded by the grounding.

## METHODS

Field sampling took place quarterly between August 1984 and November 1986, then again in September 1988 and August 1989. During 1988 and 1989, coral population level assessments were made in only two of the four areas sampled in 1984-1986. These were in the area most heavily impacted by the grounding (Area BB in Figure 2) and in one control area (Area XBE). Based on topographic characteristics, depth ranges, and preliminary recovery data, Gittings (1988) suggested that these two areas may have had similar pre-impact coral communities and may eventually have similar communities after recovery.

Random photographic techniques were used to assess hard coral and gorgonian abundance and distribution in Areas BB and XBE. Seventy-two randomly located photos were taken in each area, each providing coverage of 0.5 $m^2$. They were analyzed to determine sizes and numbers of scleractinians, gorgonaceans, hydrozoans, and zoanthideans by species for each area. Areal cover was considered the vertical projection of a colony onto the substrate (like canopy cover in terrestrial ecosystems) and was calculated using a digital planimeter. For upright gorgonians, relative size was determined ("small" being 0-10 cm height, "medium" 10-30 cm, and "large" over 30 cm).

To obtain percent cover estimates which included information on gorgonian corals, measurements of percent cover were also made using a point-intercept technique. Clear acetate overlays containing 100 randomly located points were laid over photographs. Colonies under each point were counted. The total number of points occupied by each group (hard corals or gorgonians) on a photograph represented one estimate of percent cover.

Recruitment was assessed from random photographic data making underwater counts of juvenile corals in Area BB. Numerical abundances on random photographs were compared between sampling periods. Recruitment rates were determined in terms of net increases in individual groups (gorgonians, scleractinians, and hydrozoans) and species, where possible. In November 1986, September 1988, and August 1989, underwater counts in 1 $m^2$ quadrats were made in Area BB to determine the population of recently settled corals in the area. During each of these periods, scleractinians, gorgonians, hydrozoans, zoanthideans, and selected associated invertebrates were counted in 18 quadrats. Samples were spaced approximately 1 m apart on a line from the southernmost to the northernmost portion of Area BB. The substrate was visually inspected, spending approximately five minutes per quadrat searching for and enumerating the inhabitants. This visual method was employed because some juvenile corals are found predominantly on the undersides or sides of reef surfaces, and may not be accounted for using down-looking photographic techniques.

## RESULTS

Figures 3 and 4 compare abundances of scleractinian and gorgonian corals in Areas BB and XBE from 1984 to 1989 (confidence intervals are not displayed on figures, since they are reflected in multiple range groupings below). For hard corals, statistical analyses indicate significant differences between time periods in Area BB, but no significant differences between periods for Area XBE. Differences in Area BB are illustrated below (sample periods underlined together are Tukey multiple range test groupings which are not significantly different at $P = 0.05$ *using a Kruskal-Wallis Test; abundance increases from left to right):*

**Hard Coral Populations in Area BB: $F = 30.61$, $p < 0.0001$**

| Dec | Nov | May | Mar | Mar | Nov | Aug | Jun | Aug | Sep | Aug |
|---|---|---|---|---|---|---|---|---|---|---|
| 85 | 84 | 85 | 86 | 85 | 86 | 86 | 86 | 85 | 88 | 89 |

Tukey groupings below reflect the fairly consistent increase in gorgonian population levels with time:

**Gorgonian Coral Populations in Area BB: F = 110.58, p < 0.0001**

| Dec | May | Mar | Nov | Mar | Aug | Jun | Aug | Nov | Sep | Aug |
|---|---|---|---|---|---|---|---|---|---|---|
| 85 | 85 | 85 | 84 | 86 | 85 | 86 | 86 | 86 | 88 | 89 |

Bright *et al.* (1987) and Gittings (1988) showed that population levels in Area BB had not recovered by November 1986. Though coral population levels increased significantly with time in Area BB after 1986, they were still statistically distinguishable from those of Area XBE for both scleractinian and gorgonian corals in 1989. That is, scleractinian and gorgonian coral populations were still significantly lower in Area BB.

Figure 5 compares the numerical abundance of scleractinians, gorgonians, and all hard corals combined (scleractinians plus *Millepora* spp.) relative to populations of these groups in Area XBE. The data suggest population recovery of some 78% for scleractinians, 57% for all hard corals, and 65% for gorgonians.

Percent cover of hard corals, gorgonian corals, and total coral cover all were significantly lower in Area BB than XBE during all sampling periods between 1984 and 1989 (p < 0.0001). Within Area BB, however, percent cover increased significantly with time for all three groups, especially after 1986. Tukey groupings of sample periods are given below for each group (percent cover increases left to right, except in cases when certain months had to be reversed due to multiple range test pairings):

**Hard Coral Cover in Area BB: F = 8.93, p < 0.0001**

| Nov | May | Dec | Nov | Mar | Jun | Mar | Aug | Aug | Sep | Aug |
|---|---|---|---|---|---|---|---|---|---|---|
| 84 | 85 | 85 | 86 | 86 | 86 | 85 | 86 | 85 | 88 | 89 |

**Gorgonian Coral Cover in Area BB: F = 107.54, p < 0.0001**

| May | Mar | Dec | Jun | Aug | Mar | Nov | Aug | Nov | Sep | Aug |
|---|---|---|---|---|---|---|---|---|---|---|
| 85 | 86 | 85 | 86 | 85 | 85 | 84 | 86 | 86 | 88 | 89 |

**Total Coral Cover in Area BB: F = 60.48, p < 0.0001**

| May | Dec | Mar | Nov | Jun | Mar | Aug | Nov | Aug | Sep | Aug |
|---|---|---|---|---|---|---|---|---|---|---|
| 85 | 85 | 86 | 84 | 86 | 85 | 85 | 86 | 86 | 88 | 89 |

Gorgonian cover increased from virtually 0% of that in Area XBE early in the study to approximately 40% of cover in Area XBE by August 1989 (Figure 6). Hard coral cover has increased from an average of 12.4% of cover in Area XBE during the initial 27 month study to 22.1% in 1988 and 1989.

The abundances of small, medium, and large gorgonians for Areas BB and XBE (Figures 7 and 8) indicate a disproportionately low population of large gorgonians in Area BB. Small and medium gorgonians, however, dominated in both areas. The paucity of large specimens reflects the lack of age class structure recovery, even though numerical populations probably approximate 65% of pre-impact levels.

Table 1 shows the abundance of various taxa in 18 quadrats in which underwater counts were made by a diver during 1986, 1988, and 1989. These quadrats were located along transects in Area BB, and were in the same general location, but were not repetitively sampled. Scleractinian and gorgonian data show a gradual and significant increase in coral populations in Area BB between 1986 and 1989, which is consistent with data from other elements of the study. The total number of corals in 1989 was approximately $20.8/m^2$, with gorgonians and scleractinians having approximately equal populations (nearly $10/m^2$ each), and accounting for nearly 95% of all corals with *Millepora* spp. representing 5%. There has been little change in *Millepora* sp. abundance. Note that scleractinian population estimates made by visual censuses were approximately twice as high as those made using random photographic techniques. Gorgonian population estimates were nearly the same using both techniques (compare data in Table 1 and Figure 3). This reflects the preference of juvenile hard corals for the sides and undersides of reef surfaces in shallow water rather than surfaces exposed to direct sunlight (e.g. Lewis, 1974). Apparently, young gorgonians do not exhibit such a preference.

Stony coral recruitment that occurred over the first five years of recovery was dominated numerically by *Favia fragum, Agaricia agaricites, Porites* sp., and *Millepora alcicornis*. Along with *Pseudopterogorgia* spp. the dominant gorgonians, these species accounted for 90% of all corals in the area in 1989 (Table 1). Nevertheless, the number of coral species represented in the samples has also increased gradually. This is due primarily to the increase in richness of the scleractinian fauna. The number of gorgonian species observed has apparently decreased with time.

Among the dominant hard corals, *Favia* in particular represented a significantly higher proportion of the numerical population in Area BB than in Area XBE in 1988 and 1989 (18-25% vs. 2-3%, as estimated from random photographs). More equal relative abundances were found in these areas through 1986 (Gittings, 1988). *Favia fragum* abundance remained constant between 1984 and 1986, increased significantly after 1986, then increased again between 1988 and 1989 ($F = 30.40$, $p < 0.0001$; using Kruskal-Wallis Test and Tukey Multiple Range Test groupings).

*Millepora* spp., on the other hand, represented only 16-18% of all reef corals on random photos in Area BB during 1988 and 1989 and 37-45% in Area XBE. During the initial study, *Millepora* sp. represented over 40% of the population in Area BB, which was comparable to other areas. The increase in the number of Favia colonies resulted in the decreased relative abundance of *Millepora*. Though significant differences in *Millepora* spp. populations occurred between periods ($F = 4.97$, $p < 0.0001$), no long-term increase was observed.

The relative abundance of *Porites* spp. also increased from 1988 to 1989 in Area BB (from 6 to 21%). Population density also increased after 1988 ($F = 24.05$, $p < 0.0001$). In 1984-1988 samples, these corals represented 1-6% of hard corals in Area BB and population levels had been similar ($p > 0.05$). They have consistently represented 8-10% in Area XBE.

*Agaricia* populations remained stable in Area BB through 1986 ($p > 0.05$). Significant increases occurred between 1986 and 1988, and between 1988 and 1989 ($F = 17.30$, $p < 0.0001$). Relative abundance in Area BB increased from approximately 9% of hard corals during 1984-1986 to 14% in 1988 and 18% in 1989. Relative abundance of *Agaricia* in Area XBE has remained between 18 and 25% since the grounding.

Generally speaking, the massive corals such as *Montastraea* spp., *Diploria* spp., and *Dichocoenia stokesi*, which were conspicuous in surrounding habitats, were only rarely encountered in Area BB. Their relative abundances, however, were similar in both areas. Therefore, though conspicuous due to their larger size in undisturbed habitats, these corals do not represent numerically dominant species in any area.

The 1988-89 data indicate that gorgonian recruitment in Area BB was dominated by *Pseudopterogorgia* spp. Most of these were *P. americana*, which represented 71-81% of all gorgonians in Area XBE. Until 1989, this relative abundance also occurred in Area BB. In 1989, however, the proportion of *Pseudopterogorgia* in Area BB was 91%, suggesting significant recent recruitment relative to other gorgonian species. *Pseudopterogorgia* abundance began to increase significantly after June 1986, then continued between 1986 and 1988 and between 1988 and 1989 ($F = 111.30$, $p < 0.0001$).

Conspicuously absent or rare species in Area BB in 1989 included *Briareum asbestinum* and *Gorgonia ventalina*. *B. asbestinum* was not found in Area BB in 1989, even though it represented 8.1% of gorgonians in Area BB during the initial study, and averaged 11-14% of gorgonians in Area XBE over the entire study period. No significant differences were found between sample periods for this species ($F = 0.88$, $p < 0.55$). A low relative abundance of *G. ventalina* might be expected in Area BB, since values in Area XBE averaged between 1 and 3% over the study period. In 1988, however, the relative abundance of *G. ventalina* in Area BB was 24%. The absolute abundance was four times higher than in 1989 (significant differences; $F = 21.63$, $p < 0.0001$). In fact, population levels in September 1988 were significantly higher for *G. ventalina* in Area BB than all other sample periods.

## DISCUSSION

### *The Status of Reef Recovery*

By the end of the summer of 1989, estimated scleractinian abundance in Area BB was approximately 78% of that in control Area XBE, and gorgonian abundance was 65% of that in the control area. These levels are higher than would have been predicted from extrapolation of data collected between 1984 and 1986 (see Gittings, 1988). This is because recruitment rates have increased with time. Figure 9 shows a curve that accounts for much of the variability in the population data (a second order polynomial) in Area BB ($r^2 = 0.975$). Extrapolation of these data would suggest numerical population recovery at a time approximating six years following the grounding. When such a model is applied to individual groups, complete scleractinian population recovery would be predicted at 65 months and gorgonian population recovery at 72 months. We are currently in the process of developing a model that more accurately reflects natural conditions than the polynomial applied. However, initial evaluations suggest that the polynomial curve estimates are fairly accurate over the time periods involved in this study. For example, complete numerical recovery is estimated at approximately 80-85 months for total corals for the model being developed as opposed to 70 months by the polynomial. This is because recruitment rates are expected to decrease as the carrying capacity of the habitat is approached, a factor not accounted for by the polynomial.

A similar evaluation of percent cover suggests average recovery through 1989 of some 35% for all corals (40% for gorgonians, and 22% for hard corals). As recruitment rates currently appear to be increasing with time, and as areal cover of individual colonies increases as the square of colony radius, the percent cover recovery rate should also increase with time.

As suggested by the percent recovery estimates given above, however, gorgonian corals, which grow much faster in area than stony corals, have contributed most significantly to the recovery of cover on the reef. Percent cover of gorgonians, therefore, would be expected to approach control levels much faster than stony coral cover. Extrapolation of best fit curves on percent cover data suggest that, if recovery continues to increase at a rate comparable to rate increases between 1984 and 1989, control community percent cover could be reached in Area BB at approximately seven years for gorgonians ($r^2 = 0.965$), and 12.5 years for hard corals ($r^2 = 0.192$).

Nevertheless, several other community characteristics must also develop in addition to numerical population and percent cover recovery in Area BB before community recovery can considered complete. These include, but may not be limited to, recovery of an age class structure similar to that of control areas, development of three-dimensional habitat structure in the area comparable to that in control areas, and development of a diverse community of associated reef algae, reef invertebrates and fishes.

Species dominating the recovery community in Area BB are the same as those dominating mature communities in areas surrounding the grounding site. However, relative abundances changed considerably over the course of the study. The scleractinian coral species dominating Area BB (*Favia fragum, Porites* sp., and *Agaricia agaricites*) have been described by van Moorsel (1983) and Szmant (1986) as having reproductive strategies involving larval brooding rather than gamete broadcasting and external larval development. Planulae released from brooding adults are able to settle soon after release and may colonize areas near parent colonies. This strategy is characteristic of species with small colony size, multiple reproductive cycles per year, and high recruitment rates, and are generally species in unstable habitats. They are analogous to r-selected, opportunistic species in some respects (Pianka, 1970), especially in their ability to colonize substrates made available through removal of other organisms, as occurred during the ship grounding. Thus, a high relative abundance of these species in the early recovery community should be expected.

On the other hand, species occurring in surrounding habitats that broadcast gametes, such as *Montastraea annularis, M. cavernosa, Diploria strigosa, Acropora* spp., and *Siderastrea siderea* might be expected to colonize Area BB at a much slower rate and reach maximum abundance in a more mature recovery community. These species have, until now, been found only occasionally in Area BB. Such species generally occur as larger colonies than brooding species, and adults have only one spawning period per year (Szmant, 1986). They become conspicuous in mature communities due to their size, and contribute substantially to coral cover on the reef, but may not be numerical dominants.

For gorgonian corals, there appears to have been a recent shift in the community in Area BB to a more monospecific assemblage, dominated by *Pseudopterogorgia* sp. (predominantly *P. americana*). Unfortunately, very little is known about gorgonian reproductive strategies (Brazeau and Lasker, 1989), making recovery patterns difficult to interpret. Unlike most scleractinian species, most gorgonians are thought to contain separate sexes, have internal fertilization, and brood larvae. The known brooding species include *Briareum asbestinum, Eunicella singularis, E. stricta, Muricea californica,* and *M. fruticosa* (see references in summary table in Brazeau and Lasker, 1989). *Pseudopterogorgia bipinnata*, which occurs on Molasses Reef and is a congener of the most abundant species in the recovery community in Area BB (*P. americana*) is a broadcasting species. The abundance of *Pseudopterogorgia* colonies in Area BB, however, and the dominance of these species in surrounding habitats, suggests that these species are probably brooders and parent colonies are local.

### *Implications for Amelioration*

The study conducted over the first 27 months following the WELLWOOD grounding resulted in a number of suggestions for potential ameliorative measures that might minimize secondary damage and enhance recovery following mechanical disturbance to reef communities. These measures included fine sediment removal, rubble removal, and coral transplantation into denuded areas. Sediment removal can enhance recruitment and can increase habitat complexity (Gittings *et al.*, 1988). Rubble removal reduces secondary damage caused by resuspension during storms and increases bottom stability (Endean and Stablum, 1973; Wulff, 1984; Gittings, 1988). Coral transplantation may increase recruitment in denuded areas (Gittings *et al.*, 1988), increases habitat complexity (Maragos, 1974; Gabrie *et al.*, 1985), and has aesthetic value (Shinn, 1976).

Recruitment data suggest that coral reproductive strategies should be considered in decisions regarding species to be included in a transplantation program. It is apparent that a number of species quite naturally become abundant in very few years in denuded habitats (e.g. *Agaricia* spp., *Favia fragum*, and *Porites* spp., *Pseudopterogorgia* sp.). At least for scleractinians, young colonies of these species probably arise from brooded planulae from local populations. Furthermore, these species tend to be small and abundant rather than large and conspicuous. In fact, large colonies tend to be much less abundant. Therefore, it makes little sense to include most brooding species in a transplantation program.

Corals that might be considered for transplantation should be chosen from large, massive broadcasters, which on Molasses Reef include *Montastraea annularis, M. cavernosa, Diploria strigosa, Siderastrea siderea*, and possibly *Acropora* spp., among others. These corals generally broadcast gametes into the water column, where fertilization takes place, and dispersal is often over long distances (Szmant, 1986). Successful recruitment is fortuitous and larval mortality high, but survival of colonies, once a safe size is reached, can be high. As with all massive corals, these species are slow growing (excepting *Acropora* spp.). Because such species are usually found in mature communities as large colonies in relatively low abundance, these types of species would be the best candidates for reef restoration. It should be recognized, however, that even without transplantation, these species occurred in 1989 in relative abundance comparable to the control area. They would, therefore, be expected to recover naturally over a long period of time to the pre-impact age class structure. But the chances for natural recruitment into any restricted area for these species are low, and natural recovery time can, therefore, be considerable. Furthermore, while transplantation offers the community sexually reproductive individuals, more importantly it provides the habitat complexity necessary for recovery of the full complement of reef invertebrates and fishes that characterize these diverse assemblages.

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**Table 1. Quadrat counts made underwater by a diver in 1986, 1988, and 1989. Visual counts of Scleractinia, and other conspicuous taxa were made in eighteen 1-m2 quadrats during each year.**

| Taxa | Nov 1986 (#/$m^2$) | Sep 1988 (#/$m^2$) | Aug 1989 (#/$m^2$) |
|---|---|---|---|
| **Scleractinia** | | | |
| *Acropora cervicornis* | - | 0.06 | 0.06 |
| *Agaricia* sp. | 0.28 | 1.17 | 2.22 |
| *Dichocoenia* sp. | - | - | 0.22 |
| *Diploria strigosa* | - | - | 0.06 |
| *Diploria labyrinthiformis* | - | - | 0.11 |
| *Diploria* sp. | 0.11 | 0.11 | - |
| *Eusmilia* sp. | 0.06 | - | - |
| *Favia fragum* | 0.44 | 1.00 | 2.17 |
| *Montastraea annularis* | - | 0.06 | - |
| *Montastraea cavernosa* | 0.11 | 0.33 | 0.39 |
| *Mussa*? sp. | - | - | 0.17 |
| *Porites* sp. | 0.33 | 1.72 | 4.22 |
| *Siderastrea siderea* | - | - | 0.17 |
| *Siderastrea radians* | - | - | 0.06 |
| *Siderastrea* spp. | - | 0.22 | - |
| *Stephanocoenia michelini* | - | - | 0.11 |
| **Total Scleractinia** | 1.33 | 4.67 | 9.94 |
| Std. Error | 0.35 | 0.62 | 1.09 |
| **Gorgonacea** | | | |
| *Briareum asbestinum* | 0.06 | 0.06 | - |
| *Gorgonia ventalina* | 0.06 | 0.28 | 0.67 |
| *Plexaura* sp. | - | 0.06 | - |
| *Plexaurella* sp. | 0.06 | - | - |
| *Pseudopterogorgia* spp. | 1.39 | 4.72 | 9.11 |
| *Pterogorgia citrina* | 0.06 | - - | |
| **Total Gorgonacea** | 1.61 | 5.11 | 9.78 |
| Std. Error | 0.30 | 0.97 | 1.15 |
| **Hydrocorallina** | | | |
| *Millepora* spp. | 0.83 | 1.28 | 1.06 |
| Std. Error | 0.25 | 0.30 | 0.27 |
| **Total Corals** | 3.78 | 11.06 | 20.78 |
| Std. Error | 0.59 | 1.10 | 1.45 |
| Total Coral Taxa | 12 | 13 | 15 |

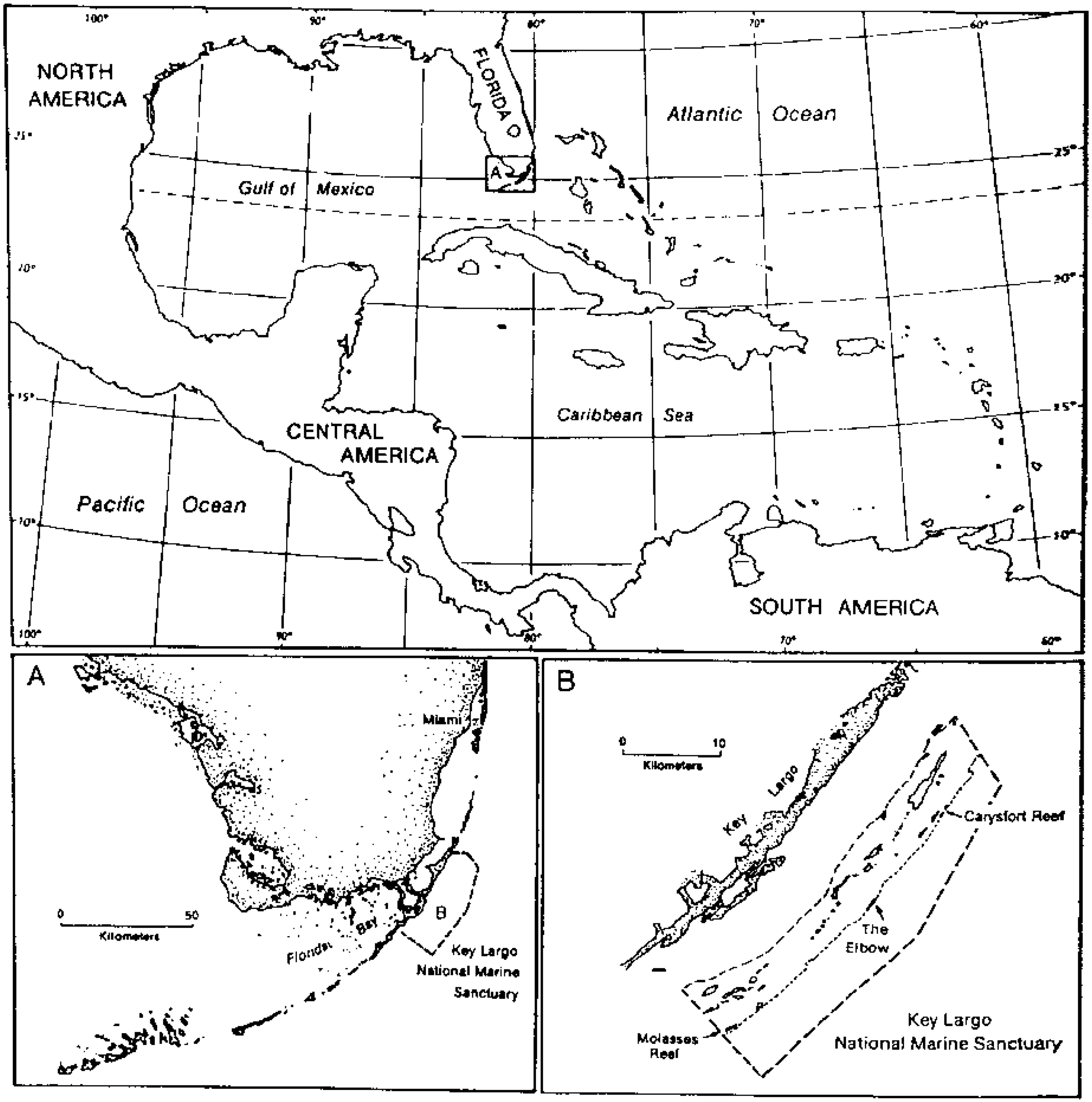


**Figure 1. Chart of the Caribbean Sea and Gulf of Mexico showing the locations of the Florida Keys (A), the Key Largo National Marine Sanctuary (B), and Molasses Reef.**

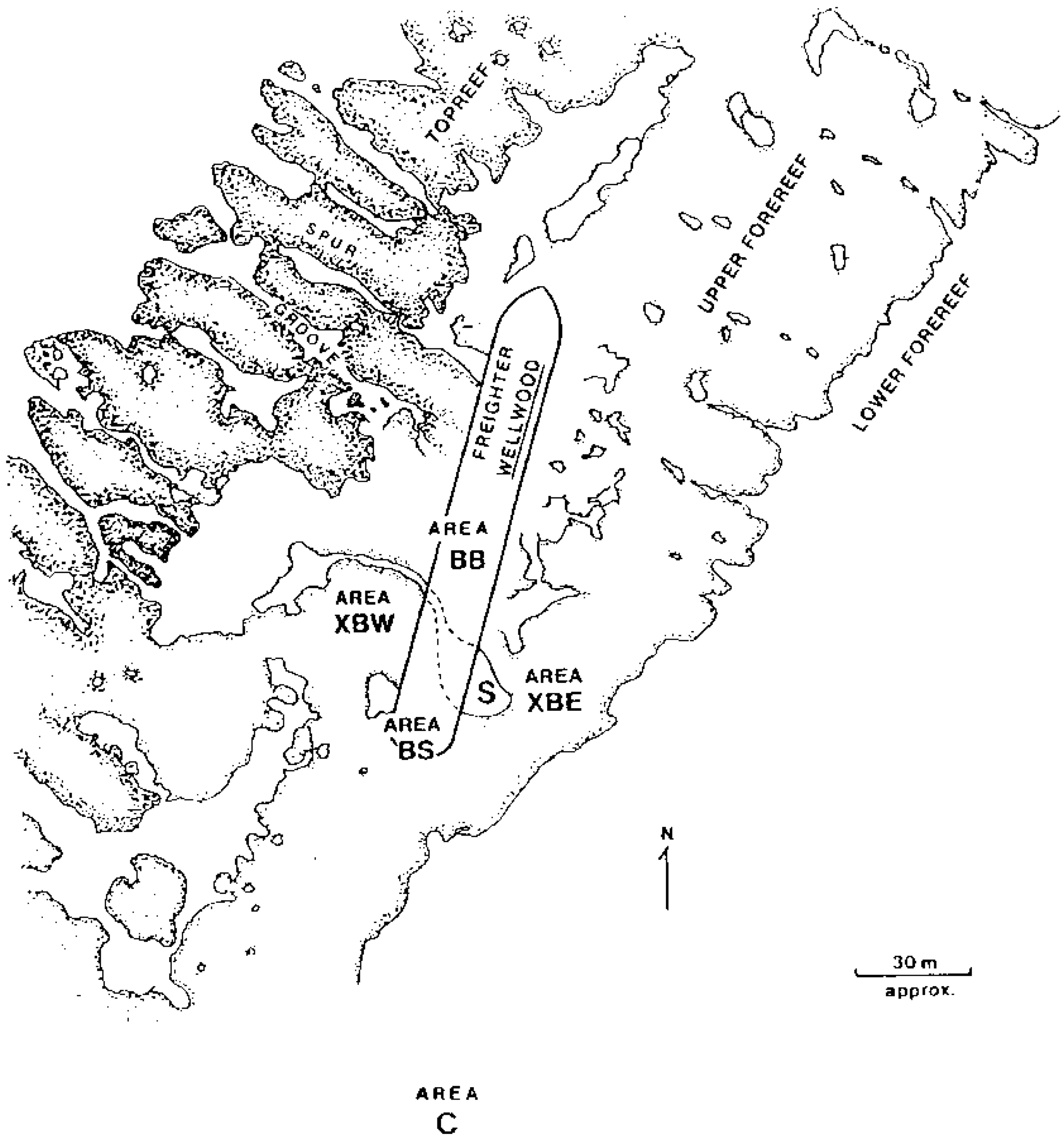


**Figure 2. Locations of the freighter WELLWOOD, hard aground between 4 and 16 August 1984, on the upper forereef of Molasses Reef, Key Largo National Marine Sanctuary (shallow water to the northwest, deeper water to the southeast).**

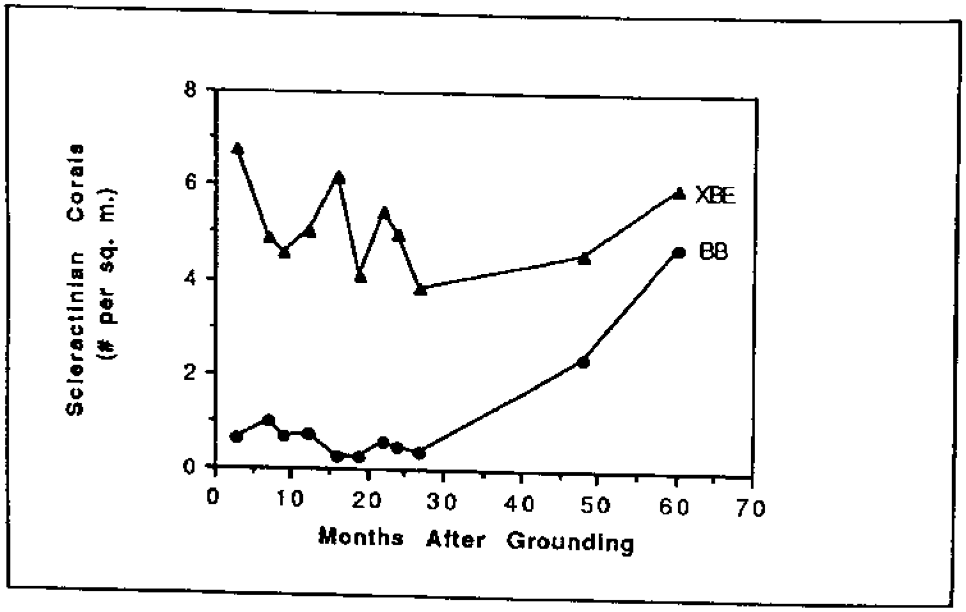


**Figure 3. Scleractinian coral population in Areas BB and XBE between November 1984 (three months following the grounding) and August 1989 (month 60) as estimated using random photography.**

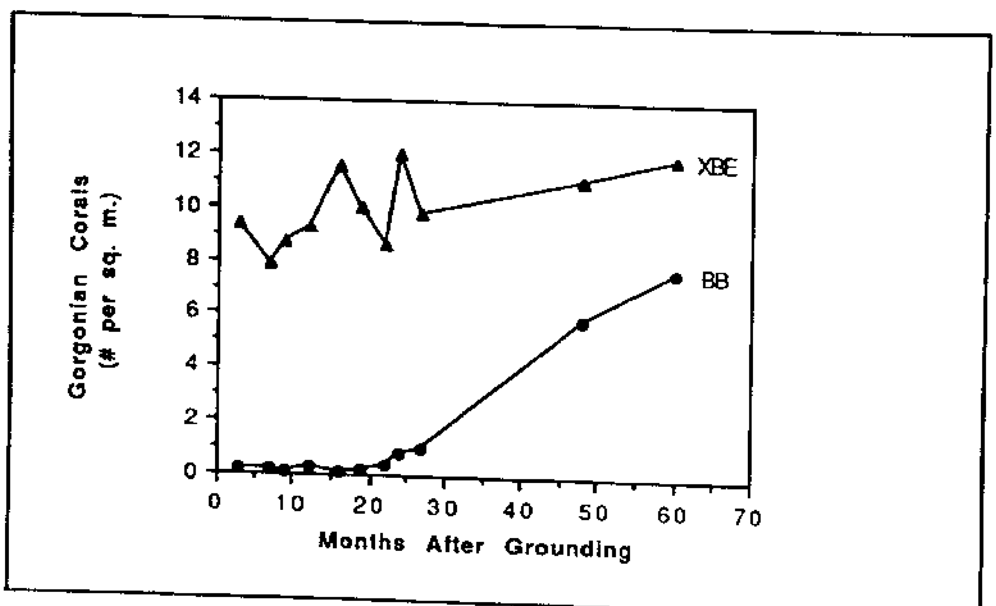


**Figure 4. Gorgonian coral population in Areas BB and XBE between November 1984 (three months following the grounding) and August 1989 (month 60) as estimated using random photography.**

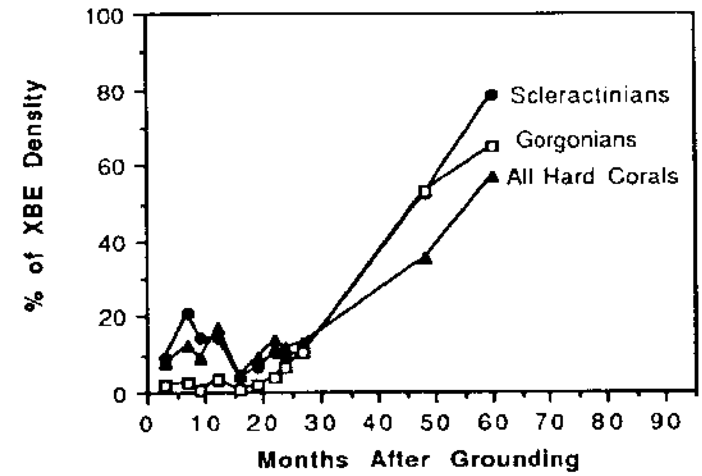


**Figure 5. Populations of scleractinians, all hard corals combined (i.e., including Millepora spp.), and gorgonians in Area BB, expressed as percent of corresponding population in Area XBE for the five years since the grounding.**

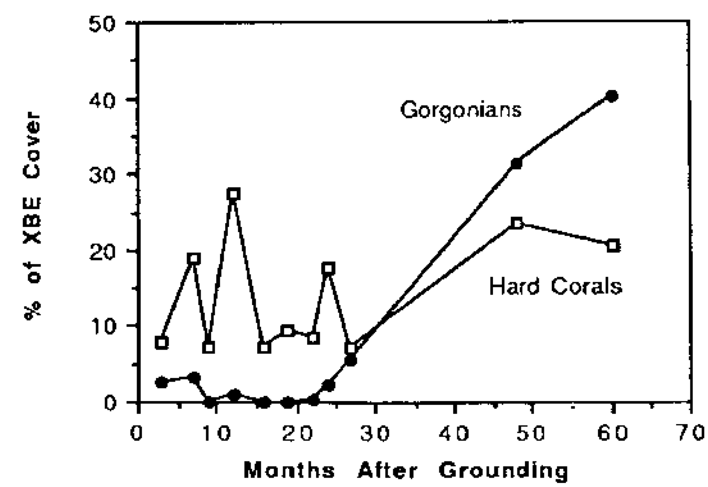


**Figure 6. Percent cover of gorgonians and stony corals in Area BB between 1984 and 1989, expressed as percent of corresponding cover in Area XBE.**

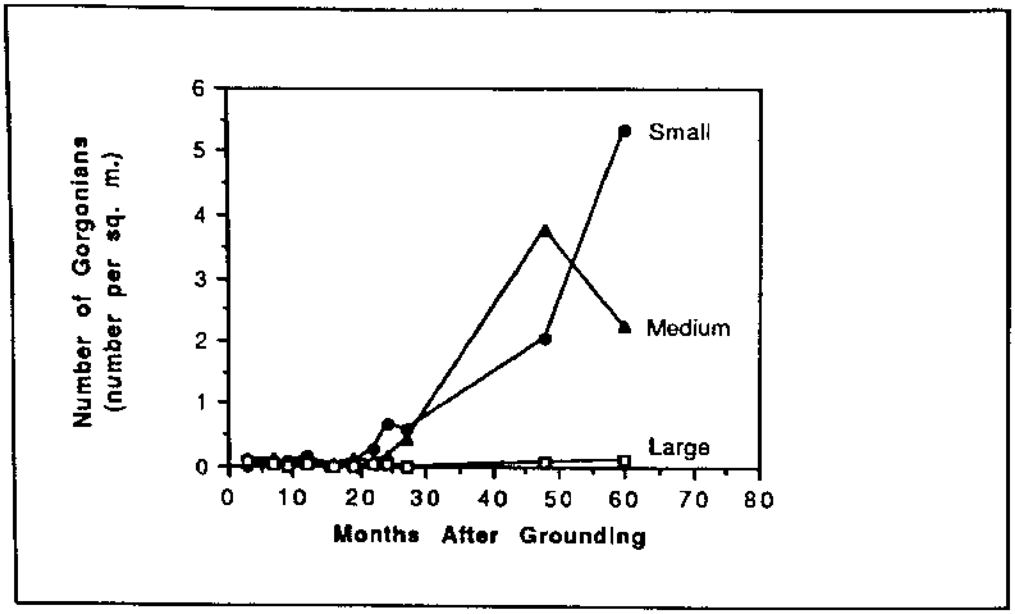


**Figure 7. Density of "small" (0–10 cm tall), "medium" (10–30 cm), and "large" (over 30 cm) gorgonian corals in Area BB throughout the study.**

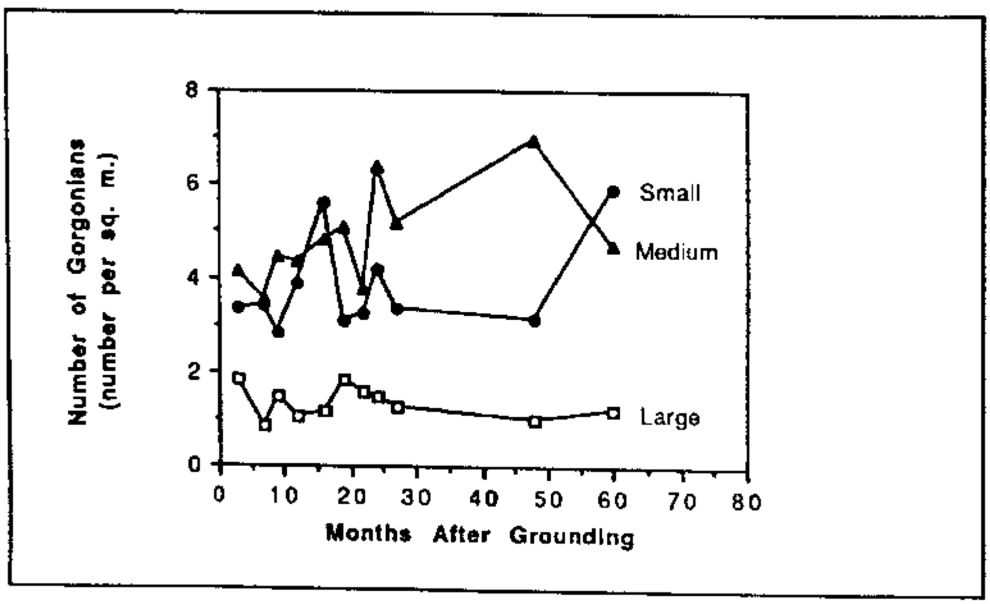


**Figure 8. Density of "small" (0–10 cm tall), "medium" (10–30 cm), and "large" (over 30 cm) gorgonian corals in Area BB throughout the study.**

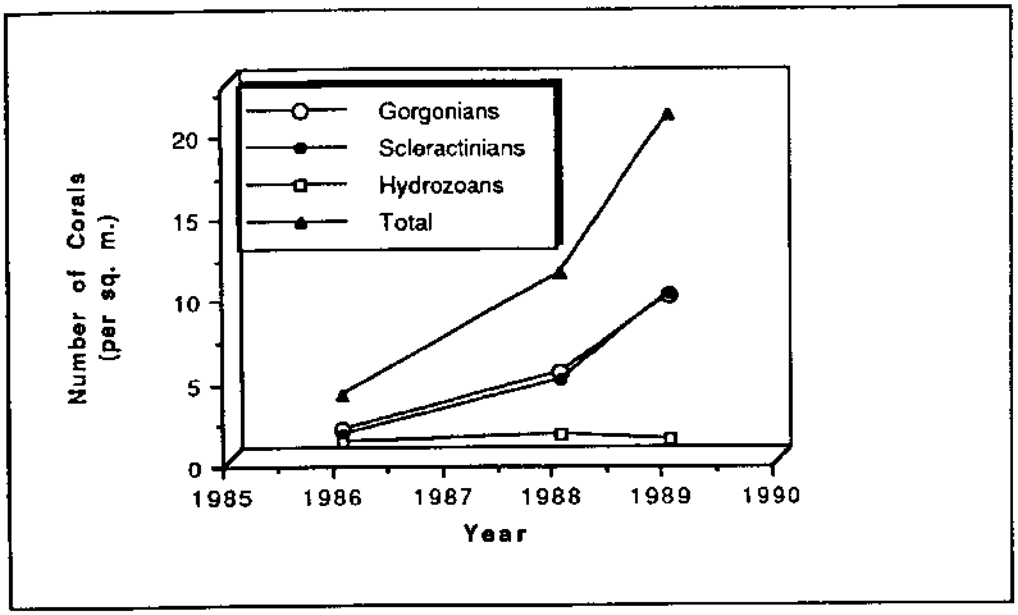


**Figure 9. Gorgonian, scleractinian, hydrozoan, and total abundance of corals, as estimated by diver counting all corals in eighteen 1-m² quadrats in Area BB in November 1986, September 1988, and August 1989.**

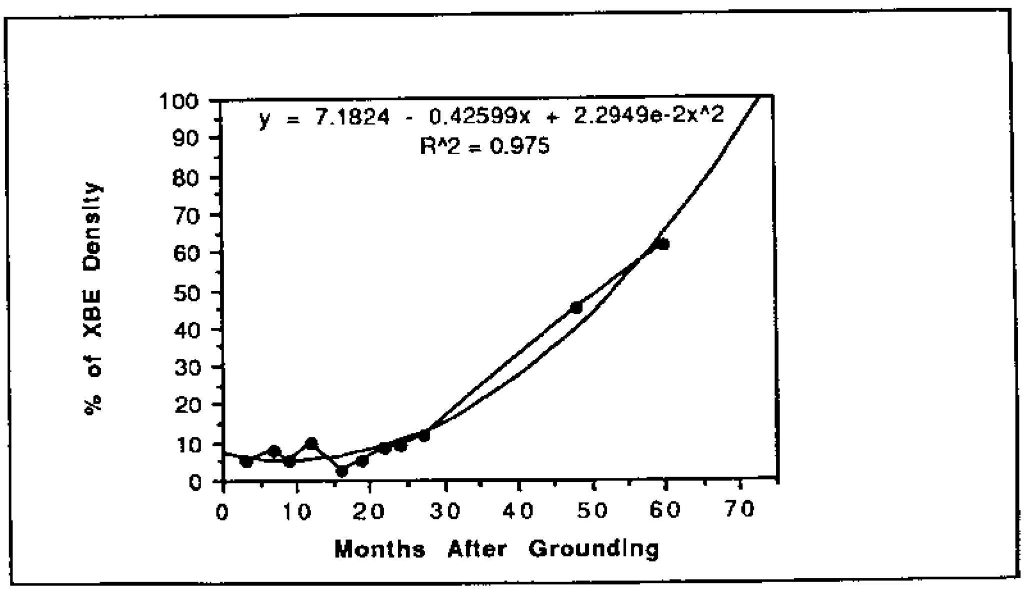


**Figure 10. "Best fit" second order polynomial curve applied to coral population data in Area BB. Extrapolation predicts 100% recovery in terms of colony abundance at approximately 72 months following the grounding.**

# ECOLOGICAL MONITORING ON THE FLOWER GARDEN BANKS: STUDY DESIGN AND FIELD METHODS

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*A long-term ecological monitoring program is being conducted at the East and West Flower Garden Banks, in the northwestern Gulf of Mexico. Sampling takes place semi-annually. Three of six scheduled cruises over a three-year initial study period have been completed. There are 100 m² monitoring sites on reefs on the two banks. Each site has 120 permanent, repetitive photographic stations for monitoring the encrusting growth of two dominant coral species, 40 posts to mark 8 m² repetitively photographed stations for studying individual coral colonies, and 30 stations to measure accretionary coral growth. All stations are located by divers using underwater site maps and sampled using underwater photography or by direct measurement. Also, during each sampling effort, twenty 10 m stratified random transects are photographed at each site and two repetitive 100 m transects are videotaped. Data will be used to assess: 1) coral population levels; 2) temporal variability in coral cover, coral growth, relative abundance, relative dominance, diversity and evenness; and 3) periodic changes in macrophytic algae cover (e.g., blooms) and abundance of other conspicuous associated organisms.*

## INTRODUCTION

Deterioration of coral reef communities can be a rapid process, especially during episodes of catastrophic natural or man-induced mechanical disturbance (e.g., hurricanes, blasting, dredging, mining, and shipwrecks). Thermal, oil, chemical, or nutrient pollution may cause gradual deterioration of a coral reef (e.g. Marszalek 1987). Similarly, chronic low level mechanical impacts imposed by coral collection, destructive fishing techniques, high levels of diver use, or boat and ship activities may also cause the gradual decline of coral populations or coral viability (Tilmant and Schmahl 1983).

Coastal emergent reefs receive the majority of man-induced impact, but submerged reefs far offshore are not immune. In 1985, for example, a portion of Bright Bank, a reef at 37 m (121 ft) depth on the outer continental shelf of the northwestern Gulf of Mexico, was blown apart by treasure hunters (Bright 1986). The nearby Flower Garden reefs, which peak at approximately 18 m (59 ft) depth, are adjacent to commercial shipping lanes. They have been used as offshore anchoring sites by large vessels for decades. Concern over the fate of the Flower Garden reefs has been an important factor leading to their nomination for National Marine Sanctuary status.

The summits of the East and West Flower Garden Banks consist of actively growing coral reefs. Eighteen species of tropical Atlantic reef-building corals exist on the reefs, or approximately one-third of the reef-building coral species of the Caribbean. The coral fauna is dominated by massive head corals. No acroporids (elkhorn or staghorn corals) or shallow water gorgonians occur on the reefs. Cover of reef substrates by living coral approximates 50% on the top of each bank. Over 250 species of associated reef invertebrates and over 130 species of fish also exist. Coral cover and growth rates are considered to be comparable to other western Atlantic coral reefs at similar depths (Bright *et al.* 1984).

Environmental concerns on these reefs include the long-term effect of oil and gas production activities (platforms are located within 2 km of each bank), and discrete and cumulative effects of mechanical impacts caused by ship anchors and ground tackle. A long-term monitoring program at the East and West Flower Garden Banks is currently being conducted by Texas A&M University. The goal of the program is to address concerns related to both gradual and punctuated degradation of these unique offshore ecosystems. The program will also augment a data base relating to coral community viability dating from the 1970s. Such data are useful not only from the standpoint of assessing the impacts of industrial activities, but also since 1) the Flower Gardens are scheduled to become a National Marine Sanctuary in the fall of 1990, and 2) recreational use of underwater areas tends to increase following establishment as a marine park, preserve, sanctuary, or reef authority (Tilmant 1987). A long-term data base may allow the identification of impacts caused by this expected increase in recreational use. Furthermore, due to differences in the nature of recreational and industrial activities, and the nature of the damage potentially caused by such activities, it may be possible to determine the principal factors leading to any community changes observed in future years at the Flower Gardens.

This paper discusses the field techniques and laboratory methods used to evaluate changes in coral population levels, coral and algae cover, growth rates, and other community characteristics at the Flower Gardens. Details of sample site establishment, recurrent sampling efforts, dive program logistics, laboratory data acquisition, and data analysis are discussed.

## METHODS

### Field Techniques

During the winter of 1988 and spring of 1989, a monitoring site was established at the East Flower Garden Bank comparable to that established at the West Flower Gardens by

Continental Shelf Associates in the summer of 1988 (CSA conducted monitoring for Union Oil Co.). This involved implanting eyebolts and marker floats around a 100 m by 100 m study site, temporarily installing boundary lines around the sites, establishing and producing study site maps indicating the locations of 120 permanent photographic stations for monitoring lateral encrusting growth of the corals *Montastraea annularis* and *Diploria strigosa* (60 stations for each species), implanting and mapping 40 permanent posts to mark 8 $m^2$ repetitive photographic stations for studying individual coral colonies, and implanting and mapping 30 permanent accretionary growth spikes in *M. annularis* coral colonies. Eyebolts were cemented in 6.5 cm holes drilled using a pneumatic impact wrench and a coring bit at study site corners. Portland Type II Cement was used with moulding plaster as a catalyst (12:1 ratio). Boundary lines are 100 m long, 0.5 cm polypropylene with knots and loops every 25 m indicating the direction to the nearest corner of the site. The lines are wrapped on and deployed by divers from extension cord reels. Station markers (stainless steel, 3.2 mm diameter nails for encrusting growth stations and 6.4 mm diameter spikes for accretionary growth stations) were installed using pneumatic air hammers with customized heads (Figures 1 and 2). The blunt end of nails or spikes were inserted into holes in the hammer heads and driven into reef rock, leaving a specified length of each marker exposed. Repetitively photographed 8 $m^2$ stations were established using 9.5 mm diameter stainless steel posts. Holes for the posts were drilled to 15 cm depth using a pneumatic impact wrench and 1 cm star drill bit (Figure 3). Stud anchors (Figure 4) were welded onto the ends of the posts. After inserting these posts into their respective holes, the diver hammered the top of the post, causing the stud anchor to flare inside the hole. None of the posts have come loose in the one year since installation. All stations at both banks were tagged using numbered, plastic, goat ear tags (black on white). Small sections of clear tubing were placed over the markers before the tags were attached with plastic tie wraps, assuring a more secure hold. All tools were stored in ethylene glycol (antifreeze) between dives to avoid seizing, and dismantled and cleaned completely between cruises.

Following site establishment, and in October 1989 and April 1990, we conducted photographic and video field work at both banks, and will continue to do so at six month intervals over a three-year study period.

The monitoring study calls for two sampling efforts each year. During each sampling trip, twenty 10 m stratified random transects are photographed at each of the two study sites. Seventeen immediately adjacent photographs are taken along each transect using a camera framer which describes a 60 by 85 cm area of seafloor (Figure 5). Randomness is achieved by equipping diver teams with slates containing random compass headings and random numbers. The divers are dropped at random locations within the study sites from an inflatable, and go directly to the bottom to start photographing a transect along the first random compass heading. They then kick a random number of times along a second compass heading, and start a second transect along a third compass heading. Two transects are photographed by each diver on each film roll (36 exposure print film).

Each station for monitoring lateral growth of *M. annularis* or *D. strigosa* was established using two 10 cm long stainless steel nails (Figures 1 and 6). They are spaced 23 cm apart so that a plus/5 diopter framer attached to a 28 mm lens and Nikonos underwater camera can be placed directly over the nails and encompass a repeatable 13.3 by 19.7 cm photographic area. The border of living coral tissue traverses the approximate center of each printed photograph, allowing measurement of either tissue advance over adjacent corallum or tissue retreat. Divers locate stations and record the order of station photographs on study site maps printed on underwater paper. After photographing a station, divers attach steel paper clips to the nails to indicate to others that the station has been completed. The paper clips rust and become overgrown by algae between sampling trips and are removed periodically.

Slides of each 8 $m^2$ repetitive photographic station are taken from a height of 2.0 m using a 15 mm wide angle lens and two 225 watt-second strobes (Figure 7). The base of the 2 m post of the T-shaped camera jig is positioned at the point of insertion of the implanted post in the reef. The jig has a bubble level and compass adjacent to the camera to accurately position the camera above the station center before each photograph is taken (Figure 8). These devices eliminate camera tilt and twist, respectively, which are the two factors that make repetitive photography notoriously difficult. The bubble level is centered and the compass pointing north before a station is photographed. Repetitive photographs have proven to be nearly identical in terms of area covered and colonies photographed. The sample area approximates $8^2$ m, which effectively samples the community and allows identification of most colonies at the site.

The spikes used to monitor accretionary growth of corals are implanted in living coral tissue on the tops of coral heads. Growth spikes were driven into heads of the star coral, *Montastraea annularis*. The 20 cm spikes were driven to a depth of 10 cm, leaving approximately 10 cm exposed (Figure 2). The spikes are measured to the nearest millimeter during each sampling effort. Data are recorded on study site maps indicating the locations of stations in various sections of the study area. Paper clips are attached to station tags after measurement to indicate completion. Since it is difficult to secure growth spikes so as to completely avoid movement of the spike relative to the coral head, growth measurements will also be made from cores taken from *M. annularis* heads during and at the end of the study. Two cores were taken at each bank in May of 1990 and have yet to be analyzed.

At each reef, two videotaped transects of 100 m length are flown during each visit to show the general conditions of the coral community at each study site. We use 8 mm video format to obtain relatively high resolution images. The video transects are taken by a diver from approximately 2 m above the bottom along 100 m lines tautly strung along the sides of each survey area. Taut lines serve to establish semi-repeatable survey transects that can later be mapped to show distinctive features such as areas of sand, high coral density, diseased or damaged corals, etc., and to document gross changes over time.

Light penetration is measured near 1200 hours each sampling day using a Biospherical Instruments QSP 200L Submersible Quantum Scaler Irradiance Meter. Five minute measurements are taken on the surface, at 1 m depth, and near the bottom. Discrete measurements of temperature, salinity and dissolved oxygen are also obtained daily (near 1200 hours) at 1 m depth and 1 m above the bottom.

To date, a total of 48 different divers have participated on nine separate cruises to the banks. Twelve to fifteen divers are taken on each cruise (six or seven dive teams and one diver to keep records aboard the ship). Though most have been experienced divers, few have participated in projects employing methods comparable to those used in this study. As expected, we have noticed a strong correlation between the frequency of participation and productivity for each diver. For this reason, we prefer to employ as many project experienced divers as possible and indoctrinate only a small number of first-time study divers on each cruise. However, we have also found a correlation between the familiarity of divers with the sampling protocol and productivity. Because of this, we have developed a slide set depicting sampling methods and study site characteristics that is reviewed by all divers prior to each cruise. During this session, we also review equipment use and problems to be avoided in sampling using the underwater photographic techniques of this study.

Prior to each dive, divers are informed which stations are to be found and photographed, and the locations of the stations. To expedite record keeping between dives and to minimize errors, we have developed inventory forms for each of the banks for certain sampling methods. These forms indicate the number of the stations that must be located and sampled during each cruise and their location within study sites. The station types include encrusting growth, accretionary growth, and repetitive 8 $m^2$ stations. When stations are completed, they are checked off the inventory forms and pertinent information added to the forms (e.g., film roll and exposure number, spike length, and miscellaneous information). Divers can then be informed which stations have yet to be sampled.

## LABORATORY METHODS AND DATA ANALYSIS

*Random Transects:* Areal coverage of coral and leafy algae is considered the vertical projection of a colony onto the substrate (like canopy cover using aerial photography). Objects on photographs taken along the random transects are outlined using a calibrated planimeter, and area (in $cm^2$) is automatically calculated. Percent cover data are acquired for all coral species and other appropriate organisms (e.g., leafy algae) on the photographs, and observations of disease incidence are documented. Also calculated is the number of colonies of each species, the amount of bare coral substrate (most is actually covered by calcareous or filamentous algae), relative dominance of each coral species (% cover relative to total cover), the frequency of occurrence of each species, species diversity, and evenness.

*Encrusting Growth Stations:* From developed prints of growth stations, colony borders, distinctive features, and polyp mouth positions are traced onto sheets of mylar drafting material. Minor differences in scale between sequential mylar traces at a station can be compensated for by projecting one trace onto the other using an image enlarging/reducing map projector. Individual polyp mouth positions can then be matched exactly on the superimposed traces and both colony borders are traced onto the same sheet.

Border lengths, areas of tissue advance and areas of tissue retreat are measured using a planimeter. Standardized statistics generated for each station will be the amount of tissue growth and/or retreat (in $cm^2$) and the border length over which this growth or retreat occurred. Growth and retreat can be analyzed separately, and data can be combined for analysis of net changes in tissue over time.

Also calculated are the proportions of the total border lengths exhibiting growth, the proportions exhibiting retreat, and proportions exhibiting no change. These will be plotted on ternary diagrams (three-coordinate plots). This technique was first used by our group to study coral growth on coral heads impacted by a freighter grounding in Florida (Gittings et al. 1988). The method was useful in determining the deleterious effects of the displacement of coral heads into sandy habitats by the ship.

*Repetitively Photographed Stations:* Developed color slides will be projected onto a digitizing pad. Coral colony sizes will be calculated at each station using a planimeter. Individual colony changes between time periods can then be determined directly. Other parameters to be compared will be total cover, relative dominance, species frequencies, species diversity, and evenness.

*Accretionary Growth Stations:* Coral growth will be determined for each coral head on which growth spikes are located by comparing sequential measurements taken from individual coral colonies. Differences between periods will be evaluated, as will trends through time. Underwater measurement data will be compared to data from high and low density bands in core tissue taken in May 1990 and at the end of the study.

*Video Transects*: Transcriptions of videotape records will include observations on the general health of the hermatypic coral community and counts of invertebrates and fishes. By estimating elapsed time and physical dimensions along the transects, counts and other observations can be converted to densities (number/$m^2$). These densities will provide a means for quantitative comparisons between sites, seasons and years. Other information that may be useful to community characterization may include habitat characteristics (cover of sand flats, nature of live coral cover, general health of coral, disease incidence, etc.), patterns of abundance (numbers of individuals, spatial distribution, recruitment or loss of conspicuous reef fish or invertebrates), and relationships between specific taxa and habitats or other biota.

Data Interpretation and Synthesis

A critical component of this study will be the comparison of the considerable existing knowledge on the Flower Gardens with the data that will result from this study. Some objectives are to:

- Compare data on coral populations and coral growth resulting from this study to existing published and unpublished Flower Gardens data;

- Assess time-dependent change in coral cover, relative abundance, relative dominance, diversity and evenness over the course of this study and in light of previous estimates of these parameters;
- Evaluate the nature and extent of bleaching caused by loss of zooxanthellae (as a periodic natural phenomenon or under stressful conditions) and compare these results to the findings of investigators working on other Western Atlantic coral reefs;
- Ascertain the apparent extent of human impact on the reefs, especially with respect to mechanical disturbance caused by divers, boat and ship anchors, debris, etc. and compare this with past and currently emerging information on human impacts in other coral reef ecosystems;
- Discuss the relationship between outer continental shelf hydrocarbon development activities and environmental sensitivity at the Flower Garden banks, integrating existing data on mechanical disturbance and chemical contamination of coral reefs.

## ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance provided by the 48 divers used thus far in this project. We also thank the crews of the M/V *Fling* and M/V *Eunice B.* for their assistance during field sampling efforts. Bernath Concrete Co. (Bryan, Texas) donated cement to the project. M&M Scuba and Snow Ski (College Station, Texas) and the Department of Civil Engineering at Texas A&M University provided additional field equipment during each cruise, including scuba tanks, other dive gear, inflatables, motors, and underwater propulsion vehicles. Mobil Oil Co. provided weather reports prior to and during cruises. Coral collections were made in May 1990 under collection permit number PCG-3-SR-90. This research is being conducted under the Department of Interior, Minerals Management Service contract 14-12-0001-30452 to the Texas A&M Research Foundation.

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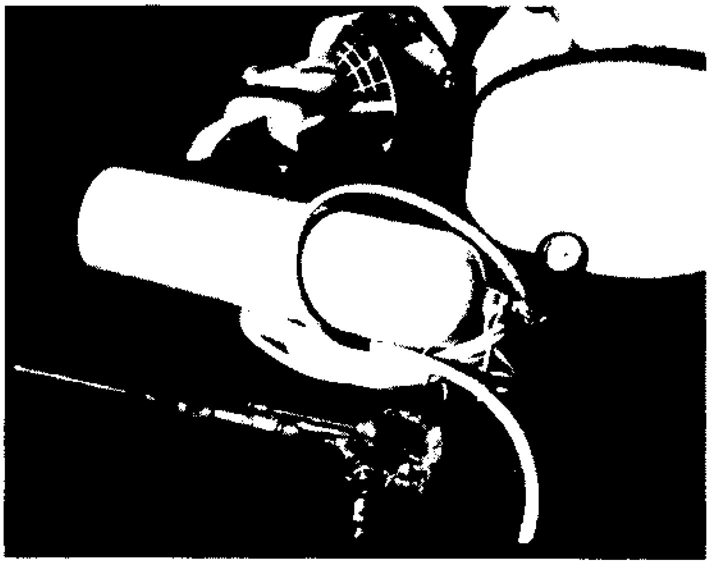

**Figure 1. Pneumatic hammer with modified head used to install stainless steel station markers for encrusting and accretionary growth stations.**

**Figure 2. Accretionary growth spike in the top of *Montastraea annularis* coral head. The spike was installed with 100 mm exposed and is measured semiannually.**

**Figure 3. Pneumatic impact wrench used to drill holes for eyebolts in study site corners and posts marking 8 $m^2$ repetitively photographed stations.**

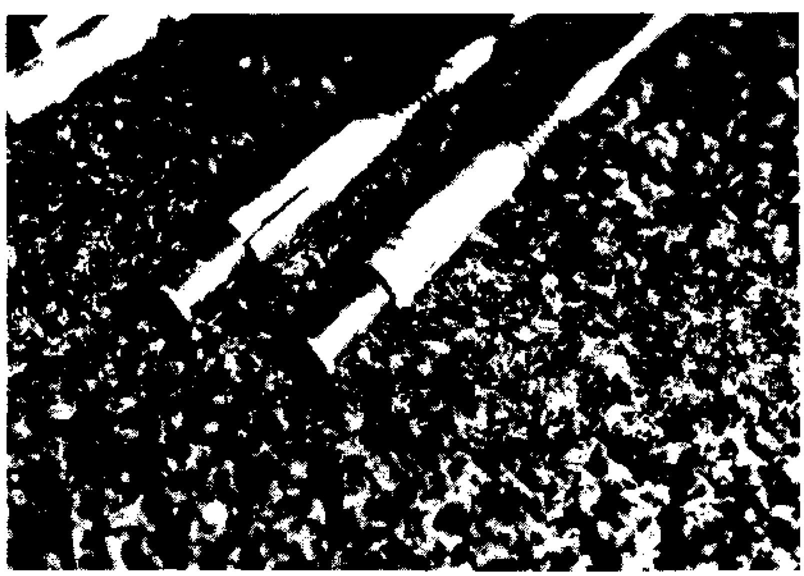

**Figure 4. Stud anchors welded to the ends of stainless steel posts marking 8 $m^2$ repetitively photographed stations. The anchors flare inside holes drilled in reef rock when hammered underwater, securing the post.**

**Figure 5. Diver photographing a random transect using a framer with attached camera and strobes.**

**Figure 6. Diver taking close-up photograph of an encrusting growth station. Diopter framer is positioned over two nails adjacent to living tissue and photo is taken normal to the station plane.**

**Figure 7. Diver operating T-shaped camera jig used to photograph 8 $m^2$ repetitive stations. The unit has a Nikonos V camera, 15 mm wide angle lens, a double sync cord, and two 225 watt-second strobes. Post is 2.0 m tall.**

**Figure 8. Compass and bubble level mounted on the top of the T-jig used to photograph 8 $m^2$ repetitive stations. These are used to adjust attitude of unit at each station prior to photography.**

# STRIP-TRANSECT SAMPLING OF A MARINE GASTROPOD USING TOWED-DIVERS

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The queen conch, *Strombus gigas*, is a sparsely distributed marine gastropod found throughout the shallow waters of south Florida, the Caribbean, and Bermuda. In 1986, the Florida state legislature appropriated funds to the Department of Natural Resource's Marine Research Institute to develop a stock assessment/monitoring program for *S. gigas* in south Florida. The goal of the program is to make recommendations to the Florida Marine Fisheries Commission on how to best manage the *S. gigas* resource. In this paper, we discuss the details of the sampling program and underwater techniques for measuring conch abundance.

The study area extended from Virginia Key near Miami to Key West and was divided into 10 approximately equal areas based on habitat charts of the Florida Keys developed by Marzalek. One additional area was added from Key West to Boca Grande Key approximately 12 km west of Key West. Sampling was further stratified using the habitats as delineated on the charts (reef, bedrock, sediment, and seagrass). Bluewater habitat was added to include the area beyond the reef crest that was deeper than the capabilities of satellite resolution but shallower than 20 meters. Each area was assigned 10 transects for each season during the first year of sampling (stock assessment). The number of transects allocated to each habitat within each area was determined by the relative coverage of each habitat. During years 2 and 3 (stock monitoring), areas 3, 6, and 9 were chosen to represent the geographically disparate locations. Each area was apportioned twenty-five transects per season. One additional habitat was added to include waters up to 3 km into Florida Bay.

During each transect, two SCUBA divers or snorkelers were towed for 32 minutes behind a research vessel at an average speed of 60m/min. An initial two minute interval allowed the divers to assess the speed of the vessel. Stops were made at each ten minute interval thereafter. Upon completing each interval, the diver on the port side signaled to the vessel operator with a series of tugs on the tow-line. One tug indicated both divers were ready and the speed was adequate. Two tugs meant slow down; three meant speed up. Poor visibility, currents, and surface sea-conditions were factors which required speed adjustments.

Tows proceeded along a course chosen to maintain homogeneity of bottom habitat. Distance traversed was calculated from latitude and longitude coordinates; approximately 1800 meters were covered on each transect. All live adult and juvenile *S. gigas* were counted by each diver in a 3 meter swath. Maximum depth, bottom time, and repetitive no-decompression times were determined from dive computers.

Safety was a prime consideration in the design of the research program. Oxygen is carried aboard all diving vessels. A diver down flag and an international Alpha flag were displayed when divers were in the water. Additionally, a spherical, fluorescent-orange fender 18" in diameter was secured to the stern of the vessel and floated above the location of the divers in the water. A 3-5 minute decompression stop at 15-20 feet was mandatory for dives exceeding 30 feet. On deeper dives, a tank and regulator were hung from the stern at the end of the transect to allow divers to decompress without the restrictions of air limitation.

During the four seasons of the stock assessment program, 424 transects were completed covering 543.8 Ha or 0.2% of the available area. During the eight subsequent seasons of stock monitoring, 587 transects were completed with an area sampled equal to 744.6 Ha or 1.11% of the total available area. Over 1250 diver hours have been completed to date without any injuries.

# WORKSHOP REPORT: SHIPBOARD DIVING SAFETY ABOARD UNOLS VESSELS

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*Two workshops were funded by the National Science Foundation and the National Oceanographic and Atmospheric Administration and convened under the auspices of the Undersea and Hyperbaric Medical Society in order to address issues relating to the safety of scientists diving at sea. The workshops' objectives included establishing research diving-related guidelines for marine operators and Masters and reviewing existing shipboard research diving safety documentation (especially as they relate to distant scientific programs).*

*These meetings specifically examined issues such as responsibility and authority of ships personnel and cruise participants, multi-institutional cruises, recompression chambers, small boats, diver evaluation and training, emergency plans and procedures, new technologies and cruise personnel requirements. The workshop participants were tasked to look to the future as* in situ *technologies evolve for both hyperbaric and one-atmosphere applications. A final report detailing a series of recommendations for changes in procedures and regulations and shipboard training materials was issued.*

## INTRODUCTION

To understand the issues underlying the current concerns regarding scientific diving at sea, one must go back in time to the late seventies. On 5 November 1976 the federal Occupational Safety and Health Administration (OSHA) first issued standards regulating commercial diving in which they defined commercial diving as, 'any diving in which an employee/employer relationship existed.' Under these rules, OSHA classified diving researchers as commercial divers thereby putting significant operational and safety constraints on the scientific diving community. Among the problems with the OSHA regulations that were cited by members of the scientific diving community were a number of specified changes in operating methods which the scientific diving community considered unsafe (Sharkey and

Austin, 1983). Additionally, these changes would have caused a substantial reduction in useful science time and vessel space at sea by reducing operational efficiency.

The scientific community strongly disagreed with the OSHA action, feeling that the scientific community had established and maintained an excellent safety record as a self-regulated entity. In order to respond to this perceived threat, the American Academy of Underwater Sciences (AAUS) was formed. The group effectively presented the scientific community's diving safety record, as well as its needs and requirements. After protracted hearings and reversals, OSHA finally exempted the research diving community on 26 November 1982 (OSHA determined that, '. . . there are significant differences between commercial diving and scientific diving. . .', and amended their rules to exempt scientific diving that is, '. . . under the direction and control of a diving program utilizing a diving safety manual and a diving control board meeting certain specified criteria.') OHSA's ruling withstood a subsequent court challenge (OSHA's amendment to Subpart T was finalized when the 7th Circuit of the U.S. Court of Appeals denied the petition of The United Brotherhood of Carpenters and Joiners on the grounds that the union lacked standing to bring the suit. This was the first time on history that a court had denied a labor union standing in such a case.)

The University National Oceanographic Laboratory System (UNOLS), an association of institutions for the coordination and support of university oceanographic facilities which deals with the operation and scheduling of academic research vessels, adopted the AAUS standards in 1985 for all shipboard diving undertaken at member institutions. In 1988 the National Science Foundation (NSF), a major supporter of both UNOLS and the academic institutions within UNOLS, expressed concern about the application of these safety standards and their relation to research-related accidents that had taken place within the scientific community. Some of the accidents occurred within the marine field, both at sea and ashore, and included two shipboard diving non-fatalities and one remote-site diving fatality. Because of this, and especially because of concerns expressed by UNOLS ship operators, NSF decided that there was a need to precipitate useful discussions among the parties involved in scientific diving operations. The ship operators felt uneasy with over-the-side diving operations, especially in the open ocean; the diving scientists felt somewhat put upon by the rules, regulations and complications of meeting the diving regulatory requirements; and the campus diving administrations found themselves in the middle of these issues.

## THE FIRST WORKSHOP

An initial workshop to discuss the diving-related issues was conducted on 29 April 1988 by the Undersea & Hyperbaric Medical Society (UHMS) under NSF/NOAA sponsorship. Its goals were defined as: establishment of guidelines for the oceanographic vessel Masters; review and assessment of control of research diving operational safety; the development of an annotated bibliography dealing with scientific diving at sea, its problems and issues (i.e., physiology, training, experience, etc.); and publishing the results of the deliberations.

UHMS is in the process of completing the output from this initial workshop (Undersea and Hyperbaric Medical Soc., 1990).

The first workshop convened three primary groups; commercial divers, Navy divers, and scientific diving administrators. A review of the transcripts from the workshop, showed that while each of the parties present had good and sufficient reasons as to why they conduct diving operations as they do, each party had differing missions, philosophies, strategies, and resources. As a result, no substantial beneficial interaction occurred. The discussion did not include a definition of responsibility for, and authority over diving operations, which led to the conclusion that further efforts were required to address the needs and interests of the scientific community. A vigorous debate regarding chamber use also appeared to warrant additional discussion.

## THE SECOND WORKSHOP

Subsequent to this first workshop, a number of other events occurred, reinforcing the need to bring together a broader and different group of people to continue the process of establishing safety guidelines and standards for shipboard research diving. A major effort had gone into revision of *The UNOLS Shipboard Safety Standards* (which included a section covering research diving); the *Research Vessel Operators' Committee* (RVOC) *Safety Training Manual* was in development (which also included a chapter on research diving); and the UNOLS Submersible Science Study ($S^3$) was ongoing (UNOLS, 1988, 1990).

Other new information that needed examination came from the AAUS, which had just put forth new research diver medical examination schedules and had published material concerning cold water diving, diving computers, and safe rates of ascent that had not been considered at the first workshop. Additionally, 58 campus diving administration representatives from 41 institutions met at Woods Hole Oceanographic Institution, as part of the AAUS Annual Symposium, and had documented their concerns relative to topics of safety, equipment, procedures, training, new diving technologies and reciprocity (AAUS, 1989).

Specific tasks set for the second workshop included:

1) Study of the new information available on remote and shipboard diving safety and effectiveness;

2) Utilization of this new information in a detailed review of the UNOLS Shipboard Safety Standards diving section and the RVOC Safety Training Manual;

3) Review of the consensual research diving safety standard of which the AAUS is custodian and which serves as the backbone of the current UNOLS Shipboard Safety Standard diving section; and

4) Examination of the need for a potential extension of the UNOLS and/or AAUS standards to specifically address the concerns raised by the operators of academic research vessels and the needs of remote diving research sites.

The planning for the second workshop differed somewhat from that for the initial workshop. The primary goal was to bring together experts from inside UNOLS and the scientific diving community to review both the output from the first workshop and the new material that was available. This review was targeted at providing the greatest possible assistance to UNOLS in the establishment of shipboard diving safety guidelines and standards that were efficient with respect to scientific resources.

A clear part of assuring diving scientists' safety was meeting the goal of improving communication between institutions and the members of the on-site teams doing the diving. General concepts and specifics concerning the assignment of responsibility and authority for shipboard diving is unclear and contradictory especially when one asks the on-board participants who is in charge of what. This is of special concern to ship Masters at sea. Documentation dealing with the qualification and interchange of research divers between institutions, is poorly defined as is the transmission, updating, and storage of that documentation.

## PHASE ONE

The second workshop began with an examination of the structure of the scientific diving community. Figure 1 shows the interrelationships defined by that examination. The federal agencies (NSF, the Office of Naval Research (ONR), NOAA and others) are coupled together through the mechanism of UNOLS to deal with academic fleet operations. UNOLS includes not only all of the academic vessel operators (who make up the membership of the RVOC) but also other institutions who conduct major activities at sea. This strongly linked system is driven by science needs. Science, through peer review, determines who gets funded and this involvement of the working scientist in both UNOLS and AAUS activities creates a strong, but informal, link. Additionally, AAUS is highly responsive to campus diving administrations. However, as Figure 1 shows, there is no direct linkage between the AAUS and the ship operators. One of the purposes of this second workshop, therefore, was to decide whether such a link was important, if so, determine an effective way to establish and maintain it.

Even though there is no formal link between the organizations, they have many members in common. The Marine Technology Society (MTS) estimates that there are 350 marine research institutions in the nation, of which 56 are members of UNOLS (Figure 2). Of this 56, 21 are members of the RVOC. Of these 21 RVOC members, all have Individual Members of AAUS on campus, 12 are Organizational Members of AAUS and four are in the process of becoming Organizational Members.

An examination of AAUS membership within UNOLS shows that all but eight UNOLS institutions have AAUS Individual Members on campus, 16 of the UNOLS institutions are

AAUS Organizational Members and seven are in the process of joining (Table 1). Despite this high degree of organizational correspondence, no formal mechanism exists for making use of these interrelationships.

In addition to issues relating to communication between organizations, concerns remain about responsibility and authority, liability and qualifications, safety and accident management, scientific efficiency, documentation, new technology and practices, and continuity. An overriding objective in dealing with these problems is to avoid setting up so much excess bureaucracy that the accomplishment of primary tasks is significantly inhibited. To expand on these questions, communication between organizations and the members of the on-site teams involved with the diving can and must be improved.

There are new technologies that will require the science community to deal with issues similar to those raised by research diving at sea. An example is the use of non-dedicated vessels with small-scale, scientist-operated submersibles. Although this single workshop was unlikely to resolve all these issues, it was hoped that, by providing a forum for learned people to respond with individual points of view, either agreement on the various issues, or equally important, documentation of disagreement would be produced so that the community could develop solutions to its problems.

Figure 3 compares the approach taken in the initial workshop with that of the second workshop. The first had groups of divergent viewpoints, practices and concerns about diving safety. The second brought the groups with specific concerns with, and influence over, scientific diving (ship operators; scientists; and campus diving administrations) together with representatives of AAUS and UHMS. Each of these three constituencies brought with it various organizational affiliations which typically were: ship operators (UNOLS and RVOC), scientists (UNOLS and AAUS) and campus diving administrations (AAUS).

Copies of existing documentation were provided by and to the workshop participants (i.e., *UNOLS Shipboard Safety Standards: Section 15 - Diving; RVOC Safety Training Manual:* Diving Section; and *AAUS Standards for Scientific Diving Certification and Operation of Scientific Diving Programs*).

The charge to the panel was to produce (at a minimum):

1. A statement, addressing the special problems of multi-institution cruises, which outlines the responsibility and authority of: the diving scientist, the research vessel operator, the research vessel Master, and the campus diving administration:

2. A review of the diving and allied sections of the UNOLS Shipboard Safety Standards and the RVOC Safety Training Manual, with clear identification of positive factors as well as suggestions for future improvement or changes as needed;

3. Recommendations to UNOLS/RVOC and AAUS covering special equipment and procedure requirements for UNOLS diving cruises and remote sites (i.e., small boats, medi-

cal equipment, decompression tables and procedures, and recompression chambers);

4. Recommendations to UNOLS/RVOC and AAUS covering special personnel requirements for UNOLS diving cruises and remote sites;

5. Detailed checklists for diving cruise and remote-site planning (especially for casualty planning);

6. Recommendations to UNOLS/RVOC and AAUS for systems that will result in the development of a set of easily applicable, measurable, performance-based standards defining the minimum diving skill and diving knowledge required of diving researchers who work from UNOLS vessels or at remote sites; and

7. A plan for linking the diving scientists (currently represented through UNOLS), the marine operators (currently grouped in the RVOC) and the Diving Safety Officers (currently grouped in AAUS), together in a manner that will improve the effectiveness of the above items.

## PHASE TWO

The attendees were selected to assure representation from science, ship, and diving administration constituencies, and included 21 participants representing various academic institutions, national oceanographic laboratories and other involved organizations including: American Academy of Underwater Sciences, Harbor Branch Oceanographic Institution, Marine Biological Consultants Applied Environmental Sciences Inc., Northeastern University's Marine Science Center, Research Vessel Operators' Committee, Smithsonian Institution, Texas A & M University, University of Rhode Island's Graduate School of Oceanography, University of California at San Diego's Scripps Institute of Oceanography, University of Miami's Rosenstial School of Marine and Atmospheric Sciences, University of Maine's Ira Darling Center, University National Oceanographic Laboratory System and Woods Hole Oceanographic Institution. The Director of the NOAA/NURP program was invited to this workshop. He declined, although NOAA co-sponsored the workshop.

Once the workshop participants were identified, they were supplied with the documents of interest and met in Washington D.C. from 18-20 February, 1990, for two and a half days. The workshop opened with welcoming statements. Each constituency was then asked to state its perceptions of shipboard scientific diving safety and expectations for the workshop.

Following a slide presentation illustrating blue water diving techniques, a matrix composed of individuals and organizations involved in the process vs. decision-making events was introduced for detailed examination and review. Three task groups were designated. The chair of each task group was drawn from one of the three different constituencies and the other two constituencies were represented. The task groups were asked to review, examine, confirm and apply the matrix. The task groups reported back and identified critical problems that were made evident through the use of the matrix.

After the reports, a series of formal presentations and discussions were held. The topics covered were multi-institutional diving cruises, additional personnel for diving cruises, responsibility statements, diver evaluation and training standards, small boats and small boat operators, emergency planning and accident management, recompression chambers, new technologies issues, and future actions. The closing sessions defined requirements to complete the current tasks.

This group of experts, representing many elements of the community, was asked to make recommendations to NSF concerning the safety of scientists diving at sea. The workshop also provided a few examples of needed products, such as the Pre-Cruise Dive Plan form, for use by organizations concerned with the process of scientific diving from academic research vessels at sea (e.g., NSF, UNOLS, RVOC, AAUS). These organizations, and others such as the Medical Advisory System (MAS, a private contractor to UNOLS) are committed through their normal processes to make the best possible use of this information in dealing with scientific diving on academic research vessels. Resulting documents were prepared and exchanged, edited and then a small working group convened at the W. Alton Jones Campus of the University of Rhode Island on 2-3 July 1990 for a day and a half to provide editorial assistance with the final report and complete work on some unresolved issues. The following is the complete report with findings and recommendations from the Washington D.C. and W. Alton Jones meetings.

## RESULTS

A final report with details of the meeting and complete findings and recommendations was issued. These findings and recommendations included:

### Topic: Authority and Responsibility

**Findings**

The documentation reviewed (UNOLS Shipboard Safety Standards, RVOC Safety Training Manual, campus diving manuals, AAUS Standards) are internally consistent.

A clearly defined requirement exists for a statement that will clarify the issues of responsibility and authority over scientific diving at sea.

**Recommendations**

Section 15 of the UNOLS Shipboard Safety Standards should be replaced with the version developed at the workshop (appended at end of paper).

Direction of, and authority over, the execution of diving operations lies with the On-Board Diving Supervisor.

## Topic: Multi-Institutional Cruises

**Findings**

The process of preparing for a diving cruise involves a discrete number of invariable steps, interlaced with project specific requirements. The process includes: selection of the lead institution; documentation of meeting all research diver certification requirements; research diver review and approval process; and an initial letter from the lead institution's campus diving administration to the ship operator documenting the above.

**Recommendations**

A formal walk-through of the ship's equipment that the research divers will need (e.g., small boats, crane) with the Master, Chief Engineer, Diving Safety Officer, On-Board Diving Supervisor and the Principal Investigator prior to a cruise is highly desirable.

