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Jeff M. Godfrey and Sandra E. Shumway
Editors

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Symposium Committee

Peter Auster, Jeff M. Godfrey (chair), Jan Heckman, Sandra Shumway, Joyce Wood-Martin

Symposium Staff

Dennis Arbige, Chris Cooper, Robin Donigian, Todd Fake, Ace Godfrey, Bridget Holohan, Joe Hoyt, Alex Jakubowski, Barbara Mahoney, Jeff Mercer, Brennen Phillips

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Fluorescence for Underwater Research: Principles, Tools, Techniques, Applications and Discoveries

Charles H. Mazel
NightSea LLC
20 New England Business Center, Andover MA 01810

Abstract

Fluorescence is the phenomenon by which light is absorbed at one wavelength and re-emitted at another, longer wavelength. Many marine organisms contain fluorescent substances, and the right excitation light source can reveal surprising new colors and patterns. While there were sporadic early scientific investigations of instances of fluorescence in the marine environment, more focused research projects are of very recent vintage. Despite this, fluorescence is already proving to be a useful tool for a variety of marine science applications. This paper reviews the history of underwater fluorescence investigation, the principles behind it, the tools and techniques for using it, current and potential applications, and some of the interesting discoveries that have already been made simply as a result of going out and conducting pure exploration for fluorescence in the sea.

Introduction

It is often the case that if you look at things in a different way you see new and potentially interesting aspects of them, and fluorescence certainly gives you a new and different view of the underwater world (Figure 1). Using fluorescence as a tool for marine biology is an idea that has appeared and re-appeared over the last 70 years, but it has only recently begun to take root as a practical technique with specific applications. As such it is still a relatively unexplored phenomenon, and we make new discoveries almost every time we go beneath the surface in the dark.

Most divers have already seen underwater fluorescence, even if they are not aware of it. If you see an intensely orange coral at a depth of 20m, it is fluorescing. The orange wavelengths of light have been removed from the downwelling solar radiation by the filtering effect of water, so the only way to be orange at depth is to fluoresce. Many corals have intense green coloration that arises from fluorescence. But many corals and other organisms that appear dull in daylight, or under a white light at night, at any depth will glow with remarkable colors and patterns when illuminated with the right light in the dark, while most organisms that are intensely colored in daylight do not fluoresce at all. You generally can't predict whether something will fluoresce from its 'normal' appearance, so you just need to get in the water and look.

This presentation reviews the history of underwater fluorescence investigation, the principles behind it, the tools and techniques for using it, current and potential applications, and some of the interesting discoveries that have already been made simply as a result of going out and conducting pure exploration for fluorescence in the sea.

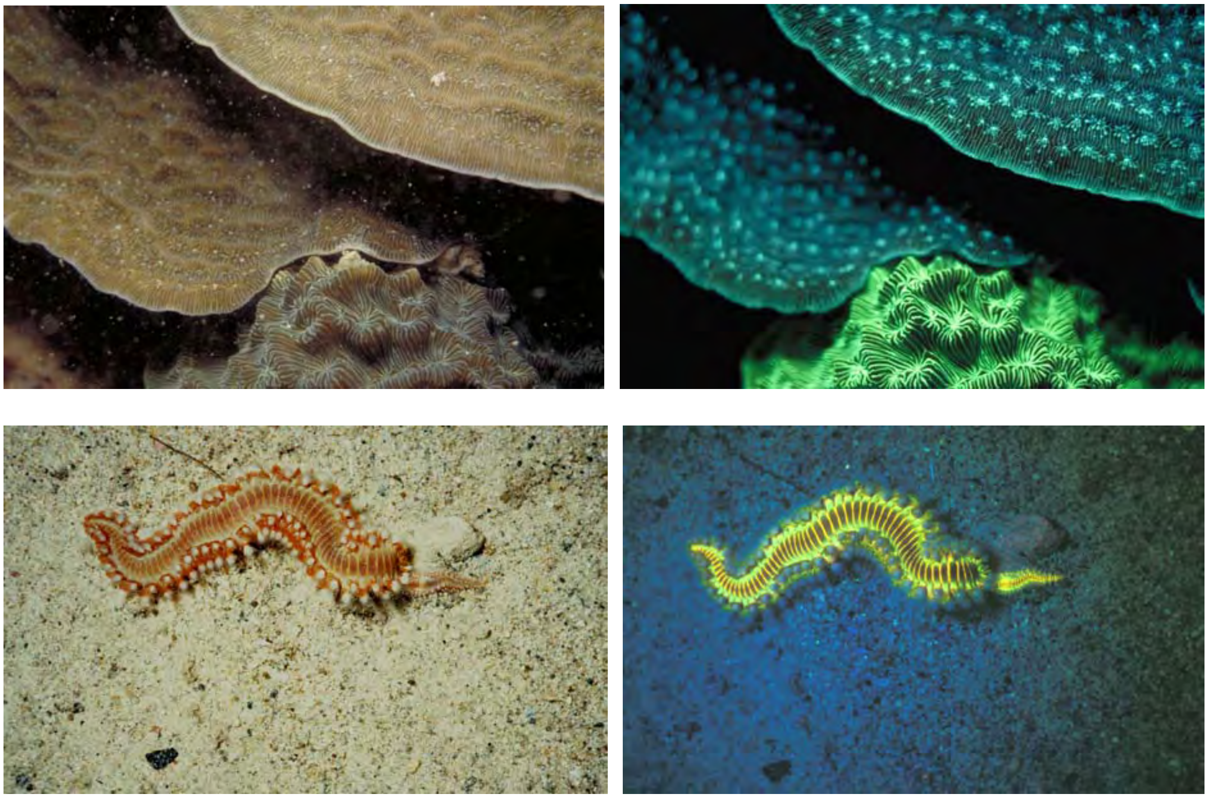

Figure 1. White-light (left) and fluorescence photographs of two corals (above, Roatan, Honduras) and a bristleworm (below, Bonaire).

History

The first printed record we have found of fluorescence of a marine organism dates to 1927. A Mr. C. E. S. Phillips (Phillips, 1927) was walking along the shore in Torbay, England, and noticed that the anemones in a tidepool seemed to be an especially bright green. He collected several specimens and used a light with a Wood's glass filter (a filter that absorbs visible light and transmits only ultraviolet) to confirm that it fluoresced under ultraviolet light. Phillips suggested that marine biologists add such a light to their repertoire of research equipment, but nothing came of his suggestion.

In the 1930's and '40's Siro Kawaguti, a Japanese marine biologist working at the Palao Tropical Biological Station, studied the pigments of corals. He noted that the most common pigment was a fluorescent green. Kawaguti carried out a number of manipulative experiments on the pigments, and authored several scientific papers on the topic (Kawaguti, 1944, 1966, 1969).

SCUBA divers rediscovered fluorescence in the 1950's. Luis Marden, a photographer for National Geographic magazine, wrote in 1956 that he noticed red anemones at a depth of 60 feet, where there should have been no red (Marden, 1956). The red color disappeared in flash photographs, and Marden correctly guessed that the effect was due to fluorescence. Conrad Limbaugh and Wheeler North, working at the Scripps Institution of Oceanography, investigated several brightly colored anemones from West Coast waters and determined that they were fluorescent (Limbaugh and North, 1956).

The biggest catalyst to the early study of fluorescence, though, was the work of Rene Catala, Director of the Noumea Aquarium in New Caledonia. Catala was the first person to systematically look for fluorescence in corals (Catala, 1958, 1959, 1960, 1964). He didn't do his looking underwater, though. His staff divers collected specimens during the day and he examined and photographed them under ultraviolet light in the Aquarium at night. Catala became enthusiastic about fluorescence and established a Hall of Fluorescent Corals in the Aquarium. In 1959 he shipped fluorescent corals to Europe and mounted an exhibition in Antwerp, Belgium. Aquarium displays of fluorescing corals have been a curiosity ever since. Possibly the first person to take ultraviolet light into the sea was Richard Woodbridge III. Not the warm waters of the Caribbean for him - Woodbridge built his own underwater ultraviolet lights and tested them in the chilly waters of Maine. He wrote articles for *Skin Diver* magazine (Woodbridge, 1959, 1961), and also published in the scientific literature (Woodbridge, 1959). Captain Jacques-Yves Cousteau mentions the use of ultraviolet light underwater in *The Silent World*, but the time when he used it is uncertain. Others have dabbled in fluorescence over the years, in both the scientific and popular realms, including Dr. Ken Read at Boston University (Read, 1967; Read et al., 1968), and Paul Zahl and David Doubilet at National Geographic (Zahl, 1963; Doubilet, 1997),

So while the idea of looking at underwater fluorescence is not new, the early attention was sporadic at best, presented mostly as a curiosity, and there has only recently been serious interest in the phenomenon in the marine research community.

For a more extensive list of references to both the scientific and popular literature, visit http://www.nightsea.com/references.htm.

Principles of fluorescence

Fluorescence is defined as the absorption of electromagnetic radiation at one wavelength, followed by its re-emission at another. Notice that I didn't say 'ultraviolet light'. It is a common misconception that fluorescence is specifically associated with ultraviolet. Yes, ultraviolet is very often used to stimulate fluorescence, but that doesn't mean that it is always the best choice. For our own research we use blue lights almost exclusively. To understand how best to see fluorescence we need to understand a few of the measures we use to characterize it.

The *emission spectrum* is the distribution of light energy as a function of wavelength for the emitted light, while the *excitation spectrum* is a graph of the relative ability of different wavelengths of light to stimulate, or excite, the fluorescence. Figure 2A shows the emission spectra for two of the fluorescent proteins commonly found in corals. We often describe spectra such as these by their peak (the wavelength of maximum energy) and their width, defined as the full width at half maximum intensity (abbreviated as FWHM). We can see that the cyan-fluorescing protein with the peak at 486 nm has a much broader emission than the green-fluorescing protein with a peak at 515 nm. Emission spectra can be diagnostic or at least strongly indicative of the identity of a fluorescing molecule, and can therefore be a tool for interpreting fluorescence responses. For example, chlorophyll has a characteristic fluorescence emission in the deep red, with a peak at approximately 685 nm. So far nothing else has been noted in the marine environment with a similar emission.

Figure 2B shows the excitation spectra for the two proteins for which the emission spectra are shown in Figure 2A. This graph tells you several useful things. The 'best' wavelength of light to excite the cyan protein is at about 440-450 nm, while the 'best' wavelength to excite the green protein is at about 500 nm. Neither of these 'best' wavelengths for either pigment is very good for exciting the other. And these are just two of the many fluorescing pigments found in nature.

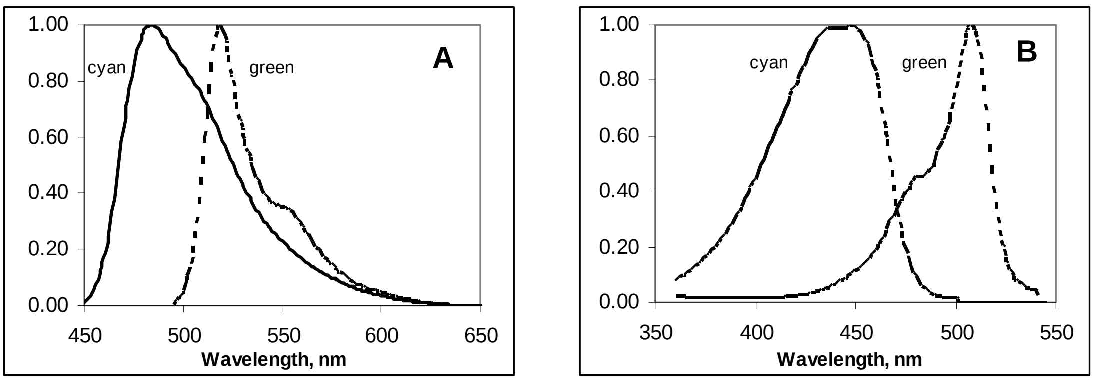

Figure 2. Emission (A) and excitation (B) spectra for two of the common fluorescent pigments found in corals.

This tells us that there is no single ideal wavelength for stimulating all fluorescence, and we have to make some intelligent compromises in choice of a light source. In practice we have found that a source with broad emission in the blue (wavelengths shorter than about 460 nm) is an effective option.

The excitation spectrum tells you what the best wavelength is to excite any given pigment, but it doesn't tell you how intensely the pigment will glow. What is important for that is the *fluorescence efficiency*, defined as the photons of light emitted divided by the photons of light absorbed. Many substances absorb light, but not all fluoresce, and among those that do, some fluoresce more brightly than others. This is because some substances are more efficient than others at converting absorbed energy into emitted energy. Intensity will also depend on the concentration of the fluorescing material – if there just isn't very much of it, it can't be very bright.

It is worth noting here that fluorescence is related to but quite distinct from bioluminescence. In both processes the emission of light comes from electrons that have been stimulated to an unstable excited state. The difference is in how electrons get the energy to reach the excited state. In fluorescence they do it by absorbing photons of incident light. In bioluminescence the energy comes from reactions of chemicals present in the organism. Thus bioluminescent organisms emit their own light, while those that are fluorescent will only glow when there is an external light source of the right wavelength.

Tools – light sources and filters

The principles of fluorescence provide guidance as to the tools we need to visualize fluorescence, whether by eye or with a camera. The basic ingredients are a light source to provide the excitation energy, a filter to restrict the wavelength output of the light source, and a barrier filter in front of the imaging device (eye or camera). You need the barrier filter because there will be two types of light reaching the imager – the fluorescence you want to see, plus reflected excitation light that you do not. Fluorescence is almost always a weak effect, and the reflected excitation light can easily overwhelm the fluorescence, or at least give you a false color impression. The barrier filter is selected to reject the excitation light and transmit the fluorescence so that you see the true fluorescence effect.

The light source to excite fluorescence could be a broadband (white-light) source fitted with an excitation filter that only passes the desired wavelengths. Broadband sources for divers include filament bulb dive lights, arc discharge dive lights, and electronic flash. Filament-type lamps tend to be weak at the short wavelengths (ultraviolet and blue) desirable for inducing fluorescence, so the more power the better. Continuous arc discharges (such as diver HID lamps) and electronic flash are rich in short wavelengths and are excellent sources. Keep in mind that you will be throwing away most of the energy because the filter only passes a narrow portion of the spectrum.

An alternative is to use an inherently narrow-band light source such as a light-emitting diode (LED) or a laser. Lasers are generally not practical for diver use as an illuminator, but high intensity LEDs can be a good choice. Even with LEDs it might be desirable to use a filter to trim the output.

Techniques

Visual observation

To explore for fluorescence you need to dive at night. In addition to your usual night diving equipment you would carry a that is designed to excite fluorescence and wear a barrier filter over your mask. Figure 3 shows one version of a diver flashlight and barrier filter that enable fluorescence exploration. The light incorporates a high intensity blue LED combined with a custom interference filter to trim the output. The yellow barrier filter is worn over the mask and can be easily moved out of the way as desired.


Figure 3. Underwater flashlight with a high intensity blue LED for fluorescence excitation, and the yellow barrier filter that the diver wears over the mask.

In the water you use your normal dive light to navigate to the work area and orient yourself, then turn the white light off and switch to the excitation light. Often when you do find something that fluoresces it will not be obvious what it is, and you will be switching back and forth between your white- and excitation-light sources.

Photography
Just as for conventional nighttime photography you use your dive light to find subjects of interest, then use your electronic flash to take the photograph. A conventional electronic flash can be adapted to be an excitation source by the addition of an external filter. A barrier filter will be needed over the camera lens. Figure 4 shows an example of filters that can be used with an underwater camera and strobe. For fluorescence photography you will generally need to use relatively high speed (ISO 200 or more) film, or a high ISO setting on a digital camera. Even then you will need to shoot at relatively open f-stops, from f2.5 to f11 depending on the brightness of the fluorescence.

Figure 4. Nikonos V underwater camera and Ikelite underwater flash, showing the barrier and excitation filters that would be used with each.

Videography
The technique for videotaping fluorescence is along the same lines as described above for diver viewing and photography. The main ingredient is an intense light source to excite the fluorescence brightly enough to be recorded.

What fluoresces underwater

Fluorescence has been discovered in a wide range of underwater life. Very few people have really undertaken this kind of investigation, so we have still barely scratched the surface, and much more remains to be discovered. The following summary should not be taken as a comprehensive listing, but just as an overview of what has been learned to date.

Algae
The fluorescence from photosynthetic pigments in marine algae has been known for a long time. Chlorophyll emits red with peaks at about 685 and 730 nm. Phycoerythrin, an accessory pigment in the red algae and cyanobacteria, emits orange with a peak at about 575 nm. This fluorescence is widespread in shallow-water environments, and can be used to photographically map the distribution of the algae. Many corals and other reef cnidarians contain symbiotic algae (dinoflagellates) and will exhibit the same red fluorescence as the macroalgae, although usually with greater intensity.

Invertebrates
We have found fluorescence in most invertebrate phyla. Sponges (Porifera) do not tend to be very fluorescent, but in shallow water they often have associated cyanobacteria that

fluoresce, and in deep water we have observed a general yellow-green fluorescence of the entire body. This fluorescence is noticeable, but not very intense. In some cases it is only the interior structural spicules that fluoresce.

Fluorescence is best known and usually most intense and widespread among the cnidarians (phylum Cnidaria), especially in the class Anthozoa, which includes the corals, anemones, and zoanthids. There are a wide variety of colors and patterns, and the fluorescing proteins are the ones that are proving to be so valuable for biotechnology.

In the phylum Annelida (segmented worms) only the polychaetes (class Polychaeta) are marine, and we have observed fluorescence in several varieties, both under blue and ultraviolet light. Interestingly, in some species the bristles fluoresced while the body did not respond, while in others that pattern was reversed.

Among the echinoderms, starfish, sea urchins, and sand dollars do not seem to be fluorescent, but we have seen fluorescence in numerous crinoids. The pattern in the crinoids is quite variable, with some having fluorescence only in the stalk, others only in the arms, and others fluorescing everywhere. We observed weak red fluorescence in a deep-water sea urchin from the Gulf of Mexico.

Fluorescence occurs in numerous mollusks. Among the gastropods the operculum is usually brightly green-fluorescent. Fluorescence is observed in some of their shells, either in part or whole. Some nudibranchs (shell-less gastropods) fluoresce over all or part of their body.

Among the Arthropoda we have observed fluorescence in deep-water pycnogonids (sea spider), and have found intense responses in some isopods, decapods (shrimp, crabs, and relatives), stomatopods (mantis shrimp), and ostracods (bivalve crustaceans).

Vertebrates

We have observed fluorescence in both shallow- and deep-water vertebrates, including fish, eels, and even a shark (at a depth of 560 m on a submersible dive in the Gulf of Mexico). Intense fluorescence in fish is far from common, but it is proving not to be extremely rare. While the observational sample size is still very small, we can say that lizardfish (genus *Synodus*) and small blennies are often (usually? always?) fluorescent, with observations of both from the Bahamas, Bonaire (Netherlands Antilles), Great Barrier Reef (Australia), and the Red Sea. Lizardfish routinely exhibit an intense green fluorescence that quite destroys the lizardfish’s white-light camouflage in the sand.

We have also observed differences within types – no parrotfish (at night, sleeping) observed in the Caribbean has so far been fluorescent, but the first one we observed in Okinawa glowed bright green. Moray eels in Okinawa glowed yellow-green over the entire body, while only the fin fluoresced on one observed in Hawaii.

Applications

There are a number of possible applications of fluorescence for marine research. This is still an emerging technology, so the applications are not mature, but interest is growing and numerous scientists are beginning to apply fluorescence techniques to their research.

Coral recruitment
Fluorescence is showing promise as a useful tool for research on coral recruitment and survivorship. The challenge is that newly settled corals are only about 1 millimeter in diameter and don't look very different from their surroundings. It is almost impossible to locate juvenile corals in the field until they are at least 5 mm in diameter, except with painstaking search that is generally impractical. By the time corals can be found easily with conventional techniques they are between 6 months and a year old. This misses an important early part of their life history, and makes it difficult to estimate survivorship in natural conditions.

Fluorescence is an effective way of detecting corals in the 1 to 5 mm diameter range. Detecting small things is all about contrast, and fluorescence provides an excellent source of contrast. If a coral fluoresces it will generally appear as a bright green spot against a dark background. You do your searching at night, and since your eyes are dark-adapted the glow is easy to spot. We have found corals less than 5 mm in diameter from more than 2 meters away, and corals as small as 1 mm in diameter in routine sweeps of patches of reef. Figure 5 shows two photographs of the same patch of reef, one a conventional white-light photograph, the other a fluorescence image. It is clear that this specimen could not have been found with conventional white light, but was easy to spot with fluorescence. Not all coral recruits fluoresce, and not everything that fluoresces is a coral, but the technique is proving to be useful, and additional research and development are ongoing.

Benthic surface mapping
Some forms of marine life can have quite distinctive appearance in fluorescence, with the result that they can be recognized much more easily in a fluorescence image than in a conventional white-light image. Quantifying bottom cover by making photo or video transects is a tried and true technique, but involves painstaking and time-consuming post-processing, with frame-by-frame manual interpretation. This is because there is no automated processing technique that will subdivide the images into categories of interest.

Fluorescence may not be a complete solution, but some preliminary trials show promise. In one exercise we wrote a set of classification rules for a fluorescence image collected over a coral reef environment by a one-of-a-kind fluorescence laser line scan imager (Mazel et al., 2003). In another trial, we took fluorescence photographs of settlement tiles being used in an invertebrate settlement experiment in New England, for comparison with white-light images of the same surfaces. It was evident that algae could be recognized and quantified much more easily with the fluorescence images (Figure 6).

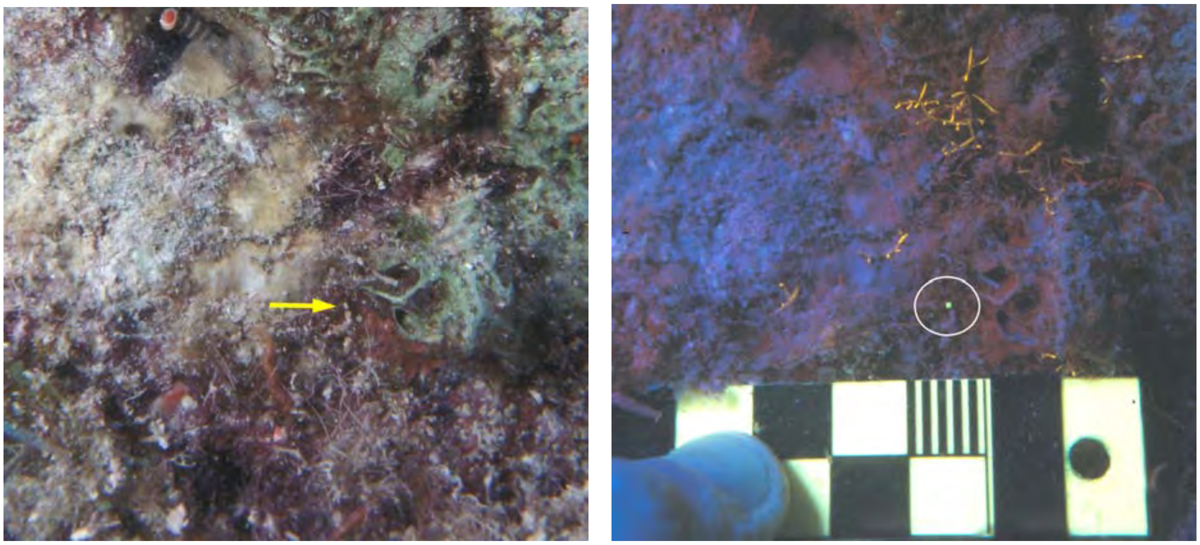

Figure 5. White-light (left) and fluorescence photographs of a patch of reef surface in Bonaire. Each image is about 7 cm on a side. The yellow arrow in the white-light image is pointing at the same target that appears bright green in the fluorescence image. The narrow lines in the measurement scale in the fluorescence image are 1mm wide.

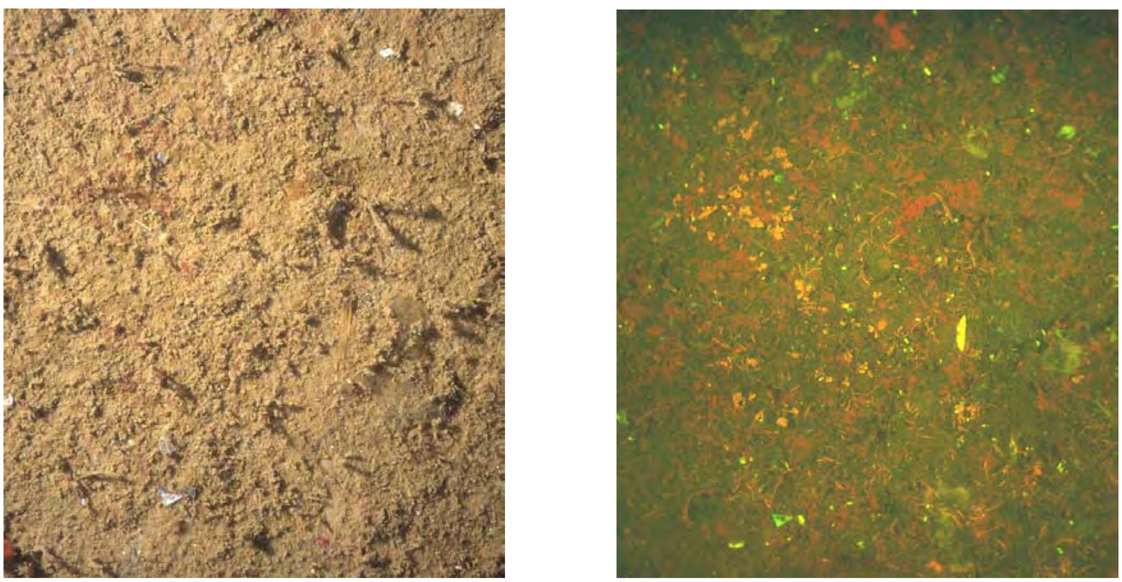

Figure 6. White-light (left) and fluorescence images of a portion of a settlement tile. The areas that appear red in the fluorescence image are algae that contain only chlorophyll, while the orange areas are indicative of red algae, which contain the orange-fluorescent pigment phycoerythrin in addition to chlorophyll.

Discovery of novel fluorescent proteins

Much of the bright fluorescence in corals and their relatives (cnidarians - anemones, zoanthids, corallimorpharians, etc.) arises from proteins that belong to a group generally referred to as 'green fluorescent protein' (GFP) (Matz, 1999), or simply 'fluorescent proteins' (FPs). Green is certainly the most common fluorescence color, but almost any color of the rainbow can be found. The name is tied up in the history of the discovery of these special proteins in *Aequorea victoria*, a bioluminescent jellyfish (Morise et al., 1974), and is now used to refer loosely to the entire family of related proteins, no matter what their color.

What is so special about GFP? Most natural fluorescence does not come directly from a protein, but from other molecules that are attached after the protein has been made by the cell. This means that in order to become fluorescent an organism would not only have to make the right protein, but would also need to do some additional chemistry, having the right substances available to the protein. What is magic about GFP is that the fluorescence comes directly from the protein itself, with no additional chemistry needed. If a cell makes the protein, it becomes fluorescent. This property makes GFP incredibly valuable for a wide range of applications in biomedical research, where it serves as a marker for gene activity (Chalfie et al., 1994). Several companies sell GFP's derived from corals and other organisms. It is not necessary to harvest large numbers of corals from the reef to meet the demand. The gene for the GFP can be transferred to bacteria, and colonies of bacteria can be used to grow supplies of the gene.

Several researchers are using fluorescence equipment in the field to discover new fluorescing proteins, and in the laboratory to work with the proteins. There is a need for new FP's in order to have better properties, such as new colors, brighter fluorescence, improved resistance to photobleaching, better compatibility for a wider range of experiments, and more.

Discoveries

The exploration for fluorescence has already led to discoveries of scientific interest. As noted above, the ability to find very small targets is already being applied to coral reef recruitment research. The process of discovering more and more types of fluorescing organisms is leading to greater understanding of evolutionary relationships.

In one instance our dive team happened upon a mantis shrimp (stomatopod) in its burrow in just 2 m of water within a stone’s throw of the dock at a Bahamas research station. The mantis shrimp had two bright yellow fluorescent spots on its back. Our video of the mantis shrimp captured the interest of a researcher who specialized in their vision. This in turn led to a 4-person collaborative effort to understand the significance of the fluorescence through observation, measurement, and modeling. We were able to determine that the fluorescence was a part of the animal’s visual threat response and published the results in *Science* (Mazel et al., 2004).

Discoveries are easy to come by since so little as known. Applications are just now emerging as more and more scientists begin to experiment with the technique. It is not particularly difficult to learn and apply, with the major disadvantage being the need to do much of the work at night. Beyond specific scientific applications, experiencing fluorescence in the sea is a broadening of one's horizons. Fluorescence is a very real aspect of the underwater world, one that relatively few divers have ever experienced. Seeing this added dimension of underwater life adds a new appreciation for the diversity of nature. And it's just plain beautiful.

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Counterdiffusion Diving: Using Isobaric Mix Switching To Reduce Decompression Time

Glenn H. Taylor
NOAA Undersea Research Center, University of North Carolina at Wilmington
5600 Marvin Moss Lane, Wilmington, NC 28409

Abstract

Switching a diver's breathing mix from heliox to nitrox at a specified time during the bottom portion of the dive can reduce the total stop time for long dives in the deep nitrox range. Isobaric Mix Switching with oxygen decompression reduced calculated total stop times by an average of 38% compared to calculated total stop times using nitrox with oxygen decompression. The optimal mix-switch time was determined empirically using mixed-gas decompression software.

Introduction

This paper describes a diving procedure called Isobaric Mix Switching (IMX) that reduces the total stop time for long dives in the deep nitrox range. "Isobaric" means equal pressure, so Isobaric Mix Switching, as described in this paper, consists of changing a diver's breathing mix with no shift in depth, during the bottom portion of a dive. The mix switch is from heliox to nitrox with the oxygen percentage constant.

Switching the diver's breathing mix from heliox to nitrox takes advantage of differences in diffusion and saturation rates between the two inert gases. Helium is eliminated from body tissues faster than the nitrogen is taken up causing a transient reduction in total inert gas tissue tension. This results in a decrease in total stop time that will vary with the timing of the mix switch and can be optimized using mixed-gas decompression software.

Background

Experiments begun in 1959 by Keller and Bühlmann (Keller and Bühlmann, 1965; Keller, 1967 & 1968) first made use of the idea that different inert gases have different saturation speeds and that by switching mixes containing these inert gases, based on the rate at which these gases are taken up and eliminated by the body, a decompression advantage would result. Beginning in 1962, experiments sponsored by the U.S. Navy used multiple inert gases to optimize decompression from deep dives ranging from 130 fsw to 1,000 fsw (Keller and Bühlmann, 1965; Keller, 1967). Of the many experimental dives in this series, only one used an isobaric mix switch (Keller and Bühlmann, 1965). That dive was performed in a chamber to a depth of 130 fsw for 120 minutes, used seven human subjects, switched from oxygen /helium (40/60) to oxygen /argon (40/60) after seventy minutes, and used oxygen for the final portion of the decompression. In 1975, Bühlmann described the theoretical benefits of Isobaric Mix Switching in an identical dive profile that substituted nitrogen for argon in the second mix. These experimental and theoretical dive profiles demonstrated a major decompression advantage over conventional methods, but are impractical for open-water diving because they exceed oxygen exposure limits, such as those published by NOAA (Joiner, 2001).

Inert Gas Diffusion and Counterdiffusion

Gases typically diffuse from regions of higher concentration to regions of lower concentration (Wienke, 2001). Following an isobaric mix switch the inert component of the initial mix breathed by the diver will begin diffusing out of the tissues, and the inert component of the second mix will begin diffusing into the tissues. Since there is no change in pressure and the gases are moving in opposite directions, this is called “isobaric counterdiffusion” (Wienke, 2001; Lambertsen, 1978; Lambertsen and Idicula, 1975). Counterdiffusion can have favorable or unfavorable consequences, depending, in part, on the physical characteristics of each inert gas. Graham’s Law states that the volume of gas diffusing into a liquid is inversely proportional to the square root of the molecular weight of the gas (Keller, 1967). A “light” gas, such as helium, is taken up and eliminated faster than a “heavy” gas, such as nitrogen. For example, in the Bühlmann decompression model (Bühlmann, 1975), helium halftimes are 2.65 times faster than corresponding nitrogen halftimes for similar compartments.