Through a procedure not dissimilar to that used for ALVIN proposals, the grant proposal, as written, should specify to the greatest extent possible details of the planned diving including the divers, the institutions, the ship (by class and preferably by name), the time, the location, the specialized and routine equipment required, the costs to be uniquely attributed to the diving operation, and an outline of an emergency plan. This could be assisted by requiring the attachment of a completed Pre-Cruise Dive Plan Form.

Prior to the submission of the grant proposal, the Principal Investigator should work out with the desired ship operator and the respective campus diving administrations the details of the planned diving as outlined above.

Uniformity in diving support requirements across the fleet is highly desirable to avoid Chief Scientists' shopping for the 'cheapest set of rules.'

## Topic: Small Boats and Small Boat Operators

### Findings

The platform considered most appropriate, for standard operations, is an inflatable hard bottom boat with jet drive or shrouded propellers.

The primary boat operator should normally be a member of the ship's crew. Science party operators must demonstrate and document acceptable qualifications to the vessel Master's satisfaction. Having a boat operator with diving knowledge is useful to both the ship and the science party and should be encouraged.

### Recommendations

As a matter of urgency, UNOLS/RVOC should develop a common set of guidelines for small boats and their operators, not unlike (in form) the standards AAUS developed for research diving. These guidelines should be incorporated, as appropriate, into the UNOLS Shipboard Safety Standards, the RVOC Safety Training Manual and other UNOLS or RVOC documentation. These new guidelines should include coverage of the use of small boats for diving operations. Small boat topics that relate to diving should be incorporated into the documents mentioned above in both the small boat and diving sections.

## Topic: Diver Evaluation and Training Standards

### Findings

It is not uncommon for diving cruises to include diving personnel from institutions other than the vessel operator. It is sometimes difficult for foreign divers and divers from institutions which lack an AAUS model research diving safety program to demonstrate their qualification for research diving cruises.

The responsibility for the establishment of minimum standards for qualifying and training scientific divers, as well as running research diving safety programs rests with AAUS. The implementation of those standards rests with the campus diving administrations. AAUS standards cover basic diver training but do not directly address day-to-day shipboard scientific diving operations.

### Recommendations

When a cruise is leaving from a port other then the home port, and there are research divers who are not yet qualified meeting the ship, inclusion of the Diving Safety Officer (or an authorized representative) in the scientific party as the On-Board Diving Supervisor is the preferable mode of operation. This approach permits the On-Board Diving Supervisor to conduct the required in-water checkouts of the divers and to qualify them on the spot. Research divers need to consider when this approach is used that they will not be permitted to dive if they do not meet the qualification criteria.

The development of common policy approaches, evaluation criteria, and protocols for the testing of the proficiency of shipboard scientific divers and support personnel is needed. Consensual standards covering these items should be developed.

All UNOLS members whose scientists carry out diving research or who operate a UNOLS research vessel should be Organizational Members of the AAUS so that they can fully participate in the development and evolution of research diving safety standards.

## Topic: Emergency Planning

### Findings

Diving cruises require specific plans to deal with medical advisory communication, evacuation, and location of operational hyperbaric chambers that have medical support.

Available chamber location information receives little distribution even though it is useful in operational area planning.

### Recommendations

Research divers (working with the vessel EMT) should be prepared to deal with oxygen administration and emergency management.

Emergency drills should be held on vessels conducting diving operations.

With the appropriate approval of UNOLS an emergency planning database should be established at the UNOLS office. It would be a long-term dynamic program, capable of growing and becoming more refined as data are accumulated and assimilated. The database would contain information on medical and evacuation support, recompression facilities, and perhaps personal medical information. The database should include a collection response chart documenting 'response-radius' of the evacuation facilities.

## Topic: Recompression Chambers

### Findings

A review of the history of academic research diving does not justify the requirement of on-board recompression chambers.

Chambers may be desirable for diving techniques/equipment that are outside of the current practices of the scientific diving community.

### Recommendations

Normal at-sea scientific diving from UNOLS vessels does not require the provision or use of an on-board recompression chamber.
Diving beyond the experienced norm, especially in a remote-site, should be reviewed on a case-by-case basis as part of the dive planning process to determine if a chamber is warranted.

In-water, oxygen decompression or the use of NITROX should be evaluated as techniques capable of providing greater safety margins.

## Topic: New Technologies

### Findings

Relatively new hyperbaric technologies such as use of NITROX, HELIOX, new diving tables, diving computers, and multiple tethered diving have now entered the academic diving community. Additionally, both manned (One Man Atmospheric Diving Systems: OMADS) and unmanned (Remote Operated Vehicles: ROV, Autonomous Underwater Vehicles: AUV) technologies are extending our subsea horizons.

Regulatory mechanisms appropriate for hyperbaric exposure exist, but, while satisfactory for classical diving techniques, they must now address emergent innovations.

Issues to be dealt with include availability of access to vehicles and resources, handling technical complexities, and training of scientist participants.

### Recommendations

UNOLS should establish a standing committee called the 'In-Situ Science Committee' (ISSC), composed of competent, interested, and involved parties including vessel operators, academic and commercial submersible operators, academics, Diving Safety

Officers, organizational representatives (UNOLS/RVOC, AAUS) and agency representatives. The committee should deal with issues such as the establishment of guidelines for operating, contracting, safety and insurance, coordinating and scheduling, and shared use as well as provide advice to agencies. The ISSC is visualized occupying a position comparable to the Research Vessel Operators Committee (RVOC) and the Fleet Improvement Committee (FIC) and should encompass the current ALVIN Review Committee (ARC) in addition to newly established interest groups dealing with OMADS and ROVs.

## Topic: Future Needs and Projects

### Findings

Since 1977 the AAUS has been the national body representing the U.S. Scientific Diving Community. However, no formal links exist between AAUS and UNOLS/RVOC despite commonality of interest and congruity of membership.

AAUS has the expertise to provide services to UNOLS/RVOC in the area of diving information, standards, statistics, reciprocity, expert assistance and representation as well as a forum for resolving research diving issues.

### Recommendations

UNOLS/RVOC should utilize the AAUS to provide consultation and advice on research diving issues. In support of thus utilization UNOLS/RVOC and AAUS should establish formal and consistent links to assure such benefits as cross representation at significant meetings, cross reporting in newsletters and, most importantly, cross convening of joint issue topical conferences such as this workshop.

As a way of supplying technical links and in consonance with the report of the UNOLS Submersible Science Study (S3), the Diving Safety Officers of the UNOLS institutions should form a sub-committee under the proposed UNOLS In Situ Science Sub-Committee (ISSC).

The AAUS Board of Directors should consider establishing a UNOLS Diving Officer's Committee within the AAUS.

UNOLS and its member institutions should pursue, through the AAUS an agreement with NOAA concerning the reciprocal recognition of each other's research diver credentials.

For proposals that have a research diving element, the proposal reviewers should include a Diving Safety Officer from an RVOC institution who is specifically tasked to review:

dive planning, operational adequacy, equipment suitability, and above all, safety and emergency planning.

Statistics should be kept by UNOLS concerning diving from vessels in the academic fleet. Copies of institutional diving logs from all cruises should be provided to UNOLS as part of the Post-Cruise Report.

The diving-related portion of the UNOLS research vessel inspections should be enhanced. This review should concentrate on the diving equipment and the ship equipment (i.e., small boats and motors) as well as procedures for use and access to accident-response equipment.

All UNOLS member institutions who either conduct scientific diving or whose ship's are used for research diving cruises should be Organizational Members of the AAUS.

Develop methodologies for divers from institutions without formal scientific diving programs to fulfill certification requirements when they need to participate in UNOLS cruises.

## SUMMARY

This workshop was one of the first times all of the major constituencies involved in shipboard scientific diving appreciated the problems and concerns of the others. As a result of this increased level of understanding effort will be made to increase the level of communication between these constituencies and to increase the future level of formal cooperation between the organizations that represent these constituencies.

## DRAFT UNOLS Shipboard Safety Standards

### 15: Diving Operations

**15.0 Policy:** Scientific diving is a normal part of oceanographic research vessel operations. Such diving conducted from a University National Ocean Laboratory System (UNOLS) vessel must be under the auspices of a diving program that meets the minimum American Academy of Underwater Sciences' (AAUS) *Standards for Scientific Diving Certification and Operation of Scientific Diving Programs*. Operators without a program may accommodate scientific diving cruises which are under the auspices of an institution with such a diving program.

**15.1 Diving Procedures, Rules and Regulations**: For all cruises a single lead institution's campus diving administration will be designated. This is usually accomplished by agreement of all campus diving administrations involved. Items which refer to the campus diving administration may, in fact, be the concern of the Diving Safety Officer according to the practices of the institutions involved. The procedures, rules and regulations that govern the diving operation are those of the designated lead institution, subject to the approval of the operator's Marine Office.

**15.2 Cruise Planning:** In a timely fashion prior to the cruise:

1) The Principal Investigator will insure that a cruise dive plan is supplied to his or her campus diving administration who will forward the cruise plan, once approved, to the lead institution's campus diving administration. The dive plan, prepared in a standard format includes: diving credentials for all diving members of the scientific party; detailed operational plans; emergency plans including accident management and emergency evacuation protocols; a list of needed medical supplies; a specified quantity of medical grade oxygen with a positive pressure demand delivery system; and required diving support equipment (e.g., small boats).

2) The lead institution's diving administration will, after approving this plan, forward it to the operator's Marine Office.

**15.3 Cruise Personnel:**

1) The Master has responsibility for the safety of all activities aboard including diving (Section 13.4).

2) The Chief Scientist is responsible for the co-ordination and execution of the entire scientific mission (Section 13.5).

3) The Principal Investigator of the diving project (who may or may not be the Chief Scientist) is responsible for the planning and co-ordination of the research diving operations.

4) The On-Board Diving Supervisor will be proposed by the Principal Investigator and approved by the lead institution's diving administration. The On-Board Diving Supervisor is responsible for the execution of the research diving operations in accord with the cruise dive plan. He or she has the authority to restrict or suspend diving operations and alter the cruise dive plan in consultation with the Master and the Principal Investigator/Chief Scientist. The On-Board Diving Supervisor's responsibilities include:

A) Meeting with the Master and Chief Scientist to review the cruise dive plan and emergency procedures prior to diving.

B) Remaining in regular communication with the Master on the progress of the research diving operation.

C) Assuring that both the lead and operating institution's diving manual are available to the scientists and crew aboard the vessel.

D) Inspecting high pressure cylinders and breathing air compressors to assure that they meet the lead institutions' standards.

5) Research Divers must recognize their individual responsibility for their safety.

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Univeresity National Oceanograph Laboratory System. 1990. *Research Vessel Operators' Committee Safety Training Manual*, Seattle, WA.

| Institution Name | AAUS Org. Member | AAUS Indv. Members. |
|---|---|---|
| Alabama Marine Env. Sci. Consort. | | Yes |
| Univ. of Alaska | | Yes |
| Bermuda Biological Station | App. | Yes |
| Bigelow Lab. for Ocean Sci. | | |
| Brookhaven National Lab. | | |
| Univ. of Cal, San Diego - SIO | Yes | Yes |
| Univ. of Cal, Santa Barbara | | Yes |
| Cape Fear Technical Inst. | | Yes |
| Columbia Univ., LDGO | | Yes |
| Univ. of Connecticut | R.A. | Yes |
| Univ. of Delaware | | Yes |
| Duke Univ/Univ. of North Carolina Consort. | Yes | Yes |
| Florida Inst. for Ocg. | | Yes |
| Florida Inst. of Technology | | Yes |
| Florida State Univ. | Yes | Yes |
| Harbor Branch Oceanographic Inst. | Yes | Yes |
| Harvard Univ. | | Yes |
| Univ. of Hawaii | Yes | Yes |
| Hobart & William Smith Colleges | | |
| Johns Hopkins Univ. | | Yes |
| Lehigh Univ. | | |
| Louisiana Univ. Marine Consort. | Yes | Yes |
| Univ. of Maine | App. | Yes |
| Marine Sci. Consort. | | Yes |
| Univ. of Maryland | | Yes |
| Massachusetts Inst. of Tech. | | Yes |
| Univ. of Miami, RSMAS | Yes | Yes |
| Univ. of Michigan | | Yes |
| Monterey Bay Aqua. Research Inst. | Yes | Yes |
| Moss Landing Marine Lab. | Yes | Yes |
| Naval Postgraduate School | | |
| Univ. of New Hampshire | | Yes |
| New York State Univ.-Buffalo | | Yes |
| New York State Univ.-Stony Brook | | Yes |
| North Carolina State Univ. | | Yes |
| Univ. of North Carolina-Wilmington | Yes | Yes |
| Nova Univ. | | Yes |
| Occidental College | | Yes |
| Old Dominion College | | Yes |
| Oregon State Univ. | App. | Yes |
| Univ. of Puerto Rico | | Yes |
| Univ. of Rhode Island | Yes | Yes |
| San Diego State Univ. | Yes | Yes |
| Sea Education Association | | Yes |
| Univ. of South Carolina | | Yes |
| Univ. of South Florida | R.A. | Yes |
| Univ. System of Ga., Skidaway Inst. of Ocg. | | Yes |
| Univ. of Southern California | App. | Yes |
| Univ. of Texas | App. | Yes |
| Texas A & M Univ. | Yes | Yes |
| Virginia Inst. of Marine Sci. | Yes | Yes |
| Univ. of Washington | Yes | Yes |
| Univ. of Wisconsin- Madison | | |
| Univ. of Wisconsin-Milwaukee | | |
| Univ. of Wisconsin-Superior | | |
| Woods Hole Ocg. Inst. | Yes | Yes |

RVOC Institutions are underlined.
App.=Application under review.
R.A.=Requested application.

Table 1 UNOLS Members showing RVOC & AAUS Affiliations.

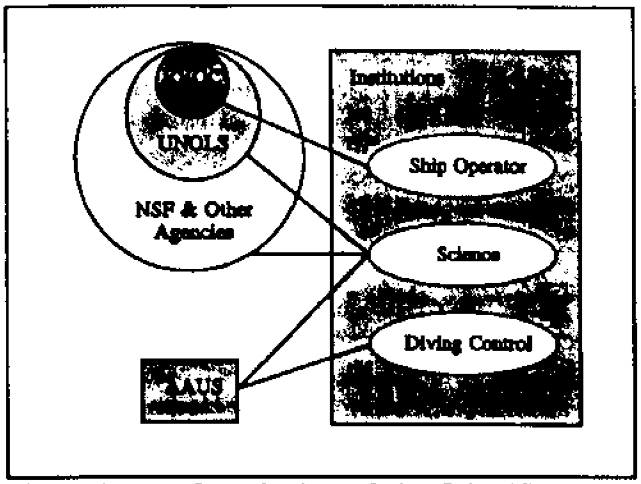


**Figure 1:** Organization of the Scientific Diving Community.

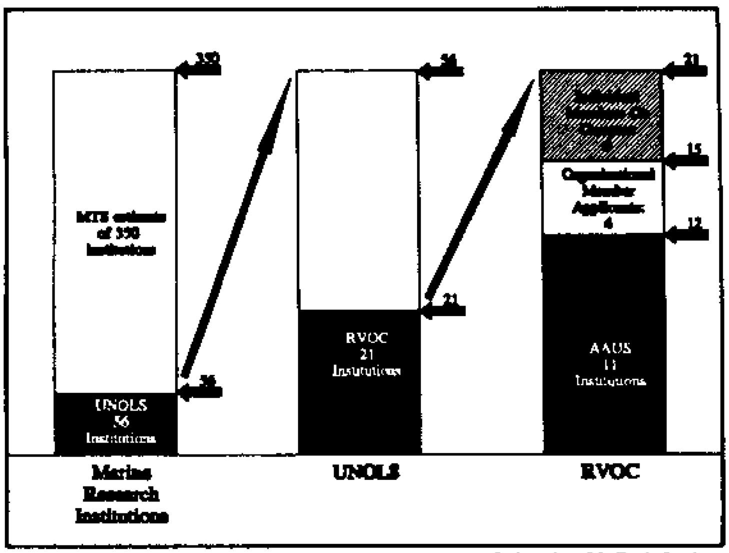


**Figure 2** UNOLS, RVOC and AAUS in the U.S. Marine Research Community

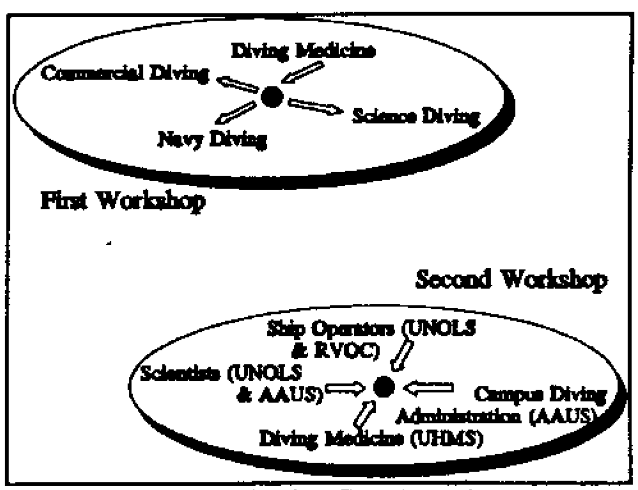


**Figure 3** Participating Constituencies in the First and Second UHMS Workshops

# RESEARCH DIVING ON REMOTE SHOALS OF THE NICARAGUAN RISE, SOUTHWEST CARIBBEAN

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*As a part of a study investigating the sedimentology and morphologies of carbonate platforms of the Nicaraguan Rise, a dive team carried out photographic and video-recorded observations of the benthos and sediments at selected sites on Serranilla and Pedro Banks during March and April 1987. Divers were deployed from the research vessel R/V* Cape Hatteras *to an inflatable chase boat. Diver observations of poorly developed reefs on Pedro Bank and the lack of reef development on the windward margin of Serranilla Bank were instrumental in understanding sedimentologic patterns found using seismic profiling, grab sampling and dredging.*

## INTRODUCTION

The Nicaraguan Rise in the western Caribbean is a structural high that exends from Jamaica on the east to the continental shelf of Honduras and Nicaragua on the west (Fig. 1a). Limestone platforms cap bedrock highs (Arden 1975), creating a series of banks. Bank tops are typically deeper than 15 m, although shoals and small islands occur on the eastern banks, particularly Pedro and Serranilla Banks. The depths of these banks provoke questions. Why are these banks not atolls similar to those found at similar latitudes in the Pacific? Why are they not shallow banks similar to those of the Bahamas? After all, these banks lie in tropical waters, well south of the chilling influence of winter-air masses that occasionally kill corals in south Florida and the Bahamas (e.g., Roberts et al. 1982). Strong, easterly trade winds blow most of the year, though continental storm systems bring strong northerly winds on an average of every two weeks between October and March (DiMego et al. 1976). The Caribbean Current is deflected northward by the Central American land mass and accelerated into a western boundary current that flows over the Rise (Molinari et al. 1981). The banks are isolated from terrigenous runoff from the Central American mainland (Roberts and Murray

1983). Yet, in an environment seemingly suitable for reef growth and limestone production, these banks do not appear to be accreting and are therefore failing to keep up with relative sea-level rise.

With the goal of answering some of these questions, we conducted a multidisciplinary research cruise aboard the R/V *Cape Hatteras* in March and April 1987. Because the Nicaraguan Rise is a tectonically active area (Bonini et al. 1984), located adjacent to the Cayman Trough, our original hypothesis was that tectonic subsidence was responsible for the failure of the banks to keep up with sea level. Thus, where banktop and margin depths and substrata are suitable for coral-reef development, we expected to find thriving coral-reef communities. The purpose of the SCUBA-diving operation was to visually examine shallow benthic communities on Serranilla and Pedro Banks to determine if there was anything unusual about them that would provide clues as to why these banks are not accreting.

## METHODS

Because this was the first dive team to be deployed from the R/V *Cape Hatteras*, a University National Oceanographic Laboratory System (UNOLS) vessel, and because diving was to be conducted in waters remote from a decompression facility, a safe diving operation was a primary consideration. All divers were experienced open-water divers, trained in CPR, and met AAUS open-water diving standards as required by UNOLS.

The dive team consisted of four divers including the Dive Master. The dive officer for the R/V *Cape Hatteras* also participated in some dives. Divers were deployed from the chase boat, a 5.2 m inflatable raft equipped with a 80 HP motor, which was operated by the first mate. Radio contact was maintained with the R/V *Cape Hatteras* using a hand-held VHF radio. A small depth recorder attached to a hand-held transducer was used to determine deployment location. One diver, with full equipment, stayed on the surface as a safety diver, observing the dive from above. The submerged team trailed a surface buoy to facilitate visual contact by the safety diver and boat operator. The submerged team consisted of a still photographer who trailed the surface buoy, a video operator, and a sediment collector. When four divers were working below, the fourth trailed the surface buoy. All divers maintained visual contact at all times. This procedure was used for five dives, four on Serranilla Bank (Fig. 1b) and one on Pedro Bank (Fig. 1a). A second dive on Pedro Bank was conducted by two divers to examine a deployed current meter. In this case, divers entered the water directly from the stern of the research vessel and were retrieved by the chase boat with boat operator and safety diver. In addition, a dive at Montego Bay, Jamaica, provided comparison with an area of substantial reef development.

## SITE DESCRIPTIONS

Site 1 (Fig. 1b) was on the banktop of eastern Serranilla Bank at a depth to 10 m. The bottom was limestone outcrops surrounded by rippled skeletal sands. Hardbottom was mostly covered by fleshy brown algae of the following genera: *Dictyota, Stypopodium, Sargassum,* and *Turbinaria*. Individual corals were common but never large nor abundant; the most common species were *Millepora alcicornis* and *Montastrea annularis*. Sponges were common. Fish were scarce, apparently because refuge shelter was lacking.

Site 2 (Fig. 1b) was also on the banktop of eastern Serranilla Bank at a depth of 8-13 m. Eroded limestone substrata sloped gently into sand patches at 12-13 m. The bottom was even more dominated by fleshy brown algae than Site 1, and green algae (especially *Halimeda* and *Dictyosphaeria*) were common. Corals were generally small and sparse with the exception of a nearly 3-m head of *Porites porites* and *Montastrea annularis*. Fish were abundant around this bioeroded head, which provided shelter, but were otherwise scarce. Sponges and octocorals were common.

Site 3 (Fig. 1b) was on southeastern Serranilla Bank in the lee of Beacon Cay. We dived on flat sand and rubble bottom at a depth of 12 m. Pieces of *Halimeda* plates, molluscan shells, and foraminiferal tests made up the skeletal sand that was stabilized by sea grass *(Syringodium)* and calcareous algae *(Halimeda, Penicillus,* and others). *Manicina* corals, conch *(Strombus gigas)*, sponges, and octocorals were also common.

Site 4 (Fig. 1b) was on the eastern margin of Serranilla Bank near the northeast breakers. We began the dive at 18 m on gently sloping limestone substrata and worked upslope to intertidal depths. The hard bottom was "paved" by coralline algae upon which the fleshy brown alga *Turbinaria* proliferated, with a variety of other brown, red and green macroalgae, especially below 5 m. *Halimeda* was present but not common. The second most common benthos was sponge, particularly extensive carpets of boring clionids. At 10-18 m, small heads of *Montastrea annularis* and scattered *Millepora alcicornis* were common. In shallower water, *M. complanata* and *Palythoa caribbea* were abundant. One small cluster of *Acropora palmata* was also seen, as were occasional pieces of *A. palmata* rubble. Shallow substrata was cavernous, providing habitat for abundant fish.

Site 5 was a reef dive south of Montego Bay Harbor (Fig. 1a). Hard substratum cover was mixed coral and algae, with a substantial number of sponges. Coral formations rising from about 6 m depth to the surface were cavernous and undercut; bioersion was evident and active. Between about 6 and 9 m depth, the mixed and hard substrata bottom sloped gently offshore. The hard substrata was covered predominantly by filamentous algae, though small corals were abundant and diverse and the 1-2 m of local relief was obviously constructed by coral.

Site 6 (Fig. 1a) was the current meter site at 26 m depth on southwestern Pedro Bank. The substratum was rippled sand molded into large-scale (20-30 m long) sand waves. The sand was populated by green algae, including *Halophila, Caulerpa, Halimeda, Udotea,* and

*Avrainvillea.* Rubble recovered was predominantly *Manicina* corals and bivalve shells encrusted by coralline algae.

Site 7 (Fig. 1a) was off Southwest Rocks, Pedro Bank at a depth of 10 to 13 m. Hard substratum was dominated by filamentous algae. *Halimeda* was the most abundant macroalga. *Acropora palmata* was abundant and head corals were diverse though not large. Coral-constructional, spur-and-groove relief was about 3-4 m, providing shelter for abundant fish populations. Sponges were abundant and evidence of bioerosion was ubiquitous.

## DISCUSSION

The lack of coral-reef development observed on Serranilla Bank, along with the rather poor development on Pedro Bank, provided evidence that the failure of these carbonate platforms to keep up with Holocene sea level rise is at least in part biological and cannot be fully explained by rapid tectonic subsidence. If tectonic subsidence was the whole story, the shoals of Pedro and Serranilla Banks ought to support lush coral reefs.

The differences in benthic communities observed between Montego Bay and Serranilla Bank appear to coincide with the changes in benthos that can be expected along a regional nutrient gradient (Fig. 2). Birkeland (1987, p. 47) observed that "along a gradient of decreasing nutrient input, whether on a geographical or a local scale, the predominant occupants of primary substrata in shallow water change from heterotrophic suspension feeders to benthic plants to phototrophic animal-plant symbionts". Hallock et al. (1988) compared platform depth, benthos, and chlorophyll concentrations in sea-surface waters along the Nicaraguan Rise, showing that all three show corresponding east-west gradients: banktop depth increases westward as reefal development declines and chlorophyll concentrations increase. The relatively abundant nutrient resources indicated by chlorophyll concentrations favor algal-dominated benthos over coral-dominated benthos. As a result, most of the Nicaraguan Rise banks lack a rapidly accreting reefal rim that can keep up with sea level. Without a reefal rim for shelter, banktop sediments produced by calcareous algae are swept off into deeper waters by the strong Caribbean Current (Triffleman and Elrod, 1989).

Diver observations were obviously only a small part of the total data base from which interpretations of Nicaraguan Rise sedimentation were developed. However, they were an absolutely essential piece of the puzzle; they provided a focus for interpreting many of the subsequent observations. Since the diving operation took place very early in the study, some of the subsequent work was adapted to further develop ideas spawned by the early diver observations. The importance of sea-surface chlorophyll measurements and estimates of chlorophyll concentrations from Coastal Zone Color Scanner (CZCS) images collected by the Nimbus-7 satellite (Hallock and Elrod 1988) became particularly evident after the diver observations. Direct diver observations, supplemented by diver-collected video images, proved so useful in understanding benthic communities and sedimentary regimes that during a second cruise to the deeper banks west of Serranilla Bank (Fig. 1a), we used a NOAA-NURP remotely operated submersible to recover video images of the benthos.

An interesting corollary to the story of the relationship of nutrient availability to benthic community dominance is the role of bioerosion in providing habitat for bottom-dwelling fish. Such fish were abundant in the heavily bioeroded reefs of Pedro Bank. But on Serranilla Bank, they were scarce probably because shelter was lacking. The extremely low relief and fleshy algal cover only provided refuge for small fish. Larger fish were mostly seen in the cavernous limestone that made up the breakers or around the rare larger coral heads. Thus, it appears that even though food resources for fish should be plentiful at intermediate nutrient resources that promote algal growth, lack of coral-constructional topography limits the shelter and, therefore, the population density of larger bottom-dwelling fish.

There are several other advantages to using a dive team on projects similar to this. This team was able to collect key data in water too shallow to be explored remotely from the research vessel. Furthermore, a dive team is much lower impact than conventional geologic bottom sampling by dredge or grab sampler. Thus, a dive team is essential for work in environmentally sensitive shallow waters. Although the Duke/University of North Carolina Oceanographic Consortium, who operate the R/V *Cape Hatteras*, were reluctant to allow diving from their vessel, the safety and effectiveness of our operation has helped promote subsequent diving research, as well as increased diver training and awareness among R/V *Cape Hatteras* crew members.

## CONCLUSION

Use of a SCUBA-diver team in the early reconnaissance of benthic communities and carbonate sedimentation on Serranilla and Pedro Banks provided observations that contributed substantially to subsequent research design. The observed lack of coral-reef development also provided a key piece of evidence that permitted interpretation of recent carbonate depositional history on the Nicaraguan Rise.

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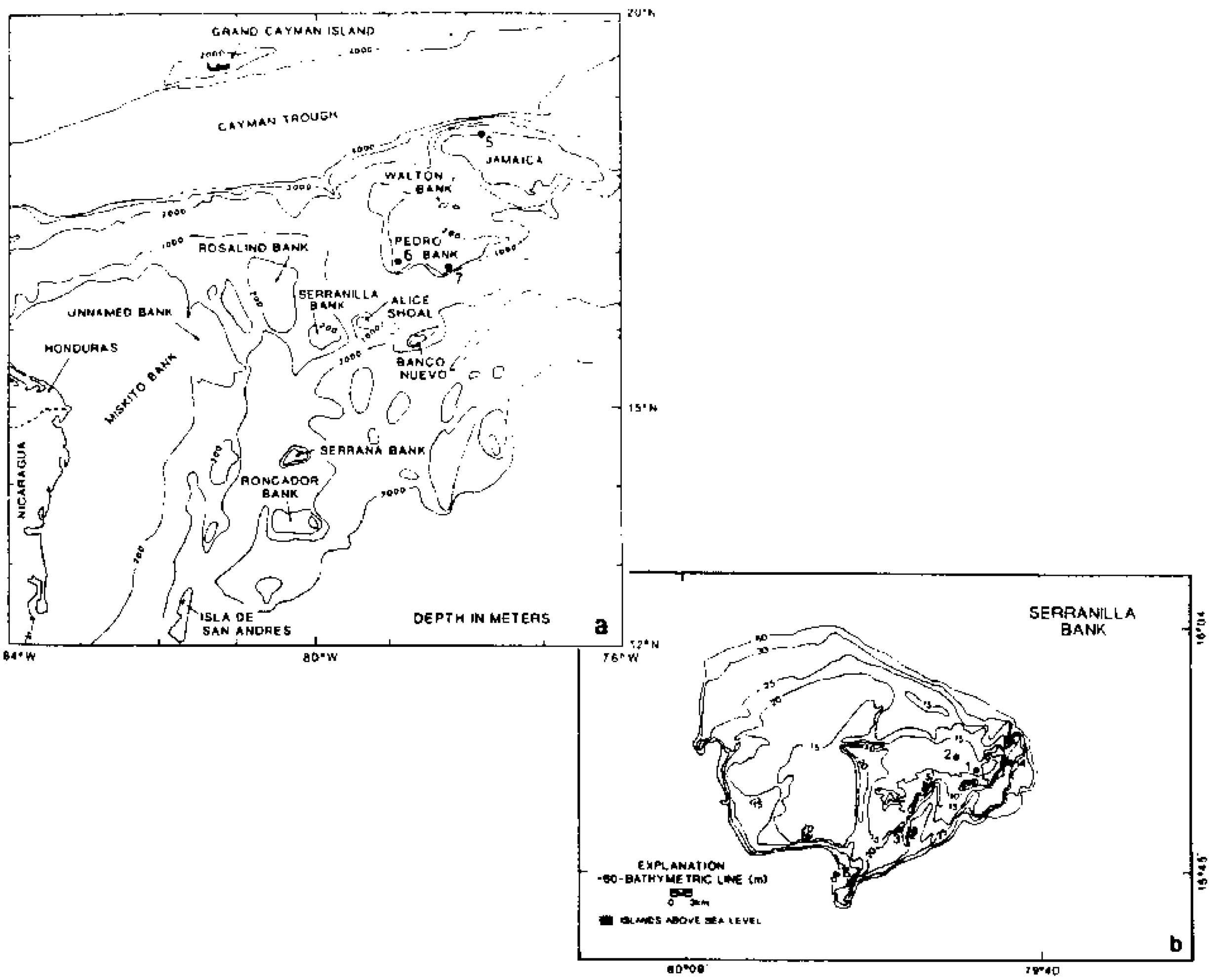


**Figure 1a. Location of the Nicaraguan Rise, southwestern Caribbean. Dive sites 5 (Montego Bay, Jamaica), 6 and 7 (Pedro Bank) are shown.**
**Figure 1b. Serranilla Bank showing locations of dive sites 1–4.**

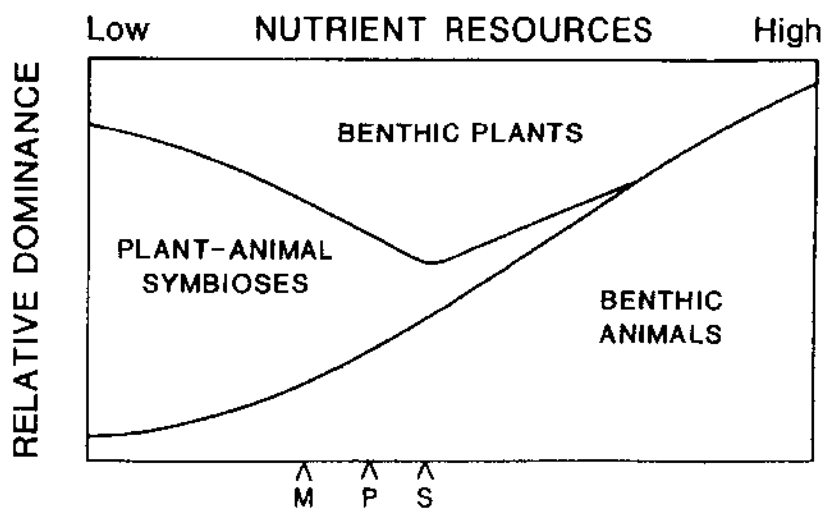


**Figure 2. Benthic community dominance gradient as it corresponds to the nutrient gradient (adapted from Hallock et al. 1988). Approximately where Montego Bay (M), Pedro Bank (P) and Serranilla Bank (S) fall on this gradient are indicated on the figure.**

# THE WARM MINERAL SPRINGS DECOMPRESSION PLAN AND TABLES

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*Archaeological work in the Warm Mineral Springs (WMS) sink hole had achieved considerable success in working at depths approaching 50 msw (165 fsw), using air as a breathing gas with inwater oxygen decompression, but with the drawbacks of rather inefficient decompression and significant narcosis at the working depth. To improve this situation procedures using "trimix" with custom decompression tables of the sort developed by "high-tech" cave and other advanced recreational divers have been adapted to the WMS operation. This was done under new guidelines on the validation and implementation of new decompression procedures by the Undersea and Hyperbaric Medical Society (74(VAL)1-1-88). An extensive decompression plan supported by a data base of relevant dive experience includes medical support, an on-site chamber, training, ongoing monitoring (including doppler), oxygen tolerance procedures, and a Decompression Monitoring Board. Our tables use trimix of 20% $O_2$, 40% He, balance $N_2$, with 50% $O_2$ enriched air "nitrox" intermediate mix (21-6 msw) and inwater oxygen at 6 and 3 msw.*

## INTRODUCTION

For many years underwater archaeological work has been carried out in the anaerobic sink hole at Warm Mineral Springs south of Sarasota, Florida, by the Warm Mineral Springs Archaeological Research Project. This has involved work to depths as deep as 50 msw (metres of sea water, a measure of pressure; 1 msw = 10 kPa) or 165 feet of sea water (1 fsw = 1/33 atm or 3.070 kPa) and has been done primarily with air as the breathing gas. Using air, decompressing from dives with a useful amount of time at this depth is tedious, and the traditional tables do not provide an adequate degree of reliability. To deal with the latter problem and in order to carry out air dives in this depth range, oxygen was breathed in the water at the 6 and 3 msw (20 and 10 fsw) stops. This improved table reliability, but it did not improve the dive efficiency by reducing decompression time, nor did it remove the narcosis caused by the nitrogen in the breathing gas at the working depth.

One benefit of this experience with inwater oxygen was that it set a precedent for the use of non-standard, somewhat sophisticated, diving procedures. Since the stops and times on the tables were the same as published in the US Navy Diving Manual and only the breathing gas was changed, this substitution of oxygen breathing would not normally be regarded as being an "untested" procedure.

## OBJECTIVES

In recent years the scientific diving community has seen the development of an increased awareness that improvements in diving technology could increase the capability of scientists engaged in underwater projects. Chief among these is the increase in bottom time that can be achieved by tactics involving breathing gas and decompression. The WMSARP sought the ability to work longer on the bottom and to gain relief from narcosis, without sacrificing operational safety from the point of view of decompression table reliability. Another aspect of longer working time was the need for improved thermal protection, achieved here by the use of dry suits. Improved medical backup and emergency procedures were also felt to be needed. In an administrative change the state-funded program would be monitored by the Florida State University Academic Diving Program and would meet the approval of the FSU Dive Control Board.

## METHODS

### *The trimix technique*

Techniques that could meet the WMSARP requirements were already well under development by a "high tech" branch of the recreational diving community, the cave divers. Certain cave divers had the requirement to go to depths great enough for narcosis to be a significant problem with air as the breathing gas, and in particular they needed long bottom times. Commercial divers had long practiced replacing some or all of the nitrogen with helium in order to reduce or eliminate the narcosis problem. However, commercial and military operations working in the depth range in question nearly always meet the need for longer working time on the job by using multiple dives by several divers rather than to try to extend a single dive into a long bottom time. Further, commercial divers rarely if ever use scuba equipment for dives in this depth-duration range. Cave divers and other entrepreneurial, technologically oriented, recreational divers with similar objectives had developed this technique into a refined practice.

Being scuba-bound, cave divers often have to exchange tanks many times during a dive and are thus more acclimated to the concept of gas switching. Where appropriate decompression tables are available, considerable efficiency can be achieved by switching gases. Tables had been developed by using trimix or heliox for bottom mixes, usually an intermediate gas mix of oxygen-enriched air ("nitrox" or "EANx"), and oxygen at the shallow stops. "Heliox" is helium and oxygen, and "trimix" is a mixture of helium, nitrogen, and oxygen. Thus the cave diving community had developed a technique of using special gas mixtures for efficient decompression and reduction of narcosis.

This development provided two benefits to the WMSARP project. First by development of the techniques in the first place, but also quite significantly by providing a **track record** in the field use of these techniques that could be used as a basis for developing a set of procedures for Warm Mineral Springs.

*The validation process*

Even with the precedent that this type of diving procedure was already in use, it could still be a problem to introduce what could be regarded as a "new" set of decompression tables into a state sponsored, university controlled, scientific diving program. Fortunately a new set of guidelines had recently been issued that addressed this point. The Undersea and Hyperbaric Medical Society, under the sponsorship of the NOAA Undersea Research Program, US Department of Commerce, had held a workshop covering the validation of decompression tables (Schreiner and Hamilton, 1989). This workshop convened most of the leading experts on decompression from the US and a few from Europe. It covered the decompression table validation issue from a wide variety of perspectives, ending up with a flow chart of an exemplary table development process and a clarification of several important concepts.

A main contribution of the Workshop was to address the question of how to deal with the issues that cannot be (or at least have not been) delineated specifically and therefore require some judgement. First, the Workshop made the point that the **organization** developing new decompression tables has the responsibility for making the judgement decisions (it could not be passed off to some government agency). The Workshop further recommended that the responsibility within the organization for these decisions could rest with a **specified group** set up for this purpose and charged with this responsibility. For want of a better name this is called the Decompression Monitoring Board (DMB). The DMB is responsible for making the decisions, for example, as to when a new table formula is ready for testing, when sufficient testing has been done in a laboratory and sea trials can start, and when sufficient "provisional" operational evaluation has been performed and a procedure can then be called "operational." The DMB can also be responsible for continued assessment of the use of tables within the organization, and the several feedback loops. While some or all of these concepts have more or less been practiced in the past, putting them into a concise form that was agreed to by the Workshop constituted a major step for the diving community.

Another relevant point made by the Validation Workshop was a set of operating conditions recommended for the situation when new decompression tables are moved into provisional use in the operational setting. In addition to being under the cognisance of the DMB, this situation should involve expert supervision and on site training, understanding and acceptance by higher levels of management, a decompression chamber on site with a crew trained to use it, training in the recognition and treatment of decompression sickness and other dysbaric maladies, and a specific medical response plan.

For WMSARP to proceed it was judged necessary to have a DMB. This was duly appointed, approved by the Dive Control Board, and a plan was developed. The FSU Academic Diving Program DMB consists of the WMS archaeologist, the FSU diving officer, a consultant in decompression physiology, a physiologist faculty member, and the ADP's diving medical officer. The DMB proposed to present to the Dive Control Board a decompression plan, to include documentation of the field experience behind the proposed tables, the rationale for the tables to be used, and the tables themselves.

The plan was prepared and approved by the DMB along with a comprehensive series of additional considerations. These included a training program, the hiring of an experienced diving officer for the site, the acquisition and installation of a decompression chamber at the site with training for the personnel in its use, and a medical management protocol dealing both with diver fitness and handling of decompression sickness and diving accidents.

An additional aspect of the WMS decompression plan was the identification of about 100 specific operational man dives that had been carried out using trimix tables for exposures of the same or greater stress than those proposed for WMS. Not all of these dives were totally relevant nor were they all run to the maximum time and depth of the specific table but they were all run in the operational setting and all have satisfactory results in that no decompression sickness was reported.

Thus the WMS operation met recommended criteria for the use of provisional or **operational evaluation** tables in the operational setting. The DMB took the position that the WMS operation could enter the validation process at the operational evaluation stage. This is the step following laboratory testing during which tables are in provisional use under operational conditions prior to being declared operationally ready. As mentioned, this step requires special considerations and these were judged to be met by the planning and preparation made by WMS.

The plan was presented to the Dive Control Board of FSU by the DMB, and was approved. The various requirements were implemented, and the diving operation was begun.

## DESCRIPTION OF THE TABLES

The WMS Decompression Tables are procedures for diving with helium-nitrogen-oxygen trimix in the depth range 45-55 msw for times 20-60 min, using "enriched air nitrox" as an intermediate decompression gas and oxygen breathing in the shallow stops.

### *Calculations*

The tables were generated with DCAP, a computer program designed for the general purpose computation of decompression tables (Hamilton and Kenyon, 1990). The computational "model" used was the neo-Haldanian method designated Tonawanda II, which allows different inert gases to be used. Eleven compartments with half times ranging from 5 to 240 min for helium and 5 to 670 min for nitrogen were used, with an ascent-limiting matrix of M-values designated MF11F6. This computational algorithm was the same one used for computing the collection of earlier operational dives mentioned above. The matrix was derived for long, deep air dives with air decompression, and had been through initial validation testing for that mode (Hamilton et al., 1988).

*Scope of the WMS tables*

For practical reasons the WMS tables are presented here in their original English units, with pressure in fsw, feet of sea water, as defined above.

Depths covered were chosen to match the excavation site in the "cone" area of the spring, for current and near-future diving. These were for 150, 160, 170, and 180 fsw. Tables for each of these depths were produced in both detailed and condensed formats, with coverage of times from 20 to 90 minutes; plans call for operational dives to be limited to a maximum of 60 minutes bottom time, but 75 and 90 minute tables were prepared for contingencies.

An additional conservatism factor was used for those tables which we felt might entail greater decompression stress. This was invoked for tables with more than 22 min of time at the 30 fsw stop. This was implemented, when needed, by the DCAP "M-factor" feature, which multiplies the prevailing M-values by 0.94, making them more conservative. The choice of this factor and how it was invoked was arbitrary, but we felt it is supported by the deep air work mentioned above.

A single bottom gas mixture was selected as 40% helium, 21% oxygen, balance nitrogen. This is breathed from the surface through descent, the bottom work period, and ascent to 70 fsw. At 70 fsw the breathing mixture is charged to an intermediate enriched air nitrox mixture, 50% oxygen, balance nitrogen, which is breathed until 20 fsw. At 20 fsw the diver switches to pure oxygen for the remainder of the dive. The oxygen breathing may all be taken at 20 fsw, with the time for the 10 fsw stop added to the 20 fsw time.

No provision is made for more than one dive in a day, and it is recommended that a day off be taken after three consecutive days of diving; calculations showed no gas loading "violations" after 4 days of diving, but after there is a buildup that has to be considered. Oxygen tolerance calculations using the Repex method (Hamilton, 1989) show that this diving pattern will not exceed conservative operational limits.

The treatment for decompression sickness, should it be required, would be by the US Navy oxygen tables 5 or 6 or 6A, according to the USN manual.

*Sample WMS tables*

A summary of the set of detailed tables is given in Figure. 1. This shows bottom depth, time, mixture name, running and decompression time in both minutes and hours and minutes, the depth of the first stop, the number of Oxygen Tolerance Units accumulated over the dive, and the amount of time spent on pure oxygen.

Figure 2 shows a sample of the detailed table for 160 fsw for 60 min. Most heading entries are obvious; the name of the "Basecase" containing input data for DCAP is D9DBT7.B00, and the matrix name is MF11F6.DCP. The oxygen range shows the values used in the calculations; the lower $O_2$ value was used for decompression and the higher for oxygen tolerance. The decompression clock is started when the diver leaves bottom; he departs each stop depth at the time indicated. At the end of the table are summary times (rounded differently from the dive time) and some oxygen tolerance data.

Figure 3 shows a condensed table which includes stop data on several bottom times for the same depth on a single page. The entries are stop time and total decompression time at each stop; timing is done in the same manner as with the detailed tables.

The dives shown here are presented as examples of a contemporary dive plan. A substantial investment has been made in training, equipment, and support capabilities in order to use these tables. Divers who might be tempted to use them with inadequate preparation are warned that to do so will impose significant risk, both operationally and in decompression. No decompression table, no matter how conservative, can guarantee that decompression sickness will not occur following a significant exposure to pressure.

## RESULTS

Diving on the new tables at WMS began on 90Feb21 and was carried out intensively through 90Mar22.

For several reasons unrelated to the decompression tables the diving program had a period of reduced activity after that time. A summary of the initial period of deep diving activity is included in Figure 4. This shows the dive depth in fsw and time in minutes, the table used for that dive, and some doppler data. Many of the dives are to the full time and depth of the table, according to the plan.

This is not intended to be a report on the doppler studies, but a summary of the highest doppler scores is included. The highest score from each dive is shown, with the location and time. Equal high scores occurring more than once are all listed. Doppler readings were taken at 20 min and 60 min after the end (surfacing) of each dive; predive recordings were also taken.

Scoring is by the K-M method. The table shows a few Grade II scores in the precordial region, but Grade III readings from the right subclavian are common.

An interesting finding was a few doppler bubbles on the predive reading on 90Mar14.

In general the doppler scores would be considered quite acceptable (that is, the doppler scores would indicate that the tables are quite acceptable) if we were to consider only the precordial values. Grades I and II with a rare Grade III reading would be acceptable. Repeated Grade III scores are cause for concern. However, the Grade III scores are predominately in the right subclavian vein. The diver-archaeologist's right arm is in constant motion throughout a working dive of this sort, so we would expect the most bubble activity in that limb. Whether this represents a requirement to make the tables more conservative is not certain. Another peculiar thing is the finding of higher scores at rest before flexing than after flexing the arm; this is the opposite to what is normally found.

The operational decision at this point is to continue as planned and get more experience before making a change. At at the end of the season the results will be examined carefully by the DMB and any changes deemed necessary will be made before proceeding with next season's diving.

This diver has performed many dives in this depth range using air; he feels the dive with trimix, even though longer, is less stressful, and he feels better afterwards than he did following air dives in the past.

## CONCLUSIONS

An efficient decompression plan has been set up for archaeological diving at WMS. Trimix tables with intermediate enriched air nitrox and oxygen breathing afford minimal narcosis and acceptable decompression times. A total of 10 dives in the 160 fsw range show that the plan is working. Doppler scores suggest a slightly more conservative decompression may be found to be desirable in due course to account for the high level of right arm activity, but for the moment the plan seems acceptable.

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**Table 1. Diving activity at WMS 1990 Feb–Mar. Shows date of dive, time and depth of dive and table, maximum K–M doppler score recorded, location (precordial or subclavian), and time after end of dive (min). Equal scores are all shown.**

| Date | Bottom depth/time fsw/min | Table depth/time fsw/min | Maximum doppler, rest | flex | Location | Time after dive |
|---|---|---|---|---|---|---|
| Feb21 | 159/29 | 160/30 | II | II | PC | 20,60 |
| Feb22 | 160/30 | 160/30 | II | II | PC | 20 |
| Feb27 | 159/21 | 160/30 | III | | RS | 20 |
| Mar01 | 160/39 | 160/40 | III | | RS | 20,60 |
| Mar07 | 162/35 | 170/40 | not done | | | |
| Mar13 | 160/39 | 160/40 | III | | LS; RS | 20 |
| Mar14 | 160/49 | 160/50 | III | | RS | 20,60* |
| Mar19 | 160/30 | 160/30 | III | | RS | 20 |
| Mar20 | 160/50 | 160/50 | | II+ | RS | 20,60 |
| Mar22 | 160/49 | 160/50 | III | | RS | 20 |

*Grade I doppler bubbles detected predive.

```
SUMMARY:    Basecase    D90BT7.B00       Matrix   MF11F6.DCP       DCAP+  (c)  6.12-08    90Jan18

------   BOTTOM   ------         ----  RUN  ----      DECOMPRESSION       1ST  STOP
DEPTH    TIME     MIXTURE         MINS     HH:MM       MINS    HH:MM       DEPTH       OTU    O2  TIME

 150.     30.     TX21/40          64.     01:03        34.     00:33        50.        90.       23.
 150.     40.     TX21/40          93.     01:32        53.     00:52        60.       131.       33.
 150.     50.     TX21/40         120.     01:59        70.     01:09        60.       167.       39.
 150.     60.     TX21/40         148.     02:27        88.     01:27        60.       209.       48.
 150.     75.     TX21/40         190.     03:09       115.     01:54        70.       269.       60.
 150.     90.     TX21/40         248.     04:07       158.     02:37        70.       359.       89.
 160.     30.     TX21/40          69.     01:08        39.     00:38        60.       102.       26.
 160.     40.     TX21/40         100.     01:39        60.     00:59        60.       145.       35.
 160.     50.     TX21/40         129.     02:08        79.     01:18        70.       187.       42.
 160.     60.     TX21/40         157.     02:36        97.     01:36        70.       230.       51.
 160.     75.     TX21/40         220.     03:39       145.     02:25        80.       325.       80.
 160.     90.     TX21/40         269.     04:28       179.     02:59        80.       397.       97.
 170.     30.     TX21/40          75.     01:14        45.     00:45        60.       114.       29.
 170.     40.     TX21/40         107.     01:47        67.     01:07        70.       159.       37.
 170.     50.     TX21/40         138.     02:18        88.     01:28        70.       207.       46.
 170.     60.     TX21/40         170.     02:50       110.     01:50        80.       254.       56.
 170.     75.     TX21/40         239.     03:59       164.     02:44        80.       357.       88.
 170.     90.     TX21/40         288.     04:48       198.     03:18        90.       434.      105.
 180.     30.     TX21/40          80.     01:20        50.     00:50        70.       125.       32.
 180.     40.     TX21/40         114.     01:54        74.     01:14        80.       173.       39.
 180.     50.     TX21/40         148.     02:28        98.     01:38        80.       226.       50.
 180.     60.     TX21/40         185.     03:05       125.     02:05        80.       278.       61.
 180.     75.     TX21/40         257.     04:17       183.     03:02        90.       391.       95.
 180.     90.     TX21/40         315.     05:15       226.     03:45        90.       476.      116.
```

**Figure 1. Summary list of WMS tables on detailed format.**

WMSARP 21/40 TRIMIX
RWH/BE (FACTOR) 90Jan18
D9DBT7.B00 MF11F6.DCP

DEPTH 160 FSW
BOTTOM TIME 60 MIN
BOTTOM MIX TX21/40
BOTTOM PO2 1.29 ATM
Times in minutes

| DEPTH FSW | STOP TIME | DECOM TIME | MIXTURE | PO2.RANGE ATM ATM | COMMENTS |
|---|---|---|---|---|---|
| 00 | 00 | 00 | AIR | 0.21-0.21 | DESCEND TO BOTTOM AT COMFORTABLE RATE |
| | 00 | 00 | TX21/40 | 0.20-0.22 | BREATHE TRIMIX 21%02 40%HE FROM SURFACE |
| 160 | 60 | 00 | TX21/40 | 1.17-1.29 | ASCEND TO FIRST STOP AT -60 FPM |
| 70 | 00 | 01 | NX50 | 1.44-1.62 | BREATHE 50% 02, 50% N2 70 TO 20 FSW |
| | 03 | 05 | NX50 | 1.44-1.62 | RATE -30 FSW/MIN AFTER FIRST STOP |
| 60 | 04 | 09 | NX50 | 1.30-1.47 | |
| 50 | 06 | 15 | NX50 | 1.16-1.31 | |
| 40 | 14 | 30 | NX50 | 1.02-1.15 | |
| 30 | 16 | 46 | NX50 | 0.88-0.99 | |
| 20 | 20 | 66 | OXYGEN | 1.45-1.61 | BREATHE 100% 02, 20 FSW TO SURFACE |
| 10 | 30 | 97 | OXYGEN | 1.17-1.30 | |
| 00 | 00 | 97 | OXYGEN | 0.90-1.00 | REACH SURFACE |
| | | | | | TOTAL TIME = 02:36 HR:MN |
| | | | | | DECOM TIME = 01:36 HR:MN |
| | | | | | OTU = 230 VC DROP=-1.4% |

**Figure 2. Sample of the detailed table for 160 fsw for 60 min.**

WMSARP 21/40 TRIMIX 90Jan17
RWH/BE MF11F6.DCP
D9DBT4.B00

DEPTH 160 FSW
MIX TX21/40
PO2 1.29 ATM

| Bottom time | 20 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 75 | 90 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| t to 1st | 4.0 | 3.3 | 3.3 | 3.3 | 3.0 | 3.0 | 3.0 | 3.0 | 1.3 | 1.3 | |
| Depth FSW | | | | | | | | | | | Depth |
| 80 | | | | | | | | | 02 | 05 | 80 |
| | | | | | | | | | 03 | 06 | |
| 70 | | | | | 01 | 01 | 02 | 03 | 04 | 06 | 70 |
| | | | | | 03 | 03 | 04 | 05 | 08 | 13 | |
| 60 | | 01 | 01 | 02 | 02 | 03 | 04 | 04 | 07 | 11 | 60 |
| | | 03 | 03 | 04 | 05 | 06 | 08 | 09 | 15 | 24 | |
| 50 | | 01 | 02 | 03 | 04 | 05 | 04 | 06 | 12 | 12 | 50 |
| | | 04 | 05 | 07 | 09 | 11 | 12 | 15 | 27 | 36 | |
| 40 | 01 | 03 | 05 | 05 | 05 | 09 | 13 | 14 | 14 | 18 | 40 |
| | 03 | 08 | 11 | 13 | 14 | 21 | 26 | 30 | 42 | 55 | |
| 30 | 02 | 05 | 06 | 12 | 16 | 16 | 16 | 16 | 23 | 27 | 30 |
| | 06 | 13 | 17 | 25 | 31 | 37 | 42 | 46 | 65 | 82 | |
| | BREATHE 100% O2, 20 FSW TO SURFACE | | | | | | | | | | |
| 20 | 03 | 10 | 13 | 12 | 12 | 15 | 17 | 20 | 33 | 40 | 20 |
| | 09 | 23 | 30 | 37 | 43 | 52 | 59 | 66 | 98 | 122 | |
| 10 | 11 | 15 | 18 | 22 | 25 | 26 | 29 | 30 | 46 | 56 | 10 |
| | 21 | 39 | 49 | 59 | 69 | 79 | 89 | 97 | 145 | 179 | |
| | REACH SURFACE | | | | | | | | | | |
| 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 |
| | 21 | 39 | 49 | 60 | 69 | 79 | 89 | 97 | 145 | 179 | |

**Figure 3. Condensed table for 160 fsw, covering times 20–40 min.**

# A COMPARISON OF THE INCIDENCE OF DECOMPRESSION SICKNESS IN MEN AND WOMEN DIVERS USING DECOMPRESSION TABLES AND DIVING COMPUTERS FOR 77,680 DIVES

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*Much debate has taken place concerning the relative risk of decompression sickness in divers using dive computers versus those using dive tables, but little data is available. Utilizing the dive tracking system of Ocean Quest International's diving cruise ship Ocean Spirit, we have retrospectively analyzed the 70,000 dives made by participants. Dives made from March, 1989 through February, 1990 were examined. Thirty-two thousand dives were made by divers using the ship's Dacor Microbrain and ProPlus Decobrain computers. Thirty-eight thousand dives were made with diving tables. Both sets of divers dove under the same diving rules and divemasters. Divers using diving computers sustained no cases of decompression sickness. Divers using tables sustained 3 cases of DCS, which responded to treatment by the on-board hyperbaric facility. The statistical significance of this data and that of sub-groups, such as divemasters and deep divers, will be discussed.*

## INTRODUCTION

There has long been a need for an examination of the incidence of decompression sickness (DCS) and arterial gas embolism (AGE) in a truly large number of recreational men and women diving under similar conditions while using decompression tables and diving computers, and this paper attempts to fill that need. Ocean Quest International's 457 foot cruise ship, the Ocean Spirit, carried approximately 160 divers on each one week cruise, with four days available (weather permitting) for diving, and with each diver making as many as 17 dives per trip. This resulted in more than 1,000 dives per week, with one notable day in December, 1989, having more than 1,000 dives on that *day* alone. Meticulous records were kept of each diver on each dive, and a large, well-trained professional staff was present to provide instruction, guidance, and assistance for the divers, as well as another diving population: the professional dive guide/instructor. A recompression chamber with trained operators was available to treat those accidents that did occur, providing another unique look at this diving population.

## METHODS

Data from the dive logs and diving computers were extracted prospectively by the second author for diving operations conducted from March 4, 1989 to March 4, 1990. Divers with decompression sickness (DCS) or arterial gas embolism (AGE) were immediately evaluated and treated on-board, with appropriate referral for follow-up. This database consists of some 77, 680 dives by the recreational divers and the staff. This data was then analyzed by the first author, who was not involved in the diving operations nor the treatment of the stricken divers. Statistical analysis was conducted using STATS + on a Compaq PC using the tests as listed in the Results section.

## RESULTS

Sport divers performed 77,680 dives, of which 43% used decompression tables (either the US Navy No-Decompression and Repetitive Dive Tables or commercial derivatives such as "Nu-Way," or the Professional Association of Diving Instructors's (PADI) Recreational Dive Planner or Tables), and 57% used diving computers. Of the computer users, 70% used the Dacor Microbrains or Microbrain ProPlus (100 of which were available for rental on the ship), 20% used the Skinny Dipper and the Edge from Orca Industries, 5% used Suunto units, and the remaining 5% were distributed among the other manufacturers. These ratios are not meant to reflect the relative prevalence of these particular units within the general population, and are skewed by the rental availability. Sport divers were distributed 67% male and 33% female, with similar table and computer use rates. They ranged in age from 9 to 72 years of age, with diving experience ranging from student to experienced instructors. Divers averaged 3 dives per day, though 20% made over five dives in one day when weather permitted. Divers were instructed to limit their diving to a maximum of 130 feet, with a 30 foot per minute ascent rate above 60 feet, or to conform to their computer's required ascent rate, whichever was more conservative. 75% of dives were in water of 100 feet of depth or less, but over 40% of the computer using divers admitted to dives greater than 130 feet, with several dives beyond 200 feet of depth. Reverse profile dives, where the deepest dive of the day is not the first dive, were common, representing 25% of all dives due to operational considerations. The water temperature ranged from 77-84 degrees F during study.

**Diving Accidents:**

Eight cases of DCS and two cases of AGE occurred during the study period. All of the DCS cases were type II occurrences, and all were successfully treated in the ship's recompression chamber. One AGE was successfully treated and one was pronounced dead without an attempt at recompression. Seven of the eight DCS cases occurred in divers using tables, even though all of the dives were made within the no-stop limits of the tables. The eighth case of DCS occurred in a computer diver who violated his ceiling. There were no cases of DCS among computer users who used their dive computers properly. The surviving AGE case resulted from breath-holding during ascent from 15 feet, and the only death occurred following a panic ascent from an out-of-air (according to his buddy) situation. Of the seven cases of DCS that occurred during proper table use, 4 victims were women and three were men. The one diver who misused his computer was a male. Stricken divers were from 26-45 years of age. All of the cases had limited dive experience, with only one diver having made as many as 40 dives during his diving career. Five of the DCS cases occurred following dives with a maximum depth of less than 100 feet. Five of the seven dive table cases did not make the recommended safety stop at 15 feet, and in four of these cases the ascent rate was estimated by observers on that dive to have exceed 60 feet/minute. All DCS occurred on Day 4.

The incidence of DCS overall was .00013 cases/dive, and when the misuse is excluded, this become .00009 cases/dive. The incidence in the table using group was .0002 cases/dive, while the incidence among users properly using computers was 0 cases/dive. (.00002 cases/divewhen misuse is included). There is a statistically significant difference between the rates for table and computer users at $p < 0.01$ (including the misused computer case) by chi-square testing. The incidence rates for men and women were not statistically significantly different ($p < 0.1$).

**Staff:**

The professional diving staff of 28 experienced divers was heavily engaged in diving operations, completing from 500-720 dives during the study period. All of their diving was done using either the Dacor Microbrain or Microbrain Plus, with the latter predominant due to its greater capabilities. The age distribution ranged from 21-43 years of age, and the sex distribution was 30% female: 70% male. No DCS or AGE occurred in the professional staff.

The professional staff was engaged in an on-going deep diving project during the study period. Over 600 dives were made on air to depths of 250 feet, often with more than one dive per day, with decompression obligations calculated using the Buhlman model. The distribution of experimental divers' age and sex were similar to the overall professional group. One staff member made an additional 100 dives to depths in excess of 300 feet, with one dive to an unofficial world record 452 feet, with decompression performed using a proprietary schedule. No DCS or AGE occurred during any of these experimental dives.

## DISCUSSION

It was not practical to directly compare each of the 77,680 dive profiles, so it has been assumed that the distribution of profiles between table users and computer users was similar, and that the same was true for men and women. The authors feel, based upon direct observation of divers over their combined 44 years as divers and instructors, that this assumption is reasonable, and is probably conservative if anything in that most table divers tend to be less aggressive ( shallow, shorter, and less frequent dives on a given trip) than most computer users. All of the divers had many similarities as they were a self-selected group diving from the same dive ship. Regardless of their decompression obligation calculation method or their sex, they dove on the same sites, with the same guides, and under the same conditions.

There was a statistically significant higher incidence of DCS in divers using tables compared to divers using dive computers. Moreover, this data actually represents an optimal situation for table use, since none of the table-users were allowed by the dive logging system to make an error in calculation, a very different circumstance than in uncontrolled diving. Work done by the first author (Hill and Hill, 1989), indicates the expected accuracy of sport divers in working even a short series of decompression problems on their own is less than 50%. According to our data, when computers and tables are both properly used, the incidence of DCS among computer-users is significantly less, and in fact, there were no cases of DCS in any diver properly using a computer.

The lack of a significant difference in the incidence of DCS in women divers when compared to their male counterparts was unexpected. Basset's work with the incidence of DCS in female altitude chamber students indicates a much greater incidence of DCS among the women (Bassett, 1978). Zwingleberg found no increased risk of DCS among women diver trainees at the Navy's Diving and Salvage Training Center, but their study involved only a small number of dives and dive profiles that were dissimilar from those of the sport community (Zwingleberg et al., 1987). We believe our study more closely models the sport diver. As virtually all of the women dove with male partners and had a similar incidence of use of tables versus computers, we believe this lack of a difference in DCS incidence to be valid.

The new diving computers are remarkably reliable given the predilection of the sea to destroy any machinery, especially electronics. The only failures that occurred were minor malfunctions of the DACOR LCD screens, all of which were replaced by the manufacturer. No Edges failed, and there were only a small number of battery failures on Skinny Dippers, a fault that has been rectified by the factory and can be retro-fitted. Suunto errors were solely from improper activation of the immersion switch, more an operator failure than an equipment one.

Of note is that all of the DCS cases had Type II DCS. The treated cases may have first noted pain-only symptomatology, but over time, or when they were examined by a trained individual, neurological findings were noted. This finding is compatible with the work of the first author on the high incidence of abnormal neuropsychological findings in what are otherwise believed to be Type I cases. (Bassett, 1978; Zwingleberg *et al.*, 1987; Hill, 1988). The additional two and one-half hours of chamber time from using a USN Table 6 (Boyd, 1984) rather than a Table 5 (Boyd, 1984) is time well-spent, and may well be the treatment of choice for the sport diver with DCS of any type.

It is not the position of the authors that deep air diving is a recommended sport activity. The reported dives were conducted under strict experimental guidelines, by specially trained and experienced divers, and in conjunction with an on-board recompression chamber. Such is not usually the case for the average sport diver.

Education is the key to safe diving. All of the stricken divers were relatively inexperienced. Several of the divers had improper ascent rates. The one computer case was either due to a lack of knowledge about the device, or ignoring the displayed information. The two AGEs were related to diver error: the first from breath-holding on ascent, and the second for running out of air. All of these errors should be preventable with proper student selection and training. The close guiding aboard the ship helps to lower the incidence of problems, but ultimately it is the diver who must know how to dive safely.

Finally, diving is a safe activity. One death out of 77,680 dives gives a fatality rate of .0000128 or roughly 1.3 in one hundred thousand, making diving substantially safer than many other sports. Moreover, that single death occurred in a diver who did not follow proper procedures. It is our conclusion, based upon our data, that divers using a dive computer in this sport environment are at less risk for DCS than divers using tables to calculate their decompression obligations, and that the risk of DCS in women is no higher than that for men.

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# EFFECTS OF DIVER TOOL USE ON DIVER HEARING

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*It has been reported that divers are experiencing vertigo, bleeding, hearing loss and related problems as a result of very high noise levels underwater. These noise sources include underwater power tools, impact noise (such as explosions) and air turbulence in diving helmets. While the actual correlation of these detrimental effects to the cited sources is not known, it is believed that a causal link exists. Accordingly, this paper is focused on a theoretical explanation of these potential relationships. Specifically, when submerged, a diver experiences a marked reduction in peripheral hearing. This "loss" varies -- as a function of frequency -- from 40-60 dB SPL and results in a dynamic range reduction of from 0-130 dB SPL to 60-130 dB SPL on a somewhat frequency independent basis. In turn, these changes in hearing sensitivity and dynamic range result in the diver not being aware of the actual strength of waterborne sound and its effects on the (auditory) sensory modality. Further, the high force, low amplitude transmission of sound through water serves to confound these negative effects. The theory to be presented demonstrates that the acoustic properties of the underwater medium coupled to the restricted dynamic hearing range of the submerged head can account for the problems being reported.*

## INTRODUCTION

Noise induced hearing loss currently is recognized as a major occupational-based disease. It adversely affects millions of individuals with a resulting economic loss as well as frequent psychologic and social stress. A large body of research has provided substantial knowledge about damage risk criteria (DRC) of this type -- and hearing conservation programs in those contexts where noise is a noxious hazard. However, these relationships and programs have been established almost exclusively in response to airborne sound.

In the subpopulation of the working diver, the problem is a serious one and appears to be increasing in its impact. Indeed, divers appear to be at risk due to explosions, engine noise (induced into the water), use of power tools for underwater work (they are on the increase) and chamber/helmet noises resulting from the operation of life support equipment. Yet, only a few responsible/relevant agencies, organizations or individuals seem to be aware of this threat to both operations depending on diving personnel and the well-being of the individual diver. Worse yet, very little pertinent research has been carried out and the results that have been obtained are not always consistent with respect to either data or theory. Indeed, so little is known about the noise threat to diver hearing (and the status of the submerged ear relative to suprathreshold hearing dynamics), that procedures generated 40-50 years ago for airborne sound appear (initially anyway) to be the most relevant as a basis for research design in this area. Except for relatively good data on auditory thresholds plus a little on suprathreshold DL's and sound localization, practically all concepts about underwater hearing are, at best, theoretical or, at worst, based on questions and guesses. Practically nothing is understood about the dynamics of suprathreshold auditory function, what sounds can and cannot be tolerated and what factors interact with the detrimental effects of noise on hearing.

## AUDITORY SENSITIVITY IN AIR

Among those dimensions that can be used to describe auditory sensitivity, the two most relevant are absolute and differential thresholds. Absolute thresholds refers to a "curve relating the smallest intensity required for detection to the frequency of a tone...for some arbitrary level of performance" (Yost and Nielsen, 1977). Normal human hearing threshold values in sound pressure level (SPL) range from about 7-45 dB (re: 0.0002 dynes/sq.cm.) for frequencies between 125 and 8000 HZ. Since absolute threshold is one measure of the lowest intensity detectable by an individual, it is reasonable to infer that it is a measure of signal registration by the sensory system, and that it specifies the normal sensitivity of the intact auditory system. Figure 1 presents ANSI standard threshold of audibility values.

The differential threshold, or difference limen (DL) is the amount of change in a stimulus that is required for the observer to detect that shift "for some arbitrary level of performance." Consequently, the ability to discriminate between two stimuli which are similar in frequency or intensity is an indication that the sensory registration of the two signals is different and that it is independent of the amplification provided by the mechanical systems of the outer and middle ear. These several relationships will be used as a basis for the discussions to follow.

## HEARING UNDERWATER

### Sensitivity.

Auditory sensitivity information about underwater hearing function tends to be both sparse and (somewhat) primitive. One of the reasons for this situation is that it is difficult-to-impossible to duplicate ordinary psychophysical research techniques underwater. As Goerters (1972) points out, a human simply cannot be immersed and tested. Rather, a great variety of life support gear must necessarily be attached to the diver/subject with all of its concomitant -- and perhaps shifting -- effects on the response to heard stimuli. Moreover, heightened stress and demands on the divers' attention often result in reduced or impaired underwater performance (Weltman and Egstrom, 1966). On the other hand, it is now well established that immersion of the head in water results in a detection threshold at about 60 dB SPL. The basis for this statement is as follows.

In 1947, Sivian published a theoretical paper in which he discussed the effects of submersion of the head on human hearing. He speculated that water "plugging the ear canal would enhance hearing by bone conduction." He tested his predictions to some extent and estimated the hearing loss in water (relative to air) to be between 44-49 dB. Later, four studies were published in which the authors attempted to define underwater human hearing thresholds. Hamilton (1957) found both upward threshold shifts of 35-45 dB in divers and no change in the loudness for occluded ears; these data provided evidence to support the bone conduction theory and Sivian's predictions. The second investigation was by Wainwright (1958) who suggested an upward threshold shift of 43-75 dB and that the occlusion of the ear canal had no effect on perceived loudness -- and Reysenback de Haan (1957) tended to concur. Finally, Montague and Strickland (1961) tested divers' hearing with and without hoods. They reported an upward threshold shift of 40-70 dB relative to air, depending on the frequency. Furthermore, they noted an additional upward threshold shift of 20 dB at frequencies above 1000 Hz when the divers wore hoods.

Since data from these studies often were confusing, a coordinated underwater research program was initiated at the University of Florida in an attempt to resolve the conflicts and develop new models of underwater hearing. The first of these studies (Brandt and Hollien 1967) established stable mean thresholds at about + 60 dB SPL. These data were well within the range of values reported by previous investigators, explained them and supported those authors who argued that some sort of bone conductive mechanisms were likely to be operative in the underwater hearing processes. To test this question directly, Hollien and Brandt (1969) obtained thresholds of divers with and without air bubbles in the external auditory canal. They reasoned, as Sivian had in 1947, that if an air bubble rested against the tympanic membrane, the impedance characteristics of the canal would be altered and if, these structures were crucial to underwater hearing, a difference in threshold level would be noted. They reported no significant differences between the two conditions -- a finding which suggested that sound travels to the cochlea by bone conduction. Later, Bauer (1970) argued that bubble occlusion of the external auditory canal does not constitute a valid test of middle ear function. Accordingly, Hollien and Feinstein (1975) further examined the question by obtaining thresholds for the divers who wore: 1) no neoprene hood, 2) an intact hood and 3) a hood with earholes and rubber tubes coupling the outside milieu to the external auditory meatus. When the divers wore either the hood or the hood with the earholes/tubes, threshold values were recorded that were greater than those reported by Brandt and Hollien (1967); they also were greater than the values obtained for the no-hood condition. In other words, a difference was found between the hood (all types) and no-hood conditions. These findings appeared to support the hypothesis that, when submerged, the human hearing mechanism is primarily bone conductive rather than tympanum, or "water" conductive.

Finally, the approach taken by Smith (1965,1969) to the question of bone conduction was quite different from those previously cited. He suggested that it would be necessary to know his subjects bone conduction thresholds in air before it would be possible to determine if diver hearing is accomplished by such a mechanism. He was able to demonstrate good correspondence of the bone conduction thresholds for the two environments.

## The General Nature of Underwater Hearing.

Basically, Hollien and his associates have reasoned that, if underwater hearing loss was peripheral, then there should be no evidence of a neurological deficit -- i.e., neural (auditory) components underwater should parallel those in air. In response, thresholds for speech were obtained by Brandt and Hollien (1968) who found that mean (underwater) speech reception thresholds (SRTs) were 13-15 dB above the mean thresholds for the 0.5 - 2.0 kHz frequency range. This relationship roughly parallels the SRT/sinusoidal ratio found in air. Moreover, when all of the data reported by Hollien and his associates were plotted, they revealed that underwater thresholds for sound detection were relatively flat and lay just above 60 dB SPL (see again Figure 1).

Other evidence is available to demonstrate normal (auditory) neurological function underwater. For example, the ability of divers to localize sound underwater -- especially in view of the increased speed of sound and the acoustic transparency of the head in this milieu -- suggest that impairments here are due to mechanical rather than neurological constraints. To be specific, as early as 1944, Ide reported near normal underwater sound localization for his divers. Moreover, so did Feinstein (1973a, 1973b), Hollien (1973, 1987), Hollien, et all (1974, 1976, 1986) and Smith, et al., (1974). They utilized minimum audible angle and direct angle estimations to compare the precision of diver's underwater localization judgments with those made in air. Their results demonstrated that humans have the capacity to localize sound sources underwater with some degree of accuracy. The fact that Hollien and Hicks have been able to establish a diver navigation procedure on the basis of sound beacons that appear to move (UAPP) is yet a further case in point (see Hicks and Hollien, 1982; Hollien and Hicks, 1982, Hollien, et al., 1986; Hollien, 1987).

It should be noted that the few studies cited in this section are virtually all that have been reported on underwater hearing dynamics. To date, there are no available data on such issues as equal loudness contours or hearing tolerance. As would be expected information about human tolerance for sound underwater is of critical importance to DRC and hearing conservation.

The Effects on Hearing of High Ambient Pressures.

A number of investigators have examined the effects of increasing ambient pressure on auditory sensitivity. Farmer, et al., (1971) carried out air and bone conduction threshold measurements at several simulated depths (HeO2) to 600 feet. They found, as had Fluur and Adolfson (1966), reversible increases in air conduction thresholds (up to 26 dB in the lower frequency ranges) with increases in pressure. Finally, the effects of deep diving (and the concomitant pressures involved) may limit divers' ability to make fine auditory discriminations. Hollien and Hicks (1982) have theorized that High Pressure Nervous Syndrome (HPNS) may be partially responsible for the breakdown in communication task performance on deep dives. Furthermore, while there is no direct evidence up until now of the HPNS influence on auditory sensitivity, it is plausible that hyperbaric pressures and varying breathing gasses could temporarily affect a whole array of sensorineural and cognitive processing functions (Bennett, 1967; Brauer, et al, 1966; Miller, et al, 1967; Rostain, et al, 1980; Zaltsman, 1968).

Underwater Dynamic Hearing Range.

While the dynamic hearing range for humans in air is well established, it is not for the submerged ear. For example, as early as 1947, Silverman published a classic paper in which he established thresholds of tolerance in a variety of subjects for sinusoids and speech. His data also provide "normative" values for our model of underwater hearing (see below). As would be expected, many other aspects of the dynamic hearing range (in air) have been studied in the past four decades but the situation is substantially different when hearing underwater is considered! With the exception of the cited sound localization studies and the work of Thompson and Herman (1975) and Klepper (1981) on DL's, virtually no data at all are available in this area. Indeed, even the thresholds of tolerance for sound underwater remain undiscovered.

## SOURCES OF UNDERWATER/HYPERBARIC NOISE

It is now well recognized that many divers have developed noise induced hearing problems of a sensorineural nature (see among others, Edmonds, 1985; Molvaer and Lehmann, 1985; Smith, 1984; Soss, 1971; Summitt and Reimers, 1971). Of course, sources other than noise can cause hearing loss in divers (barotraumas of all types, decompression effects, and so on); however, they are not directly relevant and will not be reviewed. Rather, it is important to document that noise induced deficits occur in divers. The sources include: power tools used underwater, explosions (including diver recall devices), the racket in diving helmets, chambers and personnel transfer capsules, and engine noise (ships). These noises are of two types: steady state and impulse. Steady state noise levels are more easily measured (both peak intensity and intensity by frequency band) and related to human hearing. However, as Bromer

(1985) points out, there is now evidence that the high peaking of impulse/impact sounds can cause hearing damage virtually from the first exposure. Hence, both the effects of high ambient noise and impact sounds must be taken into account.

Chamber Noise.

The sources of chamber noise include pumps, compression noises and especially thermal type noise caused by rapid gas flow (venting, for example). Not very much is known about the energy levels of these sources and how they operate to create auditory traumas. Only Brown et al (1977), Murry, (1972) and Summit and Reimers (1971) have systematically measured the noise levels in hyperbaric chambers of any type. Brown et al (1977) report that the overall ambient noise levels range from 78-84 dB SPL (re. 0.0002 dynes/sq.cm.), but that these levels were higher below 1 KHz (and lower to much lower above that reference). Murry's (1972) data were consistent with these findings but Summitt and Reimers' (1971) levels were somewhat higher. In any case, energy of this extent probably is hazardous. Peak chamber noise levels that were much higher than those cited above also were reported by Brown, et al., (1977); indeed, they observed magnitudes as high as 90 dB for the compression phase of "travel" and even higher for venting. Summitt and Reimers (1971) also measured chamber noise during "travel" (decompression) and when the chamber was being ventilated. Their data varied from 107 - 121 dB. As can be seen, ambient noise levels this high would be hazardous to hearing even if they lasted only for relatively short periods of time.

Noise in Diving Helmets.

It has been long recognized that relatively high noise levels can exist in diving helmets; however, about the only data reported on this issue are those published by Summitt and Reimers (1971). They measured ambient noise levels in six different types of diving helmets, with the intake valves partially and fully open -- and as a function of depth in sea water. All values were found to be unacceptably high -- varying from 93-99 dB in the "best" helmet to 109-113 dB in the "worst." As with most chamber noise, these values represented steady state noise and, in this case, it could be characterized as "thermal" (or pink) in nature.

Underwater Power Tools.

Most of the available information in this area has been gathered by Smith (1984), Mittlemann (1976) and Molvaer and Gjestland (1981). Many (if not all) of their measurements were made at ear level during simulated dives. Tools such as impact wrenches, high pressure cleaning tools, rock drills and so on were evaluated. They report energy levels ranging from 90-105 dB depending on the device employed. They demonstrate that even older power tools (much less those now in the development stage) create sound fields that undoubtedly are detrimental to diver hearing.

Explosions.

The tools described above produce (in most cases) both steady state and impulse noises. Of course, it is more difficult to measure the peaks of impulse noises due to their very brief duration. Nevertheless, they clearly have a detrimental (if not devastating) effect upon diver auditory function. Additionally, the work of Mittlemann (1976), combined with reports by Hollien and Hicks (1982), reveal that various kinds of explosives result in rather high (peak) energy levels. For example, an M-80 explosive detonated at a depth of 3 meters, can exhibit a peak energy level of as high as 144 dB SPL and this level drops only to 120 dB at distances of over 1 km. Peak energy levels of a .38 caliber revolver (fired underwater) and stud guns are somewhat lower but not by much (i.e. 137 dB at 75 meters to 106 dB at over a kilometer for the .38 revolver). Admittedly, the durations of these explosions are quite short (200-350 msec). Nevertheless, they do occur at durations long enough and of sufficient energy to damage a diver's hearing. Worse yet, even at distance, larger explosions can produce energy fields that can severly damage diver hearing (the work of Christian, 1967; and Goertner, 1984 among others, provides a basis for this statement). In summary, there are a rather substantial number of noise sources where the signal is of sufficient strength and character to damage diver hearing. Adequate data on peak levels, and frequency bands are available for only in a few them.

## ISSUES RELATED TO HEARING CONSERVATION AND DRC

Occupational noise standards were established to assist specialists in preventing injury to hearing. OSHA (see the 1983 standard, for example) has established specific criteria for measuring and computing noise levels and exposures; workplaces are required to adjust their noise settings to meet these standards. In this regard, Dear (1986) defines two key concepts that relate to noise regulation. These include: Damage Risk Criteria and Percentage Risk. Damage Risk Criterion (DRC) specifies the maximum allowable noise quantity to which persons may be exposed if risk of hearing impairment is to be avoided. Percentage Risk (PR) is defined as the difference between the percent of persons exposed to industrial noise who reach impairment and the percent of those not exposed to any such noise who exhibit similar losses. Selection of a Damage Risk Criterion implies that there will be some percentage of the exposed population remaining at risk at that level.

Effects of Noise on Hearing:

A rather substantial literature is available in this general area -- see, for example, Fausti et al. (1981) and Staiano (1986). Yet, another dimension to the issue was reported by Sataloff et al. (1983) who tested the effect of intermittent noise versus steady-state noise on hearing thresholds. While previous reports had indicated that intermittent noise exposure would be less detrimental than continuous exposure noise of the same intensity, these authors found that "intermittent exposure to intense noise resulted in severe losses in the high frequencies and little to no loss in lower frequencies, even after many years of exposure." These investigators encouraged further research designed to determine if these effects were specific to jackhammer noise or were generalizable to other intermittent noises. In any case, their results support the model to follow.

Hearing Conservation Programs.

Effective programs of this type already have been developed for air (none for underwater noise control, however). To be specific, Pell (1973) has shown that protection of almost all employees can be accomplished through an effective hearing conservation program. Emphasis on effective programs should be established also for underwater work if maximum prevention of hearing impairment is to be achieved. Three issues should be considered in keeping complex noise environments in context with the OSHA regulations -- i.e., routine noise exposure rates, noise exposure accumulation rates, and impulsive/continuous noise environments. According to OSHA standards, it is only necessary to measure the continuous noise (an arguable concept) in order to provide a reasonable basis for DRC. In any case, this information should assist in the development of underwater hearing conservation programs once DRC can be established.

To summarize, when the available data are reviewed, it is obvious that there still is some question as to the exact nature of underwater Damage Risk Criteria (DRC) for hearing and some upgrading of these concepts will be needed if we are to enjoy the advantages of the current technological gains in this area. Thus, while existing data/concepts can be used, it also holds that specialized underwater DRC and hearing conservation techniques will have to be developed. However, before such work can be initiated, it would appear necessary to structure an appropriate theoretical model.

## THEORETICAL FRAMEWORK

Theories of Hearing Underwater.

Without doubt, some sort of an integrated theory is required for the cited purposes. In this regard, several of the older theories of underwater hearing should be considered. The first of these was called the "tympanic" theory and was developed by Bauer (1970). He states that underwater hearing is accomplished in essentially the same manner as hearing in air. Sound enters the submerged ear canal and vibrates the tympanic membrane with its consequent transmission to the cochlea through the ossicular chain. However, because the human ear is adapted (impedance matched) to function in air, and because the characteristic acoustic impedance of water is much greater than that of air, a large mismatch exists between the water and immersed ear. Consequently, the human ear is not as sensitive to water-borne sound as it is to sounds which are air-borne and the loss of sensitivity is frequency dependent. Bauer's model predicts no loss of sensitivity at 100 Hz but an almost linear drop in sensitivity of about 12 dB per octave as frequency increases from 100 Hz tp 5000 Hz.

The second theory involves Sivian's "dual-path" approach (1947); he theorized that underwater hearing is mediated by both the tympanic and bone conduction mechanisms and that they are of approximately equal sensitivity at 1000 Hz. At other frequencies, one or the other of the two paths may predominate. One implication of the dual-path theory is that given two equally efficient routes by which underwater acoustic energy reaches the cochlea, a deficit in only one route may not result in degraded underwater hearing. It is also stated that, in some circumstances, these two mechanisms may interact.

A third theory is the "bone-conduction" theory; as such, it was first suggested by Reysenbach de Haan (1957). Basically it can be said that because the impedance of human soft tissue and the skull is very close to that of water, sound is readily transmitted from water to the cochlea through these tissues, bypassing the acoustically inefficient route of the external and middle ear. Further, it is suggested that the ear canal is acoustically transparent in water and that the middle ear is not therein effective primarily because the ossicles lack sufficient mass. Finally, it is postulated that the two cochlea are not as independently stimulated underwater as they are in air due to cross-conduction of sound through the skull -- a condition that could somewhat impair the effectiveness of underwater sound localization in humans.

It is obvious that the data cited in the earlier sections of this paper serve as the basis for easy rejection of the first two theories. However, the third appears attractive although somewhat incomplete. That is, even when it is generally modified by Hollien and his associates, it cannot fully predict the nature of underwater hearing. On the other hand, when Hollien's (1973) descriptions of underwater hearing mechanisms are added to this approach, reasonably accurate predictions appear possible. Specifically he suggested that the observed underwater hearing "loss", while indeed conductive, results from the *mechanical* relationships among sound transmission in air and water and the mechanics of the human head. To be specific, the observed threshold shifts are the consequence of a change in the (mechanical) force/amplitude (FA) arrangements within the external and middle ear. As is well known, sound travels through air in a high amplitude, low force mode (Af), yet through a fluid such as water as high force, low amplitude (aF). The external and middle sections of the ear function to increase force from its air-borne level to one which will interface properly with the viscous fluid of the vestibular system. Hence, hearing in air is Af to aF whereas hearing underwater involves a third sound transmission component (aF to Af to aF) with all the reduction in efficiency this multiple change implies. In short, the external and middle ear mechanisms are not needed for either transduction or energy transformation, and sound waves enter the cochlea directly from the skull.

A Model for Underwater Hearing.

Our model for underwater hearing can best be understood by consideration of Figure 2. A stylized representation of the threshold of human hearing can be seen in the lower portion of the figure; the thresholds of discomfort, tickle (feeling) and pain at the top. The bar which can be found at approximately the 60-65 dB level (SPL re: 0.0002 dynes/sq cm) is a compellation of underwater hearing thresholds (UHT). Note that most of the frequency nonlinearities induced by the external and middle ears are not reflected in the UHT. A 5 dB "bar" is included because it is hypothesized that variation in differential middle ear pressure can reflect on cochlea efficiency by increasing or decreasing the impedance at the round and oval windows. To illustrate: divers sometimes experience a slight increase in hearing sensitivity when they "clear their ears".

In short, we theorize that the underwater shift in the threshold of hearing is a mechanical one and the dynamic range of the submerged ear is sharply reduced; see the difference between UHT and the thresholds of tolerance. We further hypothesize that hearing function *within* this frequency/intensity window essentially parallels that found in this region for hearing in air but is restricted (i.e., since the thresholds of tolerance do not naturally shift upward underwater along with UHT, no compensation is provided). Simply stated, our model specifies that the human dynamic hearing range is reduced from one that can exceed 130 dB (for some frequencies anyway) in air to one that ordinarily is not much over 55 dB in water. This reduction causes the diver to be less resistant to the detrimental effects of waterborne noise -- especially since 1) underwater sound does not decay as rapidly as it does in air and 2) due to elevated thresholds of detectability, divers tend not to be aware of the great intensity of the sounds they are experiencing. However, if these hypothesis are supported by experimental data, establishment of hearing DRC for underwater noise can be accomplished -- primarily because compensatory elements can be included in the procedures adopted. It is recognized, of course, that the development of hearing conservation programs for underwater noise will be somewhat more complex than were those for air-borne sounds. Nevertheless, it is our contention that they *can* be established.

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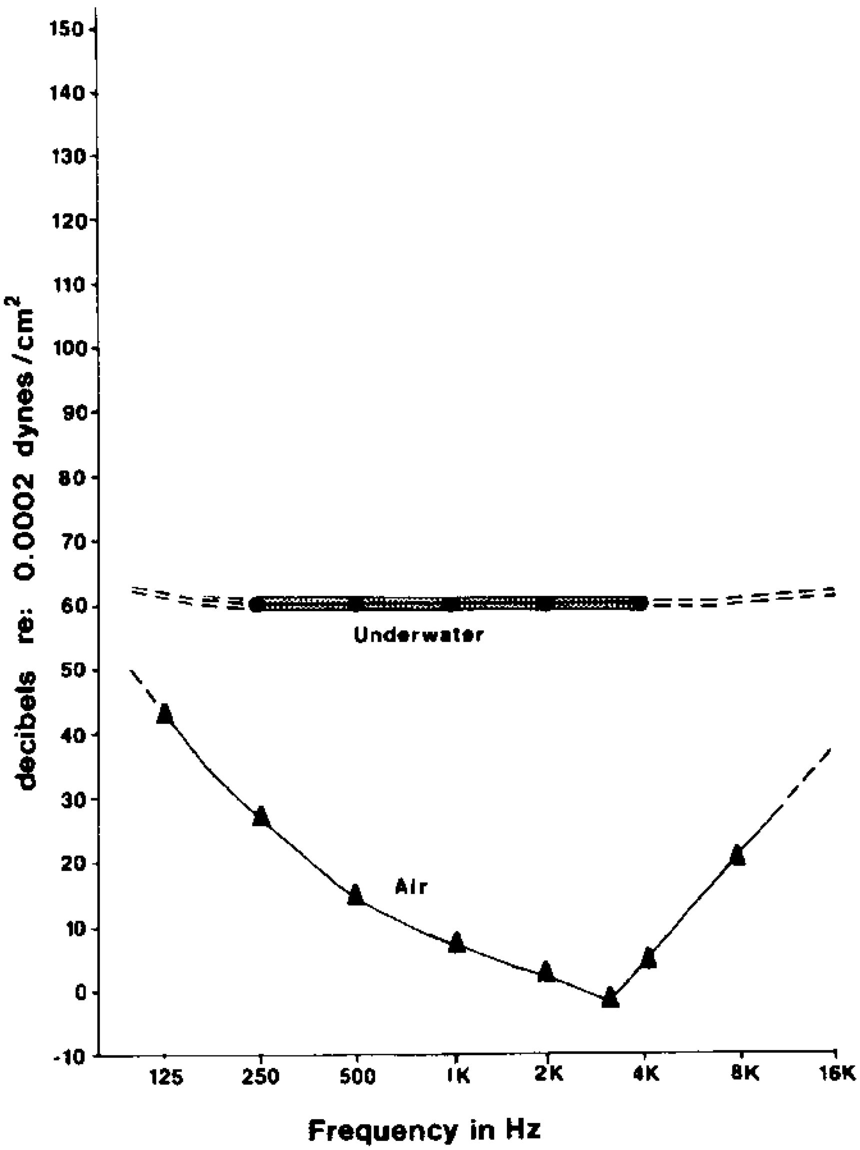


**Figure 1. Thresholds for audibility in air (lower curve) and in water (upper curve).**

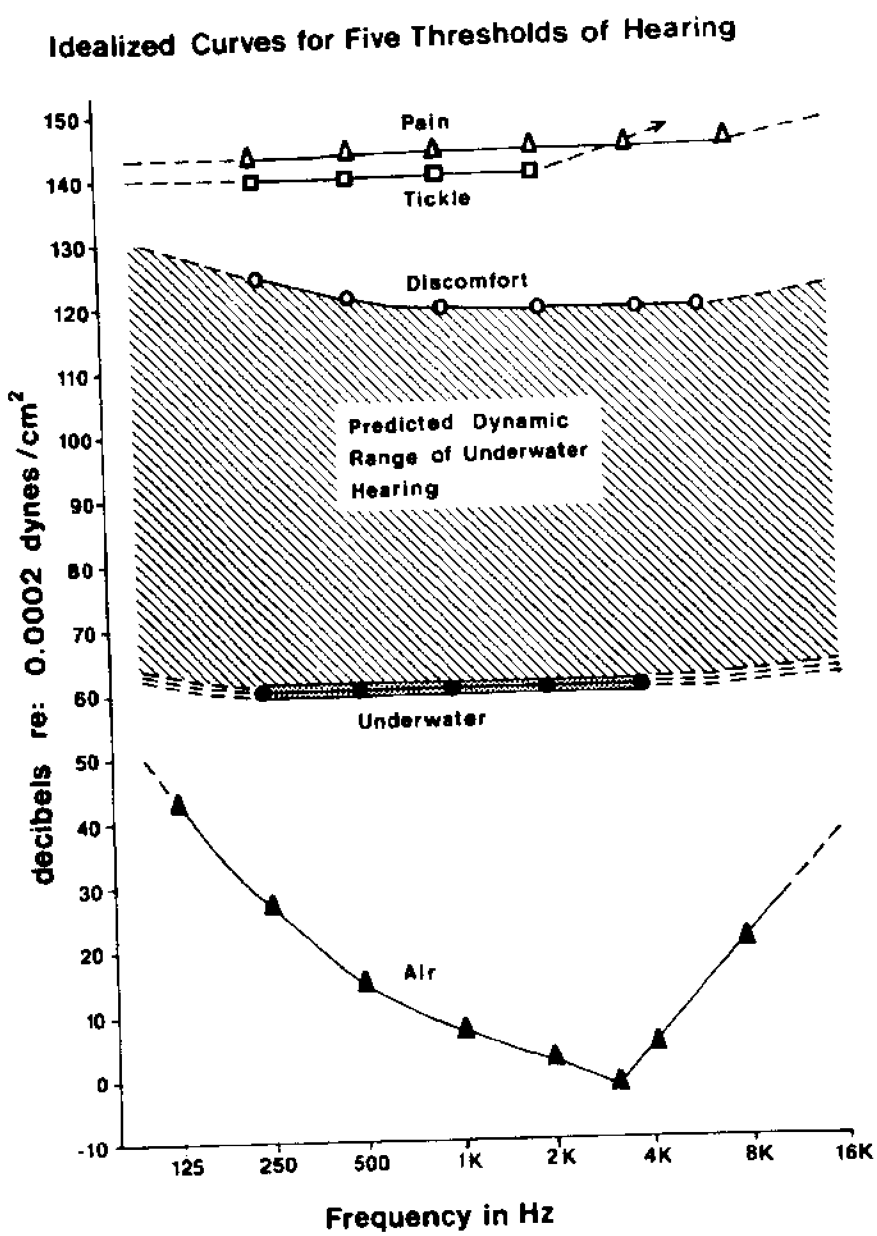


**Figure 2.** Thresholds for audibility and resistance to sound. The dynamic hearing range in air probably encompasses the lowest to the highest curves. The proposed dynamic hearing range underwater may be seen as the shaded area.

# EFFECTS OF LISTENING EXPERIENCE ON DECODING SPEECH IN HELIOX ENVIRONMENTS

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*The purpose of this experiment was to assess 1) the ability of auditors to decode speech produced in the HeO2 environment and 2) the effects of listening experience upon this skill/ability. Three paired groups of auditors listened to equated speech tasks and were tested on their ability to decode the heard utterances. The samples were produced by divers situated in an underwater habitat at depths up to 1000 fsw. Of each pair, one listener group was subjected to daily exposure of He02 speech samples (no feedback) for two weeks; the second group received no exposure. Findings demonstrated that normally hearing adults can decode about 25% of He02 speech as heard and that some individuals are much more adept at the task than are others. Second, it was found that a simple exposure to He02 speech resulted in a near doubling of decoding ability and familiarity with the talkers further enhanced this capability.*

## INTRODUCTION

As may be seen in Figure 1, it is now well established that the combined effects of the 1) high ambient pressures, 2) helium/oxygen breathing gas mixtures and (possibly) 3) high pressure nervous snyndrome, associated with saturation diving, lead to severely distorted speech (Bennett, 1967; Brauer, 1982; Brauer, et al, 1966; Fant and Sonnesson, 1964; Fant and Lindquist, 1968; Fant, et al, 1971; Flower, 1969; Gelfand, et al, 1978; Hollien and Hicks, 1981; Hollien and Rothman, 1976; Hollien and Thompson, 1968; Hollien, et al, 1973; Hollien and Hollien, 1972; Holywell and Harvey, 1964; MacLean, 1966; Rothman, et al, 1980; Sergeant, 1963; Sergeant, 1968; White, 1955). Indeed, even some of the specific speech distortions that have resulted in the observed communicative degradation have been identified (Beil, 1962; Brubaker and Wurst, 1968; Hollien and Hicks, 1982; Hollien, et al, 1984; Hollien and Rothman, 1976; Hollien, et al, 1977; Rothman and Hollien, 1972; Sergeant, 1967). These distorting effects are further complicated by 1) restricted system frequency response and 2) the high ambient noise levels commonly found in habitats, chambers and the sea (Brown, et al, 1977; Hollien and Rothman, 1976). In short, there appears to be an inverse relationship between the level of speech intelligibility and hyperbaric depth (see Figure 2). This situation leads to substantial communicative difficulties among aquanauts and with support personnel at the surface.

## Speech Processing Approaches

The approach primarily employed to compensate for this debilitating situation has involved the development and use of machine/computer speech restoration procedures (Anonymous, 1988; Belcher, 1980; Belcher, 1982; Copel, 1966; Gill, 1972; Giordano, et al, 1973; Golden, 1966; Hollien and Rothman, 1972; Quick, 1970; Richards, 1982; Wible, 1968). A number of methods have been tried with varying results. Included have been frequency domain processing, vocoder techniques, time domain processing, digital coding, convolutional processing and homomorphic deconvolution. The basic problems encountered here are that the cited systems 1) tend not to be speaker independent and 2) only partially process the speech signal. For example, the frequency domain systems operate to lower vowel formant frequencies (which have been raised as the result of the use of helium) but do little to reconstruct the spoken consonants. The difficulty in this case is that, while the the vowels tend to "carry" speech, it is the consonants that contribute most heavily to intelligibility. Moreover, the cited systems often "process" speech changes that are psychologically motivated rather than due to the effects of the speaking environment. Speaking fundamental frequency is one such factor; sometimes it is raised, sometimes not (Hollien, et al, 1977), yet most "unscramblers" (ordinarily anyway) tend to lower it. In short, while some of the cited approaches work fairly well--at least, under limited conditions--none of them appear to provide an acceptable solution to the problem.

## Human Decoders

An informal but rather widespread observation that can be made is that some divers and topside personnel demonstrate what appear to be remarkable decoding abilitites for speech distorted by heliox gas mixtures and high ambient pressures. They are able to do so even in the face of 1) noise (Brown, et al, 1977), 2) poor transmitting conditions (if topside), 3) the effects of the sea (if submerged) and the effects of hearing loss if pressurized (Edmonds, 1985; Hollien and Feinstein, 1976; Molvaer and Lehmann, 1985). Are these skills due to experience, native ability, inadvertent training (to our knowledge, no formal training programs of this type exist), familiarity with talker idiosyncrasies or some combination of these factors? Obviously, experimentation is needed in order to determine which of these elements is controlling. As a matter of fact, it is essential to demonstrate that this phenomenon exists in the first place.

## PURPOSE

The primary goal of this project was to discover if simple exposure to distorted speech--specifically utterances produced in the He02/P environment--would enhance an auditor's ability to decode it. Subjective observation would suggest that, while a prediction of this type is possible, there presently are no published data on the issue. Secondary goals were to discover if: 1) some auditors could be expected to show greater native ability re: the task than others, 2) the greatest increases in skill (were they to occur) would be demonstrated by those individuals exhibiting the highest native ability and 3) familiar voices would lead to an upgrade of decoding ability. Of course, it would be expected that some listeners would show superior talent for this task. However, it is not at all clear as to whether or not they also would demonstrate the most positive response to "training". Nor was it at all clear if individuals who were exposed to particular talkers and, hence, became familiar with them, also would show the greatest amount of improvement.

## METHOD

Three experiments were carried out. The first one was conducted in order to test the hypothesis that exposure to He02/P distorted speech would result in improved decoding accuracy. The second experiment was a simple replication of the first and the third focused primarily on the postulate that auditors familiar with a talker would demonstrate enhanced ability to correctly understand the speech uttered.

### Speech Materials

Several types of speech materials were utilized in these experiments. They included: 1) phonemically balanced lists (see Campbell, 1965) of 25 words each, 2) the Rainbow passage (prose; 99 words) and 3) extemporaneous speech. The word lists were used as stimuli when the experimental (or "training") groups were exposed to the heliox speech at high pressures (ie., He02/P).

### Talkers

The talkers utilized in all three experiments were eight aquanauts who had participated in the U.S. Navy's "Sealab" program. They were selected from over 25 individuals who had been employed as subjects in a large number of communication experiments carried out by the investigators. To be included in these experiments, it was judged that 1) each talker should exhibit about average speech intelligibility, 2) all talkers within a group of four exhibit similar scores and 3) the two sets of talkers exhibit mean intelligibility levels that were approximately equal. Additional selection criteria specified that each talker be assigned to read only a *single* Campbell list and that the mean score when doing so should reflect about a 25% correct intelligibility level (see Table 1). Most words were drawn from readings (in a hyperbaric chamber) at a simulated depth of 450 fsw; however, in order to make up equated tests, some words were obtained from lists read at other depths. The other speech materials were drawn from divers speaking at all depths. As may be seen from Table 1, diver scores ranged from 24.4% to 30.7% with the means for each group slightly above the desired 25% and approximately equal. These data were obtained by repeatedly playing the tapes to groups of 10-15 listeners who had normal hearing and some experience with heliox speech. The final 100 words produced by the four aquanauts comprising Group A were employed to construct Test I and the 100 words uttered by Group B constituted Test II.

Listeners

The auditors utilized in this research were 64 young, healthy university students of both sexes. To be utilized as a subject, a volunteer had to pass a speech discrimination hearing test with a score of 92% correct or better. Twenty individuals were randomly assigned to Experiment-1; 20 to Experiment-2 and the remaining 24 to the third experiment.

Procedure

The same procedure was utilized for all three experiments. First, the subjects assigned to each experiment were (randomly) divided into two equal groups; thus, there were two groups of 10 subjects each in Experiments-1 and 2 and two groups of 12 listeners in Experiment-3. While the groups were not controlled for sex, each consisted of roughly half men and half women. The equipment utilized to record the speech samples varied; it was dictated by that available for use in the particular experiment from which that test material was drawn. However, it was pretty much state-of-the-science for the time-frame during which the experiment was conducted. The apparatus used in the listener procedures was high quality laboratory equipment. It consisted of a Ampex 251 reel-to-reel tape recorder operated at 7.5ips, Marantz power amplifiers and two AR-1 speaker systems. All listening sessions were conducted in a large sound treated room which had been specifically constructed for aural-perceptual experiments.

The same procedures were utilized for all three experiments; Test I was administered to one group of the pair and Test II to the other. After the two-week period had elapsed, subjects in Group A (who previously had been administered Test I) responded to Test II and those in Group B (who had heard Test II) were administered Test I. During the interim two week period, Group A received "training" and Group B did not. That is, all members of the first of the two groups (only) came to the laboratory and listened to tape recordings of diver/talkers producing speech under a variety of He02/P conditions; they did so for two hours each weekday for the entire period (total "exposure" time equaled 20 hours). No other training or any feedback was provided. As stated, the "non-training" group simply was administered Test II and then Test I two weeks later. Experiments 1 and 2 were identical except different listener groups were employed. On the other hand, not only were slightly larger groups of auditors employed in Experiment-3, but there also was a slight change in the "training" procedure. Specifically, the subjects in the "training" group associated with Experiment-3 continually heard speech samples produced by the four diver-talkers who then provided the utterances for their second test -- whereas the "training" groups on the first two experiments first heard the voices of these talkers when they were administered the final test. It was by this procedure we tested the hypothesis that the speech of familiar voices would be easier to decode than that of unfamiliar voices.

## RESULTS

The results of these three studies may be found summarized in Table 2. As has been stated, the first two experiments were carried out primarily to discover if simple exposure to He02/P distorted speech would improve a listeners decoding capabilities with Experiment-2 a simple replication (validation) of the first. Experiment-3 was completed at a later time. It also was carried out in order to assess reliability and validity, of the stated postulates; however, a secondary purpose here was to discover if the familiarity which would develop from hearing a particular speaker's voice over time would lead to improved decoding.

As can be seen by consideration of Table 2, auditors who responded to tape recorded tests of He02/P speech were able to understand about a quarter of the materials presented them. It also may be observed that effects of the so called "training" was to shift this capability in an upward direction. Indeed, the subjects from Experiments 1 and 2, who heard the 20 hours of He02/P speech, just about doubled their decoding accuracy and this shift was statistically significant (Chi Square test). The cited trend is even more apparent when the data from Experiment-3 are considered. In this case, the experimental group was tested by evaulation of their responses to the voices of speakers with whom they had become familiar.

In any event, the data for the first two studies were combined and will be found in the third set of rows in Table 2. As can be noted, the untreated groups do not change from intelligibility test to intelligibility test (26.0-25.8%) whereas the decoding scores for the "training" group essentially double (22.2-45.6%). Not shown are the individual scores which varied from 9=39% for all subjects on the pretest and a roughly similar dispersion on the post-test for the untrained subjects. For those that received "training", the distributions on the second test ranged from 23% to 68%. A correlation of $r = + .79$. was obtained from the "training" group on the pre-and post-tests; the correlation for the untrained group was only $r = .11$. The patterns were approximately the same for Experiment-3 with the pretest disbursions for both groups, and the post-test range for the "non-training" group, all varying between about 10% and about 40%. The post test for the Experiment-3 "training" group ranged from 31% to 69%. Again, a high correlation was found for the pre-and post-test rankings of the "training" group and a very low one for those subjects who had not been exposed to He02/P speech in the interim.

Finally, there appeared to be a marked trend for individuals who were tested on familiar voices to exhibit higher correct intelligibility scores (58.7%) than did those that were "trained" on voices which were different from those who provided the test utterances (45.6% correct).

Nevertheless, when this apparent difference in improved decoding capability was tested, it failed to reach statistical significance.

## DISCUSSION

As has been stated, the trends among the data obtained from these investigations support the three stated postulates and two of the three achieved statistical significance. That is, 1) simple exposure to distorted speech of the type studied resulted in improvement in decoding capability, 2) some people are better at the decoding task than are others--with those who exhibited the greatest initial talent tending to exhibit greater improvement and 3) it appears easier to decode utterances produced by familiar speakers.

The first of the three relationships, perhaps, is the most important. That is, auditors who were exposed to only 20 hours of He02/P distorted speech greatly improved in their ability to understand what was being said. They did so even though 1) no feedback (ie, formal training) was provided, 2) several different talkers provided the test materials, 3) various types of speech (test words, a read passage, extemporaneous speech) were heard, and 4) the utterances were produced at different depths (ie., at various pressures and helium gas mixtures). These findings serve to explain, to a great measure anyway, the common observation that some individuals are better able to understand He02/P distorted speech than are others. Simply put, they probably have learned to decode it because they have been exposed to it. Indeed, the fact that some of the communication personnel observed in the field have had substantial experience with this task probably explains their competency.

These relationships take on even greater import when individual differences are taken into account. As will be remembered, it was found that some individuals exhibited a greater native competency at this task than did others. Further, these auditors tended to show greater improvement in decoding skills than did their less gifted counterparts. It may be possible that this relationship aids in explaining why some individuals exhibit skillfulness in the field situation. Finally, the almost predictable observation that it is easier to learn to decode the utterances of a familiar talker also is considered important. Since high quality communication among friends and co-workers often has been observed, enhanced experience with deep-diving personnel should yield upgraded speech understanding. The results of this research appear to support that postulate.

It is the first and third factors that are the most important for improved communication with divers speaking in the mixed gas environment. That is, once the decoders involved are trained to task and become familiar with the speech/voice of the divers involved, they should be able to make optimum use of the communication links available. That they may have a specific talent for activity of this type (and learn the task fairly easily) constitutes a bonus. So too, would any attempts made to formally train these decoders.

On the other hand, it is unfortunate but it has been shown that the problem of decoding He02/P speech cannot be solved even by the presence of high quality decoders. That is, even communications personnel who: 1) show talent for this activity, 2) have been formally trained to task (there should be schools of this type), 3) are experienced and 4) are quite familiar with the speech of the divers, will not be able to decode enough of their utterances to be effective--at least, when the ambient pressure and helium content of the gas mix are great. Moreover, these decoders probably will show the greatest deficits when emergencies occur and the divers are talking under stressful conditions.

Accordingly, a more complex strategy is suggested; one that can be seen portrayed by the model in Figure 3. Please note that what appears necessary for good deep-diving communications is a combination of procedures. First, modified speech by the diver and a special lexicon designed for this type of interaction are required. What is meant by modified speech is that the diver/talker adapt his speech to the environment so that higher intelligibility levels can be achieved. The process is much the same as an aircraft pilot modifying an utterance so as to produce the word "niner" rather than "nine". Enough information (Beil, 1962, Brubaker and Wurst, 1968; Hollien and Hicks, 1982; Hollien and Rothman, 1976; Hollien, et al, 1977, Rothman and Hollien, 1972; Sergeant, 1967) is now available to make this suggestion a reality. Second, the use of special divers languages and set, prelearned, phrases would serve to enhance the input intelligibility even more. Third, the use of State-of-the-Science speech processors (or He02 "unscramblers") also should upgrade the end product utterance. Finally, it is at this point that the insertion of trained, experienced decoders would reduce the problem to managable proportions. In short, it appears that voice communications will not be improved in saturation diving until a three-way interface program is instituted. The structure involved will require the use of specialized/modified input utterances, upgraded electronic speech processors and highly trained He02 speech decoders.

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**Table 1. Intelligibility scores of eight diver-talkers. The speech materials were drawn from the Campbell (10) speech intelligibility lists with a different list assigned to each talker. Words were drawn from several experiments and five depths. Listeners were experienced; at least 10 were included in each group.**

| Diver/talker | List | Depths (fsw) | Mean Percent Correct |
|---|---|---|---|
| Group A | | | |
| A-M-1 | Q | 200-450 | 25.0 |
| A-M-2 | M | 450 | 30.4 |
| A-M-3 | S | 450-1000 | 26.6 |
| A-M-4 | N | 450-600 | 25.4 |
| Mean | | | 26.8 |
| Group B | | | |
| B-M-1 | O | 450-600 | 30.7 |
| B-M-2 | T | 250-1000 | 28.7 |
| B-M-3 | P | 200-450 | 25.6 |
| B-M-4 | R | 450-600 | 24.4 |
| Mean | | | 27.4 |

**Table 2. Summary table of the three main experiments. Listeners were 10–12 naive students with normal hearing; talkers were eight experienced divers each reading their own Campbell split-list. Experiment 2 was a replication of Experiment 1; Experiment 3 included known talkers in the training. All values are mean percent or percent difference.**

| Condition | Pre-test | Post-test | Difference |
|---|---|---|---|
| Experiment 1 (Group A) | | | |
| Training | 25.9 | 43.4 | 68 |
| No Training | 32.3 | 25.1 | -29 |
| Experiment 2 (Group B) | | | |
| Training | 18.6 | 47.8 | 157 |
| No Training | 19.7 | 26.5 | 34 |
| Combined Experiments (1 and 2) | | | |
| Training | 22.2 | 45.6 | 105 |
| No Training | 26.0 | 25.8 | - |
| Experiment 3 | | | |
| Training | 22.6 | 58.7 | 160 |
| No Training | 24.3 | 26.1 | 7 |

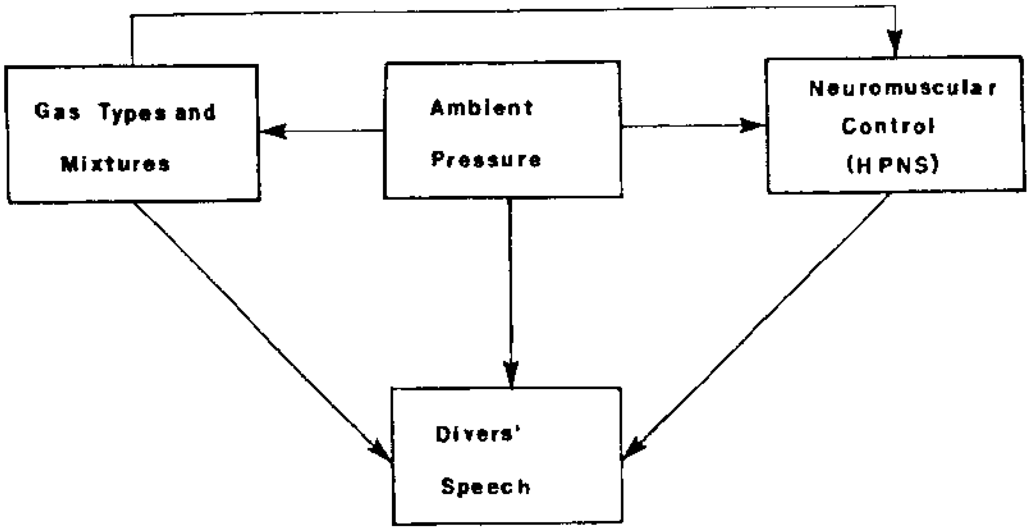


**Figure 1. Model of the parameters that effect speech -- and the interactions among them -- in the deep diving situation.**

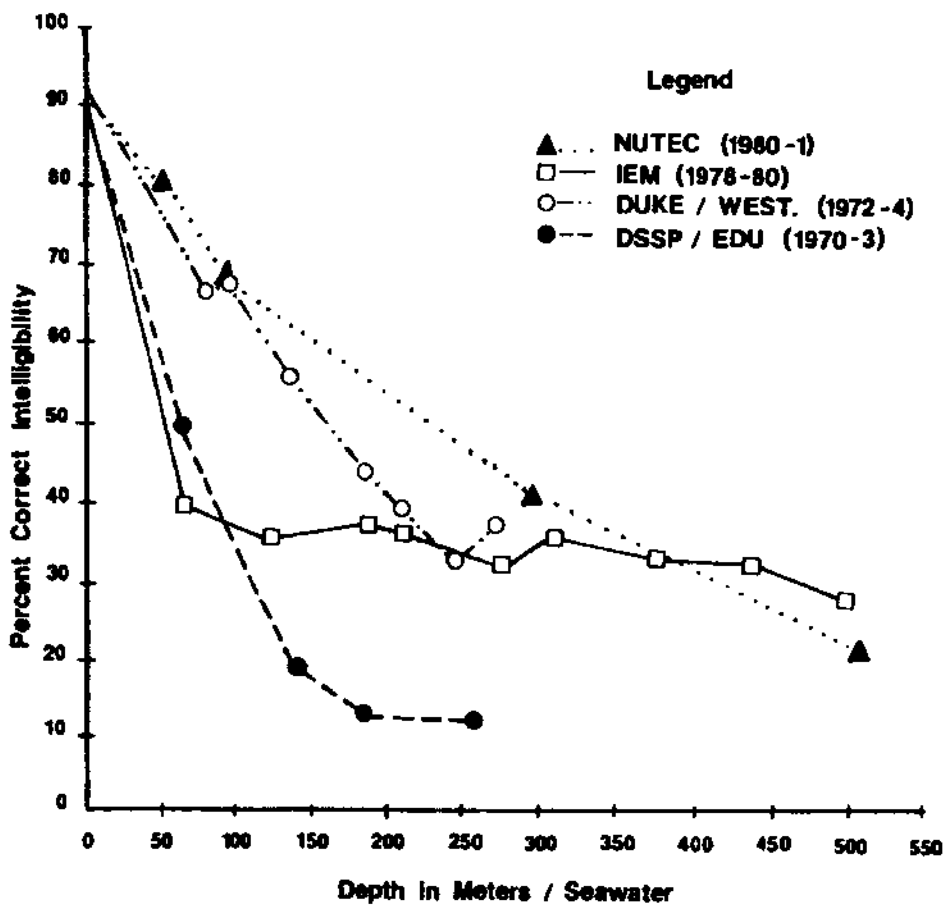


**Figure 2. Speech intelligibility as a function of increases in ambient pressure and helium breathing gas.**

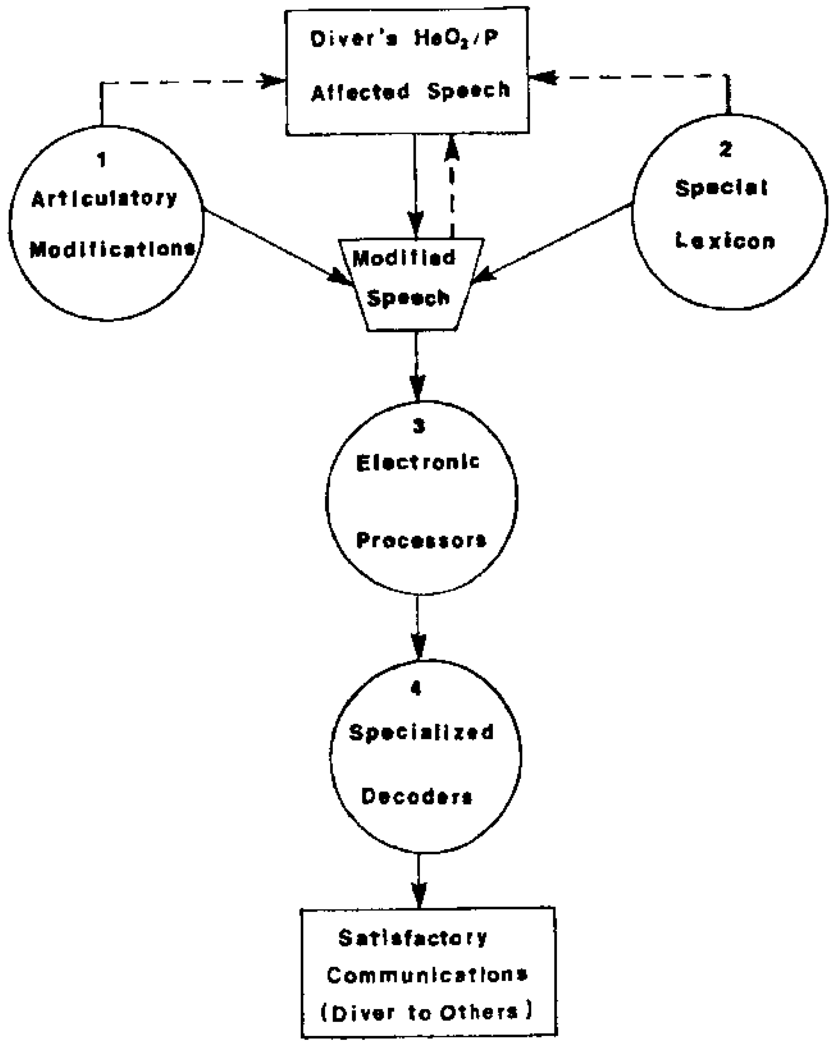


**Figure 3. An integrated approach for improved communication in the deep diving environment.**

# MATERIALS AND METHODS TO ESTABLISH MULTIPURPOSE, SUSTAINED, ECOLOGICAL RESEARCH STATIONS ON CORAL REEFS AT DRY TORTUGAS

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*Sustained research requires precise, repetitive data acquisition to accurately evaluate patterns of change in species abundance and community structure. Permanent reference markers are essential to resample stations over time. The methods described here use solid markers from which several sampling devices can be deployed. A hydraulic drill is used to core 18-in deep holes into rock. A square stainless steel stake is inset, aligned, and cemented into each hole. Quadrats, photogrammetric and video apparatus, and recruitment arrays are deployed on or in reference to the stakes. Transects are extended between stakes. The method is suitable for coral reef and other hard-bottom investigations.*

## INTRODUCTION

Gislen (1930) used photography to survey biotopes. Adaptation of his technique provides a tool for efficient underwater data collection that coral reef ecologists use to investigate coral reef dynamics (Connell, 1973; Laxton and Stablum, 1974; Done, 1981; Jaap, 1984; Hughes and Jackson, 1985; Hughes and Connell, 1987; Hanisak et al., 1989).

The principal nondestructive sampling techniques that ecologists use to sample hard-bottom communities include quadrats (Manton, 1935; Goldberg, 1973), transects (Loya, 1972; Porter, 1972; Dustan and Halas, 1987; Ohlhorst et al., 1988), photography (Lundälv, 1971; Ott, 1975; Done, 1981; Hughes and Jackson, 1985; Littler and Littler, 1985), and combinations of those methods (Dana, 1976; Wheaton and Jaap, 1988; Gittings et al.,1988). The common element in most of these studies is a reference marking system to relocate sites.

When photography is used as a sampling technique, a mounting apparatus for photographic and video systems is required to insure that the camera is a consistent distance above the sea floor. Examples of such apparatus include monopods, tripods, quadrapods, and minirail systems. Ideally, the apparatus is attached to a reference marker or moved between two reference markers to insure that photographic coverage is precisely the same during each successive sampling. A scale, compass, timepiece, and identifying reference can be included in the photo or video image.

Sustained ecological research (monitoring) requires that data acquisition be repeatable. Photographic, video, and other sampling techniques only provide this if the sites can be precisely resampled. In an underwater investigation, relocation of sampling sites is difficult if reference markers are inconspicuous, damaged, or destroyed. Although triangulation, loran, and acoustic pingers and releases can be used for precise site relocation, placement of robust reference markers in the sea floor can greatly expedite the process.

Installation of solid, secure reference markers in hard-bottom habitat is difficult. Driving nails, spikes, rods, or pipes into the substrate with a hammer is impractical or, in some situations, virtually impossible. Also, reliance upon hammer-driven markers can bias the sampling strategy by limiting stations to areas where there are crevices or holes in the rock surface.

Installing markers in hard substrate can be accomplished with use of a drill with a carbide bit powered by air from a scuba cylinder or a surface-deployed compressor. However, drilling with compressed air becomes less efficient with increasing depth because of effects described by Boyle's gas law. Hydraulic systems provide an efficient, but relatively expensive, alternative to other installation methods. Because hydraulic fluid is virtually incompressible, hydraulics are unaffected by pressure-volume dynamics (Boyle's gas law) in depths where most diving scientists conduct studies ($< 30$ m). Additionally, underwater hydraulic systems do not produce the loud exhaust noise characteristic of underwater air tools.

This paper provides information on equipment, materials, and methods used to install reference stakes and to sample coral reefs at Fort Jefferson National Monument, Dry Tortugas, Florida. The short-term goal of this project is to develop precise methods to monitor coral reef benthic communities. The long-term objectives are to determine the status of reef biological resources, document community dynamics, and delineate possible cause-and-effect relationships.

## MATERIALS

### I. Hydraulic System

A hydraulic drilling system was installed on a 34-ft (10.4-m) diesel-powered (twin GM 8.2 liter turbo-charged) vessel. The power source for the system is a belt-driven clutch pump (Gresen model CP16-85A-26S). Associated components include a hydraulic reservoir with 25 gallon (94.6 liter) capacity, filter, mounting brackets, hoses, and selector, pressure relief, and volume control valves. A control station with a clutch switch, volume control valve, and stainless steel quick-disconnect fittings complete the vessel installation. Underwater hydraulic equipment includes the following: a 9-lb (4.1-kg) drill motor (Fairmont Hydraulics model HU6976A) that operates at 1000 to 2000 psi (70.3 to 140.6 kg/cm$^2$) at 8 to 10 gpm (30.3 to 34.1 liter/min -- drill rpm is 850 at 9 gpm [34.1 liter/min]); a 36-in (91.4-cm) long, 2.5-in (6.4-cm) diameter diamond core barrel (Hoffman Diamond Products, surface set bit design); and 100 ft (30.5 m) of polyester hose (Aeroquip Hytrel FC373-08) that links the drill to the control station connectors (Aeroquip model FD45-1001). The supply hose (O.50 in [1.3 cm] id) and the return hose (O.75 in [1.9 cm] id) are lashed together with nylon ties and float on the surface, making deployment and recovery easier and reducing habitat damage during drilling. Our total cost of the hydraulic system (drill motor, bit, hoses and connectors) was $5,155.00. Portable systems can be leased for $300 to $400 per week.

**II. Reference Stakes**

Square, 1-in (2.5-cm) stainless steel tubing (0.125-in [3.2-mm] wall thickness) is cut to 2-ft (61-cm) lengths with a carbide-abrasive blade to make reference stakes. Burs are removed with a grinder. The tubing is sold in 20-ft (6.1-m) lengths ($70.00 per length).

**III. Quadrat Frame**

Aluminum square stock (0.50 in [1.3 cm]) is cut to form a quadrat frame (1.6 m by 1.6 m) for deployment over the reference stakes to census benthic components. A 1-in (2.5-cm) square sleeve, machined to fit snugly over the stakes, is centered in the quadrat and welded to the frame perimeter with aluminum rods (Figure 1).

**IV. Photographic Apparatus**

The photographic apparatus (Figure 2) is constructed from tube, angle, and channel aluminum. A vertical square tube is welded to a horizontal channel, and three pieces of angle are welded perpendicularly across the channel. The vertical sleeve fits over the stake and is secured with a stainless steel jam bolt. A male dovetail fitting is bolted to the tripod thread fixture of a Nikonos camera which fits into one of six female dovetail camera positions on the apparatus. Other cameras or video equipment can be attached to the apparatus (e.g., a 35-mm single lens reflex camera with a wide-angle lens in a housing with a dome port). In our program, the camera is positioned 46 in (117 cm) above the reef surface. Total areal coverage is approximately 27.5 ft$^2$ (2.56 m$^2$) with a 28-mm Nikonos lens. Coverage varies depending on surface relief. A strobe (150-watt output) is attached on the apparatus using a dovetail fitting such that the illumination originates above and to the left of the camera. Color print film, ISO 100 or 125, is used for photography. Our total cost of materials and labor (excluding the camera, strobe, and wiring) was approximately $260.00.

**V. Video Transect Apparatus**

The principal component of the video sampling device is a Sony 8-mm video camera (CCD-M8U) in a Sony underwater housing (MPK-M8) mounted on an aluminum carriage (Figure 3). The carriage for the camera and housing has four grooved, nylon wheels that roll on two cables deployed between two T-shaped aluminum poles installed on the reference markers (Figure 4). Each pole is 52 in (132.1 cm) high. Eyebolts are mounted 15 in (38.1 cm) apart on the cross bar to position the cables. A 0.1-in (2.5-mm) diameter stainless steel cable is deployed from a "down-rigger" fishing winch mounted vertically on one pole. Supplies, equipment, and fabrication costs for the poles, winch, and carriage were approximately $300.00. Video camera, housing, light, case, and batteries cost $2007.00.

**VI. Recruitment Sampling Apparatus**

Settling arrays are constructed from PVC pipe, flat stock, and ceramic tiles in the form of a vertical tree with four horizontal branches. Pipe arrays (Schedule 40, 1.25-in [3.2-cm] diameter) are designed to fit over the stainless steel stakes (Figure 5). Two 7-in (17.8-cm) pieces of pipe are glued with PVC cement into opposite ends of a cross fitting; a tee fitting is inserted into the top piece. A 3.5-in (8.9-cm) piece of pipe with a 4.25 x 1.5 x 0.25-in (10.8 x 3.8 x 0.64-cm) length of PVC flat stock is glued into the open ends of the tee and cross fittings. Each recruitment array consists of four couplets of ceramic tiles (4.25 x 4.25 in, 10.8 x 10.8-cm) bolted to the flat stock piece with 0.25-in stainless steel hardware so that unglazed surfaces are exposed. Two couplets each are arranged horizontally and vertically on an array in an attempt to determine whether organisms prefer particular orientations for settlement. The array is secured to the stainless steel stake by two 0.25-in set screws. Materials for each unit cost about $5.00.

## METHODS

Sampling stations are located using previously selected random numbers plotted along a fiber glass tape measure on a compass bearing from an initial point. Two stations are arbitrarily positioned 20 to 25 m apart for chain transect and video sampling. Flagging tape is used to indicate where the hole is to be drilled. Maps are drawn using measured distance and compass bearings between stations and include conspicuous submarine landmarks to assist in relocating stations. Vessel loran coordinates (latitude, longitude, and time difference data) and triangulation bearings on fixed surface landmarks (lighthouses, etc.) are used to assist in relocating sites.

### Reference Stake Installation

The drill is deployed overboard and the pump clutch is engaged, providing power to the drill motor. Two divers position the drill vertically over the indicated site. After the drill penetrates about 2 in (5.1 cm), a 15-lb (6.8-kg) lead weight is fixed on the drill to enhance performance. A bull's-eye bubble level is attached to the top of the drill motor with velcro to vertically align and drill an 18-in (45.7-cm) hole into the sea floor. The drill motor is placed in reverse rotation to clear the hole and break loose the core. Core remnants that remain in the hole are removed with a hammer and chisel. Ten to twenty minutes are required to complete the drilling.

Hydraulic cement (four parts of Type II Portland cement to one part molding plaster) is used to secure the reference stake in the hole. Cement and seawater are mixed aboard the boat and placed in plastic bags. Immediately, divers transport the semi-solid cement to the hole and pack it full. The stake is driven into the mortar mixture and aligned with a bull's-eye bubble level perpendicularly to the sea floor. The cement hardens rapidly and is solid within 24 hours. A crew of four (2 for mixing, 2 for drilling and cementing) was required to install five reference stakes at each of the five sites at Dry Tortugas. At Pulaski Shoal, stations were situated along a 78-m long transect in depths ranging from 27 to 35 ft (8.2 to 10.7 m). Positioning the stations, drilling the holes, and installing the stakes required 9 hours (an average of 1 hour and 49 minutes per stake).

**Quadrat and Transect Sampling**

The quadrat frame is deployed over the stake, and observers map organisms found within the quadrat perimeter on polypaper printed forms. Transects are sampled between stakes using a technique developed by Porter (1972) and refined by Rogers et al. (1983). A fiber glass tape is stretched above the reef surface between two stakes located 20 to 25 m apart. A 2-m length of small (17.5 mm per link) chain is laid under the tape in conformity with bottom topography. The number of chain links that cover an organism or abiotic substrate is recorded by meter increments. The transect is sampled 3 times to provide data for estimating variability among observers and within the habitat. The data provide an estimate of sampling adequacy, species richness, and surface heterogeneity (the ratio of measured chain length to the linear distance of the tape measure).

The photographic apparatus is also deployed over the reference stake. A 25-lb (11.3-kg) lift bag is used to maneuver the device. The distance from the camera film plane to the reef surface is measured with a rod marked in 1-in (2.5 cm) increments, and the lens aperture and distance adjustments are set, taking into account the refractive index of water. An identification reference is placed in the frame of the photograph, and the photo is taken. The camera is moved to the next position on the apparatus and the process is repeated for a total of six camera positions.

**Video Transect Sampling**

The video apparatus poles are set over the reference stakes at the ends of the video transect and adjusted so that the tops of the "T"s are parallel. The clutch on the winch is released. A diver then swims with the cable to the other pole, slips the cable through the two eyebolts on the top of the T, returns the cable to the first pole, and snaps the stainless steel clip on the cable end to the fourth eyebolt. Tension is taken up with the winch until the cable is taut, and the clutch is re-engaged. The video carriage, with the camera aimed vertically, is suspended on the cables, and the diver pushes the carriage very slowly to the opposite pole and back, providing a video record of benthos between the stakes. A tape measure in the video field provides a size reference. Because there is some bowing in the middle of the cable and the sea floor is irregular, the camera is not maintained at fixed distance from the bottom. Once on site, the time required to deploy and recover the equipment is approximately ten minutes.

**Recruitment Sampling**

After other sampling has been completed, a recruitment array is placed over each stake and secured with two jam bolts. A pair of tiles will be removed and replaced with clean plates annually for the duration of the project. Encrusting organisms will be identified to the lowest possible taxon and enumerated to determine their abundances and densities. Particular attention will be focused on scleractinian recruitment at each of the five reefs.

Because recruitment arrays provide protection from fouling, and corrosion of the stainless steel stakes is minimal, cleaning of reference stakes prior to resampling requires only an abrasive pad.

## ACKNOWLEDGEMENTS

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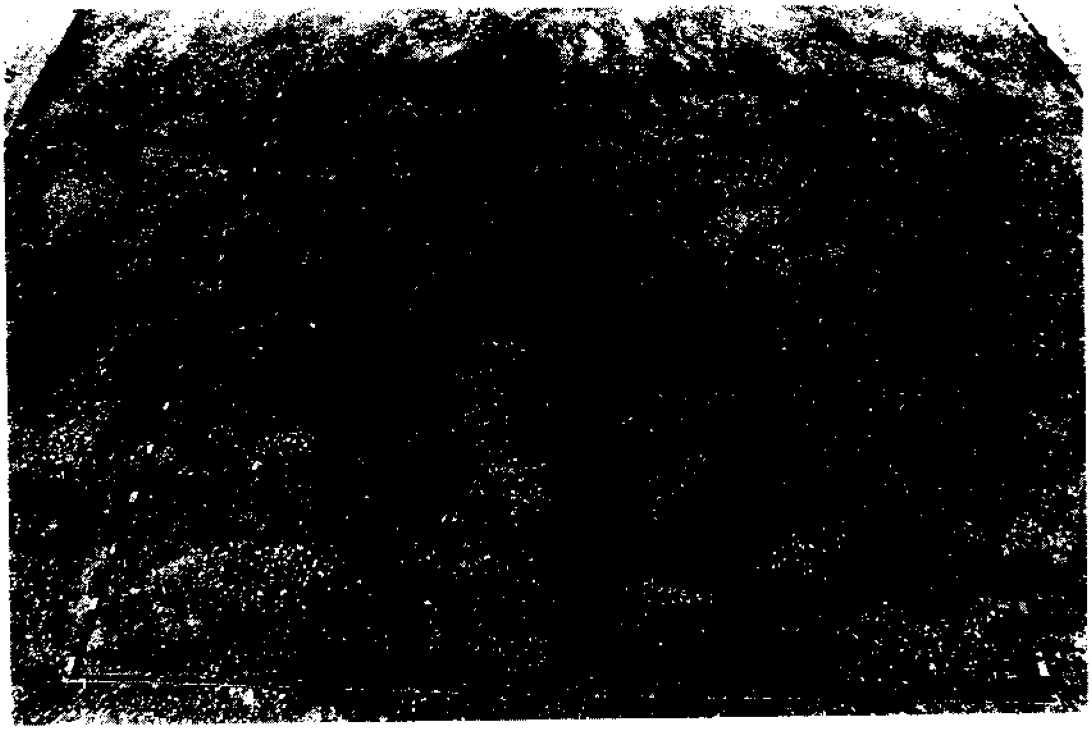

**Figure 1. Quadrat frame.**

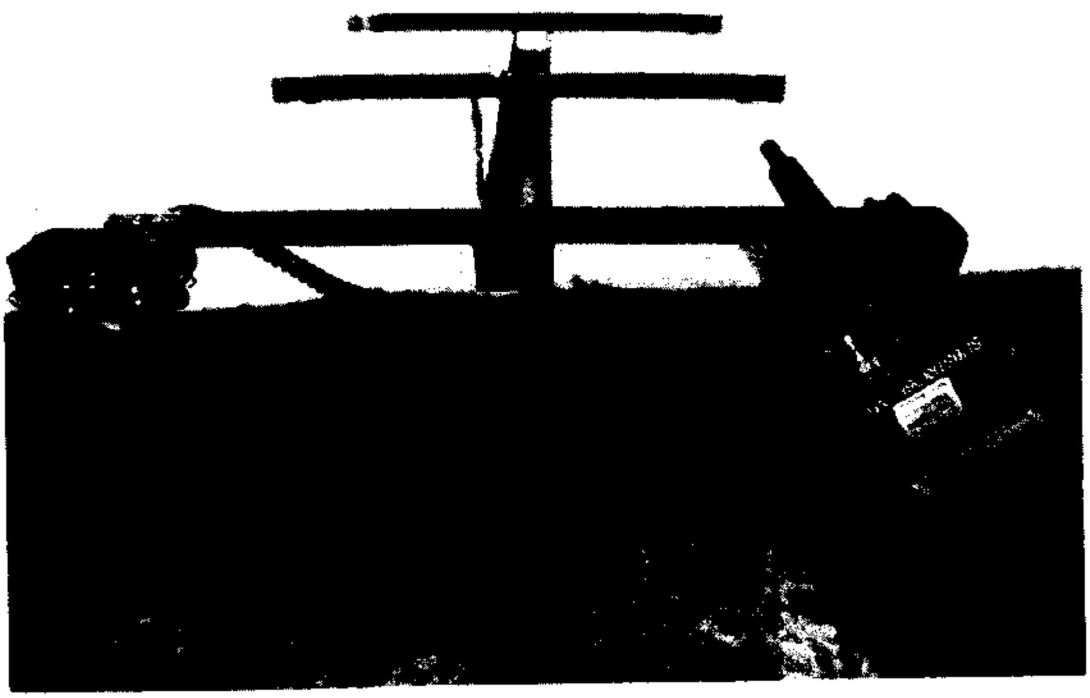

**Figure 2. Photographic apparatus.**


Figure 3. Video carriage.

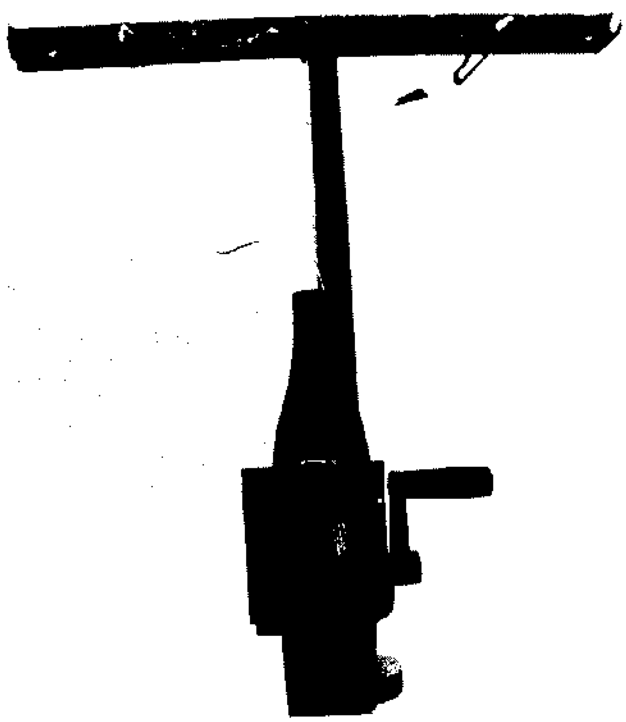

Figure 4. Video T-poles.

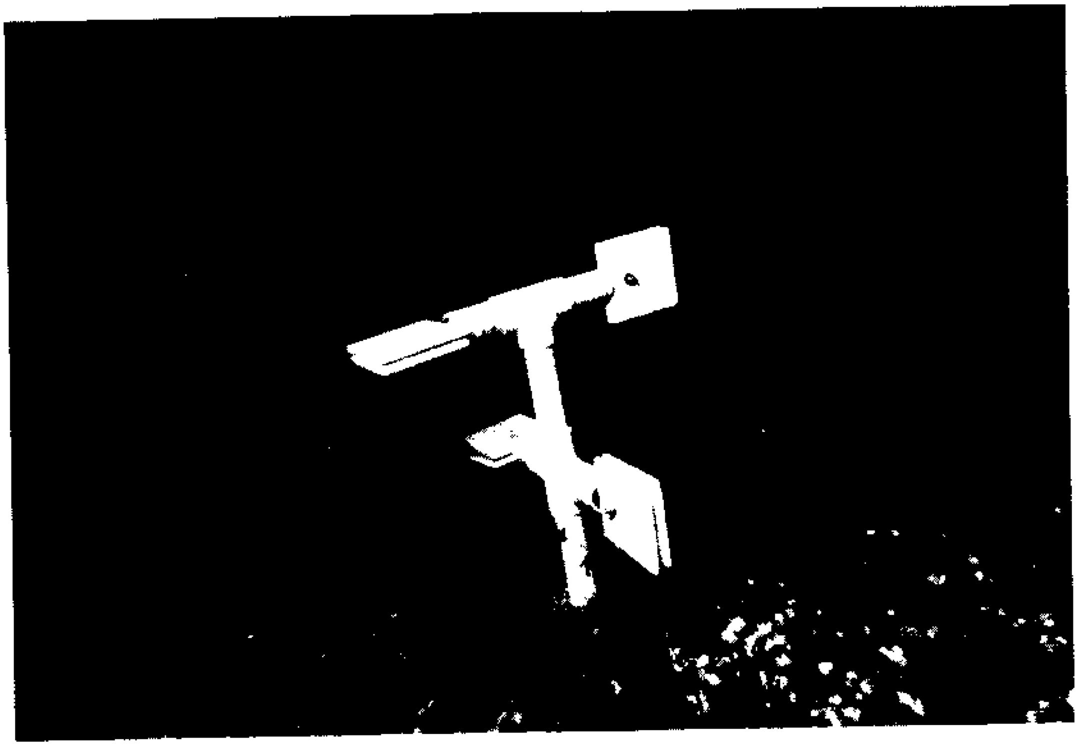

**Figure 5. Recruitment array.**

# LEGAL AND RISK MANAGEMENT ASPECTS OF WARM MINERAL SPRINGS PROJECT

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*The legal aspects of the Warm Mineral Springs project flow directly from the statutory authority which the University has under Florida law. As a state agency, the University is endowed with a mission and legal authority to carry it out. This statutory authority also defines the legal liability of the University and any of its projects. It provides the basic insurance "umbrella" covering all employees and agents against claims for personal or property damages. The perimeters of that protection are directly related to the scope of the activity. If a claim against an employee or agent arises out of an activity within the scope of his/her employment by this program and the standard of care was reasonable (as that is defined by safety, industry and other appropriate standards), the state risk management insurance will cover it. Reasonable care requires clear lines of authority, supervision and implementation. There are a number of suggested ways of staying within the umbrella of protection.*

## THE LEGAL ASPECTS

To understand the legal and risk management aspects of this project, it is necessary to understand the general legal responsibility of a state agency such as The Florida State University. There are essentially two aspects to this legal responsibility. The first is the enabling authority within the structure of the state as defined by Florida statutory law; the second is the responsibility, and thus liability, which the statutory and common law has imposed on state agencies in dealing with employees, agents, and third parties.

Chapters 20 and 240 of the Florida Statutes create the technical legal structure of the educational system in Florida. Among other things, those statutory provisions create the relationship (and authority) of the university to the other components of that educational system. The university authority is historically unique and extensive, particularly in terms of its interface with not only the Board of Regents but with other state agencies. The importance of specific statutory authority relates directly to the extent to which the university can operate and accomplish its mission. The best way I have learned to describe it is that whereas a private entity can do anything it wants unless a law says it can't, a state agency can only do something if a law says it can.

The Board of Regents is essentially the director of the Division of Universities, under the Department of Education. It is a body corporate by statute with presumably all of the rights attached to such status. The university is not. Nevertheless, within the realm of the Administrative Procedures Act (Chapter 120, F.S.), the university is separate and distinct from the Board of Regents and the other universities. But for customary and general legal purposes it must act on behalf of the Board of Regents.

Initially, because states are sovereign they were immune from any liability for their negligent acts. In recent times, however, states, including Florida, have waived that immunity to varying degrees by specific legislative statute. Chapter 768.28, Florida Statutes, is Florida's partial waiver of sovereign immunity. That statute does at least two things.

It authorizes claims against the State for the tortious conduct of its employees and agents; it further defines the perimeters and process for perfecting those claims. This statute forms the basis for defining what is that legal liability of the State (and university) regarding any of its projects, including this project. It also defines the basic insurance "umbrella" which will cover all employees and agents of the university against claims for personal or property damages.

This umbrella of protection opens only if, and always when, the claim arises out of any action or inaction *within the scope of employment of the employee or agent*. But if the employee's action or inaction is found to be committed in "bad faith or with malicious purpose or in a manner exhibiting wanton and willful disregard of human rights, safety, or property," then the umbrella closes and the employee or agent rather than the State shall be liable.

The State shall be liable for tort claims in the same manner and to the same extent as a private individual under like circumstances but such liability shall not include punitive damages nor be for claims exceeding $100,000.00 individually or $200,000.00 in the aggregate. No officer, employee or agent of the State shall be held *personally* liable in tort or named as a party defendant in any action for any injury or damage suffered if the employee or agent is within that umbrella. There are other procedural limitations, including time limits and the specific process to be followed, in perfecting the claim.

All such claims and insurance coverage related thereto are generally under the State Division of Risk Management, although both the Board of Regents and the university have specific additional statutory authority to purchase insurance and otherwise indemnify their employees, students or agents. Normally court claims and insurance coverage for personal injury and property damage are handled through the State Risk Management program.

Thus, when the university has in place an approved program, the State waiver of sovereign immunity attaches both in its responsibility/liability aspect and in its insurance/indemnification aspect. The trick, usually not complicated at all, is to be within the umbrella and to stay there.

This project is under the umbrella. Thus, all of its employees and agents should be also. Once you are operating within the scope of your employment, the next trick is to stay there. There are some common things you can do to prove you are; for example, keeping logs, calendars, mileage, expense records. Having conferences such as this is especially important as well. In other words, whether you can stay under the umbrella depends on how you conduct yourself once you are there.

Negligence in Florida boils down to two things in this context, a breach of a specific duty owed to the claimant and provable damages. Generally, the duty is defined by the nature of the relationship. The boundaries of the duty are measured by what is reasonable under the circumstances. In this project, reasonable care is largely defined by safety, industry and agency standards. The program standards are your guide and directive as to what is due or reasonable care.

Thus, in the unfortunate event of a diving accident, if it occurred within the scope of employment and it happened to an employee of the program, that employee will be entitled to applicable benefits including workers' compensation. If the employee caused the injury to a third party, still within the scope of his/her employment and in accord with such reasonable standards, that claim against the employee should be indemnified by the State.

In the event of any emergency, including the necessity for emergency treatment, similar guidelines apply. For example, if such emergency treatment requires a professional medical person's intervention, as in the use of the hyperbaric chamber, the appropriate procedure must be followed and treatment should be pursuant to applicable medical emergency standards.

In risk management assessment, recordkeeping is a critical element and is also of assistance in showing that reasonable care is being used so that foreseeable risks can be avoided. University risk management in this regard takes the position that, for example, it can be permissible to make a distinction between a clear case of the bends or other diving related illness and simply being "under the weather." The former situations require accident reports along with appropriate entries in the diving and ADP logs.

Reasonable care also requires that the program supervisors be responsible for assuring that use of the facilities and equipment be only done by trained and approved individuals.

Application of a reasonable standard in dealing with employees as well as agents or the public will ensure being under the umbrella and entitled to full coverage and indemnification by the State.

Similarly, the State's authority to contract is created by specific statutes for each agency. An officer or employee of any state agency, including the University, can legally bind the agency to a contract only if he or she has been appropriately delegated that authority. Such delegation should be authoritative, in writing and clear. Likewise, certain provisions are by law required and others are not permitted. Thus, improperly drawn contracts could be invalid and those signing them personally liable. Here again prevention means taking the time to see to it that the contracting process has been properly reviewed and approved. That is the best kind of risk management and insurance.

# FURTHER EVIDENCE OF COOPERATIVE FORAGING BY THE TURKEYFISH *PTEROIS MILES* IN THE GULF OF AQABA, RED SEA WITH COMMENTS ON SAFETY AND FIRST AID

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*Cooperative foraging by piscivorous fishes is believed to be an evolved response to the schooling defenses of prey species. In 1987, cooperative foraging was suggested for the first time for the turkeyfish Pterois miles (formerly P. volitans) in the Gulf of Aqaba (Eilat), Red Sea. Further evidence of turkeyfish exhibiting such behavior is reported here with a discussion of its ecological significance of permitting a relatively slow, predominantly benthic predator to capture faster moving, pelagic prey. On several occasions, in the late afternoon, six to ten turkeyfish were observed leaving their daytime resting station and proceeding to herd dense schools of small fish. In what appeared to be a cooperative effort, the turkeyfish were able to offset the speed and well-developed schooling ability of their prey. Aspects of this and similar foraging behaviors are discussed as topics for additional study; first-aid and safety considerations to be observed in the study of such venomous species are also reviewed.*

## INTRODUCTION

It has been the contention for some time that individual fish in groups (schools) are less vulnerable to predators than are solitary individuals (Neill and Cullen, 1974; Seghers, 1974; Pitcher, 1986; Landeau and Terborgh, 1986). Group members may suffer less predation because predators are detected earlier (Magurran *et al*, 1985) or because predators are confused by the abundance and the movement of the prey (Neill and Cullen, 1974; Hobson, 1978). Members of a school may also derive a feeding benefit because of the decrease in time an individual spends watching for predators (Pitcher and Magurran, 1983), shorter between-patch search times (Pitcher *et al*, 1982), mimicking other school members (Pitcher and Magurran, 1983), and by overwhelming the defender of a territory (Foster, 1985).

Cooperative foraging by piscivorous fishes is believed to be an evolved response to the schooling defenses of prey species (Hobson, 1968; Major, 1978; Schmitt and Strand, 1982). While some marine mammals use elaborate cooperative hunting behaviors to capture prey (e.g., Martinez and Klinghammer, 1970; Tarpy, 1979; Smith *et al*, 1981), such cooperation has been infrequently documented in the foraging behaviors of piscivorous fishes (Schmitt and Strand, 1982).

To differentiate cooperative foraging from other less complex forms of group hunting behaviors, Schmitt and Strand (1982) established two criteria: (1) individual predators adopt different, mutually complementary roles during foraging ventures (i.e., a division of labor), and (2) individuals exercise temporary restraint by not feeding until prey have been rendered more vulnerable.

## OBSERVATIONS AND DISCUSSION

### Gulf of Aqaba, Red Sea

The term "Red Sea" generally denotes the main basin beginning in the south at the Straits of Bab al-Mandeb and extending northward to include the deep Gulf of Aqaba and the shallow Gulf of Suez (Figure 1). In terms of the distribution of species, this forms a single area in which sea temperature seasonal ranges relative to latitudinal differences are believed to exert a more significant influence on the geographic distribution of species than do any physical barriers between the main basin and its two northern extremities (Vine, 1986).

The marine life of the Red Sea is essentially a modification of the Indo-Pacific assemblage. In most groups, the majority of species also occur in the Indian Ocean with relatively few species regarded as Red Sea endemics. It is, however, a measure of the degree of isolation of the Red Sea fauna from that of the Indo-Pacific that endemic species do exist, and in greater numbers than one would find in more open regions such as the western Indian Ocean (Vine, 1986).

The coral reefs of the northern Gulf of Aqaba belong to some of the best ecologically investigated reefs of the world (e.g., Benayahue and Loya, 1977; Fishelson, 1970; 1973; 1977; Loya and Rinkevich, 1980; Mergner, 1981; Vaissiere and Seguin, 1984). The reefs are of the fringing type with scleractinian corals as the most important hermatypic organisms (Loya and Slobodkin, 1971). The mean annual temperature of the surface water is 23.0°C (Loya and Slobodkin, 1971) but may fall to 21.2 °C in the winter (Mergner and Schuhmacher, 1974). The water is hypersaline with salinities of 41.0 to 42.0 parts per thousand. Surface currents typically flow counterclockwise from north to south along the Sinai coast (Loya and Slobodkin, 1971). Normal tide levels are 0.4 to 0.7 m, with occasional spring-tidal differences of more than 1.2 m (Mergner, 1981).

### Scorpionfishes

The scorpionfish family, Scorpaenidae, has more than 300 species worldwide, of which approximately 35 are known from the Red Sea (Randall, 1983). Scorpionfish have been divided into three groups on the basis of the structure of their venom organs: (1) turkeyfish and lionfish (e.g., *Pterois*); (2) scorpionfish proper (e.g., *Scorpaena*); and (3) stonefish (e.g., *Synanceja*) (Bridges, 1970). There are a number of different genera and species in each of these basic groups.

'Members of the genus *Pterois*, scorpionfish subfamily Pteroinae, have been referred to as turkeyfish, zebrafish, lionfish, dragonfish, and devilfish. *Pterois* live in the shallows of the tropical Indian and western Pacific oceans (Bridges, 1970). They are predatory carnivores (Mills, 1987) feeding on crabs, shrimps, and small fishes (Bridges, 1970). *Pterois*, like most scorpionfishes, are lie-and-wait or ambush predators, feeding on small fishes and crustaceans that mistakingly venture too near. In contrast to most scorpionfishes, which rarely move, *Pterois* can often be found swimming slowly just off the bottom (Randall, 1983). It is possible to distinguish the gender in all *Pterois* species at breeding time since the males darken and the females become paler and have noticeably larger abdomens (Mills, 1987).

*Pterois volitans* is the most well-known fish in this group. It can attain a length of 35 cm and was once believed to occur throughout the Indo-Pacific (Randall, 1983). However, the specific epithet *volitans* is now reserved for the Pacific Ocean variety. Based on meristic (number of dorsal and anal rays) and morphometric (length of pectoral fin, size of spots on vertical fins) evidence, two allopatric species are now recognized: *P. volitans* in the western and south-central Pacific and off Western Australia, and *P. miles* in the Indian Ocean from South Africa to the Red Sea and east to Sumatra (Schultz, 1986).

**Behavioral Observations**

The observations reported here were made in 1984 and 1985 during several dives at a reef formation approximately 0.5 km south-southwest of the H. Steinitz Marine Biology Laboratory (now the Marine Biology Laboratory of the Inter-University Institute of Eilat), Eilat, Israel. The Laboratory is located on the coast of the Gulf of Aqaba, 6 km south-southwest of the city of Eilat, and adjacent to a coral reef nature reserve (Figure 2). All photographs were taken by the author during a single dive made on April 6, 1984, between 1710 and 1750 h local time. Photographs were taken with a Nikonos IV-A underwater camera complete with a 35-mm lens, and an Oceanic 2000 underwater strobe.

The reef formation runs roughly north-south and is approximately 25 m from shore, 25 m long, and 5 to 10 m wide. The reef is bordered on its shoreward side by rock and coral rubble and seaward by coral rubble grading into a sand flat 20 to 25 m from the base of the formation. The water depth at the base of the reef varies from 4 to 5 m. At mean low water, the top of the reef is at the water's surface and is exposed during exceptionally low tides: tired and/or careless tourists were often seen walking across the top of the reef. A cavern-like tunnel penetrates the formation at its northern end (Figure 3). The tunnel is approximately 5 m long; has a maximum depth of 4 m; and has several short, blind chambers to either side. During daylight hours 6 to 12 turkeyfish were frequently found suspended from the ceiling and walls of the tunnel and side chambers. On several occasions, the turkeyfish were observed leaving this daytime resting station in the late afternoon (Figure 4) to herd schools of small fish (henceforth referred to as baitfish). These schools of baitfish were generally 2 to 3 m in diameter and were common to the area. The turkeyfish would position themselves around the schools of baitfish (Figures 5 to 7), spreading their dorsal and pectoral fins and spines in what were apparent attempts to prevent the escape of their prey (Figures 8 and 9). Several times during these encounters 1 or 2 turkeyfish would quietly swim into the school, gulping down several of the small fish. The turkeyfish made no obvious attempts to outswim and/or outmaneuver their prey, including stragglers. In what appeared to be a cooperative effort, the turkeyfish were able to offset the speed and schooling defense of their prey. This is particularly noteworthy since the turkeyfish is a slow-moving bottom feeder, and this posture of spread fins and spines further reduced their speed and maneuverability.

For some time this reef has been an excellent location for observing fish behavior. Because of its constant use by both tourists and scientists, it is assumed that the fishes have become relatively accustomed to the presence of divers. Turkeyfish make little attempt to evade divers. When approached, however, they react by bringing their dorsal spines fully erect and then rotating their bodies to direct the spines towards the intruder (Steinitz, 1959). If provoked further, they may strike forward with a rapid darting or thrusting motion (Miller, 1979; Randall, 1983). Such a defensive posture was not witnessed during these observations of foraging. Even when the observer was in the center of the school of baitfish, the turkeyfish ignored him, concentrating their attention on their prey.

**Ecological Significance**

Cooperative foraging by *P. miles* was suggested for the first time by Doubilet (1987):

*A school of small fish hung like a chandelier beneath the surface. Five turkeyfish circled, herding the school into a tighter mass. Two turkeyfish drifted closer, lunged, and a few silvery fish disappeared. Then the hunters became herders again, while the others took their turn.*

Schooling is generally believed to be an effective prey defense only during noncrepuscular daylight hours. Only when light is diminished (twilight periods) are predators effectively able to overcome schooling defenses (Hobson, 1968). Cooperative foraging tactics allow a predator to specialize on diurnally schooling species during periods of the day when non-cooperative foraging behaviors are largely ineffective (Schmitt and Strand, 1982). This may be of particular benefit to such a predator as the turkeyfish.

Turkeyfish, like most scorpionfishes, are ambush predators. They are commonly observed hovering about in a crevice or swimming slowly over the bottom. They are a relatively slow-moving fish, often remaining motionless under ledges or in cave mouths waiting for a potential meal to pass. Another technique of capture observed in aquaria is for the turkeyfish to maneuver its prey into a corner or area of no retreat, the outspread fins preventing escape, followed by a quick gulp (Mills, 1987). A film made of a stonefish at the New York Aquarium showed that the opening of the mouth, the snap at approaching food, and the return to the resting position took place in only one-sixteenth of a second (Bridges, 1970).

Various aspects of these behavioral characteristics may be integrated into a "behavior profile" of the cooperative foraging of the turkeyfish. The herding with outspread appendages effectively "cornered" the prey, reducing the possibility of its escape (i.e., Mills, 1987). This permitted individual predators then to enter the schools and feed in more of a lie-and-wait predator fashion. Furthermore, the foraging took place in the late afternoon when the baitfish may have been less likely to depend upon schooling as a defense. Being forced to school at this time may have subjected them to a reversed confusion-effect (Miller, 1922). Among fishes, species that primarily consume pelagic prey are likely to meet the conditions fostering cooperative foraging behaviors. These observations of *P. miles* suggest that cooperative foraging is also utilized by species generally believed not to consume pelagic prey.

The great protection afforded by a schooling defense should increase the importance of predator mechanisms that deny these prey refuge through schooling. Patchily distributed resources that are locally superabundant, such as schooled prey, will reduce the importance of competition among predators for a specific prey individual (Schmitt and Strand, 1982). Hamilton (1971) proposed that schooling may be selected for by the continued incidence of predation and predicted that centrally located individuals would be safer than their peripheral counterparts. This "selfish herd" theory predicts that, as long as predators concentrate on the nearest prey, peripheral individuals should be at higher risk relative to central individuals, as some part of the former is directly exposed to the outside and therefore closer to predators. A predator using an attack strategy of marginal predation would support this model. It has been demonstrated that stragglers are attacked more frequently than the school and suffer a significantly higher risk in comparison to those in the school proper (Hobson, 1968; Parrish, 1989). However, the relative benefit of occupying a given location within an aggregation is dependent upon the school size and the mode of predator attack. Under some circumstances central members of a school may sustain a significantly higher percentage of risk than peripheral individuals (Parrish, 1989).

In this case, the schooling behavior may have been detrimental and the baitfish better-off if they had not schooled. The turkeyfish were observed to ignore stragglers, preferring to concentrate their efforts on cornering prey rather than chasing them down. This strategy allowed for a typical, lie-and-wait predator to utilize a faster moving, pelagic food source.

**Topics for Additional Study**

These observations, and those of Doubilet (1987), support previous reports that cooperative foraging behavior has evolved in piscivorous fishes, including *P. miles*. However, while these observations may further support the notion of an evolved response to schooling, there are a number of areas requiring additional study. For example, do other species of *Pterois* exhibit this behavior? Does the behavior exhibited by *P. miles* entirely fulfill the two criteria used by Schmitt and Strand (1982) to distinguish cooperative foraging from other, less complex forms of group hunting behaviors? What is the minimum and optimum number of individuals (predators) necessary for this behavior to be effective? Does *P. miles* use different feeding tactics to capture fish prey with qualitatively dissimilar defenses? Schmitt and Strand (1982) observed different feeding tactics by the yellowtail, *Seriola lalandei*, to capture prey utilizing different defenses. The yellowtail herded an open water schooling prey, jack mackerel (*Trachurus symmetricus*), against the shore, offsetting the speed and well-developed schooling abilities used by the prey to evade predators in pelagic waters. Yellowtail were also observed herding a school of the Cortez grunts (*Lythrulon flaviguttatum*) into open water away from reef substrata where they normally take refuge. These different hunting behaviors suggest that in the yellowtail group foraging behavior is plastic enough to respond to the different prey species hunted. Is this plasticity found in *P. miles* and how flexible is it?

## SAFETY AND FIRST-AID CONSIDERATIONS

Fishes that can inflict poisonous puncture-type wounds are found throughout the world but are most common in tropical waters. These fishes, however, are usually not aggressive, and the injuries that do result are generally due to carelessness on the part of the diver (Steinitz, 1959) or aquarist (Wasserman and Johnson, 1979). Because of the potential for injury to researchers, technicians, and aquarium personnel during the handling of these animals, as well as the necessity of *in situ* observations during behavioral studies such as the above, the following is a brief synopsis of safety and first-aid considerations for work with such venomous fishes.

While the specific symptoms and signs vary with the type of fish inflicting the wound, general indications of a venomous injury include a puncture in the affected area; excruciating pain; fainting, weakness, nausea, and shock; local swelling, inflammation, or welts; mental confusion; spreading numbness; paralysis; convulsions; respiratory depression or arrest; and sometimes cardiac arrest (PADI, 1987). Treatment of any venomous fish sting should include immediate attention towards alleviating the pain, combating the effects of the venom, and preventing secondary infection (Halstead, 1976). The pain from such stings is produced by a combination of factors, including trauma from the offending spine, venom, and the introduction of foreign substances into the wound. Puncture-type wounds are usually small in size, and removal of the venom is difficult. Suction may be of limited value since the venom tissue is part of the integumentary sheath of the spine, and a portion of the sheath may become lodged in the wound and continue to envenom the victim after the spine itself has been removed.

Scorpionfish are the most widespread and numerous family of venomous fishes. This family has representatives throughout the world, but the most dangerous species occur in the tropics (Miller, 1979). At least 80 species of scorpionfishes have been known to cause injuries to swimmers and divers. Scorpionfish stings vary according to the species.

The type of sting, species, amount of venom released, and the age and health of the victim all affect the severity of the injury (PADI, 1989).