The tissue tension for an inert gas is dependent on diffusion rate, perfusion, solubility, time, temperature, and other factors. When two or more inert gases are present in a dissolved state within the body, their tissue tensions are additive (Shilling et al., 1976). This means that the degree of tissue saturation is dependent on the combined tissue tensions of the inert gases and how their sum compares to ambient pressure.

“Good” Isobaric Counterdiffusion

Researchers studying isobaric counterdiffusion used the terms “subsaturation” (Lambertsen, 1978), “desaturation” (Wienke, 2001; Lambertsen and Idicula, 1975), and “undersaturation” (D’Aoust, 1983) to describe the theoretical decrease in total inert gas tissue tensions following an isobaric mix switch from heliox to nitrox. Yount (1982) used hypothetical tissue halftimes to illustrate that mix switching from one gas to another could reduce decompression below that of either mix used alone. Animal experiments (D’Aoust, 1983) supported the theory that specific mix switches, such as helium-to-nitrogen, could produce a decompression advantage.

Figure 1 illustrates the case where tissues are at or near saturation with an inert gas having a relatively fast diffusion rate, such as helium, and the diver’s breathing mix is switched to a mix with an inert gas with a slower diffusion rate, such as nitrogen. The total inert gas tissue tension will temporarily drop (Keller and Bühlmann, 1965; Wienke, 2001; Lambertsen, 1978; Lambertsen and Idicula, 1975, D’Aoust, 1983) because the helium is diffusing out faster than the nitrogen is diffusing in. This creates a decompression advantage that may be optimized by carefully timing the mix switch (Keller, 1967).

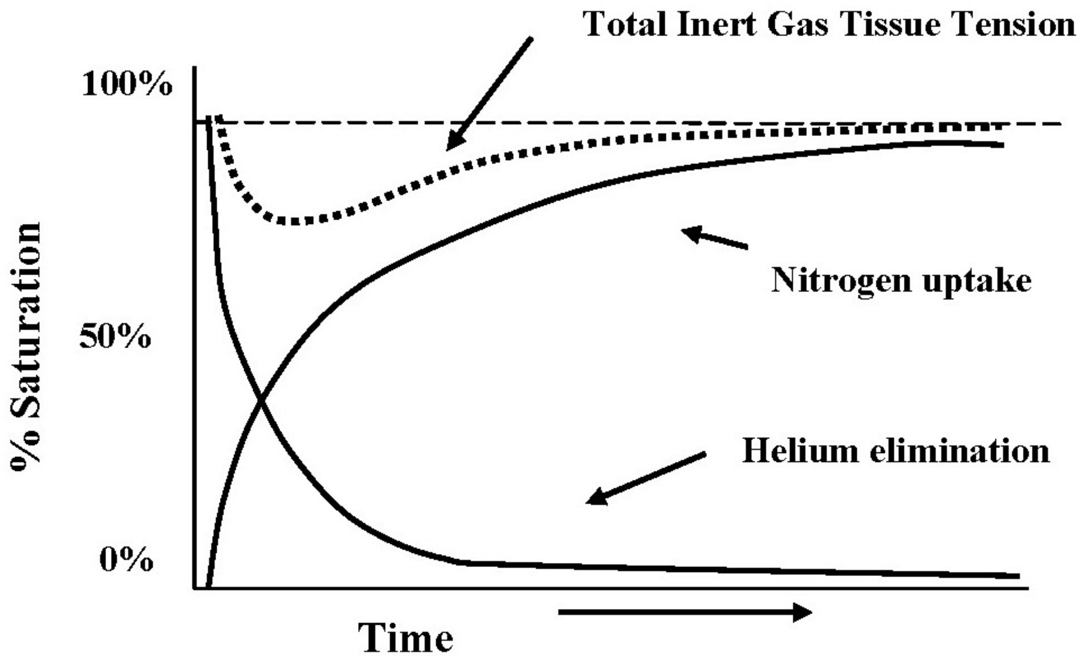

Figure 1. Showing the reduction of total inert gas tissue tension following an Isobaric Switch from heliox to nitrox.

"Bad" Isobaric Counterdiffusion

Nearly all the literature on isobaric counterdiffusion concerned the opposite case, where tissues at or near saturation with an inert gas having a slower diffusion rate, such as nitrogen, were exposed to an inert gas with a faster diffusion rate, such as helium (Lambertsen, 1978; Lambertsen and Idicula, 1975; D'Aoust, 1983; Blenkarn et al., 1971; D'Aoust et al., 1977; Hill, 1977a; Vann, 2004; Peterson et al, 1980; Strauss and Kunkle, 1974). These researchers found that tissue supersaturation and bubble formation could occur isobarically when the combined tissue tensions of the inert gases exceeded ambient pressure. "Counterdiffusion supersaturation" resulted because an inert gas with a fast diffusion rate, such as helium, diffused into the tissues faster than an inert gas with a slow diffusion rate, such as nitrogen, diffused out. This may occur most commonly in the following situations:

- A diver breathing a mix containing nitrogen, is surrounded by a mix containing helium. This could occur in a chamber or dry suit and lead to "superficial" (skin) lesions similar to "skin bends" (Lambertsen, 1978; Lambertsen and Idicula, 1975; Blenkarn et al., 1971; Vann, 2004; Peterson et al, 1980).

- A diver switches from a breathing mix containing nitrogen, to a mix containing helium, leading to "deep tissue supersaturation" and bubble formation (Lambertsen and Idicula, 1975, D'Aoust, 1983; D'Aoust et al, 1977; Vann, 2004). Since this phenomenon is well understood, both cases are easily avoided. A diagram of this situation is shown in Figure 2.

A third type of "bad" counterdiffusion may be involved in vestibular symptoms (Vann, 2004) seen isobarically in a deep (1,200 fsw) chamber dive (Lambertsen, 1978; Lambertsen and Idicula, 1975), in divers following a switch to air during decompression from deep heliox dives (Hill, 1977b; Doolette and Mitchell, 2003), and more commonly during helium saturation dives (Lambertsen and Idicula, 1975; Hill, 1977b). Researchers (Lambertsen and Idicula, 1975) suggest that the cause may be counterdiffusion of helium from the middle ear through the round window, but the mechanism and parameters are poorly understood (Vann, 2004).

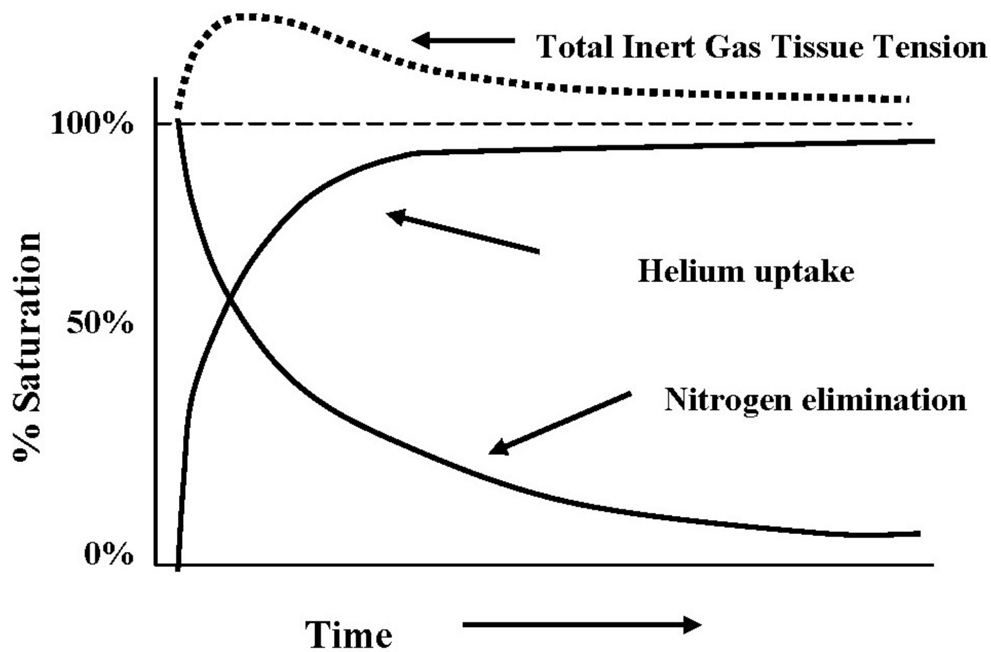

Figure 2. Showing a case of supersaturation caused by switching from nitrox to heliox (Bove and Wells, 1990).

Methods

Determine Mix: The first and most critical step in planning an Isobaric Mix Switch dive is to determine the oxygen percentage of the heliox and nitrox mixes. The author used Pro Planner™ Trimix v. 7.12C (Bushnell and Gurr 1997) decompression software to empirically determine the highest possible oxygen percentage (adjusted in 2% increments) that still allowed the dive and decompression to stay within oxygen exposure limits.

Determine Optimal Switch Time: The next step is to determine the Optimal Switch Time. The author used Pro Planner™ decompression software to calculate total stop times for a given dive profile with a fixed depth and bottom time, while systematically increasing the heliox portion of the dive in five-minute increments for each trial, until a minimum total stop time was found. For example, in planning a 60-minute dive for a given depth, the author calculated total stop time for 5 minutes of heliox and 55 minutes of nitrox; 10 minutes of heliox and 50 minutes of nitrox; 15 minutes of heliox and 45 minutes of nitrox, and so on. The author continued to increase the heliox and decrease the nitrox in five-minute increments until a minimum total stop time was found. This minimum total stop time provided the Optimal Switch Time. Using this technique, the author calculated total stop times for a matrix of depths and bottom times from 100 fsw to 150 fsw and from 50 minutes to 120 minutes both with and without oxygen decompression.

Using these Optimal Switch Times, the author then compared total stop times using four different decompression techniques: Nitrox Dive with Nitrox Decompression, Isobaric Mix Switch Dive with Nitrox Decompression, Nitrox Dive with Oxygen Decompression, and Isobaric Mix Switch Dive with Oxygen Decompression.

The author also compared selected profiles generated using Proplanner™ with those generated using Abyss™ 120 v. 2.30.17 software (Hemingway and Baker 2003), and V-Planner™ VPM-B software (Parrett, 2001).

Results

For a given depth and bottom time, the calculated total stop time decreased as the length of the heliox segment of the dive increased, reaching an optimal minimum value before increasing again. APPENDIX A contains a matrix of Total Stop Times for depths from 100 fsw to 150 fsw and bottom times from 50 minutes to 120 minutes for dives using Isobaric Mix Switching with Nitrox Decompression with the minimum stop times highlighted.

APPENDIX B contains a similar matrix of Total Stop Times for dives using Isobaric Mix Switching with Oxygen Decompression with the minimum stop times highlighted. These matrixes show how the timing of the mix switch affects total stop time for dives with and without oxygen decompression and gives the Optimal Switch Time for each dive profile. Tables 1 and 2 contain samples of the matrixes found in APPENDIX A and B for an 80-minute dive. Using Pro Planner™ the Optimal Switch Time generally increased with the bottom time and depth of the dive.

APPENDIX C contains a matrix of Total Stop Times for depths from 100 fsw to 150 fsw and bottom times from 50 minutes to 120 minutes for dives using four different decompression techniques: Nitrox Dive with Nitrox Decompression, Isobaric Mix Switch Dive with Nitrox Decompression, Nitrox Dive with Oxygen Decompression, and Isobaric Mix Switch Dive with Oxygen Decompression. The oxygen percentages of bottom and decompression mixes used in the decompression calculations for APPENDIX C were adjusted in 2% increments to optimize total stop times so that realistic comparisons could be shown. Table 3 contains a sample of APPENDIX C for an 80-minute dive.

Table 1 Sample profiles from the APPENDIX “A” Matrix used to determine Optimal Switch Time for dives using Isobaric Mix Switching with Nitrox Deco. Shaded boxes show shortest total stop times and therefore the Optimal Switch Time.

Depth	Time to Mix Switch from Heliox to Nitrox						Bottom
	20 min	25 min	30 min	35 min	40 min	45 min	Mix
	Total Stop Time for an 80 Minute Dive						
100 fsw	20	17	15	15	16		36%
110 fsw	30	27	24	25	27		36%
120 fsw	53	50	49	49	51		32%
130 fsw	79	74	71	71	72		30%
140 fsw	111	105	100	97	98		28%
150 fsw	133	125	119	116	116	117	28%

Table 2 Sample profiles from APPENDIX “B” Matrix used to determine Optimal Switch Time for dives using Isobaric Mix Switching with Oxygen Decompression. Shaded boxes show shortest total stop times and therefore the Optimal Switch Time.
Boxes marked N/A exceed ProPlanner oxygen exposure limits.

Depth	Time to Mix Switch from Heliox to Nitrox						Bottom
	20 min	25 min	30 min	35 min	40 min	45 min	Mix
	Total Stop Time for an 80 Minute Dive						
100 fsw	11	10	9	9	11		36%
110 fsw	18	17	17	18			34%
120 fsw	27	26	27				32%
130 fsw	40	38	37	37	40		30%
140 fsw	57	54	52	N/A	N/A		28%
150 fsw	77	73	70	N/A	N/A		26%

Table 3 Sample from APPENDIX “C” comparing total stop times using different techniques for an 80 minute dive

Depth	Nitrox Dive Nitrox Deco	IMX Dive Nitrox Deco	Nitrox Dive Oxygen Deco	IMX Dive Oxygen Deco
100 fsw	34	15	18	9
110 fsw	55	29	26	17
120 fsw	77	49	40	26
130 fsw	109	71	55	37
140 fsw	182	110	87	52
150 fsw	217	131	103	70

Using Pro Planner™, Nitrox with Oxygen Decompression reduced total stop times more than Isobaric Mix Switching with Nitrox Decompression for most dives shorter than 100 minutes. In the longer and deeper ranges, Isobaric Mix Switching with Nitrox Decompression reduced total stop times more than Nitrox with Oxygen Decompression. Some nitrox dives were not allowed by oxygen exposure limits, even when the oxygen percentage was reduced to that of air, while these same dives were permitted using Isobaric Mix Switching. In all cases, Isobaric Mix Switching Dives with Oxygen Decompression produced the greatest reduction in total stop time.

Reduction in Total Stop Time

Table 4 shows the reduction in Total Stop Time, in minutes, using Isobaric Mix Switching with Oxygen Decompression compared to Nitrox with Oxygen Decompression for dives from 100 fsw to 150 fsw and from 50 minutes to 120 minutes. Isobaric Mix Switching with Oxygen Decompression reduced total stop times within these ranges by an average of 38% compared to Nitrox with Oxygen Decompression.

Table 4 Reduction in total stop time in minutes using isobaric mix switching with oxygen decompression compared to nitrox with oxygen decompression.

Depth	Bottom Time							
	50	60	70	80	90	100	110	120
100 fsw	4	6	7	9	9	11	15	25
110 fsw	5	6	7	9	12	19	33	37
120 fsw	6	7	10	14	22	31	32	44
130 fsw	9	12	14	18	34	33	68	66
140 fsw	11	17	20	35	34	53	65	
150 fsw	18	20	27	33	60	54		

Comparisons Using Different Software Programs

Table 5 compares the optimal mix switching times of three different software programs for a 120-fsw dive for 80 minutes with a mix switch time from heliox to nitrox varying from 5 minutes to 50 minutes. This table was used to determine the optimal switch time for each software program's dive profile. The optimal switch time for the Abyss™ and V-Planner™ profiles occurred a few minutes later than that of the Pro Planner™ profiles.

Table 6 compares total stop times for three decompression programs using various decompression techniques. Isobaric Mix Switching with Nitrox Decompression reduced total stop times more than Nitrox with Oxygen Decompression in the Abyss and V-Planner programs. In all cases, Isobaric Mix Switching with Oxygen Decompression produced the greatest reduction in total stop time.

Table 5 Total Stop Times for 120-fsw for 80 minutes using Mix Switching Only.
Shaded boxes show minimum total stop time used to determine optimal switch times.

	Time to mix switch from heliox to nitrox									
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min	45 min	50 min
	Total Stop Times for a 120-fsw Dive for 80 Minutes									
ProPlanner	71	65	59	53	50	49	49	51		
Abyss 120	70	63	56	51	45	40	35	35	37	
V-Planner	66	61	56	51	46	36	31	29	29	31

Table 6 compares total stop times for three decompression programs using various decompression techniques. Isobaric Mix Switching with Nitrox Decompression reduced total stop times more than Nitrox with Oxygen Decompression in the Abyss and V-Planner programs. In all cases, Isobaric Mix Switching with Oxygen Decompression produced the greatest reduction in total stop time.

Table 6. Comparison of Total Stop Times for a 120-fsw dive for 80 minutes.

	Nitrox Dive Nitrox Deco	IMX Dive Nitrox Deco	Nitrox Dive Oxygen Deco	IMX Dive Oxygen Deco
	Total Stop Times for a 120-fsw Dive for 80 Minutes			
ProPlanner	77	49	40	26
Abyss 120	88	35	43	24
V-Planner	71	29	38	18

Open Water Dives:

In December 2003, four NURC/UNCW staff divers performed eight square dives to an average maximum depth of 130 fsw off Key Largo, Florida using Isobaric Mix Switching and technical open-circuit scuba equipment. The divers breathed a 27/73 oxygen/helium mix, then switched to a 27/73 oxygen /nitrogen mix after 20 minutes. Since the heliox breathing time was relatively short, the divers carried a side-mount cylinder containing heliox and breathed it upon beginning the dive. Following the Isobaric Mix Switch, the divers breathed the nitrox from doubles for the balance of the bottom time and the ascent to 20 fsw. The divers carried a decompression cylinder containing 100% oxygen and breathed that gas at the 20-fsw and 15-fsw decompression stops. Each diver carried a VR-3 trimix dive computer (Delta P Technologies) with ProPlanner™ decompression software that provided primary decompression information. Bottom time for the eight dives totaled seven hours. The first four dives had a bottom time of 60 minutes and an average total decompression time of 27 minutes. The second four dives, performed the following day, had a bottom time of 45 minutes and an average total decompression time of 15.5 minutes. Decompression time included four minutes of deep stops. Three of the four divers reported elevated, transient narcosis immediately following the mix switch, and higher consumption rates for heliox than for nitrox. One diver reported a decrease in visual acuity following the mix switch.

In 2004, NURC divers used Isobaric Mix Switching in four operational dives (two square, two multilevel) at an average maximum depth of 135.5 fsw and for an average bottom time of 58.5 minutes. No DCS symptoms were reported on any IMX dive.

Discussion

Following a single chamber experiment by Keller and Bühlmann in 1962 (Bühlmann, 1975), Isobaric Mix Switching seems to have been forgotten. Perhaps this is because the military, commercial, and technical diving communities have focused on systems and techniques for deeper capabilities. Mix switching, although common in technical diving, is typically done during the decompression portion of the dive where mixes with increasingly higher oxygen percentages are used to shorten stop times.

Several factors now make Isobaric Mix Switching practical as a technique for reducing total stop times. Technical diving techniques and equipment have made mix switches routine. Dive planning software for mixed-gas diving is now widely available and easy to use. Newer dive computers can handle isobaric mix switches in real-time.

Operational Considerations:

Dive Planning: A good first step in dive planning is to compare the total stop time using Isobaric Mix Switching with the same profile using Nitrox to see if the reduction in decompression time is worth the additional operational complexity. Oxygen exposure is the single most important limiting factor on the deeper and longer dives and will drive the choice of both bottom and decompression mixes. As mentioned earlier, the author used ProPlanner™ decompression software and trial-and-error to determine the highest possible oxygen percentage that still allowed the dive and decompression to stay within oxygen exposure limits. As a practical matter, NURC has found it easier and more convenient to use 27% oxygen in both the heliox and nitrox, since these mixes are useful over a broad range of depths and times. The use of a single, reduced oxygen percentage mix also provided a margin of error and additional safety with regards to oxygen toxicity.

The exact time of the mix switch is not critical. Trials with mixed gas decompression software show that variations of +/- 10 minutes in mix switching times have little effect on the total stop time. Should it become necessary to leave bottom during the heliox portion of the dive, it is beneficial to switch to nitrox for the ascent. Water temperature, thermal protection and voiding should be considered. Divers using Isobaric Mix Switching must be qualified in mixed-gas diving for the equipment used.

Gas Management: Because of the longer bottom times available with this technique, gas management calculations must be performed to assure adequate supplies during each phase of the dive. Normal gas management rules, such as the rule of thirds, apply to the nitrox and the oxygen, but not to the heliox. This is because the diver can switch to the nitrox at any time during the dive, but should not switch back to the heliox. On the operational dives, the divers sent the used heliox cylinders to the surface on a "sausage" lift bag for recovery by the vessel. Normal technical diving gear can be used in many of the IMX dives, but for the long duration dives in the deeper range rebreathers or surface-supplied gear may be more appropriate.

Decompression Information: Tables or a mixed-gas dive computer may be used for decompression information. If computers are used, divers must carry contingency tables that allow them to leave the bottom at any time. Table 7 shows one of the contingency decompression tables used on the NURC dives.

Table 7. Sample Isobaric Mix Switching Contingency Tables.

138 fsw 27/73 Heliox → Nitrox IMX; 99% Oxy.							
Gas Used	**Bottom Time in Minutes**	**Micro-bubble Stops**		**Decompression Stops**			
		Nitrox 27/73				**Oxygen 99%**	
		2 min	**2 min**	**40'**	**30'**	**20'**	**15'**
Heliox 27/73	**5**	**69'**	**36'**				**1**
	10	**75'**	**46'**			**1**	**1**
	15	**82'**	**52'**		**1**	**1**	**5**
	20	**82'**	**56'**		**1**	**1**	**10**
Nitrox 27/73	**25**	**79'**	**46'**			**1**	**10**
	30	**75'**	**46'**			**1**	**11**
	35	**75'**	**46'**			**1**	**13**
	40	**79'**	**46'**			**1**	**15**
	45	**79'**	**49'**			**1**	**18**
	50	**79'**	**52'**		**1**	**2**	**19**
	55	**82'**	**52'**		**2**	**3**	**21**
	60	**82'**	**56'**		**4**	**4**	**23**
	65	**85'**	**59'**	**1**	**7**	**4**	**25**
	70	**85'**	**59'**	**1**	**10**	**4**	**28**
	75	**89'**	**62'**	**3**	**12**	**4**	**31**
	80	**89'**	**62'**	**4**	**14**	**5**	**33**

Conclusion

Calculations using decompression software as well as demonstration and operational dives conducted by divers from the NOAA Undersea Research Center confirm that Isobaric Mix Switching is a practical technique for reducing total stop times for long dives in the deep nitrox range. Isobaric Mix Switching with oxygen decompression reduced calculated total stop times by an average of 38% compared to calculated total stop times using nitrox with oxygen decompression. The optimal mix-switch time was determined empirically using mixed-gas decompression software. This technique should have scientific, commercial, and military applications using technical open-circuit scuba, rebreathers, and surface-supplied diving equipment.

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Matrix of Total Stop Times Using Isobaric Mix Switching Only

(Shaded boxes show minimum total stop times used to determine optimal switch times.)

Depth	Time to mix switch from heliox to nitrox										Oxygen Percent in Mixes
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min	45 min	50 min	
	Total Stop Times for a 50 Minute Dive										
100 fsw	9	6	3	3	3	6	9	14			36%
110 fsw	15	12	9	8	9	11	15	19			36%
120 fsw	30	26	22	20	21	24	28	33			32%
130 fsw	38	33	29	27	28	30	36	46			32%
140 fsw	54	47	42	38	39	43	48	54			30%
150 fsw	74	64	56	53	55	57	63	69			28%
	Total Stop Times for a 60 Minute Dive										
100 fsw	16	12	9	7	6	7	10	13			36%
110 fsw	24	20	16	14	13	14	17	21			36%
120 fsw	43	37	33	30	28	29	33	37			32%
130 fsw	54	48	42	38	36	39	42	46			32%
140 fsw	74	65	58	54	53	54	57	62			30%
150 fsw	100	90	81	76	73	74	76	80			28%
	Total Stop Times for a 70 Minute Dive										
100 fsw	24	20	16	13	11	10	11	14			36%
110 fsw	33	28	24	21	19	18	20	23			36%
120 fsw	58	52	46	41	38	38	40	43			32%
130 fsw	79	72	64	59	57	56	57	60			30%
140 fsw	110	100	92	85	80	78	79	81			28%
150 fsw	133	122	111	102	97	94	93	96			28%
	Total Stop Times for an 80 Minute Dive										
100 fsw	31	27	24	20	17	15	15	16			36%
110 fsw	42	38	34	30	27	24	25	27			36%
120 fsw	71	65	59	53	50	49	49	51			32%
130 fsw	101	92	84	79	74	71	71	72			30%
140 fsw	143	132	121	111	105	100	97	98			28%
150 fsw	171	157	144	133	125	119	116	116	117		28%

NOTE 1: All times calculated using ProPlanner with 10% MicroBubble Factor.

NOTE 2: Oxygen percentage in mixes has been adjusted in 2% increments to minimize stop times while staying within ProPlanner oxygen exposure limits.

Appendix A - Page 2 of 2

Matrix of Total Stop Times Using Isobaric Mix Switching Only

(Shaded boxes show minimum total stop times used to determine optimal switch times.)

Depth	Time to mix switch from heliox to nitrox										Oxygen Percent in Mixes
	30 min	35 min	40 min	45 min	50 min	55 min	60 min	65 min	70 min	75 min	
	Total Stop Times for a 90 Minute Dive										
100 fsw	21	19	20	22							36%
110 fsw	38	38	39	40							34%
120 fsw	61	60	61	62							32%
130 fsw	89	87	85	86	88						30%
140 fsw	124	120	118	119	121						28%
150 fsw		166	161	159	158	159					26%
	Total Stop Times for a 100 Minute Dive										
100 fsw	28	25	25	27							36%
110 fsw	48	47	46	47							34%
120 fsw	76	73	72	72	73						32%
130 fsw		105	102	101	102						30%
140 fsw			144	142	142	142	144				28%
150 fsw				190	186	183	182	182	186		26%
	Total Stop Times for a 110 Minute Dive										
100 fsw	35	31	31	31	32						36%
110 fsw	59	57	55	56	56						34%
120 fsw	91	88	85	83	83	85					32%
130 fsw		125	122	120	120	121					30%
140 fsw			174	169	165	163	162	162	162	165	28%
150 fsw				225	217	210	206	205	206	208	26%
	Total Stop Times for a 120 Minute Dive										
100 fsw	43	40	38	37	38						36%
110 fsw		67	66	65	64	65					34%
120 fsw			99	98	97	98					32%
130 fsw				142	140	139	138	138	139		30%
140 fsw					192	187	183	180	179	181	28%
150 fsw						241	234	231	230	231	26%

NOTE 1: All times calculated using ProPlanner with 10% MicroBubble Factor.

NOTE 2: Oxygen percentage in mixes has been adjusted in 2% increments to minimize stop times while staying within ProPlanner oxygen exposure limits.

Appendix B – Page 1 of 2

Matrix of Total Stop Times Using Isobaric Mix Switching with Oxygen Decompression

(Shaded boxes show minimum total stop times used to determine optimal switch times.)

Depth	Time to mix switch from heliox to nitrox										Oxygen Percent In Mixes	Oxygen Percent in Deco Mix
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min	45 min	50 min		
	Total Stop Time for a 50 Minute Dive											
100 fsw	6	4	3	3	3	5					36%	99%
110 fsw	9	7	6	5	6						36%	99%
120 fsw	13	12	10	11							34%	99%
130 fsw	19	18	16	16	17						32%	99%
140 fsw	27	24	22	22	23						30%	99%
150 fsw	38	34	30	29	30						28%	99%
	Total Stop Time for a 60 Minute Dive											
100 fsw	9	7	6	5	4	5					36%	99%
110 fsw	13	11	9	8	9						36%	99%
120 fsw	21	19	17	16	16	18					32%	99%
130 fsw	31	28	25	23	23	25					30%	99%
140 fsw	44	39	35	32	32	34					28%	99%
150 fsw	58	53	49	45	44	45					26%	99%
	Total Stop Time for a 70 Minute Dive											
100 fsw	12	11	9	8	7	7	8				36%	99%
110 fsw	19	17	15	14	13	14					34%	99%
120 fsw		25	23	22	21	21	23				32%	99%
130 fsw		37	33	30	30	31					30%	99%
140 fsw			47	45	42	41	43				28%	99%
150 fsw			64	60	57	56	57				26%	99%
	Total Stop Time for an 80 Minute Dive											
100 fsw	16	14	13	11	10	9	9	11			36%	99%
110 fsw		21	20	18	17	17	18				34%	99%
120 fsw			29	27	26	27					32%	99%
130 fsw			43	40	38	37	37	40			30%	99%
140 fsw				57	54	52	N/A	N/A			28%	99%
150 fsw				77	73	70	N/A	N/A			26%	99%

NOTE 1: All stop times calculated using ProPlanner with 10% MicroBubble Factor.
NOTE 2: Oxygen percentage in mixes has been adjusted in 2% increments to Minimize stop times while staying within ProPlanner oxygen exposure limits.
NOTE 3: Boxes marked N/A exceed ProPlanner oxygen exposure limits.

Appendix B – Page 2 of 2

Matrix of Total Stop Times Using Isobaric Mix Switching with Oxygen Decompression

(Shaded boxes show minimum total stop times used to determine optimal switch times.)

Depth	Time to mix switch from heliox to nitrox										Oxygen Percent in Mixes	Oxygen Percent in Deco Mix
	25 min	30 min	35 min	40 min	45 min	50 min	55 min	60 min	65 min	70 min		
	Total Stop Time for a 90 Minute Dive											
100 fsw	13	12	12	12	14						36%	99%
110 fsw	21	20	21	22							34%	99%
120 fsw	32	31	32	33							32%	99%
130 fsw	54	52	52	51	51	54					28%	99%
140 fsw	75	72	69	69	N/A	N/A					26%	99%
150 fsw		110	107	105	103	105					21%	99%
	Total Stop Time for a 100 Minute Dive											
100 fsw	16	15	14	15							36%	99%
110 fsw	N/A	24	25								34%	99%
120 fsw	46	43	43	42	43						30%	99%
130 fsw	75	71	68	67	N/A						26%	99%
140 fsw		109	108	108	109						26%	50%
150 fsw			136	135	135	135	136				24%	50%
	Total Stop Time for a 110 Minute Dive											
100 fsw	20	18	17	18							36%	99%
110 fsw	N/A	N/A	33	34							32%	99%
120 fsw	71	68	64	63	62	62	N/A				26%	99%
130 fsw		94	91	88	N/A						24%	99%
140 fsw			127	125	125	125	126				26%	50%
150 fsw			173	170	167	165	164	166			21%	50%
	Total Stop Time for a 120 Minute Dive											
100 fsw	26	25	24	24	24	25					34%	99%
110 fsw	N/A	54	52	51	49	N/A					28%	99%
120 fsw		89	86	82	80	N/A					24%	99%
130 fsw			125	121	116	112	N/A				21%	99%
140 fsw				155	152	150	148	148	148	150	24%	50%
150 fsw				194	188	184	182	182	183		21%	50%

NOTE 1: All stop times calculated using ProPlanner with 10% MicroBubble Factor.
NOTE 2: Oxygen percentage in mixes has been adjusted in 2% increments to To minimize stop times while staying within ProPlanner oxygen exposure limits.
NOTE 3: Boxes marked N/A exceed ProPlanner oxygen exposure limits.