Anatomically, the venom organs of scorpionfishes differ from one group to the next, but generally consist of dorsal, pelvic, and anal spines and associated venom glands. The turkeyfish has long, slender, delicate spines; the scorpionfish moderately stout spines; and the stonefish heavy, robust spines covered by a thick, warty integumentary sheath (Bridges, 1970). Eighteen of the striped and spotted spines of the turkeyfish are venomous; thirteen are dorsal, the remaining five anal and pelvic (Bridges, 1970). The spines are "T" or "anchor-shaped" in cross section. The glandular tissue producing the venom lies in the longitudinal groove on each side of the spines (Randall, 1983). Stonefish also have thirteen venomous spines on their back; however, the venom is contained within paired venom sacs at the base of each spine (Bridges, 1970).

The pain from scorpionfish (general designation) stings is usually described as immediate, intense, sharp, shooting or throbbing, and radiating from the affected part. Untreated, the pain reaches its peak in 60 to 90 minutes and persists 6 to 12 hours. The character of the pain varies greatly with the amount of venom delivered and the species. The most severe pain is produced by *Synanceja*, the stonefish, and may persist for several days. Complete recovery from stonefish stings may require months (Wasserman and Johnston, 1979) and may have an adverse effect on the general health of the victim (Halstead, 1976). Stonefish stings have been known to be fatal (Bridges, 1970; PADI, 1989). Scorpionfish and turkeyfish stings generally result only in pain (Steinitz, 1959; Saunders, 1960; Wasserman and Johnston, 1979).

Stonefish venom is an unstable protein with a pH of 6.0 and a molecular weight of 150,000. It produces an intense vasoconstriction and thereafter tends to localize itself. It is destroyed by heat, alkalis and acids (pH greater than 9 or less than 4), potassium permanganate and congo red. The toxin is a myotoxin, which acts on skeletal, involuntary, and cardiac muscles, blocking conduction in these tissues and causing muscle paralysis, respiratory depression, peripheral vasodilation, shock, and cardiac arrest. It is also capable of producing cardiac arrhythmia (Edmonds, 1989).

The venom of other scorpionfishes, including *Pterois*, is water soluble and a heat labile polypeptide. It reduces the rate of inactivation of the sodium channel and produces a fall in arterial pressure, an increase and then a decrease in central venous pressure, respiratory depression, and abnormalities in electrocardiogram and electroencephalogram tracings (Edmonds, 1989).

A stonefish antivenom serum has been developed by the Commonwealth Serum Laboratories, Melbourne, Australia (Wiener, 1959; Dueker, 1970; Wasserman and Johnston, 1979; Edmonds, 1989) and is prepared by hyperimmunizing horses with the venom of the stonefish *Synanceja trachynis* (Edmonds, 1989). One unit of stonefish antivenom neutralizes 0.01 mg of stonefish venom: typically there are 5 to 10 mg of venom in each of 13 dorsal spines of the stone fish. The initial antivenom dose will depend on the number of visible punctures and is given by intramuscular injection, but in severe cases may be administered intravenously.

Stonefish antivenom is issued in containers of 2,000 units (approximately 2 ml) and should be stored protected from light at 2 to 8$^{o}$C (not frozen). Because of the possibility of severe allergic reactions, the serum should be used only under strict medical supervision (Dueker, 1970). Stonefish antivenom has also been found to be effective in the treatment of other scorpionfish stings (Edmonds, 1989). Injected emetine hydrochloride has also been found to give dramatically quick release from the intense pain (Bridges 1970). Morphine may or may not be effective when treating stonefish stings (Wiener, 1959).

First aid for the victims of venomous fishes, including scorpionfish, can be found in a number of texts (e.g., Halstead, 1976; Auerbach, 1987; PADI, 1987; 1989; Edmonds, 1989). While the precise treatment will vary with the species encountered, the extent of envenomation, the general health and sensitivity of the victim, and the available medical care, some generalizations regarding first aid can be made. Treatment should include immersing the punctures in nonscalding hot water of 43 to 48°C (110 to 120°F). Face or body wounds will necessitate the use of hot moist compresses. The heat will neutralize the venom, contributing greatly to the relief of pain. This treatment usually requires 30 to 90 minutes and may have to be repeated if pain recurs. If the area affected is a limb, the victim should be kept in a position allowing the limb to remain below the level of the heart. Prompt treatment for shock must be included because fainting is common with venomous wounds. Any visible pieces of the spine(s), sheath, or other foreign bodies should be removed with probing instruments or by flushing the wound with water. However, the hot-water soak should not be delayed during attempts to remove foreign pieces from the wound. The wound should be scrubbed with soap and water, then irrigated vigorously with fresh water. The wound should not be taped or sewn closed, but may be covered after the pain has subsided. If the wound shows signs of infection, antibiotics should be administered. For treatment of stonefish stings, the antivenom should be administered by a physician. Other symptoms may include fever, hypertension, respiratory and heart effects, and shock. In the case of cardiac arrest, cardiopulmonary resuscitation (CPR) may be required.

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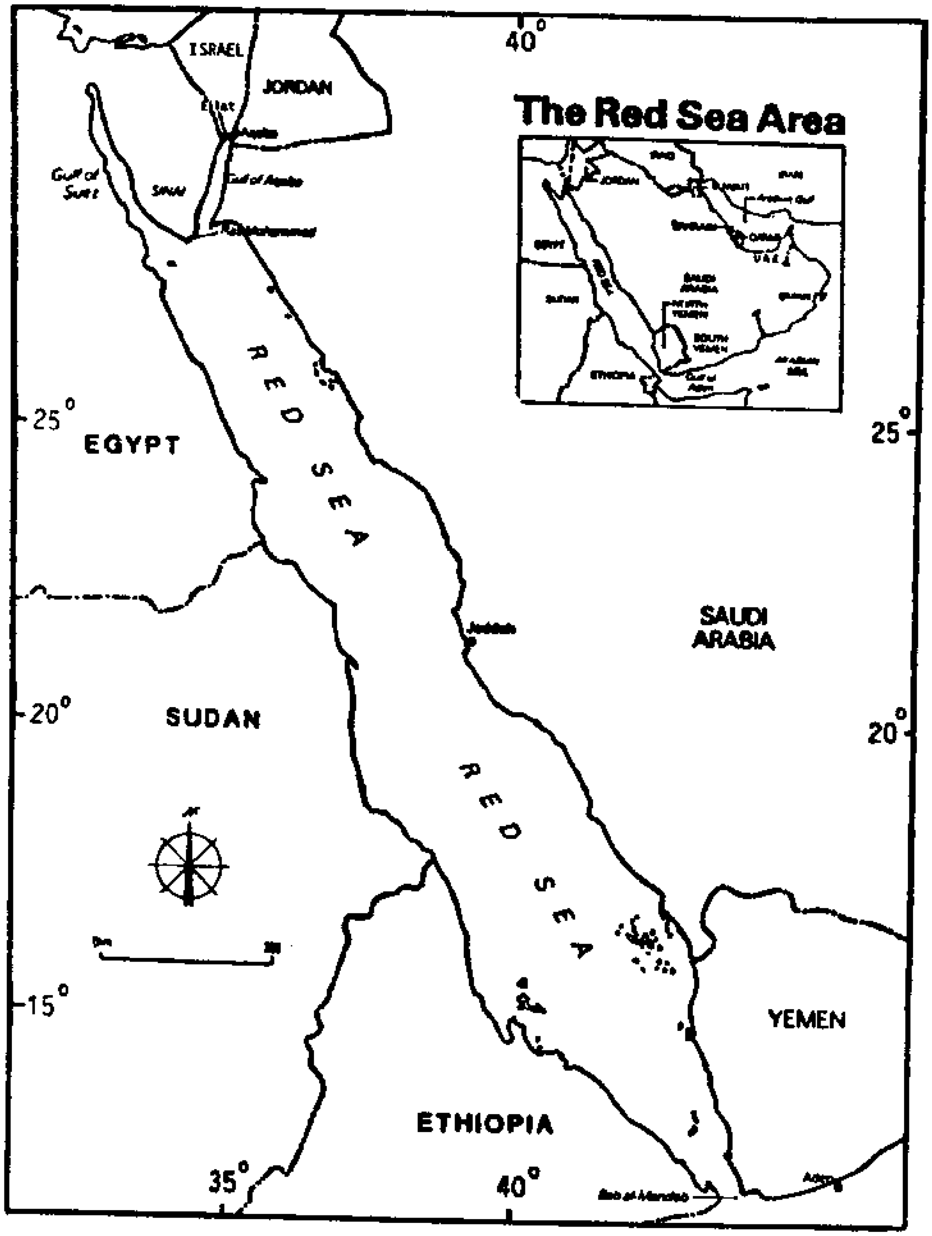


**Figure 1.** The Red Sea, extending from the Straits of Bab al-Mandeb northward to include the deep Gulf of Aqaba (Eilat) and the shallow Gulf of Suez (adapted from Randall, 1983).

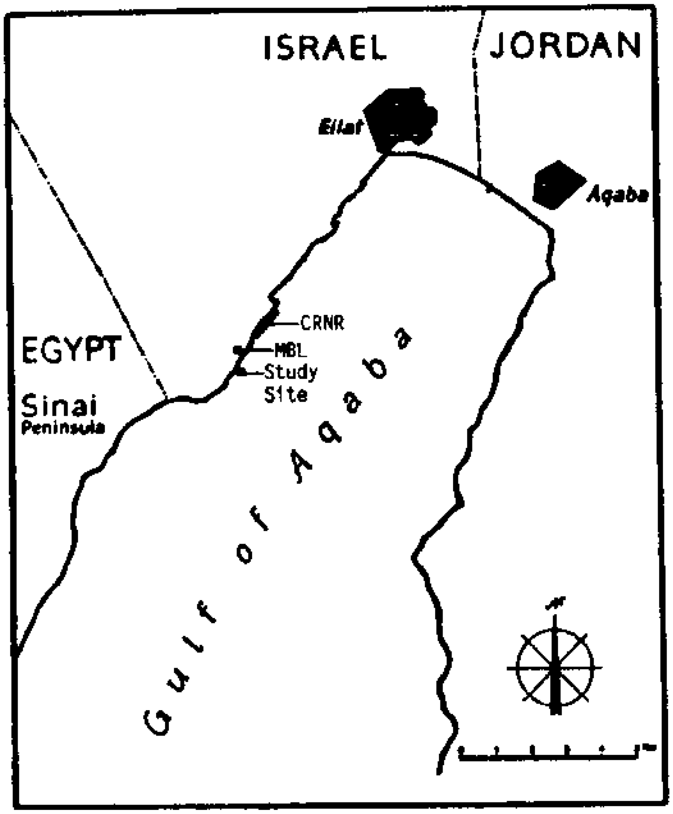


**Figure 2. The northern Gulf of Aqaba including the city of Eilat, the Marine Biological Laboratory (MBL), the coral reef nature reserve (CRNR), and the study site (adapted from Mergner, 1981).**

**Figure 3. View from inside the cavern-like tunnel looking outward. The tunnel is approximately 5 m long; has a maximum depth of 4 m; and has several short, blind chambers to either side.**

**Figure 4. During the daylight hours 6 to 12 turkeyfish *(Pterois miles)* were frequently found suspended from the ceiling and walls of the tunnel. In the late afternoon they would leave the tunnel.**

**Figure 5. Immediately upon leaving the tunnel the turkeyfish would begin to position themselves to herd schools of small baitfish.**

**Figure 6. The turkeyfish surrounded schools of baitfish. The schools of baitfish were typically 2 to 3 m in diameter and common to the area.**

**Figure 7. The turkeyfish spread their dorsal and pectoral fins and spines in what were apparent attempts to prevent the escape of their prey.**

**Figure 8. Several times during these encounters one or two turkeyfish would quietly swim into the school, gulping down several of the small fish. The turkeyfish made no obvious attempts to outswim and/or outmaneuver their prey, including stragglers.**

**Figure 9. This cooperative foraging behavior allowed the turkeyfish, a slow, primarily benthic predator, to capture a pelagic prey.**

# MEDICAL SUPPORT CONSIDERATIONS FOR MIXED GAS DIVING AT WARM MINERAL SPRINGS ARCHAEOLOGICAL RESEARCH PROJECT

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*This paper will describe the necessary medical support for the underwater archaeological studies in the deep portion of Warm Mineral Springs, including considerations for treatment of accidents, prevention of accidents by decompressing on gas mixtures other than air, monitoring for possible venous gas emboli with doppler technique and utilization of "Trimix" air-helium mixed gases for more effective deep water diving by decreasing risks of inert gas narcosis as well as increasing bottom time available. This information may be employed as a template for other deep water (greater than 130 feet) scientific dive projects which can be managed by similar support considerations. It is offered as part of a series of papers about the Warm Mineral Springs Archaeological Research Project which in continuity will approach the scope of utilization of mixed gas diving in scientific research.*

## INTRODUCTION

For 15 years research in the unique environment of Warm Mineral Springs has been providing valuable information from the archaeological and paleontological remains that are well preserved at multiple levels of the spring. However, a large part of this valuable material is located in depths in excess of what is considered to be safe for underwater research done by divers on compressed air. In 1987, the oversight of the Warm Mineral Springs Archaeological Research Project moved from Manatee Community College to the Department of Anthropology at Florida State University and began working with the Academic Diving Program (ADP) to develop diving standards and procedures for this deep site. The already well established link between the ADP Medical Advisor, as well as the ongoing integration with the Dept. of Archaeology allowed for these resources to be applied to the problems of the deeper diving research. What was not readily available at the ADP systems was significant expertise in mixed gas (other than air) diving.

The rationale for the use of mixed gas was based upon two factors. The first was a concern about the risk of decompression involved with prolonged hyperbaric exposures on air.

Underwater research at this site required labor-extensive long bottom-times at depths below 150 fsw. This resulted in increasingly longer periods of decompression, often on exceptional exposure tables, which had an unacceptable risk of decompression sickness. The philosophy of the ADP has been conservative with regard to the risk of exposure to decompression sickness. For example, for routine air diving, we recommend using the D.C.I.E.M. Tables which are recognized as ultra-conservative in the industry. Prior to FSU's involvement in the Warm Mineral Springs Archaeological Research Project (WMSARP), shallow water O2 decompression had been employed to diminish decompression risks. Moving to the use of Nitrox (oxygen fortified air) to increase the off-gas gradient at deeper decompression stops in conjunction with the shallow O2 stops was an important enhancement we recommended to lessen decompression risks.

Breathing nitrox at deeper depths, however, looses its advantages because of increased risks of O2 Central Nervous System toxicity. Yet the air mixture at these depths includes too much nitrogen, inducing an unacceptable level of narcosis. Our second concern for these deeper dives (and to avoid unnecessary hypothermia and expense of heliox), was resolved by using a trimix of helium, nitrogen and oxygen. This would reduce the risk of diving accidents and allow for greater efficiency in the precise work of underwater archaeology.

Because of the complexity in dealing with mixed gases, ie. decisions regarding what tables to use, optimal gas mixtures and the calculations involved, we referred the expertise and experience of R. W. Hamilton, Ph.D. He was able to extrapolate data from dives made to the depths that our researchers would be making and develop tables with reasonable decompression times utilizing the trimix, nitrox, and in water O2 decompression gases. Since decompression sickness has been described as, at least in part, a statistical event, and because of the many variables involved, doppler monitoring of our research divers was included as a check of our procedures and as an indicator of the reliability of our tables.

The addition of an on site fully operational double lock multiplace recompression chamber for treatment of possible diving accident was integral to our plans to insure diver safety should decompression symptoms appear. In order to fully support the chamber it was necessary for the Program Physician (author) to become acquainted with the operations of recompression chambers and become qualified in their use to treat diving accidents. There are quite a few programs around the country where Hyperbaric Medicine is taught. The two week duration program taught by N.O.A.A. and the military programs of Navy & Air Force tend to be the most inclusive. There are other programs which concentrate on the use of Hyperbaric Oxygen for Medical reasons. We choose the week long course taught by former NOAA instructor Dick Rutkowski at Hyperbaric International, because of its emphasis with hands on use of a fully operational double lock multiplace chamber and its concentration on treating diving related maladies. Both the Program Physician and the Assistant Director of the ADP attended the class so that our direction of the chamber operator and dive supervisor would be more meaningful. This also provided the ADP & WMSARP with a person who was capable of operating the chamber should that be needed in the future.

Choice of a chamber operator-dive supervisor was done by a combined effort of the managements of Warm Mineral Springs Archaeological Research Project and the ADP. An agreement was reached (as part of total plan of how the dive supervisor would interact with the chief scientist and his relationship with the ADP) that allowed adequate communication between all parties without undue interference with the research effort. In order to enhance communication, and to develop proper procedures for the scope of the project, an on-site visit was made by the Program Physician to familiarize himself with the dive site, support facilities, the operation of the chamber and to consult with the chief scientist as well as the dive supervisor.

Part of the purpose of the on site visit was to develop a Medical Plan for WMSARP to be used in evaluation and treatment of potential diving mishaps. The contents of the standard ADP first aid kit and related equipment were augmented with the addition of stethoscopes, sphygmomanometer (blood pressure cuff), reflex hammer, and a positive pressure, resuscitator. Attempts were made to enlist the local E.M.S. as a secondary assist to our initial handling of diving related injury. This would allow further treatment to be initiated such as intravenous fluid administration and respiratory assist during recompression of a diver.

Further refinement of the medical plan continued in Tallahassee over a period of several months. Decisions regarding access to the chamber by the public, procedures for precautionary treatments, return to work policies, etc. were debated extensively before a final draft was agreed upon. The final document was drafted by Mrs. Barbara O'Horo Benton, manager of the WMSARP, and is included as appendix 1.

An integral part of the Medical Plan was the development of an evaluation and emergency network system which could be activated by the Diving Supervisor. All divers undergo doppler evaluations at set intervals after their dives. In an attempt to quantify any intravascular bubbles that were detected by the Diving Supervisor, we hoped by early treatment either by 100 % oxygen at the surface or a precautionary chamber treatment (Table 5 USN) to avoid the occurrence of an injury and delay of on-going research due to the injury. The plan also included allowing the scientist who ascended without symptoms of DCS or with complaint of fatigue to request a precautionary treatment if he/she felt it appropriate (100% O2 or a run in the chamber). The 100% O2 would have to be continued for at least 1/2 hour if begun, and the diver would be monitored for signs and symptoms of DCS and for bubble formation with the doppler. If diagnosis of DCS was not made at this time, the treatment is recorded without penalizing the researcher.

The medical plan addressed the intricacies of immediately notifying the needed personnel should an incident occur, in spite of the remote location of the research site. It was decided that rapid transmission of written, and printed material to and from the dive site was best served by a "facsimile" machine. This permitted dive statistics and the diver's condition, now reduced to a report sheet, to be communicated to FSU's ADP (where it could be walked to Dr. Kepper and other FSU administrative offices) as well transmitted by FAX to our consultant Dr. Hamilton for his input. The program physicians' home, office and voice beeper number were all included in the medical plan in order to be able to expedite getting the most immediate contact. Dr. James Lowenhertz of Mercy Hospital's Hyperbaric Unit in Miami was contacted and agreed to serve as our backup physician and referral center.

A decision was made by FSU (in conjunction with the office of Environmental Health & Safety) to restrict the hyperbaric chamber usage to the needs of the diving program only. This decision was made in light of the recognition that the chamber facility was expressly designed to care for medical problems that would arise as a result of an accident or incident at the dive site. Neither the number of required trained staff nor the equipment and expertise necessary for state of the art diagnostic and therapeutic management of all diving related incidents could be supported by the WMSARP or FSU. It was felt that other diving accident victims should be referred to one of the hospital chambers located in S. Florida.

FSU ADP has taken advantage of the expertise generated by this program to enhance other diving research projects. The use of nitrox diving is quite routine now with some of our relatively medium (50-100 ft) depth diving exposures. The use of doppler monitoring has become an important safety measure in use with our prolonged exposure "decompression dives" that are being done to conduct research in cave systems and other deeper depth projects (80-130 ft.) The doppler may help us to identify those divers who are more prone to intravascular bubbles and possible DCS. We will be able to offer treatment earlier and modify their dive exposure to compensate for their potential increased risks.

## CONCLUSIONS

Whereas it is impossible with a sample of one or two research divers to verify any set of exposure tables as being safe with any degree of statistical significance, the ADP has set up at Warm Mineral Springs a mechanism to provide exceptional safety precautions for deep research diving which may be used as an example or template for other research projects of similar nature with modification being made based on the particular needs of the host agency. This has the potential to open up new frontiers for scientific investigation by diving scientists with the cooperation of their respective institutions and Diving Control Boards.

## APPENDIX I

## WARM MINERAL SPRINGS ARCHAEOLOGICAL RESEARCH PROJECT

## MEDICAL MANAGEMENT PLAN

Reviewed version 02-12-90

In Effect Until
Further Notice
___G. Stanton

___B. O'Horo
Benton

___W. Kepper

___R. Matthews

### I. RESPONSIBILITIES

The Warm Mineral Springs Archaeological Research Project is a Legislatively funded research project, administered through Florida State University, Department of Anthropology. In accordance with FSU diving policy, all WMSARP personnel are required to meet the University's Diving Control board standards before they are permitted to dive. These standards involve both an initial assessment of water skills and a determination of medical soundness through an annual medical exam. The WMSARP is responsible for payment of annual physicals for its personnel. All personnel medicals must be reviewed and approved by Dr. William Kepper prior to clearance for diving.

The FSU Diving control Board and its agent, the University's Diving Officer (UDO), are responsible for the overall safety of the WMSARP.

In his capacity as Medical Officer for the Florida State University Diving Control Board, Dr. William Kepper is also the Medical Officer for the Warm Mineral Springs Archaeological Research Project. He has the overall medical responsibility for the project, including determining medical qualifications of divers, medical management of diving accidents, and recommendation of followup therapy. Dr. Kepper also has the responsibility of notifying WMSARP of those times when he will not be available to be on-call for medical emergencies. In those instances WMSARP will contact Dr. Loewenherz in Miami during an emergency.

All personnel are responsible for maintaining their own general health.

Diving safety operational responsibility rests with the on-site Dive Officer. He makes final daily decisions on fitness to dive and diving operations, and manages treatments conducted in the WMSARP chamber. As an extension of Dr. Kepper, he performs local neurological exams and general physical assessments as needed.

## II. DECOMPRESSION SICKNESS/EMBOLISM TREATMENT PROCEDURES

### A. When to Treat

The primary decision to treat suspected cases of decompression sickness and embolism rests with the Dive Officer, ultimately to be confirmed by the Medical Officer or his designee. The Dive Officer will also decide if the diver's condition warrants calling in the local rescue squad at this time, subject to the review of the Medical Officer if the decision is made not to involve the local rescue squad. (The purpose of the rescue squad is to assist, if necessary, in placing an i.v. tube.)

### B. General Procedures

1. Specific procedures for chamber set-up and personnel duties are in place in another document, and are not addressed here.

2. For after work hours treatment, the diver is to page the Dive Officer, who will return the call. If the decision to examine and possibly treat the diver is made, the Dive Officer will page the remaining crew, leaving on the digital display 426-9550. This will be their notification that they are required to report to the dive locker immediately.

Page numbers are:

| | |
|---|---|
| Bob Matthews | (813) 952-4582 |
| Jack Lotito | (813) 952-4583 |
| Joe Nelson | (813) 952-4370 |

3. For routine pain-only DCS a neurological exam will be given to the diver before treatment begins. For serious cases it will be given as soon as practical after the diver is under pressure.

4. Recompression on 100% oxygen to 60 feet will begin as quickly as possible. The choice of treatment table (USN Tables 6 or 6A) will be made on a case by case basis according to USN treatment procedures. Because Table 5 is not regarded by all as adequate, it shall only be used with permission of the Medical Officer, at the time. Additionally, special therapy as directed by the Medical Officer is permitted.

5. After treatment is underway, the Dive Officer or his designee will call the WMSARP administrative office (426-9559) and leave instructions that the number is not to be answered there and to disconnect the answering machine. WMSARP personnel will then connect a dive locker telephone to that line (on-site), which will be used for incoming calls during the treatment. The Dive Officer will then make the following notifications:

| | |
|---|---|
| a. Dr. William Kepper | (904) 599-7183 (Voice Beeper) |
| | (904) 877-5143 Office |
| | (904) 877-3261 Office |
| | (904) 385-9336 Home |

<u>OR</u> HIS ALTERNATE, WHEN DR. KEPPER WILL NOT BE AVAILABLE: (regular telephone call)

| | |
|---|---|
| Dr. Loewenherz | (904) 274-4880 |

| | |
|---|---|
| b. WMSARP Coordinator | (904) 298-2920 (Beeper) |

If a page (beeper) is used, the Dive Officer will leave the number (813) 426-9559 for the so notified parties to return his call.

Coordinator will contact UDO during office hours at (904) 644-1439. If UDO is not available a message will be left. After hours call will be made at (904) 926-3389 for Gregg Stanton, or (904) 878-3357 to Dan Orr, and he will then have the responsibility of contacting the Dive Officer. WMSARP Coordinator shall notify the Chairman, Department of Anthropology, and any other University contacts required of her. The UDO shall make any University contacts required of him.

Should any media contact (press) become involved, the WMSARP Coordinator is the only individual authorized to make statements or to manage that situation in any way.

6. All medical decisions during treatment, after contact has been made, are the responsibility of the Medical Officer. In those cases where Dr. Kepper is not available, the alternate Medical Officer will direct medical treatment. The Medical Officer may, at any time require additional on-site medical aid (i.e., rescue squad, local physician).

The Medical Officer can, at any time require the use of fax to provide him with copies of treatment underway, dive profile, etc.

7. The Medical Officer has several individuals who are available to offer advice. See Attachment B.

8. The use of extra treatment time/oxygen modification is authorized at the discretion of the Medical Officer and Dive Officer.

### C. Transportation of Diver to a Medical Facility

At the discretion of the Medical Officer and the Dive Officer, the diver will be transferred to a full treatment facility. Transportation by ambulance or helicopter is preferred, and a 100% oxygen cylinder and demand mask, as well as any other medical supplies that may be required for the particular incident, will accompany the diver. If at all possible another WMSARP person will accompany the diver. Transfer will be made (in order of preference) to Mercy Hospital in Miami, or to Shands Hospital in Gainesville, Prior to the transportation, the medical facility will be notified and any documents they require will be sent by fax or hand-carried, at the discretion of the receiving facility. The diver will not be processed through the Venice or Port Charlotte emergency rooms unless directed by the Medical Officer, through the local emergency medical service.

### D. Return to Work

A diver who has received chamber treatment shall be cleared by the Medical Officer and the Dive Officer before returning to work. The Medical Officer may require examination by a physician before authorizing a return to work.

Additionally, depending upon the circumstances surrounding the injury, diving may be temporarily suspended for a reevaluation of the diving procedures, tables, etc. In such instances, any reevaluation must be made on a priority basis and as quickly as can be safely done in order to authorize a return to work in a timely manner.

### E. Documentation of Treatment

All recording documents and document submission requirements are the responsibility of the site Dive Officer and must comply with the requirements set forth in item V.

## III. PRECAUTIONARY TREATMENTS

A treatment is "precautionary" when the diver has no symptoms of decompression sickness, but for reasons of suspected table irregularities or any feelings on the part of the diver or supervisor a treatment is felt to be desirable. If there are **any** signs or symptoms at any time then the standard treatment shall be used.

### A. When to Implement

In the event a diver or the Dive Officer determines that a diver may not be in satisfactory condition following a dive, precautionary treatment may be implemented at the discretion of either the Dive Officer or the diver in question. If there are any signs or symptoms the standard treatment shall be used. See Attachment D for procedures to be followed when doppler monitoring indicates a cause for concern (grade 4 bubbles).

**B. Choice of Treatment**

Following a neurological exam, precautionary treatment shall consist of either breathing 100% oxygen on the surface for a minimum of 30 minutes or more, or chamber treatment of a minimum of USN Table 5, as determined by the Dive Officer. In the case of chamber treatment, follow procedures in item II above and in Attachment A. Either treatment will be preceded and followed by serial neurological exams.

**C. Notifications Required**

If diver is to be treated on surface oxygen for 30 minutes or more only and passes a repeated neurological exam with no symptoms or signs, no notification is required to either the Medical Officer or the ADP, except for the standard end of week reporting which shall reflect the details of the treatment used. If there is a specific reason for the precautionary treatment (such as uncertainty about the table) this should be logged. Notification of the WMSARP Coordinator is required.

If the diver is treated in the chamber, treatment notification requirements are in effect, as outlined in item II and Attachment A, with the explicit information that it is a precautionary treatment only.

**D. Return to Work**

If all neurological exams are performed as required and no signs or symptoms develop then the diver may return immediately to work following a precautionary treatment.

**E. Investigation**

Each precautionary treatment shall be investigated by the Decompression Monitoring Board.

## IV. TREATMENT OF NON-WMSARP PERSONNEL

University policy in this matter shall be strictly adhered to, under any circumstances. At no time are exceptions to be made. University policy is stated in Attachment C.

## V. DOCUMENTATION

The Dive Officer shall report routine deep, mixed gas, and any relevant air dive operations to the ADP on a weekly basis. A weekly compilation of reports will occur on the Friday of every week in which such operations take place, and these shall be mailed no later than 5:00p.m. on those Fridays. These routine reports will consist of copies of daily dive logs, copies of any Doppler tapes run, a DCB diving summary sheet, and a written narrative of the week's diving activities, including the Dive Officer's observations. During monthly periods when shallow and air dives only are made, reports will be made monthly in accordance with established DCB regulation. A copy of all these reports shall be sent at the same time to the WMSARP Coordinator.

In those cases when operations are not routine (e.g., injury, recompression) the Dive Officer shall complete all on-site documentation and forward to the ADP within 24 hours of such an occurrence. At the discretion of the ADP, the documentation may be forwarded by fax. Copies of the same will be forwarded to the WMSARP Coordinator in like manner at the same time.

To summarize policy, if a treatment has been used and the diver is regarded as "cured" then no accident report is needed. If the treatment does not resolve all symptoms then an accident report shall be filed.

## VI. WORKMEN'S COMPENSATION AND EMERGENCY OVERTIME

University regulations shall be strictly adhered to in reporting accident or injury. Any treatment required from outside the University or its employees will be paid for through Workmen's Compensation.

University regulation Series P, Section 1, Subject 3.1, regarding OPS employee overtime work will be followed.

## ATTACHMENT A

## EMERGENCY TREATMENT PROCEDURES OUTLINE

THIS IS A SIMPLE OUTLINE OF VERY BASIC EMERGENCY PROCEDURES. REFER TO PAGES 2 THROUGH 5 OF THE WMSARP DIVING MEDICAL MANAGEMENT PLAN.

**I. Dive Officer makes decision to treat in chamber, gives neurological exam, may call in rescue squad.**

A. If decision is made after working hours, Dive Officer is to contact crew by page.

| | |
|---|---|
| Jack Lotito | (813) 952-4583 |
| Joe Nelson | (813) 952-4370 |

B. Recompress to 60 feet on oxygen as quickly as possible.

1. Treatment on USN Tables 6 or 6A are possible-Dive Officer determines which one.

2. Dive Officer may elect to use extra oxygen.

C. Dive Officer/designee makes notifications after treatment underway.

1. WMSARP Administrative office notified not to answer phone, disconnect answering machine

2. A dive locker phone is to be connected to 9559 outlet for incoming calls to Dive Officer

3. Dive Officer/designee make outgoing calls on 9550, make notification to the following:

| | |
|---|---|
| a. Dr. Kepper | (904) 599-7183 (Voice Page) |
| | (904) 877-5143 Office |
| | (904) 877-3261 Office |
| | (904) 385-9336 Home |

If using page, leave (813) 426-9559 and brief message

<u>OR</u> ALTERNATE MEDICAL OFFICER
Dr. Loewenherz (305) 274-4800 (regular telephone call)

b. Barbara Benton (904) 298-2920 (Page)
Leave 813-426-9559

4. Barbara Benton immediately notifies University Diving Officer at (904) 298-3427.

D. Medical Officer returns call, assumes responsibility for medical management of treatment. May require fax, outside medical help, etc.

E. Transport to Medical Facility at direction of Medical Officer.

1. Ambulance or helicopter preferred, need 100% O2 and mask, any other required medical supplies.

2. Avoid Venice or Port Charlotte ER's unless ordered by Medical Officer.

3. Transport to either Mercy Hospital, Miami, or Shands, Gainesville (Mercy preferred)

4. Dive profile and chamber treatment documents to be either faxed or hand-carried-ask hospital

5. If at all possible accompany the injured diver to the hospital.

F. Medical Officer and Dive Officer must approve return to work.

1. Medical Officer may require examination by physician.

2. Diving may be temporarily suspended if conditions warrant.

G. Dive Officer responsible for documentation-see Items V and VI in Narrative for details.

## ATTACHMENT B

## PHONE NUMBERS FOR WMS CALL SHEET

DAN (916) 684-8111 — Ask for Dr. Richard Moon
Duke University

USNEDU (904) 234-4361 — Ask for Dr. Schwartz H.
Panama City — (904) 234-1841 or
Chief Medical Officer

USAF Hyperbaric Unit (512) 536-3281
USAF School of Aerospace Medicine, Brooks AFB, San Antionio

**EXPERTS**

Decompression sickness
Dr. Eric Kindwall (414) 259-2060 h. (414) 781-5453
Froedert Memorial Lutheran Hospital, Milwaukee

Decompression sickness, recreational diving.
Dr. Alfred A. Bove (215) 221-3346, op. 221-2800 h.
Department of Cardiology, Temple University Health Science Center

Decompression sickness, Navy and recreational
Dr. Tom S. Neuman (619) 294-6643 h. (619) 755-0795
University of California San Diego Medical Center

HBO/Trauma
Dr. Roy A. M. Moyers (301) 528-6152 (or 328-) h. (301) 721-1429
Maryland Institute for Emergency Medical Services Systems

Decompression sickness and everything else (vast experience)
Dr. Christian J. Lambertsen (215) 898-8692 h. (215)
Institute for Environmental Medicine, University of Pennsylvania

# PRELIMINARY REPORT: EFFECTS OF HURRICANE HUGO ON THE BENTHIC CORAL REEF COMMUNITY OF SALT RIVER SUBMARINE CANYON, ST. CROIX, U. S. VIRGIN ISLANDS

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*In February 1989, the National Oceanic and Atmospheric Administration (NOAA) and the National Undersea Research Center of Fairleigh Dickinson University (NURC/FDU) accepted a proposal from the U.S. Virgin Islands Government's Department of Planning and Natural Resources and the University of the Virgin Islands to establish a long term environmental monitoring project to assess the changes in the benthic coral reef community in Salt River Submarine Canyon, St. Croix, U.S. Virgin Islands. The Aquarius Undersea Habitat and saturation diving techniques were utilized at the commencement of this project. Saturation diving allowed the project participants to maximize bottom time for careful site selection, permanently mark study sites, photographically document each quadrat, and collect data to establish a baseline for future monitoring periods in the Salt River Submarine Canyon area.*

*On September 17th and 18th, 1989, Hurricane Hugo, with sustained winds of 140 miles per hour and gusts over 200 miles per hour, hit St. Croix inflicting major damage to the terrestrial portion and causing significant changes to the submerged lands surrounding the island. During the months of November and December of 1989, the permanent quadrats were relocated and photographed, providing data for an initial comparison between the pre and post Hurricane Hugo state of the benthic coral reef community in Salt River Canyon.*

*This paper will address the preliminary data compiled from comparing the photographs taken at the start of the project and again at the first sixth (6) month monitoring interval.*

## INTRODUCTION

With the recent increase in coastal development throughout the Caribbean and the world, scientists, resource managers and government officials realize the need to establish monitoring programs to record baseline data for evaluating changes in coastal and marine resources. Baseline data collection and recording can help in assessing changes that are occurring in near-shore marine communities and whether the changes are the result of natural processes or are a direct result of man's intervention.

In February 1989, the National Oceanic and Atmospheric Administration (NOAA) and the National Undersea Research Center of Fairleigh Dickinson University (NURC-FDU) accepted and funded a proposal from the U.S. Virgin Islands Government's Department of Planning and Natural Resources and the University of the Virgin Islands to establish a long term environmental monitoring project to assess the changes occurring in the benthic coral reef community in Salt River Submarine Canyon, St. Croix, U.S. Virgin Islands.

This project required two saturation missions (89-3 and 89-4C) and involved using the Aquarius Undersea Habitat. The Habitat program is sponsored by NOAA's National Undersea Research Program and is operated by NURC-FDU in St. Croix. By utilizing saturation diving techniques, it was possible for the project participants to maximize daily excursion bottom times from the undersea habitat for careful selection and permanent marking of study sites, photographically documenting each permanent quadrat, and to collect data used in establishing a baseline for future monitoring periods in the Salt River Submarine Canyon area.

Salt River Canyon provides a unique study area. The characteristics of the east slope and west wall are dramatically different. The western wall is steep, often vertical, and has many spur and groove formations which sand is transported to the canyon floor. In several instances, overhangs and caves are present. The first significant groove formation occurs at a point where the wall meets the canyon floor at a depth of 60 ft (20 m). This area is the beginning of station 1. In deeper portions of the canyon, [90-120 ft (30-40 m)], large portions of the wall have broken off and have become part of the canyon fill.

The eastern wall, in contrast, is characterized by alternating zones of near-vertical rock wall and cobble-filled side tributaries, at angles of 15-20 degrees. The innermost 650-800 ft (200-250 m) is of the latter type. Further seaward the wall becomes vertical.

The canyon floor has a gently seaward slope comprised of medium sand to silt (Mz.25 mm). The floor is generally inactive except for the periodic sorting of burrowing organisms, but can become mobile during periods of high wave or current activity.

The lip of the canyon begins at the barrier reef fronting the Salt River estuary. The depth is between 30 and 50 ft (9-15 m) and continues downward to a depth of 12,000 ft (3500 m) where it joins with the Christiansted Canyon. At the lip of the canyon there are scattered *Acropora palmata* stands and head corals (primarily *Diploria* spp.) *Millepora* spp. are also present in this area. The canyon walls are dominated by flattened *Agaricia* spp., *Montastrea annularis* and other corals which are tolerant to lower light levels. Gorgonians and sponges are extremely common. The canyon floor has isolated sea grass (*Halophila decipiens*) and rhizophytic algae that can be found to depths of 100 ft.

## METHODS

Eight permanently marked monitoring stations were established throughout the Salt River Canyon, one at 30 ft (10 m), four at 60 ft (20 m), two at 90 ft (30 m), and 120 ft (40 m ), as shown in Figure 1.

At each station, except station number eight, there were six, ten meter long transects placed along a depth contour. At station eight, there were ten, ten meter long transects placed along a depth contour. Two brass stakes marked the ends of each transect. Holes were drilled into the substrate with an underwater hydraulic drill. Stakes were placed in each hole and cemented into place with underwater epoxy. A number was stamped into the top of each stake for identification purposes. Along each transect, benthic cover was assessed and quantified by using the chain line method Rogers et al., (1983). This type of measurement gives a three dimensional view of the coral reef. It involves placing a small chain along the transect which is used as a scale for the measurement of the percent of benthic cover along each line.

Fifteen 0.5 $m^2$ quadrats were sampled at the 30, 60, and 90 ft stations. At the 120 ft site only 12 quadrats were established, due to time constraints. Two corners of the quadrat were marked by using four inch cut nails pounded into the substrate. Each nail has a numbered tag attached to it with a plastic cable tie. These tags were placed in the upper right and left hand corners to insure exact photographic replication.

An aluminum quadrapod with a quadrat size of approximately 0.5 $m^2$ was used in a frame with a NIKONOS III underwater camera and 15 mm lens with two strobes securely mounted to this frame assembly (Suchanek et al. 1983). The quadrapod was positioned by placing the permanent numbered tags in the upper left and upper right corners of the quadrapod to ensure exact replication.

This monitoring project also included 8mm video recording of each transect line for later analysis, water quality testing, queen conch (*Strombus gigas*) monitoring, and *Acropora cervicornis* growth measurements. This data can be found by writing the National Undersea Research Center and referring to Aquarius missions 89-3 and 898-4C. This paper will only focus on a preliminary analysis of the quadrat measurements.

On September 17th and 18th, 1989, Hurricane Hugo, with sustained winds of 140 miles per hour and gusts over 200 miles per hour, hit St. Croix inflicting severe damage to the terrestrial portion of the island and causing significant changes to subtidal areas. Hugo was a classical Cape Verde hurricane that left a trail of destruction across the Leeward Islands, U.S. Virgin Islands, Puerto Rico, North Carolina and South Carolina (Figure 2 ). The eye of the Hurricane made landfall on the east end of St. Croix at approximately 0230 hours on the 18th of September and exited the West end at approximately 0400 hours. Minimum surface pressures were approximately 940 mb near the center of the storm.

In its path, it left a trail of destruction estimated to be 2 billion dollars for the U.S. Virgin Islands and Puerto Rico. The Federal Emergency Management Agency estimate of money outlay is currently 0.731 billion for the U.S. Virgin Islands and Puerto Rico and is subject to upward revision.

Between May and June of 1989, the first photographs of the quadrats were taken to establish a baseline for the long term monitoring project. Saturation diving was used initially to carry out this task. Between November and December of 1989, a resurvey of the quadrats was accomplished. A direct comparison can be made of the effects of the storm on the coral reef in Salt River Canyon based on pre and post Hurricane Hugo sampling.

The 35mm color photographic slides were analyzed using the random point method. Each slide was projected onto a poster board with a grid background scaled for a one to one reproduction size. This grid was composed of 231 evenly spaced points. The entire frame was analyzed by counting how many points each material component encompassed within the grid boundaries.

## RESULTS

*Living substrate.* The pre- and post- hurricane substrate counts are illustrated in Figures 4, 5 and 6. The significance of each change was tested using the chi-square test and a level of significance of 0.05. When looking at the significance of each substrate as a whole, the amount of significant change was dramatic, however when viewed on an individual scale, the comparison between the different stations was not as dramatic (Table 1). *Diploria clivosa* had a level of significant change overall but only station 4 was shown to be significant (Table 1).

The proportional coverage of the corals was determined by dividing the total numbers of points counted for that coral by the total number of all coral points in all the different stations. *Dichocoenia stokesi* was most affected by the hurricane, its coverage was reduced by 81%. The other coral species common on the reef, *Diploria clivosa, Colpophyllia natans, Porites porites,* and *Porites astreoides* were all reduced in coverage by values ranging from 28% to 14% (Table 2). Overall, the changes to the coral coverage were minor, however, certain stations received more damage and alteration than others (See Table 3 for pre- and post-hurricane substrate counts). Station 3, located on the 60 ft outer East Slope, station 4, located on the 60 ft inner East Slope, and station 6, located on the 90 ft East Slope, showed the most significant change. It was not possible to re-survey the 120 ft station, located on the East Slope, due to the depth and time constraints. A visual observation was made by a NURC-FDU staff member who reported that on the afternoon of the 17th of September, the entire shallow ridge of the East Slope area of the canyon had breaking water. One possible reason why the East Slope stations suffered the most damage was that the East Slope took the direct hit of the waves, thus somewhat reducing the severity of the waves for the West Wall.

The storm tracked from the SE to the NW across St. Croix. Directional shifts were recorded on a S-4 current meter deployed in Salt River Canyon at a depth of 60 ft (20 m). The

**Table 1. Significance of changes in substrate per station by chi-square test. x = significant, o = not significant**

| | Station number | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 8 |
| *Agaricia spp.* | 0 | 0 | x | 0 | x | 0 | 0 |
| *Colcophyllia natans* | 0 | 0 | 0 | - | - | x | x |
| *Dichocoenia strellaris* | 0 | - | - | x | - | - | x |
| *Dichocoenia stokesi* | - | - | - | - | - | - | x |
| *Diploria clivosa* | - | - | - | x | - | 0 | 0 |
| *Diploria labyrinthiformes* | - | 0 | 0 | 0 | - | - | 0 |
| *Diploria strigosa* | 0 | x | 0 | 0 | 0 | 0 | 0 |
| *Montastrea annularis* | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Montastrea cavernosa* | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Mycetophyllia ferox* | 0 | - | 0 | 0 | 0 | 0 | 0 |
| *Porites asteroides* | 0 | 0 | x | 0 | 0 | 0 | 0 |
| *Porites porites* | 0 | 0 | 0 | 0 | 0 | - | 0 |
| *Siderastrea radians* | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Siderastrea siderea* | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sponge spp. | 0 | x | x | 0 | 0 | 0 | x |
| Gorgonian spp. | x | 0 | x | x | 0 | x | x |
| Rubble | - | x | x | x | x | x | - |
| Sand | 0 | x | x | x | x | x | - |
| Bare rock | x | - | - | - | - | - | - |
| DCA | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

DCA = Dead Covered with Algae

**Table 2. Percentage loss of coral species**

| Coral species | Pre-hurricane counts | Post-hurricane counts | % Loss |
|---|---|---|---|
| *Agaricia spp.* | 3312 | 2986 | 10 |
| *Colpophyllia natans* | 249 | 189 | 24 |
| *Dichocoenia stokesi* | 26 | 5 | 81 |
| *Diploria clivosa* | 109 | 78 | 28 |
| *Diploria strigosa* | 644 | 584 | 9 |
| *Montastrea annularis* | 979 | 956 | 2 |
| *Montastrea cavernosa* | 945 | 841 | 11 |
| *Mycetophyllia ferox* | 128 | 113 | 12 |
| *Porites astreoides* | 279 | 240 | 14 |
| *Porites porites* | 111 | 95 | 14 |
| *Siderastrea siderea* | 401 | 380 | 5 |
| *Stephanocoenia michelinii* | 31 | 27 | 13 |

**Table 3. Pre and Post Hurricane Substrate Counts**

| Substrate | Station 1 | 2 | 3 | 4 | 5 | 6 | 8 |
|---|---|---|---|---|---|---|---|
| Agarcia spp. | 824/833 | 599/567 | 158/93 | 149/124 | 1076/893 | 310/300 | 196/176 |
| Colpophyllia natans | 8/6 | 39/34 | 162/149 | -- | -- | 34/- | 6/- |
| Dendrogyra cylindricus | -- | -- | -- | -- | -- | -- | 80/97 |
| Dichocoenia strellaris | -- | 5/7 | -- | 4/1 | -- | -- | -/4 |
| Dichocoenia stokesi | -- | -- | -- | -- | -- | -- | 26/5 |
| Diploria clivosas | -- | -- | -- | 39/5 | -- | 28/23 | -- |
| Diploria labyrinthiformes | -- | 5/5 | 64/56 | 15/17 | -- | -- | 52/62 |
| Diploria strigosa | 100/96 | 45/28 | 225/186 | 123/118 | 38/41 | 60/65 | 53/50 |
| Eusmilia fastigiata | -- | -- | -- | -- | 1/- | -- | -- |
| Meandrina meandrites | -- | 2/2 | 1/2 | -/2 | -- | -- | -- |
| Millepora alcicornis | 9/11 | -- | 3/- | -- | -- | -- | 7/1 |
| Millepora complanata | -- | -- | -- | -- | -- | -- | 4/4 |
| Montastrea annularis | 196/196 | 174/185 | 150/135 | 112/105 | 11/14 | 293/275 | 43/46 |
| Montastrea cavernosa | 122/116 | 25/14 | 178/149 | 250/242 | 9/11 | 217/181 | 144/128 |
| Mycetophyllia ferox | 14/16 | -- | 21/13 | 37/31 | 17/17 | 19/12 | 20/24 |
| Porites astreoides | 25/23 | 14/10 | 82/57 | 72/78 | 5/2 | 64/57 | 17/13 |
| Porites porites | 16/13 | 48/43 | 8/2 | 20/23 | 6/4 | -- | 13/10 |
| Siderastrea radians | 19/14 | 30/32 | 21/22 | 8/8 | 258/264 | 19/20 | 15/16 |
| Siderastrea siderea | 121/118 | 21/27 | 62/51 | 94/91 | 23/23 | 39/28 | 41/42 |
| Stephanocoenia michelinii | -- | 31/27 | -- | -- | -- | -- | -- |
| Tubastrea aurea | -- | -- | 3/- | -- | -- | -- | -- |
| Crinoids | -- | -- | 2/- | -- | -- | -- | -- |
| Sponge spp. | 22/25 | 195/156 | 224/136 | 128/112 | 217/222 | 478/472 | 64/34 |
| Gorgonian spp. | 151/88 | 56/40 | 169/95 | 412/321 | 3/5 | 250/194 | 222/169 |
| Rubble | -- | -/17 | -/396 | -/117 | -/7 | -/56 | -- |
| Sand | 181/161 | 95/34 | 218/278 | 6/20 | 63/134 | 52/96 | -- |
| Bare rock | -/119 | -- | -- | -- | -- | -- | -- |
| Dead Rock Covered with Algae | 1852/1876 | 1724/1837 | 1629/1549 | 1671/1722 | 1558/1643 | 1066/1130 | 2101/2191 |

meter was located near station 1 on the inner West Wall (See Figure 1 for location). After the storm, the current meter was found to have moved laterally 10 ft (3 m) toward the West Wall of the canyon. There was newly exposed substrate along the wall indicating that sand transport and scouring had taken place. The current meter had dropped in level about 3 ft (1 m) indicating how much the floor of the canyon was scoured. Further along the canyon to the north, the depth of scouring had reached twelve (12) ft (4 m) (Taylor and Tragester, 1990).

The sponges and gorgonians were affected significantly by the storm. Sponges decreased by 13 percent and the gorgonians by 28 percent. Stations 2 (West Wall, 60 ft, 3 (East Slope, 60 ft), 4 (East Slope 60 ft), 6 (East Slope, 90 ft), and 8 (West Wall, 30 ft) had higher losses. As discussed earlier, stations 3, 4 and 6 are on the East Slope and that waves were breaking on the East Slope. Station 8 is located on the West Wall in 30 ft depth, therefore, it is conceivable that the wave energy is greater than at a deeper depth.

*Non-living substrates.* The amount of rubble, sand, and dead rock covered with algae was greater in the resurvey. The classification of rubble for this paper is any dead gorgonians, sponges or coral that was placed there after the storm. Sand increased from 615 counts before the storm to 734 counts after the storm. Rubble increased from zero before the storm to 593 counts after for the greatest significant change. Dead rock covered with algae (DCA) increased only slightly from 1852 to 1876 counts (Table 3). These gains were at the direct expense of the living components of the reef. The increase in sand coverage may have been directly related to the fact that so much sand transport occurred in the canyon itself and thus sand settled into the low lying areas. In some areas the canyon floor dropped a maximum of twelve (12) ft (4 m).

The changes in living and non-living substrates types are significant on an overall scale but when viewed station by station, the changes are significant in only certain areas, predominantly on the East Slope. Figures 7 and 8 are photographs taken before and after the storm of the same quadrat. These pictures are from station 3, 60 ft East Slope. Figure 7 was taken June, 1989, notice the large tubular sponge. Figure 8 was taken November, 1989. The large tubular sponge was missing and there was an increase in gorgonian rubble and sand. Figures 9 and 10 are pictures again taken from station 3. Figure 9 was taken June, 1989 and Figure 10 taken November, 1989. When comparing the two, notice the gorgonian rubble and coral rubble present and pieces of *Acropora cervicornis* found in the bottom right of Figure 10. Figures 11 and 12 are taken from station 4, 60 ft inner East Slope. Figure 11 was taken in June, 1989, and Figure 12 taken November, 1989. In Figure 12 the large *Colpophyllia natans* was completely missing from the site and that there was a significant increase in coral and gorgonian rubble.

These pictures are the more dramatic photographs taken. Others show very little change between monitoring intervals, such as an increase in sand settlement on top of the plating corals.

## CONCLUSIONS

This is a preliminary report prepared to describe techniques used in establishing a Long-Term monitoring program using reproducible photographic documentation and initial analysis by comparison of the Salt River Submarine Canyon, in both a Pre and Post Hurricane Hugo state. Follow-up photographs have also been taken for the one year sampling interval and final analysis is planned using computer assisted techniques.

## ACKNOWLEDGEMENTS

Many thanks to Susan Rhoades and Bill Cleveland for their diving assistance. A big thanks to all the staff of the Aquarius underwater habitat for their help and assistance in almost every aspect of this project. Also to Doug Kesling for his moral, as well as technical and logistical support that he gave me throughout the entire project - Thank You.

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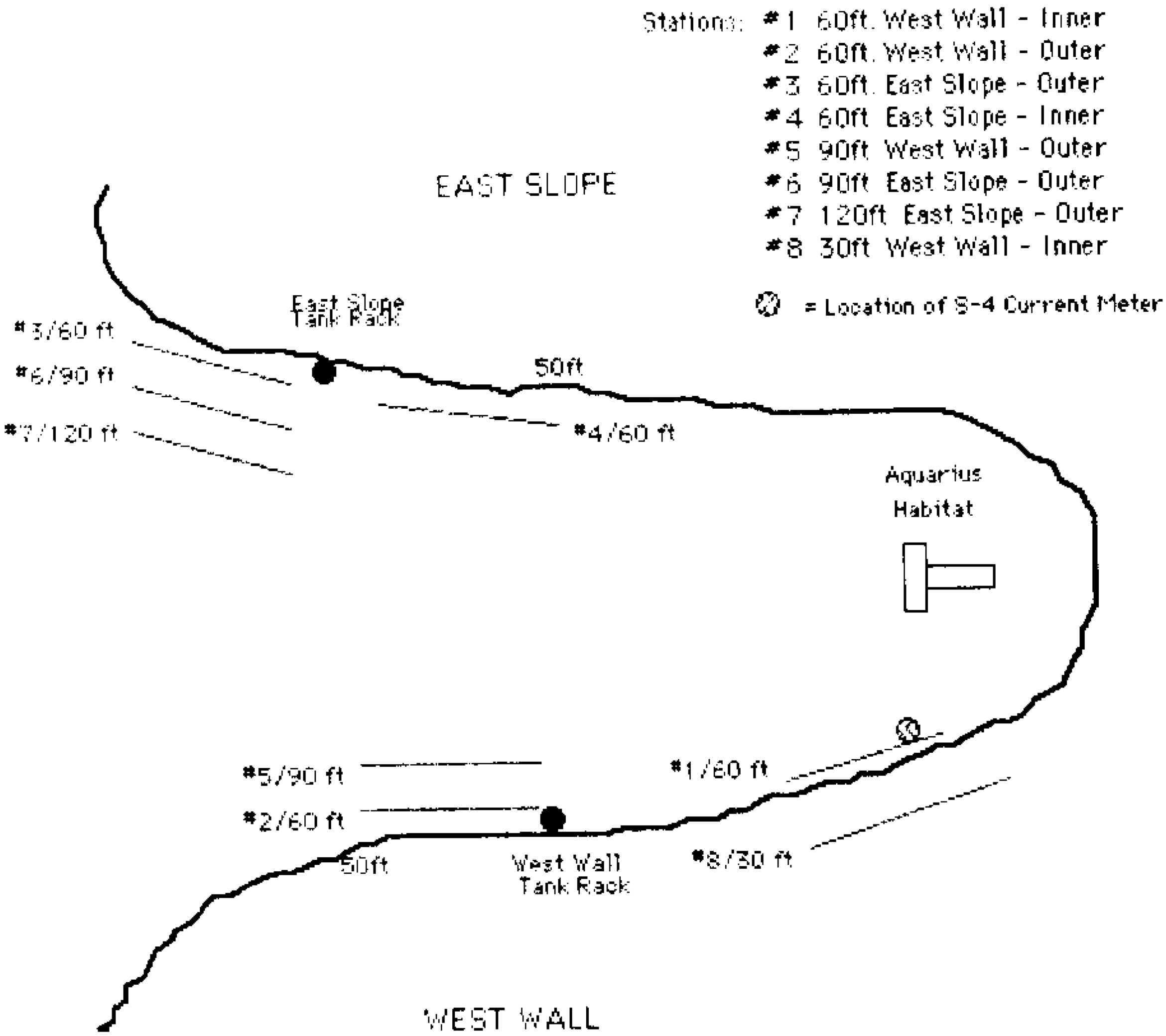


**Figure 1. Location of permanently marked stations 1-8. Salt River Submarine Canyon, St. Croix, U.S.V.I.**

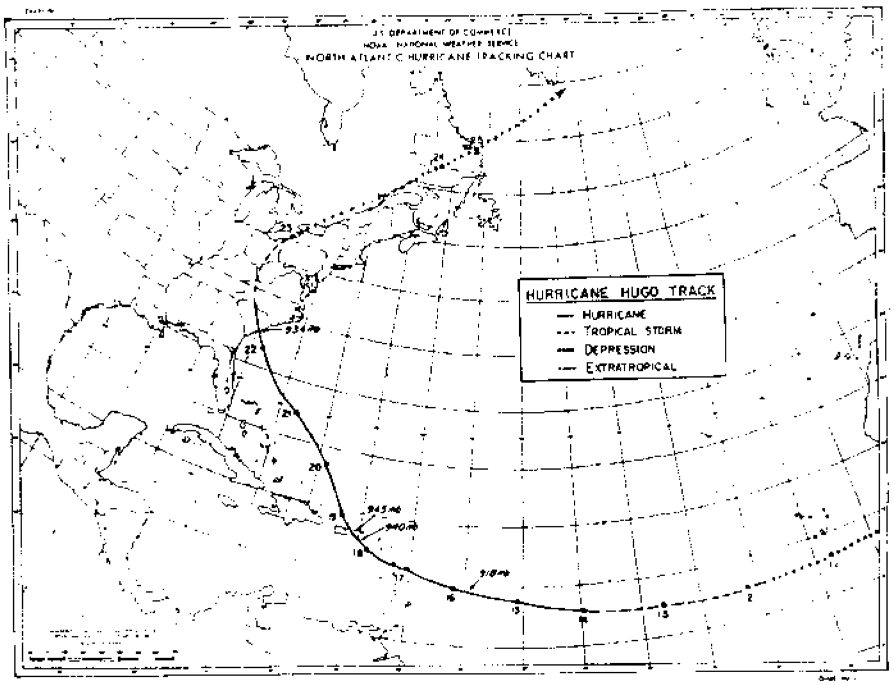


**Figure 2. The path of Hurricane Hugo. Map supplied by the U.S. Department of Commerce NOAA - National Weather Service.**

**Figure 3. Photo credit D. Kesling.**

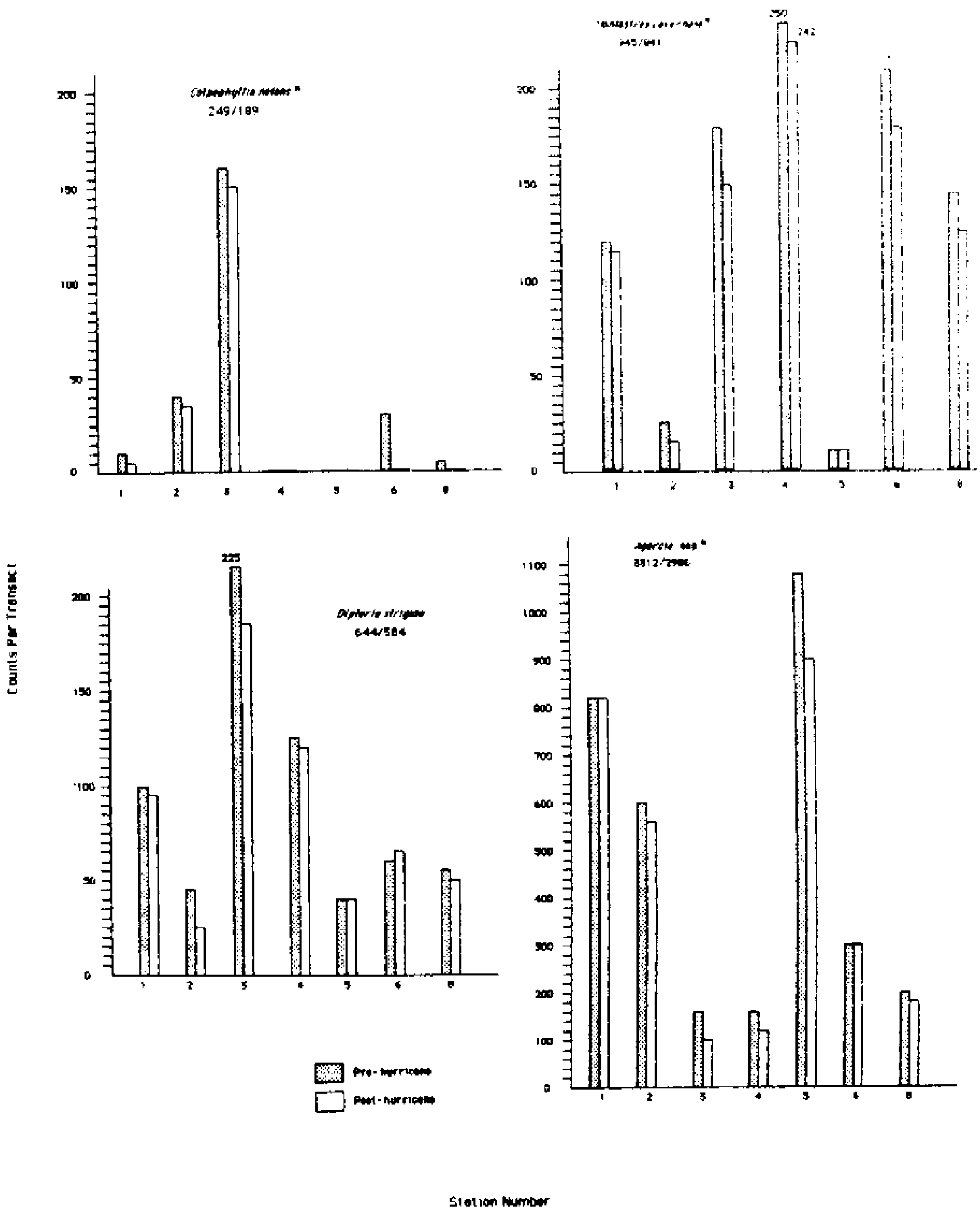


**Figure 4. Histograms of the substrates by counts per stations before and after Hurricane Hugo. The numerator of the fraction on each histogram is the total pre-hurricane counts; the denominator is the total post-hurricane counts for the substrate. An asterisk (*) marks a statistically significant difference (x test, significance level of 0.05) between pre- and post-hurricane counts for each substrate.**

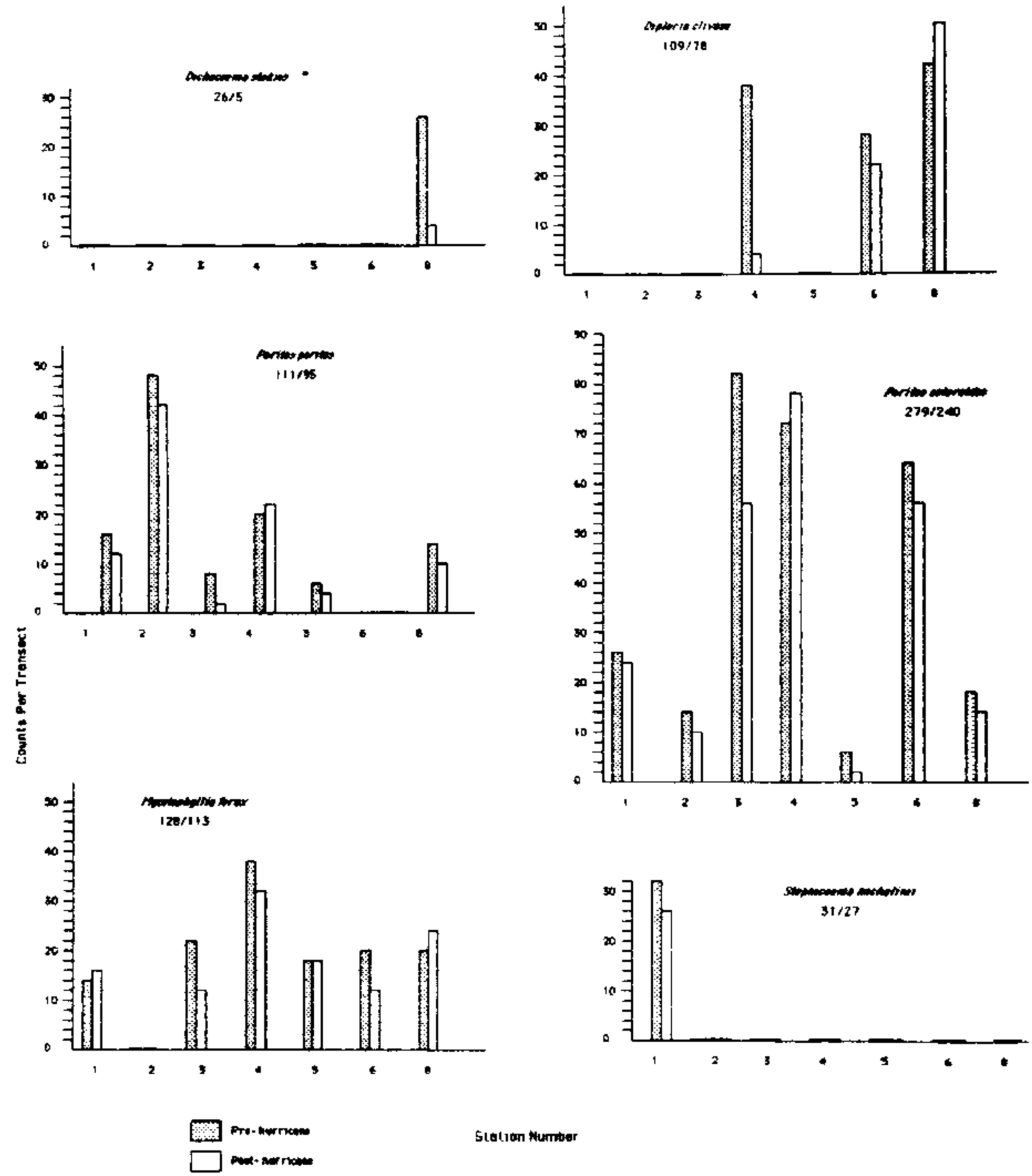


**Figure 5. Histograms of the substrates by counts per stations before and after Hurricane Hugo. The numerator of the fraction on each histogram is the total pre-hurricane counts; the denominator is the total post-hurricane counts for the substrate. An Asterisk (*) marks a statistically significant difference (x test, significance level of 0.05) between pre- and post-hurricane counts for each substrate.**

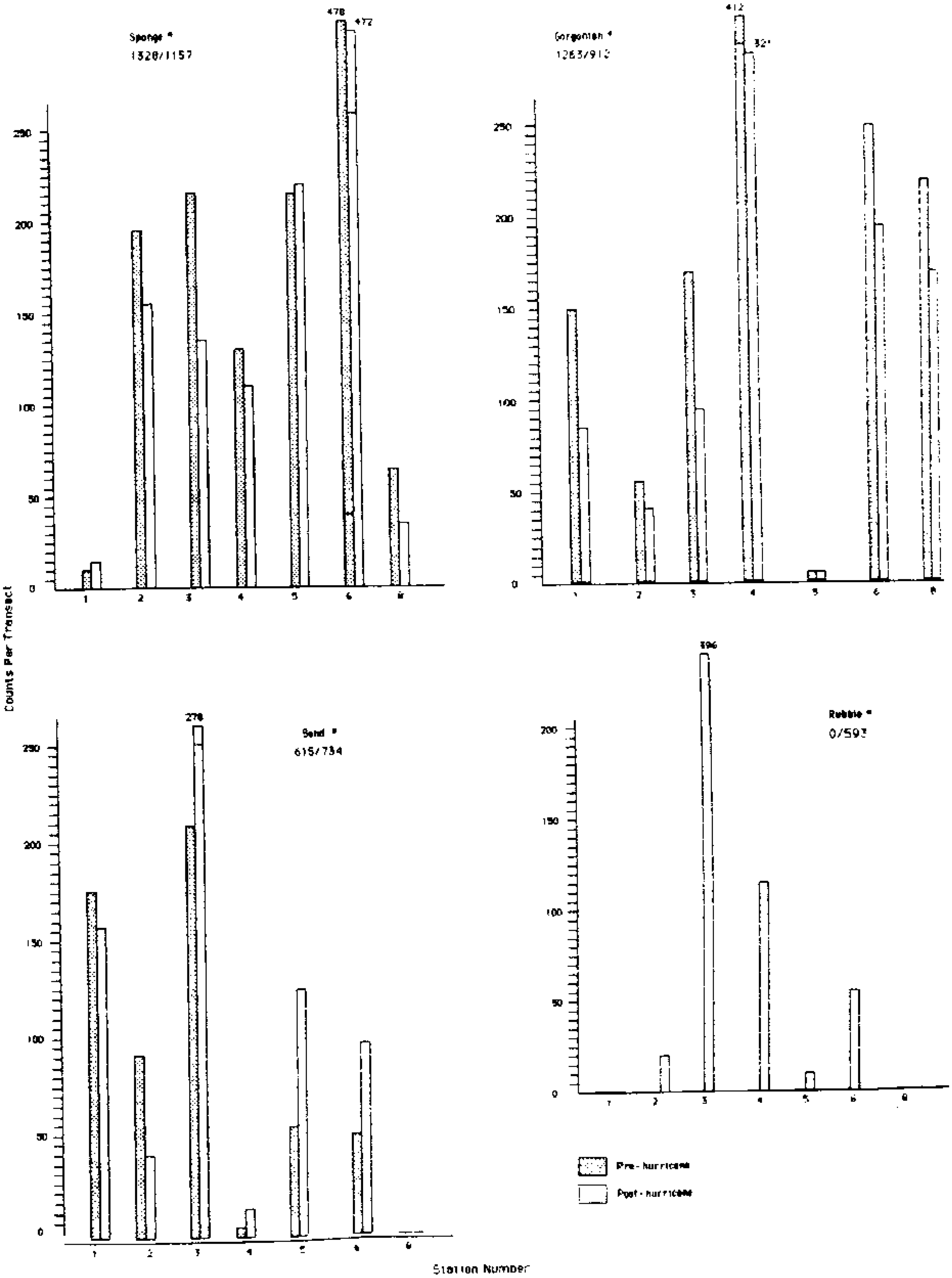


**Figure 6. Histograms of the substrates by counts per stations before and after Hurricane Hugo. The numerator of the fraction on each histogram is the total pre-hurricane counts; the denominator is the total post-hurricane counts for the substrate. An asterisk (*) marks a statistically significant difference (x test, significance level of 0.05) between pre- and post-hurricane counts for each substrate.**

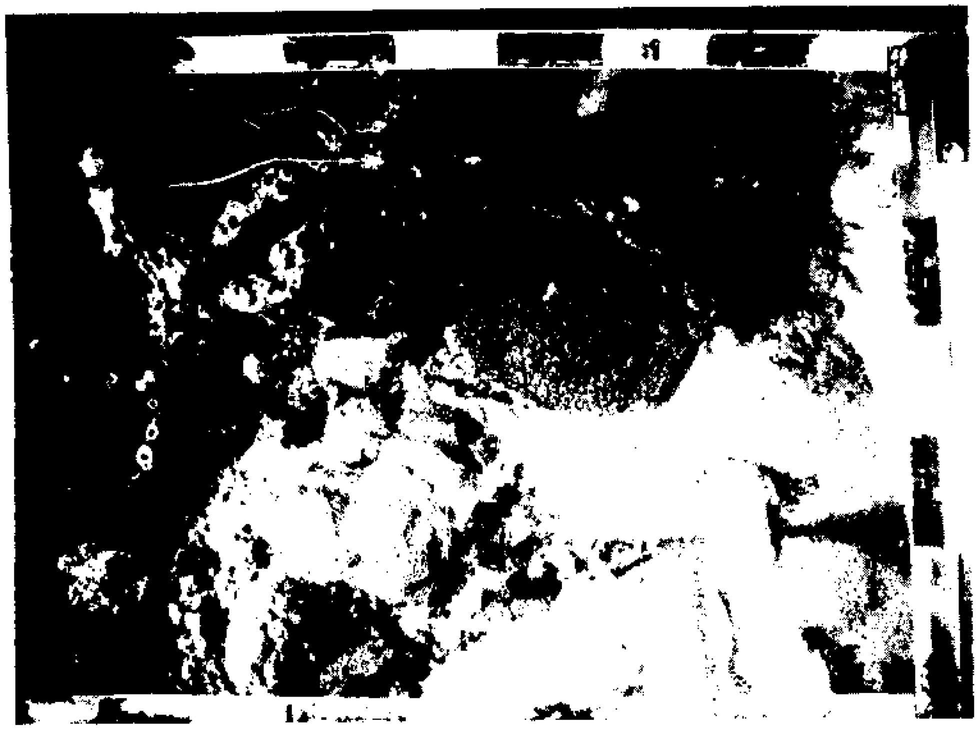

Figure 7.

Figure 8.

**Figure 9.**

**Figure 10.**

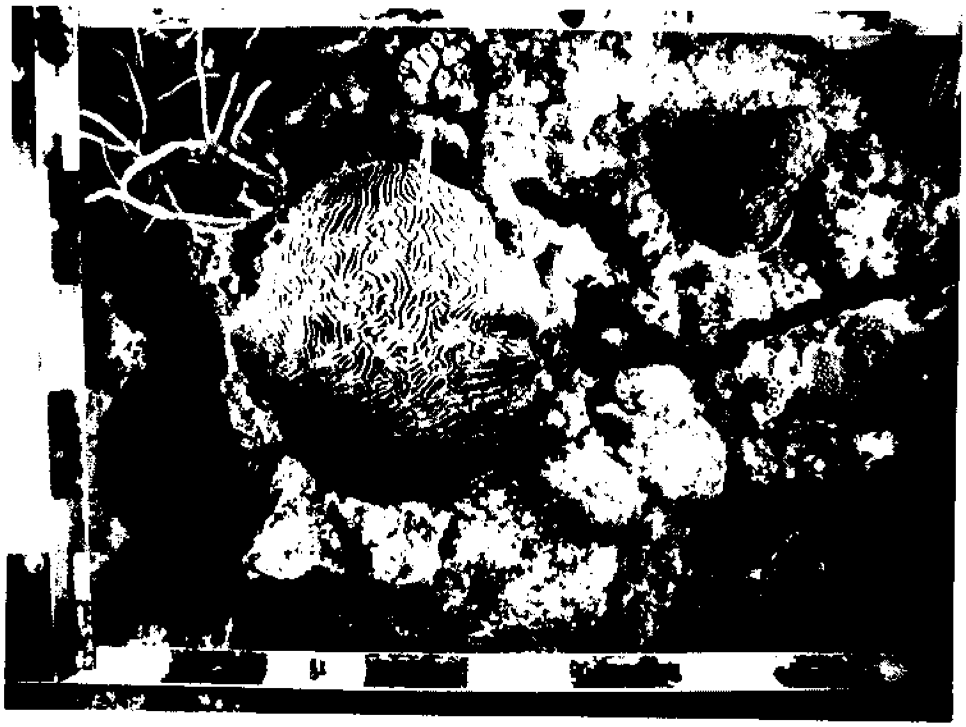

Figure 11.

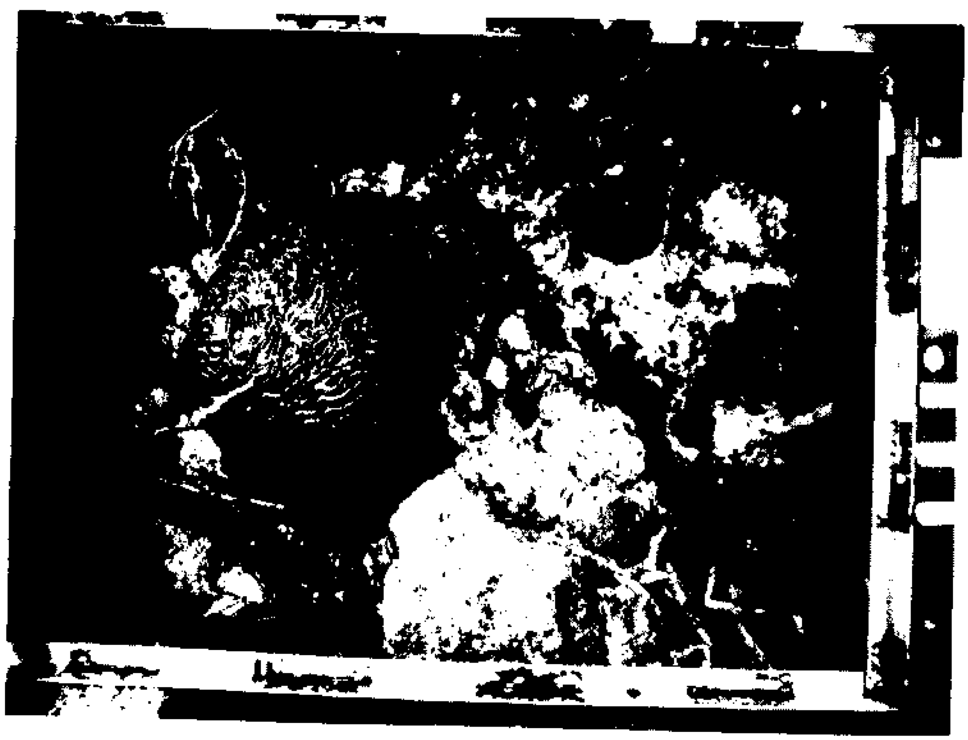

Figure 12.

# QUANTITATIVE TECHNIQUES FOR UNDERWATER VIDEO PHOTOGRAPHY

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*Recent video technology has provided the underwater scientist with a valuable research tool. Video cameras have become more compact, have improved resolution, and work under very low light conditions. Research applications include; measuring water flow near surfaces, sessile benthic and fish surveys, mapping and quadrat photography, monitoring predation, and time lapse studies of organism abundance and activity. A technique for image and motion analysis from video using microcomputers will be introduced.*

## INTRODUCTION

The use of underwater video has greatly expanded the abilities of the diving scientist to collect data. Traditionally the best means of recording events underwater was by using still or complex and bulky movie photography. A compact video camera can be placed in a housing for use underwater, with recording capability up to 120 minutes. The newest cameras have high resolution and work under very low light conditions. Video cameras also can be mounted on ROVs and used in areas not accessible to divers. Many quantitative research techniques employing still photography can be adapted for video systems. Some advantages of video over still or movie photography are; instant results, longer recording times, continuous recording, and excellent stop-frame resolution.

## EQUIPMENT USED

The following is a listing of the equipment used by the authors. Appendix 1 lists some of the underwater video equipment manufacturers (also listed in the 1990 DEMA Directory). The cameras used are Sony 8 mm format video cameras. The CCD-m8 has a fixed focus and comes with a separate playback deck. The CCD-V9 and V99 (Hi8 format) have variable focus with zoom and macro. The V9 features a 6x power zoom lens with f = 12-72 mm, F 1.6 with macro while the V99 features an 8X power zoom lens with f = 11-88 mm, F 1.4 with macro. Both cameras feature on-screen time/date/counter functions. They both have built in play back decks which can produce excellent still frames and forward by single frames. The V99 uses high resolution (Hi8) tapes which have over 400 lines of resolution and a minimum light requirement of 4 lux. The Sony Hi8 recorder deck ( EV-S900) allows single frame advance forward and backward and features digital audio capabilities. The video housings used are manufactured by Ikelite, Hypertech, Aqua Vision and Quest along with underwater video lights by Ikelite, Hypertech, and Subatec.

For scaling, two Metrologic laser lights (Model ML811) in a custom housing can be mounted on the video system (laser dots at 10 mm apart) (Caimi and Tusting 1986). Alternate ways of producing a scale are by suspending a plastic ruler in the field of view, or by following a transect line or a series of quadrats.

Adjustable camera stands can be made by cementing two pieces of metal or PVC pipe into a concrete base. A sliding tray to hold the camera can be made of aluminum angle stock and held onto the pipe by split ring pipe hangers (Witman and Sebens, 1990). If height off the bottom is not critical, the video camera can be secured to a cinder block. For long term time lapse studies, a camera holder consisting of a heavy concrete base and custom mounting brackets is required.

## TECHNIQUES

### MAPPING AND QUADRAT PHOTOGRAPHY

Video enables easy mapping of fairly large areas. By having a scale in the field of view, the investigator can sweep an area with the video camera. The area is instantaneously recorded on video and can be mapped on the surface rather than actually drawing a map of an area while underwater. The tape can be played back and still framed as often as needed to produce an accurate map, although problems of parallax still exist. Using video thus replaces the need to create a photo mosaic using still photography.

For quadrat photography, a quadrat can be placed and recorded on video (the quadrat size will depend on the level of resolution or size and composition of the community to be analyzed). The quadrat can then be moved across the area or along a transect to be analyzed while the video records continuous images. Alternately, a video camera can be mounted on a quadrapod and focused to record a fixed quadrat area (see Witman, 1985 for still camera quadrapod). A great advantage of this method versus 35 mm photography is that the number of photos is not as limiting. This allows for more quadrats to be photographed, increasing the sample size greatly for a given dive. Potential uses of this technique include; percent cover analysis of community structure and competition of encrusting organisms on hard substrates , direct counts of organisms in randomly placed quadrats (Dayton, 1971, 1975; Connell, 1961a, b), and photographs of organisms in permanent quadrats (Connell, 1972).

Percent cover analysis can be performed by freezing a video frame and digitizing (Buss 1980) or by using random dot patterns (still photography: Connell, 1970, Dayton, 1971, Menge, 1976, Lubchenco and Menge, 1978; video technique: Sebens and Johnson, 1990). Alternatively, a single video frame can be grabbed using a computer system and areas of distinct color can be quantified using a program such as 'Image'.

## QUANTITATIVE SURVEYS

Underwater video cameras can be used to conduct two types of surveys to estimate the abundance and distribution of animals and plants living on the sea floor: 1) line transects (Burnham *et al.*, 1980) and 2) random, haphazard or and systematic sampling using quadrats (Pielou, 1974). The primary advantages of videotaping over still photography are that large areas can be sampled quickly and the images can be viewed immediately after the survey, eliminating the potential problem of losing data in the event that film is lost or ruined in processing. The only disadvantage of using video vesus still photography for quantitative surveys is that the resolution of a photograph taken with fine grained film is still higher than a video image, meaning that small organisms (less than 1 cm size) will be difficult to identify in an area $> 0.25\ m^2$.

The procedure of videotaping a line transect is extremely straightforward; a diver simply runs a transect tape across the bottom or attaches it to a permanent position marker in the case of repeated sampling of the same area, and videotapes a swath of a certain width, usually from an aerial perspective to avoid foreshortening and image distortion. It is necessary to keep the camera to subject distance constant throughout the length of the transect to ensure that the same width of bottom along the transect is covered. This can be achieved by any one of the following four methods 1) by swimming at the same distance above the bottom by achieving neutral buoyancy, 2) by attaching a fixed rod to the front of the camera housing, 3) by suspending a plumb bob on a line below the camera, 4) or by using a system of laser dots that converge at the correct distance from the bottom as developed by Harbor Branch Oceanographic Institution for focusing their 80 mm camera (Caimi and Tusting, 1986). Videotaped line transects enabled Edmunds and Witman (1990) to survey large reef tracts rapidly to assess the impact of Hurricane Hugo on coral distribution and abundance. In this application, line transects 1.0 m wide were videotaped with a Sony V99 camera in a Hypertech housing held above and perpendicular to the transect. The percent cover of live and dead corals was estimated for the entire 20 m long transects by identifying corals under 200 randomly placed circles (2 mm diameter) on a transparent acetate sheet placed over a "freeze-framed" video images. Because the actual surveyors transect tape only provides a frame of reference, it is not strictly needed as long as the camera to subject distance is maintained by another method. For example, Witman and Sebens (1989) estimated the abundance of macrobenthic invertebrates at 30 - 70 m depths in the Gulf of Maine by videotaping the bottom from the Johnson Sea-Link submersible. A line transect was not needed because a scale was provided by two laser dots 10 cm apart. In a similar approach using SCUBA divers insead of submersibles, Sebens and Johnson (1990) surveyed coral abundance along 10–50 m depth gradients off the north coast of St. Croix with a Sony V9 camera in an Ikelite underwater housing. They were able to swim at the same distance off the bottom along the entire transect. Replicate images from 10 m depth contours were randomly sampled with the frame counter on the video cassette recorder and analyzed for coral percent cover by the random dot method.

Quadrats can be videotaped as individual replicates for abundance surveys or for monitoring change over time (*e.g.* fixed or permanent quadrats). Excellent reviews of quadrat sampling designs are given in Pielou (1974), Green (1979) and Krebs (1989) and will not be discussed further here. Once the quadrat has been placed on the substratum by the designated sampling design, the diver swims over it to videotape it. A better method is to attach a quadrat frame or "quadrapod" (Witman, 1985, plans in Coyer and Witman, 1990) to the front of the videocamera to maintain exact camera to subject distance. Videotaping permanent quadrats has great potential as a method of detecting the influences of biological and physical factors on benthic community structure but it is not widely used, probably because high resolution video cameras have only recently become available.

## MEASURING WATER FLOW NEAR SURFACE

(1) *Dye Release Methods:* Dye release can be used to track water movement over short periods of time in subtidal habitats, either on a relatively large scale (meters) using wide angle video photography or very close to surfaces (millimeters) using video in macro mode (fluorescein dye is commonly used). Video photography of dye streams has been used to track flow through the prey capturing apparatus of a suspension feeding invertebrate in laboratory flumes (Trager *et al.* 1990). Similar techniques work well in field trials, as long as the video camera in its housing can be stabilized on a solid base that allows the housing to move back and forth to achieve the best focus and framing. One problem with very close-up photography is that the camera housing could affect the flow around the organism or surface under study. Additional focal distance in macro mode can be achieved by adding diopter lenses (e.g. #3 diopter for 35 mm cameras) in front of the video lens and focusing in macro mode. This modification works well for particle tracking also (Sebens and Johnson, 1990).

In addition to flow visualization methods using dye, dye release can also be used to estimate mass transport and the dispersion of particles in a water mass over time (diffusivity) in subtidal habitats. Release of a dye cloud (e.g. from a syringe with tubing attached) at a fixed distance from the substrate, followed by video photography of the dye cloud (preferably from directly above and from the side), allows calculation of movement of the center of mass, rotation and spread of the dye over at least several minutes. Principal components analysis from digitized video images of the dye cloud is used for these calculations. This technique has been tested in rocky subtidal habitats, and computerized methods of analysis have been developed (T. Powell, M. Denny, M. Koehl, pers. comm.). Dye release methods of this type are particularly useful in studies of how larvae or gametes might disperse as they are released or how other neutrally buoyant particles behave in flow.

(2) *Particle Tracking Methods:* Flow near surfaces, such as around the feeding structures of sessile invertebrates, can be measured directly using electronic flow meters and other sophisticated instrumentation in either laboratory or field situations. However, any video camera system with macro photographic capabilities also can be used to both visualize and measure flow non-intrusively on a very small scale. Particles such as naturally occurring (non-motile) plankton, artificial neutrally bouyant spheres, or hydrated *Artemia* (brine shrimp) cysts, can be released upstream of the area under study. As these particles pass through and around the structures of interest, a region can be photographed perpendicular to the main axis of flow, with sufficient distance between the port of the camera housing and the object of study such that flow is not affected by the presence of the housing. Such techniques have been used successfully in laboratory flume studies of crinoid feeding (Leonard *et al.* 1988) and in field studies of particle capture by scleractinian corals (Sebens and Johnson, 1990). In field situations, it is easiest to illuminate the area with a slit of light from an underwater video light. The light beam should be only several millimeters wide where it reaches the surface to be photographed, so that it illuminates only those particles in the focal plane of the camera,those travelling parallel to the major flow axis. If the light is mounted above or below the subject, such that it does not obstruct flow, the beam can be oriented perpendicular to the camera, and thus parallel to the major flow axis and to the focal plane.

Particle movements are analyzed by replaying the tape and using the stop-frame function. A clear acetate sheet can be taped to the video monitor, and colored markers used to mark the positions of particles in focus as the single frames are displayed sequentially, resulting in a 'track' of particle locations over 5-10 frames (1/30 sec between frames). Particle direction and speed in that plane (two dimensional) are then calculated using an appropriate scale in the field of view and the known time between frames. If particles are moving more rapidly than about 20 cm/sec, they appear as streaks on the stop-frame image, and the length of each streak is the distance moved in 1/60 of a second. In field situations, flow is often bidirectional and turbulent. Several minutes of recording, followed by regular or random sampling of flow throughout the recording, are necessary to give an accurate characterization of flow for that time period.

## TIME LAPSE VIDEO

Time lapse video is especially useful for investigating animal behavior and for studying the effects of short-term physical processes (eg. currents, wave surge, storms) on benthic communities. We have been using two systems in our research on the ecology of offshore benthic communities in the Gulf of Maine (Witman and Sebens, 1988), 1) a system developed for the Sony V9 and V99 cameras by Quest Marine Video , and 2) a variable intervolometer designed for the same video cameras by K. Sebens after circuits developed by Mims (1984). The time lapse system is, of course, limited by battery life, power requirements of the camera, duration of the video tape, and the range of time settings built into the intervolometer circuit.

The Quest Marine Video systems feature a molded polycarbonate housing (model 450) with power supplied by 10 and 20 amp hour Nicad batteries. A Micronta™ digital timer (V9) or Sony RM-95 digital controller has been modified to turn the camera on and off up to 7 times daily with the V9 and four times a day with the V99. We have used these cameras as remote stations for both short and long term monitoring of fish predation in coastal and offshore rocky subtidal habitats of the Gulf of Maine (Witman and Sebens, 1990). For long term (*e.g*. months) deployment of video cameras, it is important to consider the potential of pressure to deform plexiglas elements of the camera housing. A wise precaution against this is to ensure that latches closing the back of the housing are equally spaced all around the perimeter of the seal.

The variable intervalometer circuit can be constructed from a Radio Shack™ kit and modified to interrupt the power supply of the camera. We have successfully used a circuit timed for three second recordings at 1 minute intervals with a Sony V9 camera to document rapid predation on tethered invertebrate prey by cod and wolffish in the Gulf of Maine (Witman and Sebens 1990).

## MONITORING PREDATION

Video allows predation to be monitored without the disturbing presence of divers. It also allows predation events to be recorded for longer periods of time than would be possible with SCUBA especially at depth. Prey can be tethered to two 1m length of chain and placed approximately 1.5 m in front of the video camera (Witman and Sebens, 1990). The camera is placed on a camera stand), turned on, and focused on the chain with the tethered prey. The camera is allowed to run for 90 - 120 minutes (tape length or battery time), then retrieved by divers. If a longer interval is required, a second video camera could be placed down to continue the recording or a video with a time lapse circuit could be used. Predator abundance and predation attacks can be counted from the tape. Care must be taken when doing counts to distinguish individuals and to separate them from return visits by the same individual.

## IMAGE AND MOTION ANALYSIS FROM VIDEO USING MICROCOMPUTERS

At the Marine Science Center in Nahant, we are implementing a Biological Image Analysis Center under support from the N.S.F. Instrumentation and Instrument Development Program. Fundamental to this project is the implementation of systems and software which allow the cataloging of video tape data and quantitative analysis of video images using digital image analysis techniques. To interface video equipment to laboratory computers we have utilized the VidClip system developed by Abbate Systems (Norfolk, MA). VidClip implements an interface between the Macintosh serial line interface and the Control-S and Control-L editing controller interfaces of the video decks and camcorders. The Control-S interface is unidirectional and only sends commands from the computer to the video device while the Control-L interface both accepts commands as well as returns status and counter information to the computer, allowing precise interactive control of tape registration. VidClip is available both as a Hypercard interface as well as a library of programming objects.

## INDEXING AND CATALOGING VIDEO TAPE DATA

To keep track of video data we utilize the ClipKeeper™ Hypercard stack which maintains a record of the start and stop times of segments of video tape. Basically, the stack maintains a "card" for each segment of data which supports a comment field as well as choices (buttons) to control the deck and to control searches. To record a clip, the user creates a new card, queues the point of interest on the tape and clicks on a mark button which acquires the counter index over the Control-L interface and enters it into a field on the card, then repeats this for the end of the segment of interest. Once this procedure has been completed, the data segment can be repeatedly played by clicking on a "play" button on the card. Once a tape has been indexed in this fashion a section of data can be retrieved by merely clicking on a button.

## VIDEO TAPE MOTION ANALYSIS SYSTEM

Software support for our video image analysis systems is based on extensions to the *NIH Image* image analysis program developed by Wayne Rasband at NIMH and the VidClip™ Control-L and Control-S serial line interface developed by Mark Abbate (Abbate, Inc., Norton, MA). Our video-based motion analysis system consists of three components (1) A Macintosh II with DataTranslation frame grabber which supports a general purpose color image analysis program (ColorImage). (2). Hi8 video camcorders (Sony V9, V99 and CCD-V5000) and Decks (Sony ECV3, ECV900, SLV757) which are used for the acquisition of both video (motion) and analog (sensor) data and are controlled on a frame by frame basis by the Macintosh II for video motion analysis. Our software platform, ColorImage, (Think Pascal Source Code), developed by J. Ayers and G. Fletcher (Fletcher Applied Sciences, Mason, NH), supports both the standard measurements used in *NIH Image* such as area, mean density, center of gravity, and angle of orientation of a user defined region of interest, as well as segmentation of objects on the basis of color and time-based measurements from sequential video frames. Measurement results can be calibrated and exported directly as spreadsheet files. At present, ColorImage supports the following capabilities from video data.

(1) *Color Image Acquisition*. We have developed color-based extensions to *NIH Image* which allow us to aequire color images from RGB video sources. For laboratory acquisition and macrophotography, we use a RGB Camera (Javelin JE3462RGB, 480 lines Horizontal Resolution) or a Sony ProMavica electronic still video system which supports NTSC to RGB conversion. The various Sony video decks differ in the format of stop frame images making acquisition of stopped-frame images somewhat more difficult. The CCD-V500 generates a true NTSC frame signal in stop frame while all the other decks display only the odd field lines. For this reason it is necessary to interpolate the even field lines. For Example, the Sony EVS-900 Hi8 deck displays only the odd field in stop frame mode, so we have implemented (in ColorImage) a two pass filter which first interpolates the even field lines and then performs a median filter using 3x3 convolutions to restore the full frame.

To digitize color digital images from video, we utilize either a RGB source directly or convert the NTSC (camcorder) data to RGB using the ProMavica or a TrueVision VidI/O box to perform a NTSC to RGB conversion. By connecting the three inputs of the frame grabber to the red, green and blue outputs of the RGB source, we sequentially acquire 8-bit monochrome images by switching between the red, green and blue inputs to generate separate red, green and blue plane files which are then analyzed internally in ColorImage. To generate color files, we perform a 24 bit to 8 bit conversion through a median cut procedure which establishes a color look up table of the 256 most common colors in the image and then generate an 8-bit indexed composite color image.

(2) *Color Image Segmenation.* A set of 8 and 24 bit segmentation algorithms allows us to segment objects (organisms, cells, etc) from the digitized video images on the basis of their color. 8-bit segmentation operates on color look up table (LUT) values and allows us to (1) select ranges of gray-scale or hue, (2) segment out the LUT entries corresponding to pixels in arbitrarily segmented regions or (3) segment 3D ranges of RGB space. The 24 bit algorithm segments region-based objects into color segments at much higher resolution allowing multiple color segments to be separated simultaneously. Using these algorithms we can pick individual organisms or cells out of complex images. For example, orange seastars can be picked out of an image by selecting a range of "orange" pixels resulting in a bitmap of black starfish (or any other blob) on a white background.

(3) *Binary Object Analysis.* An edge tracing algorithm is utilized to trace the outline of the "blob" and convert it to an object. Each object is then quantified in terms of its area, periphery length, x and y coordinates, optical density, principal components, orientation and the computed object parameters are stored in a tab-delimited "spreadsheet" file for later statistical analysis.

(4) *Digital Motion Analysis from Video.* An important function for many of our experiments is to be able to simultaneously and continuously acquire both kinematic and analog sensor data for long periods of time. We now use the CCD-V5000 which supports both high resolution ( >400 horizontal lines) video and stereo digital analog (40-40000 hz) recording. ColorImage supports two modes of moving image acquisition. A stepping movie option opens a window, grabs a video frame, steps the deck to the next frame and repeats this cycle until a movie of the specified number of frames is acquired. In this option, the interframe interval is an integer multiple of the video framing interval (33 msec) or 30 frames/second. The CCD-V5000 is a shutter camera which stores the stopped frame in a digital buffer and therefore provides full frame output in stop mode as well as a time base corrector which provides extremely stable stills and resultant frame grabs at high resolution. In the moving movie option, the program opens the requested number of windows, rewinds the deck, starts it in play mode and grabs frames on-the-fly for the requested number of frames. This option permits time-lapse video digitization of slower phenomena with the inter-frame interval specified as a variable prior to digitization.

**ACKNOWLEDGEMENTS**

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**Appendix 1**

Underwater video and accessory dealers and manufacturers listed in the 1990 DEMA Directory.

Amphibico, Inc.
9563 Cote de Liesse Rd.
Dorval, PQ H9P1A3
Canada

Aqua Video Inc.
5055 NW 159th St.
Miami, FL 33014

Aqua Vision Systems, Inc.
804 Deslauriers St.
Montreal, PQ H4N1X1
Canada

Bennett Marine Video
730 Washington St.
Marina Del Rey, CA 90292

Equinox Underwater Video Housings
10101 Shaver Rd.
Kalamazoo, MI 49015

Helix Camera And Video
310 South Racine Ave.
Chicago, IL 60607

HYPERTECH Inc.
750 East Sample Rd.
Pompano Beach, FL 33064

Ikelite Underwater Systems
50 West 33rd St.
P.O. Box 8100
Indianapolis, IN 46208

Ocean Technology Systems
2610 Croddy Way, Unit H
Santa Ana, CA 92704

Quest Marine Video
505 Calle Sorpreso
San Clemente, CA 92672

Sea & Sea/GMI Photographic
1776 New Highway
P.O. Drawer U
Farmingdale, NY 11735

Signal 3 Corporation
1400 26th St.
Vero Beach, FL 32960

Sony Corporation of America
Sony Drive (MD 1–31)
Park Ridge, NJ 07656

Underwater Kinetics
1020 Linda Vista Drive
San Marcos, CA 92069

UPL, Inc.
P.O. Box 19851
Houston, TX 77224

UR/Pro International
P.O. Box 455
Naperville, IL 60566

# DESCRIPTION OF A LOW-COST, SHALLOW-WATER, SURFACE-SUPPLIED DIVING SYSTEM

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*Research and maintenance diving tasks that are conducted in shallow water, particularly those involving extended periods of time, are cumbersome using SCUBA. Consequently, these tasks are often conducted using gasoline-powered small air compressors. These air sources have several drawbacks which may compromise the health and safety of divers or support personnel. A relatively low-cost ($200-225) alternative surface-supplied system is described that performs as well as gasoline-powered systems, and yet improves the safety of diving operations and is also more reliable and requires much less maintenance. Air is supplied easily and economically from large volume SCUBA cylinders (80-100 $ft^3$). This system should be useful to researchers as well as to persons involved in underwater inspection and maintenance operations, and may be of interest to shallow water fisheries such as sponge and clam industries.*

## INTRODUCTION

Many research and maintenance diving tasks are conducted in shallow water (5-30 ft). These tasks often involve extended periods of time underwater and, because of the depths and bottom time involved, are cumbersome using traditional SCUBA gear. Consequently many divers involved in shallow water surveys, periodic maintenance of experiments, hull cleaning, etc., use small gasoline-powered low-pressure compressors which feed one or two low pressure hoses and second stage demand regulators. This system allows a diver to be relatively unencumbered, but presents other inherent problems.

Paramount are potential health and safety risks to both the diver and the support personnel. The air quality of gasoline- powered "hookah" systems is questionable and unpredictable. Most models simply draw air through a valve in the head of the compressor. Since the compressor is driven by a shaft from the gasoline engine, this places the air intake in close proximity to engine exhaust. Unpredictable wind conditions may cause carbon monoxide, carbon dioxide, and hydrocarbon emissions to enter the compressor. Since these low pressure compressors are oil free, they deliver unfiltered air directly into the low-pressure hose. Other problems associated with the air delivery systems include water vapor and temperature. Because the air is unfiltered, water vapor is also carried into the low-pressure hose in appreciable amounts, and the temperature of the air leaving the compressor may reach 88 °C (190 °F). In addition, engine failure may place a diver at risk, although the use of an in-line reserve tank may help mitigate the temperature, moisture, and engine failure drawbacks. Finally, gasoline used to power the engine is a fire hazard, the noise of the engine running as well as its emissions are a health hazard to the tender, and the engine and compressor require significant maintenance.

An alternative surface-supplied diving system exists that performs as well as the gasoline-powered hookah, and yet improves the safety of diving operations, is more reliable, and requires much less maintenance. In this paper we describe the system, its components and assembly, and provide examples of its use in research diving tasks undertaken by FMRI scientists and technicians.

## MATERIALS AND METHODS

Our system differs from most traditional low-pressure hookah systems in that it provides intermediate pressure air to the second stage, not low pressure air. This eliminates the need to have the second stage modified to accept low-pressure air. The heart of the system is a conventional single hose SCUBA demand regulator complete with a pressure gauge. The first stage mounts on a conventional SCUBA valve which is threaded into a high-volume cylinder, 80-100 $ft^3$, although any compressed air cylinder is acceptable. The second stage is connected to the first stage by 100 ft. of Synflex 3600-06 light weight intermediate pressure hose (working pressure 250 p.s.i.) with an in-line non-return or check valve. This quantity of hose weighs only 10 lb. and floats above the diver's head during diving operations. Based on the equation of Somers (1972) for surface- supplied requirements, this hose is more than adequate for delivering air at shallow depths. In fact if one conservatively assumes that the first stage provides 110 p.s.i., then this type of hose will adequately supply a diver to a depth of 100 ft.

Both ends of the hose are fitted with 3/8" female hose fittings. In order to mate the Synflex hose with the regulator first stage a modified intermediate-pressure hose must be fabricated; this involves removing the female fitting from the distal end of the intermediate-pressure hose and replacing it with a 3/8" male fitting. The check valve is mounted to a surface-supply harness with a fabricated aluminum bracket and plate, and the distal end of the long hose threads into this valve. On the distal end of the check valve a swivel cross is fitted to facilitate the connection of three intermediate pressure hoses, one for the regulator second stage, and two for inflator hoses. The long intermediate pressure hose is connected to the harness by a snap shackle so that strain on the distal fitting is reduced, and all threaded connections are wrapped with Teflon tape (Fig. 1). For depths greater than 15-20 ft a redundant air source is utilized. This consists of a 14 $ft^3$ cylinder and a single hose demand regulator strapped to the diver's harness, with the valve in a position which is easy for the diver to reach. The cost of this surface-supplied system, without the redundant air supply, is one regulator and approximately $200-225. With the bailout bottle the cost is two regulators and approximately $325-350. All equipment necessary to fabricate this system is available from any commercial diving supply firm. Air hose fabrication can be performed by any pneumatic or hydraulic supply firm.

## RESULTS AND DISCUSSION

The surface-supplied system is operated in the following manner: The harness is simply strapped on over the diver's environmental suit as the last piece of equipment donned. In shallow water (less than 15 feet) we do not wear a buoyancy control device because the diver can easily swim to the surface and then ditch the weight belt if the situation arises. The tender assists the diver in dressing, especially if a dry suit is being worn, monitors the diver's air supply and tends the intermediate pressure hose. In depths exceeding 15 feet both a buoyancy compensator and a redundant air supply is worn. We most commonly use the system with 100 $ft^3$ cylinders, and regularly experience bottom times of 3-4 hours on one cylinder. We find great advantage in this system when multiple stations must be dived because a diver can enter and exit the water with ease, greatly reducing fatigue and greatly increasing the efficiency of the diver. As many as 25-30 stations can be sampled in one day by one diver using this system.

Most of the dives using this surface-supplied system have been in association with the hard clam project in the Indian River lagoon and Florida's east coast. We have used it to survey densities of adult clams, and in a variety of field- monitoring and manipulative experiments. A good deal of our research has involved sampling for juvenile clams in the lagoonal substrate. This involves placing a circular aluminum 0.25 $m^2$ quadrat into the substrate and removing the substrate to a depth of 5-10 cm using a venturi-powered suction dredge. The surface- supplied system allows an unencumbered diver to wrestle around with the quadrat and the suction dredge underwater without great difficulty, however experience has demonstrated that it is desirable to be overweighted while suction dredging in shallow water. This same technique has been used by us to survey areas of the Looe Key National Marine Sanctuary reef flat for spiny lobster prey items. It works equally well in both soft-sediments and in seagrass meadows. Other projects at the Florida Marine Research Institute utilize the surface-supplied system to survey seagrass beds, to monitor the progress of restored seagrass habitat, and to inspect and clean fish ponds at the redfish and snook stock enhancement facility in Port Manatee, Florida. In addition, members of DNR's Division of Marine Resource Regulation and Management use the surface-supplied system to survey oyster reefs in Apalachicola Bay.

This system could be utilized by any project which involves long hours of underwater survey or observation work, especially where tasks involve a lot of manipulating of collecting gear or require divers to perform maintenance tasks. It is limited by the length of the intermediate pressure hose to perhaps 30 ft, but is extremely useful in depths of less than 20 ft. Other possible uses for the system would be in commercial fisheries such as clamming or sponging where a great deal of diving is performed in very shallow water, and a large number of operations are currently using gasoline-powered compressors. Additionally, hull cleaning and inspection services will find this a safe and useful alternative to the traditional low-pressure compressors.

Maintenance of this system is no more difficult than maintaining a conventional SCUBA regulator. Freshwater rinses are all that are routinely needed, and the entire system should be overhauled by a certified regulator repair technician at least once a year. With 4 systems currently in operation and over 300 hours of diving to date, we have experienced only one free-flowing second stage and one worn o-ring, in both cases requiring minimal repair. We consider this system to be safe, easy to use, and economical, and recommend it to all scientific diving programs that perform diving tasks similar to those described in this paper.

## ACKNOWLEDGEMENTS

We wish to thank Gregg Stanton of the Florida State Academic Diving Program for supplying the check valve for our prototype system, and the University of South Florida Marine Science machine shop for fabricating the bracket to mount the check valve to the diver's harness.

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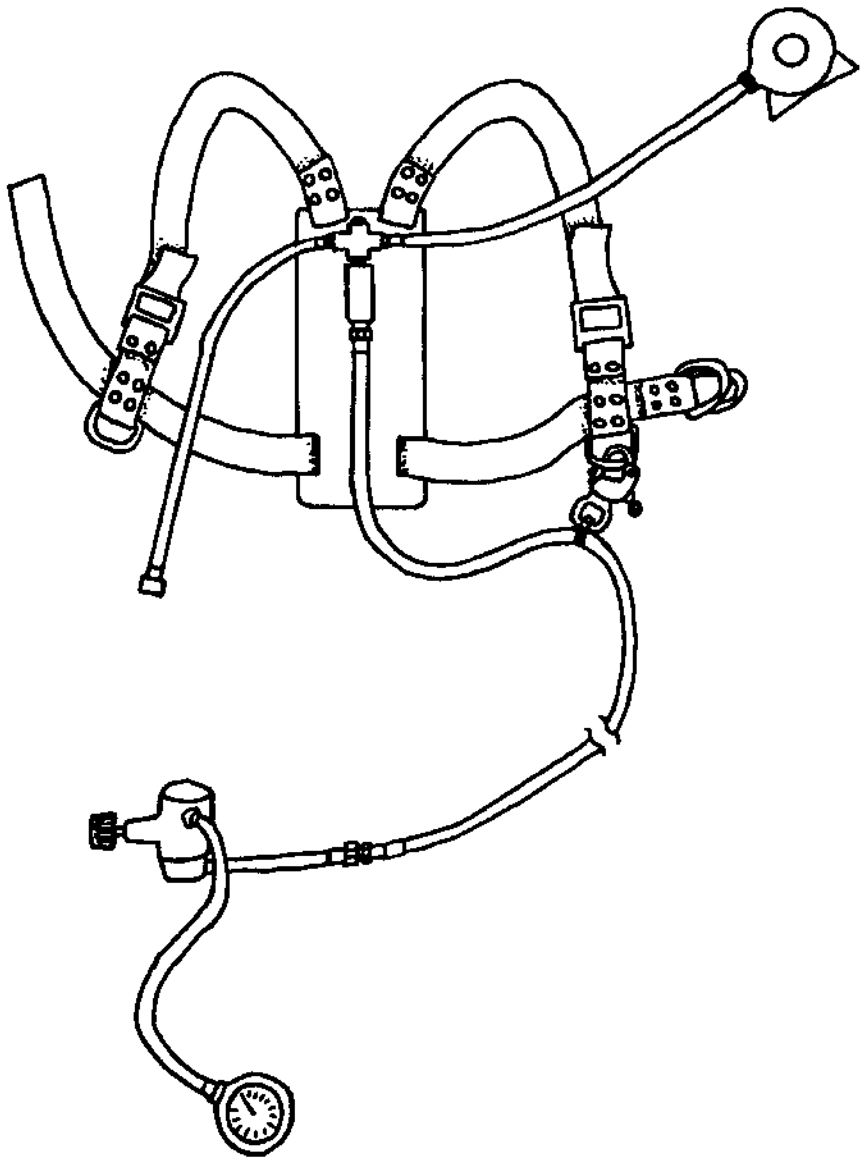

**Figure 1. Schematic of shallow-water surface-supplied diving system.**

# UNDERSTANDING THE PALEOECOLOGY OF FOSSIL VERTEBRATES: CONTRIBUTIONS OF SUBMERGED SITES

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*Recent studies in taphonomy and paleoecology have emphasized the importance of recognizing information loss in making accurate paleoecological reconstructions. This is a major consideration in understanding the ecology of extinct vertebrates, especially when supplemental data is lacking to aid in determining preferred habitat or plants used as food by herbivores. Without this additional information only broad generalizations can be made. Any situation that minimizes or at least reduces this information loss makes a major contribution to our understanding of the autecology of an extinct species and becomes the standard against which interpretations of future discoveries can be compared.*

*Biological material that readily decomposes and normally is absent from the fossil record is commonly preserved in a variety of late Pleistocene and early Holocene deposits. These include dry caves in arid environments, permafrost, asphalt deposits, and peat bogs. The mode of preservation is different in each and includes desiccation, freezing, and anaerobic conditions, all of which can contribute to the preservation of plant remains and invertebrates such as insects along with vertebrates. Because of the unusual conditions required by each of these deposits they are uncommon in many parts of the world and limited in distribution. The invention of SCUBA and the development of underwater excavation techniques have now made accessible additional sites in which anaerobic conditions have preserved botanical and other normally perishable biological materials in addition to vertebrate remains. Warm Mineral Springs, Florida, is such a site. Two extinct Pleistocene species,* Megalonyx jeffersonii *and* Smilodon fatalis *along with associated microvertebrates, invertebrates, macrobotanical remains and pollen, have been recovered. The associated botanical material makes possible a better understanding of the environment inhabited by* Megalonyx. *As more submerged sites are excavated, recovery of additional extinct vertebrates with associated plant remains and other biological materials not normally preserved will provide an expanded understanding of the ecology of many extinct species, and perhaps, in turn, their extinction.*

## INTRODUCTION

No matter how great the diversity of species or number of individuals preserved in a locality, its contribution to our knowledge of earth history, both in paleontology and archaeology is ultimately judged by the quality of the material's preservation. Often in paleontology, a site becomes well known simply because of the high quality or uniqueness of the fossil's preservation. Sheer numbers or diversity of specimens is useless unless the quality of preservation is sufficient to permit identification and study. The better the quality of preservation, the greater the amount of information obtained from the specimens.

In paleontology, those sites that preserve tissues or biota not usually seen in the fossil record are referred to as "Konservatt Lagerstatten" (Seilacher, 1970). These are areas that yield unusual amounts of paleontological information because of the incomplete decay of protein in organic remains. Such sites are represented throughout geological time and include such famous localities as the Burgess Shale in the Cambrian, Mazon Creek in the Pennsylvanian, Solnhofen in the Jurassic, and numerous others. Traditionally the term has been applied only to marine or aquatic sites that contain remains of soft-bodied organisms not usually preserved. Because of the extraordinary quality of preservation, these sites provide more detailed information on the paleoecology of a particular time period or region than is available from contemporaneous sites with less well-preserved specimens. Such rare preservational sites often provide the only evidence indicative of the true biotic diversity of an ancient environment. In a broader sense any site preserving biological diversity approximating that occurring at the time of deposition is a Lagestatte. [Because the term applies only to community reconstructions it cannot be applied to finds of single individuals that are unusually well preserved, although these unique individuals do make major contributions to our understanding of a species.]

Taphonomy is a relatively new subdiscipline of both paleontology and archeology. The transition of organic remains from the biosphere to the lithosphere commonly results in the destruction of all or part of the original organism or community. Loss of soft tissues or species lacking hard parts are common examples. Taphonomic studies aid in the identification of biases and information loss or alteration that occurs during this transition. A revised definition proposed by Behrensmeyer and Kidwell (1985) is that taphonomy is the "study of processes of preservation and how they affect information in the fossil record." In this regard a taphonomic study is not an end unto itself but a tool that permits the recognition and resolution of particular paleoecological problems. As noted in the above definition, one aspect of a taphonomic study is the nature of the material's preservation, whether faunal, floral, or cultural. Knowledge of the environmental conditions that permitted their preservation, including the recognition of the types of material preserved and of those that can be potentially lost in a given environment, can contribute to our understanding of ancient ecosystems.

Biological materials are composed of a wide variety of organic and inorganic molecules and crystals. Because of this diversity of chemical composition, conditions that permit or contribute to the preservation of one kind of substance may be detrimental to the preservation of others. Hence, a certain amount of information is usually lost from a site. "Hard" tissues such as bone and shell are more commonly preserved, while "softer" tissues lacking a mineral constituent, quickly decompose. Bone is a composite material formed by crystals of the mineral hydroxyapatite (hydrated calcium phosphate) in an organic matrix of collagen, but it is its mineral components that contribute to its preservation. Insect chitin in contrast is a polysaccharide formed by chains of sugar molecules. Mollusc shells are formed by crystals of calcium carbonate in the form of aragonite. Wood and pollen have an entirely different composition of carbon compounds such as cellulose and lignin. Where a low pH dissolves shells, pollen is unaffected, but an environment that permits the oxidation of pollen does not affect shells. Animal dung, a prime source for identification of food resource utilization, can contain either plant fibers or bone, depending on the species that produced it. It is a rare site that permits the preservation of all or even a majority of the different biological compounds that can occur in a particular environment.

With regard to Pleistocene and Holocene terrestrial environments, there are a number of different types of localities with the necessary conditions to preserve a wide variety of biological materials. Some reflect specific environmental conditions and are thus restricted in distribution. The dry caves of the southwestern United States are one example of these. Preservation of normally perishable material is possible because of the lack of moisture to support bacterial activity. The permafrost regions of Alaska and Siberia are another such environment. In both cases soft tissues remain preserved only as long as a specific set of environmental conditions exist: aridity in the first example, freezing in the latter. Asphalt deposits such as Rancho La Brea in California are more sporadic in occurrence but are not limited by a specific environmental parameter (aridity or cold), but rather by the distribution of oil deposits that can seep to the surface. Peat deposits reflect a combination of the above in that peat will accumulate only under certain environmental conditions but, like asphalt, can continue to exist after it is formed and continue to preserve the enclosed specimens even after the original surrounding environment changes. In addition to the above types of localities known to preserve a wide variety of biological materials can be added submerged sites with anaerobic conditions, such as Warm Mineral Springs.

## CONDITIONS AFFECTING PRESERVATION

As noted by Behrensmeyer and Kidwell (1985), preservation is strongly affected by predeath circumstances such as habitat: terrestrial vs. aquatic, marine vs. nonmarine, etc. Quality of preservation is therefore determined by a combination of local environmental parameters and those characteristic of the site of preservation. In a terrestrial environment the unique preservational conditions provided by a site such as Warm Mineral Springs will most likely not represent the habitat in which the majority of the preserved flora and fauna lived. In this case transport into the site and related informational biases (Voorhies, 1969a) affecting the paleoecological interpretation must be taken into account just as at any other site.

Each site therefore contains specimens that represent "primary" and "secondary" preservation. Primary preservation refers to specimens initially deposited in the "stabilizing" conditions of the site, whereas in cases of secondary preservation, the specimen has already passed through some stages of decomposition prior to its transport into the stabilizing environment. Recognition of this factor permits a better evaluation of the differences between the environment of preservation and the environment inhabited by the preserved flora and fauna. Depending on the rate of accumulation at the site, the preserved flora and fauna can show temporal changes in local ecology or may only represent a geological instant. The difference between catastrophic vs. attritional accumulations have been considered in other contexts (Voorhies, 1969b).

## QUALITY OF PRESERVATION AND SOURCES OF ECOLOGICAL INFORMATION

Many of the questions regarding the ecology of an extinct species are exactly the same as those investigated in an extant one. A schematic of the types of information that might be determined about the autecology - the study of an individual organism or species - for an extinct species such as the ground sloth, *Megalonyx jeffersonii*, is presented in Figure 1. Some of the information shown also has the potential of providing details regarding the synecology - the study of groups of organisms that are associated together as a group, also known as community ecology. Most paleoecological studies have dealt with the interpretation of communities (Behrensmeyer, 1975; Voorhies, 1969) and are synecological in nature. For the purposes of this paper the emphasis is placed on what can be learned about the ecology of a single species, such as *Megalonyx jeffersonii*.

Although the questions regarding the ecology of an extant and extinct species are the same, the sources for attempting to answer those questions are quite different. Because the ecology of an extinct species cannot be directly observed, it must be inferred. The degree of accuracy of the inference is directly dependent on the information sources, the quality of which in turn is dependent on the quality of their preservation.

Some of the factors that affect preservation and need to be taken into consideration are pH, Eh (dissolved oxygen, which affects oxidation and reduction reactions), temperature, humidity, and chemical environment, such as types of minerals in solution. In an aquatic situation this last factor is in turn dependent on water temperature, pH and Eh.

Before the contributions of submerged sites to our understanding of paleoecology can be evaluated we first need to determine the questions to be asked, types of information needed, and how differences in preservation will affect those information sources. I have roughly divided the primary sources of information for interpreting the paleoecology of an extinct species into five broad categories. Each of these categories could be subdivided and defined on a finer scale but as utilized here generally reflect the influence of a site's preservational factors.

Traditionally the skeleton of the animal has been the primary information source for interpreting its ecology. Analysis of the skeleton in the sense of understanding its functional anatomy or biomechanics still serves as the starting point for any analysis. Information gained from studying the teeth and limbs provide at a gross level some indication of the animal's trophic level, such as whether it's a carnivore or herbivore. Other important basic information potentially derived from the skeleton include age and sex. The skeleton also provides an indication of the species size, an important source of information, because size controls many aspects of a species' ecology (Peters, 1987). Quality of preservation is represented in two ways. The degree of completeness of the skeleton is important. Anything ranging from a single bone to a complete articulated skeleton can be used to identify the animal as a member of the fauna; however, the more parts of the skeleton preserved, the greater the number of details available regarding its functional anatomy and physical characteristics. Bone pathologies, whether due to trauma or disease, also provide insight into the ecology of the animal. There is also the possibility of finding the skeletons of groups of individuals that died simultaneously (Finch, et al., 1972). In this latter situation some details of the social structure of the species can be determined, especially when combined with recognition of age and sex. Another rare situation in which additional ecological information can be gained from the skeleton is the preservation of a pregnant female, thus indicating the number and size of young.

The second aspect of the quality of preservation is that of the bone itself. Besides the gross anatomy of the skeleton, the chemistry of bone can contribute to a refining of our understanding of an extinct species' ecology. Bone is subject to various types of degradation (Hare, 1980), which can result in the destruction of the whole bone or merely loss of amino acids or minerals. Besides leaching prior to preservation, information can be lost during the preservation process itself, because permineralization, which helps preserve bone, also alters the abundance of trace elements. Therefore the environment of preservation must leave the bone unaltered for the purposes of this level of analysis. Recent work on trace element analysis of bone (Parker and Toots, 1980; Toots and Voorhies, 1965) suggests that bone that has not undergone any alteration of its original mineral content can be utilized in reconstructing the paleoecology of an extinct species. Amino acid ratios in the collagen of unaltered bone have been used to determine core body temperature of extinct species (Ho, 1967). Knowledge of body temperature in turn provides insight into aspects of a species' paleoecology affecting its distribution (McNab, 1985). As in the case of preserved soft tissues or dung, unaltered bone only occurs under restricted circumstances such as peat bogs, dry caves, asphalt deposits, and anaerobic water such as that at Warm Mineral Springs.

The second category requires more than just the preservation of the skeleton. Here paleoecological information is derived from the preservation of soft tissues and dung. Soft tissue, such as skin and hair, or other clues to the animal's external appearance can provide important information with regard to the environment in which the species lived. The long hair of the woolly mammoth, *Mammuthus primigenius,* is a classical example. Dung, when associated with a particular species, is an important source of information as to the food resources utilized by that species (Hansen, 1978). Preserved dung may also preserve the remains of parasites (Ringuelet, 1957) or insects (Waage, 1976) and thus reveal other aspects of the species' ecology. Besides dung, preserved plant material useful in identifying plants utilized as food can be preserved as "tooth jam" compacted boluses of vegetation formed when plant material becomes trapped in the fossettes of an herbivore's tooth during chewing (Akersten, *et al.*, 1988).

The third source of information useful in determining the paleoecology of an extinct species consists of the fauna and flora with which it is found. This is a more indirect line of evidence because it utilizes what is known about the ecology of the associated plants and animals to aid in defining the ecological parameters of the species being studied. Many extinct late Pleistocene megafauna are found associated with extant species of plants and animals. The known environmental parameters of living species can then be used to extrapolate environmental parameters of the extinct species. The associated fauna and flora provide two types of information. First, they can aid in identifying the potential direct interaction between the species in question and possible predators, or herbivores that could compete for food resources. In this regard it is to some extent synecological because it also helps define how the species fits into that particular ecological community. Second, although there may be no direct interaction with associated vertebrates, invertebrates, and plants, all of these can provide important information on environmental conditions that existed in the area at the time the animal was alive. Therefore, the wider the variety of biological materials preserved, the greater the amount of information that can be derived from the associated fauna and flora. Recent work by Morgan (1987) has shown that when conditions permit the preservation of insects, some forms, specifically beetles, can make major contributions to our understanding of local paleoenvironments. The role of anoxic conditions in the preservation of proteinaceous materials of invertebrates has been discussed by Allison (1988).

The strength of the degree of association and all the inherent biases that have been observed in recent taphonomic studies of faunas are important considerations in utilizing this information. As with the other sources, the information derived from a single site will not usually be sufficient to completely interpret the species' ecology, but when utilized with information derived from other localities, the combined data can be used to determine patterns characteristic of the species being studied.

The next category for interpreting the paleoecology of an extinct species is the most theoretical in nature and is based on extrapolating patterns seen in modern species to fossil ones. This is commonly utilized in circumstances when the species in question have no close living relatives, such as dinosaurs, or, in the case of the extinct ground sloths, when their closest living relatives, i.e., tree sloths, are quite dissimilar and cannot be used as a modern analog. Rather than actually saying what the animal did, this approach provides a reasonable model of what the animal was capable of doing, based on our knowledge of patterns derived from observing a wide range of living unrelated species. More important, this approach can show what is beyond a reasonable interpretation of the animal's capability and aid in defining the limits by which a reasonable interpretation of its paleoecology can be made. One example is an animal's size. Based on studies of modern species it is known that size is a major factor affecting a species' ecology (Peters, 1987) independent of the species' systematic position. Therefore, if size or body weight can be determined for an extinct species, certain limiting factors such as food requirements, life span, home range size and physiological tolerances associated with size can be inferred.

A final source of ecological information is the geological context in which the remains are preserved. Sediment types, conditions of deposition, and other associated information can provide insight into the surrounding environment. This information has commonly been used in taphonomic studies of sites and has been an area of active research (Behrensmeyer and Kidwell, 1985 and references cited there).

As already mentioned, no single site can possibly provide all the evidence necessary to interpret an extinct species' ecology. Only the combined information from numerous sites can provide the insight into determining many aspects of an extinct species' ecological requirements. Although we may pose many questions regarding the ecology of an extinct species it is necessary to remember that even for many living species, which can be directly observed, many of these questions have yet to be answered.

The quality of interpretation of an extinct species' paleoecology is directly dependent on the availability of the various potential sources of information, and these in turn depend on the quality of their preservation. Differences in the mode of preservation of the variety of fauna and flora associated with the species in question will dictate the quality of information gleaned from each site.

It is beyond the scope of this paper to actually integrate all of the available information regarding *Megalonyx jeffersonii* and provide an outline of the state of knowledge regarding its paleoecology. Rather, the emphasis is to identify the potential contributions that submerged sites with exceptional preservation such as Warm Mineral Springs can make to our understanding of extinct species, and, when possible, utilize *Megalonyx* as an example.

## WARM MINERAL SPRINGS

Warm Mineral Springs is a sinkhole in the Tampa Limestone (Miocene) formed by the collapse of the cavern roof (Rosenau *et al.*, 1977). The Tampa Limestone is not homogeneous but consists of interbedded marine sands, clays, marls and sandy limestone. Differential erosion of these sediments has resulted in ledges and overhangs projecting from the sides of the sinkhole. One prominent ledge at 13 m has accumulated large amounts of organic debris, including vertebrates, invertebrates, floral, and cultural material (Clausen, *et al.*, 1975; Cockrell and Murphy, 1978; Cockrell, 1987, 1988). Maximum constriction of the sinkhole occurs at 30 m and gives it a distinctive hour-glass shape. The floor of the sinkhole is approximately 70 m below ground surface. Extending upward from the bottom of the sinkhole is a debris cone formed by the accumulation of both inorganic and organic sediments. Top of the debris cone is at a depth of about 38 m. Like the 13 m ledge, the debris cone is a major site of accumulation of faunal, floral, and cultural materials. However, because of the vertical distance that separates the two areas, their mode of accumulation is different and they preserve different aspects of the spring's history and that of the surrounding environment.

Water in the spring is primarily derived from the Floridan Aquifer 1,000 m below present land surface and secondarily mixes with cold water springs entering the springs at higher levels (Cockrell, 1986). Initially the water is 33 °C but the later mixing of the water from these sources results in an average water temperature of 30.5 °C at the surface. Water entering the springs at the lowest level is anaerobic and dissolved oxygen is present only in the upper 7 m of the springs. The water is brackish with a chlorinity of $9.05 \pm 2$ parts per thousand. Minerals are commonly precipitated in the form of a calcite *tufa* that encrusts rocks and exposed bones. In addition to the high mineral concentration (Table 1), the water is highly charged with hydrogen sulfide. The high sulfur content contributes to the growth of sulfur bacteria and blue-green filamentous algae in the upper parts of the water column where light penetrates (Tuttle and Molyneaux, no date).

**Table 1. Dissolved Minerals in Water at Warm Mineral Springs. Analysis made by United States Geological Survey in 1972 at discharge point of spring, from Rosenau et al. 1977.**

| | |
|---|---|
| Total Dissolved Solids | 18,000 ppm |
| Chloride | 9,500 mg/l |
| Calcium | 500 mg/l |
| Magnesium | 580 mg/l |
| Sodium | 5,200 mg/l |
| Potassium | 150 mg/l |
| Bicarbonate (HCO3) | 160 mg/l |
| Sulfate (SO4) | 1,700 mg/l |
| Chloride | 9,500 mg/l |
| Fluoride | 1.9 mg/l |
| SiO2 | 16 mg/l |
| Total Calcium Hardness | 3,500 mg/l |
| Alkalinity as CaCO3 | 130 mg/l |
| pH | 7.3 |
| Dissolved Oxygen | 1 mg/l |
| Total Organic Carbon | 3 mg/l |
| Ammonia NH4 as N | .38 mg/l |
| Total Phosphorus | .01 mg/l |
| Strontium | 31,000 micrograms/l |
| Arsenic | 10 micrograms/l |
| Chromium Cr | 66 micrograms/l |
| Copper Cu | 20 micrograms/l |
| Zinc Zn | 20 micrograms/l |
| Iron Fe | 40 micrograms/l |
| Manganese Mn | 20 micrograms/l |

The Floridan Aquifer and water table of peninsular Florida is intimately tied to sea level. Pleistocene sea level was inversely related to glacial growth or decline, with glacial expansion resulting in a lower sea level and glacial melt raising sea level. Although Warm Mineral Springs is currently close to the Florida Gulf Coast, during the Pleistocene it would have been an inland site. However, the porosity of the underlying limestone permits changes in sea level to affect the spring's water level. Research by Brooks (1973) indicates that during glacial maximum Florida would have been more arid than at present with fewer areas of surface water. Hence sinkholes such as Warm Mineral Springs took on a significant role as watering holes for the local fauna and humans. Although this increased emphasis on the springs as a water source would have increased its potential for accumulating vertebrate remains (Haynes, 1985), for the purposes of this paper it is also important to note how changes of the water level in the spring would have affected the preservation of accumulated organic remains. Current estimates place the water level of the spring 30 m lower during glacial maximum. One consequence of the fluctuating water level was a shift in the positions of contact between air and water and between aerobic and anaerobic water within the sinkhole relative to the fossiliferous deposits. Organic remains could accumulate on projecting ledges subaerially and subsequently become submerged by the rising water of the springs, first being submerged in aerobic water and subsequently placed in anerobic conditions. In contrast; the debris cone was never subaerially exposed and has been maintained under relatively constant anaerobic conditions and temperature.

Indications of changes in preservation and evidence of subaerial exposure as opposed to continuous immersion are important factors in the interpretation of the history of the springs and the surrounding environment, especially with regard to the potential destruction of specimens and resulting loss of information. Recognition of the position of the springs' water level and correlation with the areas of accumulation of faunal and floral material at that time provides some indication of the relative degree of aridity to which the plants and animals were subjected. Although this source of information will not be available in all submerged sites, it is another source of information regarding the climatic or environmental conditions that were tolerated by some of the extinct species found in the spring.

The vertebrate fauna so far recovered from the springs proper consists of 48 genera (Table 2), of which only two are extinct. These are Jefferson's Ground Sloth, *Megalonyx jeffersonii*, and the sabertooth cat, *Smilodon fatalis*. The remains of both the ground sloth and sabertooth were found at Feature 30 on the 13 m ledge. Additional remains of both species have been reported from the springs but lack provenance. Land excavations next to the spring have recovered remains of a lama, horse, and proboscidean, none of which have yet been recovered from the springs proper. With regard to preservational aspects of the site only those animals recovered from within the springs will be considered. Emphasis will be placed on the ground sloth, *Megalonyx*, as an example of how submerged sites can contribute toward our understanding of the paleoecology of an extinct species.

Sediments on the 13 m ledge can be divided into three zones. The uppermost zone is recent organic subaqueous muck composed mainly of algae and filamentous sulfur bacteria. Below this layer are bedded organic deposits, formed mostly by leaves and other plant material.

This zone also contains large numbers of small vertebrates and dates from 9 to 11,000 years B.P. The lowest zone of the Pleistocene sediments is composed of clay and decomposed limestone. It is in this lowest zone that the remains of the ground sloth and saber cat are buried (Cockrell and Murphy, 1978). In addition to the bone, pieces of wood are intermixed in the lowest deposit. This lowermost zone is in direct contact with a Miocene clay.

Preservation of the ground sloth and the sabertooth cat suggests that at the time of their deposition the ledge was exposed and dry. Although remains of the two species were recovered in close proximity, differences in preservation suggest that their accumulation on the 13 m ledge represents two separate events.

**Table 2. Warm Mineral Springs Faunal List**

Class Osteichthyes
- Order Siluriformes
  - Family Ictaluridae - Catfish
    - *Ictalurus* cf. *catus* (White Catfish)
    - *Ictalurus* cf. *punctatus* (Channel Catfish)
    - *Ictalurus* sp.
- Order Perciformes
  - Family Centrarchidae - Sunfish
    - cf. *Pomoxis* (Crappie)
    - cf. *Micropterus* (Bass)

Class Amphibia
- Order Anura
  - Family Bufonidae - Toads
    - *Bufo terrestris* (Southern Toad)
  - Family Ranidae - Frogs
    - *Rana catesbieana* (Bullfrog)
    - *Rana* (small species)
- Order Urodela
  - Family Sirenidae - Sirens
    - *Siren* sp. (Siren)

Class Reptilia
- Order Chelonia
  - Family Testudinidae - Pond Turtles and Tortoises
    - *Deirochelys reticularia* (Chicken Turtle)
    - *Chrysemys scripta* (Pond Slider)
  - Family Chelydridae - Snapping Turtles
    - *Cheldyra serpentina* (Snapping Turtle)
  - Family Kinosternidae - Musk and Mud Turtles
    - *Kinosternon* sp. (Mud Turtle)
    - *Sternotherus odoratus* (Musk Turtle)
  - Family Trionychidae - Soft Shelled Turtles

**Table 2 Continued**

*Trionyx ferox* (Florida Softshell Turtle)
Order Squamata
Family Colubridae - Constricting Snakes
*Elaphe* sp. (Rat Snake)
*Nerodia* sp. *(Water Snake)*
*Family Crotalidae - Rattlesnakes*
*Crotalus adamanteus* (Eastern Diamondback Rattlesnake)
*Sistrurus miliarius* (Pigmy Rattlesnake)
Order Crocodilia
Family Crocodylidae - Alligators and Crocodiles
*Alligator mississippiensis* (American Alligator)
Class Aves
Order Pelecaniformes
Family Phalacrocoracidae - Cormorants
*Phalacrocorax auritus* (Double-crested Cormorant)
Order Ciconiiformes
Family Ardeidae - Herons
*Ardea herodias* (Great Blue Heron)
medium size species
Order Falconiformes
Family Accipitridae - Hawks
*Buteo jamaicensis* (Red-tailed Hawk)
Family Falconidae - Falcons
*Polyborus planeus* (Crested Caracara)
Order Galliformes
Family Phasianidae - Pheasants and Bobwhites
*Colinus virginianus* (Northern Bobwhite)
Family Phasianidae
*Meleagris gallopavo* (Turkey)
Order Greiiformes
Family Rallidae - Rails
*Gallinula choropus* (Common moorhen)
Order Strigiformes
Family Tytonidae - Barn Owls
*Tyto alba* (Common Barn Owl)
Order Passeriformes
Family Corvidae - Crows and Jays
*Corvus brachyrhyncos* (American Crow)
Family Icteridae - Black Birds and Grackles
*Quiscalus major* (Boat-tailed Grackle)
Class Mammalia
Order Marsupialia

**Table 2 Continued**

Family Didelphiidae - Opossums
*Didelphis virginiana* (Virginia Opossum)
Order Insectivora
Family Soricidae - Shrews
*Cryptotis parva* (Least Shrew)
Family Talpidae - Moles
*Scalopus aquaticus* (Eastern Mole)
Order Xenarthra
Family Megalonychidae - Medium Sized Ground Sloths
*Megalonyx jeffersonii* (Jefferson's Ground Sloth)
Order Primates
Family Hominidae - Humans
*Homo sapiens* (Modern Man)
Order Lagomorpha
Family Leporidae - Rabbits and hares
*Sylvilagus sp.* (Cottontail)
Order Rodentia
Family Sciuridae - Squirrels
*Sciurus carolinensis* (Eastern Gray Squirrel)
*Glaucomys volans* (Southern Flying Squirrel)
Family Cricetidae - Field Mice and Voles
*Neofiber alleni* (Round-tailed Water Rat)
*Oryzomys palustris* (Marsh Rice Rat)
*Sigmodon hispidus* (Cottonrat)
*Neotoma floridana* (Eastern Woodrat)
*Pitymys pinetorum* (Pine Vole)
Family Geomyidae - Pocket Gophers
*Geomys pinetus* (Southeastern Pocket Gopher)
Order Carnivora
Family Mustelidae - Weasels, Skunks and Otters
*Lutra canadensis* (River Otter)
Family Canidae - Dogs, Foxes and Wolves
*Urocyon cinereoargenteus* (Gray Fox)
*Canis* sp. (wolf size)
Family Procyonidae - Raccoons and Ringtail Cats
*Procyon lotor* (Raccoon)
Family Felidae - Cats
*Felis concolor* (Panther)
*Smilodon fatalis* (Sabertooth Cat)
Order Artiodactyla
Family Cervidae - Deer, Elk and Moose
*Odocoileus virginianus* (White-tailed Deer)

The skeleton of the ground sloth is that of a juvenile or subadult. This age determination is based on the absence of fusion of the epiphyses of the limbs. Although not yet fully excavated, enough has been uncovered to indicate that the skeleton is not fully articulated. For example, both maxillae have separated from the braincase along their sutures. Yet the majority of the skeleton that has been uncovered is in correct relative positions with little to no mixing of anterior and posterior skeletal elements, suggesting there was minimal post-mortem disturbance of the skeleton prior to burial. As the skeleton is that of a juvenile or young adult most of the skeleton is not fully ossified, yet bone preservation is good with little sign of weathering. One indication of post-mortem modification is rodent gnawing on the distal end of a fibula.

The skeletal remains of the sabertooth cat, *Smilodon fatalis*, are of an adult. In contrast to the sloth its bones are scattered. The degree of scatter is not great and is less than a meter in distribution. Whereas it appears that the sloth skeleton is relatively complete, only a handful of *Smilodon* bones have been recovered so far. None of the bones was closely associated or suggestive of being in its original anatomical relationship. The maxilla fragment had been broken from the skull, the edges are weathered and the surface is pitted. The upper canine was found separate from the maxilla. All indications are that the skeleton of the sabertooth cat had lain exposed on the 13 m ledge for a longer length of time than that of the sloth.

Other vertebrate remains are usually recovered as isolated bones, although accumulations representing single individuals are occasionally found. Small bones are easily scattered by scavengers such as opossums or raccoons, both of which are common in deposits on the 13 m ledge and may account for the degree of disarticulation seen. Small bone accumulations could also be the result of accumulations below roosts of raptors such as the barn owl *(Tyto alba)* or red-tailed hawk *(Buteo jamaicensis)*. Isolated larger bones may be the result of partially decomposed carcasses floating onto the ledge. Proper interpretation of the modes of accumulation requires the utilization of many of the taphonomic techniques that have recently been developed before a full understanding of the site is possible.

So far the only vertebrate coprolites recovered that have been identified are alligator. Other smaller coprolites have been recovered but their source has not yet been determined. The presence of a wide size range of coprolites, however, suggests that the spring provides the preservational potential for coprolites or dung of extinct species. Additional excavations, especially in the debris cone, will be needed to confirm this potential.

The invertebrate fauna so far recovered consist of gastropods, both terrestrial and freshwater, and ostracods and freshwater molluscs (W. A. Cockrell, pers. comm.). No comprehensive studies have been done on the ostracods, and the faunal list for the gastropods (Table 3), taken from Clausen, *et al.*, (1975), should be considered as a preliminary one.

Plant material, both macrobotanical and pollen, is preserved in the sediments. Macrobotanical remains include intact bud scales, small twigs, fruit fragments, leaves, seeds, and wood as was noted by Sheldon (1976) and Sheldon and Cameron (1976). The variety of parts preserved reflects the unusual preservational qualities of the site. Only limited work has been done on pollen from the spring. Pollen from the sediments of Zone 2 near Burial 1 were analyzed by King (no date) and so post-date the ground sloth and sabertooth cat. A tentative floral list for the site is provided in Table 4. All of the botanical material studied so far has come from the 13 m ledge.

The sediments on the 13 m ledge preserve a variety of organic remains and represent a long period of deposition. As expected, the species composition of the flora and fauna changes through time and not all of the species preserved in the deposits were contemporaneous with the sloth. In order to gain greater insight into the paleoecology of the sloth it is now necessary to identify plant species in direct association with the sloth on the 13 m ledge.

**Table 3. Fossil Gastropods from Warm Mineral Springs (modified from Clausen, Brooks and Wesolowsky, 1975)**

Order Mesogastropoda
  Family Hydrobiidae
    *Heleobops docima* Thompson
    *Pyrogophorous platyrachis* Thompson
Order Bassommatophora
  Family Planorbidae
    *Planorbella trivolvis intertexta* (Jeffreys)
    (originally listed as *Heliosoma trivolvis*)
    *Physella cubensis* (Pfeiffer)
    (originally listed as *Physa cubense*)

**Table 4. Fossil Plants from Warm Mineral Springs**

P indicates a taxon represented by pollen, M indicates identification of a taxon based on macrobotanical material. Data from Sheldon and Cameron, 1976; Sheldon, 1976; King, n.d. and Clausen et al., 1975.

| | | |
|---|---|---|
| Class Filicineae | | |
| Order Filicales | | |
| Family Polypodiaceae - Fern Family | | |
| *Thelypteris normalis* (shield fern) | | M |
| Class Gymnospermae - Cone Plants | | |
| Order Pinales | | |
| Family Pinaceae - Pine Family | | |
| *Pinus* (pine) | P | |
| *P. elliotii* (Slash Pine) | | M |
| Family Juniperaceae - Juniper Family | | |

**Table 4 Continued**

| | | |
|---|---|---|
| *Juniperus/Taxodium* (cedar/cypress) | P | |
| *Taxodium* (cypress) | | M |
| Class Angiospermae - Seed-pod Plants | | |
| Order Pandanales | | |
| Family Typhaceae - Cat-tail Family | | |
| *Typha* (cattail) | P | M |
| Order Graminales | | |
| Family Gramineae - Grass Family | P | |
| Order Poales | | |
| Family Cyperaceae - Sedge Family | P | |
| Order Arecales | | |
| Family Arecaceae - Palm Family | | |
| Palmatae | P | |
| *Sabal palmetto* (Cabbage Palm) | | M |
| Order Liliales | | |
| Family Liliaceae - Lily Family | P | |
| Order Juglandales | | |
| Family Juglandaceae - Walnut Family | | |
| *Carya* (Hickory) | P | M |
| Order Salicales | | |
| Family Salicaceae - Willow Family | | |
| *Salix* (Willow) | P | M |
| Order Fagales | | |
| Family Corylaceae - Hazel-nut Family | | |
| *Ostrya* / *Carpinus* (Hornbeam) | P | |
| *Corylus* (Hazelnut) | P | M |
| Family Betulaceae - Birch Family | | |
| *Betula* (Birch) | P | M |
| Family Fagaceae - Oak Family | | |
| *Quercus* (Oak) | P | |
| *Q. virginiana* (Live Oak) | | M |
| *Q. laurifolia* (Laurel Oak) | | M |
| Order Urticales | | |
| Family Artocarpaceae - Mulberry Family | | |
| *Morus* (Mulberry) | P | |
| Family Ulmaceae - Elm Family | | |
| Ulmus (Elm) | P | M |
| *Celtis* (Hackberry) | P | |
| Order Chenopodiales | | |
| Family Chenopodiaceae - Goosefoot Family | P | |
| Family Phytolaccaceae - Pokeweed Family | | |

**Table 4 Continued**

| | | |
|---|---|---|
| *Phytocacca rigida* (Pokeweed) | | M |
| Order Papaverales | | |
| Family Papaveraceae - Poppy Family | P | |
| Family Cruciferae - Mustard Family | P | |
| Order Rosales | | |
| Family Hydrangeaceae - Hydrangea Family | | |
| *Philadelphus* (Syringa) | P | |
| Family Altingiaceae - Sweet-gum Family | | |
| *Liquidambar* - Sweet-gum | P | |
| Order Sapindales | | |
| Family Spondiaceae - Sumac Family | | |
| *Rhus* (Sumac) | P | |
| Family Aquifoliaceae - Holly Family | | |
| *Ilex* (Holly) | P | |
| Order Rhamnales | | |
| Family Frangulaceae - Buckthorn Family | | |
| *Rhamnus* (Buckthorn) | P | |
| Family Vitaceae - Grape Family | | |
| *Ampelopsis arborea* (Pepper-Vine) | | M |
| Order Malvales | | |
| Family Tiliaceae - Linden Family | | |
| *Tilia* (Basswood) | P | |
| Order Hypericales | | |
| Family Hypericaceae - St. John's Wort Family | | |
| *Hypericum* (St. John's Worts) | P | |
| Family Violaceae - Violet Family | | |
| *Viola* (Violets) | P | |
| Order Myricales | | |
| Family Myricaceae - Myrtle Family | | |
| *Myrica* (Myrtle) | P | M |
| Order Ammiales | | |
| Family Nyssaceae - Dogwood Family | | |
| *Nyssa* (Gum) | P | |
| Family Umbelliferae - Carrot Family | P | |
| Order Ebenales | | |
| Family Ebenaceae - Ebony Family | | |
| *Diospyros* (Persimmons) | P | |
| Order Oleales | | |
| Family Oleaceae - Olive Family | | |
| *Fraxinus* (Ash) | P | M |
| Order Asclepiadales | | |
| Family Asclepiadaceae - Milkweed Family | | |

**Table 4 Continued**

| | |
|---|---|
| *Lyonia mariana* | P |
| Order Polemoniales | |
| Family Borraginaceae - Borage Family | P |
| Order Carduales | |
| Family Ambrosiaceae - Ragweed Family | |
| *Ambrosia* type (Ragweed) | P |
| Family Carduaceae - Thistle Family | |
| *Artemisia* (Sagebrush) | P |

As can be seen, submerged sites with anaerobic conditions such as Warm Mineral Springs have the potential of providing the variety of information needed to provide much of the basic information required to interpret the ecology of an extinct species. The preservation of unaltered bone permits analysis of the skeleton at both the gross and chemical level. Additional information is provided by the associated fauna, both vertebrate and invertebrate. Interpretation of the local vegetation is possible by utilizing both macrobotanical specimens and pollen, while the sediment types provide details of additional parameters. A comprehensive understanding of the site will require the utilization of standard techniques as well as new technology from many disciplines. The wide range of preserved biological materials demands an interdisciplinary approach, and only by utilizing such an approach will a fuller and more realistic understanding of ancient environments be achieved.

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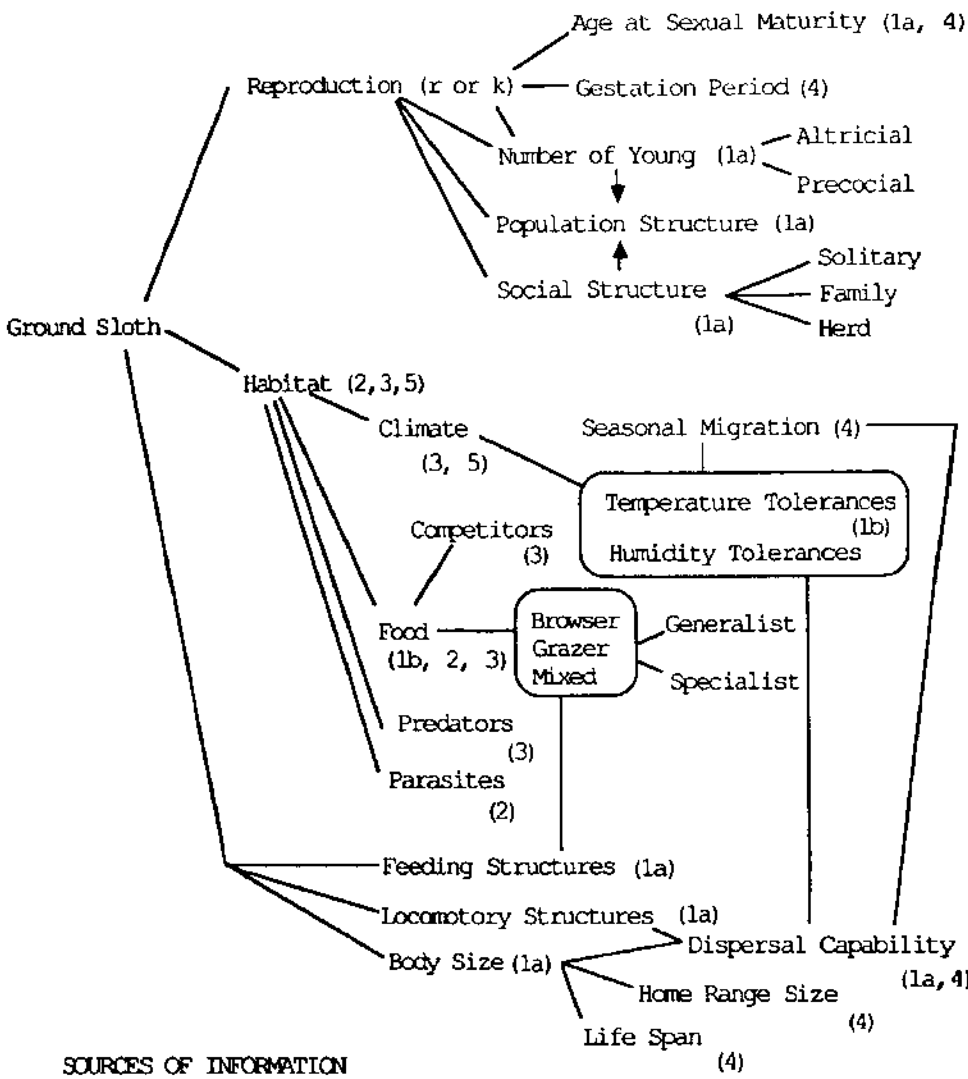


SOURCES OF INFORMATION

1a. SKELETON gross anatomy
1b. SKELETON biochemical
2. PRESERVED SOFT TISSUES, DUNG
3. ASSOCIATED FAUNA/FLORA
4. INFERRED FROM MODERN ANALOG
5. GEOLOGICAL CONTEXT

**Figure 1. Areas of interest regarding the ecology of an extinct species and potential sources of information.**

# DIVING IN SUPPORT OF AN UNDERWATER ACOUSTIC INVESTIGATION IN A VERY SHALLOW WATER, NEARSHORE ENVIRONMENT

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*An underwater acoustic experiment was conducted from the La Jolla pier at The Scripps Institution of Oceanography, The University of California at San Diego. The objective was to study environmental characteristics affecting sonar performance in very shallow water. Ambient noise and acoustic backscatter data were collected using a set of three transducers mounted on a 7 ft tripod assembly weighing 500 lb in water. The assembly was positioned 100 ft north of the pier at a depth of 20 ft. Divers were an integral part of this experiment throughout. Divers' tasks included the deployment, maintenance, and recovery of the tripod assembly, and the placement of targets (glass and fluid-filled spheres) at various locations. An Orcatron wireless underwater communications unit was utilized during certain portions of the diving operations.*

## INTRODUCTION

Applied Research Laboratories (ARL:UT) is an organized research unit of The University of Texas at Austin which conducts basic and applied research and development in the areas of underwater acoustics, electromagnetics, and computer engineering. The major emphasis is on underwater acoustics. The laboratory has supported a research dive team for 25 accident free years. The dive team provides support for various underwater acoustic experiments and maintains the in-house acoustic test tanks and the testing facility at Lake Travis. On occasion the dive team provides diving support for experiments at remote sites. This paper describes the participation of the dive team in an acoustic experiment and also discusses the problems associated with diving in nearshore shallow water environments.

## EXPERIMENTAL DESIGN

The objective of this experiment was to study sonar performance in a very shallow water environment with an emphasis on the collection of ambient noise and backscatter data. The experiment was conducted during the month of July from the pier of Scripps Institution of Oceanography, La Jolla, California (Figure 1). The pier is 1200 ft long and rises 37 ft above the water surface, and is oriented roughly east-west. The surface support electronics were housed in portable buildings 220 ft from the end of the pier. The experiment equipment to be positioned on the bottom consisted of a steel tripod with leveling adjustments on each leg, and a remotely operated rotation canister with an attached transducer assembly positioned on top of the tripod. The mounting unit for the rotation canister was designed to allow the rotation canister and transducer assembly to be rotated 90°, from vertical to horizontal. The transducer assembly consisted of a receiving array, covering the band from 20 to 600 kHz, a circular projector for frequencies of 150-600 kHz, and a rectangular projector for frequencies up to 80 kHz. The tripod and attached electronics weighed approximately 500 lb in water, stood 7 ft tall, and measured 6 ft across at the base. The tripod assembly was cabled to a receiver unit housed in the portable buildings on the pier via coaxial cables encased in air-filled Tygon tubing. Acoustic targets were three 10 in. glass spheres separately encased in a 5/16 in. nylon mesh monofilament cast net, and two 6 in. fluid-filled metal spheres. Each glass sphere was approximately 10 lb positive in water and each metal sphere was 3 lb negative. Targets were placed 120 to 300 ft from the transducer assembly.

## EQUIPMENT DEPLOYMENT

The study site was selected in order to meet specifications for this experiment. An area that was relatively level, smooth, and free of debris, roughly 20 ft deep and located 100 ft from the pier on the north side was selected. The water conditions at the study site varied during the month long experiment. The visibility ranged from 3 to 30 ft and the water temperature ranged from 15.2 to 22.2°C. A 2-3 ft swell was persistent throughout most of the month and little to no longshore current was present.

Once the area was chosen, a swim line was positioned along the bottom from the pier pilings to the deployment site. Divers entered and exited the water from a stairwell positioned at the north side of the pier near the overhead bridge crane. The line was then anchored with a 4 ft auger and marked with a buoy. The tripod assembly was deployed over the side of the pier by the bridge crane and set on the bottom. To facilitate this operation a set of variable buoyancy canisters were attached to the top of the transducer assembly. With these canisters in place the tripod assembly was only 25 lb negative in water. Due to the design of the experiment it was necessary to deploy the equipment with the instrument cables attached. The use of the Tygon tubing made the cable almost neutral so it did not add significantly to the weight of the tripod, though it did add to the handling problems, mainly due to the increase in drag.

Once the tripod was on the bottom it was disconnected from the crane and moved into position. This was accomplished by two divers lifting the tripod and carrying it approximately 200 ft to the buoy marker. Another diver was tasked to shepherd the instrument cable as the tripod was being moved into position. Orientation and alignment of the tripod was done by compass. Once in position the flotation was removed and returned to the pier.

The configuration of the transducer assembly created a large sail area so at this point it was necessary to place additional weight on the tripod to stabilize the assembly and to reduce its movement due to surge and breaking waves. Approximately 600 lb of 2 in. thick steel plate cut into six triangular pieces were moved from the pier via a 1000 lb lift bag and placed at the base of the tripod inside its framework. The tripod was then leveled using the leveling device incorporated on each tripod leg. Level indication was provided by a bull's eye level indicator located at the middle of the rotation canister housing.

Divers then proceeded to anchor the instrument cable along the bottom. A 700 lb steel block was positioned 30 ft out from the pier and between this block and the tripod, 4 ft lengths of 1 in. steel rigging chain were wrapped around the instrument cable every 8 ft. From the steel block to the top of the pier, where the instrument cable reel was positioned, a 1/8 in. stainless steel cable was run out. The instrument cable was secured to the steel cable from the steel block to the pier railing with nylon cable ties.

The operation of the transducers and rotation canister were tested top-side, and then the acoustic target field was put into position.

Two additional swim lines were positioned from the tripod, one extending out 300 ft toward the shore and the second placed 150 ft out from the tripod to the north. Each line was anchored at the end with a 3 ft auger. Two of the glass spheres were placed at the end of each line and the third one was placed 120 ft from the tripod on the line pointing shoreward. The two metal spheres were hung 1 ft below the glass spheres attached at the end of each swim line. The sphere assemblies were moored to the bottom, via a 140 lb test monofilament nylon line, to two 3 ft augers and a 10 lb lead weight. The monofilament cast net and line were used because of their acoustic transparency, and the monofilament had enough strength to survive undamaged throughout the environmental conditions experienced throught the experiment. All targets and the tripod were marked by a small fishing float at the surface via a length of monofilament line.

Deployment of the equipment and placement of the target field was completed in three days, including a one day delay for poor weather conditions. Eight dives were required. Removal of the equipment was done in reverse order and took only one day. In all, 28 dives were performed in 14 days in support of this experiment.

## DIVER SUPPORT/ADDITIONAL OBSERVATIONS

Some tasks performed in support of the experiment included, but were not limited to, daily inspection of the tripod and target field, removal of biofouling material (e.g., kelp, barnacles, trash), reorientation of the transducer assembly from the vertical to the horizontal position and back again, and numerous repositionings of the acoustic targets. Divers also did extensive underwater photodocumentation and made many bottom sand ripple measurements in and around the experiment site.

On several occasions divers used a wireless underwater communications device made by Orcatron Manufacturing, Ltd., of Vancouver, Canada. The "Scubaphone" proved to be a valuable tool when surface personnel and divers in the water needed a realtime form of communication. Divers were tasked to make depth measurements and bottom observations over the entire area where the tripod and target field were located (290° around the tripod and 320 ft out). Divers used a swim line and swam arcs of increasing radius out from the base of the tripod. Every 30 ft or so, or when an irregular feature was discovered (e.g., scour marks, rocks, dense vegetation), the divers informed surface personnel of the type of feature found and the depth. A small fishing float was then deployed to the surface where its position was accurately measured by two Theodolites located on the pier. In this manner a very detailed bathymetric map, including bottom features, was produced. The communications system did have one limitation. Divers discovered that the broadband noise produced by the surf and biologics in the area of the pier had a tendency to activate the system's automatic gain control, thus making it difficult to use the scubaphone any closer than 35 ft from the pier.

Several minor problems encountered during the course of diving operations provided insights into the special requirements for diving in shallow-water, high-energy environments.

In areas of strong surge, such as the breaker zone, divers need to work as closely to the bottom as is possible and should align themselves parallel to the direction of the surge. This technique worked well in our diving operations, but the fine sand suspended in the water in this area was found to decrease visibility and infiltrate the diving equipment. The Scubapro A.I.R. II™ power inflater/safe second, used as an alternative air source by ARL:UT divers was found to be sensitive to this sand. The regulators had a tendency to free flow when fine sand got in and around the diaphragm, and though the free flow condition was occasionally bothersome, it did not negate the use of the A.I.R. II™.

Additionally because of the nature of surge, tending to move divers very rapidly in the direction of the surge, divers had to be careful not to place themselves in a position where the surge could impinge them upon objects such as the transducer assembly.

Finally, we found it useful to confer with personnel familiar with the experimental site, gathering as much information as we could on the environmental conditions of the area and obtaining suggestions on operational techniques. We found that these conversations contributed to the success of the ARL:UT dive operation.

**ACKNOWLEDGEMENTS**

Many thanks to Dr. Nick Chotiros, Robert Altenburg, and Rob Stewart for providing great surface support and in being so receptive to the divers' input. Much credit is due the divers of Applied Research Laboratories and Scripps Institution of Oceanography for doing such an exemplary job.

Thanks also to Jim Stewart, Diving Officer at Scripps Institution of Oceanography, for all his support, expertise, and much appreciated words of encouragement.

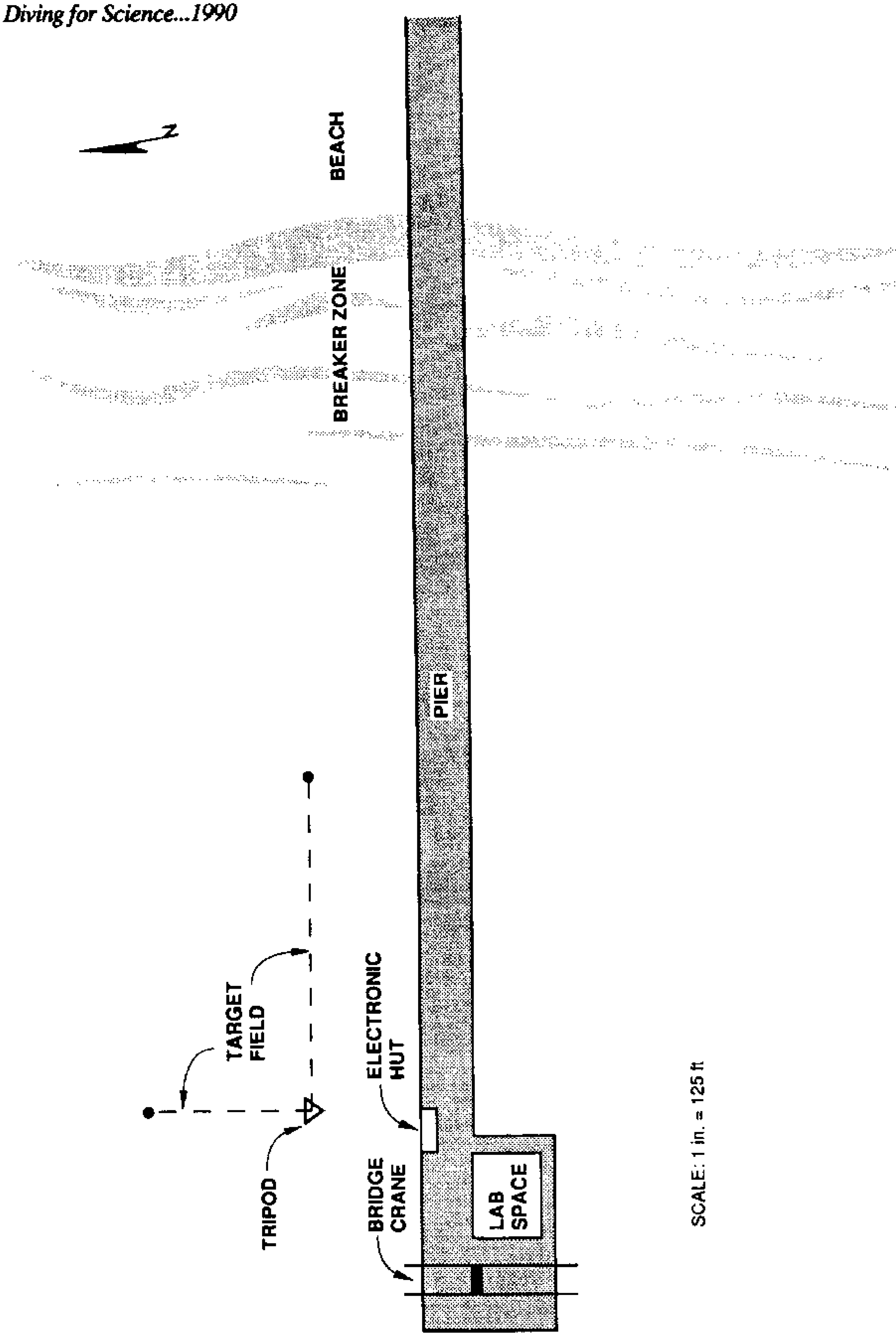


**Figure 1. The Pier at Scripps Institution of Oceanography.**

# A PRACTICAL AND EFFECTIVE MOORING FOR CURRENT METERS IN SHALLOW-WATER, HIGH CURRENT SPEED LOCATIONS

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*An easily-constructed and inexpensive design for a current meter mooring for use in shallow-water, high current speed locations is described. The system has been used successfully in tidal channels for over three years and appears to be a practical and effective alternative in studies where strong current speeds would incline a taut-line mooring with a subsurface float. The mooring consists of a concrete base with four "outriggers" for stability, a vertical aluminum "upright" of desired height, and a delrin-steel ball swivel that allows the current meter to rotate with the current. It is easily assembled underwater by divers and relatively light in weight to permit installation and recovery by small boat.*

## INTRODUCTION

Approximately four years ago the physical oceanography program at Harbor Branch Oceanographic Institution (HBOI) received a grant from NOAA to investigate water circulation patterns in and around Looe Key National Marine Sanctuary in the Florida Keys. Part of the research involved collecting current data from channels between islands north of the sanctuary. These channels have characteristically strong tidal currents of approximately two knots during maximum floods and ebbs. Attaching a current meter to a taut-line mooring would not have been appropriate since strong currents tend to incline the mooring such that sampling occurs at various depths depending on the strength of the current.