Appendix C – Page 1 of 2

Comparison of Total Stop Times Using Different Techniques

Calculated Using ProPlanner

Depth	Nitrox Dive Nitrox Deco	IMX Dive Nitrox Deco	Nitrox Dive Oxygen Deco	IMX Dive Oxygen Deco
	Total Stop Time for a 50 Minute Dive			
100 fsw	13	3	7	3
110 fsw	19	8	11	5
120 fsw	36	20	18	10
130 fsw	44	27	22	16
140 fsw	62	38	32	22
150 fsw	84	53	44	29
	Total Stop Time for a 60 Minute Dive			
100 fsw	19	6	10	4
110 fsw	28	13	15	8
120 fsw	49	28	23	16
130 fsw	70	42	35	23
140 fsw	94	60	49	32
150 fsw	128	82	64	44
	Total Stop Time for a 70 Minute Dive			
100 fsw	27	10	14	7
110 fsw	37	18	19	13
120 fsw	64	38	31	21
130 fsw	88	56	45	30
140 fsw	123	78	62	41
150 fsw	171	105	84	56
	Total Stop Time for an 80 Minute Dive			
100 fsw	34	15	18	9
110 fsw	55	29	26	17
120 fsw	77	49	40	26
130 fsw	109	71	55	37
140 fsw	182	110	87	52
150 fsw	217	131	103	70

NOTE 1: **All stop times calculated using ProPlanner with 10% MicroBubble Factor.**

NOTE 2: **Oxygen percentage in mixes has been adjusted in 2% increments to minimize stop times while staying within ProPlanner oxygen exposure limits.**

Appendix C – Page 2 of 2

Comparison of Total Stop Times Using Different Techniques
Calculated Using ProPlanner

Depth	Nitrox Dive Nitrox Deco	IMX Dive Nitrox Deco	Nitrox Dive Oxygen Deco	IMX Dive Oxygen Deco
	Total Stop Time for a 90 Minute Dive			
100 fsw	44	19	21	12
110 fsw	65	38	32	20
120 fsw	95	59	53	31
130 fsw	137	85	85	51
140 fsw	192	119	103	69
150 fsw	267	158	163	103
	Total Stop Time for a 100 Minute Dive			
100 fsw	52	25	25	14
110 fsw	78	46	43	24
120 fsw	115	72	73	42
130 fsw	164	101	100	67
140 fsw	228	142	161	108
150 fsw	334	182	189	135
	Total Stop Time for a 110 Minute Dive			
100 fsw	59	31	32	17
110 fsw	91	55	66	33
120 fsw	135	83	94	62
130 fsw	193	120	156	88
140 fsw	276	162	190	125
150 fsw	397	205	N/A	164
	Total Stop Time for a 120 Minute Dive			
100 fsw	69	37	49	24
110 fsw	108	64	86	49
120 fsw	184	97	124	80
130 fsw	268	138	178	112
140 fsw	390	179	N/A	148
150 fsw	600+	230	N/A	182

NOTE 1: **All stop times calculated using ProPlanner with 10% MicroBubble Factor.**

NOTE 2: **Oxygen percentage in mixes has been adjusted in 2% increments to minimize stop times while staying within ProPlanner oxygen exposure limits.**

NOTE 3: **Boxes marked N/A exceed ProPlanner oxygen exposure limits for air.**

Design Of Semi-Closed Rebreathers To Minimize Variations In Circuit Oxygen Levels

M. L. Nuckols[1] and Terry W. Adams[2]

[1]Center for Hyperbaric Medicine And Environmental Physiology
Duke University Medical Center, Durham, NC 27710
[2]Deep Submergence Systems Branch
Naval Surface Warfare Center PC, Panama City, FL 32407-7001

Abstract

While all rebreathers offer a provision for longer bottom times when compared to open-circuit SCUBA, they each have their own inherent dangers. Semi-closed circuit rebreathers re-circulate a mixture of nitrogen and oxygen (nitrox), or helium and oxygen (heliox) for deeper applications, by way of a breathing loop consisting of a counter-lung (breathing bags or bellows), hoses, a carbon dioxide scrubber, and a mouthpiece equipped with a closure mechanism to exclude water when the diver does not have the mouthpiece in the mouth. A small volume of fresh, oxygen-rich supply gas is injected into the breathing loop to compensate for the oxygen that the diver consumes during each pass of this re-circulated gas through the diver's lungs, thereby maintaining an acceptable partial pressure of oxygen in the re-circulating gas stream. There are several design approaches taken to control the injection of fresh make-up gas into semi-closed circuit rebreathers. The manner in which gas is injected into the circuit has been found to have a significant impact on the variations that are seen in circuit oxygen levels during a dive. This paper will address the inherent dangers and means to best control circuit oxygen levels in semi-closed rebreathers. Lessons learned from developmental efforts for military missions can be directly applied to scientific diver applications.

Background

There has been a recent surge of interest in semi-closed circuit rebreathers (SCR) within the scientific, military, and sport diving communities (Carson, 1998). Methods for predicting the circuit oxygen partial pressures in traditional semi-closed circuit underwater breathing apparatuses (UBA) have verified their wide variation over the full range of diver activity (Clarke *et al*, 1996; Nuckols *et al*, 1998; Nuckols *et al*, 1999). Limited experimental test results from the Navy Experimental Diving Unit (NEDU) have partially confirmed these theoretical predictions. Recently, these predictive methods were applied to an alternative semi-closed circuit design concept (Nuckols *et al*, 2001). This analysis confirmed that respiratory-coupled design concepts give much tighter control of circuit oxygen levels over the full range of diver metabolic requirements.

Working in conjunction with several commercial rebreather manufacturers, the authors have designed a new respiratory-coupled semi-closed rebreather that is switchable to closed-circuit, pure oxygen . Designated the CSCR 190 (Closed circuit/Semi-Closed Rebreather capable of diving to 190 fsw), this non-electrically controlled rebreather, shown in Figure 1, has the capability to satisfy shallow water, operations using pure oxygen in closed circuit mode and deep excursions up to 58 msw (190 fsw) in a mixed-gas, semi-closed mode. The diver has the ability to switch between closed and semi-closed modes in water as required.

Full Assembly Cover Removed

Figure 1: CSCR-190 -- a back-mounted, entirely mechanical rebreather which operates in either a semi-closed circuit mode to depths of 190 fsw or closed circuit, pure oxygen mode at shallow depths. It can be switched in water as necessary to satisfy multiple dive modes.

Table 1: CSCR 190 Characteristics

Positioning	Back-mounted
Size	Height – 28 in, Width – 17.2 in, Thickness –11.2 in Height – 71 cm, Width – 43.8 cm, Thick – 28.5 cm
Weight (Dive ready)	In air – 73.5 lbs (with 6.5 liter nitrox bottle) In water – 1.5 lbs (negative)
Gas Supply	Nitrox – 6.5 liter nitrox 28% at 250 bar (approx 57 SCF) Oxygen – 2 liter at 200 bar (approx 14 SCF)
Max Operating Depth	Semi-closed, nitrox mode – 190 FSW Closed, pure oxygen mode – 25 FSW
CO_2 Scrubber	Radial canister design – approx 5.16 lbs (8-12 Sofnolime) Axial canister design – approx 6.7 lbs (8-12 Sofnolime)
Buoyancy Adjustment	Integral BCD (optional)
Safety Bailout	Open circuit

This respiration-coupled gas make-up design is based on the well-known fact that a diver's respiratory rate is roughly proportional to his metabolic oxygen requirements. This circuit design uses a mechanical coupling device with the counter-lung to control the rate at which gas is exhausted from the circuit loop; i.e., the circuit volume is controlled by dumping carbon dioxide-rich circuit gas as the diver exhales. The injection of fresh make-up gas occurs passively as the counter-lung volume decreases below a level necessary to inflate the diver's lungs. This fresh gas injection is accomplished via a simple demand regulator, similar to the add mechanism that is used to inject oxygen into closed circuit, pure oxygen systems.

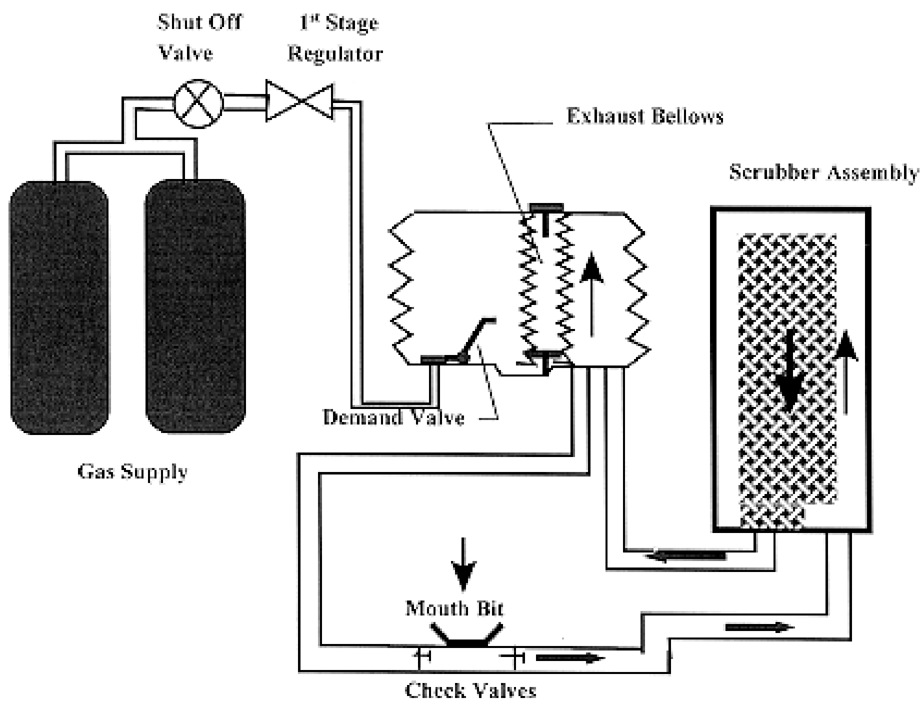
The circuit design consists of a small, compliant exhaust bellows that resides within a larger bellows. The larger container serves as the circuit counter lung that accepts the diver's exhaled breath during the exhalation phase and provides a gas source during inhalation, as shown in Figure 2. A direct coupling connects the top of the small exhaust bellows to a rigid plate on the large bellows. During the exhalation phase, the volume of the large bellows expands as it accepts the diver's exhaled breath. This expansion causes the exhaust bellows to inflate this inner bellows with a small, fixed volume of stale circuit gas through a one-way check valve. During the inhalation phase, the volume of the large bellows contracts, forcing the rigid top plate to dump the exhaust volume overboard through a second one-way check valve. Fresh make-up gas is added to the circuit during inhalation through a demand valve when the gas volume in the counter lung is inadequate to inflate the diver's lungs.

In so doing, the rate at which gas is exhausted from the circuit is tied directly to the diver's breathing rate. The ratio of the exhaust bellows volume relative to the volume of the large bellows, referred to as the exhaust volume ratio (EVR), dictates the amount of fresh gas that will be injected during each breath. Fresh makeup gas is injected into the circuit, on demand, as the volume of gas in the breathing circuit falls below that which is required to inflate the diver's lungs during inhalation. This is accomplished using a conventional supply demand valve.

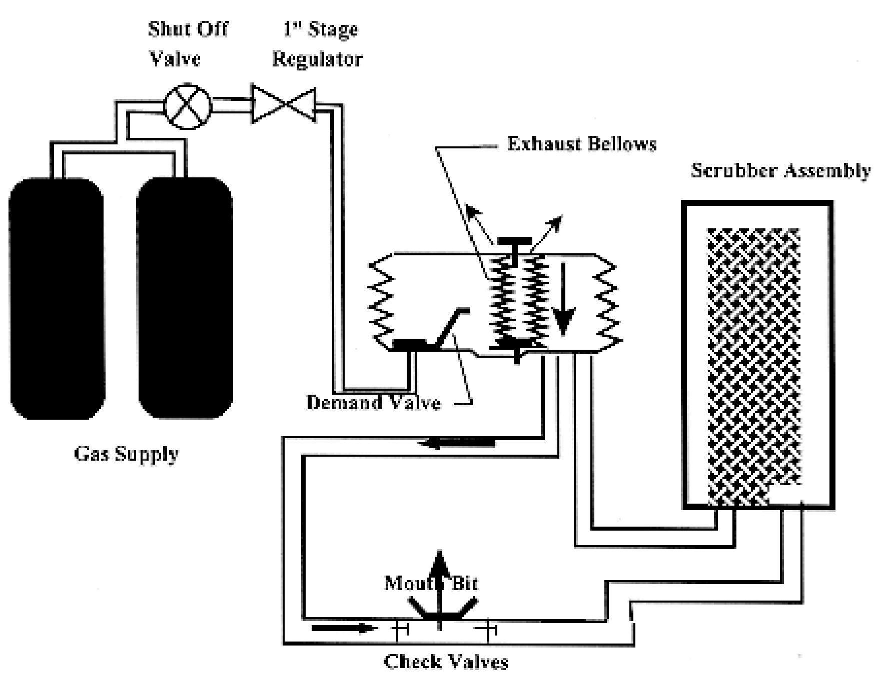
Thus, the higher the diver activity the higher the exhaust rate, and consequently the higher the injection rate of fresh make up gas. This coupled injection system reduces the variation in circuit oxygen levels as diver activity levels change, as shown in Figure 3. At 18 msw (60 FSW) the circuit oxygen levels are seen to converge to the same level of approximately 1.05 Ata over the entire range of diver activities when injecting a 50% oxygen make-up gas.

Evaluation of CSCR 190

A series of unmanned tests was recently completed at the Hydrospace Laboratory at NSWC/PC during the summer of 2004. The CSCR 190 was shown to provide predictable and safe circuit oxygen levels over the full range of diver activity level and depths up to 58 msw (190 FSW); see Figure 4. Figure 5 shows that this rig has the capability to mimic the circuit oxygen levels of the closed circuit, pure oxygen rebreathers at shallow depths between the surface and 7.6 msw (25 FSW), and approximate the circuit oxygen levels for open circuit SCUBA when operating in the semi-closed, mixed-gas mode.



EXHALATION PHASE



INHALATION PHASE

Figure 2: Schematic representation of a bellows-driven, variable volume exhaust (VVE) UBA; a respiratory-coupled gas injection apparatus.

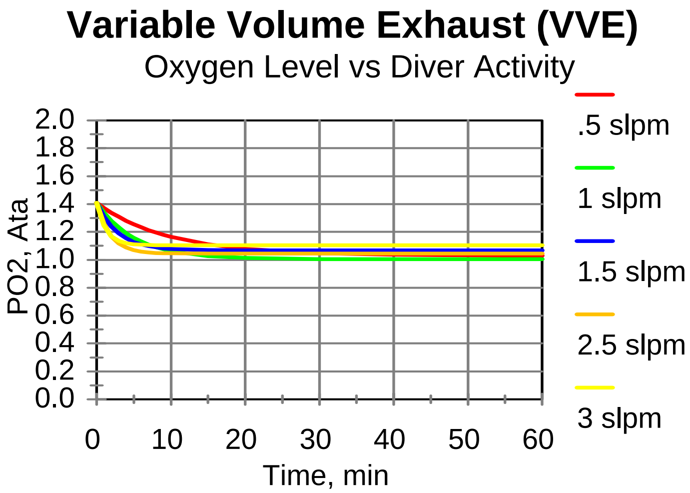


Figure 3: Circuit oxygen levels vs time delivered to a diver at a depth of 60 FSW when using a VVE semi-closed rebreather at oxygen consumption levels ranging from 0.5 - 3.0 slpm. A 50% oxygen mix is injected with an EVR of 6.25% into a circuit volume of 6 liters.

Circuit Oxygen Levels

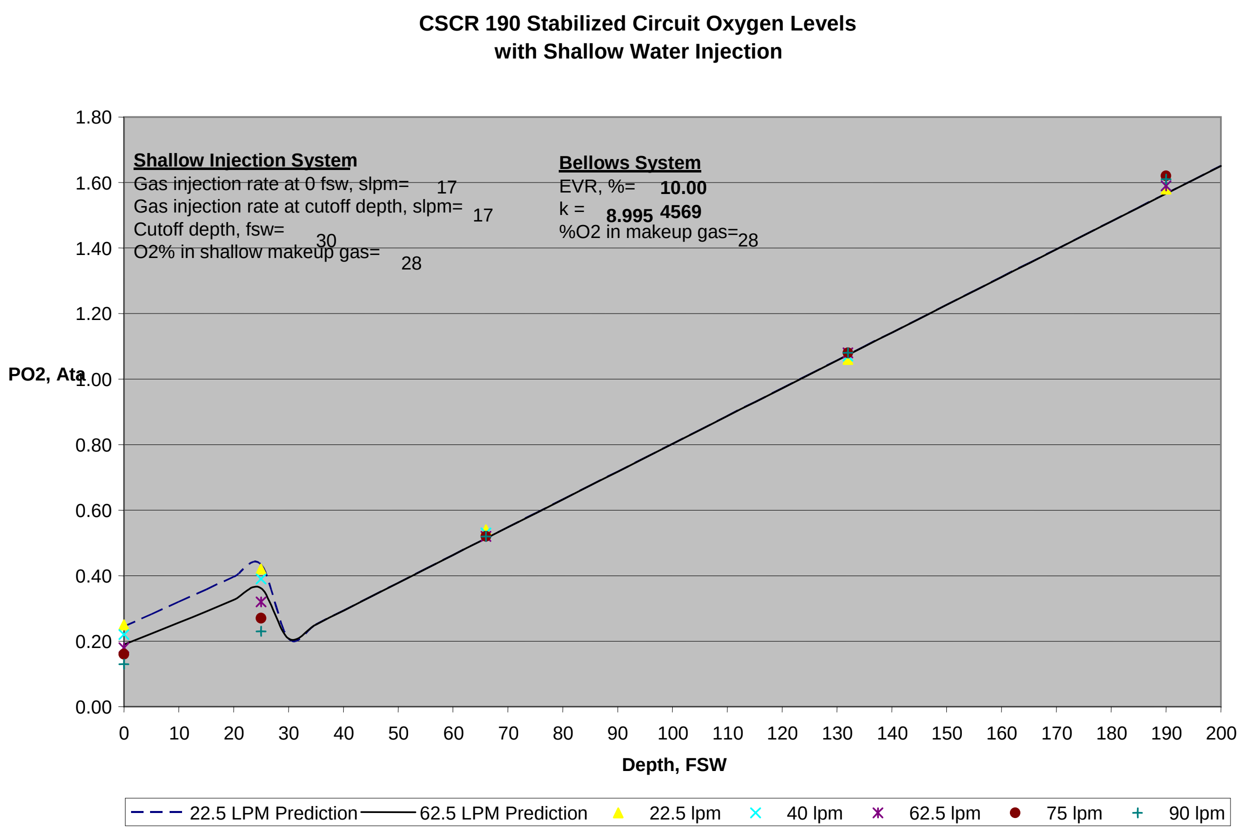


Figure 4: Comparison of predicted circuit oxygen levels with those obtained in unmanned testing. Minimal variations were observed for RMVs between 22.5 lpm and 90 lpm at depths beyond 30 FSW. Shallow water injection was shown to elevate circuit oxygen levels near the surface, as predicted.

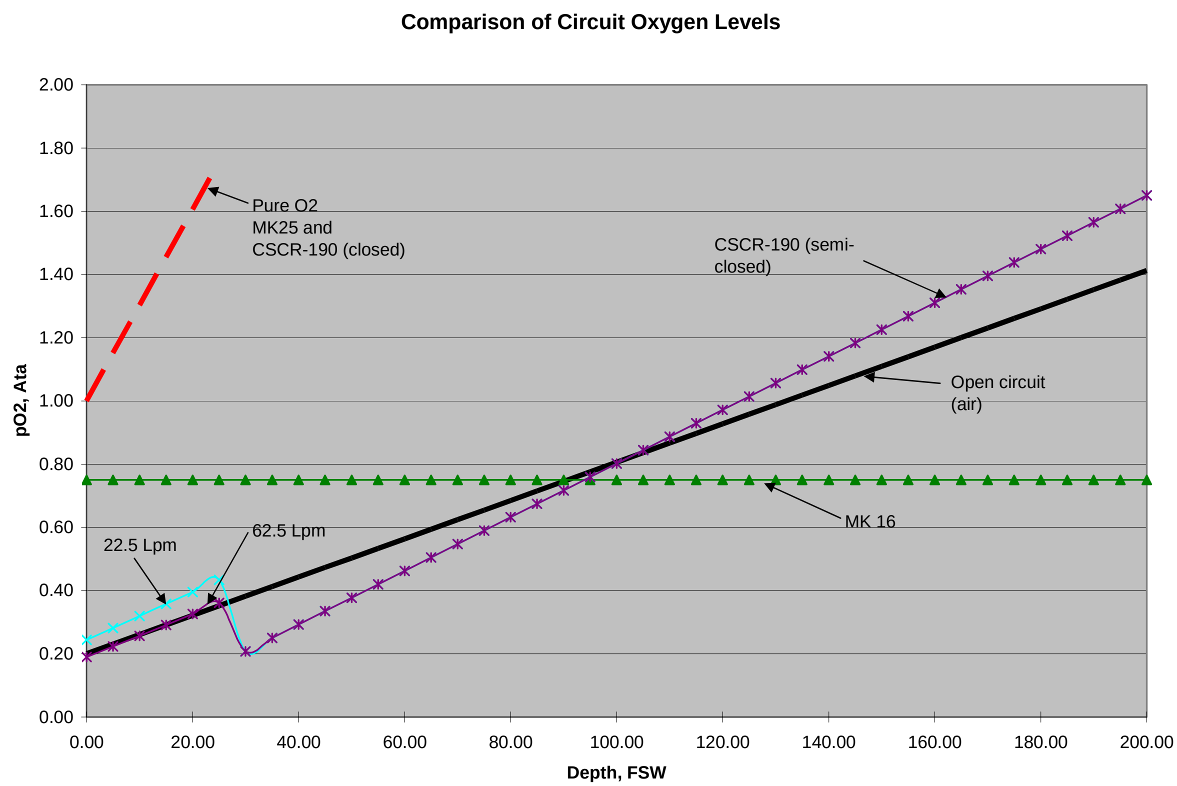


Figure 5: Comparison of circuit oxygen levels in the CSCR 190 (EVR = 10, 28% oxygen makeup gas, and 17 slpm shallow water injection between 0-30 FSW) with the MK 25 Closed Circuit Rebreather, the MK 16 Closed Circuit Rebreather, and open circuit SCUBA with air.

Resistive Breathing Effort (WOB)

Additionally, Figures 6 and 7 show that the mechanically-coupled CSCR 190, a semi-closed rebreather, has breathing resistances comparable to the MK 16, an electronically controlled, closed circuit rebreather. Although Figure 6 shows that the WOB values exceed the NEDU guidelines established by NEDU Test Standard 01-94 at depths beyond 33 FSW, they are comparable to the MK16 (Figure 7).

Canister Duration

Table 2 summarizes the results of canister duration tests conducted on the CSCR 190 at depths of 25 FSW in the closed circuit mode and 66 FSW in the semi-closed circuit mode. Axial and radial flow canisters were evaluated with both 4-8 Sofnolime and 8-12 Sofnolime. Figure 8 shows that the axial canister consistently out performed the radial flow canister at both depths tested. It should be noted however that most, if not all, of this performance enhancement could be attributed to the additional absorbent weight available when using the axial canister.

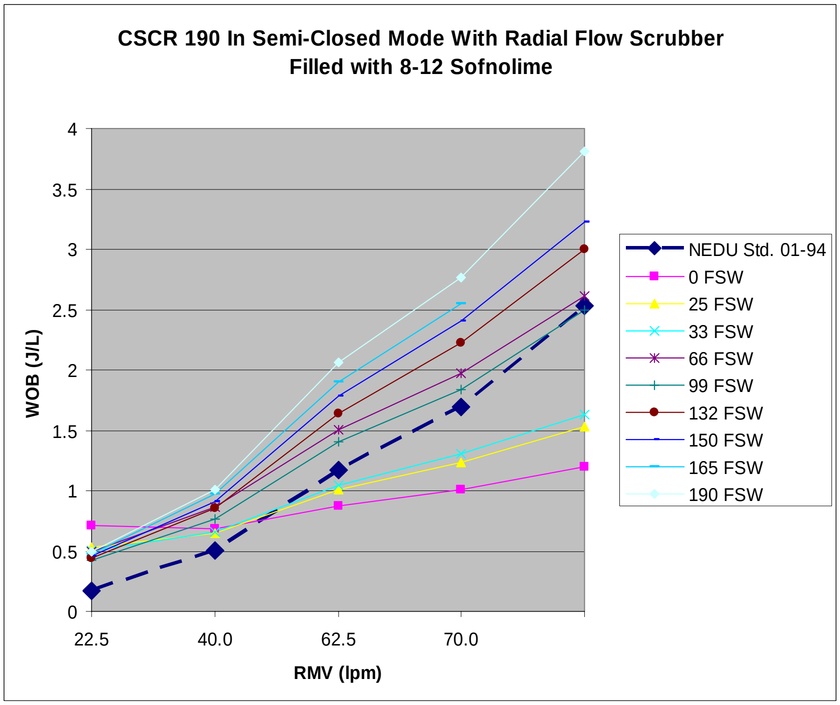


Figure 6: Resistive breathing efforts (WOB) of the CSCR 190 over a range of respiratory minute volumes (RMVs). CSCR 190 is equipped with a radial flow scrubber filled with 8-12 Sofnolime

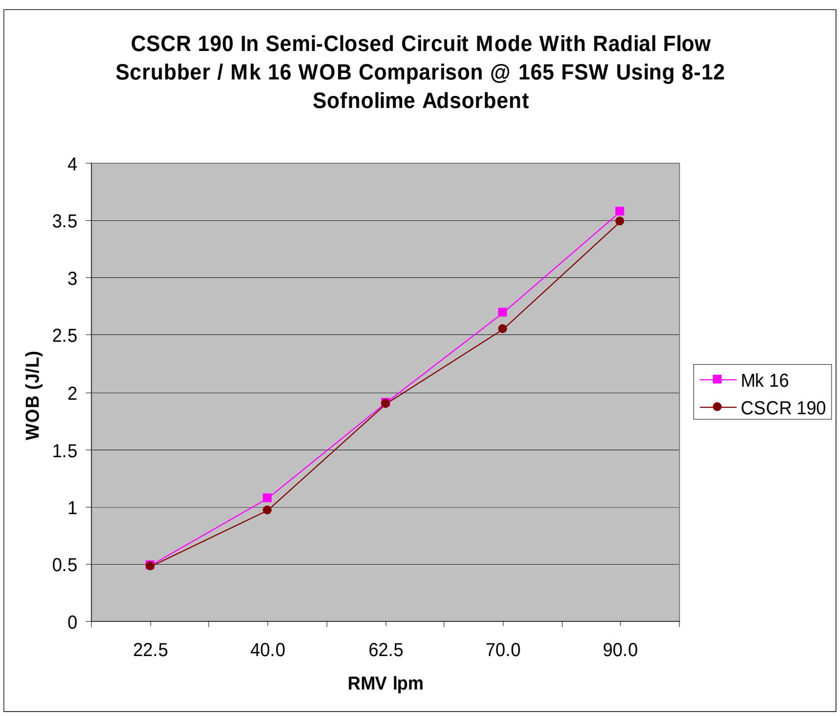


Figure 7: Comparison of the resistive breathing efforts of the CSCR 190 at 165 FSW with those for the MK 16.

Table 2: Summary of CSCR 190 Scrubber Test Results

Radial Flow Canister
RMV, lpm= 40
CO2 Injection rate, slpm= 1.35
Water temperature, F= 40

				Duration, min	
Depth, FSW	UBA mode	Absorbent Type	Weight, lbs	0.5% SLE	1.0% SLE
25	Closed	8-12 Sofnolime	5.16	197.1	227
66	Semi-Closed	8-12 Sofnolime	5.16	153.5	176.7
25	Closed	4-8 Sofnolime	5.08	132	166
66	Semi-Closed	4-8 Sofnolime	4.98	67.5	101

Axial Flow Canister
RMV, lpm= 40
CO2 Injection rate, slpm= 1.35
Water temperature, F= 40

				Duration, min	
Depth, FSW	UBA mode	Absorbent Type	Weight, lbs	0.5% SLE	1.0% SLE
25	Closed	8-12 Sofnolime	6.72	248	272
66	Semi-Closed	8-12 Sofnolime	6.75	234.8	254.3
25	Closed	4-8 Sofnolime	6.5	208	243.5
66	Semi-Closed	4-8 Sofnolime	6.52	163.5	193.5

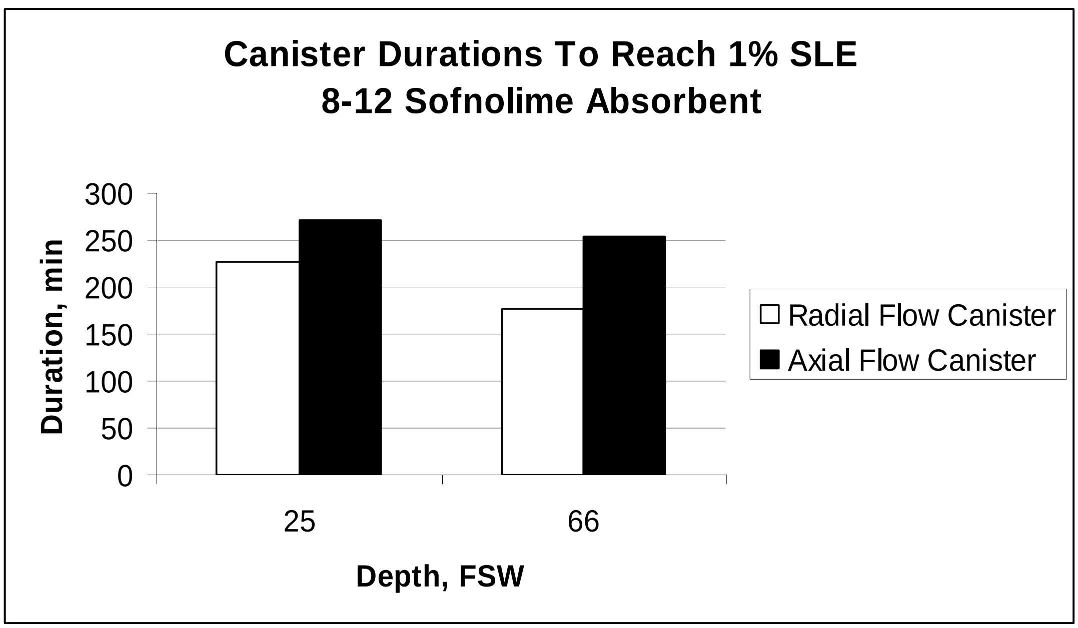


Figure 8: Comparison to canister durations for axial and radial flow scrubbers tested with the CSCR 190.

Conclusions

The CSCR 190 has been shown to meet operational requirements for shallow water, pure oxygen diving missions currently satisfied by the U.S. Navy MK 25 Closed Circuit Breathing Apparatus, with the added capability of being switched to semi-closed, mixed-gas operations to make excursions to depths up to 190 FSW. Its simple, mechanically-controlled gas injection system is respiratory-coupled to minimize the effects of variations in diver activity on circuit oxygen levels. Additionally, a shallow water injection system provides safe circuit oxygen levels even when the rig is operated in the semi-closed mode near the surface. In effect, this new UBA design crosses over between the capabilities of the U.S Navy MK 25 (closed-circuit, pure oxygen) and the U.S. Navy MK 16 (closed circuit, electronically-controlled mixed gas) while satisfying the following

- depth capability beyond that of the MK 25
- reduced complexity, cost, and maintenance as compared to the MK 16
- expanded versatility to satisfy multiple missions
- predictable circuit oxygen levels over the full range of diver activities (unlike conventional semi-closed rebreathers) resulting in increased safety

Conceivably, the CSCR 190 could approach a fixed oxygen partial pressure, simulating electronically controlled rigs, by reducing the exhaust volume ratio as the diver depth increases. This reduction in the EVR could potentially be achieved mechanically using a piston/cylinder design to reduce the volume of the exhaust bellows as depth increases. This would reduce the injection rate of makeup gas as the diver descends, resulting in a reduction in the circuit oxygen level rise with depth.

Acknowledgments

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Evolution of The NOAA Minimum Manufacturing and Performance Requirements for Closed Circuit Mixed Gas Rebreathers

N. Eugene Smith[1] and David A. Dinsmore[2]
[1]NOAA's Undersea Research Program, 1315 East-West Highway, Silver Spring, Md 20910-3282
[2]NOAA Diving Program, 7600 Sand Point Way, NE, Seattle, WA 98115-0070

Abstract

The NOAA Diving Program (NDP) and NOAA's Undersea Research Program (NURP) together support more than 25,000 dives per year. Under the Outer Continental Shelf Lands Act, NOAA has the mandate to increase the safety and efficiency of divers through advanced diving technologies. To increase the allowable working depth to 300 feet for NOAA-supported scientific dives the NDP and NURP initiated a program to investigate the introduction of closed circuit mixed gas rebreathers (CCRs) into NOAA dive programs. During this investigation it was discovered there was no consensus standard covering CCRs; the European Union Standard was not issued at that time. To answer this need, a NOAA-sponsored working group generated a safety standard titled *NOAA Minimum Manufacturing and Performance Requirements for CCRs*. This paper will discuss the purpose, development, intended use, and status of the requirements.

Introduction

The National Oceanic and Atmospheric Administration (NOAA) has two major programs that utilize diving to conduct undersea research - the NOAA Diving Program (NDP) and the National Undersea Research Program (NURP). The goal of both of these federal programs is to help NOAA describe and predict changes in the Earth's environment, and to conserve and wisely manage the Nation's coastal and marine resources.