The problem was to design a rigid mooring to secure a current meter at mid depth in a relatively shallow (4-7m), high-velocity tidal channel. The mooring design that solved the problem consists basically of a concrete block with four outriggers for stability and a vertical post of desired height with a swivel at the top that allows the current meter to rotate with the current (Fig. 1).

## MATERIALS AND CONSTRUCTION

One of the considerations in designing the mooring was availability of materials. The final design called for materials available at HBOI or nearby hardware stores to facilitate construction. Concrete, polyvinylchloride (PVC), and aluminum pipe were used as foundation materials, while stainless steel and delrin were used in the swivel assembly. The total cost of one stand, including labor and materials was roughly $250.00.

The most complicated portion of the stand is the swivel assembly (Figure 1 inset). Manufacturing the swivel requires a competent machinist but is not difficult. It has two main parts: an aluminum pipe and a stainless steel pivot arm. The pivot arm is secured in the pipe using two special delrin bushings. The top bushing has a spherical depression around its center hole which receives a stainless steel ball welded to the pivot arm. The steel ball and delrin bushing serve as the low-friction pivot for the arm. A second delrin bushing 10 inches below the first reduces side loading. The vertical part of the pivot arm extending through this bushing is kept in place with a cotter pin inserted into the arm through a service hole in the aluminum pipe. The opposite end of the stainless steel arm extends upward and away from the aluminum pipe at about a 20° angle from horizontal. The distal end of the arm is bent into a hook for attaching the current meter.

Construction of the base and outriggers was also simple. A square-shaped wooden form was made into which concrete was poured for the base. Holes were provided in each of the four sides of the form such that 15 inch lengths of 2 inch inside diameter, 40 gauge PVC pipe could be inserted before pouring the concrete. The four pipes would function as sockets into which the aluminum outriggers could be inserted. After pouring, a fifth PVC pipe was placed vertically into the concrete which would serve as a socket for the aluminum pipe (or upright) holding the swivel assembly. The outriggers were made by placing the ends of four 6 foot lengths of 10 gauge aluminum pipe into individual disposable paper paint buckets filled with concrete. The inside diameter of the PVC sockets was only slightly larger than the outside diameter of the outriggers' aluminum pipe and that of the swivel assembly's aluminum upright to ensure a snug fit. The outriggers and aluminum upright were then secured to the base by inserting PVC pins through holes drilled in the PVC sockets and aluminum pipes. The pins were locked in place with plastic tie wraps.

The mooring has several desirable features. Firstly, the outrigger concept greatly improves stability and reduces the needed size of the central block. Secondly, the mooring is very portable since individual pieces are light weight. It can be easily deployed and recovered using a small boat. Thirdly, it can be assembled underwater by divers in less than five minutes (the PVC pins speed up assembly time significantly). Lastly, the cost of materials and labor was very reasonable when compared to off-the-shelf moorings available through hydrographic instrumentation manufacturers.

The design has shown good durability. Some of the moorings have been in the field continuously for over three years yet the swivel assemblies still work like new. Also, experience has shown that the moorings are appropriate for high wave energy study sites as well as the high velocity locations for which they were designed.

## CONCLUSION

In conclusion, a unique hydrographic mooring has been developed for use in high current velocity study sites. It is easily assembled underwater by divers, relatively light in weight for portability, and inexpensive to manufacture.

## ACKNOWLEDGEMENTS

I thank Dr. Ned Smith and Chris Tietze for their role in designing the mooring. Thanks also to Tony Wilson and Tom Smoyer for the graphics and photography, respectively. Special thanks to machinist Mike Hyde. The work was supported by NOAA Cooperative Agreement No. NA86AA-H-CZ071.

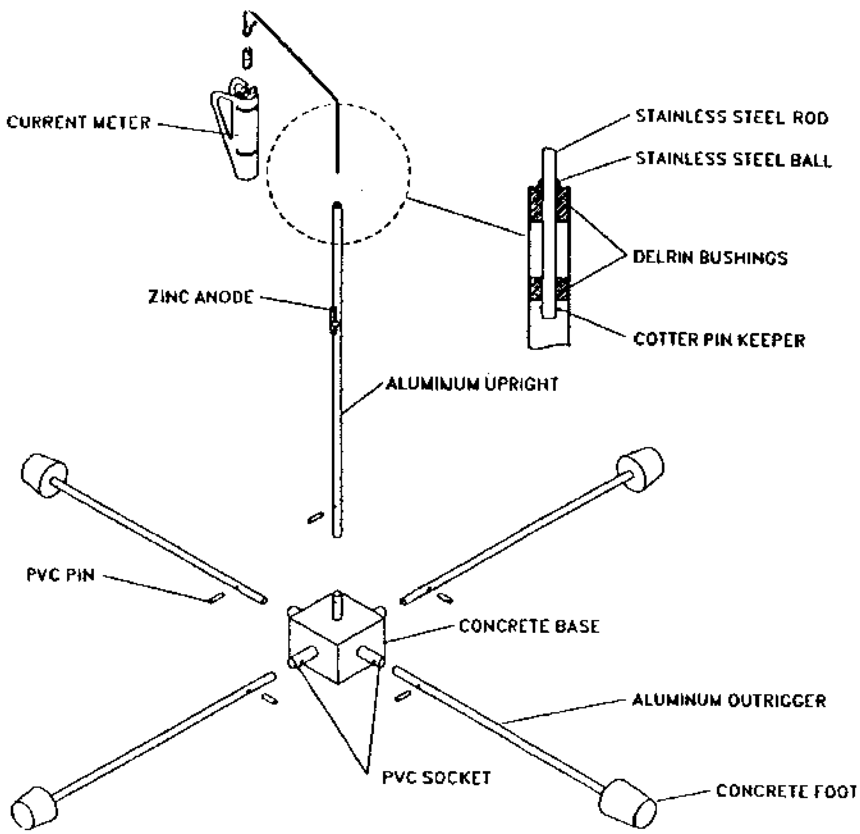


**Figure 1. Exploded view of mooring design. Magnification of swivel assembly is shown at upper right.**

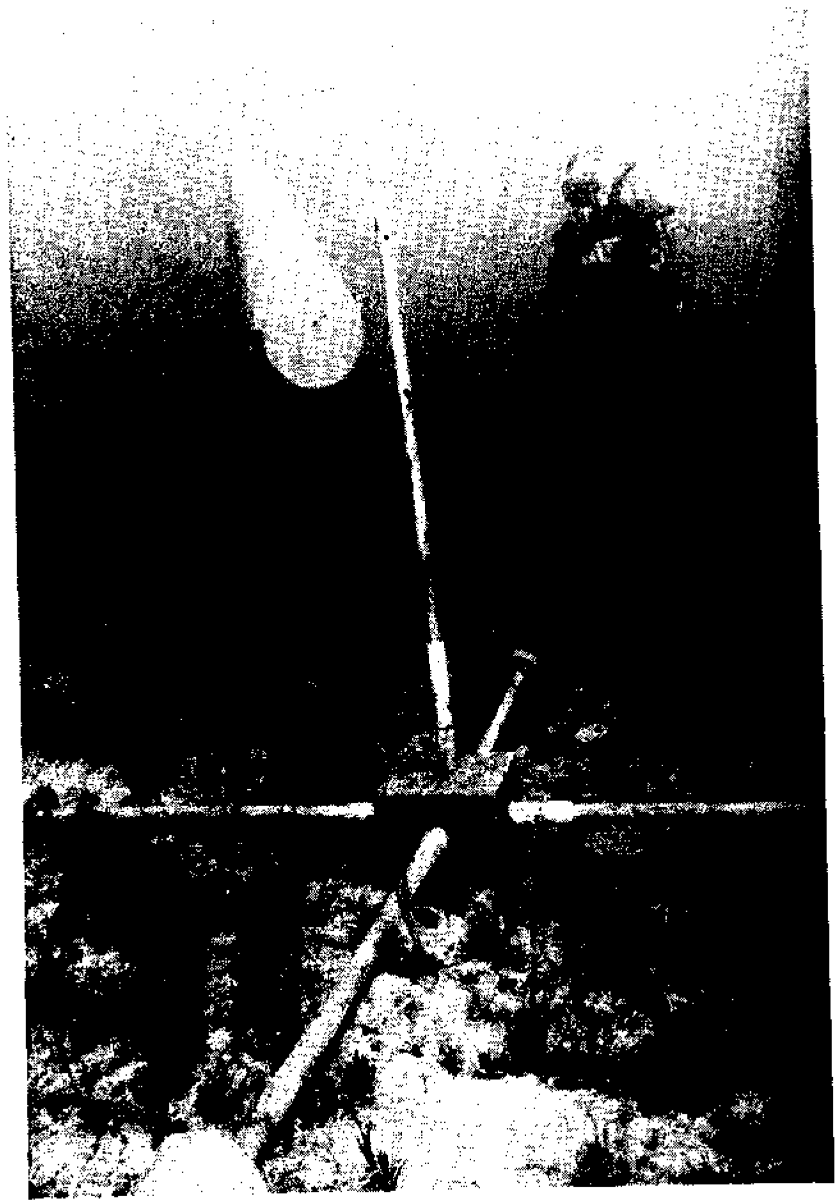

**Figure 2. Photograph shows mooring in use in Adderley Cut, a tidal channel in the Exuma Cays, Bahamas.**

# ARE DIVERS DESTROYING THE GREAT BARRIER REEF'S COD HOLE?

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*The Cod Hole is one of the best known dive sites on the Great Barrier Reef. It harbors an assemblage of up to 16 potato cod (*Epinephelus tukulas*), each weighing up to 100kg. The cod are exceptionally tame and eagerly wait to be fed scraps by recreational divers.*

*In the last four years the number of divers has increased dramatically. Although the area is part of the Great Barrier Reef Marine Park, there is no restriction on the number of boats, divers or the activities of divers. Divers commonly attempt to touch the cod and hold their tails for a ride.*

*During the black marlin season game boats entertain their clients on slow days by dangling a tail roped tuna from the back of the boat. The cods fight for the bait as the crew tug the rope. In the process the fish inflict wounds on each other. The cod who gets the bait incurs additional mouth and body damage in the resulting tug of war. The wounds commonly leave scars.*

*To reduce anchor damage on the corals from increased boat usage, moorings were installed. Concrete mooring anchors further diminish the beauty of this wilderness area.*

## LOCATION

16,000 km from the east coast of the US lies Australia's Great Barrier Reef. The reef stretches 1,700 km from the Tropic of Capricorn (23°S) to the Torres Strait north of Australia (11°S) and lies between 10 and 100 km off the mainland. The reefs are accessible only by boat or from reef fringed offshore islands.

Australia is almost the size of the United States, but has a population of only 17 million people (US 240 million) - approximately five people per square mile. The northern most city on the east coast of Australia is Cairns with a population of 60,000 people. It provides the easiest access to the Great Barrier Reef.

In 1984, the Cairns international airport was improved to accept flights from Japan and the US. Tourism took off. Many of the tourists were divers interested in seeing the Great Barrier Reef. The number of dive boats regularly visiting the reef out of Cairns increased from 4 to 11. Larger, faster boats carrying up to 28 divers were constructed to take people to reefs ever more distant from Cairns.

## DISCOVERY

The Cod Hole (14°40'S, 145°40'E) was discovered in July 1973, by the famous dive couple Ron and Valarie Taylor. It is located 250 km north of Cairns, in a very small section of reef (about 100 m in length) at the northern tip of Number 10 Ribbon Reef. At that time the site was inhabited by an assemblage of 25 friendly giant groupers *(Epinephelus tukulas)*, schools of sergeant majors *(Abudefduf* spp.), gold lined sweet lips *(Plectorhynchus goldmanni)*, Maori wrasse *(Cheilinus undulatus)* and moray eels *(Gymnothorax undulatus)*.

Australians call giant groupers potato cod. We will use the Aussie term throughout the rest of the paper as the area is named after the potato cod.

The cod are the main attraction. They have grayish white skin with large uneven patches of black. They are up to 1.7 m long and weigh 20 to 100 kg. The cod are naturally cautious, but inquisitive. In an effort to draw the cods in closer, divemasters feed them food scraps. Initially only taking food scraps floating in the water, the cod soon learned to feed directly from the diver's hand. Once one species learned the activity others followed. Now moray eels, coral trout, Maori wrasse and snapper wait to be fed.

## PROTECTION

In the late 1970's only 12% of the Great Barrier Reef was within the Great Barrier Reef Marine Park. This was in the most southern barrier reef waters near Heron Island. The Cod Hole remained unprotected.

On one of the Taylor's first encounters with the cod, a diver on the same boat as the Taylors killed one of the cod by shooting a spear down its throat. Ron and Valerie were horrified by this act and vowed never to expose these fish to man again. They steered clear of the Cod Hole for more than six years, never once divulging the secret of its location nor what lay beneath the surface. It was not until 1979 that they returned to the Cod Hole while shooting underwater footage for a Time Life television special. Despite their long absence, the cod responded with enthusiastic friendliness.

As a result of the filming several skippers in the Cairns area learned of the location. As the word spread boat skippers began bringing line and spear fisherpeople to the Cod Hole.

The cod were hooked, reeled and slaughtered. By 1981, they had reduced the population to less than 10 fish. The surviving cod had hooks dangling from their mouths or mouths severely damaged by hooks that had wrenched away chunks of flesh.

Concerned that the cod at the Cod Hole would be wiped out by foolish fisherpeople, Valerie Taylor successfully lobbied the members of the press, the Great Barrier Reef Marine Park Authority and Australian Government to protect the area. In late 1981, a Marine National Park Buffer Zone was established in Cormorant Pass, which included the Cod Hole. People were encouraged to "look but not take". Bottom fishing, spearing and collecting were prohibited; trolling was still allowed. The cod were to some degree protected from fisher-people, but not from divers.

## INCREASED USAGE

In 1986, *M.V. Volare* from the Lizard Island Lodge was the only dive boat regularly visiting the Cod Hole. It visited on average 2-3 times per week with 2-8 divers. Most of the divers were novices and spent an average of 30 minutes in the water. During the calm spring season, October to December, occasional charter boats with up to 16 divers would dive the site. The total number of dives per annum would be around 400 - 500 representing 300 - 400 hours. That is about 1 diver hour per day.

Between March 1989 and June 1990, a survey of the usage of the Cod Hole was conducted. We recorded an average of 1.2 boats per day with a conservative estimate of an average of 10 divers per boat. The number of boats and seaplanes at the Cod Hole was the greatest from late September to December. There was a mean of 5.5 boats per day. This is nearly three times the number of boats visiting at other times.

Divers on the Cairns based dive boats were generally more experienced and did two dives on the Cod Hole. Assuming the dives averaged 45 minutes a total of 6570 hours were dived. To this add 650 diver hours for *M.V. Volare* divers and you get 7220 diver hours per year. That is a mean of 19.7 diver hours per day. An 1800% increase in human contact hours underwater for the cod in less than four years!

The Cod Hole is limited to about a hundred meters of reef. Although it was never noted for its coral (percent live hard coral cover 20-35% (Ayling and Ayling, 1984)), the increased boat frequency noticeably scarred large *Porites* bommies and broke off and damaged smaller *Acropora* colonies. In 1988, Queensland National Parks positioned four large ( > 2 sq m) and four small (approximately 1 sq m) concrete blocks at the Cod Hole to serve as anchors for moorings. However, only two of the four large boat moorings are near the preferred area for the cod. When boat numbers are up and the weather is good, boats unable to obtain a good mooring will anchor near the Cod Hole, again causing coral damage. The concrete mooring anchors further diminish the aesthetic beauty of this wilderness area.

## RESEARCH

In March 1989, we started a monitoring program with the divemasters (Mark Nissen, Belinda Morris and Tony Carroll) of the *M.V. Volare*. On trips to the Cod Hole the dive masters would complete a form with various questions recording individual fish presence, number of select species and number of boats and divers. This was supplemented by dives where we would photograph the fish and observe their behavior.

Individual cods, Maori wrasses and moray eels could be identified by scars, marks in fins, behavior and coloration. Some of the cod were more habituated than others and were named. One was called Cuddles because it liked to be touched. Another with an obvious piece missing from the dorsal region of the caudal peduncle was named Mr. Munchback. Scarface is obvious. The Sheik had a scar on his side and was followed by a school of small, golden jacks. Needles had a damaged lip and its teeth visible. A bump was obvious on the head of Bumpy.

The biggest Maori wrasse was named Mr. Green Jeans. Up to four Maori wrass would come around. Moray eels were labeled Merlin (the largest at 2 m with a scar on left side of face), Cinderella (white spot on left of body) and Sneaky (smallest and most cryptic in behavior).

A total of 75 trips were recorded from March 1989 to June 1990. There was a mean of 9.5 (standard deviation 3.2) cod on each trip. The total numbers of cod present ranged from 2 to 16. There was no significant difference in the mean number of cod present from March - June 1989 (mean 8.7 cod) and March - June 1990 (9.6 cod). The numbers of Cod present appear stable.

There was a significant negative correlation between the numbers of cod and the number of boats present. The more boats present, the fewer cod recorded. It is probable that with more boats the cod are dispersed among the boats' dive groups and not seen by the recorders although present in the area. At subsequent times when *M.V. Volare* was the only boat or only one other boat was present, the numbers of cod increased. Consequently, detailed temporal variation in the population numbers would be difficult to interpret and was not attempted.

Individual cod were not always present. Cuddles, a favorite at the survey start was never observed after June 1989. Mr. Munchback was a common denizen until December 1989. He returned in June 1990 after being away for 6 months. Scarface was commonly there appearing in 53% of the samples. Bumpy and Lumpy appeared in June 1989 and were present more than 80% of the observations since then.

Where do the cod go when they are not in the shallow waters? The Cod Hole is on the edge of an important channel between the lagoon and the Coral Sea. Swimming down to 30 m you commonly see single cods. Unfortunately, the cod at 30 m will never let you approach close enough for identification so we are unsure if they are the same individuals that inhabit the shallow water of the Cod Hole. Individual cod are occasionally seen around the front of

Number 10 Ribbon Reef. Solitary cod have been observed at other adjacent reefs, but do not behave or have wounds or marks like the cod at the Cod Hole.

The Maori wrasse, Mr. Green Jeans, was nearly continuously present being seen on 89% of dives. The eels Merlin, Cinderella and Sneaky were there nearly half the time (49%, 40% and 47% respectively); an average of 1.9 eels per trip. The number or Maori wrasse and moray eels significantly increased during the overlapping months of the study (1.2 to 2.9 wrasse; 0.9 to 1.8 eels)

Although a lot of scrap fish and food wastes entered the water, there were remarkably few sharks. Black tip reef sharks *(Carcharhinus melanopterus)* (0.5 m to 1.5 m long) were the most common. There was a mean of 1.2 sharks per dive. On 49% of the dives no sharks were seen. Generally, the sharks observed were not associated with the cod feeding, but were located about 50 m away near a natural gutter between coral formations. Valerie Taylor has observed 3 cod and several sharks feeding simultaneously at Osprey Reef 90 kilometers east of Lizard Island. She hypothesized that when larger families of cod are found in an area, such as at the Cod Hole, the cod function to keep the sharks away.

## THE CIRCUS

In the October-November Marlin fishing season game boats frequently moor at the Cod Hole to entertain their clients on slow days. Tying a rope around a bait fish they tease the cod and even cause them to jump out of the water. Frequently a cod will catch the bait and play tug of war with the fisherperson. As the line does not contain a hook it is not technically fishing and therefore not illegal. Occasionally the bait is partly swallowed and cannot easily be released. Abrasive action has worn away part of the lip on Needles. Another favorite activity is to tie off a large fish to the reef and watch the cod fight each other.

Most of the Cod Hole divers are inexperienced reef divers. On the dive boat they are told that they are lucky to be able to dive one of Australia's greatest dives. They leave with no further understanding of the natural order of the ocean. Instead they have witnessed a marine circus where chaos reigns.

## FISH WOUNDS

Many of the cods have scars or open wounds around the mouth and head. Some have gashes that look like they were caused by propellors. Other wounds near the mouth look like encounters with small hooks. Boats trolling through the Cormorant Pass and nearby waters will sometimes hook a potato cod. Most cut the line and let the cod go. In some cases this only means damage to the cod's mouth and a hook and line dangling until the hook either rusts or is rejected by the cod. In other cases the struggle and position of the hook can cause severe damage.

After feeding the cod, most divers want to touch the fish and hold on for a ride. The fish are covered with a mucus which protects them from bacterial infections and fouling organisms. We suspect that frequent touching reduces the protection provided by the mucous coating and directly places human associated bacteria on the fish. Natural wounds take longer to heal and human induced sores may develop.

## DIVER ACCIDENTS

Feeding the cod and eels, and playing tug of war using tail roped fish, has changed the cod's and eels' behavior. This is especially noticeable in late September through December when use of the Cod Hole is high. Often the cod become agitated during feeding, bumping divers and fighting each other for food scraps. It was especially at this time that divers had their hands bitten by eels and cods. It did not seem to be an aggressive act. It primarily occurred while the animals were being fed and the hands were either grabbed along with the food or were mistaken for food. Several divers have had injuries so severe that they had to be flown to the hospital.

A hierarchy among the cod normally exists. Certain cod normally have first preference for feeding. However, during busy periods this order breaks down and the fish will charge for anything that looks like food. Most of the accidents occur in these situations.

There has been one reported death attributed to the cod. Evidence of cod involvement is highly circumstantial. An engineer on a dive boat was snorkeling alone while the rest of the crew and passengers dived. At the end of the dive he was found dead in 10 m of water. He was an experienced snorkeler and was known to snorkel dive to more than 10 m. He had been to the Cod Hole many times before and was familiar with the local conditions and fish. An autopsy on the body in Cairns found a bump on his head and small punctures in his skin. (Cod have thousands of minute needle sharp teeth 2 mm long.)

The coroner concluded that he was drowned by a cod. It was hypothesized that while snorkeling a cod had grabbed him and held him under long enough for him to drown. No motive was given. No arrests were made.

## FUTURE

The Great Barrier Reef Marine Park Authority is currently reviewing the zoning of this part of the reef (GBRMPA, 1989). Its new zoning plan calls only for the removal of trolling from the general area of the Cod Hole. It does not put any specific restrictions on diver interactions with the Cod.

We would like to recommend the following restrictions:

1) The existing levels of diver/cod contact hours are already excessive on some days and should be limited.

2) Divers should not touch the fish.

3) Feeding should be limited to fish scraps held in rigid containers, not plastic bags. Dumping of kitchen wastes and other food scraps should be prohibited.

4) Provoking the cod or moray eels using rope tied bait should be prohibited.

5) Boats over 10m should be restricted from the Cod Hole. Larger boats should anchor elsewhere and ferry divers to the Cod Hole.

6) The number of dive boats should be limited to the number of moorings available at present. No additional moorings be should deployed. Anchoring around the Cod Hole should be prohibited.

The Cod Hole is one of the world's best dives. It is imperative that management practices be implemented to preserve this wilderness area for divers in the next century.

## ACKNOWLEDGEMENTS

We would like to gratefully acknowledge the assistance of the Lizard Island Lodge divemasters, Mark Nissen, Belinda Morris and Tony Carroll and the Master of *M.V. Volare*, Don Wills. Diving assistance for the behavioral observations were provided by U Meischner and S Utichke. We are particularly appreciative of the assistance given by Valerie Taylor in reviewing the manuscript and for her constructive comments and suggestions.

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# A DEVICE FOR SAMPLING SMALL-SCALE SPATIAL PATTERNS OF CORAL EPIZOITES

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Living coral colonies have long been known to harbor a variety of invertebrate associates. In addition to the decapod residents of branching corals, smaller motile taxa (e.g. copepods, amphipods and polychaetes) may be found on coral colonies of any species. Current knowledge of the community structure and dynamics of coral associates has largely been limited by the absence of nondestructive sampling methods. The quantification of larger associate taxa has historically necessitated the removal and destruction of the host corals. Obviously, this approach is not suitable for extensive studies or monitoring programs. Studies of smaller associates have been limited to the capture of demersal taxa in traps suspended above the host colonies. This approach is limited to the study of demersal species, and trapping does not give information on small-scale spatial patterns. Many questions pertaining to coral associate communities require equipment similar to devices used in studies of terrestrial arthropods.

For the present study, a diver operated suction-type sampler has been devised to remove coral associates from a twenty square centimeter area of living coral surface without damage to the host colony. Water flow through the sampler is driven by an airlift connected to the operator's SCUBA cylinder. The "nozzle" of the sampler is applied to the colony surface, and a foam ring seals the area to be sampled while protecting the living coral tissue. Water is filtered and drawn across the surface at a precisely-controlled rate to scour epizoites from the surface. Up to six samples may be taken in succession by switching valves to different mesh sample bags. The bags are easily changed underwater, so over thirty samples are often collected on a single dive. Typically, one diver operates the sampler, and another archives the samples. An additional diver is often useful in studies requiring extensive abiotic data or randomization techniques. Random location of samples upon an area of coral surface can be accomplished using a compass, plastic calipers and a table of compass and distance values. When surfaces upon which the sampler operated were revisited, no evidence of damage to the colonies was found. The sampler has proven easy to use in both back reef and high-energy fore reef areas.

Present work is directed toward defining major physical influences on the small-scale spatial patterns of the small associates of *Montastrea annularis* colonies. *M. annularis* colonies on the fore reef area of Carysfort Reef, in the Key Largo National Marine Sanctuary, have been selected as the host corals because of the similarity in shapes, sizes and orientations among colonies in this area. The colonies at this site are also well-suited for the present study with regard to their simple dome-shaped growth form. Standard errors have indicated that, given the variability observed to date, sample sizes adequate for the questions of interest are easily obtainable. In preliminary samples, copepods and copepod nauplii associated with the *M. annularis* colonies have been located on the eastern (i.e. sunward) sides of the colonies during the morning and on the westward sides of the colonies during the evenings. Specific taxonomic breakdowns of this phenomonen, as well as manipulative investigations of causative factors are to be done. An investigation of the additional effects of water flow around the host colonies on these spatial patterns of associates is planned, pending further small-scale characterization of the flow patterns. Hopefully, the resulting understanding of physical influences will lead to a reduction of sampling error in addressing more complex questions about the composition and dynamics of coral-associated assemblages.

This sampler will not eliminate all need for coral removal in certain studies. The sampler should complement coral removal and trapping data by providing small-spatial scale samples of demersal and non-demersal taxa directly from coral surfaces. The sampler will afford a better understanding of the presence and distributions of these taxa upon coral surfaces as other investigators determine their possible roles in the trophic and mechanical (e.g. mucus and sediment removal) processes at the coral surface. In addition to allowing the investigation of a wider variety of questions concerning coral associates, samplers might eventually allow the use of these animals in monitoring environmental stress in reef systems.

# TRAINING SCIENTIFIC DIVERS FOR ZERO VISIBILITY DIVING

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*East Carolina University (ECU) supports scientific diving programs in Marine Geology, Marine Biology, Maritime History and Intercoastal Marine Resources. Research objectives are sometimes found in low or zero visibility waters, which can subject divers to environmental and personal hazards. The diving safety office provides a training program through the use of a zero visibility obstacle course and related skills that are designed to develop composure and skills for diving under zero visibility conditions.*

## INTRODUCTION

Diving Safety Programs train and evaluate divers for a variety of conditions, of these, zero visibility presents possibly the greatest challenge. Referred to as blackwater diving in some circles and brownwater diving in others, zero visibility diving distinguishes itself from limited visibility and night diving by a total absence of light and by rendering artificial lighting useless. Zero visibility diving conditions magnify composure and skill problems present in inexperienced divers, and can produce composure problems in experienced divers who are competent under other circumstances. The total lack of light makes the use of the traditional buddy system ineffective; underwater communication and navigation techniques must be modified; and hazards such as entanglements, entrapments, lacerations and punctures become more likely. Blackwater makes simple in water tasks such as checking psi and depth virtually impossible by traditional means, and complicates the evaluation process of divers in training. Diving safety personnel must safely evaluate divers' competence under zero visibility conditions, identify and correct potential problems, and provide divers a learning experience so they can recognize potential problems and recognize their limitations under blackwater conditions.

## REVIEW OF SWIMMING AND DIVING SKILLS

Applicants for training in the ECU scientific diving programs must meet all training requirements as outlined in the University Diving Safety Manual. Only after a reasonable level of competency in basic diving skills and technical knowledge have been demonstrated can specialized training necessary to safely participate in blackwater diving be undertaken. Operating in total darkness must be practiced to perfection. The diver must learn the importance of self-discipline and be conditioned to react spontaneously and correctly to a variety of situations.

Everyone is not suited for zero visibility diving as there are important and perhaps critical psychological factors to be considered. The diver cannot be prone to panic, be easily excited or have the slightest form of claustrophobia.

## THE CONCEPT OF SOLO DIVING

In zero visibility ones' ability to navigate and orientate are greatly reduced. There is a constant possibility of "happening" into a dangerous situation where extrication may be difficult and sometimes impossible without the assistance of a stand-by diver.

Preparation for diving in zero visibility conditions requires some special considerations. Besides the stand-by diver, an additional set of equipment and/or air sources should be readily available in the event of entrapment and the diver being in danger of exhausting his/her air supply.

In scientific diving, diving with a partner is required unless tethered with diver to surface communication and other stand-by procedures are in place. Under zero visibility conditions, it may be difficult to safely dive with a buddy and perform scientific work. It is not the intent of this paper to promote or defend the concept of solo diving, but merely to train divers to develop problem solving skills under zero visibility conditions. These conditions make caution, self control and self rescue more practical in many situations than relying on the traditional buddy team. Assistance should always be available, but we believe that the confidence that is developed through the zero visibility training procedures presented here will go a long way toward preventing a panic or crisis situation.

## INTRODUCTORY SKILLS FOR ZERO VISIBILITY DIVING

To operate successfully under zero visibility conditions the diver must take into account the effects of the water and must utilize special skills to accomplish tasks in zero visibility conditions. It is important for the diver to develop the concept of "seeing" images by touching or feeling. During the development of these skills, the diver should be aware of the probability of having to contend with cold water, currents, surges, entanglements, restrictions, dangerous marine life and other harsh environmental conditions.

In order to meet the objective of developing equipment familiarity for working in zero visibility, divers are required to successfully complete objectives related to removing and replacing equipment with and without the aid of vision. To accomplish this a blind buddy exchange is utilized. This skill not only develops equipment familiarity, but also helps to develop composure for dealing with stressful situations. For the blind buddy exchange, two divers share one set of equipment and swim to a designated area and then switch equipment from one diver to the other.

The blind buddy exchange has proven to be an excellent drill for developing teamwork, composure and the desirable skills required to deal with zero visibility conditions. Any drill that assists the diver in this capacity is valuable. It may also be desirable to complete similar drills while using equipment other than Scuba, such as hookah or surface supplied. Training should reflect the practical problem solving ability for use in a scientific diving program.

The only sure way of determining if a diver is suited for work in the blackwater environment is actual exposure to zero visibility conditions. However, taking inexperienced persons on a zero visibility dive as their first exposure is not the safest approach. Most divers who balk at blackwater do so very early in a dive. Field conditions limit safety personnels' ability to anticipate and deal with composure problems which, if left unchecked, could lead to a panic state of life-threatening potential.

Blacking out the face mask in the skills previously mentioned produces only limited information as to the divers composure and problem solving abilities under stress. Although safety personnel may properly monitor the divers this will do little to teach the diver skills needed to safely dive in the blackwater environment. To accomplish these goals a more realistic simulation is required.

## THE ZERO VISIBILITY OBSTACLE COURSE

The Zero Visibility or Blackwater Obstacle Course is not a new concept. It has been used as a composure exercise by emergency services diving teams throughout the country for years. The idea is to present a diver with a series of problems that could be encountered under zero visibility conditions then observe how the diver handles each obstacle.

A diver should have no prior knowledge of the obstacles to be encountered. Isolation present in blackwater should be reinforced by advising the diver that no help will be given by the observers unless the diver gives a predetermined distress signal.

The course itself can range in difficulty from a simple straight line with minor restrictions and puzzles, to a complex maze of dead ends and difficult challenges. The order of the obstacles and their difficulty are left up to the imagination of the persons supervising the individual course. However, to be most effective the obstacles and tasks encountered by the diver should simulate actual diving tasks and potential problems as closely as possible.

Obviously, it is impossible to line the bottom of a pool with 2-3 feet of silt, mud and leaves; but barring this limitation, an extremely challenging and informative exercise may be designed at a very limited expense.

The following is an example of one version of a blackwater obstacle course:

The diver is brought to a staging area where the pool is not visible. The diver sets up his/her equipment and receives instructions. Instructions are simple and include:

1. Emergency signals if the diver feels he/she is in trouble and needs help.
2. A statement that the diver is on his/her own and will receive no help unless there is a life threatening problem.
3. The diver should move slowly, carefully, and think.
4. The obstacles encountered are real and the hazards simulate actual problems a diver could encounter in blackwater.
5. No tools such as a knife may be used by the diver in the negotiation of the course.
6. The importance of staying in contact with the guide line.
7. The diver may not bypass any obstacle and must follow the guide line as closely as possible.
8. The diver can be designated as "dead" by the observer if his/her actions are determined to be foolish and unsafe for the conditions encountered, or if the diver does not meet any time or air limits set down as part of the scenario.

Other instructions would be task specific and would change as the tasks change from course to course.

The diver then has his/her mask blacked out and is led to the waters edge. Blacking out the mask is easily accomplished by stretching a bathing cap over the face plate. The diver enters the water and is placed in contact with the guide line. This is the last contact the diver will have with the safety diver/observer unless there is a safety problem.

In Figure 1, the diver is placed in contact with the guide line at station 1 where he/she is given a nuts and bolts puzzle to disassemble and reassemble. The diver must remove all of the pieces of the puzzle and replace them in the original order. This task allows the diver time to acclimate to a zero visibility environment while causing the divers' attention to be focused on a specific task.

After reassembling the nuts and bolts puzzle the diver follows the guide line to the first obstacle of the course (station 2). Here, floating line and monofilament are attached to a series of metal benches or other stable objects. The floating line crosses the guide line in several places and may entangle loose pieces of equipment and a diver not moving slowly and deliberately.

Station 3 is a plastic 55 gallon drum suspended in mid-water. The line runs through the drum and back to the bottom of the pool. One end is cut out of the drum and is large enough for an average size diver equipped with a single 80 cubic foot tank to enter with all equipment in place. The exit end of the drum is cut so that it is slightly smaller than the entrance, a flapper style door has been left attached. The drum should be stabilized by suspending weight from the bottom of the drum. The obstacle is designed to test the divers' spacial sense, and if necessary, the divers ability to manipulate his/her equipment by performing a mid-water ditch.

Station 4 is a shrimp or gill net stretched over a portable lifeguard stand and running approximately 40 feet on the pool bottom. The edges of the net are weighted to anchor it. There is enough slack in the net to allow it to bunch up upon itself. The guide line is stretched so that it is centered in the net. The purpose of this station is to make the diver aware of the fact that equipment arrangements used in normal open water diving may not be appropriate under blackwater conditions. The station also provides an opportunity for the diver to develop techniques to avoid becoming entangled, and reinforces the STOP, THINK, THEN ACT principle.

Station 5 is an anchor point for the guide line. The line should be wrapped several times around the object so that the diver must trace its path.

Station 6 is a second plastic 55 gallon drum. The drum is weighted to keep it on the bottom of the pool. The guide line passes through a round flapper style door cut into one end of the drum. The exit forms a rectangle with a western barroom type door cut into the side of the drum. The path of the guide line requires a 90 degree turn to be made to exit the obstacle.

Station 7 starts as an archway of chicken wire and ends as a chicken wire tube. The tube, although tight, is large enough for a fully equipped diver to pass through with gear in place. The wire structure is weighted so that it offerers some resistance to movement.

Station 8 is an anchor point for the guide line.

Station 9 is the end of the guide line. At this point the diver may have been instructed to surface, or as in the case of this illustration, the diver finds his/her objective; a weighted plastic milk crate or bucket and a lift bag. The diver attaches the lift bag to the object and raises it to the surface.

Station 10 is an obstruction to direct surface access. The obstruction should be large enough so that the diver will need to search to find a way to the surface. Any floating object positioned over station 9 and loosely tethered to hold it in position will work.

After the diver has surfaced the blindfold is removed and the divers' performance is critiqued. The diver should then be given the opportunity to go through the course again with the mask unobstructed.

This completes the first phase of the blackwater obstacle course training process. Phase two of the process requires the obstacles in the pool to be rearranged and new instructions to be given.

## THE ADVANCED BLACKWATER OBSTACLE COURSE

As in phase one, the divers have no prior knowledge of the obstacles they may encounter. Their masks are blacked out and the divers are monitored by safety personnel. Unlike phase one, this advanced obstacle course has no guide line to be followed, the divers work as a buddy team in search of a specific object somewhere in the pool. All other instructions are the same. In this scenario the divers are in control of their search patterns, a situation simulating actual field conditions much more closely than phase one.

The divers must maintain communication with each other while conducting their search. They have to decide how to deal with the obstacles they encounter while meeting any time and air limitations placed on the buddy team for added realism. The divers must also complete the assigned task while avoiding potential life threatening situations. With more decision making freedom, the divers reactions in a given situation more closely resembles field responses.

Due to the free form nature of this exercise, the simulation is as real as possible without being under actual zero visibility conditions. Therefore, the observation and critique process in this phase of training provides more realistic information to the observer and the diver.

As part of the critique process in both versions of the exercise, the diver should be questioned about his/her perception of personal performance. Suggestions should be given that will help the diver improve techniques, equipment arrangements and composure.

The purpose of this exercise is not to provide the diver with a false sense of infallibility. Statements made by divers such as: "If this were real I would have taken my knife and cut my way out.", must be dealt with at the time they are made. Divers with this attitude need to be counselled to modify this thinking. This is done by pointing out the controlled nature of the exercise and the unpredictability of zero visibility diving conditions, and by stressing the avoidance of hazardous situations whenever possible.

During the exercise the observer(s) must maintain constant visual contact with the diver. Special attention is to be paid to the divers air supply, composure and regulator placement throughout the course. It is possible for a diver to become dangerously entangled, dislodge his/her mouth piece and panic. The observer is expected to give the diver every opportunity to negotiate all of the obstacles unassisted, while insuring the divers safety at all times. These considerations are of supreme importance when designing and building an obstacle course. Obstacles from which a diver can not be quickly extricated or that do not allow the diver to be easily accessed with air, have no place in this exercise.

The blackwater obstacle course process is effective in providing information to both the observer and the diver, as to the divers' skills, problem solving abilities, and composure. It is not a substitute for actual blackwater diving experience, but it can produce a controlled and safe introduction to the zero visibility environment.

## OPEN WATER TRAINING FOR ZERO VISIBILITY

A good portion of the research conducted by ECU is in rivers, estuaries and sounds. These areas offer excellent conditions for zero visibility exercises. Open water training simulating field procedures for each scientific program is the next step in the training process. This allows for a more realistic evaluation of the candidates.

It is customary for the training site to simulate actual fields conditions as closely as possible. The ECU program is fortunate in having a wide variety of zero visibility sites available which are dived regularly. This allows for a controlled exposure to actual blackwater conditions. Barring the availability of a known dive site containing the training elements required by an individual program, a suitable simulation may be created in actual blackwater conditions.

## SUMMARY

Anxiety and stress are the most serious conditions that a diver must contend with when placed in compromising situations in zero visibility. Anxiety and its association with dangerous diving conditions will effect awareness. Weltman (1966) indicated that a person's response to an environment he considers dangerous may involve a phenomenon called perceptual narrowing, which is a reduction in the ability to assimilate sensory information from the environment. Berkun (1964) reported that in high risk environments subjects performed poorly and failed to react to important stimuli.

According to Lehey (1989) stress management is the ability to differentiate between a problem and a crisis. The diver should also be equipped with problem solving skills, i.e., an habitual response involving taking time to define the problem and then attempting a solution by:

1. Responding with behavior that attempts to resolve the problem.
2. Act on the recognition that if one solution does not solve the problem, one moves to another solution.

Weltman's (1968) most significant finding was that the advantage of the experienced or trained diver was not in working faster, but in spending less time on non-productive activities. One can conclude from this that the experienced diver will be a safer diver in zero visibility conditions.

It is generally accepted that practice or experience can help to develop a positive mental attitude toward completing a task safely. Training and experience will affect the way a diver reacts to his/her environment and how well he/she can perform scientific tasks or remove himself/herself from compromising/dangerous situations. The procedures outlined here allow diving safety personnel to safely train divers for zero visibility diving conditions and provide the diver the opportunity to develop the knowledge and skills necessary to be safe and effective under zero visibility conditions.

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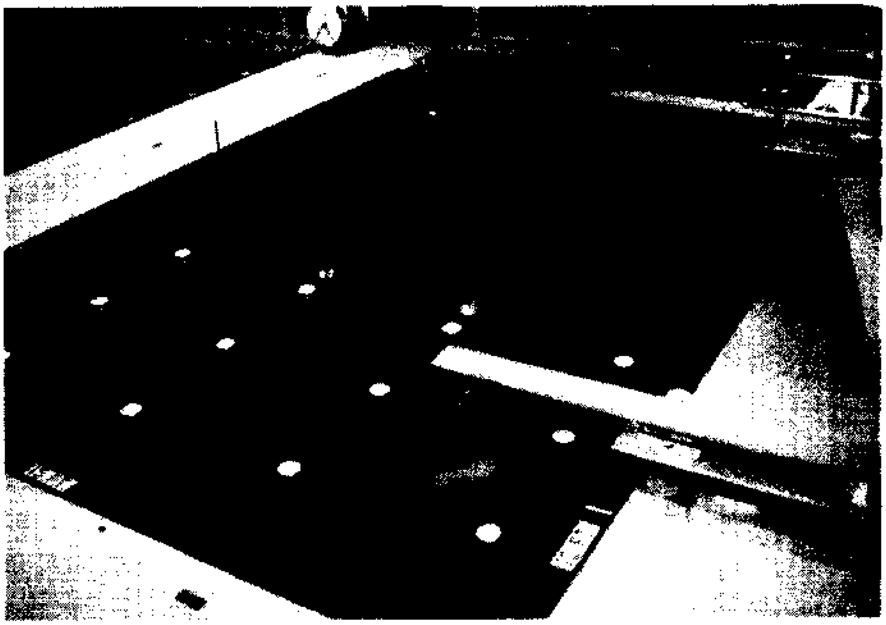

**Figure 1. One layout of a zero visibility obstacle course.**

**Figure 2. Floating line stresses the possibility of entanglements in zero visibility.**

**Figure 3. By reducing the size of the exit, the diver's spacial sense is tested.**

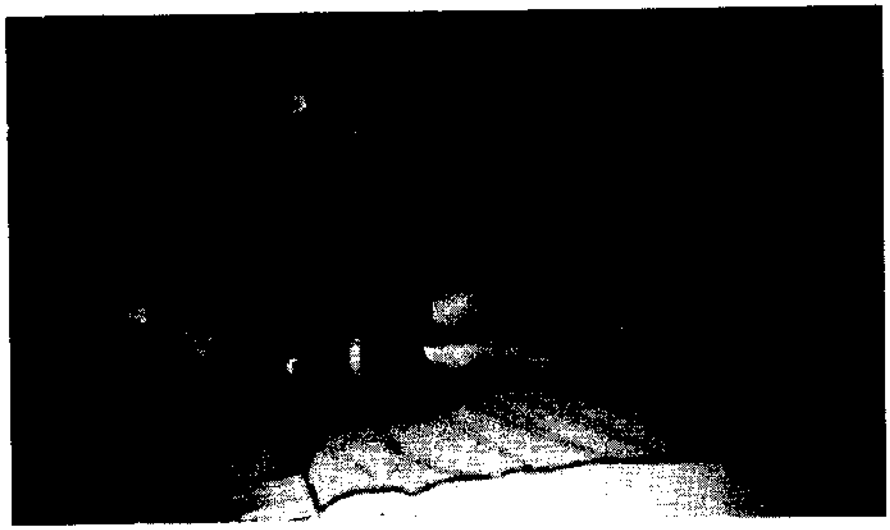

**Figure 4. The net offers a special challenge to composure and problem-solving abilities.**

**Figure 5. The 90-degree drum produces a variety of unique problem-solving techniques.**

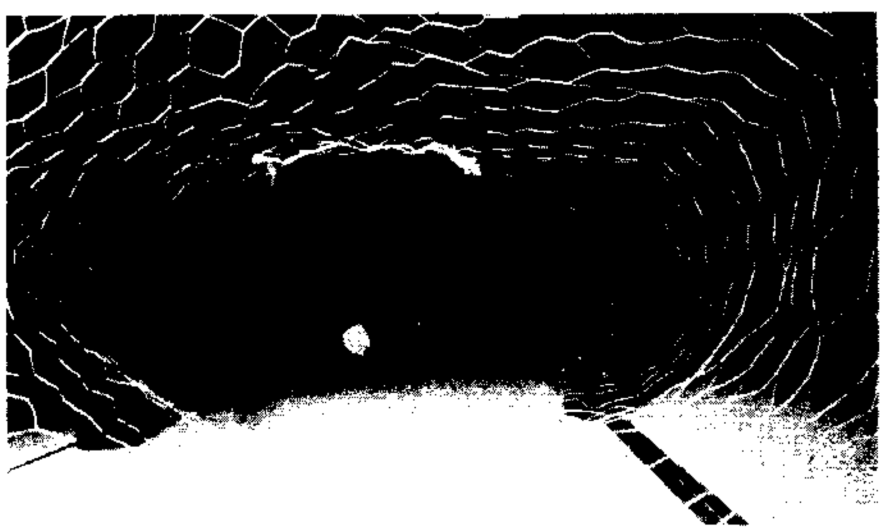

**Figure 6. The wire tube stresses proper equipment arrangement and slow, deliberate movements.**

# METHODS OF MEASUREMENT OF EXPLORATORY WELL IMPACTS, OFFSHORE FLORIDA

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*Six offshore oil well tests were drilled off Key West in the late 1950s and early 1960s. Two wells were drilled on coral bottom, two on carbonate sand, and two on mixed turtlegrass and gorgonian/sponge hardbottom. After locating the sites with a proton magnetometer, several underwater assessment methods were used to measure the ecological impacts of drilling. Because of differing environments and bottom types, no single method was applicable at every site.*

## Proton Magnetometer

An inexpensive proton magnetometer designed for wreck finding proved invaluable in locating the well sites, especially in areas of murky water. The wells had been drilled before introduction of modern electronic positioning devices and had been positioned using standard surveying techniques. To locate the well sites, the reported latitude/longitude positions (Table 1) were converted to Loran TDs and a large buoy was placed at each approximate location. A grid search was run with the magnetometer, and diving on the sites, usually only with mask and snorkel, enabled anomalies to be confirmed. All sites were located in this manner because several thousand feet of casing had been left in the earth. Magnetic anomalies produced by the buried vertical pipe were so great that the wells were usually detected from as far away as 75 m.

**Table 1. Well Site Data**

| OCS Well Site | Loran C TDs | Lat./Long. | Lease Block | Date Drilled | Rig Type | Water Depth (m) | Well Depth (m) | Lessee |
|---|---|---|---|---|---|---|---|---|
| SL 1011 No. 2 | 13887.9<br>43748.5 | 24°32.07'<br>82°06.25' | State<br>1011 | 1961 | Barge | 5 | 2,354 | California Co. |
| SL 1011 No. 3 | 13887.9<br>43748.5 | 24°32.07'<br>82°06.25' | State<br>1011 | 1962 | Pontoon | 5 | 3,917 | California Co. |
| SL 826Y No. 1 | 13905.4<br>43729.1 | 24°37.05'<br>82°02.14' | State<br>826Y | 1959 | Unknown | 5 | 4,481 | Gulf Oil Corp. |
| OCS 0665 No. 1 | 13845.7<br>43826.8 | 24°27.06'<br>82°21.40' | OCS<br>Block 28 | 1960 | Jackup | 11 | 4,662 | Gulf Oil Co. |
| OCS 0674 No. 1 | 13826.4<br>43867.9 | 24°26.01'<br>82°29.18' | OCS<br>Block 46 | 1961 | Jackup | 23 | 2,399 | Gulf & Calif. Co. |
| OCS 0672 No. 1 | 13809.8<br>43903 | 24°25.13'<br>82°36.02' | OCS<br>Block 44 | 1961 | Barge | 20 | 1,429 | California Co. |

## Chain Transects

A 10-m-long chain with 1-cm links marked with tape every 10 cm was draped over the bottom adjacent to the well bores. Corals, algae, and gorgonians lying beneath each tape mark were identified and measured.

## Quadrats

At a coral reef site (OCS 0665 No. 1), two 10-m square quadrats were marked off with polyethylene line and all corals, gorgonians and macroalgae were measured and identified. Chain transects were also run within the quadrats. Two identical quadrats were established in a nearby control area.

## Bullseye Transects

In an area of strong currents and poor visibility (SL 1011 Nos. 2 and 3), eight 50-m-long polyethylene lines, marked every meter, were attached to the area of the well site borehole and stretched radially to form a "bullseye". The bullseye was constructed by attaching the first line and allowing it to trail downcurrent with the outgoing tide. Any impacts from pollutants should have occurred along this path. A second line was placed in the opposite direction (incoming tide direction). The remainder of the lines forming the bullseye were equally spaced to form a pie diagram. Continuous underwater video transects, made above each line beginning at the bullseye and running outward, simultaneously showed meter marks and bottom type. Thus, by counting the meter marks, the distance to every change along the bottom was mapped. Probing every 5 m with a rod along each line provided data to construct a sediment isopach map.

### Underwater Video and Photography

Underwater video and still photographs were taken at all sites, and video films were reviewed aboard ship. Video films proved useful for verifying and supplementing other data, which were transferred from divers' slates and logged in a portable PC daily.

## RESULTS

Measurable impacts at all sites were of mechanical origin and were limited to small areas adjacent to the borehole. Impacts were judged to be positive and negative. Positive impacts were limited to the "artificial-reef effect": abundant debris discarded at sites on rippled sand was encrusted with corals and algae determined not to have been present before drilling. Numerous species of fish and crustaceans resided among casing, cables, discarded core, and other materials that had been routinely dumped overboard before enactment of OCS dumping regulations.

Negative impact resulted where drill rig legs and anchors impacted coral bottom, and at one site (SL 1011 Nos. 2 and 3; see Table 1), the bottom was altered when a barge load of pea gravel was dumped to level the bottom. Approximately one acre of gorgonian and sponge hardbottom was destroyed by the gravel, which harbored a new community of fleshy algae. At the same site, several dozen bags of cement had been piled over the well head. The hardened cement bags supported eight species of corals and provided an artificial-reef habitat for at least 25 species of fish.

The severest and longest lasting impact occurred where a 14-legged jackup rig (site OCS 0665 No. 1) drilled through a coral reef in 1960. In addition to the sand-filled 4.5-m-diameter "footprints," two >30-m-long anchor scars remain. The total amount of impacted bottom is 406 $m^2$ or approximately 1/10th of an acre. Sand in the impacted areas has prevented coral and gorgonian recruitment for the past 30 years. However, diversity and numbers of corals and gorgonians in a 10-m quadrat bordering the borehole are the same as in a control site 1 km from the borehole. At another site (OCS 0672 No. 1), where a floating rig was used to drill on a coral reef, no positive or negative impacts could be detected.

Although all sites may have been initially impacted by drill mud and cuttings, no evidence of effects could be detected in 1988. Because impacts are largely mechanical, it seems likely that offshore wells can be drilled on sand bottom within a few meters of a reef without causing lasting harm, provided there are no blowouts or other mishaps during drilling.

# UNDERWATER RESEARCH METHODS FOR STUDY OF NUCLEAR BOMB CRATERS, ENEWETAK, MARSHALL ISLANDS

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*Three craters, created by the explosion of nuclear fusion devices, were mapped, sampled, core drilled and excavated with airlifts at Enewetak Atoll in the Marshall Islands by using scuba and a research submersible. The craters studied were Mike, Oak, and Koa. Tests took place near sea level at the transition between lithified reef flat and unlithified lagoonal sediments, where water depths ranged from 1 to 4 m. Craters produced by the blasts ranged from 30 to 60 m in depth. The purpose of our study was to determine crater diameter and depth immediately after detonation. Observations of submerged roadways and testing structures and upturned crater rims similar to those characteristic of meteor impacts indicate that the initial, or transient, craters were smaller than their present size. At some later time, while the area was too radioactive for direct examination, the sides of the craters slumped owing to dewatering of underlying pulverized rock. Core drilling of crater margins with a diver-operated hydraulic coring device provided additional data.*

*On the seaward margin of the atoll, opposite Mike, a large portion of the atoll rim approximately the size of a city block had slumped into the deep ocean, leaving a clean vertical rock section more than 400 m high. An abundance of aggressive grey reef sharks displaying classic territorial behavior prevented use of scuba at the Mike slump site. The two-person submersible R. V.* Delta *provided protection and allowed observations down to 300 m. During the 6-week period of study, we made more than 300 scuba and 275 submersible dives. Mapping was with sidescan sonar and continuous video sweeps supplemented by tape-recorded verbal descriptions made from within the submersible. A mini-ranger navigation system linked to the sub-*

*mersible allowed plotting of bottom features, depth and sediment type with spatial accuracy to within 2 m.*

## INTRODUCTION

Between 1952 and 1958 the United States conducted atomic testing at Enewetak Atoll (Figure 1). The first fusion bomb, a 10.4-megaton-yield device called Mike, was detonated on a small island there on October 31, 1952. Two subsequent devices, Oak and Koa (8.9 and 1.4 megatons, respectively), were detonated at Enewetak. Koa, a relatively small device, was detonated May 12, 1958, on a sand spit adjacent to Mike, and Oak was detonated June 28, 1958 on a barge in 4 m of water, (Figure 2). All the tests were on or near the lagoonal margin of cemented reef flats, also called reef plates, a location that made the object of our mission doubly difficult.

Lagoonal sediments consist of soft muds and uncemented sands, and the transition from reef flat-rock to lagoonal sediment is abrupt. The devices were tested at or near the point of transition from shallow rock to relatively deep soft bottom.

In 1984 the Defense Nuclear Agency (DNA) contracted with the U.S. Geological Survey (USGS) to determine the transient dimensions of craters produced by the Oak and Koa devices. Transient craters are those created at the instant of detonation. The Oak and Koa craters that exist today are larger (1,750 and 1,316 m diameter), however, due to the gradual subsidence of fractured rock and dewatering of compacted sediment. Special techniques and methods had to be developed to determine the transient dimensions, which existed unseen by nuclear physicists when the area was inaccessible and obscured by milky contaminated seawater.

Measuring transient-crater dimensions would have been relatively simple had the tests occurred on land. Post-event subsidence would have been minor. At Enewetak not only were the sediments water saturated, but also there were differences in water depth and profound geological differences between reef flat and lagoon. Our work was further complicated by crater depth (Oak is 60 m deep) and abundant grey reef sharks in certain areas, and the location is far removed from mainland supplies.

The purpose of this paper is to describe methods and equipment used to overcome various problems related to this remote location.

## METHODS

A diagnostic product of large impact or explosive craters is upturned or overturned flaps. These flaps are formed when explosive forces push material upward and outward, causing rock layers at the crater margin to turn away and fold back on themselves. An up- or overturned flap buried within a larger crater would therefore approximate the transient-crater margin that formed before significant subsidence began.

The distribution and age of ejecta, i.e., the material excavated and thrown from the crater by the blast, can also help determine the depth and lateral extent of a transient crater. Radially oriented rays of ejecta, called ejecta rays (Figure 3), do not exist within craters but originate at the crater margin. The common point of ejecta-ray origin can therefore help delineate the transient-crater margin. Isotopically and paleontologically determined ages of ejected material can be used to determine the depth of excavation.

Methods and equipment used to search for upturned flaps and to map ejecta included: 1. scuba, 2. a two-person research submersible, 3. an underwater core drilling apparatus, and 4. airlifts. These methods were used in conjunction with sidescan sonar mapping and subbottom profiling. Underwater video films and photographs were also extensively used in the mapping effort. A possible upturned flap was located and exhumed with an airlift by scuba diving in Oak crater and a fortuitous discovery of sunken manmade objects in Koa crater provided direct evidence of post-event subsidence.

## Mapping

Mapping within the craters, because of depth (up to 60 m), and navigational requirements, was accomplished from within the research submersible *Delta*. Navigation was provided by a mini-ranger system linking the mother ship, a 50-m supply boat, to precisely located transmission towers on nearby islands. The ship location was continuously plotted to within a 2-m accuracy. The supply boat was linked with the submersible via transducers and a track point system. By use of a computer, the submersible's position could be continuously plotted on board the surface vessel.

Inside the submersible, the observer took continuous video images of the bottom and recorded verbal observations on the sound track and, as backup, on a separate tape recorder. An in-camera digital clock linked the time of observations and video images with the submersible's plotted position aboard the surface vessel. Visibility was generally in the 10- to 20-m range, thus a 10- to 20-m-wide swath of observation was recorded during each submersible transect. By criss-crossing the crater, sediment and biotic changes were noted and charted until a consistent pattern emerged. An example from Oak crater is shown in Figure 4. Figure 5 is an "air-brush" interpretation of bottom configuration at Oak crater based on diving observations and sidescan sonar surveys. Similar maps and interpretations were made for Koa and Mike craters (Folger, 1986).

Research Submersible

In addition to mapping, the submersible played another vital role in our research at Enewetak. When the Koa device was fired adjacent to the crater previously produced by Mike, the reef flat was so violently shaken that a large portion of the outer reef edge, more than $10^8$ metric tons, sheared off and slumped to oceanic depths (Figure 6 ), leaving a cirque-shaped submarine scarp extending more than 190 m into the reef. The outcrop afforded an unparalleled opportunity to collect samples and make observations on atoll reef growth. We initially attempted to examine the wall using scuba but were forced from the water by dozens of grey reef sharks displaying classic territorial defense posture.

From within the safety of the submersible, we were able to collect rocks along the wall to a depth of 400 m. The site proved to be a unique opportunity for reef studies because the wall was not encrusted and had an appearance not unlike the walls of a typical limestone quarry (Figure 6). The exposure clearly demonstrated how the outer margin of the atoll is armored by submarine cemented reef framework, an example of the "bucket of sand" hypothesis proposed by Schlager (1981). The "bucket of sand" hypothesis states that carbonate platforms and atolls are aided in their growth and become preserved in the geologic record because cemented marginal reefs grow upward faster than relative sea level rises, thus producing a "bucket" in which biogenic sediment accumulates.

Samples of reef rock were sampled to 400 m below sea level (Halley and Slater, 1987). This kind of detailed sampling could not be accomplished without a manned submersible.

Scuba

Scuba diving played an important role along the shallower crater margins. Diving along the reef-flat side of Oak crater revealed an upturned rock ledge (possible upturned flap) that airlifting and core drilling (see Figures 7 and 8) showed was composed of reef-flat rock, which is exposed at low tide elsewhere along the reef. Core material and airlifting sand from the upper surface of the rock, (Figure 9) were critical to confirmation of the origin and nature of this rock. In places, the rock layer, once at low tide-level, had been depressed to as much as 60 m below low tide.

Scuba diving was particularly important to the interpretation of transient-crater diameter in and adjacent to Koa crater. During routine submersible video mapping, we located and plotted the position of several railroad rails, which stood vertically in the sediment. Investigation by scuba diving later revealed a fence-like row of 28 rails leading toward the center of the 30 m-deep crater. The rails were bent away from "ground zero" and formed a line 46 m long that began in 15m of water near the crater margin and extended out to a depth of 18 m. Excavation along the rail line with a 15-cm diameter airlift uncovered buried timbers and rip-rap. The origin of the rail line was a mystery until examination of Air Force documents and old aerial photography showed that the rails were part of a roadway constructed across the reef flat to provide access to the small island where the Mike device had been detonated. The road was constructed by driving rails into the reef flat, lining them with timbers and then filling the space with sand and rip-rap. The rails conclusively proved post-Koa subsidence of at least 18 m. The last rail, closest to ground zero, was interpreted to indicate the maximum diameter of the transient crater.

A frame used for testing cement and another set of rails outside the present crater provided additional evidence of subsidence. The structure is shown in Figure 10 and 11)., Before the blast, the cement structure was 3.5 m above mean low tide (Figure 12). Eight days after the test, it had subsided to near sea level. Today the top of the structure is at mean low tide.

Also shown in Figure 12 is another access road buttressed by railroad rails. Today the tops of these rails, encrusted by coral, are more than 1 m below low tide (Fig. 10 and 13). In these examples scuba diving and geological detective work clearly showed that not only had the crater enlarged since the blast but there also had been significant subsidence beyond the crater's margins. Additional details are included in Folger (1986).

## Core Drilling

The diver-operated hydraulic underwater coring device shown in Figure 7 is patterned after that of MacIntyre (1975) and has been used extensively in Florida and the Caribbean by the USGS Fisher Island Field Station. As discussed earlier, the drill was used to sample depressed reef flat-rock around crater margins. as discussed earlier. It was also used to gain background information on cementation gradients, thickness of reef plates, and depth to the underlying Pleistocene reef surface. The drills portability allowed core drilling a few meters from the seaward edge of a Pacific atoll reef flat for the first time. In the lagoon the tripod was set up on a 10-m-deep, 30-m-high patch reef that been fractured by the Oak event and a 12-m-long core was obtained.

The device takes 4-cm-diameter cores in 1.5-m (5 ft) increments and by adding threaded lengths of drill pipe, is capable of coring to a subbottom depth of 20 m. Seawater is used for drilling fluid and is pumped down the drill pipe by a positive displacement gear pump powered by a 14-hp gasoline engine. Drilling equipment was deployed from the 8-m-long diver research vessel *Halimeda.*

The hydraulic drill was also used in the handheld mode with large-diameter (10 cm), diamond-tipped barrels to core massive coral heads for coral growth rate studies. These studies revealed that 100-year-old heads of *Porities lutea* that survived physical removal by the blast were still living and growing at pre-bomb rates. Some were less than 1000 m from a 1,750-m-diameter crater produced by a device approximately 500 times more powerful than those exploded in World War II. In another study, *P. lutea* (see Figure 13) was shown to have recruited to the margins of Koa crater within one month of the blast. Apparently, radiation did not prevent recruitment, although these corals lacked clear annual banding, suggesting genetic effects of radiation (Hudson, 1985).

## CONCLUSIONS

These studies demonstrated the advantages of having diving scientists do research normally contracted to commercial or military divers. It seems highly unlikely that untrained commercial or military divers could have solved the complex geological and biological problems encountered in this study.

Underwater video proved to be an inexpensive and effective tool for obtaining and recording routine data, especially during the mapping phase using the submersible. Diver operated underwater video provided documentation in areas too shallow or otherwise unreachable with the submersible. The only limitation of diver operated video was water depth and absence of on-site verbal documentation to supplement the visuals.

An air-lift constructed in the field was especially useful for removing sediment and allowing observations not otherwise possible. The underwater, diver-operated, core drill provided data on the growth of reef flats and lagoonal patch reefs that no other method could provide. Use of the core drill was instrumental in the identification of depressed reef-flat limestone.

The manned submersible allowed collection along a vertical, shark-protected wall to a depth of 400 m. Dredges and remotely operated vehicles probably could not effectively operate and collect under such conditions.

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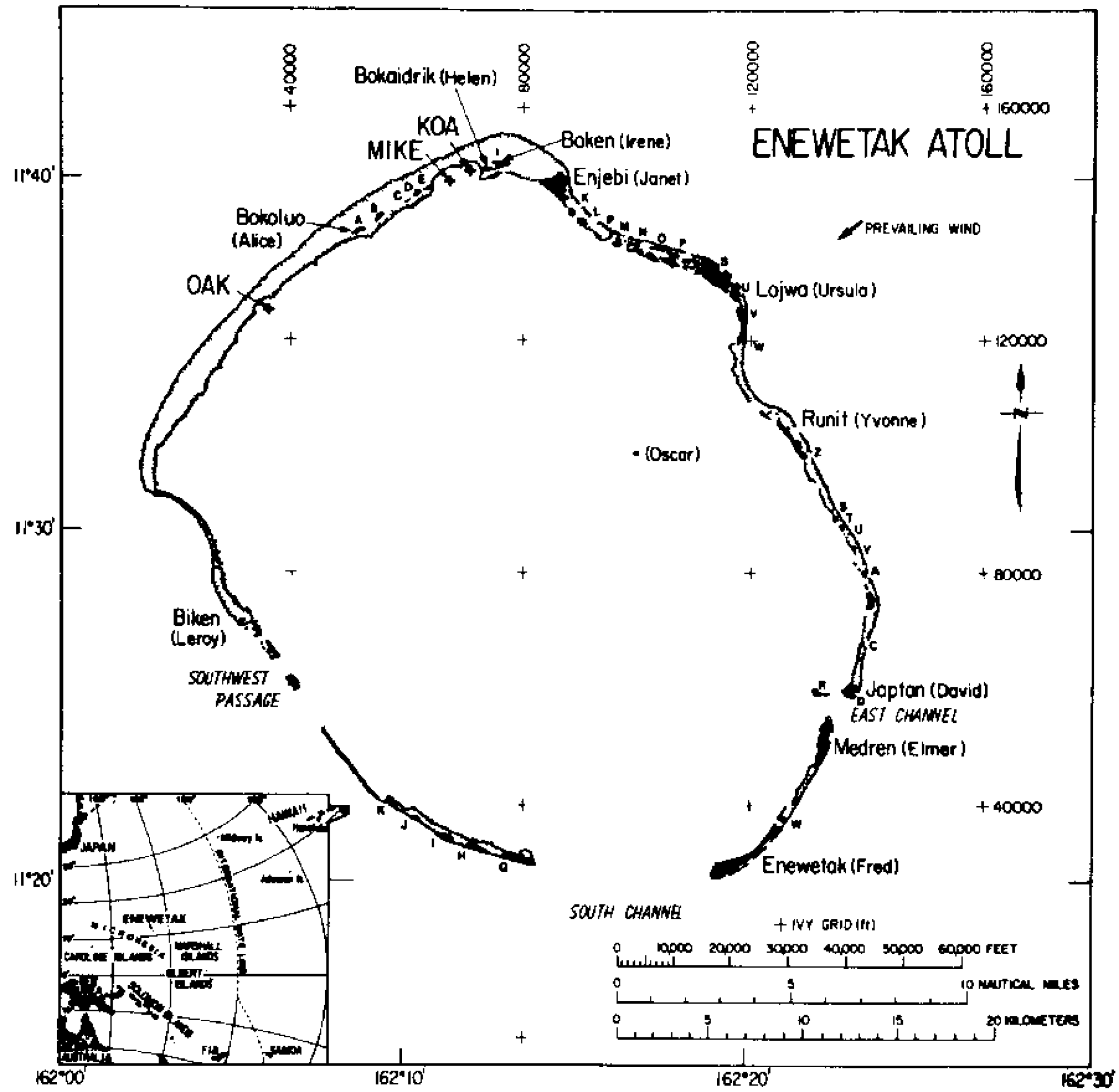


**Figure 1. Map of Enewetak Atoll showing locations of Oak, Mike, and Koa craters and many of the significant islands that make up the atoll. Only Enewetak and Medren Island are populated.**

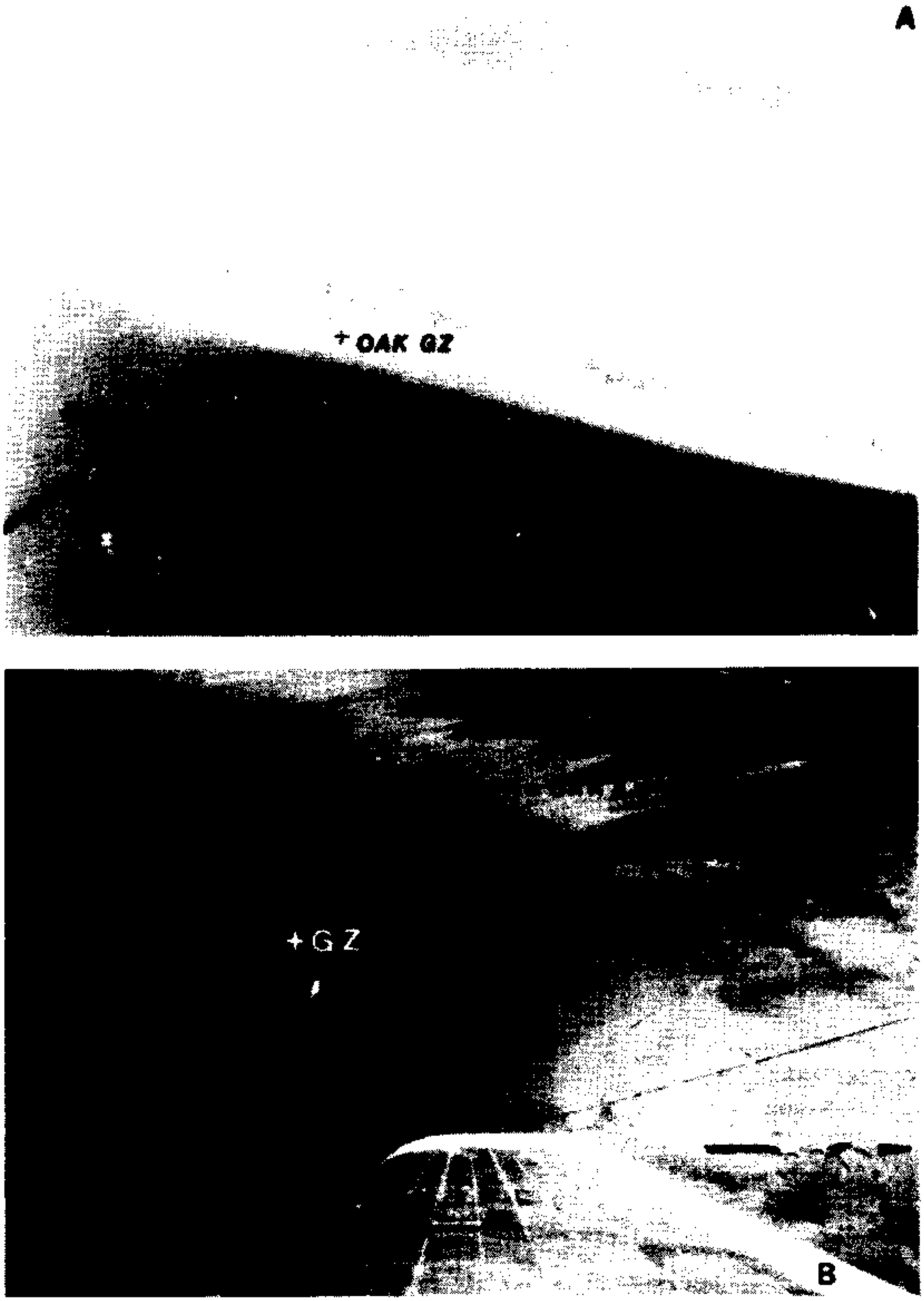


**Figure 2. Oblique air view of Oak showing ground zero before (A) and after (B) the blast. Notice that location is at transition between lagoon and back edge of the reef flat.**

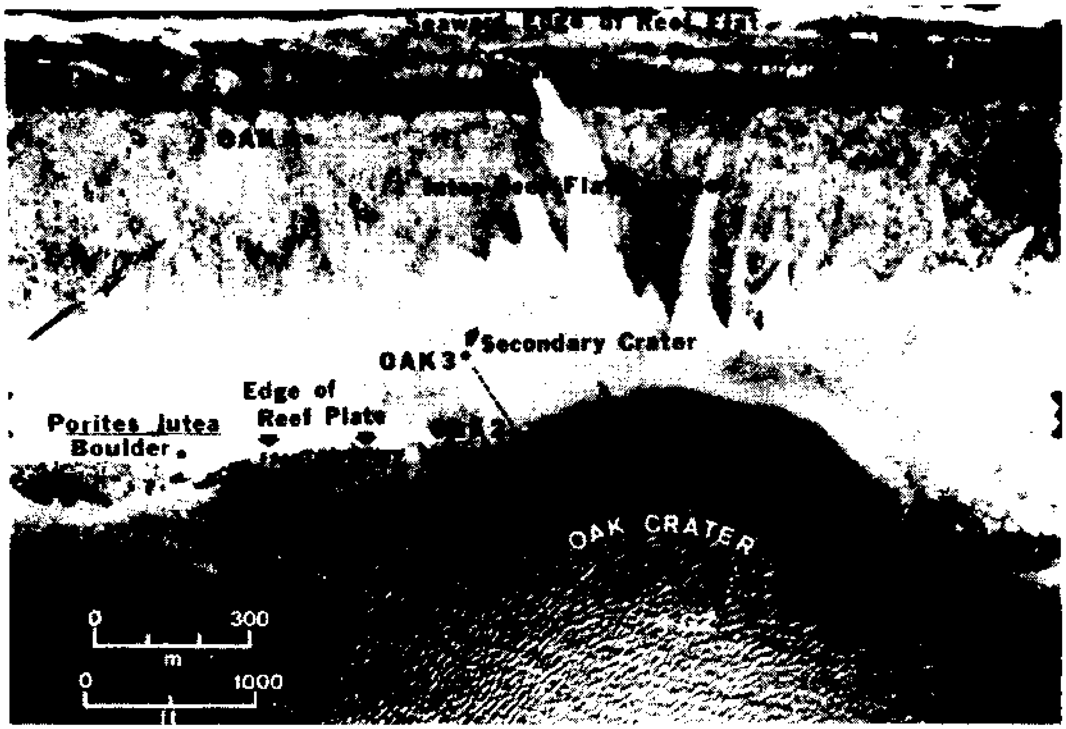


**Figure 3. Vertical air photo of Oak crater showing ejecta rays on reef flat, area of depressed reef flat rock, and a small secondary crater.**

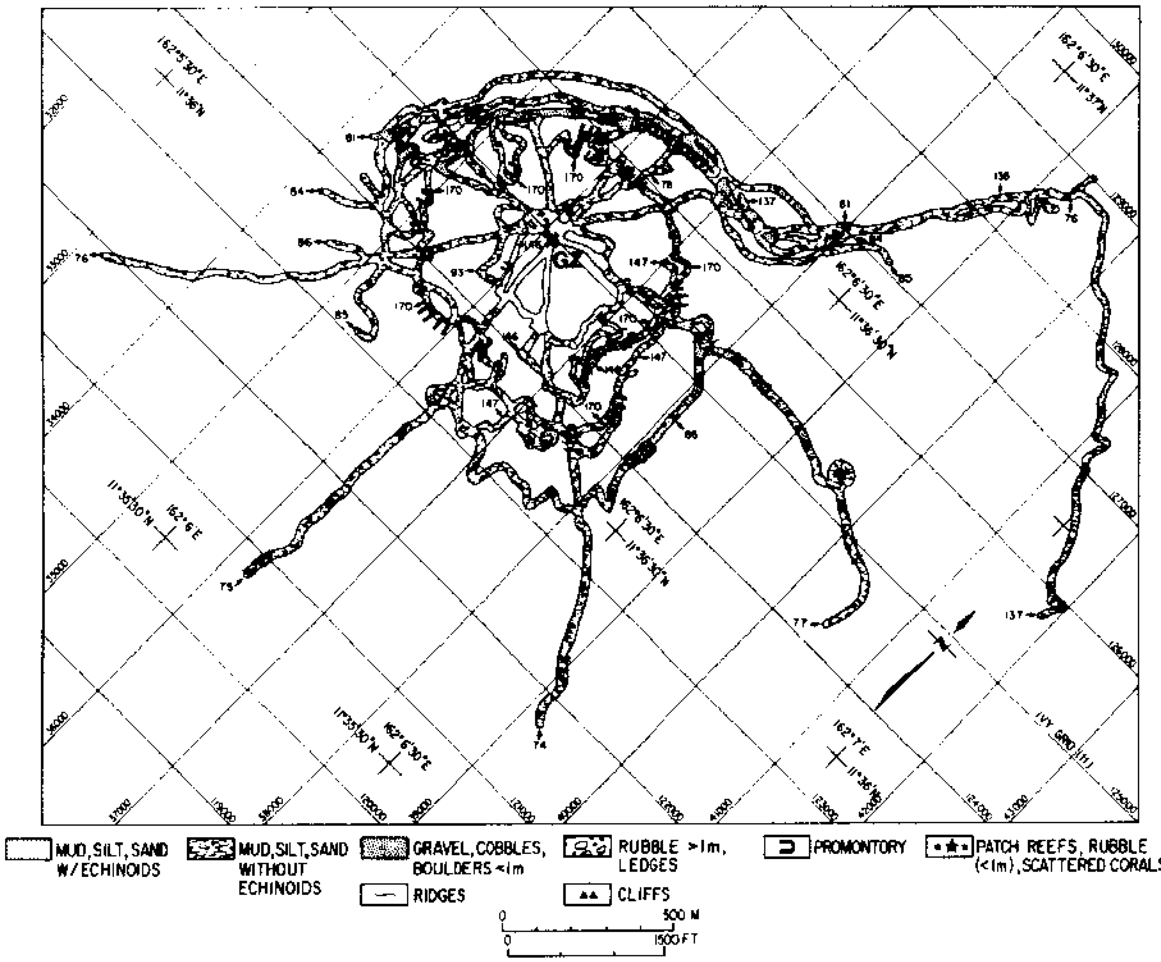


**Figure 4. Map of Oak crater showing bottom sediment distribution along submersible tracts. Carbonate mud and silt are the prominent sediment components within the crater.**

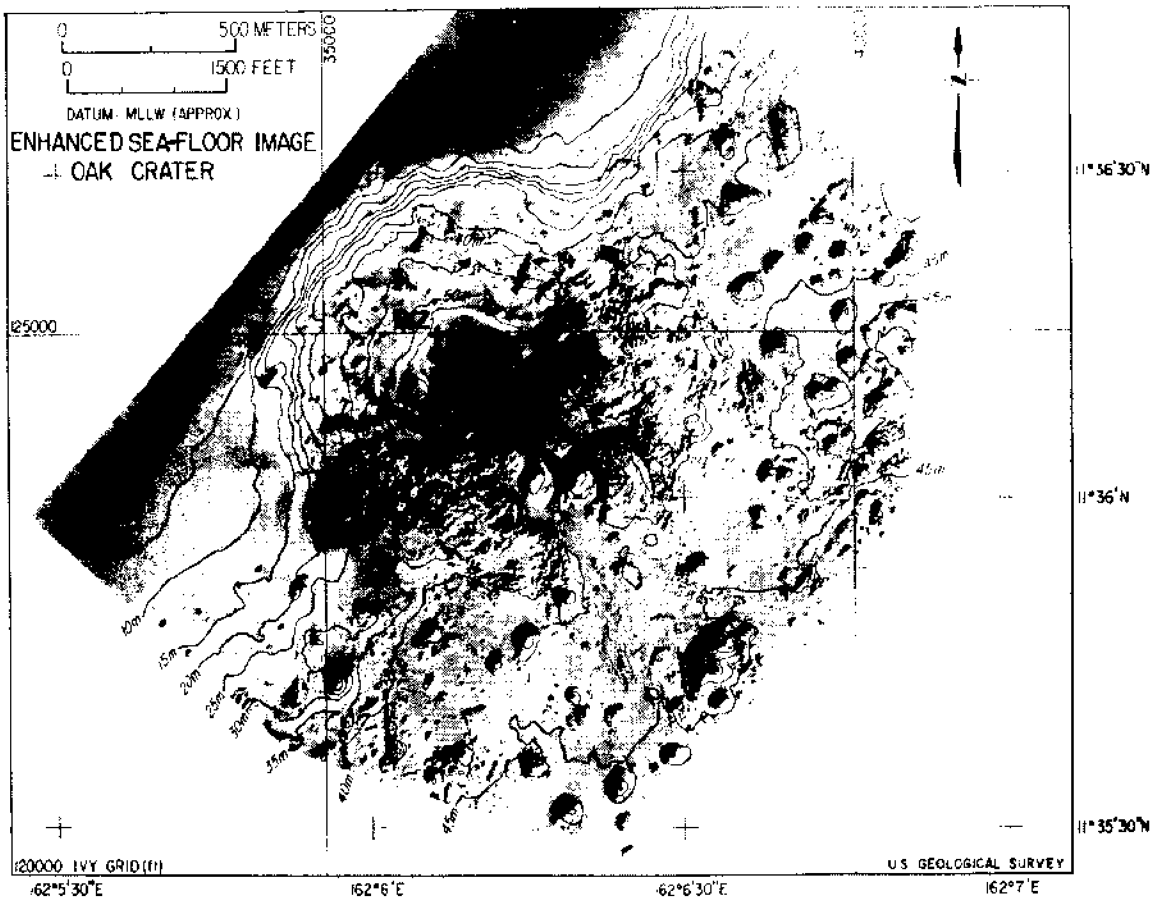


**Figure 5. Enhanced image of Oak crater with superimposed depth contours. Note abundance of patch reefs and channel southeast of crater. Water depth at ground zero (GZ) was 5 m before detonation.**

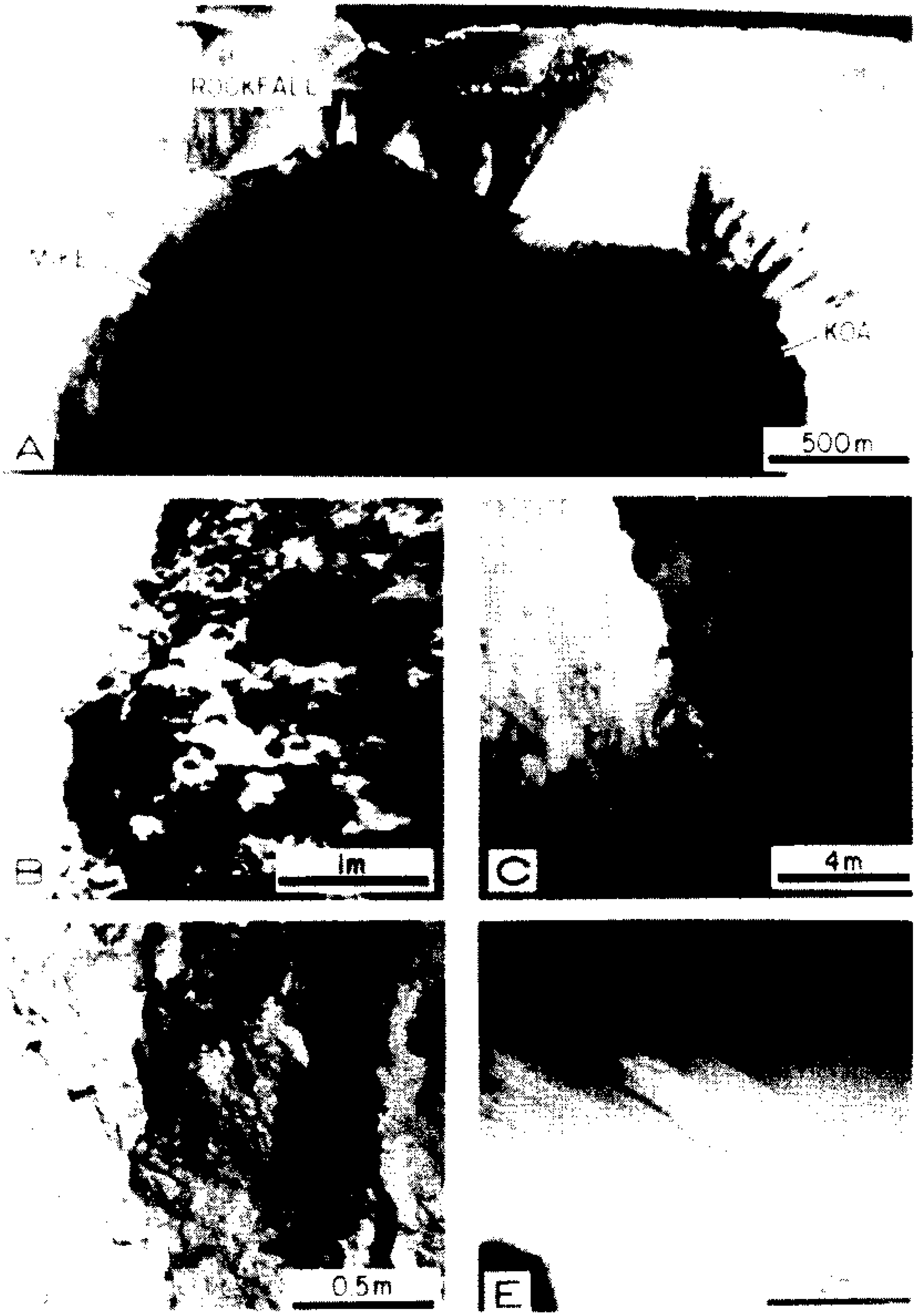


**Figure 6. (A) Aerial view of overlapping Mike and Koa craters rock fall area on seaward side of atoll opposite Mike. Note ejecta rays radiating from both craters. B–E show the outcrop produced by the rockfall.**

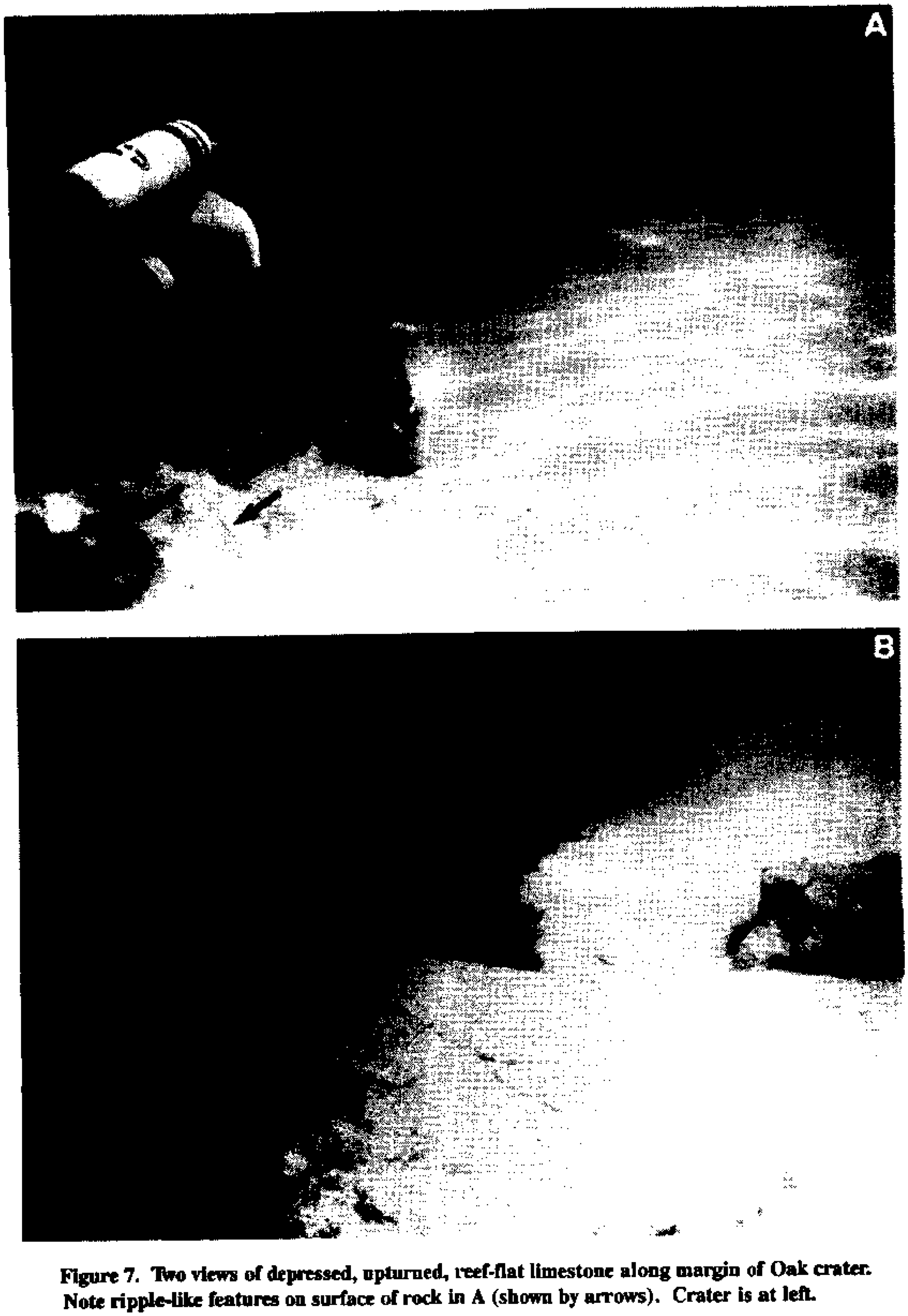


**Figure 7. Two views of depressed, upturned, reef-flat limestone along margin of Oak crater. Note ripple-like features on surface of rock in A (shown by arrows). Crater is at left.**

**Figure 8. Drilling with hydraulic drill on depressed reef-flat limestone on flank of Oak crater at a depth of 10 m. Submersible in background. View is toward crater.**

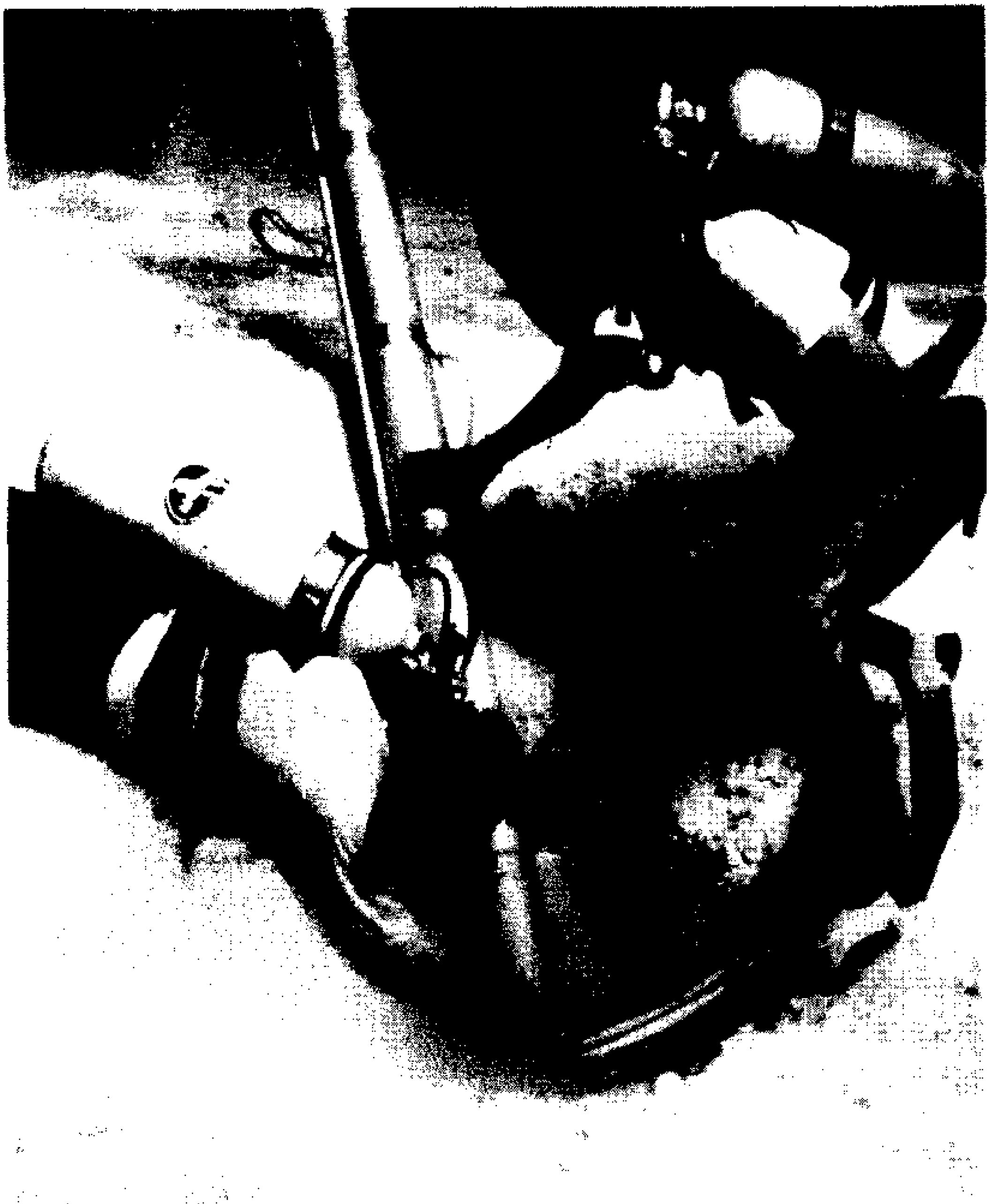

Figure 9. The air-lift being used to expose surface of reef flat rock on flank of Oak crater.

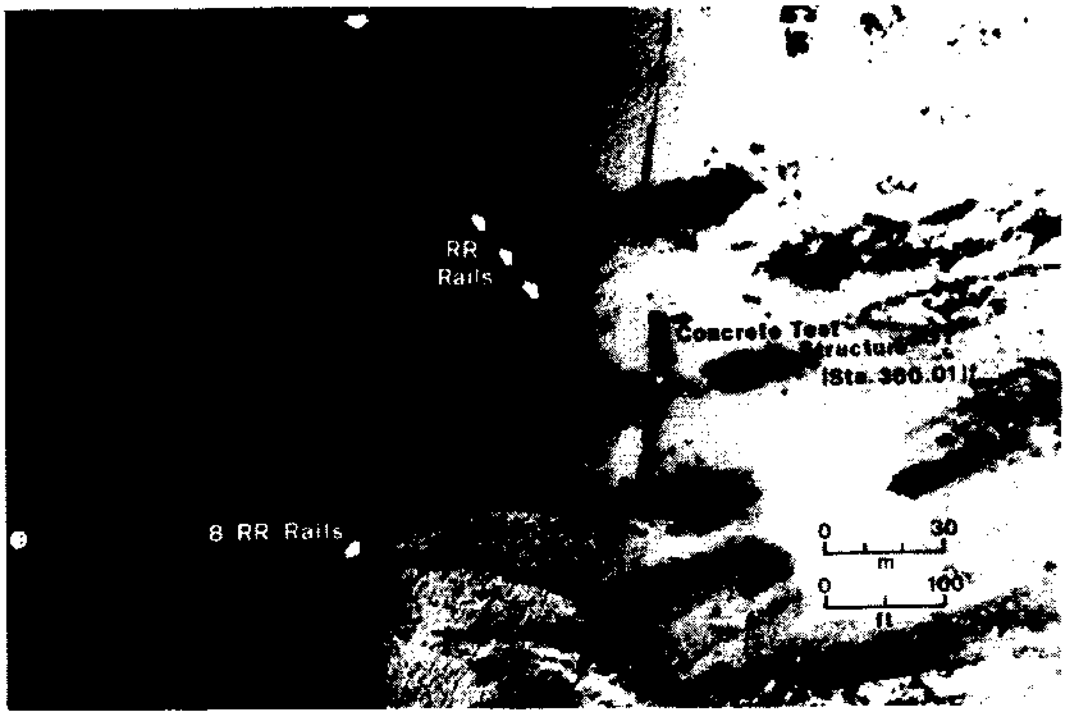


**Figure 10. Vertical air view of side of Koa crater showing position of cement testing structure shown on Figure 11 and 12 and rails shown in Figure 13. Deep rails begin at x in circle in lower left side of photo.**

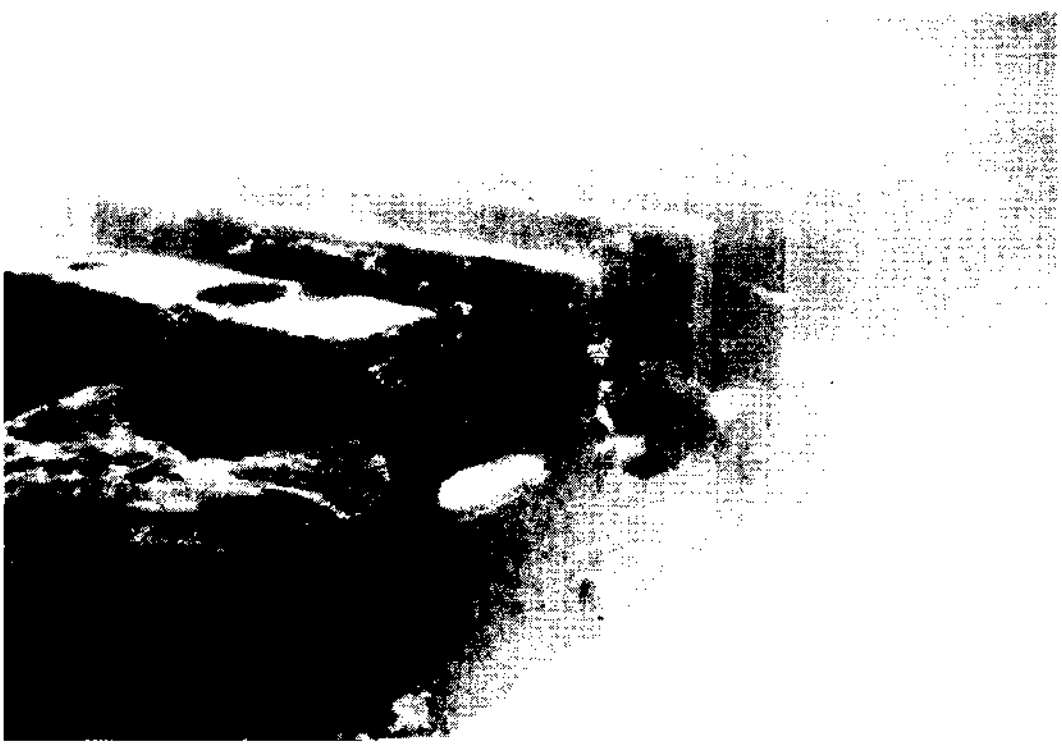

**Figure 11. Submerged coral-encrusted cement test structure near Koa crater. Surface is slightly awash at spring low tide.**

**Figure 12. Cement test structure, shown in Figure 7, when it was 3.5 m above sea level a few days before the Koa test. Arrow shows railroad rails used in construction of roadway to left.**

**Figure 13. Row of coral encrusted rails, same as in Figure 8, now 2 m below sea level. Note timbers at base of rails. Road fill was on left side of rail line.**

# USE OF TETHERED SCUBA DIVING TO IMPROVE SAFETY AND EFFICIENCY

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*Tethered scuba diving is one of the least used and most misunderstood modes of diving available to the scientist today. Modern equipment and techniques allow safe deployment of a single scuba diver for underwater observation and sampling. Inexpensive high-quality communications equipment facilitates effective diver monitoring and data transmission. Tethered scuba diving is extremely cost-effective and is the mode of choice for many diving operations in limited visibility water, shallow water, and under ice. Tethered scuba diving has many advantages over surface-supplied diving and conventional scuba diving with regard to diver efficiency, safety, operational cost, and equipment cost. Operational and safety procedures, equipment selection, and diver training is addressed.*

## INTRODUCTION

Swimming and working underwater using self-contained underwater breathing apparatus (scuba) is a standard practice in scientific diving. Accepted safety procedures for scuba diving operations generally require deployment of divers in pairs (i.e., use of the buddy system). On the other hand, commercial divers more commonly use surface-supplied (or umbilical) diving equipment and commonly deploy only a single diver to accomplish the underwater task. The diver is supported by a tender on the surface or in a diving bell.

A less commonly used mode of diving is tethered scuba diving. This generally involves the deployment of a single scuba diver who is tended from the surface by means of a safety line. Tethered scuba diving is probably one of the most under-rated and misunderstood of all diving modes. The procedures and equipment used for tethered scuba diving by some search/rescue and commercial divers are considered to be haphazard by many diving safety authorities. In the scientific diving community, tethered scuba diving has often implied attaching a rope to a solo diver using a conventional mouthpiece-style scuba regulator (hookah). There was no full-face mask security, no emergency air supply alternatives, no communications (except line-pull signals), and, generally, no specific training. Tradition, lack of state-of-the-art equipment, inadequate training, economic constraints, and narrowlyscoped recreational diving influences have compromised advancement and, in some respects, safety in scientific diving.

Tethered diving has never been officially accepted by the recreational diving community in the United States. Furthermore, only a limited number of scientific divers currently use tethered scuba techniques, probably because most scientists have been trained by recreational diving instructors. Critics of tethered scuba diving include the following concerns:

* Scuba diving without a buddy is unsafe;

* The diver could be at high risk if the safety line or tether became entangled;

* The diver would not have the assistance of a buddy in the event of air supply failure or depletion; and

* The diver would surely drown in the event of loss of consciousness.

On the other hand, advocates of tethered scuba diving consider the following factors in support of the practice:

* Tethered scuba diving may only be used for *selected* underwater activities, not as a complete substitute for all conventional scuba diving or surface-supplied diving;

* The tethered scuba diver is not diving alone since the surface tender, in reality, functions as a buddy;

* Modern diving practices include the use of voice communications between the diver and tender, thus providing a means of constantly monitoring the diver's status;

* Tethered scuba diving operations involves less equipment, less deck than conventional surface-supplied diving operations;

* An organization can easily and economically outfit and train conventional scuba divers for tethered scuba diving;

* Use of a single tethered scuba diver is probably a safer practice for diving in very limited visibility water than free swimming scuba diving where buddy separation is more probable and underwater emergency assistance requirements such as sharing air are extremely difficult at best, if not impossible;

* Loss of air supply or primary regulator malfunction emergencies can easily be resolved by using scuba fitted with dual regulators or a compact secondary scuba; and

* If a diver loses consciousness underwater, the full face mask would prevent immediate drowning and loss of communications/line response would prompt the tender to immediately recover the diver and/or deploy a standby diver.

The equipment and procedures for present day tethered scuba diving are significantly different from those used in past years. The following conditions and limitations are recommended for modern tethered scuba diving operations:

* Depth is generally limited to 60 ft (except in standby diver deployment emergency);

* Communications/strength member tether must be secured to the diver's scuba or safety harness;

* A full-face mask must be used;

* An emergency or secondary air supply and/or regulator system must be used; and

* The diver must surface when cylinder pressure is reduced to no less than 500 psi (300 psi for twin cylinder scuba).

Although tethered scuba diving is not considered as acceptable as surface-supplied diving by many researchers and commercial divers, it has proven satisfactory and safe for many scientific diving operations and for standby diver application. It has been especially useful for very limited to zero visibility shallow water research where the dive team does not have a surface-supplied system available. Under such conditions the presence of a second diver is of little or no safety benefit and may even constitute additional risk.

Tethered scuba diving has also been effectively used for extremely cold weather diving from small, open boats where the deployment of two divers would have greatly complicated logistics and increased the surface exposure time. This mode has also been successfully used for under ice diving.

## PERSONNEL

The minimum tethered scuba dive team should consist of no less than three persons – a tender/supervisor, a diver, and a standby diver. These individuals can develop an efficient diver rotation plan and work safely and comfortably from a small vessel. An additional qualified individual to serve as standby diver tender, record-keeping/timekeeper, and general diver aide is highly recommended.

Any competent scuba diver can be easily trained in tethered scuba diving techniques. Establishment of an acceptable training and operational tethered scuba diving program simply requires some special equipment (in addition to conventional scuba diving equipment), a slight modification of scuba diving philosophy, and a respect for both the advantages and limitations of this mode of diving. Furthermore, most competent scuba diving instructors can develop the knowledge and skill to teach tethered scuba. Since tethered scuba diving is more likely to be applied in working operations such as search/rescue and scientific research, the instructor should have a thorough understanding of the type of diving operations for which the diver is being trained.

The trained scuba diver will have to make some adjustments in diving philosophy and technique in addition to learning to use new items of equipment. The diver will have to adjust to working alone underwater and recognizing emotional and physical security in the tender above and special equipment. Consequently, competence and experience in scuba diving cannot be over emphasized.

**Tender**

A tender is a member of the dive team who assists the diver in dressing, donning scuba, pre-dive equipment inspection, deployment/retrieval, and post-dive activities. While the diver is under water the tender constantly tends the dive's tether to eliminate excess slack or tension. In the event of communications unit malfunction, the tender must exchange line pull signals with the diver, keep the diving supervisor informed of the diver's status, and remain alert for any signs of an emergency.

With few exceptions, the tender should also be a qualified tethered scuba diver. This insures that the tender will have a complete knowledge of all equipment and procedures. In addition, operational efficiency is highest if all members of the team can be included in a diver rotation plan. When circumstances require the use of a non-diver as a tender, it is the responsibility of the diving supervisor to assure that that individual is properly instructed in tender duties. Ideally, non-diver tenders should complete the same training course as tethered scuba divers (except for in-water activities) plus be completely familiar with scuba and scuba diving procedures. They must also be trained in general and diving-related first aid and currently certified in CPR. It is evident that one cannot simply hand the tether to a bystander and say "Will you tend the diver today?"

**Standby Diver**

A standby diver is required for all tethered scuba diving operations. The diver must be fully qualified and equipped to enter the water in response to an emergency at any time. The diver shall be appropriately dressed and have equipment assembled so that he/she can don all equipment and be deployed within one minute. This means that each tethered scuba diving team must have two complete tethered scuba outfits. Ideally, a second tender is also available to serve the standby diver.

The standby diver is deployed at the discretion of the diving supervisor. The standby diver functions in a lifeguard capacity ready to render aid to a distressed diver on the surface as well as under water. The standby diver is positioned at the diving station where he/she can observe the entire operational area and quickly deploy.

## EQUIPMENT

In addition to standard scuba diving equipment and thermal protection, the following items shall be included in a tethered scuba diving kit:

- Demand breathing lightweight full-face mask with communications;
- Twin 72, 80, or 100 cubic foot scuba unit with dual regulator manifold or a separate 15 to 40 cu. ft. emergency scuba (commonly called a pony cylinder in scuba diving) [single cylinder scuba may be used for short and/or shallow dives provided that a dual valve system with two regulators or an emergency scuba is included in the system];
- An over-pressure relief valve must be used on any first stage regulator without a downstream second stage;
- Submersible pressure gauge on primary regulator;
- Communications/strength member tether; and
- Surface communications unit.

### Mask

From a safety and communications standpoint, it is necessary to use a full-face diver's mask rather than a conventional mouthpiece-style scuba regulator. First, proper communications is very difficult with a mouthpiece-style regulator. Second, in the event that the diver is injured or loses consciousness, the mouthpiece-style regulator could easily be dislodged and lost. With a full-face mask, even if the diver is unconscious he/she could continue to receive air.

Based on personal preference, a diver or diving group may select one of several conventional surface-supplied demand breathing masks (i.e., Heliox-18, KMB-10, DM-5 or equivalent) which have been standard equipment in scientific, commercial and military diving for more than a decade or a lightweight demand breathing mask (i.e., AGA, Widolf, DSI EXO-26, or equivalent).

Most tethered scuba divers prefer to use a lighter weight, lower internal volume demand breathing full-face mask rather than the heavier, more complex commercial/military masks. These masks are constructed with either soft rubber full-face assembly or a solid support frame with a rubber face seal and are fitted with a high impact polycarbonate plastic wide-view face plate. A large, flexible nose pocket facilitates pressure equalization in the ears. The mask is secured to the diver's face using a head harness (or spider) assembly. A demand regulator is fitted to the front of the mask.

Lightweight masks do not generally include the special side block assembly for attachment of a secondary air supply as described above. However, a separate manifolding assembly is available. Communications components are fitted inside the mask with an earphone positioned in a pocket in the face seal or on a head strap. An oral-nasal mask minimizes dead air space. The lightweight masks are generally less expensive than the conventional commercial surface-supplied divers' mask and scuba divers find them to be more comfortable.

**Tether**

An excellent *combination safety and communications* line constructed of 7 mm nylon static kermantle rope with a tensile strength of 5800 lbs. is now available. The four communications wires are woven directly into the rope. This rope has the strength and handling characteristics of ordinary safety rope. Tying knots in the rope apparently has no adverse effects on the communications wires. Quick-connect electrical connectors are fitted to each end and special adapters are available. This special rope may be coiled or conveniently stored in and dispersed from rope bags.

The diver's end of the umbilical assembly is fitted with a large stainless steel snap shackle or caribiner to facilitate attachment to the diver's safety harness. This system allows any stress on the tether to be transferred to the diver's harness. The shackle is secured to the tether with an appropriate knot or a clamp that allows most of the stress to be transferred to the strength member. A D-ring is secured to the surface end of the assembly so that it may be secured at the diving station. This reduces the possibility of the tender and communicator being pulled overboard in the event of underwater stress.

The tether may be marked at 10-foot intervals starting at the diver's end using brightly colored tape or other appropriate marking system. This enables the tender to determine exactly how much tether has been deployed.

**Communications Unit**

A standard compact diver communicator is used for tethered scuba diving. Compact communicators are powered by expendable or rechargeable batteries. The tender generally wears the communicator on a belt or neck strap. A combination earphone/microphone headset is plugged into the communications box. This enables the tender to satisfactorily communicate with the diver in areas of high ambient noise levels and requires less power usage than loudspeaker systems. The tender can adjust both diver and tender volume. Some models are fitted with a tape recorder connection. Generally, any surface-supplied diver communicator may be used with a tethered scuba system; however, compact models are more convenient.

A common talk or round robin system may be used to provide all parties with simultaneously open line communications, as in telephone conference calls, without operating any controls. This system involves special wiring of the mask earphones and microphone and the use of a four conductor wire to the surface. Some current model compact communications units are designed to be used as either a two-wire push-to-talk or four-wire common talk system.

**Emergency Self-Contained Air Supply Options**

The tethered scuba diver has several independent options for resolving an air supply depletion or regulator malfunction situation. The diver may activate a second or backup regulator, or make a controlled emergency swimming ascent.

Keep in mind that the possibility of air supply depletion or regulator malfunction should be absolutely minimal if equipment is properly maintained and the diver properly monitors his/her air supply pressure gauge. Naturally, the primary regulator must be fitted with a submersible pressure gauge to facilitate convenient air monitoring throughout the diving operation. Unlike surface-supplied diving, the diver is solely responsible for monitoring remaining air supply. However, as in scuba diving, the diver must be trained and prepared to resolve such an emergency.

If the air supply from the primary first stage regulator is interrupted due to malfunction, the diver may activate the secondary or emergency air supply by turning a valve located on the separate manifold block attached to the scuba harness. Hoses from two first-stage regulators are attached to the manifold assembly (which may be mounted on the scuba harness). The air supply from the secondary regulator is secured by closing a valve on the assembly; the primary air supply passes through the assembly into a hose attached to the diver's second stage regulator. In the event of a primary first stage malfunction involving interruption of air flow, the emergency air supply is activated by turning this valve.

The secondary first stage is attached to one outlet on a single or twin cylinder scuba dual regulator outlet manifold assembly (i.e., Sherwood slingshot valve or dual outlet valves) or to a separate scuba cylinder (i.e., 15 or 40 cu. ft. cylinder with standard valve). Many divers prefer to use a separate scuba cylinder rather than a dual regulator manifold assembly. In the event of primary air supply depletion, the diver has an emergency air supply.

Divers working in overhead environments and locations with high risk of entanglement often prefer two scuba cylinders of equal size instead of the smaller cylinder. In this case two separate 70 to 100 cubic foot cylinders are mounted in a double band-harness system. Unlike the air management techniques that involve alternating regulators used by cave and wreck scuba divers, the tethered scuba diver conducts the complete dive as a single cylinder dive.

The second cylinder is only to be used in an emergency. Custom designed full-face masks with dual second stage regulators and air manifolding systems are now being used in wreck and cave diving. These units show great promise for improved safety in tethered scuba diving.

Keep in mind that this secondary first stage regulator hose leads to a closed valve during normal operation, not to a down-stream (or fail safe) second stage regulator as in conventional scuba. In the event of a first stage over-pressure malfunction in the secondary regulator, the complete cylinder pressure could be released into the low pressure hose causing a rupture and subsequent loss of air supply. Consequently, this regulator must be fitted with an over-pressure relief valve.

Most scuba diving instructors and scuba divers are unfamiliar with these safety relief valves that must be installed in a low pressure port on the regulator first stage. Consult full-face mask manufacturers and commercial diving equipment suppliers for acquisition of these special valves.

**Safety Harness/Tether Attachment**

The scuba backpack and harness assembly may also serve as the diver's safety harness. This harness is equipped with D- rings for attachment of the diver's umbilical assembly and is designed to withstand a minimum of 1000 lbs. pull in any direction. Keep in mind that the scuba harness must be securely attached to the diver. In the event of an emergency, stress placed on the harness by the tender could pull the scuba from the diver. Thus, although use of the scuba backpack and harness assembly for a safety harness appears to be a standard practice, many divers do question the safety of this method. For this reason, many tethered scuba divers prefer to use a separate body harness or safety belt worn under the scuba harness for attachment of the tether.

**Standard Scuba Diving Equipment**

Each diver will wear appropriate thermal protection garments, a buoyancy compensator with power inflator, fins, weight belt, a sharp knife, watch/time (for timing ascent rate) and depth gauge consistent with accepted practices in conventional scuba diving. Decompression tables may be considered optional since the supervisor/tender will monitor the dive time and inform the diver of his/her status. However, some tethered scuba divers prefer to use decompression microprocessors to monitor their dive status. Generally, each diver on a team is required to provide his/her personal diving outfit (excluding full-face mask, special scuba, tether, and communicator).

Depending on the dive depth, duration, and activity the diver may use standard single or twin cylinders taking into consideration the valving requirements discussed above for emergency or backup air supply.

## TETHERED SCUBA DIVING PROCEDURES

Careful and detailed planning and preparation is the key to diving safety. The pre-dive activities involve all personnel and include the inspection and assembly of equipment, activation of air supply systems, and dressing the divers. This is, of course, in addition to survey of the task; evaluation of environmental conditions; selection of techniques, equipment, and divers; fulfillment of safety precautions; establishment of specific procedures; and personnel briefing.

Tethered scuba diving is a reasonable compromise between scuba and surface-supplied diving. A single diver can work safely and efficiently in limited visibility water. Safety is maintained through a direct connection to the surface and voice communication. The status of the diver can be monitored at all times. Operational efficiency is greatly improved since only one diver is deployed at any given time. An efficient diver rotation schedule can be prepared to achieve maximum underwater time with minimum personnel. Scientific observations can be easily transmitted to the surface and recorded on tape. The diver's time, physical status, and emotional status can be monitored by surface personnel.

Tethered scuba diving cannot be considered as a replacement for either scuba or surface-supplied diving in all situations. The tethered scuba diver is effective within the distance limitations of the tether (generally, not more than 200 feet long) and up to a depth of 60 feet. As in scuba diving, dive duration is limited by the amount of air contained in the breathing apparatus. On the other hand, the surface-supplied diver is more effective for deeper work, under more extreme environmental conditions, and in higher risk situations. In the event of entrapment or entanglement, air supply duration is unlimited. The scuba diver is more effective for swimming great distances under water and performing tasks requiring extensive lateral and vertical mobility.

Finally, equipment costs becomes a factor. Ideally, most diving tasks performed by a tethered scuba diver could be performed by a lightweight surface-supplied diver. However, the cost of outfitting a surface-supplied diving team is somewhat higher than for a tethered scuba diving team, assuming that the team is already completely outfitted for scuba diving. A tethered scuba upgrade involves purchasing two tethers, two compact communicators (or one larger two-diver model), two lightweight demand-type full-face masks, and the necessary components to convert to an appropriate independent secondary regulator/air supply system. The surface-supplied diving outfit would require additional expense for an air supply and control system and a more expensive umbilical assembly.

### Tending the Diver

Tending is an art. Surface tenders should also be experienced divers or persons specially trained as tenders. The most effective assistance can be given only by a tender who is familiar with the equipment, procedures, safety precautions, conditions, and difficulties that are inherent in diving. It is the tender's responsibility to see that the diver receives proper care while both topside and underwater. He/she must check all equipment before sending the diver down.

When the diver is ready, the tender helps with dressing, checking equipment, and assists the diver to the ladder or entry point. The tender handles the tether and maintains a proper strain on the diver as he/she descends the ladder. For scuba diving type entries the tender assures that the tether plays out freely.

While the diver is submerged, the tender handles the tether, maintains communications, and monitors air usage by periodically requesting pressure readings from the diver. The usual means of communications between diver and tender is by voice intercom; however, it is important that basic line signals be memorized and practiced so they will be recognized instantly in the event of intercom failure or if apparatus not fitted with an intercom is used.

In tending the diver's tether, the tender must not hold the tether so taut as to interfere with the diver's work or movements. The diver should be given 2 or 3 ft of slack when he/she is on the bottom, but not so much that he/she cannot be felt from time to time. Signals cannot be received on a slack line; consequently, the diver's tether must be kept in hand with proper tension at all times.

Line-pull signals consist of a series of sharp, distinct pulls, strong enough for the diver or tender to feel but not so strong as to pull the diver away from his/her work. When sending signals, take all of the slack out of the line first. Repeat signal until answered. The only signal not answered when received is the emergency "haul me up", and "come up" is delayed until the diver is ready. Continued failure to respond to signals may indicate that there is too much slack in the line, the line is fouled, or the diver is incapacitated.

The tender should continuously monitor the diver's underwater timer and air supply pressure. He/she should inform the diver several minutes before the expiration of bottom time so that the diver can make necessary preparations for ascent. The tender keeps track of the diver's position by observing bubbles rising to the surface and informs the diver of his/her position relative to the boat/diving station. In addition, the tender must continually monitor the diver's activity. For example, the tender can frequently evaluate the diver's exertion by counting the number of breaths per minute. Experienced tenders will learn the diver's normal breathing rate. Significant increase in breathing rate may indicate potential overexertion. The tender may ask the diver to stop work, rest, and ventilate.

The tender may also have to serve as timekeeper. This job includes keeping an accurate record of the dive time and details of the dive. When possible, a separate timekeeper should be used or the timekeeper duties handled by the diving supervisor.

## UNDERWATER EMERGENCY PROCEDURES

The tethered scuba diver will deal with underwater emergency situations in much the same manner as a conventional scuba diver, however, he/she will not have the benefit of assistance from another diver unless a standby diver is deployed. Air supply depletion or regulator malfunction is probably the most threatening to the diver. Potential risk to the diver is reduced by the use of redundant breathing systems. The diver must also be trained in purging water from a flooded full-face mask, dealing with loss of communications, and freeing a fouled tether.

Divers entering tethered scuba diving training should already be familiar with procedures such as diver rescue on the surface, stress management, accidental ascent resulting from BC or dry suit overinflation, and so on through basic scuba diving training. Naturally, proper diving procedures and common sense precautions can prevent most, if not all, underwater emergencies from developing.

## SUMMARY

Tethered scuba diving is an acceptable alternative to conventional scuba and surface-supplied diving for performing many underwater tasks. This mode of diving can provide the scientific diver with a method to increase economical and operational efficiency while maintaining optimum safety. The additional equipment required for tethered scuba diving is readily available from commercial and rescue diving equipment suppliers. Most competent scuba divers can be easily trained in tethered scuba diving techniques.

The tethered scuba diving procedures and equipment discussed in this article are used on a limited basis at present. As this mode of diving gains popularity among rescue and scientific divers, techniques, equipment, and procedures for safer and more efficient diving will no doubt evolve. All divers and organizations are encouraged to use this mode of diving with a high respect for diver safety.

## ACKNOWLEDGEMENTS

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For additional information consult *Tethered Scuba Diving* published by the Michigan Sea Grant College Program as part of the Diver Education Series -- Publication No. MICHU-SG-87-501. This manual includes equipment descriptions, diving procedures, emergency procedures, air supply calculation formulas, an equipment list, and a training course outline.

This publication may be acquired from the Michigan Sea Grant Publications, The University of Michigan, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109-2099 ($2.25).

# THE UNIVERSITY DECOMPRESSION MONITORING BOARD

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*All compressed-gas research diving activities are supervised at American Academy of Underwater Sciences member organizations by a Diving Control Board often representing departmental and administrative units rather than diving expertise. The lack of diving specialists on the Board can result in some apprehension when new techniques are proposed by the program's participants. Such Boards will naturally be inclined to restrict new advances and inadvertently may even preserve dangerous diving practices because they are time-tested.*

*The Florida State University Decompression Monitoring Board, composed of diving, medical and physiology specialists, is based upon a model recently described by Schreiner (1989) at an Undersea Hyperbaric and Medical Society workshop on table validation. The Florida State University Decompression Monitoring Board is designed to review proposed changes from existing research diving procedures, such as new tables, breathing mixtures, rates of ascent, and dive computers, and advise the University's Diving Control Board as to what is necessary to bring about safe implementation of the technique.*

*Warm Mineral Springs Archaeological Research Project requested the use of special gas mixtures to increase efficiency of their labor-intensive excavation at 160+ fsw. After careful evaluation of the available options, the Decompression Monitoring Board, in cooperation with the Warm Mineral Springs Archaeological Research Project, proposed a gas mixture, supporting documentation, monitoring procedures and diving/medical protocol to successfully continue their proposed underwater research. The new plan was approved by the Diving Control Board and has resulted in a productive season of archaeological data collection.*

## INTRODUCTION

Agency or institutional diving programs must be capable of flexibility and growth in response to new ideas if they are to effectively continue to support their constituents. During the past decade, university diving programs have witnessed the introduction of a variety of new technology and/or techniques such as special gas mixtures, new diving schedules, ascent rates, dive computers, and a challenge to the validity of some US Navy Diving Tables. Even casual reading of the latest edition of Diving Medicine (1990) reveals the extent diving physiology has progressed over the past decade. By American Academy of Underwater Sciences (AAUS)

Standards for Scientific Diving, the responsibility to approve new technology and techniques rests squarely upon the university's Diving Control Board (DCB). The only guideline available to this DCB for the selection of diving tables, for example, is that the table and algorithm since decompression/dive computers are permitted be as conservative as the US Navy Diving Tables (1985).

Lambertsen (1989) stated that diving is no longer performed against a single set of standard tables. Validation or consensus requirements for diving should not be standardized either, as the diversity of diving activities today (and the consequences of these activities which he lists in five tables) would make the testing unmanageable. Hamilton (1989) recommended that new procedures be given appropriate testing under laboratory conditions (presumably within a chamber or with one available) and then introduced into operational use through an intermediate closely controlled "provisional" phase. While he states that procedures, such as decompression tables, should never be considered finished, a point in time is reached when the "provisional" status is lifted and fully operational diving is permitted. Clearly, in my opinion, definitions for each phase and the decision to move from one phase of procedure validation to the next must be made by recognized representatives of the agency involved.

Many university DCBs are composed of representatives from departments that have faculty, staff and/or students that collect data underwater. They are seldom selected for their expertise on diving physiology or medicine in spite of the fact that the Board holds a responsibility to the University's President for the overall safety of the science diving program. I have witnessed a reticence on the part of DCBs to adopt new ideas because of a profound lack of experience regarding a proposed technology or technique, and causing substantial frustration among its participants. This should not be surprising since Board members (faculty in Anthropology, Engineering, Geology, etc.) may not have an adequate background to make a proper or timely determination. Unfortunately, this may encourage practices such as encouraging maximum no-stop repetitive dives on the USN Diving Tables (which is known to cause intravascular bubbling) when no-bubble tables, such as from DCIEM (Eatock & Nishi, 1987) have been available for years.

Several options exist to resolve this problem. The DCB may choose to rely upon their University Diving Officer (UDO) to advise them exclusively. This option may be limited by the expertise of the individual UDO and subject to the political motivations and pressures often placed upon a single individual. The DCB may decide to exclusively follow nationally supported "time-tested" procedures as may be advocated by organizations such as the Undersea Hyperbaric and Medical Society (UHMS), Divers Alert Network (DAN), National Oceanic and Atmospheric Administration (NOAA), US Navy or the AAUS. This option may be both legally defensible, as it represents a community standard, and prudent, as these agencies represent the bulk of the experience in a particular technology. It may not, however, be sensitive enough to serve the university's unique technical or administrative needs. Since the university assumes the liability of it's actions and benefits (or losses) from the actions that it may take, I see little reason to rely "solely" upon the judgement of another agency with little or no vested interest.

Last year I proposed to form a sub-committee to the DCB, based upon a model proposed by participants of a 1988 Workshop on "Validation of Decompression Tables" (highly recommended reading). While the immediate motivation behind creating this board was the development of deep diving procedures for the Warm Mineral Springs Archaeological Research Project (WMSARP), the long term objective was the establishment of an advisory board to the DCB on new procedures in decompression. I proposed to call the board the Decompression Monitoring Board (DMB) after a model proposed by Hamilton and Schreiner (1989).

The idea that a new diving procedure must evolve through carefully supervised phases is not new. Several agencies monitor the progress of a diving project, permitting greater autonomy as they demonstrate mastery of the required skills. This model was codified at FSU over a decade ago. Projects requiring advanced diving technology (under ice, polluted water, cave, etc.) are closely assisted for the first season while new technology and techniques are tested and a dive plan is refined. This is followed by a careful monitoring period of up to two years during which alterations are made as deemed necessary. After two years, the project is listed as fully operational and ADP supervision is reduced.

This approach is not unlike the flow diagram proposed by Dr. David Elliott during a discussion period as cited by Schreiner (1989) where mathematical modeling, table calculations, and chamber testing new diving tables is followed by an operational evaluation or "provisional" period where the tables are tested in under a "real" environment, then released for field use. The challenge, of course, is to decide when to move from the laboratory to the field and what constitutes adequate monitors for this provisional phase. These difficult decisions are left to DCB.

The purpose of this new unit, the DMB, is to advise the university's DCB on procedures in decompression and monitor them. Since from a physiological reference point the entire dive directly impacts decompression, this Board may advise the DCB on procedures as divergent as gas mixtures and mixing stations, acceptable levels of pre and pro-dive exercise, rates of ascent, in-water 100% oxygen decompression, dive computers, the medical plan, as well as the expected diving and decompression tables. Monitoring these procedures permits the required feedback necessary to adjust for new information acquired during testing and provisional phases, and to recommend that a project move from one phase to the next. At no time may the DMB assume the responsibility of the DCB.

The DMB at FSU is composed of five members appointed by the DCB for an indefinite period of time. All are voting members. When matters of the DMB are voted upon by the DCB, the UDO (holding a voting position on both Boards) must abstain from the vote. Each person was selected because he/she had experience in diving physiology, including the participant representative. At present, members of the DMB are as follows:

| | |
|---|---|
| E. Haymes | faculty, Department of Movement Sciences<br>exercise physiology in hypobaric/hyperbarics |
| Wm. Kepper | consultant, Family Practice of Tallahassee<br>physician and trained in hyperbarics |
| R.W. Hamilton | consultant, Hamilton Research, Ltd., New York<br>physiologist/decompression |
| G.R. Stanton | faculty, Academic Diving Program<br>University Diving Officer, biology |
| W.A. Cockrell | faculty, Warm Mineral Springs Arch. Research Proj.<br>program participant, archaeologist |

A Special Gas Mixtures for Science Diving Workshop, sponsored by the ADP, with special assistance from WMSARP, was held in March 1989 (Stanton, 1990a). During the workshop other-than-air breathing alternatives were presented and successfully used on dives to 100 and 150 feet. Prior to the formation of the DMB six months later, numerous sessions were held between consultants, faculty and members of the DCB at FSU discussing the advisability and etiology of using trimix (nitrox had already been established on campus the previous year) as an alternative breathing mixture to air for depths below 150 fsw.

The newly formed DMB focused on the WMSARP request for dive clearance to depths from 150 to 200 feet for several reasons. Their Legislatively funded project was a high profile and well documented research effort under the Anthropology Department (strongly justified as a university endeavor, [McDonald, 1990; Cockrell, 1990]). Their site was ideally suited for a trial project as it was warm, stable, and logistically simple (Smith, 1986; Cockrell, 1988). Their requirements were not unlike others soon to be proposed in the foreseeable future (cave research). And their willingness to cooperate provided everyone with the opportunity to develop what was hoped to be a model for future special gas mixtures projects.

During the Fall semester of 1989, the DMB met formally at least six times, and informally in smaller groups dozens of times. Individual members of the Board traveled to the Springs (over 300 miles south of Tallahassee) at various times to meet with staff and consultants to the project. While not all meetings were cordial, the resulting recommendations, documents and administrative structure bear witness to the sincerity of all those who participated in their creation.

Additional advice beyond the confines of the Board was often sought. Legal opinion was sought regarding the question of public access to the on-site recompression chamber. Clarification of the definition of a diving injury and the advisability of discretionary treatments from our Office of Environmental Health and Safety resulted in a safer medical backup structure. Acceptance of the recommendations of the Validation Workshop regarding "provisional" status during operational dives based upon the DCAP algorithms was secured from FSU's Human Subjects Committee (HSC). The HSC was particularly willing to exclude the WMSARP dives from their control because the purpose of the research was archaeology, not diving physiology, and that the dives would be closely supervised and monitored with the ability to restructure the schedule if warranted. Staff requirements and their supervision were hammered out with the Anthropology Department Chairman until all parties were satisfied that both the safety and research needs of this project were adequately met.

Additional training (chamber operations) and monitoring technology (doppler) was recommended and secured for the ADP and WMSARP staff. I spent a week training with DCIEM in Toronto while Dr. Crosson (Delta P) spent time training at the springs, both using the latest Techno Scientific Ltd. ultrasonic doppler technology available. My assistant and Dr. Kepper spent a week at Hyperbarics International taking a course in hyperbaric medicine. The newly hired diving supervisor held a week long chamber course at the site.

Appropriate life support technology was recommended for the gas mixtures proposed, and adjusted as the site restrictions dictated (such as the location of the chamber, use of an in-water bell, mixing gasses on site, etc.). A medical plan was drafted (Kepper, 1990), revised and ultimately approved. Additional consultants were brought in from Reimer Engineering and Delta P to assist in the installation of the existing chamber. Air testing was provided by the Research Diving Program at the University of Florida through our terms of reciprocity.

Provisional diving and decompression tables based upon the DCAP algorithm for a trimix (21% $O_2$, 40% He, 39% $N_2$) were presented and approved after initial testing and field trial data was presented and examined by the Board (Hamilton 1987, 1990a, 1990b). Over the brief four week diving season, post dive doppler monitoring provided data back to the Board on a weekly basis with telephone discussions as needed. This data was forwarded to members through the mail or if considered critical, through a medical FAX network described in the medical plan.

An excellent example of the continued success of the DMB is cited below. Dr. Larry Abele proposed to observe and collect a new class of Crustacea (Remepedia) found in saline pockets at 95 fsw over 900 feet back in terrestrial caves in the Yucatan, Mexico. In 1988, he was able to spend less than 15 minutes maximum on air at the site because of the swim and available gas on his back. In 1990 he proposed to use nitrox and in-water 100% oxygen decompression, and increase his bottom time to 120 minutes with a decompression obligation of 43 minutes. Thirty six percent nitrox tables were generated by Hamilton (1990c) which permitted up to 180 minutes at 95 fsw with a maximum of 76 minutes of decompression (20/10 fsw stops on 100% $O_2$). The FSU DMB was asked to evaluate the proposal and associated tables. They found them acceptable for provisional status with some additional recommendations. Doppler monitoring and additional training in nitrox, and staging (transport of more than just the bottles on your back) were recommended. Training in both areas was completed by the ADP staff prior to data collection. The quality and availability of oxygen in Mexico was questioned and resolved prior to departure. A report was requested by the DCB regarding the dives and monitoring data for their next meeting (Stanton, 1990b).

As the Decompression Monitoring Board enters it's second year, it faces new challenges, including recommendations for which dive computers are advisable for use at FSU and guidelines on how to use them, alternate air diving tables such as DCIEM, rates of ascent for various gas mixtures, continued discussions regarding in-water 100% decompression, acceptable levels of intravascular bubbles, and testing for patent foramen ovale, just to name a few. A project to study the hydrology of the Woodville Karsp has requested changing over from air to trimix for their deep work in local caves. Guidance for some of these issues is available from AAUS and others and no doubt will make the job easier. However, from the DCB's perspective, seeking the recommendations of a panel of resident experts is far better than saying no.

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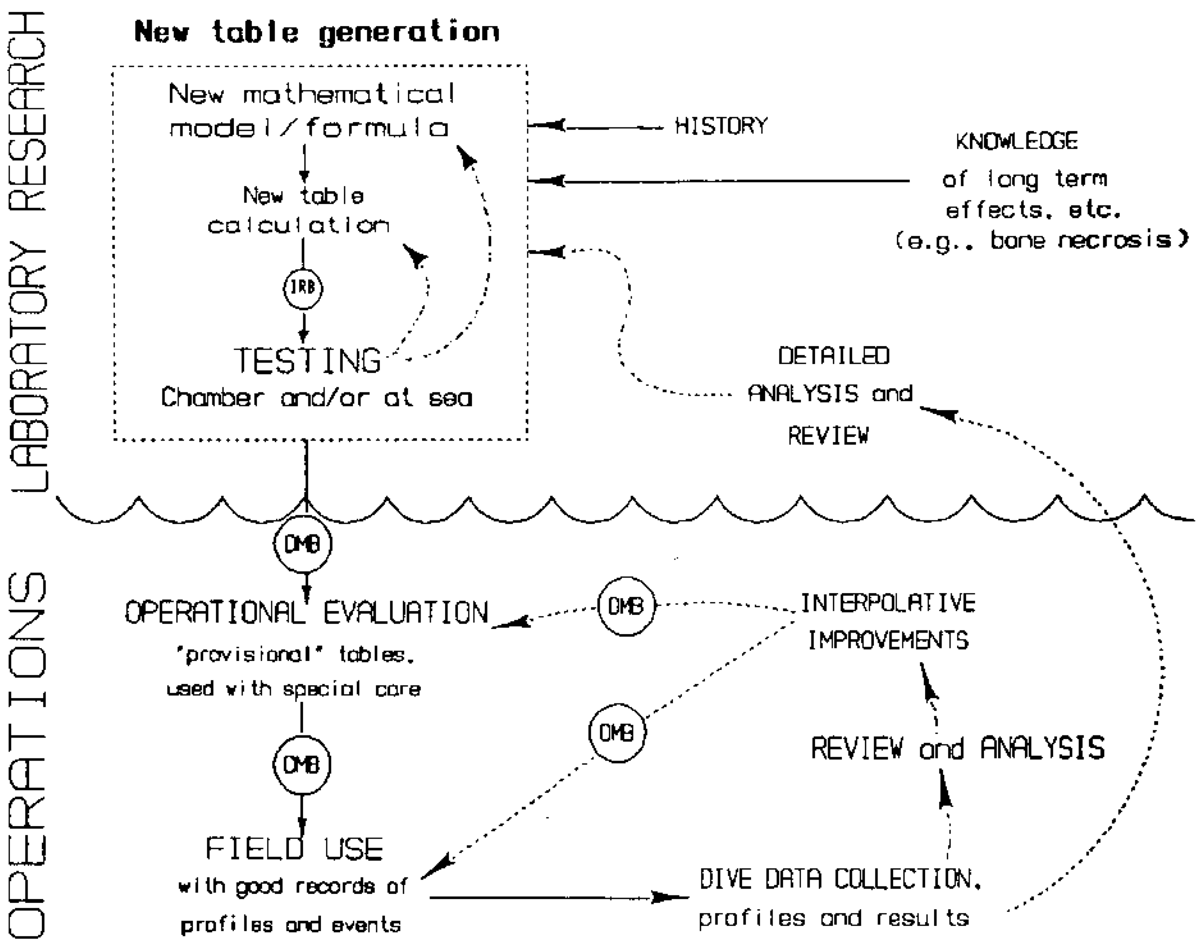


**Summary Figure 1. Flow diagram of the decompression table development and validation process. The upper part of the diagram is by intent research and subject to "informed consent" procedures. The lower half is operational, and is considered to be within the job description of the divers. Solid arrows show flow of information, dotted arrows show feedback, and those with circles imply some judgemental approval by the Institutional Review Board (IRB) or the "DMB," a competent authority (board or committee) within the organization conducting the dives; it might be called the "Decompression Monitoring Board."**

# IMPACT OF RECREATIONAL DIVERS ON CORAL REEFS IN THE FLORIDA KEYS

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*Recreational divers were systematically observed in the Florida Keys between May 10 and August 13, 1989. A total of 206 divers were observed during 66.6 hours of diving. Divers wearing gloves were responsible for 72% of the 1164 interactions observed. Out of the 135 scuba divers, 26% had one or less interactions with corals; 10% had 11 to 20 interactions; and 4% had 30 or more interactions per 30 minutes of diving time. Of the 71 snorkelers, 61% had one or less interactions with corals and none had more than 5 incidents. However, snorkelers treading water stir up large clouds of sediments and are more apt to stand on corals than scuba divers. Wilcoxon Two-Sample Tests show that divers with gloves have significantly higher numbers of interactions with corals than divers without gloves, that men have more interactions than women, and that scuba divers have more interactions than snorkelers.*

## INTRODUCTION

The beauty, diversity and uniqueness of the coral reefs of Florida have attracted large numbers of visitors from all over the world. Coral reef usage at the Looe Key National Marine Sanctuary (LKNMS) has increased 300% in the last 5 years (Figure 1); from 17,483 people in 1985 to 54,691 people in 1989 (Sanctuary records). This increase in coral reef use and concern over the degradation of the reef system along the Florida Keys (Tilmant and Schmahl, 1981, Rogers, 1985) has raised the question of how recreational divers impact the areas in which they dive. Sanctuary management and conservation organizations need to know whether repeated touching of corals by coral-reef users is sufficient to damage coral tissue or make it prone to infection or necrosis (Miller, 1988) so that appropriate steps may be taken to protect the only living reef adjacent to the Continental United States.

Diver damage to coral reefs is frequently masked by natural events and is difficult to assess. (Tilmant et. al., 1981, Jaap et. al., 1988). However, surveys of areas in the Key Largo National Marine Sanctuary have shown significant changes in diversity and populations which frequently indicate a dysfunction within the system that is the result of ecological stress (Dustan and Halas, 1987). To determine if divers are an aspect of this ecological stress, it is necessary to ascertain how divers behave in the water.

Until recently, the major human damage to the reef was thought to be anchor damage and boat groundings (Brown and Howard, 1985), diver damage was considered negligible. However, with the recent increase in the diver population, diver impact could be an important factor. To determine if this unknown human factor is related to reef stress syndrome, it is necessary to answer these questions: 1) How do stony corals and octocorals react to the repeated physical contacts with divers. 2) What is the frequency and nature of the physical contact that users of coral reefs make with reefal organisms? 3) Is this physical contact sufficient to add to the ecological stress the reefs are experiencing? Two of these questions are beyond the scope of this paper and will be dealt with in a companion study. This paper will address the question of frequency and nature of the interactions of the recreational diver with coral reef benthos.

## METHODS

The Looe Key National Marine Sanctuary (LKNMS) core area located about three miles south of Big Pine Key was the primary study site, but divers were also observed in the Key Largo National Marine Sanctuary, Sombrero Reef off Marathon, at Eastern Dry Rocks, Western Dry Rocks and Sand Key in the Key West area (Figure 2). These dive sites were chosen because of their popularity with both local and visiting divers. All observations were made from charter dive boats or concession boats operating from Sanctuaries and include both scuba divers and snorkelers. Subjects were chosen at random from divers on the dive boats.

The observed interactions between diver and corals were 1) hand on the coral to steady or to help the diver gain control, 2) kicking or brushing a coral with the fins, 3) standing on corals (especially snorkelers), 4) grabbing corals to pull themselves through the water, 5) rubbing against a stony coral with any part of the body, 6) hitting a coral with the scuba tank or other pieces of equipment and 7) creating sediment clouds.

To quantify the incidents, each interaction was recorded on a prepared slate. Damage to corals was visually evaluated and recorded, i.e. broken skeleton or the scrapping away of polyp tissue. Sediment clouds generated by divers were ranked as low, moderate, or high. Additional information included duration of dive, diver experience, buoyancy control, whether gloves were worn, meteorological conditions, and the quality of the briefings given by the captain or dive master.

To standardize observations, data on each dive was adjusted to 30 minutes. The interactions were then ranked into one of 4 categories:

a - 0 to 1 incidents
b - 2 to 10 incidents
c - 11 to 20 incidents
d - > 20 incidents

Data were compiled into tables listing diver (scuba or snorkeler), rank, sex, type of incident, whether with stony coral and/or octocoral, total number of incidents, and whether gloves were worn.

A Krustal-Wallis non-parametric analysis was applied because of the skewed distribution to show significant differences between groups. A Wilcoxon Two-Sample Test was applied to determine significant differences within groups (Sokal and Rohlf, 1981).

## RESULTS

A total of 206 divers were observed, including 113 men and 93 women, during 66.6 hours of diving time with a total of 1164 interactions, standardized to 1027 interactions. A group of 65 snorkelers was observed at the Key Largo National Marine Sanctuary and will be discussed separately. Their interactions were not included in the statistical analysis.

**Table 1: Ranking of divers observed, including number of people and percentage of each group (in parentheses).**

| RANKING | TOTAL DIVERS | SCUBA | SNORKEL |
|---|---|---|---|
| a (0-1 incidents) | 78 (38%) | 35 (26%) | 43 (61%) |
| b (2-10 incidents) | 104 (50%) | 76 (56%) | 28 (39%) |
| c (11-20 incidents) | 14 ( 7%) | 14 (10%) | 0 |
| d (> 20 incidents) | 10 ( 5%) | 10 ( 7%) | 0 |

Table 1 lists the totals and percentages of individuals in each category. Of the snorkelers, 41% had no interactions compared to 10% of the scuba divers. The average number of incidents for snorkelers is 1.1 ($n=71$, standard deviation = 2.7) The average number of interactions of the scuba divers is 7.0 ( $n = 135$, standard deviation = 15.7). Of the 1027 standardized incidents or interactions, 951 were committed by the 135 scuba divers while only 76 incidents were by the 71 snorkelers. The number of scuba divers is almost double the snorkelers, but the number of incidents by the scuba divers is 12 times the number by the snorkelers.

**Table 2: The number of incidents by type of diver, sex and whether gloves were worn.**

| DIVER | SEX | GLOVES | NO GLOVES | UNREC | TOTAL |
|---|---|---|---|---|---|
| Scuba | Male | 500 (n=50) | 96 (n=21) | 55 (n=14) | 650 |
| | Female | 232 (n=37) | 25 (n= 7) | 45 (n=12) | 300 |
| | | | | | 951 |
| Snorkel | Male | 5 (n=1) | 34 (n=33) | | 39 |
| | Female | 5 (n=1) | 32 (n=36) | | 32 |
| | | | | | 1027 |

Table 2 gives the number of incidents divided into type of diver, sex, whether gloves were worn and the total interactions. UNREC are the scuba divers of which no record was made if gloves were worn. The Krustal-Wallis Test of difference of location showed that there is a significant difference between the groups ( df=7, P. <.001). The Wilcoxon Two-Sample Test showed significant differences in that: scuba divers had more interactions than snorkelers (n=206, t=8.1 P <.001); divers with gloves had more interactions than divers without gloves (n=180, t=9.8 P <.001); males had more interactions than females (n=206, t=20.6 P <.001).

**Table 3: Number of interactions per group with corals and octocorals.**

| Diver | Stony Corals | Octocorals | Total |
|---|---|---|---|
| Scuba | 629 | 312 | 942 |
| Snorkeler | 66 | 19 | 85 |
| Total | 695 | 331 | 1027 |

Table 3 shows the number of interactions by both types of divers toward corals or octocorals. Scleractinian corals were touched more often than soft corals or octocorals: 68% of the observed encounters were with scleractinian corals as compared with 32% for octocorals.

More than twice as many incidents were recorded late in the summer than early, 173 incidents by 36 divers from May 15 to June 27, as compared to 424 incidents by 39 divers from July 15 to August 15. The early summer divers were usually out-of-state while the late summer divers were in-state. Two divers with the most interactions were from Miami and West Palm Beach.

Diver-caused breakage included a total of six breaks in three different events or 0.6% of all incidents. The number of people (3) who broke coral is 1.4% of all divers. Corals broken were a small tip from a branch of an *Acropora palmata*, one branch of *Acropora cervicornis* and one incident when four blades from one *Millepora* were broken.

The most frequent interactions were the "finning", with 704 incidents and the "push off", with 153 incidents. The two most common interactions of snorkelers is standing on corals and the vigorous treading of water that stirs up large amounts of sediment when in shallow water.

## DISCUSSION

A healthy reef is not only an esoteric and ecological necessity, but an economic one as well. A healthy reef system supports large fish populations, provides a genetic diversity reservoir, and is a renewable natural resource that encourages the economic benefits of tourism (Van't Hof, 1985). In Monroe County a viable, healthy reef system is of vital necessity that supports an economy dependent on both fishing and tourism.

A moderate amount of perturbation is a natural phenomena that is believed to maintain the high diversity of the coral reefs and from which many systems recover relatively quickly, i.e., hurricanes and large storms (Shinn, 1976; Tunnicliffe, 1981). But hurricanes are episodic events, while human impacts are much smaller but chronic over long periods of time. Brown and Howard (1985) states that stress over time will decrease diversity causing the fragile and rarer corals to disappear.

Divers inflict low-intensity, long-term stress on coral reefs by touching and breaking corals, by increasing suspended sediment, and by eutrophication of the water column. In a reef already stressed these acts can have serious repercussions. A simple touch or scratch can trigger what is called a "Shut Down Reaction" in corals that can kill a coral head in a matter of hours . This reaction is very contagious and can pass to other corals, possibly killing an entire reef (Antonius, 1977, 1981).

Breakage of branching corals can be utilized by some corals as a means of asexual reproduction (Szmant 1986, Bothwell 1981). Following hurricanes recovery of *Acropora* stands within 2 to 3 years is possible because of asexual reproduction (Shinn, 1976). However, fragment size is important in survival. The larger the fragment, the higher the survival rate (Bothwell, 1981). Diver breakage usually consists of small fragments from the tips. Size is also important in sexual reproduction in that corals must be at least 100 cm square to reproduce (Szmant, 1986). In small coral colonies, breakage would reduce the size and thus retard the ability to reproduce sexually.

When a coral is touched, brushed or stood upon, mucus is removed. This mucus layer protects the coral polyp from the harmful effects of the environment by increasing the polyps resistance to infection and bacterial attack (Crossland et al., 1980). Irritation caused by the repeated removal of the mucus layer is stressful and can cause the coral's mucous secretory cells to undergo sublethal changes (Peters et al., 1981). (A study to determine the impact of "touching" on corals is in process and will be completed by fall 1990).

Recreational divers who just want to "look", as opposed to divers with a purpose, i.e., photography, shelling, artifact collection, lobstering and/or spear fishing, have fewer contacts with corals; and snorkelers have less contacts than scuba divers since most snorkelers are just "looking". Except for one case, all the c-ranked divers were experienced, proficient divers who dove for a specific purpose. The one exception was a diver who was totally inept in the water.

Most observations were conducted in protected Sanctuary areas. The observations made in non-protected areas were limited to 12 people with a total of 68.0 interactions. While this number is not sufficient to show that divers in non- protected areas have more interactions, two of the divers had more than 25 interactions each. However, if these observations were expanded, I believe that divers in non- protected areas would have significantly more interactions than divers in protected areas.

This study shows that 5% of all recreational divers have more than 20 incidents per 30 minute period. Sanctuary personnel at the LKNMS estimate that about 3% of the diving public they observe are have "high" rates of impacts when diving in the core area (personal communication). This slight difference could be attributed to differing interpretations of "high" impact and to the time restraints imposed on the officers by other duties.

An additional concern associated with diver impact on Sanctuary reefs is the influence both the divers and their boats have on water chemistry. For example, on an optimum day, more than 300 divers may use the 1200 by 200 meter core area of LKNMS. Since reefal waters are naturally nutrient poor, 300 divers urinating in the water over the reef could increase the nitrogen concentration of the water by 25 to 50%. Kinsey and Davies (1979) experimentally documented that fertilizing a reef can reduce rates of coral calcification while stimulating algal growth. If divers are damaging corals by chronically and inadvertently fertilizing heavily used reefs, this problem can be reduced by educating divers and concession operators that metabolic wastes should be disposed of in sewage treatment systems.

The coral reefs of Florida are suffering from a stress related syndrome. Clearly, divers could be a part of that problem. To minimize diver effects, I suggest that a "one meter" rule be introduced, i.e. that divers keep at least one meter distance from all live biota. I further recommend that gloves be eliminated since there is a strong correlation between the number of incidents with and without gloves. Ankle weights should also be discouraged to lessen the possibility of sediment clouds. Dive instructors should be encouraged to improve education on the value of coral reefs and what they are, and to improve diver training in the area of buoyancy control, overweighting should be discouraged. Most of all, increase the amount of reef under Sanctuary control. My observations, though unproven, indicate that divers on Sanctuary reefs are more careful and less apt to touch.

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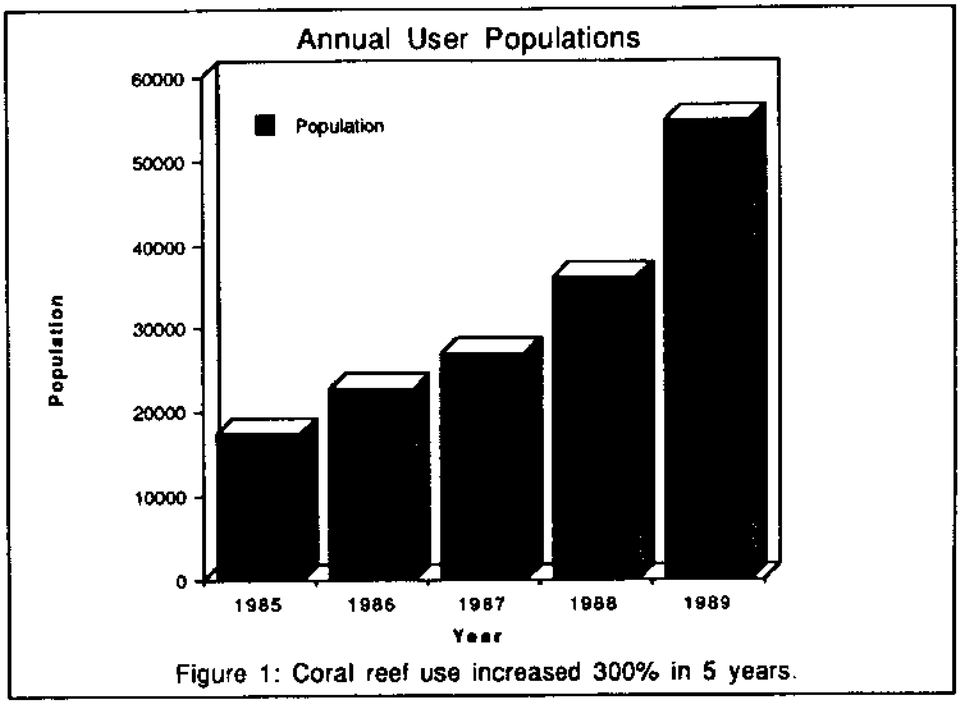


**Figure 1. Annual user populations at Looe Key National Marine Sanctuary.**

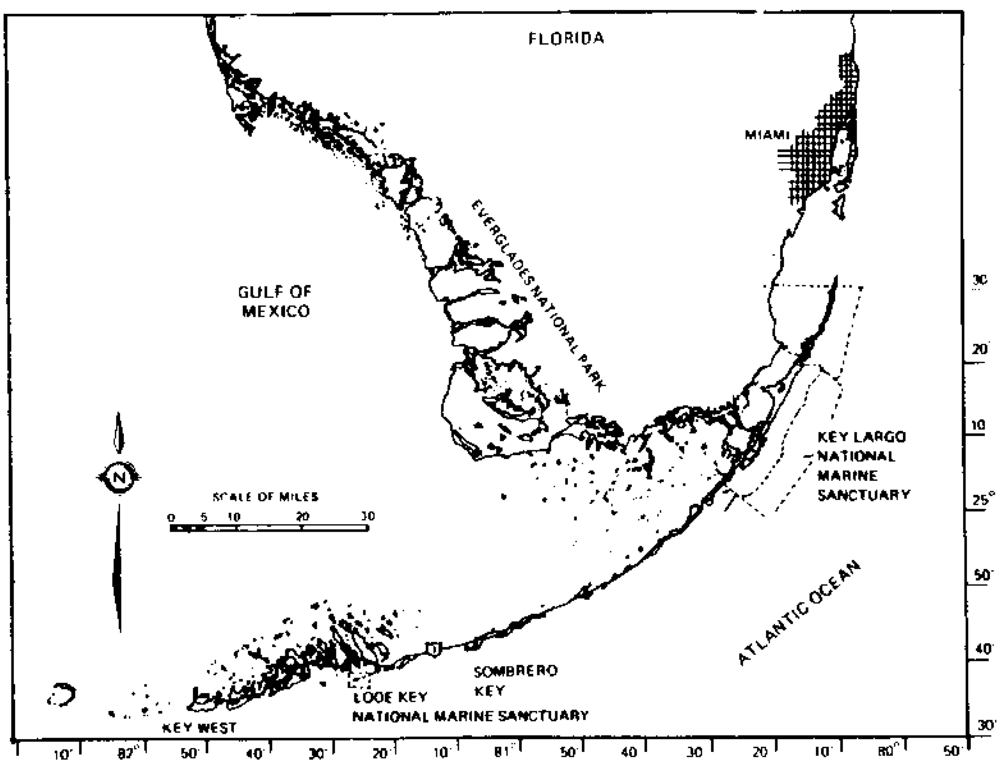


**Figure 2. Diver observation sites in the Florida Keys. (Jaap, 1984)**

# ASSESSMENT OF REEF FISHES AT SOMBRERO KEY, FLORIDA

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*We quantitatively assessed the reef fish assemblage at Sombrero Key, a bank reef off the middle Florida Keys, during May 8-11, 1988 using the stationary survey method. We divided the reef fish assemblage into three depth zones (< 3m, 3-6 m, and 6-10 m). These zones approximated, respectively, the* Millepora *ridge (zone 1), the* Acropora palmata *area (zone 2), and the reef front base which was characterized by more sand and less coral cover (zone 3). Eighty-eight species in 27 families, represented mainly by pomacentrids, labrids, and haemulids were observed in all zones. The largest number of individuals and the highest Shannon species diversity occurred in zone 1, however, species richness was higher in zones 2 and 3.*

## INTRODUCTION

Coral reef fish assemblages are complex and there exists a lack of quantitative data concerning abundance and distribution patterns of fish species, particularly for Caribbean and Florida reefs (Alevizon et al. 1985, Bohnsack et al. 1985). This has resulted in a lack of understanding of the factors which govern the structure of coral reef fish assemblages. Most studies have dealt with small patch reefs, artificial reefs, or discreet portions of a larger reef system (Ogden 1982). Only a few studies have dealt with reef fish abundance and distribution by depth. Tilmant (1984) surveyed the literature concerning Florida coral reefs and found a characteristic species composition associated with different reef types and depth zones within a particular reef. Alevizon et al. (1985) found fish species composition and abundance to vary significantly with depth at Deep Water Cay located off Grand Bahama Island. However, variation in fish community structure was influenced by coral zonation rather than depth itself. Bohnsack et al. (1985) found that fish species occurrence and abundance varied with habitat associated with different depth zones on Looe Key Reef.

Coral reef fishery resources of Florida and the Caribbean are facing increasing utilization and adverse environmental pressure by man. Uses include commercial fishing, recreational fishing, spearfishing, and collecting. Although some of Florida's coral reefs have been designated as sanctuaries, all are faced with an increase in diving and boating activities. Traditionally viewed as nonconsumptive, diving activities may now be a significant disturbance in some areas. In addition, Florida's coral reefs appear to be suffering from poor water quality associated with increased development of the Florida Keys and south Florida, in general (Ward 1990). Proper management of coral reef fisheries requires quantitative information concerning fish abundance, distribution, and structure of the fish assemblages.

The objective of this paper is to provide quantitative data regarding reef fish abundance and distribution by depth zones within the Sombrero Key reef. This reef is currently not protected under any sanctuary designation and has received increased disturbance by way of diving and spearfishing activities. Our null hypothesis is that there is no difference in fish species diversity, mean fish species richness, and fish species abundance in three vertical depth zones on the coral reef defined as < 3 m, 3-6 m, and 6-10 m.

## METHODS

### Study Area

All visual sampling was conducted at Sombrero Key located within the Florida Reef Tract approximately 8 km south of Boot Key and 35 km northeast of Looe Key National Marine Sanctuary. Sombrero Key has well defined spur and groove formations on the seaward side down to about 9.2 m. The tops of some spurs may be awash at low tide. The shoreward edge of the reef is surrounded by sand interspersed with seagrass beds *(Thalassia testudinum).* Below 10 m the spur and groove formations give way to a combination of sand mixed with low profile limestone covered with octocorals and sponges. We divided the reef into three depth zones. Zone 1 began at the top of the reef and ended at a depth of 3 m. Zone 2 ranged from 3 m to 6 m. Zone 3 started at 6 m and ended at the bases of the spur formations in 10 m of water.

### Sampling Technique

Sampling was conducted between 0900 and 1530 hours on May 8th through the 11th, 1988 with the exception of May 9th when sea conditions precluded safe diving. Six SCUBA divers, working in pairs, used the stationary visual survey methods of Bohnsack and Bannerot (1986). Each pair of divers began a sample in a zone by separating from one another a distance at or just beyond the limit of visibility. In some cases, the pair were not able to see one another such as when sampling opposite sides of a spur. However, efforts were made to stay within easy swimming distance for safety considerations. Each diver began by facing seaward and listing all species seen within an imaginary cylinder stretching from the bottom to the surface. A radius of 7.5 m was used since Bohnsack and Bannerot (1986) determined that this radius maximized the number of species and individuals that a diver could observe including cryptic and shy species. The diver rotated clockwise and listed species for 5 minutes. This usually required several rotations. Except for species not likely to remain in the area such as carangids, individuals of a species were not counted during the first 5 minutes.

Abbreviated scientific names using the first three letters of the genus and first four of the species aided in efficient coding of data onto water proof data sheets. At the end of 5 minutes, numbers of each species within the sampling area were counted beginning at the bottom of the list and working up. After all species had been counted, the percentage of sand, limestone, gorgonia, and hard coral was estimated for each sample. Each sample required 15-20 minutes. The pair of divers then swam to a different sample site. The number of swim kicks required to swim to the new site was obtained from a random numbers table printed on water proof paper. A complete description and analysis of the sampling technique can be found in Bohnsack and Bannerot (1986).

### Data Analysis

Data were analyzed using Statistical Analysis Systems, Inc. software and the UNCW VAX computer. Total number and mean number were calculated for each fish species by zone. Additional comparisons by zone included species richness (mean number of species) and species diversity. The Shannon-Weiner diversity index as presented in Smith (1974) was used to calculate species diversity.

## RESULTS AND DISCUSSION

Three days of sampling resulted in a total of 47 samples with 14, 18, and 15 being taken in zones 1, 2, and 3, respectively. The average depth sampled in each zone was 2.7 m in zone 1, 5.1 m in zone 2, and 7.2 m in zone 3.

### Habitat Description

Zone 1 was dominated by hard coral, followed by limestone, gorgonia, and sand. Coral found in this zone was primarily fire coral, *Millepora complanata*. Limestone and sand dominated zone 2 followed by hard coral and gorgonia. Elkhorn coral, *Acropora palmata*, dominated the hard corals in zone 2 although some smaller heads of brain coral, *Montastrea annularis*, were present. Zone 3 was dominated by sand followed by hard coral, limestone, and gorgonia. Both brain and elkhorn coral were present, however, brain coral dominated by forming massive heads at the bases of the spurs. As depth increased the relative percentages of gorgonia decreased and that of sand increased consistently. The increase in sand with depth was a result of the presence of the wider sand grooves between the spur formations.

**Fish Assemblage**

Eighty-eight species representing 27 families were observed during the study period (Table 1). Families containing the most species were the Pomacentridae, Labridae, and Haemulidae followed by the Scaridae and Serranidae. Forty-one species (46.6%) were observed in all three zones. Five species (5.7%) were observed only in zone 1, 10 (11.3%) were observed only in zone 2 and eight species (9.1%) were observed only in zone 3 (Table 2). The occurrence of a species in only one zone may be attributed to the habitat present in some cases. For example, the large percentage of sand found in zone 3 may have resulted in the presence of such species as the yellow stingray and bridled goby. The short study period may also have resulted in the observation of a species in only one zone.

A total of 11,996 individuals were observed during the study period (Table 1). The greatest number of species were observed in zones 2 and 3. Mean species richness was also highest in zones 2 and 3 with values of 19.9 and 19.2 respectively. Mean species richness for zone 1 was 16.5. Species diversity for zones 1, 2, and 3 was 4.5, 4.3, and 4.2 respectively. This indicates that although more species were present in zones 2 and 3, the distribution of individuals among species was more even in zone 1.