The NDP primarily supports intramural research programs conducted by personnel within NOAA's three major line offices: the National Marine Fisheries Service (NMFS), the National Ocean Service (NOS), and the Office of Oceanic and Atmospheric Research (OAR). Although not a major line office, NOAA Marine and Aviation Operations, which provides operational support for the aforementioned major line offices, also utilizes divers and therefore, falls under the auspices of the NDP.

NURP supports extramural research programs conducted by scientists from various academic and marine research institutions throughout the nation through six regional centers and one institute for undersea technology. These NOAA partners operate on funds provided by NOAA grants, and the grants require that all operations be performed in a safe and environmentally responsible manner.

Background

In the late 1990's, the NDP began receiving formal requests from several NOAA offices to undergo training in closed circuit mixed gas rebreathers (CCR) from commercial vendors. The requests were reviewed by the NOAA Diving Safety Board (NDSB) and all were approved. Upon further investigation into the rebreathers being used for training, it was discovered that very few had undergone any type of testing other than that conducted by the manufacturers' themselves.

One of the basic tenets of the NDP is that all diving equipment used by NOAA personnel be thoroughly tested and evaluated for reliability and functionality. For life-support equipment, such testing must be completed by an independent, third-party that is not affiliated with the manufacturer. The requirement for such testing is both ethically and legally justified under the NDP charter as outlined in the NOAA Administrative Order 209-123 that states: "The purpose of the NOAA Diving Program is to train, certify, and equip scientists, engineers, and technicians to perform a variety of underwater tasks in support of NOAA's mission and to ensure that all diving operations are conducted safely, efficiently, and economically." The same document also lists several goals directly tied to the testing of equipment – they are: 1) to provide safe, state-of-the-art, and well maintained dive equipment, 2) to investigate and implement new diving technologies and techniques, and 3) to provide equipment, personnel, and expertise to NOAA field operations, as needed.

Concerned by the lack of independent testing of CCRs, the NDP invoked a moratorium on further rebreather training until appropriate testing was completed and the NDP was satisfied the units were safe. The moratorium was imposed in 2001, and concurrently the NDP initiated a test and evaluation (T&E) program to investigate commercial-off-the-shelf (COTS) rebreathers for potential use by NOAA personnel.

CCR Investigation

In 2001 the NDP conducted a survey of all NOAA divers to determine what capabilities and features they most desired in a rebreather. Based on the results of the survey, four COTS closed-circuit rebreathers were identified as candidates for the T&E program. They included: the Olympic Submarine *CCR 2000*, Steam Machine *Prism Topaz*, Cis-Lunar *Mk 5P* and the Ambient Pressure Valve *Buddy Inspiration*. Two of the units, the *CCR 2000* and the *Topaz*, had already been tested, or were in the process of being tested, by the US Navy Experimental Diving Unit (NEDU) in Panama City, FL for possible use by US Navy personnel. The *Topaz* had already completed unmanned testing and was scheduled to undergo manned testing in early 2002. The *CCR 2000* was eliminated from consideration early in the process due to quality and assurance (Q&A) issues, and therefore did not undergo either unmanned or manned testing.

In 2002, the NDP approached the NEDU about conducting unmanned and manned tests on the Cis-Lunar *Mk5P* and the Ambient Pressure Valve *Buddy Inspiration* rebreathers. In preparation for testing of the two units it was necessary to determine what tests needed to be performed and what criteria would be used to determine acceptable results for each test. With assistance from several experts in the field of rebreathers, a NOAA test protocol was developed based on criteria used by NEDU for evaluating equipment for the US Navy. Although not as stringent as that used by the US Navy, the NOAA criteria were considered reasonable and appropriate for the type of work expected to be performed by NOAA divers.

The *MK5P* completed both unmanned and manned testing. The *Inspiration* only completed unmanned testing. The NEDU declined to conduct manned testing on the *Inspiration* due to concerns over potential hazards created by the location of the batteries within the breathing loop. NEDU completed testing of the two units in late 2002 and summarized the results in two reports: 1) *NOAA Diving Program Underwater Breathing Apparatus: Unmanned Evaluation*, TA02-07, NEDU TR#03-02, February 2003, and 2) *NOAA Diving Program Underwater Breathing Apparatus: Manned Evaluation*, TA02-07, NEDU TR03-07, March 2003. The NDP immediately released copies of the reports to the two manufacturers.

Consensus Standards

Following testing of the two units by NEDU, the NDP decided to develop minimum manufacturing and performance requirements for CCRs. It was at this point that NURP joined forces with the NDP to help co-develop these minimum requirements. A team of experts comprised of NOAA personnel, rebreather users, University Diving Safety Officers, and outside consultants, worked for almost two years to produce the document, "The NOAA *Minimum Manufacturing and Performance Requirements for Closed Circuit Mixed Gas Rebreathers*." The purpose of the standard is to establish minimum qualification criteria by which closed circuit mixed gas rebreathers (CCRs) will be evaluated for potential use by NOAA, NOAA sponsored, or otherwise NOAA authorized, personnel. The criteria outlined in the document were selected to provide NOAA management with a fair assurance that the equipment will not endanger the diver, will not limit his ability to perform the work, and will do what the manufacturer claims it will do. The goal of the document is to ensure that NOAA authorized CCRs are reliable and operator friendly, and meet or exceed reasonable performance standards.

Also during this time, NURP contracted the U.S. Navy Coastal Systems Station, in Panama City, FL, to further investigate the battery used in the *Inspiration* rebreather. The results of the investigation are in the report: John Camperman et. al., U. S. Navy Coastal Systems Station, *Safety Evaluation Lithium Manganese Dioxide Batteries in a Diving Life Support Recirculator*, September 24, 2003. The investigation found that under normal dive conditions, i.e., hyperbaric environment, the Lithium Manganese Dioxide battery used in the *Inspiration*, produce 1,2-dimethoxyethane, a compound that is harmful by inhalation to humans, above the maximum allowable level of 0.02 ppm. The study further substantiated the position that the breathing loop must be free of any materials or components that could provide a source of ignition, or that may off-gas noxious or hazardous gases or otherwise are potentially harmful for human life support, e.g. batteries or PVC coatings.

Framework For The Requirements Document

The NDP/NURP team established a framework for a rebreather standard based on requirements for high quality and reliability, safety features, and reasonable performance measures that would allow a NOAA-supported diver to perform scientific tasks at the specified depth. The resulting standard was designed to be free of bias toward or against any particular design or manufacturer and was not meant to create a competition among manufacturers, but to establish safety requirements that all manufacturers must meet.

The NOAA *Minimum Manufacturing and Performance Requirements for Closed Circuit Mixed Gas Rebreathers* involves three basic requirements: 1) be manufactured and tested to an acceptable quality control program, 2) possess certain components and/or perform certain functions deemed necessary and appropriate for CCRs by NOAA, and 3) meet minimum performance criteria during unmanned and manned testing by a NOAA-approved independent, third-party.

The following is an outline of the NOAA *Minimum Manufacturing and Performance Requirements for Closed Circuit Mixed Gas Rebreathers*:

Introduction

The introduction states the purpose, rationale, and goal of the standard. It also outlines to whom the standard applies.

Qualification Criteria

1. Manufactured and Tested to an Acceptable Quality Control Program
2. Capabilities/ Components And Performance Requirements.
2.1 Capabilities/ Components
2.2 Performance Requirements
Appendix A: Required Testing
A.1 Unmanned Tests
A.2 Manned Tests
A.3 Report

Consensus Review Process

The draft requirements document was reviewed (sometimes several times) by members of the NDP Diving Safety Board, NDP Technical Advisory Committee, and members of the NURP Diving Council. These three groups were condensed into a single working group that produced the first draft of a consensus document at a workshop held in Long Beach, CA following the AAUS Symposia in March 2004. The document was sent to selected individuals and organizations either nominated by the working group or those who asked to review the document during the 2004 AAUS Symposia. Finally, it was posted for public comment with a deadline for comments of January 1, 2005.

During this process, reviewers submitted extensive questions and comments and each comment was considered for inclusion. However, many of the comments suggested additional testing that was more appropriate for the purchasing phase, or that should be part of an operational procedure. The decision was to limit the focus to one of addressing minimum standards.

During the process of drafting these requirements, the European Standard EN 14143, Respiratory Equipment-Self contained re-breathing diving apparatus had not been published. The European Committee for Standardization issued their standard in September of 2003, (just after the first draft of our requirements was in review) and became the only European Standard for CCRs in March of 2004. The authors of this paper compared EN 14143 to the NOAA draft and felt that the NOAA requirements are generally consistent with the requirements of EN 14143. In several instances the actual language or specifications of the EU standard was used verbatim rather than reinventing the wheel. The biggest difference between the two documents is in manned testing where the European standard only requires diving to a depth of 3 meters, whereas NOAA requires diving to a depth of 100 meters.

Future Efforts

This paper provides background information on how the proposed NOAA CCR standard was developed and introduces its main components. A copy of the actual standard is not included in this document because at the time of this writing the proposed standard was still posted for public comment. The deadline for submission of this paper coincided with the 1 January 2005 deadline for comments from the public on the draft requirements. By the time this paper is presented at the 2005 AAUS Symposium, comments from the public will have been considered. NOAA's goal is to have a final document that has been adopted by the NDP to discuss at the symposia.

Applications for approval are to be submitted to: Director, NOAA Diving Program**,** 7600 Sand Point Way, NE, Seattle, WA 98115-0070

The documentation for each CCR submitted for approval must include a description of how and when each requirement in this standard was satisfied, and the certification reports from NOAA approved independent third party witnesses.

Conclusion

The production and adoption of these CCR standards is only the first step in the process. NOAA's goal is for these minimum requirements to be incorporated into a consensus U.S. National Standard that will form the basis for reciprocity with other national and international standards. The current version of the standard is available through the NOAA Dive Program website at http://www.ndc.noaa.gov/pdfs/NOAA_CCR_Standards_Final.pdf.

Acknowledgments

The authors would like to thank those who have participated in the development of this standard. All contributions have been considered and appreciated. Individuals who are experienced with CCRs and are aware of current diving practices provided the components/capabilities requirements. This included scientists, manufacturers, consultants, and recreational CCR divers. The authors are especially thankful for the assistance of Dudley Crosson, PhD, and Marie Knafelc, MD, PhD, CAPT MC, USN (Retired), in adapting these requirements.

Scuba Bubble Noise and Fish Behavior: A Rationale for Silent Diving Technology

Phillip S. Lobel
Boston University Marine Program, Marine Biological Laboratory,
Woods Hole, MA 02543

Abstract

Noises produced by open-circuit scuba are examined in relation to the frequency range of fish hearing and courtship/spawning associated sounds. Scuba bubbles produce both near-field water displacement and radiate a low energy broadband noise in the frequency range of about 115 to 400 Hz. The peak hearing sensitivity of many freshwater and marine fishes is in the range of 40 to 800Hz (the upper range is extended up to 10 KHz in hearing specialists, such as freshwater ostariophysian fishes. The dominant frequency of the sounds produced by many marine and freshwater fishes during courtship and spawning generally range between 175 to 700 Hz. When using standard open-circuit scuba, approximately 36 to 40 percent of dive time is dominated by bubble noise. Thus, use of a closed-circuit, bubble-free Rebreather (technical diving) not only increases the efficiency of the dive time spent making underwater acoustic recordings (tactical diving) but also alleviates a significant source of disturbance to the fishes being observed. Furthermore, rebreathers facilitate more rapid habituation of fish to a diver's presence while also extending the bottom-time available for underwater study.

Introduction

Observing near-shore fishes and their behavior underwater using standard open-circuit scuba apparatus has been the primary method for documenting species abundances, ecological interactions and behavior for the past several decades. Diver produced bubbles and the associated noise has been long recognized as a potential source of behavioral disruption and a confounding issue to observing fish unobtrusively (e.g. Collette and Earle 1972). Using a Rebreather Underwater Breathing Apparatus (RUBA) was the solution to this problem that was clearly recognized by Collette, Earle and colleagues more than 30 years ago. While the alternative diving technology based upon RUBA has been available for the past decades, the scientific community has not generally used it because of its expense, higher levels of maintenance, and increased dive training/skills required (Lobel 2001a). Commercial rebreathers were not generally available until recently while those units that were available and approved by the US Navy had high acquisition costs (ca $35,000 plus accessories). New and reasonably priced rebreather models are now available to the underwater diving community. This presents an exciting opportunity for the general scientific diving community to employ this technology for underwater research. In fact, organizations such as AAUS and NOAA are currently developing regulatory protocols and requirements for widespread use of commercial rebreathers by scientific divers (see these proceedings). The key question asked by scientists, funding sponsors and administrators is whether rebreather technology is justified in terms of its science value versus the higher costs, additional training requirements and greater inherent risks.

This paper provides direct evidence that using rebreather technology is sufficiently justified as the technology to be used in order to obtain the best quality and most reliable data possible when studying fish behavior, especially fish bioacoustics. The scientific research objectives and fisheries applications of bioacoustics were described in earlier reviews (Lobel 2001a,b, 2002, 2003a, b). Popper (2003) recently reviewed concerns regarding the impacts of anthropogenic sounds on fishes.

This paper describes the acoustic patterns generated by the bubble noise from open-circuit scuba, calculates the percentage underwater recording time lost due to bubble noise and compares the bubble noise acoustic spectrum to the range in frequencies documented for fish sounds and fish hearing. The objective of this assessment was to determine if scuba bubble noise frequencies significantly overlapped with fish sounds and hearing. If this proves true, it provides a compelling reason to use bubble-free rebreather technology for underwater observations and recording of fish behavior.

Methods

Underwater recordings were made while diving using either conventional open-circuit scuba or a mixed-gas rebreather. Rebreather models used were the MK16 and A5800 manufactured by Carleton Technologies Inc, http://www.carltech.com/marine/mk.html

Recordings of fish sounds and bubble noises were made using a custom hydrophone coupled to a digital camcorder in an underwater housing. The hydrophone characteristics included a nominal flat response 10 to 3000 Hz and calibration of -162 dB re: 1V/μPa. For additional details about underwater recording methods and fish bioacoustics, see Lobel 2003a, b (pdf files available http://web.mit.edu/seagrant/aqua/cfer/passiveacoustics/passiveacoustics.html).

Examples of fish sounds and behavior used in this paper are drawn from the author’s earlier studies and the reader is referred to these papers for more information about the fishes, the recordings and for extensive bibliographies of fish bioacoustics.

Results

Scuba bubble noise

The noise duration of scuba bubbles will vary greatly depending on a divers breathing rate. Based upon acoustic recordings from a diver breathing at a normal relaxed pace while observing fishes and remaining stationary (i.e. minimal exertion), the time between bubble bursts (diver exhaling) was typically 15 to 30 seconds. Thus, during a scuba dive, approximately 36 percent of the time spent recording was lost due to bubble noise interference.

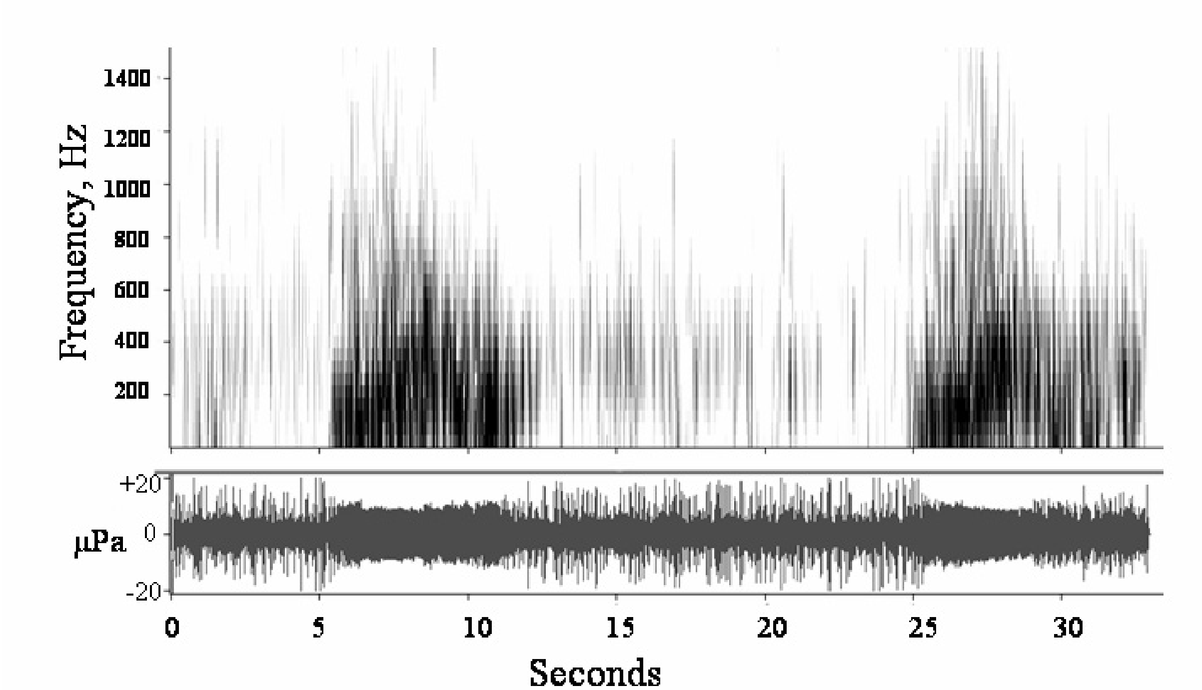

Figure 1. The bubble noise from a scuba diver during normal breathing. The top graph is a sonograph showing frequency (Hz) vs time (seconds). The bottom graph is an oscillograph showing amplitude vs time. The dark clouds in the upper graph show the bubble bursts. The bubble bursts had dominant energy at the frequencies 235 and 256 Hz.

An example of scuba bubble noise is shown in figure 1. The durations of the noise from bubble bursts were 7.1 and 8.8 seconds, respectively, with a "quiet" interval of about 12 seconds in between. The first bubble burst had a dominant frequency of 235 Hz but also had relatively high-energy output in the range from 115 to 397 Hz. The second bubble burst had a dominant frequency of 256 Hz and a range of high energy from 115 to 395 Hz.

Fish sounds, hearing and scuba bubble noise

Figure 2 illustrates typical scuba bubble noise and shows the overlap with fish sounds and hearing. This includes a majority of the fishes that scuba divers are likely to encounter and most of the species that are routinely studied using scuba based observations. The reader should note that this is a generalized example and there are some fishes that can hear sounds at higher frequencies (up to 10 Hz) such as freshwater catfishes, goldfishes and other ostariophysian species as well as the recent discovery that herring can hear in the ultrasonic range (Popper 2003). The sensitive hearing range of many teleost fish species is approxumately between 20 and 1000 Hz (Popper 2003). The hearing range of elasmobranchs (sharks, skates and rays) is roughly the same, so far as known (Casper et al. 2003).

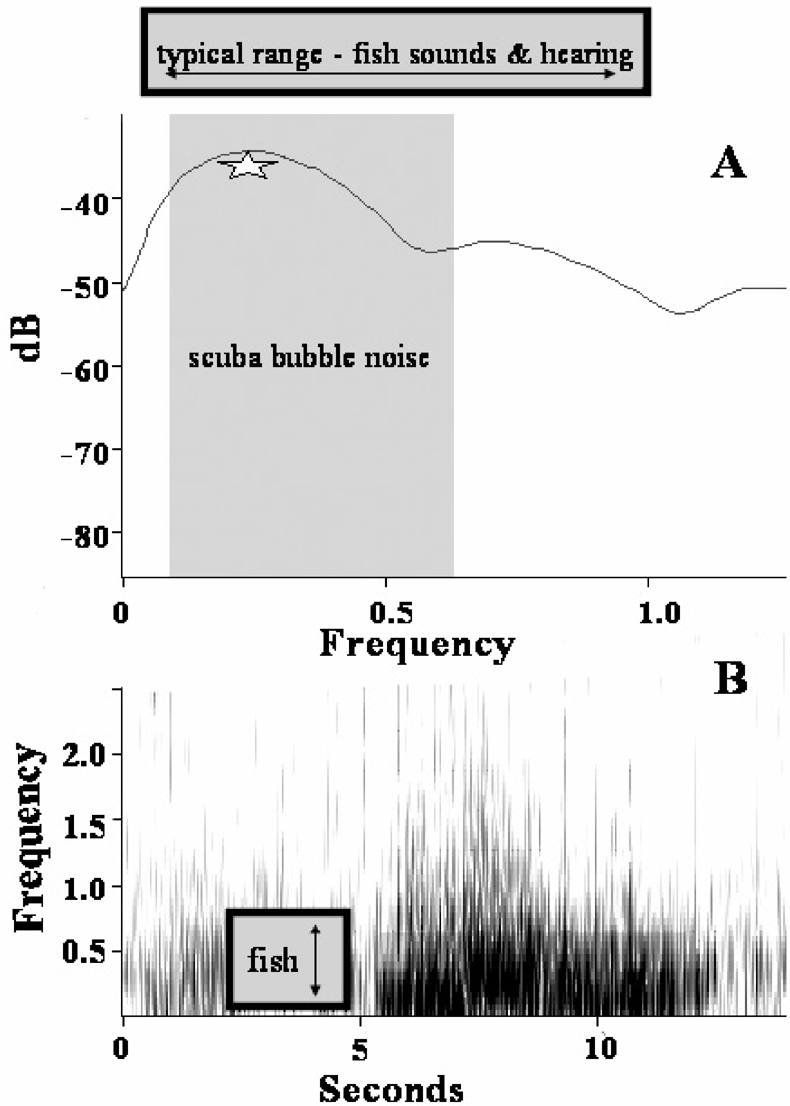

Figure 2. Schematic illustrating the frequency range overlap of typical fish sounds and hearing with (A) a power spectrum of a burst of scuba bubbles. This graph shows sound intensity (dB) vs frequency (KHz), shaded area denotes the frequency range of the bubble noise and the boxed shaded area shows the typical range of many types of reef fish sounds and their hearing. The star specifies the dominant frequency of the signal.
(B) Sonograph showing the same bubble burst plotted as frequency (KHz) vs time. The boxed shaded area shows the typical range of many types of reef fish sounds and hearing.

The dominant frequency (DF) of the courtship and/or spawning sounds produced by reef fishes typically range between 211 to 656 Hz (Lobel 2002). Examples of four coral reef fish and one freshwater fish (size range 7 to 20 cm SL):

a) *Ostracion meleagris*, Ostraciidae (trunkfish), DF 258 Hz (Lobel 1996),
b) *Dascyllus albisella*, Pomacentridae (damselfish), DF 328 Hz (Lobel and Mann 1995),
c) *Hypoplectrus nigricans*, Serranidae (grouper), DF 656 Hz (Lobel 1992),
d) *Scarus iserti*, Scaridae (parrotfish), DF (two peaks), 492 & 211 Hz (Lobel 1992),
e) *Tramitochromis intermedius,* Cichlidae (freshwater cichlid), DF 179 to 478 Hz (Ripley et al. 2002).

Three sonographic examples of low frequency fish sounds are illustrated in figure 3. The fish sounds shown have dominant frequencies in the range of 200 to 600 Hz. The noise from scuba bubbles is also dominant in this frequency range (figure 2) and can easily acoustically mask such fish sounds.

Other underwater noises from boats and submarines

Diving operations often include boats and the noise produced by engines is well within the range of hearing sensitivity of most fishes. Table 1 lists examples of the dominant frequencies produced by various types of boats and a submarine with comparison to reef background sounds and scuba bubble noise. This table lists only the dominant frequencies and not the relative amplitude of the different sounds (i.e. reef background sounds are relatively much quieter than boat motor noise).

Table 1. Examples of some boat sound sources and their dominant frequencies. Recordings are from Saipan lagoon, July 2000.

Sound Source	Dominant Frequency, Hz
Reef background noise	86
25 HP 4-stroke engine boat overhead	215
Scuba bubble noise	235
Large navy ship half mile away	345
Submarine steering and thruster hydraulics	388
28ft inboard engine boat overhead	474

Discussion

Most fishers already know that if you are sitting in a boat and making noise (such as rustling on the deck), it will “scare the fish below and they will not bite” (I can still hear my father telling me to “quit fidgeting and making noise” or I would frighten the fish while we sat in our boat fishing). As scientists, we have yet to take this advice seriously, especially during direct observation of fishes while diving. While some fishes do produce sounds loud enough to be heard by a diver underwater (e.g. toadfish, damselfish), many species only produce very quiet sounds that are easily missed or even undetectable, especially when background noises from boat and bubbles are occurring (Lobel 1992, 1998).

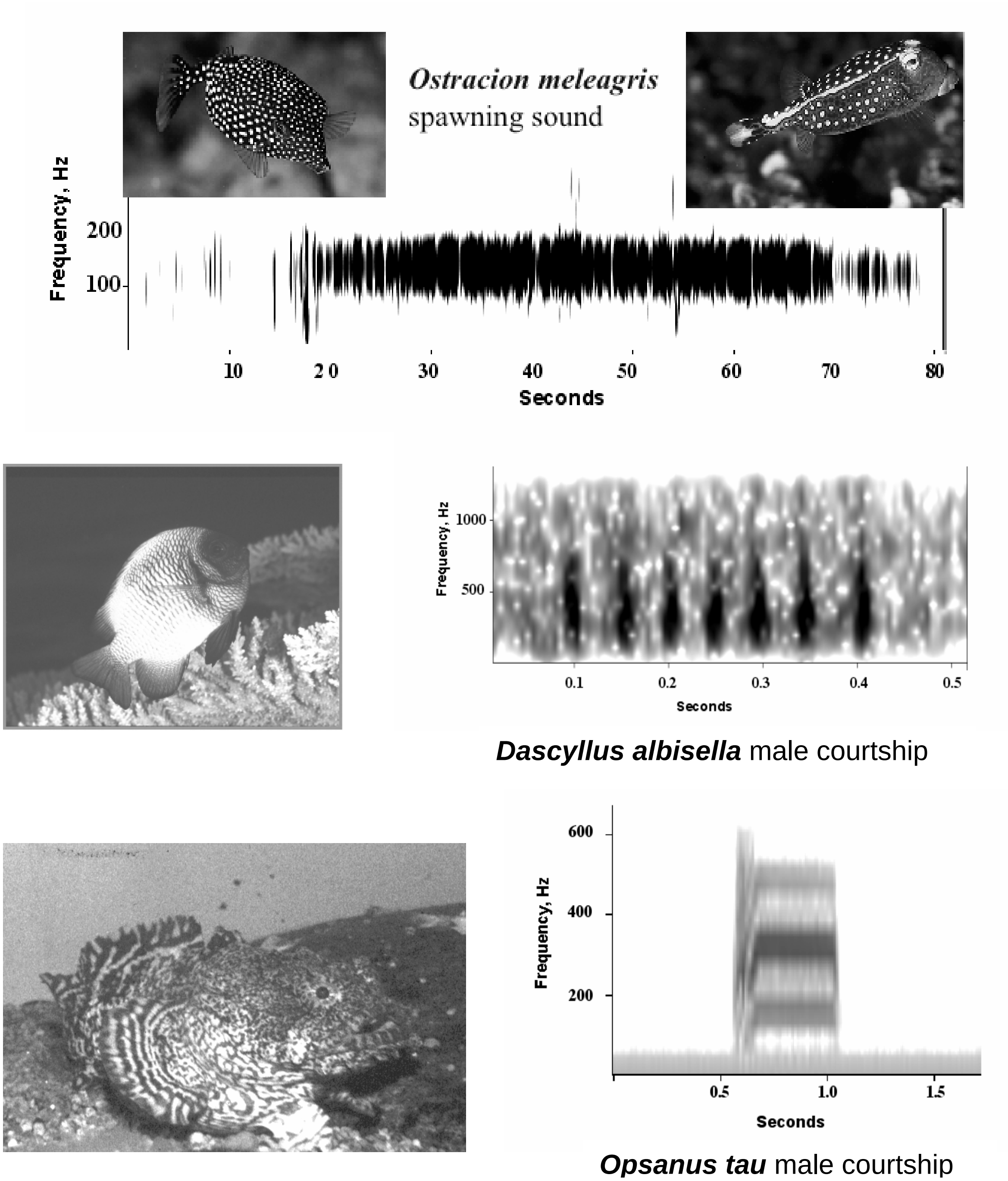

Figure 3 Three examples of low frequency fish sounds that can be acoustically maskedby bubble noise**.** The spotted trunkfish, *Ostracion meleagis*, (male on left, female onright), pair produce a several second long and quiet sound as they disperse their free floating gametes high in the water column. The male domino damselfish, *Dascyllus albisella*, produces a steady series of a pulsed calls for attracting females to mate. The courtship call of the male toadfish, *Opsanus tau,* is the classic “boat whistle” sound and is also steadily repeated.

Scuba bubbles produce not only low frequency sounds but also near-field vibrations in the water. This water disturbance is probably similar to the hydrodynamic disturbances produced by close swimming predators or competitors and to which most fishes are especially sensitive by means of their lateral line and sensory pore system. Consequently, scuba bubbles create multiple stimuli that may directly affect fish behavior. Boat motor noise is also a concern. Clearly, these noises are of concern not only when recording fish bioacoustics but also when conducting species abundance surveys or when observing behavior. While difficult to quantify, the distinct impression is that fishes are much less disturbed by a diver using a RUBA than one using open circuit scuba (Lobel 2001a). It should be noted, however, that individual fish eventually can be habituated to scuba divers and their bubbles as anyone who has dived in marine protected areas (such as Blue Corner in Palau) can attest. Habituation does require a long time investment in letting the fish become familiar with divers (and their bubbles) who pose no threats. It is the author's experience that using a rebreather significantly decreases the amount of time required for fish to become habituated to a diver in their territory.

Figure 4. Underwater recording using open circuit scuba requires careful buoyancy control and breathing discipline when recording fish bioacoustic behavior. It also requires additional bottom-time underwater to habituate fish to a diver's non-aggressive presence. The author with his first UW synchronous audio-video recorder system in 1988 at Johnston Atoll.

In order to obtain high quality acoustic recordings without scuba bubble noise interference, accurate acoustic measurements can only be made between breaths when using open circuit scuba. Thus, divers needed to be extremely disciplined in their respiratory pace and activity while recording. The safety risks to scuba divers of breath holding or "skip breathing" while diving are well known and should be avoided whenever possible (figure 4). In this regard, using a rebreather results in safer diving when trying to obtain quality underwater recordings as opposed to open-circuit scuba where extra effort is required to reduce extraneous bubble noises. Of course, at the same time, boat noises must be minimized to avoid other acoustic interference.

Figure 5 Photograph of the author's first "spawn-o-meter" device for recording fish sounds without scuba diver bubble interference. This first generation spawn-o-meter was built and deployed in 1989 and included a hydrophone (foreground) connected to a tape recorder in an underwater housing with controls. It was equipped with up to two hydrophones for stereo recording and an earphone for real-time listening option. Such autonomous recorders are deployed at a site where fish are active and then the diver leaves the area to avoid bubble interference. These can be programmed to record at various time intervals. Hydrophones are omni-directional and thus all fish sounds within several meters or more (depending on the source level) are recorded. Deployment of such devices underwater qualifies as "tactical diving". The key to obtaining meaningful data is to know where, when and how to deploy your data acquisition diver/apparatus.

Alternatively, an autonomous recording device could be deployed at specific fish activity sites (Figure 5). Such autonomous recorders are deployed at sites where fish are active and the diver then leaves the area to avoid bubble interference. These recorders can be programmed to record at various time intervals. Hydrophones are omni-directional and thus all fish sounds within several meters or more (depending on the source level) are recorded. Deployment of such devices underwater qualifies as "tactical diving" (see below). The key to obtaining meaningful data is to know where, when and how to deploy your data acquisition divers and /or apparatus. This approach works best once the species-specific sounds and spawning habits of a fish are already well defined. The major disadvantage is that without a diver present to control the recording or to follow specific fish as they move, critical behavioral data can be missed without knowing it occurred. Using a diver operated video-acoustic recorder allows the scientist to control the recording and to follow specific fish (i.e. focal animal sampling). Synchronous audio-video recording is necessary in order to discover and define the sounds produced by particular species during specific behaviors such as courtship and mating (Lobel 2001a, 2003b). Thus, using a RUBA is the best technology for this research.

Recent studies of fish bioacoustics are rapidly expanding scientific knowledge about how fishes communication, their reproductive behavior and evolution. This research also applies directly to aspects of fisheries management and conservation with the potential of developing novel instrumentation for monitoring populations underwater (Lobel 2001a). Furthermore, these studies are revealing the importance of the acoustic environment and, once more, raise old questions regarding potential adverse impacts of noise pollution to fishes and other aquatic animals. Lastly, it is noteworthy to mention that there are very few studies on aquatic invertebrate bioacoustics.

The scientific objective of the author's bioacoustics research is to determine which fishes produce species-specific sound patterns exclusively with explicit acts of courtship and mating. This research provides scientific insight into evolutionary and ecological processes and also provides data necessary to develop the passive acoustic detection technology for monitoring fish reproduction (Lobel 2001a, 2002, 2003a, b).

One goal is to evaluate specific fish vocalizations and how methods for passive acoustic localization can be applied to field studies of fish reproduction. We also evaluate how species-specific sounds differ statistically and acoustically. This provides the information necessary to identify which species have the potential to be monitored using passive acoustic detection. The ultimate objective is to develop instrumentation, deployment strategies and analytical procedures for locating spawning populations, and quantifying the spatial and temporal patterns of fish reproduction. It is important to determine whether specific spawning sites are used consistently throughout a season and between seasons, or if sites change with fluctuating environmental conditions. For example, certain groupers and snappers aggregate annually at specific sites to spawn. Determining exactly where and when these fish spawn is a critical component of assessing essential fish habitat and practicing effective marine management. The spatial and temporal patterns of fish reproduction at known sites can be recorded using a hydrophone-recording system which has been dubbed the "spawn-o-meter". When these systems are coupled with standard physical oceanographic instrumentation, it will provide quantitative data on the correlation of spawning patterns with temperature, light levels, salinity, current flow, etc. Day-length, temperature and salinity are common proximate environmental cues for fishes to synchronize breeding. However, it is probably the spatial and temporal interplay of proximate stimuli with variables affecting larval survival and recruitment that ultimately achieve regulation of reproductive cycles.

This information is essential to understand how fish reproduction may be correlated with oceanographic phenomena that influence larval distribution and recruitment patterns. Ultimately, replicates of this combined bioacoustic-physical oceanographic station could be deployed at multiple sites simultaneously to compare the timing of spawning throughout a region. To test our concepts and develop the methods we need to obtain field recordings of fish courtship and spawning sounds. Rebreathers provide the technology to do this most efficiently and accurately.

Conclusion: Technical Diving + Tactical Diving = Scientific Diving

Using advanced UBA systems (mixed gas, rebreather, etc) for underwater excursions is generally referred to as "technical diving". As a comparable but different class of diving, a new term is suggested, namely "tactical diving". Tactical diving refers to the strategic deployment of divers who, in turn, deploy oceanographic and biological instrumentation or do underwater observations/surveys in order to gather key data to critically test specific scientific hypotheses. The combination of these two modes of diving to do science becomes “scientific diving” (although scientific diving encompasses much more than these two components). For the past several decades, underwater scientists have had so many new things to describe that simple open-circuit scuba easily sufficed. More advanced technical diving was just not necessary, at least for basic marine biology. However, this has changed during the last decade. For example, Pyle (1996) has used RUBA to go to deeper depths longer and has discovered many new species that have since revealed new fish biogeographic and phylogenetic patterns.

The rationale today has evolved. Advanced diving technology, such as RUBA, currently is more affordable, reliable and safer (although it does require advanced training, extreme diligence and higher awareness while operating). Rebreathers offer the additional advantages of nitrox diving with longer bottom times at usual diving depths less than 100ft. Modern scientific issues in marine conservation revolve around determining the critical life history parameters, especially reproduction, of overly exploited species. Future discoveries of the secret lives of fishes and other aquatic animals will be greatly facilitated by using a modern silent diving apparatus.

Acknowledgments

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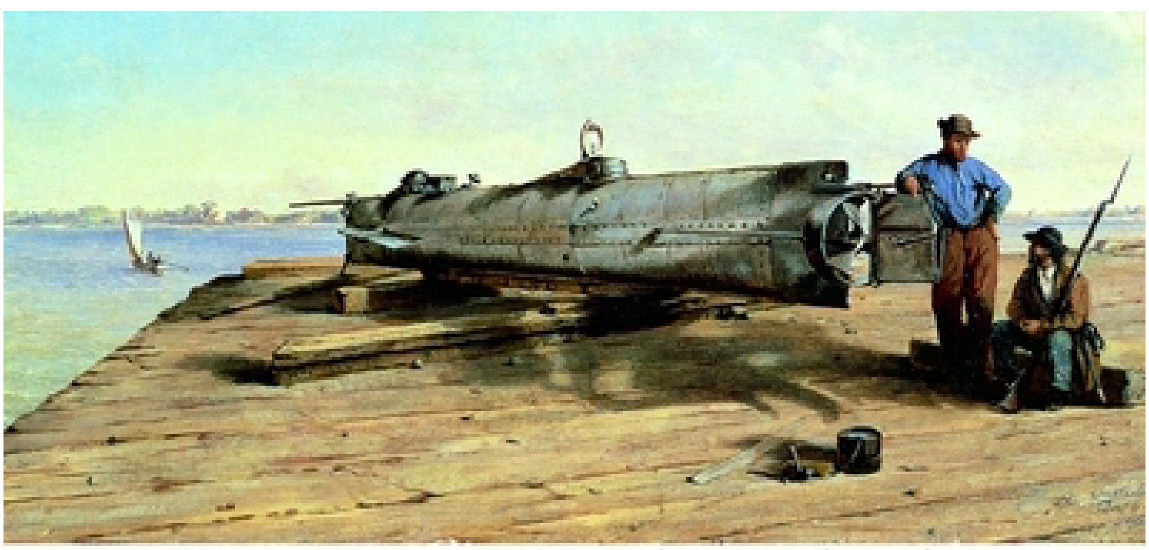
Underwater Archaeology and the Confederate Submarine *H.L. Hunley*

Robert S. Neyland,
Underwater Archaeology Branch, Department of the Navy, Naval Historical Center, 805 Kidder Breese St, SE, Washington Navy Yard Washington, DC 20374-5060

Underwater Archaeology as a Scientific Pursuit

Underwater archaeology is an interface between science and history. Materials recovered from archaeological sites are more than just ancient artifacts and objects; they are sets of data that can help us answer many questions about the evolution and development of human culture, technology, and the interaction of different peoples with each other and their environment. The study of archaeological occurrences from our more recent past enables archaeologists and historians to compare the written archival record with physical evidence left in the ground and under the sea. In the case of submerged sites, the assemblage of archaeological material can be more complete than that retained by sites above water. This is due to the fact that archaeological sites such as shipwrecks or sunken cities are often the result of a single catastrophic event rather than the gradual accumulation of discarded material such as daily refuse.

Underwater archaeology is a rapidly developing specialization in the broader spectrum of archaeology; currently, work is being conducted in every ocean and major body of water off the coast of virtually every country. Inland waterways are also being studied. In the United States, for example, states that have do not have a coast possess rivers and lakes that contain submerged cultural materials. Underwater archaeology, more than any other sub-discipline of archaeology, is heavily dependent upon technology. Areas within underwater archaeology that employ the use of cutting-edge technological innovations include SCUBA diving, survey, mapping, and conservation.



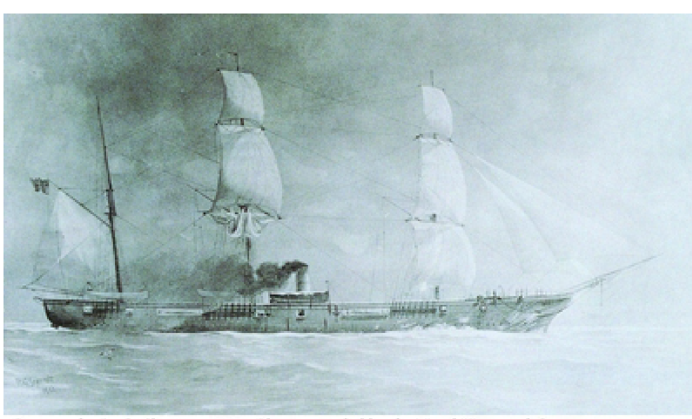
Painting by Conrad Wise Chapman, circa 1863. Courtesy of the Museum of the Confederacy.

History of *H.L. Hunley*

The Confederate submarine *H.L. Hunley* is an example of a shipwreck lost with all hands at the moment of its success in war. It represents an early submarine prototype and a wartime secret weapon for which no accurate plans or accounts existed prior to its discovery. It was a technological marvel, very much ahead of its time. Shipwrecks are usually described as time capsules. This description is especially true for *Hunley*, since two closed hatches and an intact iron hull essentially encapsulated its interior.

Hunley was the third in a line of submarines built by a group of investors and southern patriots. Both of its predecessors were scuttled or lost without ever seeing battle. The first was built in New Orleans, but was scuttled and abandoned when that city surrendered to Federal forces. The team of engineers and investors, led by Horace Lawson Hunley, a New Orleans lawyer and patriot, moved operations to Mobile, Alabama where they built yet another submarine. While in Mobile, the members of the submarine program were under the direction of the Confederate Secret Service. The second prototype, known as *Pioneer II*, was later lost while being towed outside of Mobile Bay. Although the loss of the second submarine prototype was a setback, the group remained undeterred and quickly constructed a third vessel. This submarine would later bear the name of Horace Hunley.

Shallow waters and the great distance between land and the Union blockading fleet made it impossible to successfully employ the submarine in Mobile Bay. General P.G.T. Beauregard, commander of the military defense of Charleston, South Carolina, requested that the submarine be transferred there to strike at Union ships and lift the blockade of that port. The submarine arrived in Charleston in 1863 and was put through a series of trials. Tragically, it sank on two separate occasions with the loss of 13 crewmembers. The second sinking claimed the life of Horace Hunley and members of the engineering team from Mobile. General Beauregard, although discouraged, allowed the submarine to be raised and deployed again with a new volunteer crew. The submarine was put under the command of Lt. George E. Dixon, a Confederate Army engineer from Mobile who had worked on a steamboat prior to the war, and was reputed to exhibit great courage. Dixon was convinced that the submarine could successfully attack and destroy enemy ships. He put his volunteer crew through rigorous training in preparation for an assault on one of the Federal blockade vessels.



Drawing by R. G. Skerrett, 1902. Photo provided by the Naval Historical Center.

Union sloop-of-war USS *Housatonic*

On the evening of February 17, 1864 the submarine left Battery Marshall, a Confederate gun emplacement located at Breach Inlet on Sullivan's Island. *Hunley*'s commander steered a course for USS *Housatonic*, a 207-foot steam screw sloop-of-war. At about 8:45 p.m. *Hunleys* 'screw planted a barbed torpedo in the starboard after side of the *Housatonic*'s hull and backed their vessel away. A member of the crew then pulled a lanyard and detonated the explosive charge. The torpedo was attached well beneath the *Housatonic*'s waterline and the hole that resulted from the explosion caused the ship to sink in a matter of minutes. Members of the *Housatonic*'s crew reported that the hole was so large that the officers' wardroom furniture floated out of it. Luckily for the crew of *Housatonic*, the ship was anchored in 30 feet of water. Although the ship's hull sank to the bottom, its masts and rigging still protruded from the water and the crew was able to cling to it until rescued. Only five men died aboard *Housatonic*. From their position in the wreck's rigging, *Housatonic* survivors saw a blue signal light waved from one of the submarine's conning towers. Confederate sentries ashore also reported seeing the blue signal light and in response lit a bonfire for the submarine to navigate home by. These are the last reported sightings of *Hunley*. The submarine never returned to Breach Inlet. In fact, its resting place when found was only 900 feet to seaward of the wreck of *Housatonic*.

Discovery and Responsibility for the Submarine *H.L. Hunley*

Hunley was discovered in 1995 by a dive team funded by best-selling author Clive Cussler. The discovery came at the end of a search that spanned almost 15 years. The announcement of the submarine's discovery initiated discussion about ownership, protection, and responsibility for the wreck remains. Eventually, the United States Navy and the State of South Carolina Hunley Commission were established as the entities that would oversee the submarine's recovery, excavation, and long-term preservation. The not-for-profit group Friends of the Hunley was formed to create private funding and assist with day-to-day project operations. The South Carolina Hunley Commission was created by legislators to represent the State of South Carolina and was charged with the reburial of the submarine's eight-man crew.

The federal government was involved because *Hunley* was once the property of the government of the Confederacy. The Civil War ended with the Confederacy's surrender to the United States. As victor, the government of the United States became the owner of all Confederate States' property, including all vessels afloat, abandoned and/or sunk.

Recovery and Conservation

The decision was made to recover *H.L. Hunley* and its crew because the site could not be protected indefinitely from looting while it remained offshore. Well before recovery plans were formulated, various relic collectors made offers for pieces of the submarine. The highest offer for a single piece of *Hunley*—the submarine's propeller—reached $100,000. *Hunley* was (and still is) considered a war grave, and Navy policy dictates that the remains of military personnel should be recovered for identification and burial, especially when it is likely that looters might disturb those remains. The remains of *Hunley*'s crew are being treated the same as all other U.S. military remains: with dignity, respect, and honor. When identification is complete *Hunley*'s crew will be buried with ceremony alongside the graves of the submarine's two previous crews.

Underwater archaeologists determined that the sub should be recovered intact and that the excavation of the interior should be done in a controlled laboratory environment rather than in the swift, zero-visibility waters present off Charleston, South Carolina. The marine engineering firm Oceaneering International, Inc. was contracted to assess available recovery options. The primary criteria for the engineering plan were that the submarine be recovered intact, that it be recovered in the same position in which it was found on the seabed, and that all the archaeological data surrounding the submarine be recovered scientifically. While archaeologists had determined the upper part of the hull appeared to be sound and well preserved, the condition of the bottom of the submarine was unknown. Naturally, important questions arose: Had the submarine's hull already ruptured and spilled its contents—including human remains—into the open sea? Had some of the crew attempted to leave the sub, but been drowned just outside of the conning tower hatch? Were components of the lower hull—particularly the riveted boiler plates—corroded to the extent that *Hunley*'s seams would split during excavation or the recovery process?

Some engineering options that were considered and then rejected included recovery of *Hunley* in a box with a block of sediment around it and removal of the submarine in a simple lifting frame. The first plan was impractical because the soil around the submarine was likely to liquefy if the iron plates for a box were vibrated into the seabed. Eventually a unique recovery system was designed that incorporated the use of a bridge-like supporting structure underneath which the submarine would be suspended using a series of 33 slings. Each sling held a bag that was filled with a two-part foam compound that expanded around the shape of the submarine and solidified in approximately 20 minutes. The slings and foam bags not only supported the weight of the submarine but also provided constant pressure to the hull's exterior that effectively countered the pressure exerted by the tremendous amount of sediment contained within the hull. On the end of each sling was a load cell that measured the torsion force at that position along the hull. Engineers on the surface advised divers to adjust each sling in such a way that the weight of the submarine was evenly distributed and the outward pressure against the hull from the sediment inside was effectively counteracted.

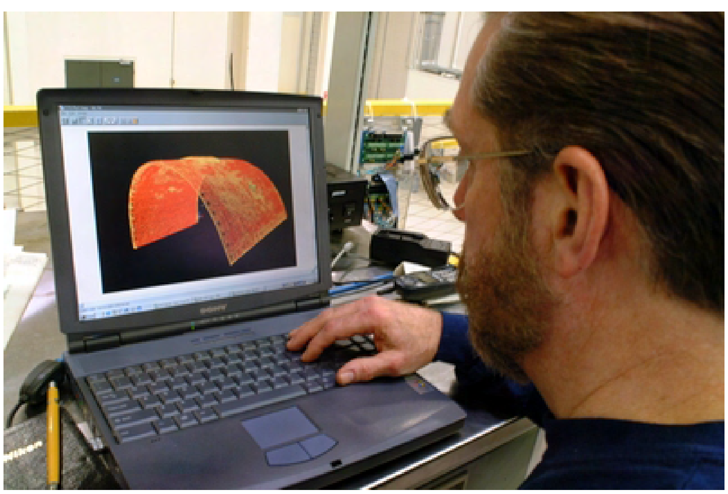
The *H.L. Hunley* being lifted from the water.
Copyright Friends of the Hunley.

The ends of the truss (support structure) had to be supported and kept from sinking into the sea bottom. This was accomplished by placing two large steel cylinders called suction piles at either end of the truss. Hydraulic suction was used to sink the 42-ton piles into the seabed. Following the recovery, the suction piles were removed by pumping water back into them. The combined truss and sling assembly containing *Hunley* was raised from the seafloor by a barge with 6 legs that could be set in the mud and used to jack the platform above the ocean's surface. A large crane with a 300-ton lift capacity was located on the barge. This crane was capable of lifting *Hunley* clear of the sea and placing it on a small barge for removal to a conservation facility located on shore.

On August 8, 2000, *Hunley* was successfully recovered and transported to the Warren Lasch Conservation Center in North Charleston, South Carolina. Prior to this event, project staff had spent a year planning and developing the recovery effort, as well as the construction of a world-class conservation laboratory dedicated to underwater archaeology and the preservation of *Hunley*. Recovery alone would eventually cost $2.5 million, and renovations for the laboratory approximately $2.7 million. It is anticipated that the conservation of *Hunley* and its artifact assemblage will take 10 years or longer to accomplish. The annual projected cost will come close to $1 million. The recovery, conservation, analysis, and interpretation efforts necessary to investigate an entire shipwreck are very expensive; and while the initial recovery may seem difficult it is actually the easy part of a shipwreck recovery project. This is why most underwater archaeologists insist that shipwrecks should be preserved in place rather than excavated, recovered, and conserved.

Once *Hunley* was raised from the seabed its transport from sea to shore involved not only archaeologists and engineers, but also the United States Coast Guard and many elements of state and local government and law enforcement. Transport of the submarine to the laboratory became a major media event. A procession of over 500 private boats followed the transport barge into Charleston harbor and thousands of people lined the sides of the Cooper River to cheer *Hunley*'s return home.

Archaeology of *H.L. Hunley*

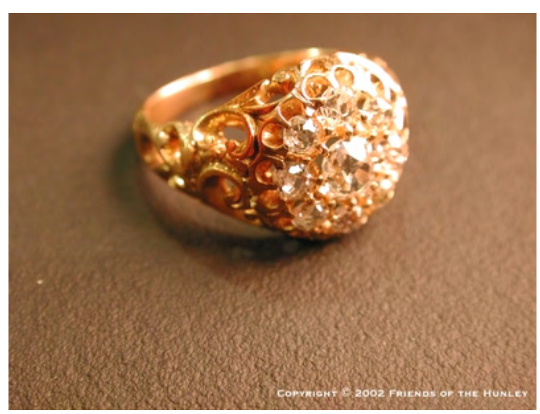


Examining a laser scan of an exterior hull plate.
Copyright Friends of the Hunley.

Hunley's interdisciplinary research team includes archaeologists and conservators from the United States and abroad, as well as leading forensic anthropologists, biologists, geologists, engineers and materials scientists. This extraordinary team of scientists is accomplishing a variety of tasks using 21st century technology, including three-dimensional laser scanning to map the submarine and the positions of artifacts; Magnetic Resonance Imaging (MRI); Computer-Assisted Tomography (CAT) scans; and virtual-reality applications. We have conducted "first-time-ever" research on the effects of industrial radiation and its effects on DNA identification and our conservation team is currently experimenting with new preservation techniques using cold-plasma reduction and sub-critical fluids. Ultimately, all of the aforementioned may impact the way archaeology and artifact conservation is conducted in the future.

As our investigation of *Hunley* has progressed, we have discovered a wealth of interesting—and surprising—information about it construction, its mission and its crew. Because *Hunley* was one of the Confederacy's most secret weapons, none of its original drawings or plans survived the Civil War. Consequently, very little was known about its construction. The vessel recovered in 2000 differs significantly from the sketches and replicas made of it following the surrender at Appomattox. We have discovered that it is more than just a converted steam boiler; to the contrary, it is a technological marvel with a sleek, hydrodynamic shape that was both practical and elegant. Sophisticated forms of internal machinery, such as a system of hand pumps, valves and plumbing to shift water between the sub's ballast tanks, were found throughout the hull. Archaeologists discovered a series of iron frames used to stiffen and provide additional integrity to the interior of the vessel. These were never reported in the historical record. The propulsion system of *Hunley* bears no resemblance to what is presented in archival sources either. Other elements of machinery previously undocumented include a steering mechanism resembling a whipstaff or aircraft joystick, counterweighted propeller shaft complete with hand brake mechanism, a wooden force bellows to pump fresh air into the crew compartment, and an innovative torpedo spar that was attached to the bottom of the prow rather than at the top, as was erroneously reported in historical accounts.

Numerous artifacts discovered within the *Hunley*'s crew compartment reveal much about the lives of those who operated the submarine. Among other things, these items will assist the identification of each crewmember, offer clues about their respective social status, age, origin, habits and health, and reveal what each man thought was important enough to bring with him on the submarine. The complete inventory of artifacts totals over 2000, and over 5000 samples have been collected as well. Perhaps the most intriguing items were associated with the remains of Lt. George Dixon. For example, the discovery of a mangled twenty-dollar gold coin (discussed later) confirmed historical accounts of Dixon being wounded at the Battle of Shiloh. However, a diamond brooch and ring, perhaps carried for his fiancé, were totally unexpected.



Diamond encrusted gold brooch (left) and ring (right).

While Lt. Dixon carried items attesting to his greater wealth or higher social status, the remainder of the crew carried possessions that suggest a more common sailor or soldier's life. These artifacts included pipes, pencils, wallets, and the occasional battle souvenir or necessity

Excavation


Photo by Christopher F. Amer. Courtesy of SCIAA

Hole discovered in forward conning tower of *HL Hunley*.

Following *Hunley*'s recovery, the team of archaeologists, forensic anthropologists, geologists and other specialists initiated plans to enter the hull and excavate of the interior of the submarine. Because the submarine was completely filled with sediment, geologists collected samples in an effort to answer questions about the submarine's loss and what happened to it after it sank and settled on the seafloor. The latter events are commonly referred to as the "site formation processes" by underwater archaeologists. Three holes were discovered in the submarine's hull, but it is currently unclear if they contributed to the submarine's loss or resulted from subsequent impacts to the wreck (for example, by anchors dragging into the hull). It is believed that sediment analysis will reveal the answer to these and other questions. Forensic anthropologists and other specialists participated in the planning phase by developing protocols for the documentation, removal, preservation, and analysis of the crew's skeletal remains.

One of the big problems confronting *Hunley* Project archaeologists was how to enter the closed hull of the submarine without damaging it or the archaeological material that it contained. Even if the hatches were to be opened the small diameter of the conning towers would prevent entry and severely limit the extent of excavation. Scientists wanted to gain the maximum amount of work area with the least amount of damage to the hull. Ultimately, project planners decided to remove every other hull plate on the submarine's upper surface. This was accomplished by drilling out the rivets holding each plate to the hull and carefully removing the plate. The conning towers and hatches were left alone. Eventually, four upper hull plates were removed; this allowed archeologist to initiate a controlled excavation comprised of extensive mapping and documentation, and the removal of artifacts, skeletal remains, and a variety of samples. Because *Hunley* was stored in a tank of chilled water and the water level in the tank could be raised or lowered, the archaeological team was able to lower the water level during excavation and maximize recovery and documentation efforts. At the close of each day, the tank was refilled with water and the submarine and its contents were completely immersed.

Project archaeologists also had to figure out how to map the distribution of artifacts and samples taken from the sub. This was no easy task, since the shape of the hull—when viewed in cross-section—resembles an egg tilted at a 45-degree. Traditional methods of mapping were inefficient because of the hull's enclosed shape and restrictive attributes. In order to solve the problem, 21st century technology was employed. A scanning device incorporating the use of lasers was able to generate extremely accurate maps of the submarine's complete interior and exterior surfaces. The "point clouds" created by the scanning device are comprised of several million individual three-dimensional survey points. Individual artifacts and samples were mapped with a system utilizing laser technology and a computer program that could calibrate distance and angle to a point in order to accurately place it within the hull.

Preservation was excellent inside the submarine. Sediment and isotope studies indicate that *Hunley* was completely filled with fine silt. The silt created an anaerobic environment that slowed the degradation of iron and organic substances such as wood, leather, bone and textile. Wood and bone were very well preserved. Leather and textiles were well preserved but extremely fragile. Wood, leather, and textile materials have had much of their cellular constituents replaced with water and cannot be allowed to dry out. Ultimately, the water in these items will need to be replaced with a preservative substance such as polyethylene glycol. Surprisingly, human hair and soft tissue (in the form of brain matter) were also preserved in the anaerobic sediments.

Archaeologist Maria Jacobsen and geologist Scott Harris examining sediment color and stratigraphy.

The submarine was completely filled with sediment. This sediment contained information that greatly complimented information exhibited by *Hunley*'s various artifacts. The silt that accumulated within *Hunley* preserved the submarine and its contents as it rested on the seafloor, while sediment outside the submarine provided clues about the marine environment that developed on and around the hull during the two decades that it took for it to be completely buried. Sedimentary studies explain the site formation process—the filling sequences inside the hull—and provide an understanding of the physical, chemical, and biological processes that occurred on the site. Geologists and other scientists are currently analyzing sediment samples for bacteria, large marine fauna, sediment textual parameters, Fourier grain shapes, microfossils (foraminifera, ostracodes, dinoflagellates, pollen, diatoms), 210PB and Cesium profiles, carbon-hydrogen-nitrogen ratios, and trace metals. These data are critical for developing a timeline of what happened to *Hunley* after it sank, and will advance scientists' knowledge of the ocean's physical, chemical, and biological environments and processes along the inner coastal shelf of South Carolina. *Hunley* is also an environmental time capsule that enables us to understand historical, geological, and climatological aspects of the region.

Sediment sampled from inside the submarine may also contain clues about South Carolina's environment in 1864, as well as the health and diet of the submarine's crew. Sediment samples recovered from inside the pelvic girdles of each crewmember's skeleton will be examined for traces of their final meal, evidence of intestinal parasites, and microfossils such as phytoliths (mineralized structures from plant cells), pollen, and starch grains.

What the Human Remains Can Tell Us

Osteological studies by forensic anthropologists can tell us many things about *Hunley*'s individual crewmembers. Their skeletal remains reveal age, ethnicity, height, health and, occasionally, occupation. The skeletal remains discovered in the submarine are largely intact and include the small bones of the feet and hands, as well as cartilaginous elements such as the hyoid. Analysis of the osteological remains revealed that the crew was comprised of men ranging in age from their late teens to mid-forties. Carbon isotope analysis revealed that four crewmembers were American and four European born by determining whether the carbon isotope sampled shows a diet rich in corn (American) or wheat (European). Some soft tissue and hair was preserved and samples from these will undergo toxicology analyses. Dietary remains can be recovered from dental calculus and bone samples removed from elements of the crew's skeletal assemblage will undergo stable isotope analysis. The latter is a common form of analysis for historic period skeletal remains and will provide comparative data for other Civil War-era burials and war graves. This data may also reveal the geographical origin of each crewmember.

Skeletal remains sometimes provide a detailed history of an individual's injuries. The commander of the submarine, Lt. George E. Dixon, suffered a severe injury at the Battle of Shiloh when a Union bullet hit a twenty-dollar gold coin in his pocket and spun off into his left leg. The left femur of Dixon clearly shows this injury. The skeletal remains of other members of the crew show evidence of old injuries that had healed by the time *Hunley* set out on its final voyage. Pathologies evident in the skeletal remains include vertebral injuries, broken noses and cheeks, and broken bones in the feet and hands. Most of the crew suffered from various forms of dental disease as well. Some of the crewmembers were such prolific pipe smokers that their teeth exhibit grooves where they habitually clenched a pipe stem in their mouths.

Genealogist Linda Abrams researched each individual's family history to the extent possible and identified possible DNA matches for two crewmembers. At this time, no photographs of *Hunley*'s crewmembers are known to exist. Facial reconstructions have been made, however, using molds taken of all eight craniums and casts were then made from these. The cranial casts were used to create the facial reconstructions of the crew. The crew is identified using archaeology and forensic anthropology. Artifacts such as LT Dixon's gold coin clearly identified him. Likewise the confederate buttons from the German artillery identified Carlson. DNA comparisons and analysis identified two other crewmembers Collins and

Ridgeway. Carbon isotope analysis based on the difference between wheat and corn diets revealed that four Hunley crewmembers were European. This carbon isotope analysis and historic details such age furthered the process of elimination, which allowed identification of remaining crewmembers. The facial reconstructions are accurate except for hair and eye color and the shape of the nose and ears.

Should photographs be found, one technique that can be used to match them to a specific set of skeletal remains is photographic superimposition. The technique employs the use of two photographic overlays—one of an individual's cranium; the other a historic photograph of a person's face—in order to see if there is a statistical match between the features exhibited by each photograph. Photographs of crewmembers, if found, would add finishing touches (such as eye and hair color, presence or absence of facial hair, and the shape of the nose) to facial reconstructions created from the craniums of the eight-crew members.

Artifacts

The aspect of archaeology that the public often finds most fascinating is a site's artifact assemblage. There are many dramatic artifacts that have been recovered from *Hunley*. Perhaps the most significant artifact is the twenty-dollar gold coin found with Lt. Dixon's remains. Queen Bennett of Mobile, Alabama reportedly gave the coin to Dixon when he left Mobile to fight in the Civil War. The coin deflected a Union bullet during the Battle of Shiloh and saved Dixon's life. Consequently, Dixon considered the gold coin to be his good luck piece. Following his recovery from the wound, Dixon had the reverse side of the coin engraved with the following words:

SHILOH
April 6, 1862
My Life Preserver
G.E.D.

Dixon not only was lucky, but also was apparently quite wealthy. His personal possessions included a gold ring and brooch set with numerous diamonds, and a gold watch and chain with a gold Masonic watch fob. He carried a pair of leather-covered brass opera glasses, a folding rule, and a penknife.

By comparison, the remaining crewmembers had relatively few possessions. The few objects that they did carry were of little value. The complete assemblage of personal items carried by the rest of the crew consisted of four tobacco pipes, one complete folding knife, one damaged folding knife, a leather wallet may or may not have contained money, and seven canteens. One crewmember carried the dog tag of a Union soldier around his neck. This was evidently a battle souvenir since the man wearing the tag was much older than the Union soldier whose name the tag bore.

Lt. Dixon's lucky gold coin. Copyright Friends of the Hunley.

The crew also possessed the clothing on their backs. Portions of each crewmember's clothing were preserved as small fragments. The elements of clothing that provided some of the best information about each individual in the submarine were buttons. Many buttons originated from military uniforms of both the Confederate Army and Navy.

Confederate artillery uniform button (left) and US Navy pea-coat button (right).
Copyright Friends of the Hunley

Surprisingly, a number of the uniform buttons originated from Union as well as Confederate clothing. The use of Union clothing by Confederate soldiers was not unusual because uniforms were in short supply in the Southern states and very expensive. Additionally, at least one member of the submarine's crew, a sailor named Wicks, was a seaman in the Union Navy at the beginning of the Civil War. The first artifact discovered in the submarine's crew compartment was a Confederate Artillery button. It was located on the bench upon which *Hunley*'s crew sat. Discovery of the artillery button generated considerable excitement because the historical record indicated that at least one member of the submarine's crew (C.F. Carlson) formerly served in a South Carolina artillery unit. As the excavation progressed, similar buttons were discovered on and below the bench.

Other artifacts discovered in *Hunley*'s cramped interior were associated with the function of the submarine and its mission. These items included a gimbaled compass in a wooden box, iron wrenches to work on the sub's machinery, fragments of a mercury depth gauge, a wax candle in a crude wooden holder, and the ship's signal lantern. The latter probably generated the blue light reported by eyewitnesses shortly before *Hunley* disappeared.

Elements of *Hunley*'s equipment were also revealed during the excavation. Water ballast tanks were found on both the forward and after ends of the submarine. A pipe and a series of valves under the bench on the port side connected these to one another. A rod located underneath the bench enabled Lt. Dixon to control the sub's rudder in the stern. The steering device consisted of a whipstaff or joystick that could be moved either left or right to steer the submarine in the desired direction. Dixon also controlled a lever connected to the submarine's dive planes. One dive plane was located on each side of the hull's exterior. *Hunley* could be safely submerged when Dixon and his crew conducted a series of coordinated actions. These included the introduction of water into the ballast tanks, forward propulsion of the submarine through the water, and controlled depression of the dive planes.

The seven men directly behind Dixon all sat on a bench located on *Hunley*'s port side and turned a hand crank that was located on the submarine's starboard side. The space within the hull was so confined that the crew could not sit upright and had to allow the crank handles to pass between their open legs. It was reported that *Hunley* could travel at four knots under favorable conditions. The crewman located at the aft extremity of the bench manned the pump for the aft ballast tank. The crewman directly behind Dixon—nicknamed "the kid" because he was the youngest member of the crew—operated the forward ballast pump and a large wooden force bellows. The bellows were connected to two three-foot long pieces of pipe (snorkels) that that introduced fresh air into the crew compartment while the submarine traveled on the surface. A series of iron bolt heads were discovered along the bottom centerline of the hull. These were connected to iron keel weights attached to the bottom of the hull. The keel weights could be dropped in an emergency in order to lighten the sub and allow it to rise to the surface.