Ten species comprised 78.1% of the total number observed for all three reef zones (Table 3). These species included 3 labrids, 3 pomacentrids, 2 haemulids, 1 carangid, and 1 lutjanid. Bluehead wrasse, sergeant major, smallmouth grunt, and the bicolor damsel numerically dominated the Sombrero Key fish assemblage. Although their relative ranking changed, they were the four most abundant fish species throughout all three depth zones. The feeding requirements of three of these species may be less restrictive than other similar species. This may have resulted in their numerical domination of the reef fish community. The bluehead wrasse readily takes plankton in the water column. Other labrids consume macroinvertebrates associated with the substratum. The sergeant major is a midwater feeding planktivore. The bicolor damsel feeds on plankton as well as algae.

Barjack was among the ten most dominant species in all three zones. Likewise, yellowtail snapper and bluestriped grunt were among the ten most numerous species in all three zones. The striped grunt was included in the top ten species in zone 1 as was the French grunt in zone 3. The grunts are macroinvertebrate bottom feeders and feed off the reef at night using the reef for shelter during the day.

The only other pomacentrid fish among the ten most dominant was the dusky damsel in zone 1. One mullid and 2 labrids in zone 2 and 2 labrids in zone 3 rounded out the ten most dominant species in each zone. Unlike the haemulids, the species from these last three families are dependent on the reef for food as well as shelter and because of this a pattern seems apparent. A herbivorous bottom feeder, the dusky damsel, in zone 1 appears to be replaced by the macroinvertebrate feeders in zones 2 and 3. The algal food source required by the dusky damsel might not be as abundant in zones 2 and 3.

**Family Accounts**

**Holocentridae**

The relative abundance of all three species of squirrelfish was greatest in zone 3 (Table 1). Nocturnally active, these fish hover in or close to crevices during the day (Thresher 1984). The numerous crevices and ledges at the base of each limestone spur provide optimum daytime habitat for these species. Bohnsack et al. (1985) reported the holocentrids on Looe Key Reef to be most abundant in the forereef and buttress zones. Both zones overlap in terms of depth and habitat composition with the zone 3 of this study.

**Serranidae**

The graysby and harlequin bass were more abundant in zone 2 (Table 1). Bohnsack et al. (1985) found these species to be relatively abundant in the forereef and buttress zones although the highest abundance was recorded over deep live bottom habitat.

**Pomacentridae**

The three most numerous damselfishes were the sergeant major, bicolor damselfish, and dusky damselfish (Table 1). Sergeant majors were most abundant in zones 2 and 3. Bicolor damselfish were most abundant in zones 1 and 3 while dusky damselfish were most abundant in zone 1. The two chromis species were most abundant in zone 3. Yellowtail damselfish were most abundant in zones 1 and 2 whereas beaugregory were more abundant in zone 2. Threespot damselfish were about equally distributed throughout all zones. Generally, the planktivores were more abundant in zones 2 and 3 while the strict herbivores were more abundant in zones 1 and 2. The consistent distribution of the threespot damsel throughout all zones may have been a result of its relatively more aggressive behavior. Bohnsack et al. (1985) reported similar distributions for the planktivorous species at Looe Key Reef.

**Labridae**

Bluehead wrasse were most abundant in zone 1 (Table 1). The clown and rainbow wrasse were also most abundant in zone 1. Yellowhead wrasse were most abundant in zone 2 and puddingwife were slightly more abundant in zones 2 and 3. Bohnsack et al. (1985) reported that most of the labrids they observed were more abundant in the lagoon rubble habitat. Although we did not sample this habitat, three species were most abundant in zone 1 suggesting a preference for the shallower habitats similar to the lagoon rubble sampled by Bohnsack et al. (1985). The preference of the shallower habitat may result in a reduction in predation pressure on these species.

### Scaridae

Striped parrotfish were slightly more abundant in zones 1 and 2 (Table 1). The rainbow and princess parrotfishes were relatively more abundant in zone 2 (Table 1). The redtail and stoplight parrotfishes were slightly more abundant in zone 1. Redband and redfin parrotfishes were most abundant in zones 2 and 3 respectively.

### Haemulidae

Smallmouth and bluestriped grunt were dominant in all zones (Table 1). Striped grunt were relatively abundant in zone 1 but were notably absent in zones 2 and 3. French grunt, tomtate, and Spanish grunt more abundant in zone 3. White grunt and caesar grunt were most abundant in zone 2. The most notable similarity between these results and those of Bohnsack et al. (1985) is the relatively high abundance of tomtate they reported in the buttress zone which is habitat most like our zone 3.

### Chaetodontidae and Pomacanthidae

The butterflyfishes and angelfishes were most abundant in zones 2 or 3 (Table 1). The complete absence of these two families from zone 1 may have been due to a lack of suitable forage. The butterflyfishes consume coral polyps and the angelfishes depend upon sponges. Both food items may have been more abundant in zones 2 and 3. Bohnsack et al. (1985) reported these families to be more abundant in the buttress zone or deeper limestone habitat which was dominated by sponges and octocorals.

### Gobiidae

The neon goby was most abundant in zone 3 (Table 1). This was probably due to the large number of brain coral heads present in that zone since this goby was observed only on this species of coral at Sombrero Key.

### Acanthuridae

Doctorfish and blue tang were most abundant in zone 1 while ocean surgeon were most abundant in zone 3 (Table 1). The greater abundances of 2 species in zone 1 suggest some similarity with those of Bohnsack et al. (1985) since they found acanthurids to be more abundant in the lagoon rubble and forereef habitats at Looe Key Reef, both relatively shallow habitats. Tilmant (1984) also reported surgeon fishes to be numerous within the top zone of patch reefs.

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**Table 1. Total number and mean number by depth zone of species observed at Sombrero Key on May 8–11, 1988.**

| | Zone 1 | | Zone 2 | | Zone 3 | | All Zones | |
|---|---|---|---|---|---|---|---|---|
| | Total Number | Mean Number | Total Number | Mean Number | Total Number | Mean Number | Total Number | Mean Number |
| Yellow stingray | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 | 1 | <0.1 |
| Goldentail moray | 1 | <0.1 | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 |
| Squirrelfish | 0 | 0.0 | 0 | 0.0 | 2 | 0.1 | 2 | <0.1 |
| Longspine squirrelfish | 0 | 0.0 | 19 | 1.1 | 35 | 2.3 | 54 | 1.1 |
| Blackbar soldierfish | 0 | 0.0 | 0 | 0.0 | 10 | 0.7 | 10 | 0.2 |
| Trumpetfish | 2 | 0.1 | 0 | 0.0 | 4 | 0.3 | 6 | 0.1 |
| Graysby | 1 | <0.1 | 8 | 0.4 | 2 | 0.1 | 11 | 0.2 |
| Red hind | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | <0.1 |
| Butter hamlet | 0 | 0.0 | 2 | 0.1 | 1 | <0.1 | 3 | <0.1 |
| Black grouper | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | <0.1 |
| Lantern bass | 0 | 0.0 | 3 | 0.2 | 1 | <0.1 | 4 | <0.1 |
| Harlequin bass | 3 | <0.1 | 9 | 0.5 | 5 | 0.3 | 17 | 0.4 |
| Sergeant major | 317 | 22.6 | 640 | 35.6 | 593 | 39.5 | 1550 | 32.9 |
| Blue chromis | 2 | 0.1 | 26 | 1.4 | 44 | 2.9 | 72 | 1.5 |
| Brown chromis | 0 | 0.0 | 3 | 0.2 | 21 | 1.4 | 24 | 0.5 |
| Yellowtail damselfish | 123 | 8.8 | 62 | 3.4 | 20 | 1.3 | 205 | 4.4 |
| Honey gregory | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | <0.1 |
| Dusky damselfish | 202 | 14.4 | 34 | 2.2 | 53 | 3.5 | 289 | 6.1 |
| Beaugregory | 6 | 0.4 | 18 | 1.0 | 2 | 0.1 | 26 | 0.6 |
| Bicolor damselfish | 305 | 21.8 | 292 | 16.2 | 410 | 27.3 | 1007 | 21.4 |
| Threespot damselfish | 7 | 0.5 | 12 | 0.7 | 10 | 0.7 | 29 | 0.6 |
| Cocoa damselfish | 0 | 0.0 | 2 | 0.1 | 1 | <0.1 | 3 | <0.1 |
| Redspotted hawkfish | 0 | 0.0 | 1 | <0.1 | 1 | <0.1 | 2 | <0.1 |
| Spotfin hogfish | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | 0.1 |
| Spanish hogfish | 0 | 0.0 | 2 | 0.1 | 0 | 0.0 | 2 | <0.1 |
| Slippery dick | 53 | 3.8 | 195 | 10.8 | 176 | 11.7 | 424 | 9.0 |
| Yellowhead wrasse | 13 | 0.9 | 201 | 11.2 | 69 | 4.6 | 283 | 6.0 |
| Clown wrasse | 147 | 10.5 | 57 | 3.2 | 87 | 5.8 | 291 | 6.2 |
| Rainbow wrasse | 24 | 1.7 | 1 | <0.1 | 8 | 0.5 | 33 | 0.7 |
| Puddingwife | 8 | 0.6 | 15 | 0.8 | 27 | 1.8 | 50 | 1.1 |
| Green razorfish | 0 | 0.0 | 5 | 0.3 | 0 | 0.0 | 5 | 0.1 |
| Hogfish | 0 | 0.0 | 0 | 0.0 | 2 | 0.1 | 2 | <0.1 |
| Bluehead wrasse | 1434 | 102.4 | 798 | 44.3 | 701 | 46.7 | 2933 | 62.4 |
| Blue parrotfish | 1 | <0.1 | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 |
| Striped parrotfish | 18 | 1.3 | 24 | 1.3 | 13 | 0.7 | 55 | 1.2 |
| Rainbow parrotfish | 4 | 0.3 | 10 | 0.6 | 8 | 0.5 | 22 | 0.5 |
| Princess parrotfish | 20 | 1.4 | 29 | 1.6 | 26 | 1.7 | 75 | 1.6 |
| Queen parrotfish | 7 | 0.5 | 13 | 0.7 | 9 | 0.6 | 29 | 0.6 |
| Redband parrotfish | 6 | 0.4 | 26 | 1.4 | 5 | 0.3 | 37 | 0.8 |
| Redtail parrotfish | 46 | 3.3 | 0 | 0.0 | 8 | 0.5 | 54 | 1.1 |
| Redfin parrotfish | 9 | 0.6 | 12 | 0.7 | 12 | 0.8 | 33 | 0.7 |
| Stoplight parrotfish | 54 | 3.9 | 17 | 0.9 | 27 | 1.8 | 98 | 2.1 |
| Yellowjack | 14 | 1.0 | 0 | 0.0 | 10 | 0.7 | 24 | 0.5 |
| Bar jack | 236 | 16.9 | 204 | 11.3 | 181 | 12.1 | 621 | 13.2 |
| Crevalle jack | 0 | 0.0 | 3 | 0.2 | 1 | <0.1 | 4 | <0.1 |
| Mutton snapper | 0 | 0.0 | 6 | 0.3 | 0 | 0.0 | 6 | 0.1 |
| Schoolmaster | 21 | 1.5 | 27 | 1.5 | 24 | 1.6 | 72 | 1.5 |
| Mahogany snapper | 0 | 0.0 | 29 | 1.6 | 54 | 3.6 | 83 | 1.8 |
| Yellowtail snapper | 190 | 13.6 | 120 | 6.7 | 248 | 16.5 | 558 | 11.9 |
| Yellowfin mojarra | 4 | 0.3 | 0 | 0.0 | 0 | 0.0 | 4 | <0.1 |
| Porkfish | 2 | 0.1 | 8 | 0.4 | 8 | 0.5 | 18 | 0.4 |
| Tomtate | 0 | 0.0 | 7 | 0.4 | 28 | 1.9 | 35 | 0.7 |
| Caesar grunt | 3 | 0.2 | 16 | 0.9 | 4 | 0.3 | 23 | 0.5 |
| Smallmouth grunt | 533 | 38.1 | 261 | 14.5 | 319 | 21.3 | 1113 | 23.7 |
| Striped grunt | 105 | 7.5 | 0 | 0.0 | 0 | 0.0 | 105 | 2.2 |
| French grunt | 28 | 2.0 | 57 | 3.2 | 95 | 6.3 | 180 | 3.8 |
| Spanish grunt | 3 | 0.2 | 5 | 0.3 | 28 | 1.9 | 36 | 0.8 |
| Cottonwick | 0 | 0.0 | 6 | 0.3 | 0 | 0.0 | 6 | 0.1 |
| Sailor's choice | 6 | 0.4 | 0 | 0.0 | 1 | <0.1 | 7 | 0.1 |
| White grunt | 21 | 1.5 | 62 | 3.4 | 3 | 0.2 | 86 | 1.8 |
| Bluestriped grunt | 181 | 12.9 | 136 | 7.6 | 81 | 5.4 | 398 | 8.5 |
| Jolthead porgy | 0 | 0.0 | 0 | 0.0 | 2 | 0.1 | 2 | <0.1 |
| High-hat | 0 | 0.0 | 0 | 0.0 | 4 | 0.3 | 4 | <0.1 |
| Reef croaker | 5 | 0.3 | 1 | <0.1 | 2 | 0.1 | 8 | 0.2 |
| Yellow goatfish | 30 | 0.2 | 82 | 4.6 | 14 | 0.9 | 126 | 2.7 |
| Spotted goatfish | 0 | 0.0 | 4 | 0.2 | 4 | 0.3 | 8 | 0.2 |
| Glassy sweeper | 1 | <0.1 | 0 | 0.0 | 3 | 0.2 | 4 | <0.1 |
| Bermuda chub | 4 | 0.3 | 15 | 0.8 | 40 | 2.7 | 59 | 1.3 |

**Table 1 (continued)**

| | Zone 1 | | Zone 2 | | Zone 3 | | All Zones | |
|---|---|---|---|---|---|---|---|---|
| | Total Number | Mean Number | Total Number | Mean Number | Total Number | Mean Number | Total Number | Mean Number |
| Foureye butterflyfish | 0 | 0.0 | 6 | 0.3 | 10 | 0.7 | 16 | 0.3 |
| Spotfin butterflyfish | 0 | 0.0 | 8 | 0.4 | 8 | 0.5 | 16 | 0.3 |
| Reef butterflyfish | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | <0.1 |
| Banded butterflyfish | 0 | 0.0 | 3 | 0.2 | 2 | 0.1 | 5 | 0.1 |
| Rock beauty | 0 | 0.0 | 4 | 0.2 | 2 | 0.1 | 6 | 0.1 |
| Gray angelfish | 0 | 0.0 | 1 | <0.1 | 1 | <0.1 | 2 | <0.1 |
| French angelfish | 0 | 0.0 | 11 | 0.6 | 4 | 0.3 | 15 | 0.3 |
| Great barracuda | 3 | 0.2 | 11 | 0.6 | 6 | 0.4 | 20 | 0.4 |
| Redlip blenny | 4 | 0.3 | 1 | <0.1 | 0 | 0.0 | 5 | 0.1 |
| Seaweed blenny | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 | 1 | <0.1 |
| Bridled goby | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 | 1 | <0.1 |
| Goby (unidentified) | 10 | 0.7 | 2 | 0.1 | 2 | 0.1 | 14 | 0.3 |
| Neon goby | 0 | 0.0 | 30 | 1.7 | 45 | 3.0 | 75 | 1.6 |
| Ocean surgeon | 26 | 1.9 | 70 | 3.9 | 82 | 5.4 | 178 | 3.8 |
| Doctorfish | 105 | 10.7 | 74 | 4.1 | 31 | 2.1 | 210 | 4.5 |
| Bluetang | 101 | 7.2 | 63 | 3.5 | 18 | 1.2 | 182 | 3.9 |
| Scrawled filefish | 1 | <0.1 | 0 | 0.0 | 0 | 0.0 | 1 | <0.1 |
| Scrawled cowfish | 0 | 0.0 | 1 | <0.1 | 0 | 0.0 | 1 | <0.1 |
| Smooth trunkfish | 5 | 0.4 | 1 | <0.1 | 1 | <0.1 | 7 | 0.1 |
| Porcupine fish | 1 | <0.1 | 2 | 0.1 | 0 | 0.0 | 3 | <0.1 |
| Number of species | 53 | | 70 | | 71 | | 88 | |
| Number of individuals | 4456 | | 3878 | | 3762 | | 11,996 | |

**Table 2. Fish species observed in only one zone at Sombrero Key on May 8–11, 1988.**

| Zone 1 | Zone 2 | Zone 3 |
|---|---|---|
| Goldentail moray | Red Hind | Yellow stingray |
| Scrawled filefish | Black grouper | Squirrelfish |
| Blue parrotfish | Honey gregory | Blackbar soldierfish |
| Yellowfin mojarra | Spotfin hogfish | Hogfish |
| Striped grunt | Spanish hogfish | Whitebone porgy |
| | Green razorfish | High-hat |
| | Mutton snapper | Seaweed blenny |
| | Cottonwick | Bridled goby |
| | Reef butterflyfish | |
| | Scrawled cowfish | |

**Table 3. Ranking and percentage of total number by zone of the ten most numerous species observed at Sombrero Key on May 8–11, 1988.**

| | All Zones | | Zone 1 | | Zone 2 | | Zone 3 | |
|---|---|---|---|---|---|---|---|---|
| Species | Rank | Percent Total | Rank | Percent Total | Rank | Percent Total | Rank | Percent Total |
| Bluehead wrasse | 1 | 25.1 | 1 | 35.4 | 1 | 20.5 | 1 | 19.2 |
| Sergeant major | 2 | 13.1 | 3 | 7.0 | 2 | 16.4 | 2 | 16.2 |
| Smallmouth grunt | 3 | 9.6 | 2 | 11.2 | 4 | 6.7 | 4 | 8.7 |
| Bicolor damselfish | 4 | 8.4 | 4 | 6.6 | 3 | 7.4 | 3 | 11.2 |
| Bar jack | 5 | 5.3 | 5 | 5.8 | 6 | 5.2 | 6 | 4.9 |
| Yellowtail snapper | 6 | 4.8 | 6 | 4.7 | 9 | 3.1 | 5 | 6.8 |
| Slippery dick | 7 | 3.6 | | | 5 | 5.5 | 7 | 4.4 |
| Bluestriped grunt | 8 | 3.4 | 7 | 4.5 | 8 | 3.5 | 9 | 2.2 |
| Yellowhead wrasse | 9 | 2.4 | | | 7 | 5.2 | | |
| Dusky damselfish | 10 | 2.2 | 8 | 4.2 | | | | |
| Striped grunt | | | 9 | 2.6 | | | | |
| Clown wrasse | | | 10 | 1.7 | | | 10 | 2.2 |
| Yellow goatfish | | | | | 10 | 2.1 | | |
| French grunt | | | | | | | 8 | 2.6 |
| Total percentage | | 78.1 | | 85.7 | | 75.6 | | 78.4 |

# SWIMMING HABITS OF CARCHARHINID SHARKS AT THE LIVING SEAS PAVILION, EPCOT CENTER

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*The swimming habits of three species of carcharhinid sharks, a tiger* (Galeocerdo cuvier), *a bull* (Carcharhinus leucas) *and four brown sharks* (Carcharhinus plumbeus), *held at The Living Seas Pavilion, were observed over a two year period (1988 and 1989). All of the sharks are females with the exception of the bull shark. Alterations in swimming habits relative to frequently visited areas and depths of the tank were noted throughout a variety of environmental changes. Changes included the introduction and removal of sharks, and the placement of a divider which decreased available space. Daily environmental stimuli consisted of diver and dolphin confrontation and artificial feeding operations. Throughout the study, sharks showed an avoidance of the areas near the dolphin. All the sharks swam next to the outer wall of the aquarium. Dimly lit, open areas near the sharks' feeding station were frequented. Divers seemed to have little effect on shark habits excepting the bull shark. The introduction of the divider produced no observable changes in the sharks' habits.*

## INTRODUCTION

Sharks live in a very concealing environment and often have wide ranging habits (McKibben and Nelson, 1986) and any study of their behavior is difficult and potentially expensive. It is often impossible to determine the stimuli that sharks encounter and hence their reactions to them.

Weihs, *et al.*, (1981) stated that captive carcharhinid sharks in a large simulated reef area, swam in established patterns. This observation was verified by Crow and Hewitt (1988) who described selected swim patterns of six captive shark species.

The large aquarium at The Living Seas Pavilion places few restrictions on shark movements and allows room for artificial reef structures and a variety of other marine life. The study of carcharhinids in this extremely large controlled environment, may yield a better understanding of spatial requirements of sharks. This simulated environment enabled us to document the sharks' swimming habits in response to additions and subtractions of other carcharhinids. It was also possible to document the sharks' swimming habits in response to daily stimuli such as diver and dolphin presence, a condition which may exist in their natural environment, but has never been adequately observed. Myrberg and Gruber (1974) reported aggressive behaviors to occur between resident bonnetheads and diver-observers. According to Thompson and Springer (1961) observations have been made of wild dolphins driving sharks away from their young. However, dolphins and sharks may feed together without apparent conflict. Gilbert, *et al.*, (1972) observed that "swimming habits of brown sharks were not significantly altered by the presence of porpoises".

## MATERIALS AND METHODS

The tracking of swimming patterns spanned January 1988 through November 1989 and consisted of 492 ten-minute observations (82 hours total). The established carcharhinid population since 1986 consisted of one female tiger shark, *Galeocerdo cuvier,* (3.4 m total length (TL) and 214 kg), one male bull shark, *Carcharhinus leucas,* (2.4 m TL and 158 kg), and one female sandbar shark, *Carcharhinus plumbeus,* (2.0 m TL and 57 kg). Over a period of two years, changes within the shark population occurred. A second female sandbar shark, Brown 2, (2.0 m TL and 58 kg) was added in May 1988. The tiger and Brown 2 were removed in January of 1989. Two female sandbar sharks, Browns 3 and 4 (each at 2.2 m and 44 kg) were added in February 1989.

The study was conducted in The Living Seas Pavilion which contains 21.5 million liters of artificial saltwater, and is cylindrical in shape: 60 m in diameter and 8.2 m deep (see Figure 1). Three submerged guest viewing areas are the Inner Tank Module (ITM), Tunnel 1, and Tunnel 2. Although these structures could be possible barriers, the sharks had been observed crossing over them. Man-made, fiberglass coralheads, ranging in height between 0.5 m and 7.9 m, are randomly dispersed throughout the aquarium. All the water parameters remained constant throughout the duration of the study. Temperature and salinity varied between 24.1 $\pm$ 0.2°C and 31.0 $\pm$ 1 ppt, respectively. The year round light:dark ratio is 17:7.

For observations, the aquarium was divided into eight pie shaped sections (numbered 1-8 in Figure 2). Each section was further divided into four areas (lettered A-D), to denote increasing distance from the ITM. It should be noted that although these sections varied in size, they were based on natural divisions in the aquarium, and were the most accurate way to pinpoint the sharks' positions. Observations were taken between the hours of 0700 and 2300 from inside the ITM or in the water using scuba gear. During each observation, a single shark was observed for ten minutes. The subject's position was plotted at 15 second intervals on hand held maps. The depth of the subject at each point was noted as high, medium, or low, corresponding to 2.7 m increments. The paths between each point were plotted to denote the shark's exact swim path. Environmental stimuli such as divers, feeding, etc., were recorded to categorize observations.

Observations were taken randomly, and covered all the different conditions which existed in the aquarium, on a daily basis. These conditions are the presence and absence of divers or dolphins, and the occurrence of fish or shark feedings. The fish are hand fed a variety of seafood, from within the water. Divers perform these feedings twice a day, morning and night. In addition to these feedings, the divers are present in the aquarium approximately 10 to 14 hours a day for maintenance and show purposes. The sharks are fed whole and cut fish, every other day from the surface of the aquarium (see shaded area of Figure 1). Three Atlantic Bottlenosed dolphins *(Tursiops truncatus)* were present in the aquarium up until February 1989. Their holding pools extend off section 4D as seen in Figure 2. The dolphins' play progressed to the point where it was necessary to separate them physically from the rest of the animals by the installation of a divider (Figure 2) made of PVC pipe and rope which allows smaller fish to swim through.

Eighty-two hours of data were collected from January 1988 through November of 1989, which were spread over seven different time periods (Cumulative 1 (Cum 1): January 1988-May 1988. (21 hours collected on three sharks), (Transition I: May 1988. Brown 2 added. (2 hours collected on four sharks), (Cumulative 2 (Cum 2): June 1988-October 1988. (28 hours collected on four sharks), January 1989: First three weeks in January 1989. Removal of Tiger and Brown 2. (2 hours collected on two sharks), Transition II: January 1989-February 1989. Browns 3 & 4 were added. (7 hours collected on four sharks),* *[Before Wall, (March 1989-May 1989) After Wall ( May 1989-November 1989). Dividing wall installed between sections 4 and 5 (see Figure 2). (15 hours collected on four sharks). After one month adjustment period. (9 hours collected on four sharks)]. Chi-square tests were performed to determine randomness of swimming.

## RESULTS

The sharks' swimming habits were not random throughout the duration of the study ($x^2 = 7.13\text{-}152.2$ df = 3 P > 0.001). Table 1 shows each shark's preferred sections throughout the seven time periods. A preferred section is one in which the subject spent greater than 10% of its time. Random swimming patterns would be reflected in 3% time spent in each section. The average amount of time spent in each non-preferred section was 1.6% ± 0.5%.

**Table 1. Frequented sections of each subject over the course of two years. Time is divided into seven periods (Cum 1 through After Wall) to represent unique environmental conditions.**

| | TIGER | BULL | BROWN 1 | BROWN 2 | BROWN 3 | BROWN 4 |
|---|---|---|---|---|---|---|
| Cum 1 | 6D 7D 8D | 6D 7D 8D | 7D 8C 8D | | | |
| Transition I | 6D 7D 8D | 6D 7D 8D | 1D 2D 8D | 1D 2C 2D | | |
| Cum 2 | 6D 7D 8D | 6D 7D | 1D 2D 8D | 2C 2D 8C | | |
| January 1989 | | 6D 7D | 2D 7D 8D | | | |
| Transition II | | 6D 7D 8D | 6D 7D | | 6B 6C 6C 7D | 6B 6C 6D 7C |
| Before Wall | | 6D 7D 8D | 7D 8D | | 6C 7C 7D | 6B 6C 7C |
| After Wall | | 6D 7D 8D | 6D 7D 8D | | 6D 7D | 6C 6D 7D 8D |

DEPTHS:

Depth data were analyzed using the three depth divisions of HIGH, MEDIUM, and LOW, corresponding to 2.7 m depth increments. Comparative relative depth profiles are shown in Figures 3-5. Percent time spent at depth is graphed as a function of depth for each subject throughout the seven time periods. The average amount of time expected to be spent at one particular depth division would be 33%. Chi square tests were performed to test randomness in each sharks depth distribution . Results are presented in Figures 4-6.

## DISCUSSION

In Cum 1, it is believed that Brown 1 was able to occupy section 8C due to her size. She was smaller and more maneuverable which would enable her to easily pass through the large coralhead occupying that section. This maneuverability is also reflected in her preference for the MEDIUM depth division during this time (as the opening in the coralhead is at the MEDIUM depth).

During Transition I, both the tiger and the bull changed swimming habits slightly in that more time was spent in the HIGH depth division. Brown 1's habits immediately changed during Transition I, when both preferred tank sections and depth level changed to correspond with the preferences of the newly added conspecific, Brown 2. This immediate change in swimming habits might reflect an interspecific relationship of schooling, which would support the findings of Gilbert *et al* (1967) and Castro (1983) or it could be attributed to dominance. Gilbert *et al* (1967) stated that individuals of the same size have been known to school together in nature. Castro (1983) stated that sandbar sharks "tend to segregate by sex...often forming schools".

During Cum 2, the tiger still did not reflect any changes in swimming habits but maintained a preference for the HIGH depth division. This small change in habits could have been due to lack of space at LOW depth division. In general the tiger displayed the least amount of change in swimming habits. Also during Cum 2, the bull shark was observed to change his preferred sections by avoiding the one that all the other sharks occupied. A possible explanation could be due to the lack of space. Throughout Cum 2, Brown 1 maintained a preference for sections and depth divisions with or near Brown 2, again possibly due to either schooling or dominance.

In January 1989, the bull did not migrate back into section 8D, but remained in the same two sections and displayed no depth preference. Brown 1 still retained a preferred section near ones previously occupied by Brown 2 most of the time, however, she did migrate over to 7D which was occupied by the bull. Similar to the bull, Brown 1 also displayed no depth preference.

During Transition II, the bull migrated back into 8D, possibly to have more space since no other sharks occupied it. He also preferred the same sections as in Cum 1. The bull also developed a depth preference for the LOW section which was the same as all the other sharks. Brown 1 changed habits immediately and preferred sections and depth divisions which were near, or occupied by, both the new sandbars and the bull. Again it is believed that this could be attributed to the schooling tendency of browns, or to establish dominance. Both of the new browns tended to prefer sections which were near Brown 1 and the bull. Those sections were also clear of any large coralheads. They also both preferred the LOW depth division.

During both time frames Before Wall and After Wall, the bull maintained the same three sections near the back wall, and continued to prefer the LOW depth division. Brown 1 altered her preferred sections during Before Wall, by occupying two preferred sections which were along the outer wall. One of the preferred sections was occupied by the bull and the other was occupied by the new brown. However, through both time frames Before Wall and After Wall, Brown 1 maintained the preferred depth LOW. The new browns both decreased the numbers of sections they preferred from four to three. It is possible that during Transition II, they were more spread out in order to test different areas, then after one month they each settled into fewer preferred sections.

After the installation of the wall, the bull still occupied the same three sections most of the time, as well as the same depth preference for LOW. Brown 1 also preferred the same three sections as the bull, and she also maintained a preference for LOW. Brown 3 preferred only two sections, both near the outer wall and with the bull and Brown 1. She also maintained the LOW preference. Brown 4 preferred all three of the sections preferred by the others and she also preferred one additional section near the others but unoccupied by them. This could possibly be attributed to lack of space. And again she also preferred LOW.

The findings of this study support those of Crow and Hewitt (1988) in that tiger sharks were found to prefer the upper one-third of the water column. Crow and Hewitt also found that bull sharks occupied the upper one-third of the water column. The first year of this study confirmed those findings, however, upon the removal of the tiger shark, the bull preferred the lower one-third of the water column. Crow and Hewitt also found that sandbar sharks occupied the lower two-thirds of the water column. Again, those findings are confirmed by this study, although more specifically, the sandbars were observed to prefer the lower one-third of the water column.

Changes in swimming habits due to the stimuli of divers, dolphins and feedings, were recorded, however, statistical analyses have not been performed. The following are notations on the effects of those stimuli.

When divers (non-feeding divers on conventional open-circuit SCUBA) were present in the environment, the tiger and the brown were generally unaffected. They seemed unaware of the divers and it was not uncommon to bump into the sharks if the diver was not looking. The bull shark, however, would veer off suddenly when confronted by a diver in his path.

The dolphins in the aquarium were extremely playful and would vocalize at the sharks and "shadow" them (follow along beside, behind or on top). This occurred rarely with the tiger and the bull. During these few instances the shark would react by increasing it's swimming speed. Most of the time the dolphins chose the sandbars for the object of their 'play'. They would nip at the shark's dorsal or caudal fins. They would poke the sharks in the sides and front of head with their rostrum. Often times this would increase to the point when the dolphins would end up in pinning the shark to the bottom so that it was motionless. Whenever possible the sandbars would react by increasing their swimming speed. The findings from this study do not coincide with observations by Thompson (1961) of dolphins driving sharks away from their young. In this situation, the dolphins had no young to protect and therefore it is believed that the dolphins were simply 'playing'. Due to the fact that the sandbar sharks did change their swimming habits in the presence of dolphins, the findings of Gilbert, Irvine and Martini (1972) in which sandbar sharks were not affected by dolphins, are not supported.

The fish feedings in the aquarium seemed to have no effect on the tiger or the bull. The browns however, were attracted to the areas of fish feeding with varying intensity. Often, they seemed attracted to divers with herring. On some occasions the sharks would retrieve any herring that other animals dropped. It was possible for the divers to ward off the sharks but the effects were not longlasting.

The sharks' swimming habits seemed to be unaffected by the installation of the dividing wall. Although the dolphins could still see the sharks and vocalize at them from the other side of the divider, this did not seem to have an effect on the sharks swimming habits (ie. they continued to swim near the divider).

This study confirmed that captive sharks generally move in definite patterns and occupy specific zones (Weihs et al, 1981; Crow and Hewitt, 1988). All of the sharks seemed to prefer sections which were away from the dolphin holding areas, near the shark feeding station, and close to the outer wall. These sections also tended to be more dimly lit and clear of coralheads compared to other sections.

Documentation of how various stimuli affect sharks' swimming habits in captivity, may yield an insight of space utilization of captive sharks under a variety of conditions. With additional studies, a better understanding of the behavior of captive sharks may be attained.

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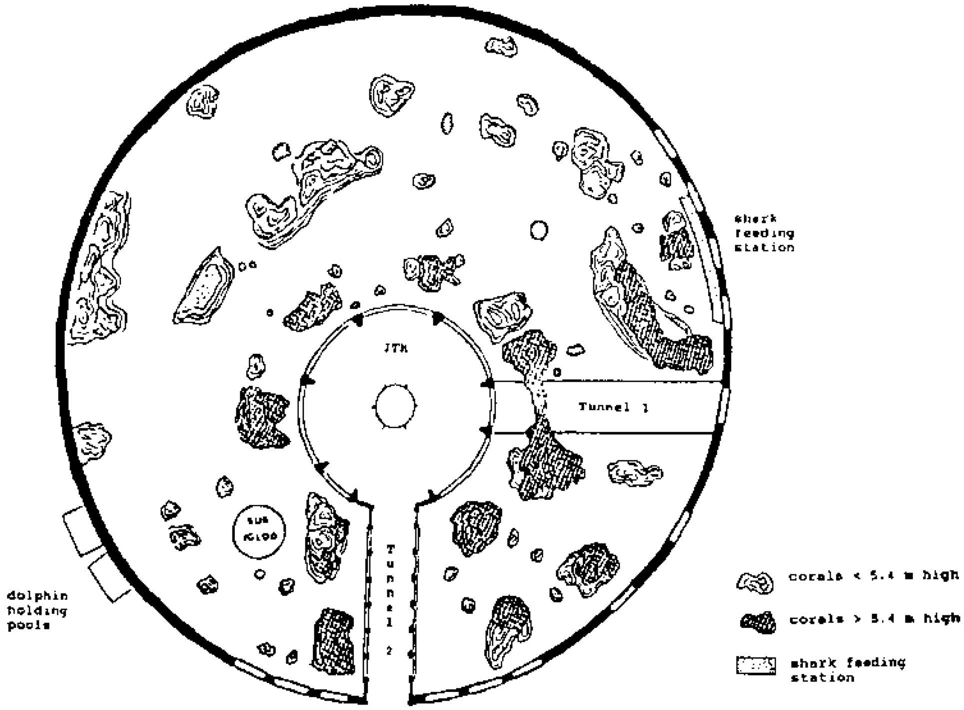


**Figure 1. Overhead view of The Living Seas Pavilion. Shaded corals represent those which extend into the "high" depth division (see main text). Diameter = 60 m.**

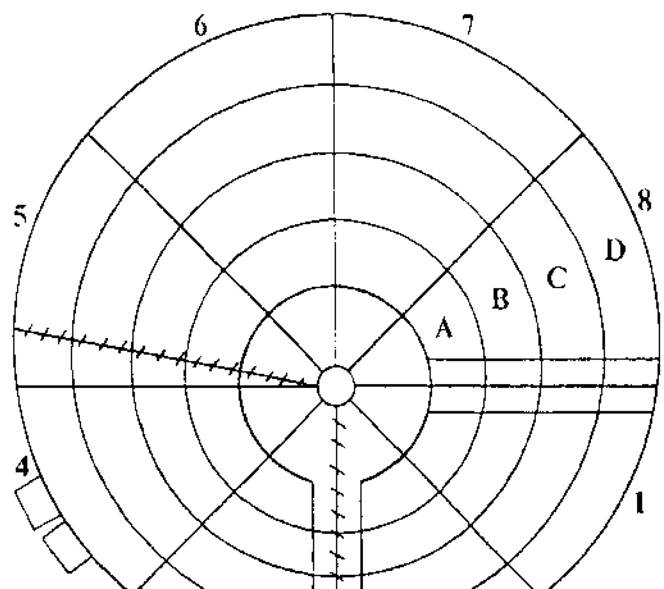


**Figure 2. Overhead view of the aquarium depicting labelled sections used for observations. "Walls" (/////) between sections 4 and 5 and also between sections 2 and 3 (above Tunnel 2) were installed May 1989. Radius (A–D) = 21.0 ±4.2 m.**

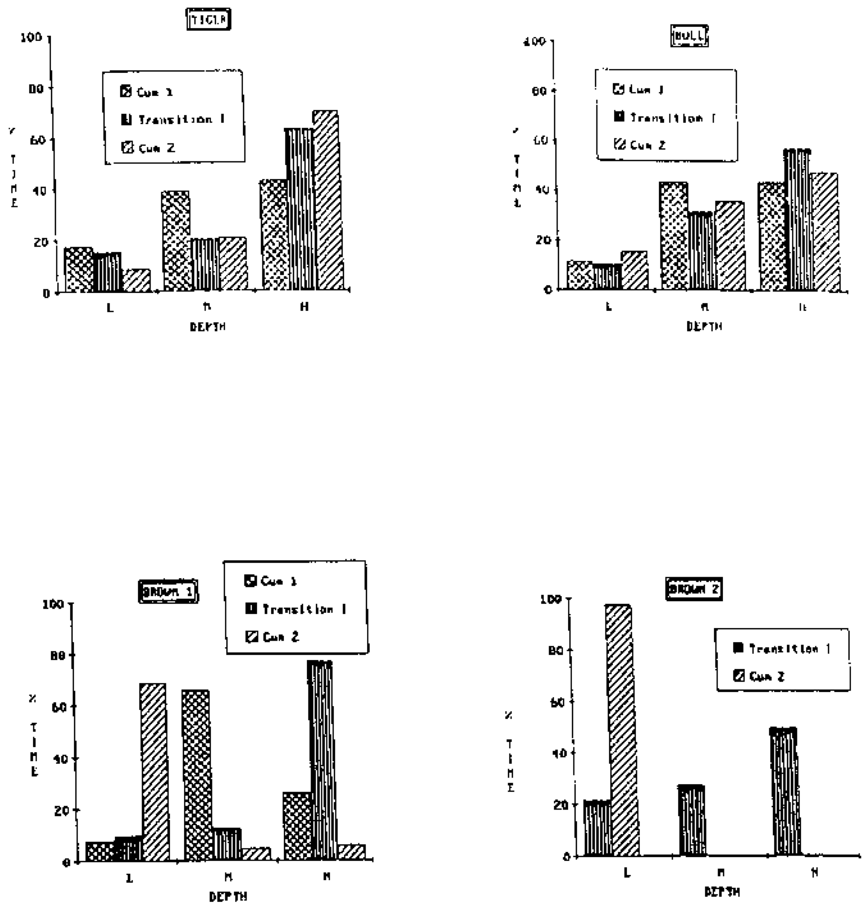


**Figure 3. Comparative relative depth profiles for the tiger, bull, Brown 1, and Brown 2 during Cum 1, Transition I, and Cum 2. Percent time is graphed as a function of depth.**

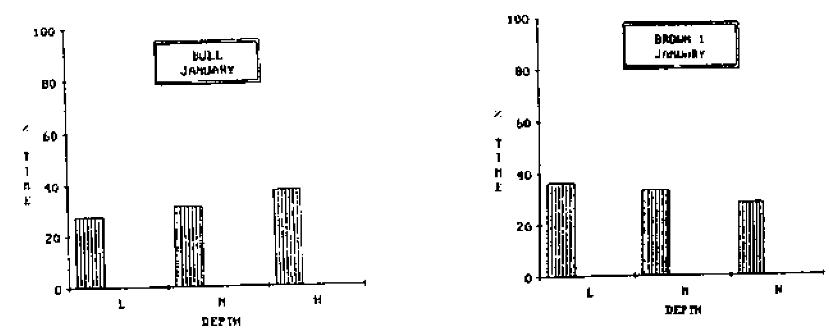


**Figure 4. Comparative relative depth profiles for the bull and Brown 1, during January 1989. Percent time is graphed as a function of depth.**

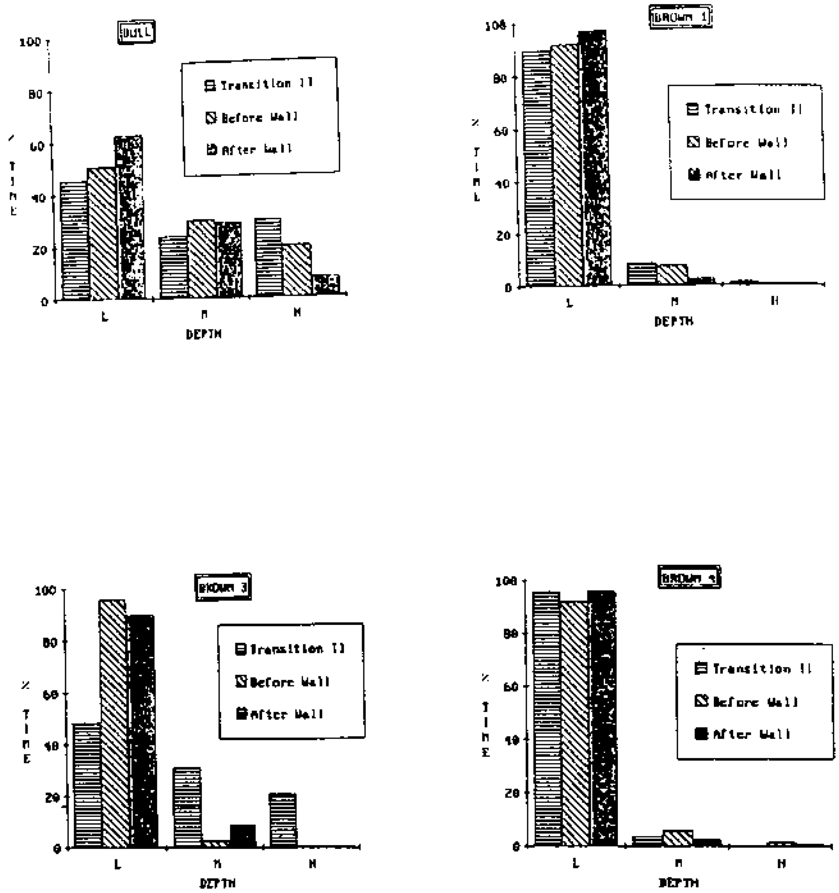


**Figure 5. Comparative relative depth profiles for the bull, Brown 1, Brown 3, and Brown 4, during the time periods of Transition II, Before Wall and After Wall.**

# BUBBLE MODEL IMPLICATIONS FOR MULTI-DIVING

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*Multi-diving (multi-level, repetitive, multi-day, deeper spike), using present models, witnesses a greater share of problems than both bounce and saturation diving. Part of the trouble arises from incompatible treatment of bubbles and gas nuclei. Within bubble models, ills are redressed through:*

*(1) reduced no-stop time limits, based on varying-permeability bubble skins;*
*(2) safety stops (or shallow swimming ascents) in the 10-20 ft zone;*
*(3) ascent rates not exceeding 60 ft/min;*
*(4) restricted repetitive exposures, particularly beyond 100 ft, based on reduction in permissible bubble excesses;*
*(5) restricted spike (shallow-to-deep) exposures based on excitation of additional micronuclei;*
*(6) restricted multi-day activity based on regeneration of gas nuclei;*
*(7) smooth coalescence of bounce and saturation limit points, consistent with bubble experiments;*
*(8) consistent treatment of altitude diving;*

*Discussion of these points is the focus, with implications for diving practice. A brief description of the reduced gradient bubble model (RGBM) is given.*

## INTRODUCTION

Validation is central to diving, and much testing of non-stop and saturation schedules (Boycott *et al.*, 1908; Buhlmann, 1984; Workman, 1965; Spencer, 1976; Weathersby, 1984; Yount *et al.*, 1976; Kunkle *et al.*, 1983; Thalmann, 1984; Thalmann, 1986; Farm *et al.*, 1986; Lang *et al.*, 1989; Lang *et al.*, 1990; Vann *et al.*, 1989; Walder, 1968; Pilmanis, 1976; Hills, 1977; Hemplemann, 1957) has transpired. In between, repetitive, multi-level, deeper-spike, and multi-day diving cannot claim the same benefits, though some programs (Thalmann, 1984; Thalmann, 1986) are breaking new ground. Application of the Haldane algorithm in the latter cases has witnessed higher bends statistics than in the former one, as reported by Vann (Vann *et al.*, 1989) in DAN newsletters, and discussed at workshops (Lang and Hamilton, 1989; Lang and Egstrom, 1990) and technical forums. Reasons can be conjectured, some of which directly impact decompression algorithms.

The Haldane approach (Boycott *et al.*, 1908) is based on a dissolved gas model, and therefore so long as the bulk of tissue gas remains in the dissolved state, the more correct and useful will prove such an approach. But as increasing proportions of free phases (Yount *et al.*, 1976; Hennessy and Hemplemann, 1977; Wienke, 1989; Yount and Hoffman, 1986; Yount, 1982; Yount, 1979; Yount *et al.*, 1979; Wienke, 1990) grow, by direct excitation of critical micronuclei or gradual bubble coalescing transitions, the classical algorithm loses predictive basis. Such conditions might attend diving activity *extrapolated* outside model and test ranges, maybe as a surprise. The fact that (some) divers push Haldane meter algorithms to limits beyond tested Haldane tables (Farm *et al.*, 1986; Lang *et al.*, 1989; Lang *et al.*, 1990; Vann *et al.*, 1989) underscores the need for more globally applicable schemes, possibly with greater focus on free phase buildup. In lock step, procedures such as shorter no-stop time limits, (Spencer, 1976) safety stops, (Lang *et al.*, 1990; Pilmanis, 1976) and slow ascent rates (Lang *et al.*, 1989) are consistent with bubble dynamics. Though not proven, these conservative protocols hopefully lower bends incidence statistics. The problems associated with multi-diving might also be addressed through reduced repetitive gradients or equivalently, tissue tensions. While reduced gradients are very difficult to codify in table frameworks, they are relatively simple to implement in digital meters.

## BUBBLE DYNAMICS

Bubbles, which are unstable, might grow from stable, micron size, gas nuclei which resist collapse due to elastic skins of surface-activated molecules (surfactants), or possibly reduction in surface tension at tissue interfaces. If families of these micronuclei persist, they vary in size and surfactant content. Large pressures (somewhere near 10 *atm*) are necessary to crush them. Micronuclei are small enough to pass through the pulmonary filters, yet dense enough not to float to the surfaces of their environments, with which they are in both hydrostatic (pressure) and diffusion (gas flow) equilibrium. Compression-decompression is thought to excite them into growth. Ordinarily, bubble skins are permeable to gas, but can become impermeable when subjected to hefty compressions (again 10 *atm*), outside nominal activity. Such a model of skin behavior, called the varying-permeability model (VPM), was proposed by Yount (1979) and Strauss, (Yount *et al.*, 1976) and extended by Kunkle and Beckman (1983) and other co-workers (Yount *et al.*, 1986; Yount, 1982; Yount 1979; Yount *et al.*, 1979). Rudiments of nucleation models can be traced to early observations of Walder (1968). By tracking changes in nuclear radius that are caused by increasing or decreasing pressure, the VPM has correlated quantitative descriptions of bubble-counting experiments carried out in supersaturated gel (Yount, 1982; Yount *et al.*, 1979). The model has also been used to trace levels of incidence of DCS in animal species such as shrimp, salmon, rats, and humans. Microscopic evidence has also been obtained which indicates the spherical gas nuclei, those persistent microbubbles, actually do exist and possess physical properties consistent with earlier assignments. For example, nuclear radii are on the order of 1 *micron* or less, and their number density in bio-media decreases exponentially with increasing radius, characteristic of a system VPM nuclei in equilibrium with their surroundings at the same temperature.

A VPM critical radius, $r_o$, at fixed pressure, $P_o$, represents a cutoff for growth upon decompression to lesser pressure. Nuclei larger than $r_0$ will all grow upon decompression. Additionally, following initial compression, $\Delta P = P - P_o$, a smaller class of micronuclei of critical radius, $r$, can be excited into growth with decompression. Table 1 lists critical radii, $r$, excited by sea level compressions ($P_0 = 33\,fsw$), assuming $r_0 = .8$ *microns*. Deeper decompressions excite smaller, more stable, nuclei. Apparently the body is able to support a certain number of *safe* micronuclei, and a certain excess for varying periods of time, decreasing with cumulative exposure time. Short deep dives excite many small nuclei, while longer shallow dives excite fewer larger nuclei. Since tissue deformation and impairment of circulation should depend upon both the size and number of bubbles, it seems plausible that the total volume, $V_{crit}$, of evolved gas would serve as an effective criteria in any model. For shorter decompression times, bubble nuclei have little time to inflate. The permissible critical radius is then smaller, and the allowed supersaturation larger, resulting in many small bubbles. Conversely, during long decompressions, bubbles may grow very large, so that only a few are permitted.

**Table 1. Excitation Radii.**

| pressure $P$ (*fsw*) | excitation radius $r$ (*microns*) | pressure $P$ (*fsw*) | excitation radius $r$ (*microns*) |
|---|---|---|---|
| 13 | .890 | 153 | .498 |
| 33 | .800 | 173 | .468 |
| 53 | .726 | 193 | .442 |
| 73 | .665 | 213 | .419 |
| 93 | .614 | 233 | .397 |
| 113 | .569 | 253 | .378 |
| 133 | .531 | 273 | .361 |

## CRITICAL GRADIENTS AND NUCLEI

Any set of non-stop time limits can be plugged into model equations, and maximum tensions across all compartments and depths assigned as the M-values. Corresponding critical supersaturation gradients, G, are obtained by subtracting off ambient pressures, P. Using a set of reduced time limits, listed in Table 2, we can construct a conservative set of gradients for purposes of illustration and discussion. The bounce gradient, $G$, is computed for each compartment, $\tau$, across the tissue spectrum, $1 \leq \tau \leq 720$ *minutes*. Non-stop exposures, with surface ascent, thus allows $G_0$ for that compartment. Both $G_0$ and $\Delta G$ are tabulated in Table 3, with $\Delta G$ taken from Buhlmann (1984) and representing the change in critical gradient with depth, $d$. Because the time limits are conservative, the supersaturation gradients are also conservative. Maximum tensions occur at threshold depths, $d_{th}$, for no-stop limits, $t_{nd}$.

What is reflected here is the body's ability to support increased degrees of supersaturation with increased pressure. Bubble and micronuclei tend to both shrink and stabilize under pressure, permitting increased levels of supersaturation because of greater surface tension pressure. Under decompression smaller bubbles and nuclei also grow more slowly for the same reason. Surface tension pressures, varying inversely as the spherical radius, $r$, helps to expel gas in the pocket by squeezing and building up a diffusion gradient across the film boundary. Unless nuclei are stabilized so that the net surface tension is zero, all nuclei would eventually collapse upon themselves because of this squeeze. When nuclei are squeezed by increasing pressure, experiments established that they stabilize at new smaller radius, not growing back to earlier size unless pressure is reduced.

**Table 2. Bounce Time Limits.**

| depth $d$ ($fsw$) | time limit $t_{nd}$ ($minutes$) | depth $d$ ($fsw$) | time limit $t_{nd}$ ($minutes$) |
|---|---|---|---|
| 10 | 1840. | 130 | 9. |
| 20 | 483. | 140 | 8. |
| 30 | 230. | 150 | 7. |
| 40 | 108. | 160 | 6. |
| 50 | 65. | 170 | 5.5 |
| 60 | 40. | 180 | 5. |
| 70 | 30. | 190 | 4.5 |
| 80 | 24. | 200 | 4. |
| 90 | 18. | 210 | 3.5 |
| 100 | 15. | 220 | 3. |
| 110 | 13. | 230 | 2.6 |
| 120 | 11. | 240 | 2.3 |

**Table 3. Bounce Gradients.**

| half-life $\tau$ ($minutes$) | threshold depth $d_{th}$ ($ft$) | surface gradient $G_0$ ($fsw$) | gradient change $\Delta G$ |
|---|---|---|---|
| 1 | 220 | 192.4 | .519 |
| 2 | 190 | 150.0 | .519 |
| 5 | 135 | 93.9 | .519 |
| 10 | 95 | 64.9 | .519 |
| 20 | 65 | 45.6 | .506 |
| 40 | 40 | 33.8 | .468 |
| 80 | 30 | 25.9 | .417 |
| 120 | 28 | 22.2 | .379 |
| 180 | 25 | 18.1 | .354 |
| 240 | 23 | 15.5 | .329 |
| 360 | 18 | 12.1 | .303 |
| 480 | 15 | 10.5 | .303 |
| 720 | 12 | 8.3 | .303 |

Although the actual size distribution of gas nuclei in humans is unknown, experiments (Yount *et al.*, 1979) *in vitro* suggest that a decaying exponential is reasonable. Under such circumstances, a larger number of smaller nuclei are excited into growth by deeper decompressions, and a smaller number of larger nuclei excited by shallower decompressions.

## SEPARATED PHASE HYPOTHESIS AND MULTI-DIVING FRACTIONS

The rate at which gas inflates in tissue depends upon both permissible bubble number, $\Delta n$, and supersaturation gradient, $G$. The phase volume hypothesis requires that the sum of the product of the two over time must always remain less than some limit point, $\alpha V_{crit}$, with $\alpha$ a proportionality constant and $V_{crit}$ the critical separated phase volume. Such a trigger point replaces the usual set, or matrix, of $M$-values in applications. The gradients, or $M$-values, in Table 3 then can be consistently generated from $\alpha\ V_{crit}$, $r_0$, and three other bubble parameters, the surface tension, crush limit, and regeneration time. Not important to elaborate here, these five parameters form a set of fundamental bubble constants, along with a time constant characteristic of body acclimatization to excess bubbles and micronuclei.

Extending (Wienke, 1990) the phase hypothesis to multi-diving, it was shown that any (conservative) set of bounce gradients, $G$, such as Table 3, can be employed for repetitive diving, provided they are reduced at successive exposures. Denoting the reduced set, $G$, we take,

$$G = \xi\, G, \qquad (1)$$

with $\xi$ a set of ***multi-diving*** fractions bounded in relative terms, that is,

$$0 \le \xi \le 1. \qquad (2)$$

As repetitive time intervals decrease, appropriate $\xi$ should get smaller and staging approach saturation limits. As repetitive time intervals increase, $\xi$ should get larger, and staging approach bounce limits. In between, total elapsed time, total surface interval, tissue compartment, and profile determine $\xi$. Considering interpolating behavior, a checklist of properties of $\xi$, correlating with diving practice, is desirable:

(1) $\xi$ equals one for a bounce dive, but remains less than one for repetitive dives within some characteristic interval;
(2) $\xi$ decrease monotonically with increasing exposure time;
(3) $\xi$ increase monotonically with increasing surface interval time;
(4) $\xi$ scale faster tissue compartments the most;
(5) $\xi$ decrease with depth of dive segment;
(6) $\xi$ scale deeper-than-previous dives the most;
(7) $\xi$ change with every dive segment, but only within any dive segment when a greater depth is reached;
(8) the time constant controlling $\xi$ is related to the regeneration time to micronuclei, $\tau_r$, and the permissible bubble excess, $\Delta n$.

Consistent with the above set, a multi-diving fraction can be constructed from the inverse of nuclei regeneration times, $\lambda_r$, the excitation radii, $r$, and the characteristic time constant for permissible bubble excess in tissues, $\lambda_m$. These $\xi$ are written in simplest form,

$$\xi \approx \Psi_{min}\ [1 - \exp(-\lambda_m t_{sur})]\ \exp(-\lambda_m t_{rep}), \tag{3}$$

with $t_{sur}$ interval (surface) time, $t_{rep}$ total (elapsed) repetitive time and $\psi_{min}$ the smallest ratio of permissible bubble excesses on consecutive dives (never greater than one). Permissible excesses depend on $1 - r/r_0$, with $r$ given in Table 1 for various pressures. Every factor in Eq. (3) is bounded by zero and one. Corresponding time scales in the exponentials are near $\lambda^{-1}{}_m \approx$ (*minutes*) and $\lambda^{-1}{}_r \approx$ (days). In repetitive application, these $\xi$ possess some general properties, consistent with the above checklist:

(1) reduce permissible repetitive gradients;
(2) approach one as surface intervals grow large;
(3) reduce multi-day permissible gradients;
(4) penalize deeper-than-previous dives;
(5) affect all tissue compartments.

Both $\lambda_r$ and $\lambda_m$ control repetitive diving, more particularly, the permissible critical tensions, $M$, or critical gradients, $G$, and $G = M - P$, for $P$ the absolute pressure, with $\lambda_r$ mostly affecting multi-day and $\lambda_m$ mostly affecting repetitive activities.

These six parameters, $\xi$, and Eq. (3) form the basis of the reduced gradient bubble model (RGBM), (Wienke, 1990), presently in development stages in a digital meter. Reduced non-stop limits, limited repetitive gradients, safety stops, and deeper-than-previous dive scaling are part of the algorithm.

## ACKNOWLEDGEMENTS

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# AN OVERVIEW OF TECHNOLOGICAL APPROACHES TO DEEP WATER RESEARCH AT WARM MINERAL SPRINGS (85019)

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*Research, under the direction of Wilburn A. Cockrell, at the Warm Mineral Springs site (8So19) over the last two decades has expanded the frontier of underwater archaeology into depths considered to be well within extreme exposure limits. Excavation of deposits located in a cone of debris at the bottom of the Springs has required working dives to depths of thirty-eight to fifty-five meters (124-180 FSW), with excursions down to seventy meters (230 FSW).*

*Current research demands have prompted the adoption of more technologically advanced diving equipment, training, and on-site facilities. The recent addition of a fifty-four inch, double lock recompression chamber staffed by a full-time operator and the use of alternate breathing gases for working dives and decompression has proven to be invaluable by increasing bottom times and decreasing in-water decompression times, while maintaining a high standard of participant safety. Furthermore, the recompression chamber offers the alternative of surface decompression. Likewise, other current diving technology being used in the commercial diving industry, including the use of remotely operated vehicles (ROV's), was examined with an eye toward choosing those technological innovations which had the greatest potential for successful utilization in the deeply submerged anaerobic environment of Warm Mineral Springs.*

## INTRODUCTION

During the last decade, the focus of underwater archaeology began to shift towards the examination of deeply submerged cultural resources on the Outer Continental Shelf as well as in lakes, springs, and sinkholes. This changing focus has made it essential that diving scientists recognize the need for the adoption of more advanced diving technology to insure not only the success of the proposed work, but the safety of the diving scientist himself.

Since the earliest stages of research at Warm Mineral Springs in 1972, its principal investigator, Wilburn A. Cockrell, recognized the need for reliance on more advanced technology to satisfy the ever increasing demands of his research design. The environmentally harsh waters of Warm Mineral Springs became the testing ground for the development of new technology and the adaptation of techniques and equipment available from other areas of the diving community.

Beginning in 1972, Cockrell, assisted at first by his colleague Larry Murphy and later by the author, instituted a multi-disciplinary effort that has gained world-wide recognition as having remained at the forefront of innovation and adaptation in the fields of archaeology and applied diving technology. Underway for nearly nineteen years now, the research has been conducted in two distinct phases. Likewise, any overview of the technology utilized should be viewed in the same way.

Research efforts during Phase I (1972-1983) were conducted under the auspices of the Florida Department of State's Division of Archives, History, and Records Management. During six consecutive field seasons, Cockrell mobilized large crews and launched successful, large-scale archaeological field projects. These initial efforts resulted in the exploration and mapping of the upper, shallow portion of the Springs and the excavation of an intentional 10,300 year-old Native American burial on the thirteen meter ledge, as well as the articulated remains of extinct Pleistocene megafauna (Cockrell and Murphy 1978). Although some exploratory dives were made to depths of up to seventy meters, the principal research focus remained the upper nineteen meters of the Springs.

In 1978, the active portion of the research was phased out due to funding cuts and a lack of support from the Florida Department of State, which began to shift its efforts away from prehistoric sites and toward the preservation of historic structures. A subsequent elimination of the Underwater Research Section of the Division of Archives forced Cockrell to seek alternate funding sources. Phase II began in March, 1983, and continues to date under the auspices of the Warm Mineral Springs Archaeological Research Project and is funded through the Florida State University Department of Anthropology by the Florida State Legislature.

Phase II is currently the only full-time underwater archaeological research project in the world and has seen the extension of work areas in the Springs into depths between thirty-six and fifty-five meters. Work in this area has only begun to reveal the mysteries of the past which lie entombed in the compacted sediments of a cone of debris thirty-four meters high at the bottom of the Springs.

The techniques and procedures applied during these two phases represent vastly different approaches and must be considered in terms of the research goals they attempted to satisfy, as well as the innovations in the field of underwater archaeology they represented.

**Phase I (1972-1983)**

Phase I saw the introduction of the first underwater archaeological field school. Conducted under the direction of Cockrell, this field school taught students from the Department of Anthropology at Florida State University the principles of doing archaeological excavations underwater with the same controls recognized as standards by terrestrial archaeologists. A strict, well documented diving program resulted in a successful program which had no incidence of decompression sickness or related hyperbaric trauma. The key to this success was a set of day-to-day diving procedures outlined by Murphy (1978).

Initial efforts in Phase I were carried out utilizing what was then considered to be "state-of-the-art" sport diving equipment. It soon became apparent that this equipment had to be reevaluated and adapted to make it more effective in the environment in which it was being used. Of immediate concern was the fact that much of the Springs represented a partial overhead diving environment. This fact, coupled with the realization that the fragile sediments found in Warm Mineral Springs required special buoyancy control by divers, revealed a need to investigate alternate diving technology that could be more field proficient and more site specifically adaptable.

Larry Murphy, then functioning as Project Dive Officer, was an early proponent of techniques developed through the efforts of the membership of the National Association For Cave Diving (NACD). He recognized the value of their specialized diving equipment in terms of the safety and control it afforded the working diver. Beginning with buoyancy compensator modifications to facilitate more precise buoyancy control and extending into the use of redundant life -support equipment to increase overall diver safety in overhead diving environments, Murphy incorporated these innovative techniques into the day-to-day diving procedures. The close of activity in 1983 saw the application of other equipment and technology attributable to the NACD and the cave diving community, including dual high pressure orifice tank valves and the use of redundant SCUBA regulators and artificial light sources (Exley, 1981)

Warm Mineral Springs was also the site of the first use of underwater video to document excavation procedures and to map significant archaeological features. Beyond documentation, the utilization of video, coupled with hardline voice communication to the surface, allowed participation in actual excavations by non-diving scientists who, otherwise, would have been eliminated from participating in the research effort due to health reasons or lack of diving credentials.

While the focus of Phase I continued to be the shallow ledges of Warm Mineral Springs, decompression procedures became crucial as long periods of time began to be spent working these areas. To facilitate faster and more complete scrubbing of excess nitrogen from the tissues of decompressing divers, medical oxygen was breathed at the twenty foot and ten foot stops, marking a sharp departure from diver training available at the time, which disdained the in-water use of oxygen. The adoption of this one innovative technique paid off in terms of the number of safe dives made by staff divers without the incidence of decompression sickness or related hyperbaric maladies. The net result of an increased number of safe working dives is the increased amount of data recovered due to the large number of in-water hours accumulated and the lack of any hours of work time lost due to injury.

Research ended in 1977, but Cockrell continued to visit Warm Mineral Springs on his own time to insure that the site was still protected against looting and preserved in its undisturbed state for future assessment and study. During these short duration visits to the site, Cockrell continued to use the diving technology developed during Phase I (Cockrell, personal communication, 1984). Through 1983 and 1984, Cockrell worked, sometimes using the last of his personal funds, to get the work at Warm Mineral Springs back on track. In 1984, he succeeded in getting the Florida State Legislature to fund Phase II with the help of state Senator Bob Johnson and Barbara O'Horo Benton, the current Project Manager of the Warm Mineral Springs Archaeological Research Project.

**Phase II (1984 to the present)**

Initial efforts during Phase II were directed toward cleaning accumulated sand from the thirteen meter ledge and reestablishing mapping points. Diving operations were hampered by limited funding, a small over-worked diving staff, and "hand-me-down" diving equipment. Nevertheless, the projected goals for the 1984-1985 fiscal year were accomplished and staff members were able to begin the tedious task of working toward more ambitious goals for forthcoming field seasons, namely the coring and establishment of deep excavation units in the debris cone at the bottom of the Springs (Cockrell, 1986).

Phase II saw the aforementioned extension of work areas into depths between thirty-six and fifty meters. With diver safety in mind, the same technology utilized so successfully during Phase I was applied again, only this time the principle of redundancy was carried still further to include redundant buoyancy control devices, redundant primary light sources, and alternate air supplies. Working at depth, well beyond the reach of ambient light from the surface and often with limited visibility due to suspended particulates in the water, the added safety factor afforded by these redundancies could not be underestimated. Short of a primary air supply failure, each diver was capable of self-rescue and the handling of most immediate equipment related emergencies independently (Exley 1981).

During the early efforts to establish an excavation unit at a depth of forty-six meters on the slope of the debris cone at the bottom of the Springs, it became apparent that staff divers were pushing open-circuit SCUBA to its maximum potential. Bottom times were limited by the amount of air a diver could carry on his back for use during the dive, as well as during the lengthy periods of decompression which resulted from working at depth. Therefore, research into increasingly more technologically advanced diving techniques began.

Of course, among the first questions asked were the all important ones. How do we shop for new technology? What criteria must be met to make responsible choices? Archaeologists are notorious for their attraction for new toys and other gadgets, but four strict basic considerations were considered.

First to be considered was the question of whether the technology being considered was going to require the participation of more individuals than were available for its successful utilization. With a perpetually limited staff, the technology chosen would have to require only a few hands to operate.

Secondly, there were the ever present financial woes to consider. Would the cost of utilizing specific advanced technology exceed budget limitations and would the increased safety and data justify the cost?

Thirdly, the training aspect was considered. Could the Project bear the lost down time and expense to train personnel to an acceptable level of proficiency?

Fourth, was the physiological and liability question. Would the intended use of the proposed technology reduce the amount of time diving personnel would be exposed to the hyperbaric environment? If not, did it contribute positively to safety or lend itself toward task overloading, creating a risk benefit concern?

Needless to say, there was a vast array of technologically advanced and innovative equipment available. Following a literature search by the staff, numerous inquiries were sent out to a wide spectrum of diving experts and consultants, seeking baseline data on what kind of equipment was available and who was available to provide the necessary training in its use. Where once the staff had borrowed heavily from the cave diving community, they now found that the most productive area in which to look for new techniques and technology was in the oil fields of the Gulf of Mexico and the North Sea. It was a logical solution to begin seeking our answers amongst the time-tested equipment of the commercial diving industry.

Our first step into the future of scientific diving was a very basic one. Based upon research performed by the Project Manager, Barbara O'Horo Benton, and the author, a commitment was made to purchase surface-air-supplied diving equipment. A compact, diving control console manufactured by Diving Systems International and designated the DCS I, was purchased following in-water testing and evaluation by staff members. This equipment, coupled with three-hundred foot umbilicals and two different configurations of diver headgear, allowed divers to have an unlimited air supply and instant contact with the surface by means of hardline radio communications or line-pull signals (Larn and Whistler 1984). The equipment chosen represents the standard of the commercial diving industry and has proven to be both durable and highly reliable. Training in its use was provided by outside consultants who came on-site and provided both classroom and in-water sessions. Although the use of this equipment required some additional personnel to handle line tending and console operation, it proved to be field proficient and project specifically adaptable. These advantages far outweighed the use of closed-circuit rebreathers or other more exotic equipment alternatives.

One overriding factor in choosing technology to do underwater research at a site like Warm Mineral Springs is its depth and the concurrent problems associated with working at depth. As diving scientists, we have long been aware of the dangers inherent in deep diving, namely the increased possibility of decompression sickness (DCS), the debilitating effects of nitrogen narcosis, and the increased time it takes for a diver to reach the surface in the event of a life-support failure. The purchase of surface-air-supplied diving equipment was a step in the right direction, but it did not address these concerns.

Throughout the history of the Warm Mineral Springs research,a heavy emphasis has been placed upon diver safety and accident prevention. Furthermore, close attention was paid to emergency evacuation procedures for treatment of hyperbaric incidents requiring recompression. Beginning with the 1985-1986 fiscal year, monies were allocated for the purchase of an on-site, fifty-four inch, double lock recompression chamber and a low pressure compressor to support it. The purchase of these vital pieces of equipment was delayed approximately twenty-six months, by questions of liability, waivers, insurance coverage, and the potential for litigation should any misuse of the chamber result in the compounding of a hyperbaric injury. These questions were effectively resolved by changing the administrating institution under whose auspices the Project operated, from a local community college to the Department of Anthropology at Florida State University. September 1987 saw the arrival of the aforementioned chamber on site. Unfortunately, complications with funding severely restricted Project spending during the remainder of the 1987-1988 fiscal year and no funds were available to get the chamber plumbed, staffed, and operational.

During this time period, diving operations were also stalled due to the time it took to integrate fully into the Academic Diving Program at Florida State University. Placement into the Academic Diving Program required that all Project dives be performed under their administrative control and had to adhere to the policies and procedures administered by their American Academy of Underwater Sciences-sanctioned Dive Control Board. The result of having to integrate into a new system, including testing and training, was a five month loss of in-water time. Furthermore, the Academic Diving Program imposed a series of depth certification limitations upon diving operations which curtailed all deep diving operations and completely changed the course of the next two years' research.

Deep diving operations began to get back on track in March, 1989, when staff members attended a workshop sponsored jointly by FSU and the Warm Mineral Springs Archaeological Research Project dealing with the theory and hardware of using mixed-gas diving techniques in scientific diving operations. It had long been proposed that the only way to continue deep excavations at the Springs was to incorporate alternate breathing gases into our system (Benton, 1988). The five day workshop at the FSU Marine Lab near Tallahassee, FL, introduced staff members to mixed-gas theory in the classroom and offered each class member the opportunity to actually mix two different diving gases and test them in nearby Wakulla Springs (8Wa24). Following the completion of this workshop, Cockrell and Benton began to work closely with Dr. Bill Hamilton of Hamilton Research, Ltd. to develop a mixed-gas program specifically for the Warm Mineral Springs site. This collaboration resulted in a series of tables which rely upon the use of a three part gas mixture, referred to as trimix, which uses

21% oxygen, 40% helium, and the balance nitrogen. An oxygen enriched air mixture, nitrox, 50% oxygen and 50% nitrogen, was suggested for use during the intermediate portion of decompression, followed by the use of pure oxygen during the last two decompression stops at twenty and ten feet (Hamilton, 1989; Hamilton, Cockrell, and Stanton, 1990)

Hamilton was quick to point out that the concept of utilizing mixed-gases was not a new one. Research into the use of helium-oxygen mixtures for diving began in 1919 with the work of Elihu Thomson and the United States Bureau of Mines and has become a standard for both military and civilian diving operations. Today, research continues to be done throughout the world regarding the use of other alternate breathing gases including a hydrogen-oxygen mixture, hydrox (Chandler, 1987). Continued research into these exotic gas mixtures should provide a framework of accumulated data upon which a training program could be developed to provide future archaeologists and other diving scientists with the necessary skills to function safely at depth on or beyond the limits of the Continental Shelf and in remote recesses of karstic caves, sinkholes, and cenote's.

Once a breathing mixture was chosen, the natural progression was to begin gathering the necessary staff and supplies to begin building a life-support system in which to use the gas. The first step taken was to find a Project Diving Officer who possessed the skills to build such a system and a series of consultants who could provide the staff with added expertise and the training necessary to bring staff members up to an acceptable level of performance in the use of the hardware. In addition, two technicians, one full-time and one part-time, were added to the staff.

The first task undertaken was the plumbing of the recompression chamber and the compressor. Due to site constraints and concerns over the noise resulting from chamber operation, the compressor had to be located in a spot remote from the chamber. Problems with distance and line loss were calculated and appropriate hose and fittings were purchased. Since the compressor needed to be manned during all chamber runs, and the distance prohibited direct communications between the chamber operator and the compressor operator, Motorola FM hand-held radios were purchased. As the system was built and problems or questions arose, viable solutions were achieved or the whole system was reevaluated and an entirely different tack was taken to move around problem areas. In this way, project-specific adaptations were made.

Sixteen high pressure compressed air cylinders were added and manifolded together into two separate eight tank banks to provide a sufficient quantity of air to run the chamber through two separate Table 6A treatment runs in case of a power failure or low pressure compressor malfunction (U.S.Navy, 1989). Oxygen is provided to the decompressing diver through a Scott BIB system inside the chamber. These facilitate decompression using oxygen, without the danger of oxygen buildup in the chamber atmosphere. Exhaled oxygen and other respiratory waste products are removed from the chamber through an overboard dump controlled by a Tescom regulator. The level of oxygen in the ambient atmosphere in the chamber is monitored constantly by an oxygen analyzer mounted outside the chamber and plumbed to a through-hull fitting. Gas is diffused throughout the chamber through handmade copper diffuser tubes mounted on inlet fittings in both the inner and outer locks. Supply to the chamber can be controlled from the inside to provide additional safety for divers being compressed.

Once the chamber was completed, work was begun on the actual mixed-gas system. The heart of the system remained the DCS I console purchased in 1986 for surface-air-supplied diving, but with basic modifications to permit the manifolding of trimix, nitrox, oxygen, and compressed air through its reducing valve and into the umbilicals leading to the divers. The manifolding in question was fabricated and remains an add-on which connects two on-line cylinders of trimix, two standby cylinders of trimix, two cylinders of nitrox, two cylinders of oxygen, and two cylinders of compressed air to the DCS I. The manifold provides for isolation of individual cylinders. Some modifications were made to the DCS I to facilitate an emergency compressed air bypass of the main reducer valve and the entire system has been cleaned for oxygen service.

Initial dives were made utilizing two types of headgear. Cockrell tried the commercial diving industry's standard, the Super-Lite 17, manufactured by Diving Systems International. Although a high quality piece of equipment, the Super-Lite 17's size and weight did not lend themselves to the bent over, head down posture required during archaeological excavation. Additional product research revealed the availability of the AGA MkII diving mask, manufactured by Interspiro, which featured a positive pressure seal and excellent communications capabilities. These features, coupled with its light weight and easy breathing quality, made it an obvious choice for use by Cockrell. Other staff divers found the Heliox-18A bandmask by Diving Systems International their headgear of choice for both working and standby tasks.

Incumbent in the use of any breathing mix which utilizes helium is the problem of body heat loss through respiration. To combat this problem, Cockrell was supplied with a high quality membrane dry suit and insulating coveralls made of Thinsulate manufactured by DUI Unlimited International, Ltd.. This suit provides adequate insulation to prevent hypothermia.

Before any actual diving operations were undertaken, extensive training programs were conducted on-site. The Project Diving Officer scheduled and carried out numerous unmanned training dives in the chamber. Staff members were taught how to conduct actual treatments based upon U.S. Navy Recompression Treatment Tables (U.S. Navy 1989). While these scheduled runs were being carried out, review classes on mixed-gas theory and diving physiology were presented on-site by Dr. Dudley Crosson of Delta P. Along with these classes in theory came two pool sessions which stressed the use of the Super-Lite 17 helmet and the new DUI drysuit. Emergency procedures were covered extensively and bailing out of the headgear into regular SCUBA was practiced until all staff divers felt comfortable with the techniques. Practice in the controlled environment of the pool allowed these critical techniques to be practiced in comfort and relative safety to insure that if an emergency should occur, the diver would be able to take the necessary action instinctively and without hesitation.

Once the system construction, testing, and training was completed, it was time to make the first working dive. On February 21, 1990, Wilburn Cockrell donned his AGA MKI mask and made the world's first scientific dive to do archaeological research on trimix. The dive was to a maximum of 17.98 meters or 159 FSW for twenty-nine minutes. The dive was performed without incident and marked the beginning of a new technological era for underwater archaeology.

At the time of this writing, the Hamilton Tables have proven to be highly reliable. There has been no incidence of hyperbaric problems. Daily testing of the diver for intravascular bubbles utilizing a Doppler Ultrasonic Monitor has been performed. In this test, a highly sensitive transducer is utilized to monitor three sites for bubble sounds, namely the precordium and each of the subclavian veins. A pre-dive test is done to obtain a reference reading. Following the dive, a post dive check is made at twenty minutes after surfacing and then again at a one hour interval. Three parameters are used to describe these intravascular bubbles, including frequency, duration, and percentage. These three parameters are combined to determine a final amplitude and then a final bubble grade which is compared against a standard developed by the Defense and Civil Institute of Environmental Medicine in Canada (Eatock and Nishi 1986).

Doppler testing and the grading of intravascular bubbles has traditionally been used to evaluate experimental decompression profiles. At Warm Mineral Springs, divers are using provisional Hamilton tables that are calculated specifically for that diving environment and their use there represents a testing phase for those specific tables. The Doppler tests provide Hamilton with sufficient data for evaluation of his calculations and an opportunity to head off any threat of DCS by recognizing the threat through an inordinate amount of bubbles following working dives.

A cooperative effort between Hamilton, Benton, the Project Diving Officer, and Dr. William Kepper of the Academic Diving Program's Dive Control Board, produced a comprehensive protocol to deal with the possibility of routine decompression sickness. This plan includes actual treatment protocol as well as a call list for medical and physiological consultation and procedures for dealing with administrative matters. Staff members are equipped with telephone pagers to assure notification and recall of all staff members in the event of a hyperbaric incident.

With an eye toward easing the existing administrative, logistical, and physiological concerns with making repeated dives to perform research tasks, efforts into acquiring a remotely operated vehicle (ROV) were begun in 1988. In recent years, the oil industry has begun to see the value of utilizing machines to do inspection tasks which do not require a diver's direct participation. In fact, industry sources indicate that the demand for ROV's is currently exceeding the rate of their production (Busby, 1988). The acceptance of their use has become so widespread that NOAA has begun a series of feasibility studies to determine whether ROV's can be used to perform obstruction detection and classification when evaluating safe passages and the maximum safe depths of channels (Ryther, Harris, and Fish, 1990). As of this writing, attempts are underway to use a tethered remotely operated vehicle to investigate the remains of what is believed to be a seventeenth-century treasure galleon in four-hundred and fifty-seven meters of sea water some seventy-five miles southwest of the Florida Keys (LeMoyne, 1990).

Although several different ROV's were considered for use at Warm Mineral Springs, the Phantom 300, manufactured by Deep Ocean Engineering, was chosen following on-site training and testing. It demonstrated remarkable maneuverability and handling characteristics, as well as high quality optics and videographic capabilities. Although its purchase price represents a high initial investment of funds, this ROV represents a cost effective alternative to the use of staff divers for certain diver tasks since ROV's are not subject to the physiological limitations of human divers. Bottom time is limited only by the availability of a power source and a trained operator. An ROV requires no gas supply and reduces on-site time since the vehicle requires no lengthy periods of decompression. Furthermore, initial testing of the Phantom 300 at Warm Mineral Springs indicates that its operation requires only a minimal staff commitment and a short term training period for personnel.

Some critics in the oil industry argue that divers are superior to ROV's for tasks which require complete visual information to facilitate the completion of complex tasks (Chandler, 1988). The excavation of delicate prehistoric sites would certainly fall into this category since excavation must constantly undergo reevaluation as actual excavation continues. The shortcoming of the ROV may be its built-in tunnel vision and its inability to transmit observer generated cues (Allgood, 1988). This would certainly affect the aforementioned evaluation process and affect the archaeologist/ROV operator's ability to "read" the situation and make corrections, resulting in lost or unrecoverable data. Nevertheless, the value of ROV's cannot be underestimated. We anticipate that the ROV can be utilized for numerous tasks, including the deployment of television cameras for the inspection of deep excavation units by non-diving contributing scientists and the deployment of remote sensing devices designed to do mapping and measure water temperature, pH, conductivity, and a host of other research parameters.

In an attempt to maintain a progressive diver training policy for staff divers, the 1989-1990 fiscal year saw the participation of staff divers in a training program conducted by Parker Turner of the National Association for Cave Diving and FSU's Academic Diving Program. Aimed at fulfilling the immediate concern of the American Academy of Underwater Sciences (AAUS) that research scientists working in an overhead environment should be certified to do so, WMSARP divers pursued their cave diving certification. The class also introduced the divers to new techniques which are standards in the current cave diving community and sharpened their overall diving skills.

## SUMMARY

There appears to be no limit to the technology being developed to accomplish underwater tasks safely and efficiently. The success and safety of the research effort at Warm Mineral Springs has demonstrated the need for the underwater archaeologist to stay abreast of the developments and to recognize that this technology can be adapted and utilized to do

site-specific archaeological tasks that insure the maximization of data recovery while minimizing the risk to diving personnel.

The future success of the Warm Mineral Springs Archaeological Research Project and research at other similar deeply submerged archaeological sites will depend entirely upon our willingness to be innovative and to embrace, nay, demand more complex, applicable technology to meet the demands of this increasingly demanding field of scientific investigation.

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