Conservation: The Long Haul

A great deal of work has gone into making the recovery and excavation of *Hunley* a success. However, the greatest challenge to the project—the complete conservation of the submarine and its artifact assemblage—remains to be accomplished. To conserve *Hunley*'s iron hull conservators must remove chlorides (corrosive salts) embedded in the submarine's various structural components. This is typically accomplished by immersing the submarine in a solution of sodium carbonate or sodium hydroxide with a relatively high pH. Another process, which incorporates the use of a low-amperage electric current and sacrificial metal anodes, is sometimes applied to speed up the elimination of chlorides. It is estimated that this process will take approximately seven to ten years to completely remove all of the corrosive salts in *Hunley*'s hull. If these chlorides are not removed the submarine's corrosion rate will accelerate, causing the metal of the hull to exfoliate. Unchecked, the process will eventually destroy the hull. Some of *Hunley*'s hull components (such as the wooden bench and glass viewing ports) will have to be disassembled in order to conserve them separately. Separate conservation of these items will prevent their destruction by the caustic solution used to treat the iron hull. Shoes, textiles, and personal artifacts will all be carefully treated so that their information potential is not lost. A team of conservators is currently developing a comprehensive plan to conserve *Hunley* and its unique collection of artifacts.

Interpretation

Many questions about *Hunley* remain to be answered. Although the remains of each crewmember have provided numerous clues about their lives, the identities of most have still not been confirmed. The life of Lt. Dixon, the only positively identified member of the crew, is largely unknown prior to his arrival in Mobile, Alabama in the early 1860's. How well *Hunley* operated as a seagoing vessel has yet to be determined. This will be accomplished by a thorough analysis of the hull's hydrodynamic elements and its equipment. Of course, the greatest mystery surrounding *Hunley* is why it and its crew never returned to shore. Presently, no positive explanation for the submarine's loss has been found. Careful examination of *Hunley* and its equipment, combined with geological analyses and the forensic study of the crew's remains, will undoubtedly solve the mystery of what happened to the submarine on that fateful night in February 1864.

The *H.L. Hunley* and some of its artifacts—including Lt. Dixon's gold coin—are currently on display at the Warren Lasch Conservation Center. Tours are available to the public every Saturday and Sunday. To date, approximately 100,000 people have visited the Warren Lasch Conservation Center to view *Hunley* and its associated material. Ultimately, the submarine will be displayed at a major maritime museum in the Charleston area where its story will be prominently displayed and interpreted.

Assessment of Abalone Stocks in Southern California: The First Stage of Recovery

Peter L, Haaker[1], Ian Taniguchi[1] and Mark Artusio[2]
[1]California Department of Fish and Game, 4665 Lampson Ave., Los Alamitos, CA 90720,
[2]Aquarium of the Pacific, 100 Aquarium Way, Long Beach, CA 90802

Abstract

Seven species of abalones are found along the west coast of North America from Mexico to Alaska. Six of these species once supported valuable cultural, commercial, and recreational fisheries, but prohibitions of take of all but one species has been prohibited, a result of over fishing, disease, habitat loss, and recovery of natural predators. Nevertheless, there is a strong desire to re-establish fisheries on some of these abalones, particularly in southern California where fisheries on five species once occurred. The State of California recently completed the Abalone Recovery and Management Plan (ARMP) to guide efforts for recovery and eventual management of abalones. Recovery of abalone populations in an area the size of California will require an ambitious effort. The ARMP is designed to regularly evaluate recovery so that decisions about future use can be made expeditiously, but not prematurely. The plan requires that a significant number of areas be recovered before any consideration of a fishery, recognizing the relationships between local populations. The early assessment involves determining population structure at many index sites, a task that strains the available resources of the State. State biologists have partnered with AAUS scientists from the Aquarium of the Pacific to assess abalone populations in southern California. From the very beginning of this partnership useful information has been gathered which has provided a optimistic view about the recovery of abalones.

Introduction

The near shore marine environment of California contains seven species of abalones (Figure 1). The largest species, the red abalone, *Haliotis rufescens*, can grow to 12 inches in maximum dimension, although most are smaller. Abalone have traditionally been valued for their shells (decorations and tools) as well as their large muscular foot (an important food source for humans to the present time) (Cox 1963). As various immigrants arrived on the Pacific coast of North America, abalone became economically important, either as a commodity or a food source. The importance of abalone to California's economy is nicely presented by Cox (1963), who documents the fishery until the 1960s during which there were several years when 4 and 5 million pounds of abalone were landed (Haaker et al. 2001).

The modern California fishery began at the turn of the 20th Century, and was documented beginning in 1916 (Haaker et al. 2001). The fishery peaked in the 1950s and 1960s, followed by dramatic declines in all five species that comprised the fishery (red, green, pink, white, and black abalones). The fishery only appeared sustainable prior to its collapse due to the expansion of fishing areas and species fished as stocks declined resulting in serial depletion of abalones in California (Karpov et al 2000). Several additional factors also accelerated the demise of the fisheries, including disease, and in some areas, the recovery of the sea otter, an efficient predator on most marine invertebrates, including abalone.

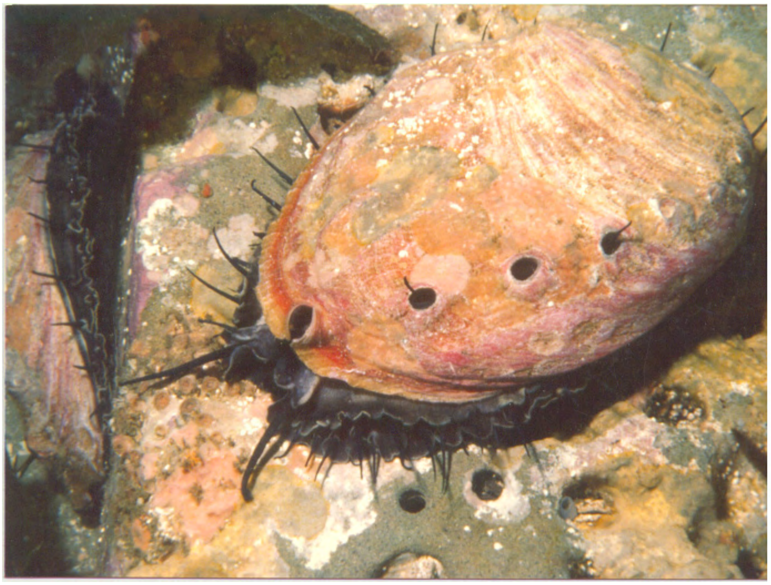


Figure 1. Red abalone, *Haliotis rufescens*. Note second abalone on left side of rock.

The fishery for abalone in California was closed in 1997, by the Fish and Game Commission (Commission), and was supported by legislative action. The latter, recognizing the importance of abalone in California's economy, mandated a plan to reestablish the abalone fishery, at least in some areas, to benefit California commercial and recreational abalone enthusiasts. The northern California recreational-only red abalone fishery was not included in the closure, because it was seen as sustainable, due to its remoteness, often severe ocean conditions, and *de facto* refugia (deeper water stocks inaccessible to skin divers) that were thought to prevent depletion. The California Legislature mandated the preparation of an Abalone Recovery and Management Plan (CDFG 2004) which was submitted to the Commission for approval and eventual implementation.

Both recovery (south of San Francisco Bay) and management (in the northern California recreational fishery) are addressed in the ARMP, but only the former will be addressed here. As abalones recover in southern California, the recovered species will be managed according to the management part of the plan.

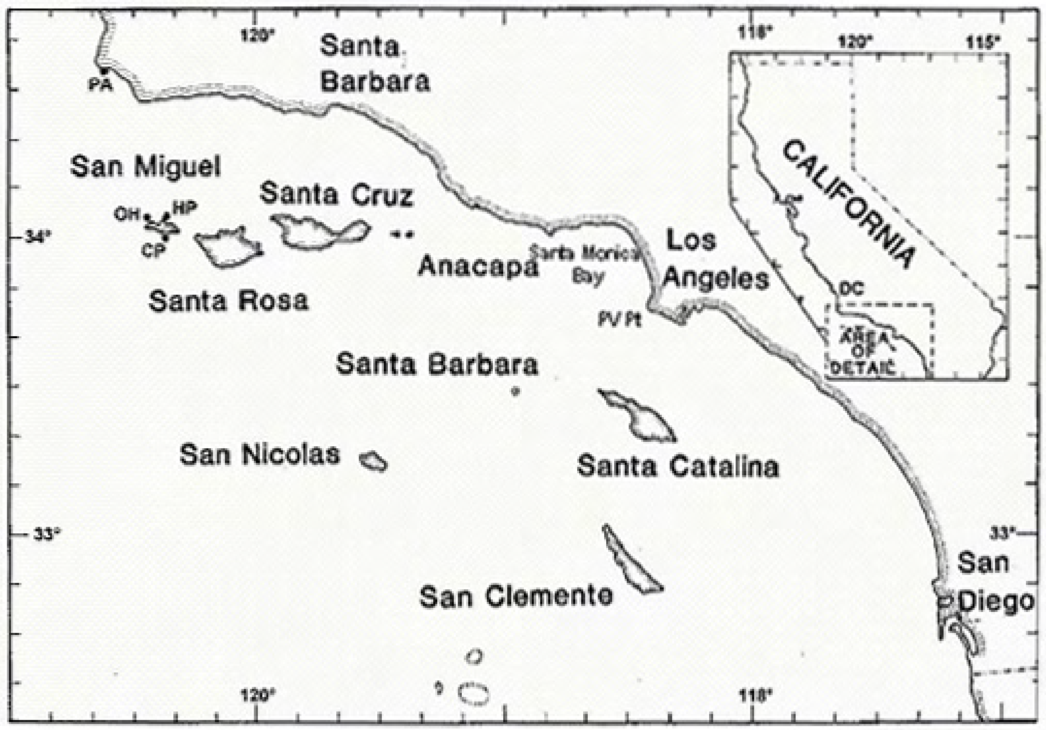
Recovery in the ARMP (CDFG 2004) includes a step wise procedure that will seek to accomplish the following recovery goals:

1. To reverse the decline in abalone populations that are in jeopardy of extinction

2. To establish self-sustaining populations throughout each abalone species historic range

3. To reach sustainable fishery levels in at least three-quarters of former ranges

To help organize and structure the recovery program to achieve the recovery goals for multiple abalone species over a large geographic area, the southern California area was divided into smaller units called key recovery locations (Figure 2). Key locations were identified for each abalone species where all recovery assessments and activities will occur. The central California coastal areas, while south of San Francisco, are excluded because presence of sea otters has precluded an abalone fishery.



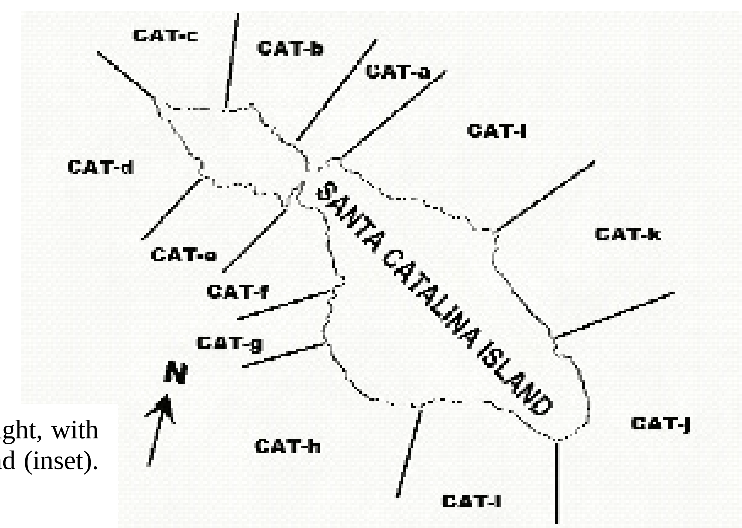


Figure 2. Map of southern California bight, with details of recovery sites at Catalina Island (inset). Each site is labeled CAT- a to l.

A qualitative resource assessment of abalone is being conducted at selected index sites (index sites are a selected subset of key locations), the number which varies by species. Each site must meet species specific size range requirements which are indicative of recent repetitive reproduction, population growth, and the occurrence of individuals that exceed minimum legal size (MLS).

The accomplishment of the criteria for the first goal triggers more intensive quantitative assessment of the index sites to assure that recovery has occurred more or less throughout southern California. While recovery at this stage would be dramatic, it would only likely be a reflection that the population is barely at the minimum viable population size, which is the point where the population can sustain itself through reproduction but there are not enough animals for a sustainable fishery. Random benthic transect surveys would quantify population density for one or more species and would be used to measure achievement of the second recovery goal, but this achievement would not trigger reopening a fishery. The third goal, is basically an extension of the second goal, with the addition of a higher abalone population density level, that when attained, would trigger consideration of a fishery by the Commission.

A major important benefit of these stepwise assessments is that initially, there is no initial necessity to conduct diver intensive, random, benthic transect surveys. Abalone populations are at extremely low levels (=rare) throughout southern California. Random transect surveys will yield zeroes at most sites, and would provide only reiteration that abalone populations are at low levels. Using a qualitative method in the first assessment yields more information; because the diver is not constrained to a specific transect area. Timed free ranging swims allow divers to inspect any appropriate habitat encountered during a dive. Any abalone found is measured and counted, and provides data that is specific to an index location. Another benefit is that timed swim surveys are not as stringent as random benthic transect surveys. In addition, any diver can be easily trained in the recording of data. This allows scientists to forge liaisons with recreational divers and other interested persons. In today's situation of under funded research, the incorporation of interested recreational and other divers into programs is a worthwhile activity that is satisfying to all parties involved.

In southern California, assessment is at the first stage. None of the abalones found in southern California can meet criteria that would shift assessment to a quantitative protocol. Here we will only be concerned with the first goal.

Methods

Site selection

Specific index sites have been established for each abalone species, and the number may vary by species (ARMP 2004). At the selected location, GPS position is typically recorded generally after the vessel is anchored. It is imperative that multiple surveys are not conducted at the same or overlapping areas. If live boat operations are used, the GPS position of each team at the start of the dive is recorded. Dive teams, usually pairs, choose a basic direction which would put them in appropriate abalone habitat, i.e., rocky bottom, sand channels, substrate relief, crevices, and an algal community. Divers swim the area around the chosen base direction always staying in appropriate habitat. Cracks and crevices are inspected, and smaller rocks on the bottom may be carefully over turned to search for cryptic individuals. If a rock is overturned, it must be carefully returned to its original position. We recommend that only experienced divers over turn rocks.

At about a third of the way through the dive, the dive team should move to one side of the base course, and then swim a reciprocal course back to the vicinity of the vessel. If live boating, the vessel should keep track of the divers.

Data collection and management

During the dive, both live abalones and empty shells (Figure 3), are identified and measured using a recording caliper (Figure 4) or standard calipers. The straight line maximum diameter of the shell is measured. Live abalone are not disturbed, but abalone shells found are returned to the vessel or can be identified and measured underwater. Each shell must be classified as old or fresh, as indicated by the luster and encrustation of the inside of the shell. Fresh shells are shiny without any encrusting organisms (Figure 3). Shells, particularly fresh shells, are used as indicators of likely abalone habitat. Live abalone and non-returned shells are marked with a forestry crayon, to indicate that data for that individual has been collected. Live abalone may be found alone, or in groups, defined as two or more individuals within a meter of one another. Groups are noted by the number of abalone in a group. A group is comprised only of abalone of the same species. The percentage of the abalone at a site (%in groups, Table 2), is an indicator of the ability of the abalone to reproduce. Since abalone need to be close together to effectively reproduce, the higher the percentage the more likely reproduction will occur (Allee et al. 1949, Babcock and Keesing 1999). We make the caveat that this is true only where there are higher numbers of abalone in the detected population, i.e., many individuals or groups.

Immediately after the dive, all data must be entered on prepared data sheets so that data is not inadvertently lost. The data collected includes basic information, i.e., Vessel, Date, Dive number (numbered consecutively for each diving day by dive teams), location, latitude and longitude of each dive. Dive specific information includes the diver's names, time in and out, search time, and depth. Each abalone, shell and groups are coded and entered. Every abalone must have species identification, a size, and a condition code. The data are archived in a computer data base for storage and analysis.

Data analysis

The primary use of the data collected is to determine if Criterion 1 (Broad Size Distribution) has been met at a location. To evaluate the resource condition two categories are established for each species of abalone. The first, 100 mm to recreational minimum legal size (RMLS), includes the emergent sublegal population that will eventually grow to legal size. The RMLS varies among species (i.e., RMLS for red, pink, green, white and black abalones are 178, 152, 152, 152, and 127 mm, respectively). The second category includes abalones greater than RMLS. The higher end of this category is the maximum known size for the species.

A third category includes sizes less than 100 mm, and represents the cryptic abalone population. Evaluating this segment of the population involves detailed habitat disruption and is not easily assessed. Data about this segment provides recent information about the population and any such data will be included in the analysis. However this data is not included in the ARMP evaluation. In the earlier stages of evaluation looking at the smaller sizes provides insight about recent reproduction and settlement trends. However, these abalone would not be expected to be seen for several years in the emergent population and are subject to high predation mortality.

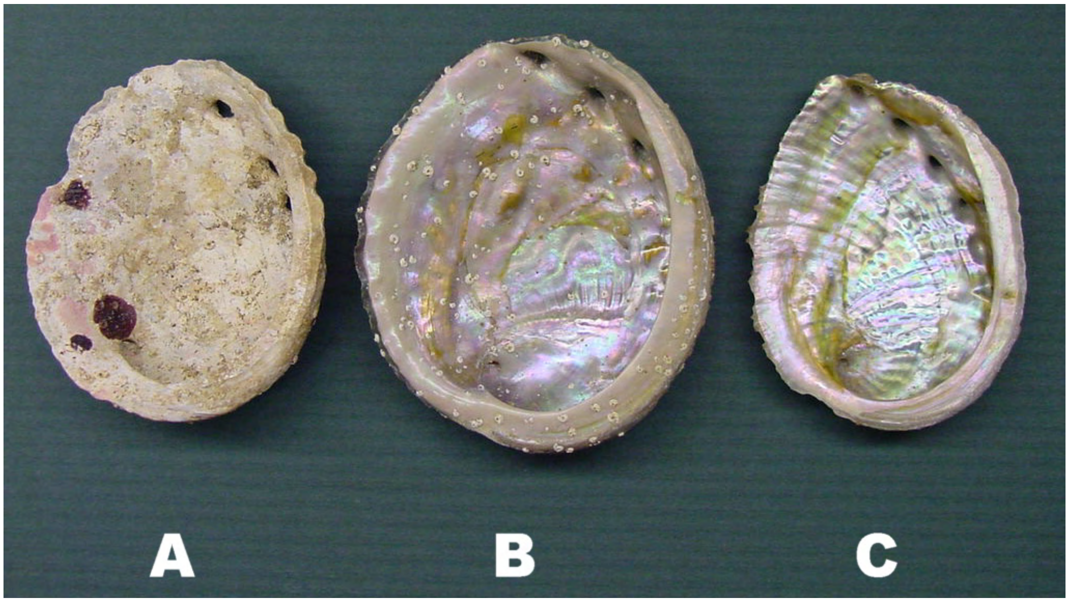


Figure 3. Abalone shells found during underwater transects. An old shell includes shells (A) that have no remaining nacreous (mother-of-pearl) layer, or has encrusting organisms growing on the shell (B). A fresh shell (C) has a clean shiny appearance.

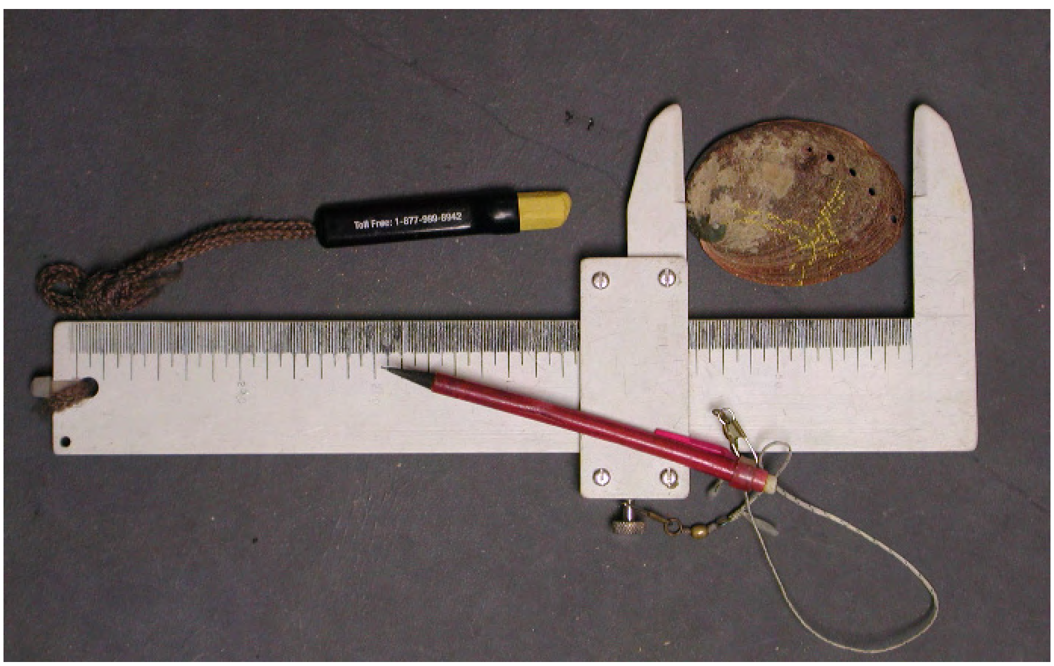


Figure 4. A recording caliper used to measure abalones underwater without the need to record every length. A mark is made on the caliper to indicate the size, which can be read and permanently recorded after the dive. The forestry crayon is used to mark the abalone to prevent subsequent re-measurement by another diver. Marks made on the caliper can be coded for different species.

Each category is further divided into 5mm groups. For instance, there are about 15 - 5 mm groups for red abalone in the emergent below legal group, (measuring 100 to 178 mm), and 24 – 5 mm groups in the larger category. The goal is to have at least one abalone occupy 90% of the first, and 25% of the second groups. When these size requirements are met at all the index sites, evaluation increases to a quantitative evaluation (Criterion 2).

Operational considerations

It likely will take many years to achieve completion of Criterion 1 goals for most abalones. The ARMP includes several ways to enhance recovery, but even with active enhancement, recovery will require a long term commitment. Current fiscal, personnel, and logistic constraints will require a considerable effort considering the size of the area of southern California. The first stage assessment does not include sophisticated scientific techniques. The actual data collection can be learned by virtually any experienced diver after a short instructional class that includes identification and location of abalones. Additionally, there is no long term commitment of the individual diver collecting the data. The actual data collection provides an excellent opportunity for involving knowledgeable divers in first stage assessment.

We have formed a partnership with the Long Beach Aquarium of the Pacific (AoP) to assess abalone populations in southern California, particularly at the southern Channel Islands. Both the California Department of Fish and Game (CDFG) and the AoP are American Academy of Underwater Science (AAUS) member organizations, and have recently joined together in a joint abalone assessment. CDFG biologists provided training classes on identification of abalones, abalone habitat, and the details of collecting and recording the data.

Results

Dive collection data

Since the beginning of the AoP/CDFG abalone assessment program in March 2004, 45 survey dives have been made at 23 locations primarily along the west end of Catalina Island. An additional seven dives were made to assess abalones in Santa Monica Bay and along the Palos Verdes Coast, a mainland peninsula north of Catalina Island (Figure 2). Eighteen AoP scientific divers have participated in at least one survey dive to date. This represents a significant effort in the assessment of abalones in southern California, an effort that could not have been accomplished by CDFG divers alone.

Table 1 presents the approximate locations of the dives, total search times, and the number of abalones found. There is also a calculation of the number of abalones found per hour.

Table 1. Results of abalone dive assessment surveys at Santa Catalina Island and Santa Monica Bay-Palos Verdes mainland coast during 2004. A dive includes the dive time and data for a two or three diver team. Time is total search time of the teams (in minutes) at a location. SCat – Santa Catalina Island, SMB – Santa Monica Bay, PVP – Palos Verdes Peninsula.

Date	Location	# dives	Time (min)	Green Abalone		Pink Abalone	
				no.	abs/hr	No.	abs/hr
31-Mar-04	SCat, Quarry	2	246	28	6.83		0.00
22-Apr-04	SCat, Arrow Point	4	396	8	1.21	4	0.61
22-Apr-04	SCat, Little Geiger	2	249	1	0.24		0.00
03-May-04	SCat, Emerald Bay	3	370	2	0.32	5	0.81
03-May-04	SCat, Blue Cavern	3	400	24	3.60	1	0.15
17-May-04	SCat, White Rock	2	206	4	1.17	2	0.58
17-May-04	SCat, Johnson Rock	2	230	24	6.26	1	0.26
27-May-04	SCat, Bird Rock	1	195	14	4.31	1	0.31
07-Jun-04	SCat, Bird Rock	3	399	23	3.46	3	0.45
07-Jun-04	SCat, Isthmus Reef	3	386	6	0.93	3	0.47
06-Jul-04	Scat, Isthmus Reef	1	180	2	0.67	1	0.33
06-Jul-04	SCat, Quarry east	1	192	10	3.13		0.00
20-Jul-04	SCat, Quarry east	1	116	3	1.55		0.00
20-Jul-04	SCat, Quarry east	1	140	3	1.29		0.00
20-Jul-04	SCat, Yellowtail Point	2	236	2	0.51		0.00
05-Aug-04	SCat, Iron Bound Cove	4	648	71	6.57	1	0.09
05-Aug-04	SCat, Star Bay	2	199	8	2.41	1	0.30
24-Aug-04	SCat, Cape Cortes	2	257	23	5.37	12	2.80
24-Aug-04	SCat, Lobster Bay	2	218	7	1.93	4	1.10
24-Aug-04	SCat, West End	2	277	24	5.20	1	0.22
06-Oct-04	SCat, Little Harbor	2	235	6	1.53	3	0.77
06-Oct-04	SCat, Little Harbor	2	232	2	0.52	4	1.03
17-Nov-04	Palos Verdes, Haggerty's	3	417		0.00	2	0.29
17-Nov-04	Palos Verdes, PV Point	3	363	3	0.50	2	0.33
17-Nov-04	Palos Verdes, Lunada Bay	1	141	1	0.43		0.00
17-Nov-04	Palos Verdes, Lunada Bay	1	141	1	0.43		0.00

Size distribution of live abalones

The abalones recorded at the dive locations were grouped together by key location, and the size frequency distributions were plotted and presented by area for green (Figures 5), and pink abalones (Figure 6).

Group sizes of live abalone

The groups of green abalone found are presented in Table 2. No groups of pink abalone were found. The range of percent in groups is broad (0 – 100%), but this is only an artifact of small sample size. Nevertheless, the occurrence of so many groups is a good sign of recovery.

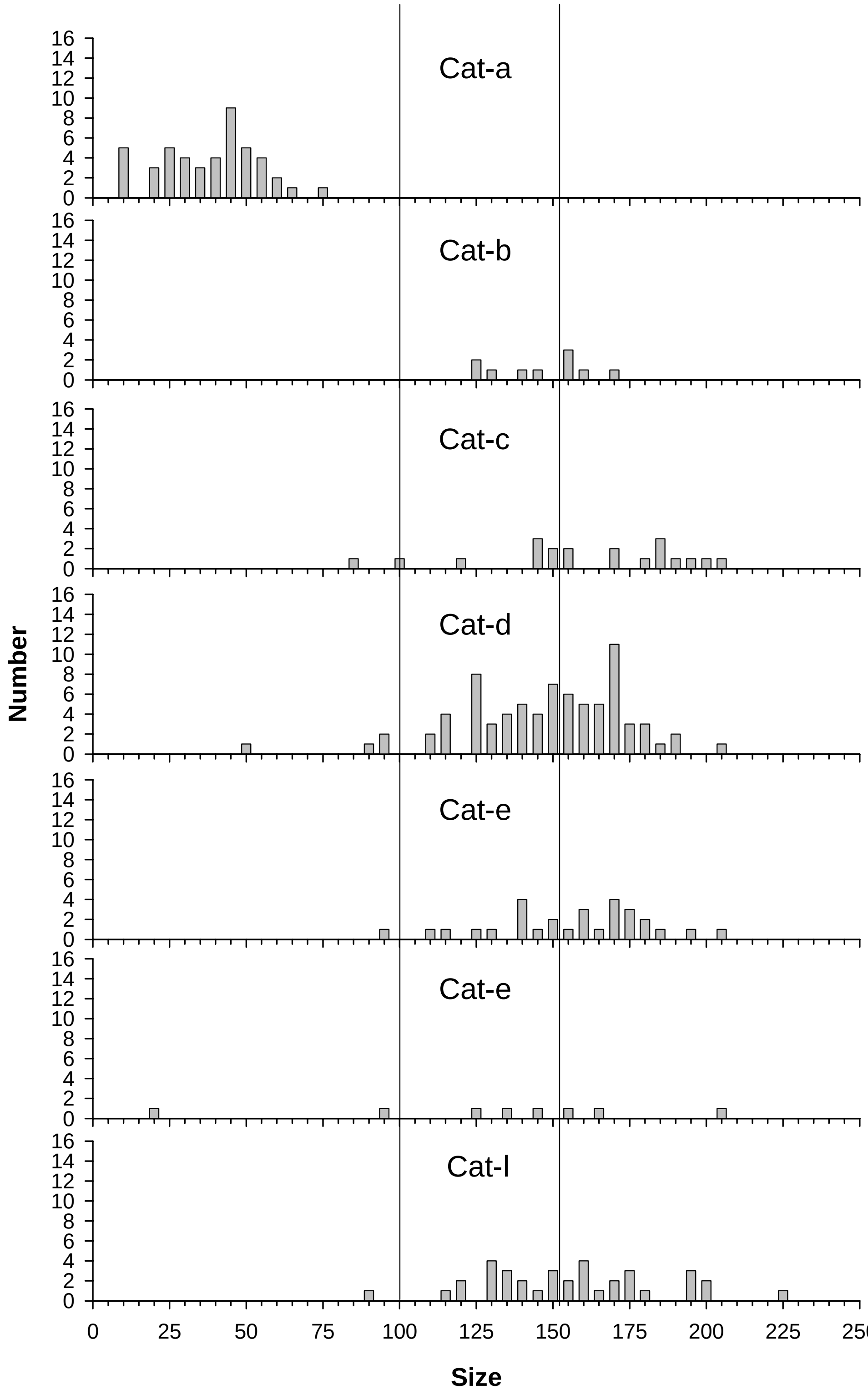


Figure 5. Green abalone size frequency at Catalina Island. The vertical line at 100 mm represents the approximate size at which green abalone become less cryptic. The vertical line at 152 mm was the recreational minimum size limit.

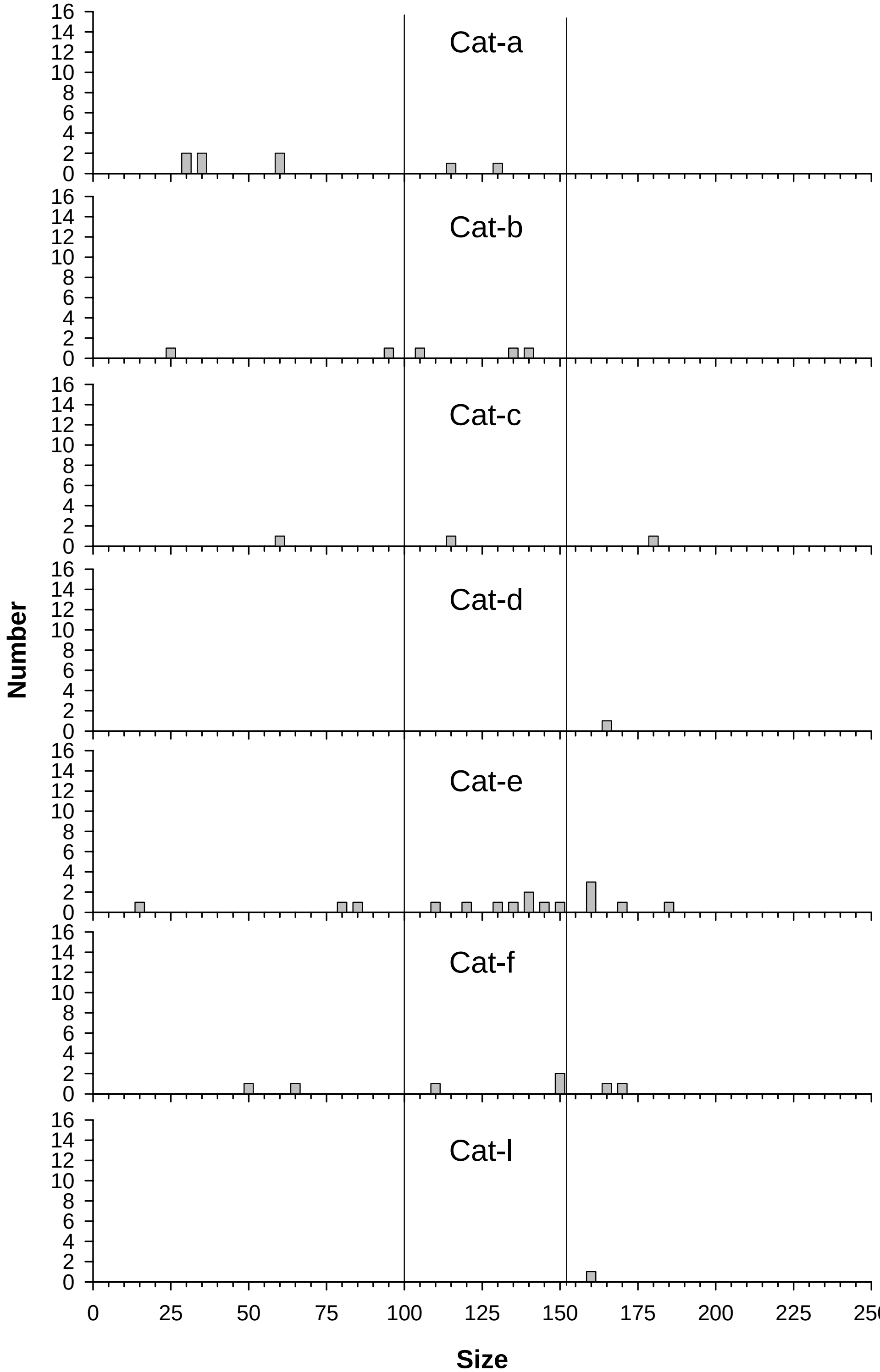


Figure 6. Pink abalone size frequency at Catalina Island. The vertical line at100 mm represents the approximate size at which pink abalone become less cryptic. The vertical line at 152 mm was the recreational minimum size limit.

Table 2. Size of groups of green abalone found during assessmentsurveys by location and the percentage of abalone in groups.

Location Date		Green abalone									
		Group size									% in
		No.	2	3	4	5	6	7	8	9	groups
31-Mar-04	SCat, Quarry		2	1					1		53.6
22-Apr-04	SCat, Arrow Point		1								25.0
22-Apr-04	SCat, Little Geiger										0.0
03-May-04	SCat, Emerald Bay	2									0.0
03-May-04	SCat, Blue Cavern	24	2	2		1					41.7
17-May-04	SCat, White Rock	4									0.0
17-May-04	SCat, Johnson Rock	24									0.0
27-May-04	SCat, Bird Rock	14	2	3							92.9
07-Jun-04	SCat, Bird Rock	23									0.0
07-Jun-04	SCat, Isthmus Reef	6									0.0
06-Jul-04	Scat, Isthmus Reef	28									0.0
06-Jul-04	SCat, Quarry east	8		2							60.0
20-Jul-04	SCat, Quarry east	1		1							100.0
20-Jul-04	SCat, Quarry east	3									0.0
20-Jul-04	SCat, Yellowtail Point	2									0.0
05-Aug-04	SCat, Iron Bound Cove	71	7	3	2	1					43.7
05-Aug-04	SCat, Star Bay	8		1							37.5
24-Aug-04	SCat, Cape Cortes	23	4	1	1						65.2
24-Aug-04	SCat, Lobster Bay	7	2								57.1
24-Aug-04	SCat, West End	24	4								33.3
06-Oct-04	SCat, Little Harbor	6	1								33.3
06-Oct-04	SCat, Little Harbor	2									0.0
17-Nov-04	Palos Verdes, Haggerty's	0									
17-Nov-04	Palos Verdes, PV Point	3									0.0
17-Nov-04	Palos Verdes, Lunada Bay	1									0.0

Discussion

The results of the CDFG/AoP abalone assessment program presented here are preliminary, as the program only began in March 2004. Nevertheless, this assessment will be mandated by the acceptance of the ARMP by the California Fish and Game Commission, and it will be extended to areas throughout southern California.

Cooperation between CDFG and AoP scientific diving programs has accelerated the assessment of abalone populations in southern California to a greater extent than CDFG divers could accomplish alone. Establishment of the program was facilitated in a large part because both CDFG and AoP were members of the American Academy of Underwater Sciences, and each had established scientific dive programs. The reciprocity afforded by the AAUS memberships, allows divers from both organizations to use each other's vessels to conduct diving operations. The AoP, which has a strong conservation ethic, was also interested in abalone from that point of view. This relationship provides an excellent opportunity for the interested non-scientist diver to become involved in a worthwhile State mandated survey of an important fishery species. It can also serve as a model for other projects which have been delayed by inadequate State and Federal funding. The results of the first year of the assessment were surprising. A total of 54 dives were made with a total of almost 113 hours of search time. During the dives 299 green and 30 pink abalones were found. The detection rate (abs/ hour) ranged from 0 to 6.83 for green abalone, and from 0 to 2.80 for pink abalone (Table 1).

The size distributions for the abalones at the various sites varied by site, but some locations had surprisingly broad distributions (Figures 5 and 6), and indication that reproduction has been occurring over the past few years. The occurrence of relatively large numbers of cryptic (< 100 mm) individuals was surprising, and constitutes a very good indication of natural recovery of green abalone. Even when there may be few individuals at a location, a broad size distribution is an indication that reproduction and subsequent growth has occurred.

Significantly higher numbers of green abalone were detected than pink abalone, i.e., 299 vs. 30, respectively. The pink abalone has a much broader depth distribution, 20 to well over 100 ft., perhaps the broadest of all California abalones. Green abalone is a shallow water species, just sub-tidal to about 20 ft., which includes less available habitat. The observed differences in the total numbers of the two abalones may be an artifact of the surveys being conducted at Catalina Island, which has a narrow rocky subtidal benthic substrate more conducive to green abalone. However, pink abalone was once common at Santa Catalina Island, where landings were higher than those for green (Burge et al. 1975). The differences in the numbers of each species found will have to be addressed after more surveys are conducted at Santa Catalina Island and locations elsewhere.

We are enthusiastic about the future of the CDFG/AoP abalone program. There certainly will be a need to continue the abalone program at Catalina, and at other areas on the mainland. Two other islands, Santa Barbara and San Clemente, once had good populations of abalones, and will need to be surveyed. When the need to move to the next level of evaluation for an abalone arises, the trained scientific diver base provided by the AoP will likely be called upon.

AoP already has liaisons with local universities, and these may soon provide opportunities for abalone research, and in other disciplines as well.

Acknowledgments

We wish to thank Peter Pehl, Long Beach Aquarium of the Pacific Dive Officer, who was instrumental in establishing the CDFG/AoP abalone assessment program. Also, the AoP research divers included, in alphabetical order: Arnold Abelson, Karen Elaine Bakunin, Dirk Bircham, Tom Boyd, Steve Conley, Don Dietrich, Erik Foresman, Mike Howard, Christine Light, Tracy Lumm, Marc Massari, Gary Sterling, Paul Watson, Charlie Winn, Diane Witmer, and Marjorie Wonham. We thank the Captains of the R/V Garibaldi, Mark Kibby and Ray Michalski. We also thank the reviewers for their helpful comments and suggestions. Both AoP and CDFG provided vessels and dive support for this program.

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The Ecology of Fishes on Deep Boulder Reefs in the Western Gulf of Maine (NW Atlantic)

Peter J. Auster[1] and James Lindholm[1,2]
[1]National Undersea Research Center and Department of Marine Sciences, University of Connecticut at Avery Point, Groton, Connecticut 06340
[2]Present Address: Pfleger Institute of Environmental Research, 901-B Pier View Way, Oceanside, California 92054

Abstract

Deep boulder reefs (DBRs) are found in the cold temperate waters of the Gulf of Maine at 50-100 m depth. Species composition and use of space resources by fishes on DBRs in Stellwagen Bank National Marine Sanctuary (SBNMS) was quantified during a series of dives using Deepworker 2000 one-person submersibles in 1999. Additional observations of fishes from SBNMS and adjacent sites in the western Gulf of Maine are included based on data collected during remotely operated vehicle (ROV) dives from 1993 through 2003. Fishes using reefs were classified as year round residents, seasonal residents, or transients (where migrant refers to fishes moving through a range of habitats within a landscape) based on period of use. Our observations demonstrate that fishes use the space resources of DBRs in much the same manner as fish taxa on shallow water reefs. That is, the vertical relief of reefs aids zooplanktivorous fishes in gaining access to increased flows that deliver prey, hard surfaces support invertebrate communities that serve as prey for scan-and-pick foragers, piled boulders provide deep crevices for shelter from predators and for reproductive activities of pair bonding fishes, and boulders provide flow refuges from tidal current flows. Strategies for use of one-person submersibles and ROVs for behavioral studies require trade-offs in terms of balancing piloting and research tasks. For example, point-count and behavioral scan methods were used when the submersible was stationary (parked) on the seafloor, allowing the operator to concentrate on piloting tasks when moving from station to station. Due to the need to constantly run thrusters on ROVs (due to a lack of variable ballast systems), fish census and behavior data were collected when first sighting individuals during strip transects in order to minimize the effects of reactions to an approaching vehicle.

Introduction

Deep boulder reefs are found in the cold temperate waters of the Gulf of Maine at 50-120 m depth and occur at or below the approximate boundary of Maine surface and intermediate water masses (Sherman et al. 1996). The reefs are discrete features composed of boulder size (i.e., minimum diameter of 256 mm) rocks and bounded by smaller gravel, sand or mud sediments and are distinct from outcrop features found elsewhere in the Gulf (e.g., see Auster2005). These deep boulder reefs (DBRs) are often found on the crests or slopes of topographic rises with sediments isolating patches of boulder-cobble. While some DBRs were formed as a result of iceberg rafting and subsequent deposition of boulders from melting, most were formed by linear mounding of boulders along lines of glacier movement with subsequent erosion of fine-grained sediments.

The regional fish fauna in the Gulf of Maine can be classified as resident, summer migrant, and winter migrant species along with species occasionally moving into the region on an irregular basis (e.g., intrusions from Gulf Stream and slope waters). Resident species are numerically dominant and migrant-occasional species are relatively rare at the regional scale (Auster 2002). At the scale of landscape features, such as Stellwagen Bank and adjacent banks and basins, species composition of fish assemblages were correlated with five groups of functionally equivalent habitats nested within landscape features (Auster et al. 1998). For example, habitats composed of sandy shell beds, sandy gravel, muddy sand, muddy gravel with attached sponges and partly buried boulders; mud, sandy silt; cerianthid anemone forest, burrowed mud; gravel and scattered boulders, sandy gravel ridges; and piled boulder reefs each exhibited unique species compositions.

Fishes that occupy reefs (biogenic or geologic in origin) and other complex habitats (e.g., kelp forests, seagrass meadows) utilize such features for shelter from predators and currents as well as to enhance prey capture (e.g., Ebeling and Hixon 1991). While much is known about the functional role that shallow reefs and other complex habitats play in relatively species rich systems, little is known about the role of deep reefs in cold temperate and boreal marine ecosystems.

Herein we present results from census and behavioral studies of fishes on DBRs at sites in the western Gulf of Maine (northwest Atlantic). In particular, we quantified patterns in species composition and use of space resources by fishes on DBRs in Stellwagen Bank National Marine Sanctuary (SBNMS) during a series of dives using a Deepworker 2000 one-person submersible in July 1999. Additional observations of fishes are included from SBNMS and proximate sites made during the course of remotely operated vehicle (ROV) dives from 1993-2003.

Methods

A Deepworker 2000 submersible (Figure 1) was used during five dives (13.25 hrs) in July 1999 to collect data on species composition and behavior of fishes on DBRs at SBNMS (Figure 2). During each dive the submersible was flown to a series of sites along reefs where, after settling to the seafloor, lights and thrusters were turned off for five minutes. After a quiescent period, lights were energized and a five-minute scan was made for species composition as well as behavior and habitat associations of each fish with particular reef structures. Data were collected from an 180^{o} arc in front of the submersible out to an estimated distance of 3 m at 49 stations (69-82 m depth). After each census, the submersible was flown to another site along each reef. Sector-scanning sonar aided in identification of locations to conduct each fish census (i.e., identify location of central and peripheral locations on DBRs). Measurements of ambient light was made during dives using a LiCor LI-192SA underwater quantum sensor mounted on the stern behind the hatch and LI-1000 data logger inside the submersible. Readings were taken with all light sources off. Values ranged from 87.5- 35.98 µ mols s^{-1} m^{-2}.

Figure 1. A Deepworker 2000 one-person submersible. Note the video and still camera at lower right. The sector-scanning sonar head is to the left of the hatch. A Li-Cor quantum light sensor to measure downwelling light was mounted astern of the hatch. The submersible used two 250 watt quartz and two 100 watt HID lights for illumination.

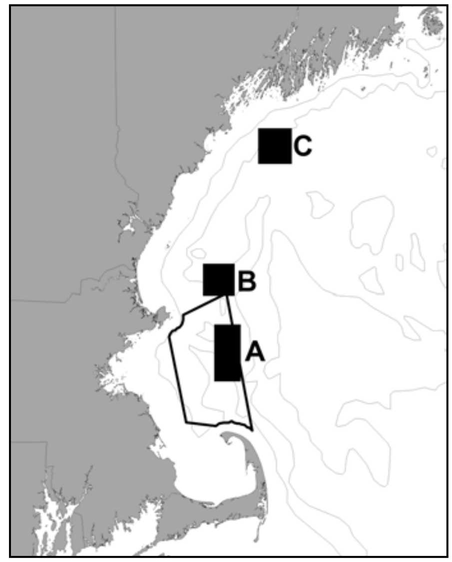

Figure 2. Location map of western Gulf of Maine region with boundary of SBNMS. Boxes indicate general dive locations (A = eastern SBNMS, B = Jeffreys Ledge, C = Edge of Bottom).

Species composition was based on total counts at each station (and expressed a percent relative abundance). Space resources on DBRs were described as follows: (1) a single layer of partially buried boulders (without crevices along the seafloor-boulder margin), (2) a single layer of boulders on a hard substrate such as gravel pavement or coarse sand such that crevices occurred along the sediment-boulder margin, and (3) piled boulders that produced deep crevices above the sediment-water interface. DBRs were isolated by cobble-pebble or sandy (i.e., flat or with sand wave or sand ripple surface textures) sediments. Generally, DBRs were composed of a combination of two or three of the reef types described above. Each fish was classified by behavior, based on a list of categories developed from *a priori* observations of fishes from earlier submersible and ROV dives. Behaviors and cues used for classification are listed in Table 1.

Additional observations of the distribution and behavior of fishes at DBRs from approximately 50-100 m depth are summarized here and were made during ROV dives from May-September in the western region of the Gulf of Maine region from 1993-2003. Total dive time at DBRs was 110.4 hrs and was conducted during the course of multiple projects (e.g., Auster et al. 1998, 2003a). The number of individuals of each species that were observed on and around DBRs is reported in each species account. When only presence-absence data were recorded, species were counted as single individuals. When notes indicated multiple individuals of a species but total counts were absent, sample size was quantified as simply two individuals, in order to avoid overestimates. Therefore, sample sizes are minimum estimates of the number of individuals of each species observed. Most dives were conducted within SBNMS but additional dives were conducted at sites on Jeffreys

Ledge and off Portland, Maine. Dives were conducted primarily during daylight hours using a variety of vehicles (i.e., MiniRover MkII, Phantom S2; and *Kraken*, a highly modified MaxROV MkI).

Table 1. Behavior categories and descriptive cues used for classification.

Behavior	**Description**
Station-keeping swimming	Maintaining position over a seafloor feature using active fin movements.
Station-keeping Cover	Maintaining position behind or alongside structure using active fin movements.
Station-keeping on bottom	Direct contact with or adjacent to structure using little or no fin movements to maintain position (e.g., resting on bottom behind boulder)
Scan-and-pick feeding	Active search and bite behaviors on rock and sediment surfaces
Ram feeding	Swimming directed at mobile prey and either consumption or attempted consumption with mouth open during forward movement.
Ambush feeding	Stationary predator using rapid opening of mouth to draw prey into buccal cavity.
Active foraging	Swimming pattern suggesting search for prey (multiple changes in direction and attitude) with no attempted acts of predation.
Continuous swimming	Directed swimming in single direction with no movements directed at obvious prey and no attempts at predation.

Species addressed in this study are: Acadian redfish (*Sebastes fasciatus*), Atlantic cod (*Gadus morhua*), Atlantic wolfish (*Anarhichas lupus*), cunner (*Tautogolabrus adspersus*), cusk (*Brosme brosme*), haddock (*Melanogrammus aeglefinus*), longhorn sculpin (*Myoxocephalus octodecemspinosus*) including other unidentified cottidae, ocean pout (*Zoarces americanus*), pollock (*Pollachius virens*) sea raven (*Hemitripterus americanus*), and silver hake (*Merluccius bilinearis*). Skates (rajidae) were also observed on DBRs and are discussed as an overall taxonomic group. Species were classified as year round residents (on yearly time frames), seasonal residents, or transients based on our observations and published reports. Other taxa (i.e., alligatorfish *Aspidophoroides monopterygius*, bluefish *Pomatomus saltatrix*, daubed shanny *Lumpenus maculatus*, four-beard rockling *Enchelyopus cimbrius*, goosefish *Lophius americanus*, hagfish *Myxine glutinosa*, lumpfish *Cyclopterus lumpus*, red and white hake *Urophycis* spp., snake blenny *Lumpenus lumpretaeformis*, witch flounder *Glyptocephalus cynoglossus* and other pleuronectids) were observed around DBRs but were associated with surrounding sediments and we did not observe interactions of these taxa with reef fauna.

Results

Behavioral Census using the Deepworker 2000 Submersible - 1999

Census stations were primarily located at reefs composed of a central piled boulder habitat with an apron of partially buried boulders and cobble and surrounded by finer grained sediments (Figure 3).

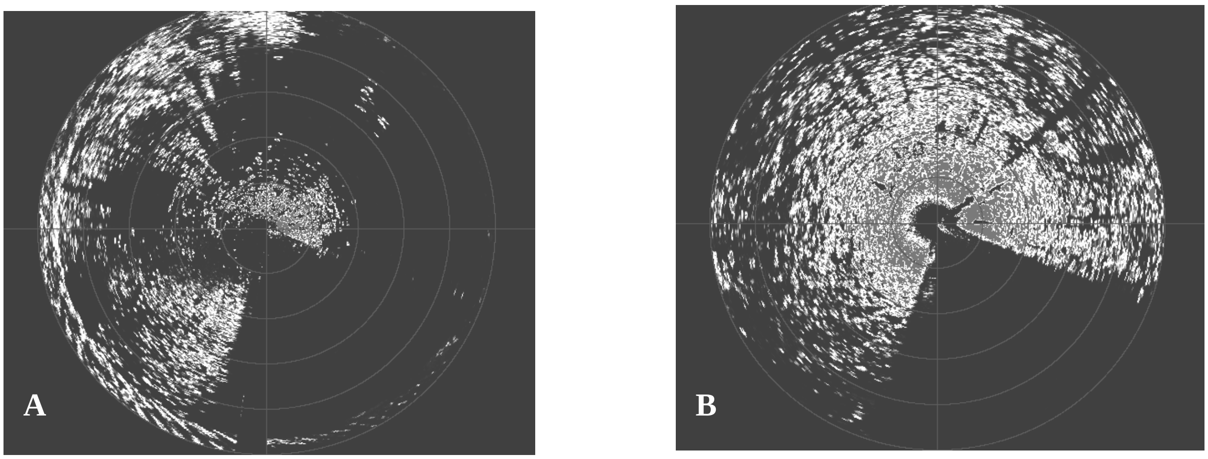

Figure 3. Sector-scanning sonar images illustrating acoustic reflectance (as a proxy for complexity) of (a) central piled boulder habitat (80 m radius) and (b) partially buried boulder sites (50 m radius) along the reef apron. Dimpled appearance of the acoustic records indicates irregular boulder surfaces. Note fewer acoustic shadows in b versus a, indicating less topographic relief. Sonar record based on data from a 675 kHz transducer.

Species composition and abundance, as well as patterns of behaviors, varied between piled boulder central reef habitats and lower profile partially buried boulder habitats along the reef apron (Figures 4 and 5). Acadian redfish and cunner were the numerical dominants on reefs. Note that the abundance of cunner increased in the areas of reefs composed of partially buried boulders. As these areas were generally found on the apron of reefs, where hard substrates graded into finer grained sediments, the location of these sites was concordant with a decrease in height above the seafloor when compared to piled boulder habitat. The differences in composition are also correlated with variation in distance to areas of accelerated flows over the tops of reef structures (maximum velocities were approximately 35-40 cm s^{-1}). Redfish were generally observed to exhibit station-keeping behaviors in the water column above reef structures while a smaller number of individuals were observed in crevices within the reef. Other than cunner, no other taxa were also observed station keeping in the water column above the reef in areas of piled boulders. However, this pattern changed along the reef apron where multiple species, although few in number, were observed station keeping above boulders, presumably in areas of reduced flows. Also, more individuals were observed station keeping on the seafloor and on boulders along the reef apron region than in the central piled boulder area. Cunner abundance increased along the apron section of DBRs where they primarily exhibited scan-and-pick feeding behavior. In general, beyond the dominant Acadian redfish and cunner, other species on reefs were patchy in distribution and low in abundance during these census dives.

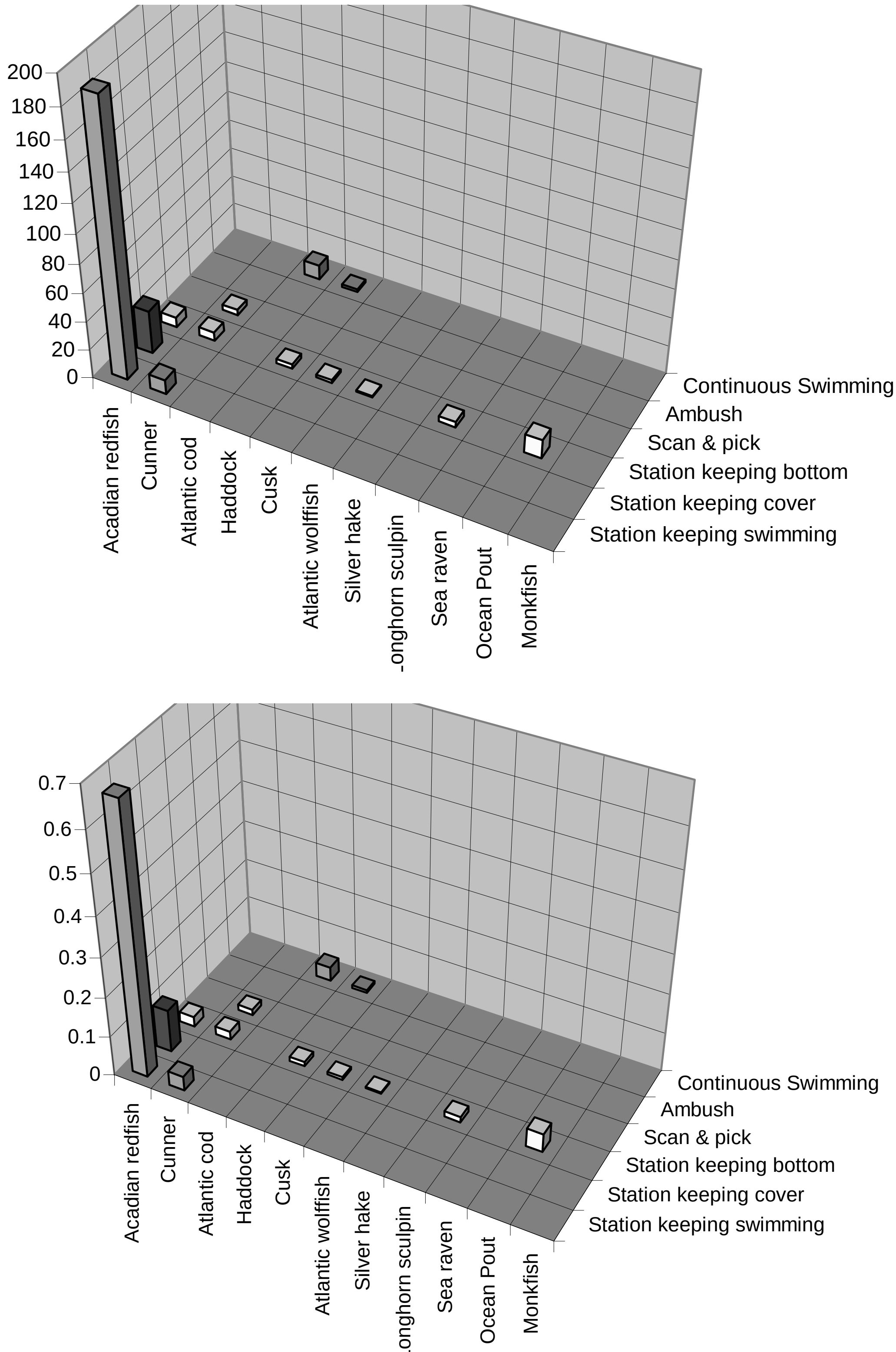

Figure 4. Summary of census data (i.e., species composition and behavior classification) from piled boulder sites on DBRs showing patterns based on (a) total numbers and (b) relative abundance. Behavior categories are described in Table 1.

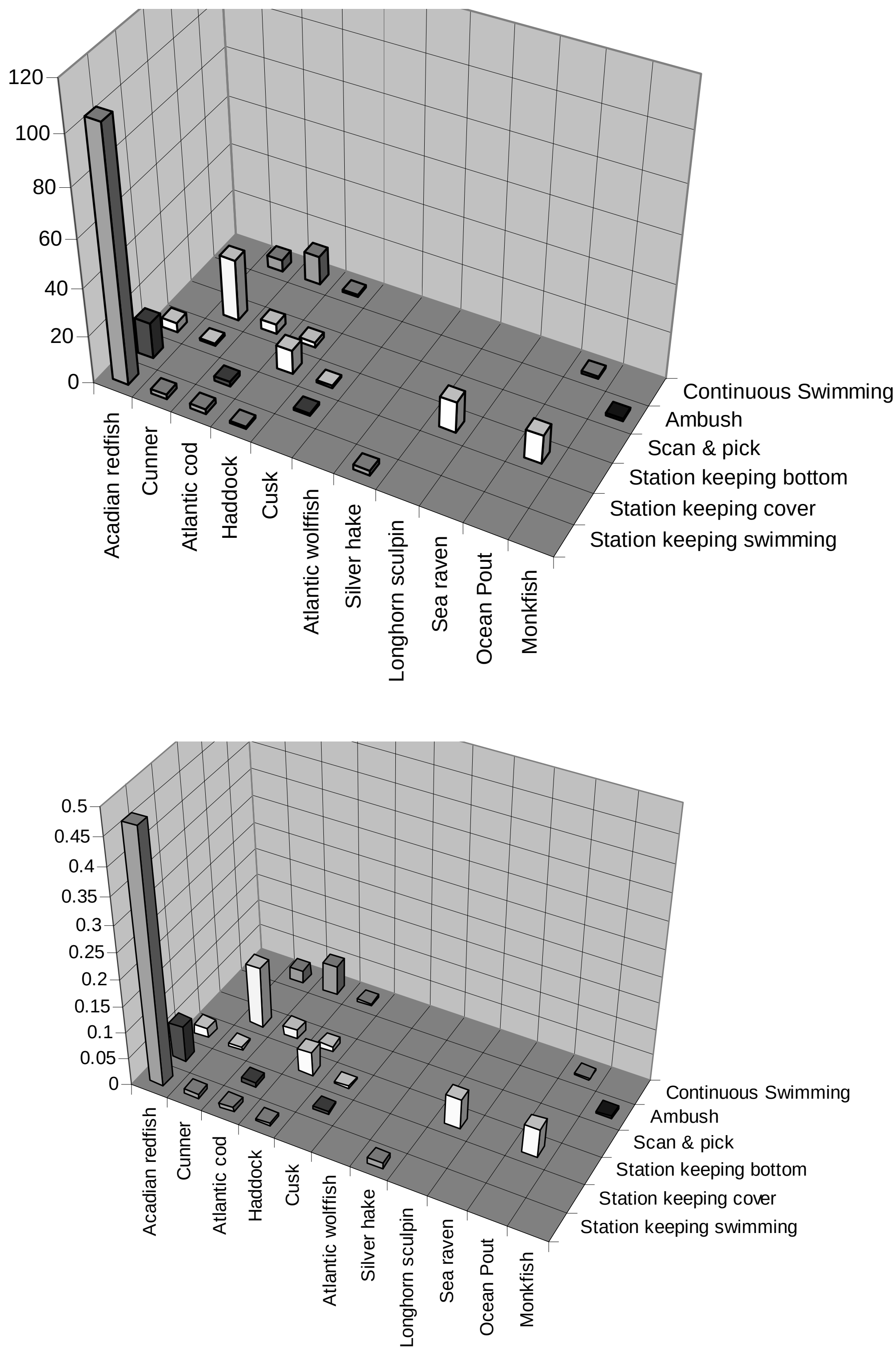

Figure 5. Summary of census data (i.e., species composition and behavior classification) from partially buried boulder sites on DBRs showing patterns based on (a) total numbers and (b) relative abundance. Behavior categories are described in Table 1.

Species Accounts from ROV Observations – 1993-2003

Here we summarize general and unique observations of the habitat related behaviors of a range of taxa associated with DBRs in the western Gulf of Maine.

Acadian redfish (n=3234)

Early and late juvenile Acadian redfish used DBRs for cover and access to increased current flows near the crest and above the reef, where drifting zooplankton prey can be encountered at higher rates (Figure 6). Early juvenile redfish are found primarily on DBRs while late juveniles are found on both DBRs and amongst dense aggregations of cerianthid anemones (Auster et al. 2003). These life history stages (up to age 5-7 yrs) can be considered as year round residents with generally small home ranges (Kelly and Barker 1961), although some number of late juveniles are assumed to emigrate from DBRs. Observations from 1993-2003 are consistent with the pattern of space resource use found in the 1999 submersible dives. That is, Acadian redfish were the numerical dominant teleost on DBRs and were observed maintaining station in the water column above piled boulder habitats. When disturbed by the close approach of underwater vehicles, individuals moved towards the substrate and either entered a crevice, or rested directly within a small depression or alongside an attached invertebrate such as a sponge on a boulder surface, or rested on the sediment substrate alongside the sediment margin of a partially buried boulder (Figure 7).

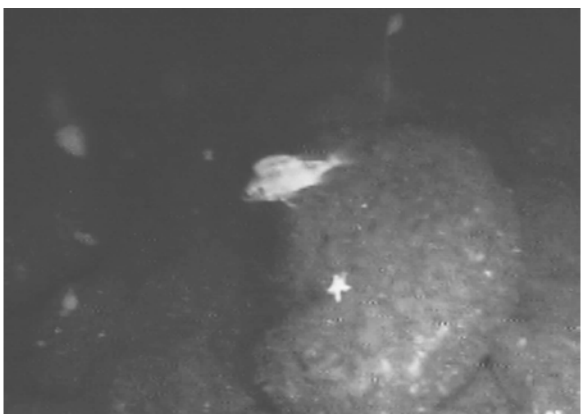

Figure 6. Acadian redfish station keeping in water column above piled boulder habitat.

Figure 7. Acadian redfish seeking shelter within a boulder crevice.

Atlantic cod (n=134)

Juvenile and adult Atlantic cod have been observed exhibiting scan and pick type foraging behavior, apparently in search of invertebrate prey on boulder surfaces and on the sediment surface between boulders. Late juvenile and adult Atlantic cod (based on size estimates) were observed arriving and leaving reef areas and were never consistently observed within the area traversed during underwater observations, suggesting they are transient visitors to individual DBRs. However, tagging studies of Atlantic cod demonstrate that a portion of local populations are resident (at the scale of kilometers) on boulder and gravel features while others are transient and move significant distances within seasons (Robichaud, D. and G.A. Rose. 2004). Acoustic tagging studies at SBNMS also demonstrate this pattern of cod movement on gravel (Lindholm and Auster 2003) and on DBRs (Lindholm and Auster,

Figure 8. Atlantic cod exhibiting scan and pick foraging behavior.

unpublished data). Such tagging studies are not inconsistent with our visual observations and suggest that resident individuals exhibit a daily ambit that includes, but is not exclusive to, DBRs. The rate and location of a fish's return to a DBR following a departure is unclear. Early juvenile Atlantic cod (0+ size classes) have also been observed along the small boulder and cobble margins of DBRs. These individuals would hide amongst the cover provided by the rocky substrate and epifauna when disturbed. Therefore, we classify Atlantic cod as both transient and resident components of the DBR fish fauna.

Atlantic wolffish (n=19)

Single and paired Atlantic wolffish were observed in crevices of DBRs. All fish used crevices under and between boulders along the sediment-boulder margin. Shell debris, from both bivalves and crustaceans, was scattered at crevice entrances and is evidence of central place foraging activities. Pairs of Atlantic wolffish were assumed to be mating pairs, suggesting movement of at least some individuals from other parts of DBRs or immigration to particular DBRs from other habitat types. In this species males provide parental care of eggs (Keats et al. 1985). Individuals in crevices were also observed to have exhibited recent tooth loss in the July-August period (Figure 10). Tooth loss is an annual process that is an adaptation to wear and breakage due to feeding on hard shelled prey. Patterns of long-term use of particular crevices by individual Atlantic wolffish are unclear. Keats et al. (1985)

Figure 9. Atlantic wolfish at crevice entrance along boulder-sediment margin.

Figure 10. Atlantic wolfish at crevice entrance showing lost teeth along lower jaw and several partially attached teeth along upper jaw. Note crushed shell around entrance that is indicative of central place foraging.

suggest that Atlantic wolffish reduce feeding or fast for several months during the period of mating, brooding and tooth replacement. The extent of shell debris in front of crevices suggests that occupancy had extended for some significant period (i.e., weeks-months?) prior to fasting. Atlantic wolffish have also been observed far from DBRs so we assume that some individuals are either transient or move between reefs. Given that mating is seasonal and requires crevices for brooding eggs, we classify Atlantic wolffish as seasonal residents of DBRs.

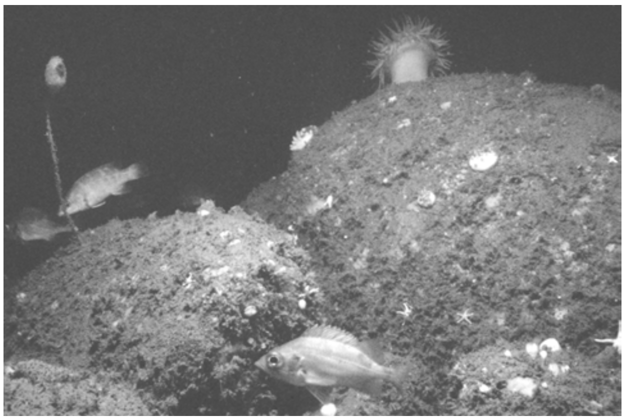

Figure 11. Cunner (left) and Acadian redfish co-occur along the margins of DBRs in areas of partially buried boulders.

Cunner (n=1170)
Cunner are primarily scan and pick benthivores. In shallow waters cunner disperse to seasonal habitats (e.g., eelgrass, macroalgae, mussel beds) from perennial habitats are occupied year-round (Olla et al. 1979). Given that there are no seasonal changes in the structural attributes of DBRs (i.e., no seasonal patterns of macroalgal growth and loss), that individuals of this species have limited home ranges, and that most DBRs are isolated, we classify cunner as year round residents on DBRs. Observations from 1993-2003 are consistent with the pattern of space resource use found in the 1999 submersible dives. That is, cunner are primarily found along the margin of reefs where vertical relief is lower than the central reef structure, current flow is reduced, and some boulders have small crevices along the boulder-sediment margin while others are partially buried and only provide shelter from flow (Figure 11). Movement of cunner through the reef complex (i.e., when not foraging) is generally close to the substrate and around boulders rather than over the tops, unless individuals are exhibiting scan-and-pick feeding. Cunner have been observed swimming through and foraging amongst dense epifauna attached to boulders. It is not clear if such behavior is random or purposeful in order to enhance predation on particular prey or for cover from predators while foraging.

Cusk (n=32)
Individual cusk were observed singly emerging from reef crevices and their distribution was patchy in areas where they were abundant. That is, cusk were found on some reefs in higher abundance than others (e.g., at one reef 4 cusk were observed emerging from reef crevices along an approximately 20 m linear distance) and were observed singly or not at all on other reefs. There was no obvious physical or biological factor to explain this patchiness in distribution. Cusk generally used crevices that were elevated above the seafloor (i.e., in areas of piled boulders; Figure 12) but used crevices under and amongst boulders at the sediment-boulder margin to a lesser extent. Cusk were observed emerging from crevices and stalking both cunner and early juvenile Acadian redfish, suggesting that reefs provide cover as well as proximate prey (Figure 13). Cusk are generally associated with complex habitats. Goode (1884) reported that fishermen found that cusk were easily fished out on newly discovered

ledges and only after leaving an area for a period of years would catches return to previous levels. Further, there is no historic or recent data to suggest that cusk exhibit any type of seasonal movement patterns. This suggests that cusk are resident to particular banks and ledges and we classify them as year-round residents of DBRs.

Figure 12. Cusk emerging from crevice in piled boulder habitat.

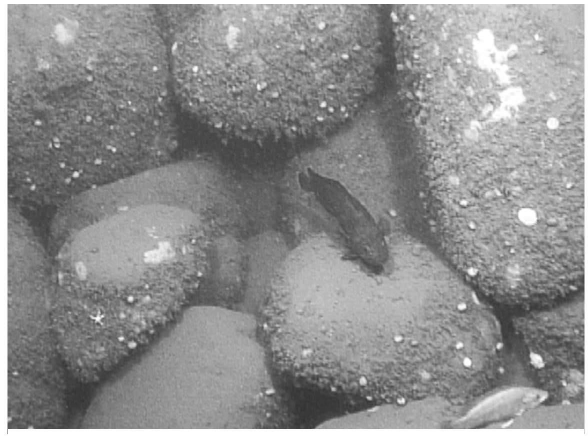

Figure 13. Cusk stalking a cunner. Cusk have also been observed to stalking and chasing juvenile Acadian redfish.

Haddock (n=28)

Haddock were observed station-keeping on bottom adjacent to partially buried boulders as well as boulders and cobble with large globular sponges along the margins of DBRs. Haddock have also been observed using isolated boulders and cobble with erect sponges in landscapes with much reduced spatial complexity (i.e., sand and mud landscapes) and suggests they use such structures as a refuge from flow. Our observations, as well as limited data on acoustically tagged haddock in SBNMS (Lindholm, unpublished data), suggest this species is a transient visitor to DBRs.

Figure 14. A haddock station-keeping on bottom on the downcurrent side of a partially buried boulder.

Figure 15. A haddock station-keeping on bottom using globular sponges as a flow refuge. Sponges were attached to cobble size rocks. Such habitat is used by haddock in a manner similar to use of boulders as a flow refuge.

Figure 16. A longhorn sculpin stationed on the top of a boulder surface along the margin of a DBR.

Longhorn sculpin (n=232)
Longhorn sculpin were generally observed along the periphery of DBRs (i.e., on boulder surfaces, on fine grain sediments amongst boulders, or proximate to the apron and oriented towards the discrete edge of reefs). As an ambush predator, longhorn sculpin were positioned to prey on fishes moving amongst boulders in the apron region of DBRs (Figure 16) or emerging from the reef proper and extending their foraging ambit over finer grained sediments. Longhorn sculpin are classified as year-round residents of DBRs.

Ocean pout (n=236)
Ocean pout have been observed singly in crevices of DBRs, on the sediment surface in the open between boulders, and as pairs within crevices. Paired ocean pout are assumed to be mating pairs. In this species females provide parental care of eggs (Keats et al. 1985). As with wolffish, due to uncertainties in patterns of movement, but with clear knowledge of reproductive habits, we classify adult ocean pout as seasonal residents of DBRs. Fishes used reef morphologies that have crevices or allow burrowing along sediment-boulder margins. We have not seen pairs in deep crevices within piled boulders. During an afternoon ROV dive on 28 July 1997, a pair of ocean pout was observed within a burrow along the boulder-sediment margin. Upon approach of the ROV to the burrow, the male exited the burrow (the determination of sex was based on the larger width of the head in comparison to that of the fish remaining in the burrow, and the pattern of larger males in mating pairs of this species; Keats et al. 1985) and faced the ROV with gill plates flared and pectoral fins spread wide which propped the head up off the seafloor. The female remained in the burrow entrance with gills flared and pectorals spread as well, essentially blocking the entrance. The male exhibited high frequency head and jaw movements (suggesting sound production) and then moved to block the burrow entrance with his body length-wise across the entrance. This male then oriented to back into the burrow but ultimately moved to an area adjacent to the den entrance. The female retreated towards the back of the burrow and retracted her pectorals to her sides and dropped her head to the seafloor. A second smaller satellite male(?) remained in proximity of the burrow but did not interact with the resident male or female. A third and larger male then approached the den and partially blocked the entrance. The female moved forward and blocked the other side with pectoral fin spread (Figure 17). The resident male approached the larger satellite male with jaws wide open, apparently in challenge for den occupancy (Figure 18). The larger satellite male then opened his jaws and, locking jaws with the resident, pushed the resident away from the den entrance (Figure 19). The resident male retreated away from the burrow. The larger male also approached and chased the smaller male. After several encounters with the resident male, apparently to establish dominance, the largest male blocked the burrow entrance with his body lengthwise and with head propped up on flared pectoral fins (Figure 20). The male then backed into the

burrow and the resident female remained. These interactions took place over a period of approximately 33 minutes. This single observation of a contest between a resident and satellite male for a burrow with a resident female suggests that ocean pout have complex mating systems that involve pair bonding and satellite males that take advantage of behaviors of resident males. The arrangement of boulders within the matrix of sand-mud sediments may mediate the distribution of mating pairs as well as satellite males and result in variation in the level of such interactions. No mating pairs of ocean pout have been observed during other seasons although this species has been observed on DBRs as well as in other habitats with patchy structures (e.g., isolated boulders, shell, and cerianthid anemones in sand and mud).

Figure 17. Female ocean pout (left) partially blocking den entrance with pectoral fins flaired and head propped. A satellite male (right) with body parallel to den entrance and partially blocking other side after resident male left den.

Figure 18. Resident male (left) challenging satellite male (larger and at right) with jaw spread.

Figure 19. Both males locked jaws and the satellite male pushed the resident to the left, away from the den entrance.

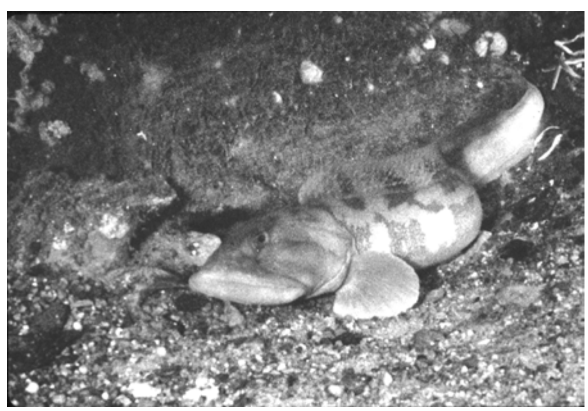

Figure 20. The larger satellite male blocking the den entrance, with at least two males including the former resident, in close proximity. This male ultimately entered the den with the female remaining.

Pollock (n=108)
Pollock form aggregations and schools above boulder reefs, feeding on drifting zooplankton and have also been observed to search just above reef surfaces for prey. Swimming just over reef surfaces and amongst emergent fauna that provide shelter for various shrimp taxa (e.g., pandalid shrimp) may cause potential prey to exhibit escape responses, exposing them to pollock and enhancing rates of prey capture. Pollock are classified as transient predators on DBRs.

Sea Raven (n=22)
Sea raven, like longhorn sculpin, exhibit ambush predation tactics. Sea raven have been observed resting on the tops of boulders along the reef apron. Several individuals were observed to swim and orient their resting attitude towards groups of fishes (i.e., cunner and Acadian redfish) amongst boulders. Sea raven are classified as year round residents of DBRs.

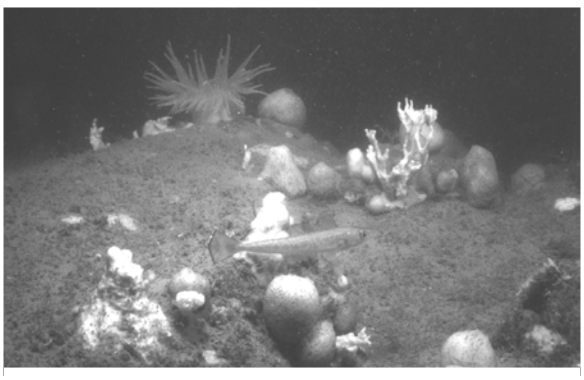

Figure 21. A silver hake foraging amongst attached epifauna on top of a boulder.

Silver hake (n=31)
Juvenile silver hake were observed at high densities in mud habitats bordering DBRs. Silver hake were also observed resting on boulder surfaces and exhibiting ambush predation as well as individuals swimming at various headings indicative of active foraging behavior. Swimming by silver hake took place in the water column above the reef as well as amongst the structures provided by epifaunal invertebrates on boulder surfaces (Figure 21). Swimming and foraging amongst patches of epifauna may expose invertebrate prey (e.g., shrimp) through flight reactions or serve as cover for predators. However, it is not clear if such behaviors are simply random or by preference. Owing to the adjacent mud habitat as the primary habitat of silver hake in this area, this species is classified as a transient predator.

Rajidae (n=25)
Skate were observed along the margins of reefs and swimming over and around boulders on reef margins (Figure 22). This orientation and behavior suggest that skates may prey on fish and crustaceans associated with DBRs. Nocturnal torpor of cunner as well as increased foraging activities by reef associated decapods during this period may make DBRs an important foraging habitat for skates.

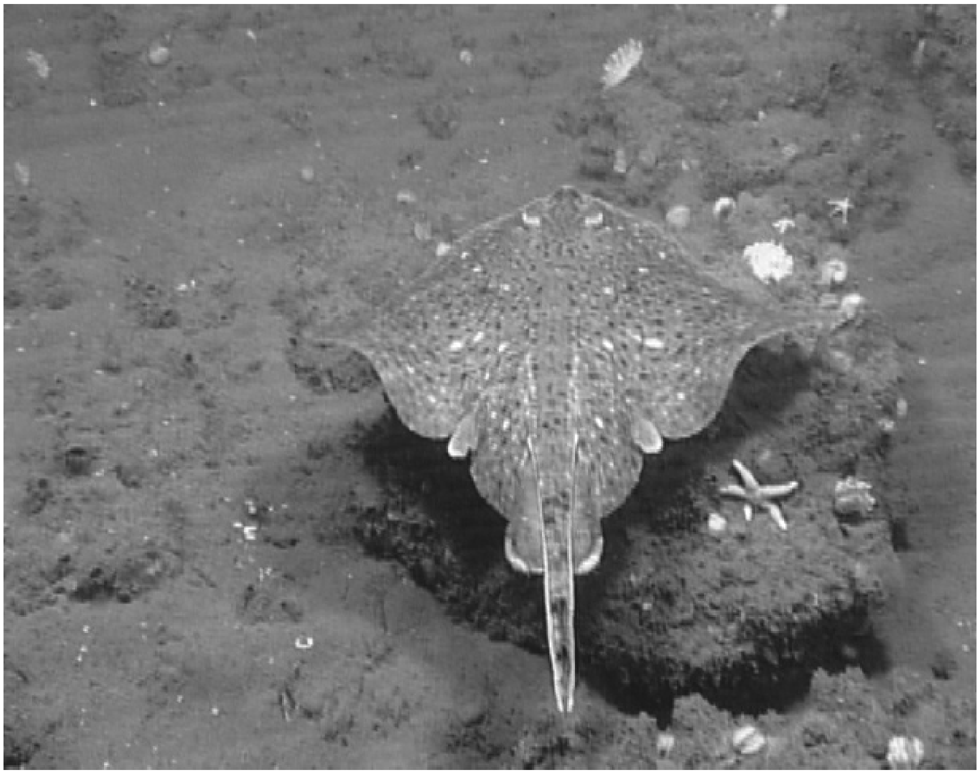

Figure 22. A skate (winter skate *Raja ocellata*?) foraging along the margin of a DBR.

Discussion

Demersal fishes in the Gulf of Maine have a range of affinities with DBRs. Some are year-round residents (i.e., either obligate throughout their life histories or during particular life history stanzas), some are seasonal residents (e.g., spawning), while the remainder are transients. Table 2 summarizes our assignment of residency status of fish species and suggests that the DBR fish community is highly dynamic in space and time. Fifty percent of the fishes associated with DBRs are considered year-round residents. While this does not necessarily mean that individuals remain year-round on particular DBRs, it does suggest that particular taxa are represented within the community throughout the year. Only two species are considered seasonal residents (i.e., for pair-bonding, mating and egg brooding) and the remaining are transients. Only Acadian redfish and cunner are numerically dominant. Acadian redfish are zooplanktivores and link secondary production to DBRs. Cunner are primarily benthic invertebrate predators and likely are a significant factor controlling patterns of invertebrate community structure and diversity. The other taxa observed at DBRs have a range of trophic requirements. It is noteworthy that both Atlantic cod and cusk are the only resident taxa that are, in part, piscivorous. Other piscivores in the Gulf of Maine fish community are wide ranging and are not known to exhibit small-scale habitat affinities.

Our observations demonstrate that fishes use the space resources of DBRs in much the same manner as fish taxa on shallow water reefs. That is, the vertical relief of reefs aids zooplanktivorous fishes in gaining access to increased flows that deliver prey, hard surfaces support invertebrate communities that serve as prey for scan-and-pick foragers, piled boulders provide deep crevices for shelter from predators and for reproductive activities of pair bonding fishes, and all boulders provide flow refuges. For example, Acadian redfish were dominant at the crests of reefs where accelerated flows deliver zooplankton prey and shelter sites (i.e., interstitial spaces between boulders) are proximate. Cunner abundance increased along reef margins where flow rates are reduced and may aid in maneuvering to a larger area for scan-and-pick foraging (Auster 1987). Wolffish and ocean pout used crevices along boulder-sediment margins that provided closest access to macro-invertebrate prey (e.g., crabs, scallops) while cusk used crevices throughout reef structures, perhaps for access to both fish in the water column over reefs and invertebrate prey on the seafloor.

Patterns of space resource use by fishes on DBRs may be mediated simply by patterns in habitat selection. However, the role of direct or interference competition within and between species remains to be determined. Processes that govern such interactions are a function of species abundances so variations in population size for each of the component taxa may alter the importance of particular processes. For example, we would hypothesize that interference competition for crevice resources between Acadian redfish and cunner may be intense when populations of both species are high. While Acadian redfish appear to use a variety of shelter types on a facultative basis, cunner are obligate small crevice users during nocturnal periods of torpor. In addition, competition for deep crevices between Atlantic wolfish, cusk, and ocean pout may also increase during periods of locally high abundance, such as during periods of mating and egg brooding.

Future work is needed to assess residency times of individuals, daily and seasonal ambits, demographic patterns on seasonal time scales (especially for new recruits and for spawners), and trophic linkages within and external to DBRs. Such information is critical for understanding the functional role of such habitats. For example, if a species (e.g., cusk) is distributed as a series of metapopulations at the scale of individual DBRs or multiple DBRs on a single bank or ledge, then high local fishing mortality can have severe consequences on populations and have cascading effects through the trophic web of DBRs.

The invertebrate epifauna on DBRs provides a scale of spatial complexity nested within that provided by the underlying geological framework. However, the role that such complexity plays in mediating the distribution and abundance of reef fishes is unclear. In habitats with less complex underlying geology (e.g., sand, cobble), invertebrate cover has been shown to provide shelter from predators and increase survivorship (Tupper and Boutelier 1995, Lindholm et al. 1999). Further, complex surface topography provides refuges from flow, that reduce the physiological requirements for station-keeping, and have been shown to mediate fish distributions (e.g., Gerstner 1998, Auster et al. 2003b). The highly complex boulder-cobble matrix of DBRs provides a level of habitat complexity that exceeds that of other deepwater habitats in the region and therefore the role of invertebrate cover may be comparatively minimal. However, we have observed both cunner and silver hake swimming amongst attached invertebrates in search of prey. This use of epifauna as cover from predators, or refuge from flow, may increase the foraging ambit. Studies to understand the relationship between spatial patterns of habitat complexity, foraging ambit, foraging success, predation risk, and growth rates are needed to better understand the functional role of invertebrate communities on DBRs. Further, there may be feedback loops between fish predators (i.e., benthivores) and the trajectories of epifaunal communities that provide shelter resources (e.g., Witman and Sebens 1992).

Both occupied submersibles and ROVs have important roles for studies on DBRs. Strategies for use of one-person submersibles and ROVs for behavioral studies require trade-offs in terms of balancing piloting and research tasks. For example, point-count and behavioral scan methods were used when the submersible was stationary (parked) on the seafloor, allowing the operator to concentrate on piloting tasks when moving from station to station. Due to the need to constantly run thrusters on ROVs (due to a lack of variable ballast systems), fish census and behavior data were collected when first sighting individuals during strip transects in order to minimize the effects of reactions to an approaching vehicle.

We need to study DBRs in the same way we have studied processes on coral reef, kelp forest, and seagrass systems. Only by understanding the role that particular elements in the undersea landscape play can we develop metrics and reference points for the conservation and sustainable use of the biological diversity.

Table 2. Species composition, residency status, and trophic guild membership for fishes observed at DBRs. Trophic guild membership is based on Garrison and Link (2000) as well as Colette and Klein-MacPhee (2002).

Taxa	**Residency**	**Trophic guild**
Acadian redfish	year-round resident	shrimp/small fish eater
Atlantic cod	year-round resident/transient	amphipod/shrimp eater; piscivore
Atlantic wolffish	seasonal resident	benthivore/shrimp eater
Cunner	year-round resident	benthivore
Cusk	year-round resident	shrimp/small fish eater
Haddock	transient	benthivore/shrimp eater
Longhorn sculpin	year-round resident	amphipod/shrimp/small fish eater
Ocean pout	seasonal resident	benthivore/shrimp eater
Pollock	transient	shrimp/small fish eater
Sea raven	year-round resident	piscivore
Silver hake	transient	shrimp/small fish eater, piscivore
Rajid spp.	transient	benthivore/piscivore

Acknowledgments

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Patterns of Mixed-Species Foraging and the Role of Goatfish as a Focal Species

Kimberly Barber and Peter J. Auster
National Undersea Research Center and Department of Marine Sciences, University of Connecticut, Groton, CT 06340

Abstract

Mixed species foraging is a common behavioral attribute in some species of reef fishes. Goatfish (Family Mullidae) are common focal species in social foraging groups on coral reefs. Video records of social foraging events occurring in the Great Barrier Reef of Australia were collected during April 2003. Analysis included the quantification of time spans of foraging events, variations in species composition, maximum group size as well as relevant behavioral patterns. Variation in species richness over the length over the course of foraging bouts was observed. The diversity of species that forage with goatfish illustrates the extent to which social foraging events occur within reef fish communities. This study provides background for the formation of hypotheses suggesting how this behavioral pattern mediates diversity of fishes in coral reef habitats.

Introduction

Many studies have focused on the social influences affecting foraging groups of animals. Results have shown that mixed and single species foraging groups can enhance prey capture and aid in predator avoidance. Some work suggests that social foraging can enhance local patterns of diversity by enhancing access to limited prey resources. Mixed species foraging is a common behavioral attribute in some groups of reef fishes (Auster & Lindholm 2002, Overholtzer & Motta 2000, Strand 1988). Understanding the role that mixed species foraging plays in mediating diversity of reef fishes in local habitats is the ultimate goal of our research. Goatfish (Family Mullidae) are common focal species in social foraging groups on coral reefs. In this study, we quantified pattern in species composition and behaviors of mixed species foraging groups with goatfish of the genus *Parupeneus* (*P. barberinus, P. pleurostigma* and *P. multifasciatus*) as the focal species (Figure 1).

Methods

Video records of mixed-species foraging bouts were recorded from 9-18 April 2003 at depths of 8-20 m during scuba dives on the Great Barrier Reef off northeastern Australia. A bout is defined as “single or mixed species group the exhibited coordinated search behavior” (sensu Auster and Lindholm 2002). Video was recorded on miniDV format videotape and viewed on a VCR with shuttle search capabilities and time code reader to facilitate data collection. Data derived from video records included the time span of foraging events, variations in species composition, maximum group size as well as relevant behavioral patterns.

Results

Variation in species richness over the course of foraging bouts was observed. Patterns of species diversity were enumerated to determine the frequency of reef fish taxa in mixed species groups (Table 1). *Coris batuensis*, *Scolopsis bilineatus,* and *Halichoeres hortulanus* occurred most frequently as focal species. Variation in species richness spanned 2 - 5 species per foraging bout. The maximum group sizes ranged from 2 - 6 individual fishes. Note that maximum group sizes of 2 - 4 animals seem to predominate (Figure 2). There were no more then 5 species of foragers in any single event. It is important to take into account time periods of foraging bouts, as well as changes in group structure and size over the time frame of individual bouts. Events lasted an average of 1.35 min. Figure 3 illustrates changes in group size for three separate foraging bouts. This illustrates the dynamics of group size over short time spans.

Table 1. Species involoved in social foraging bouts.

Species	Common name	Percent Occurrence
Parupeneus spp.	Goatfish	100%
Parupeneus barberinoides	Dash-dot goatfish	81%
Parupeneus pleurostigma	Side-spot goatfish	11%
Parupeneus multifasciatus	Manybar goatfish	8%
Coris batuensis	Batu Coris	61%
Scolopsis bilineatus	Bridled monocle bream	46%
Halichoeres hortulanus	Checkerboard wrasse	38%
Parapercis hexaphtalma	Speckled sandperch	8%
Lutjanus monostigma	One-spot sandperch	4%
Trachinotus blochi	Sub-nosed dart	4%
Ctenochaetus striatus	Lined bristle-tooth	4%
Seriola rivoliana	Almaco jack	4%
Monotaxis grandoculis	Big-eye bream	4%
Thalassoma lunare	Moon wrasse	4%
Epibulus insidiator	Sling-jaw wrasse	4%
Hologymnosus doliatus	Pastel ring wrasse	4%
Halichoeres trimaculatus	Threespot wrasse	4%
Chromis weberi	Weber's chromis	4%
Acanthochromis polyacanthus	Spiny chromis	4%

Figure 1. An example of a mixed foraging group of fishes with a goatfish as the focal species.

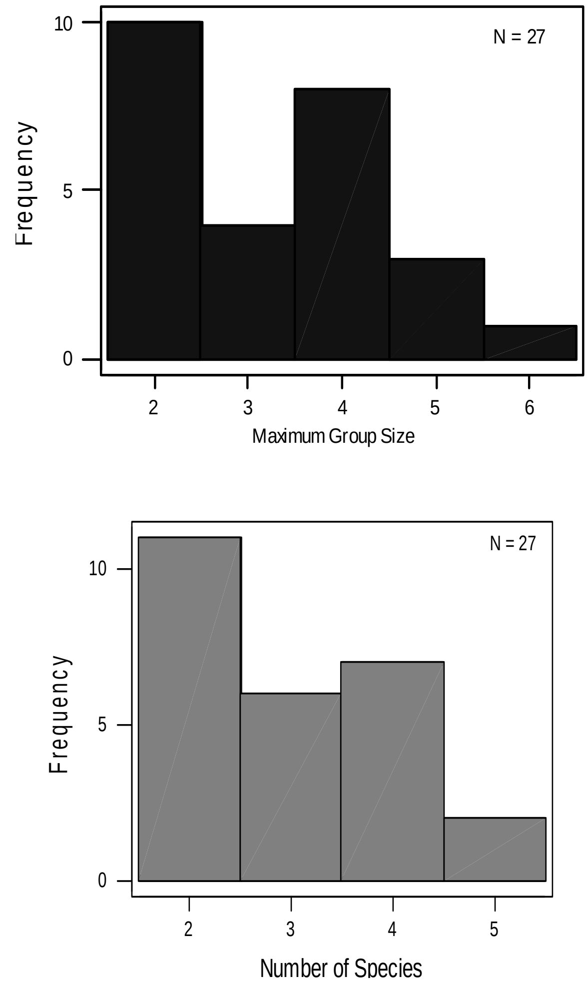

Figure 2. Frequency of maximum group size and species diversity.

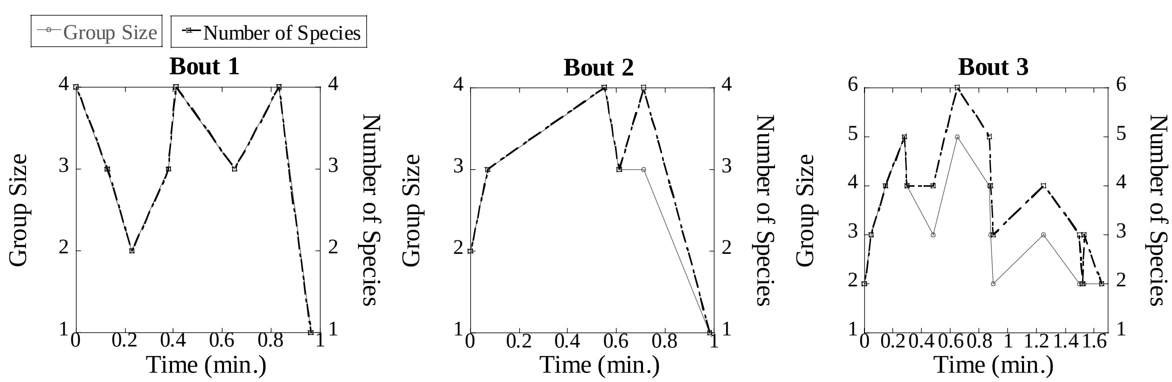

Figure 3. Group size (left and Number of species (right) vs. time for three individual foraging events

Discussion

The diversity of species that forage with goatfish illustrates the extent to which social foraging events occur within reef fish communities. Goatfish are benthivores and were associated primarily with other benthivorous species, although planktivores and piscivores had been observed as well. Fish of various trophic groups have been observed to be the focus of most mixed species foraging groups in other studies. Further study of vigilance behaviors, group dynamics, and a variety of foraging group interactions remain for analysis. Understanding the effect of social foraging behavior on species diversity and composition remains as a future goal of such studies.

A study of mixed-species avian flocks in Amazonia suggested that such behavior contributed to greater richness in the local avian communities (Powell 1989). Small individuals associated with a mixed-species flock adopted a larger home range then those of the same species feeding independently. Powell hypothesized that “the under-utilization of food resources is expected to allow smaller species to coexist with greater niche overlap resulting in increased species richness”. Patterns in social foraging of reef fishes from Bonaire, Netherlands Antilles (southern Caribbean Sea) showed that the rate of social foraging bouts increased in habitats with greater species diversity (Auster and Lindholm 2003). Various factors may mediate the duration of foraging sessions such as predation risk, availability of resources and competition (although different species may seak different food sources). Rands et al. (2003) developed a dynamic game-theoretical model to evaluate how foraging pairs determined timing of foraging and coordination patterns based on energy reserves of each individual. Investigations of how such a model can be applied to mixed-species foraging groups of coral reef fish may give insight into the dynamics of reef fish interactions and how they may mediate diversity of fishes in local habitats.

Conclusions

A diversity of species participated in mixed species foraging groups. Here we quantified relationships for a single focal taxa (i.e., goatfish). Relationships among species may be important in mediating patterns of fish diversity in local habitats. This project provides background for the formation of hypotheses suggesting how this behavioral pattern mitigates diversity of fishes in coral reef habitats.

Future Research

- Quantify patterns of group size and time span of foraging bouts. (more potential predators, low food availability)
- Roles of particular species in a group when foraging or displaying vigilant behavior (Figure 4).
- Intra and interspecies aggressive behavior and the triggers.

- The difference in distances species will travel, and habitats they will exploit, as individuals versus when they are in a foraging group.
- Examining piscivore and planktivore foraging groups.

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Predatory Behavior of Piscivorous Reef Fishes Varies with Changes in Landscape Attributes and Social Context: Integrating Natural History Observations in a Conceptual Model

Peter J. Auster
National Undersea Research Center and Department of Marine Sciences, University of Connecticut at Avery Point, Groton, Connecticut 06340 USA

Abstract

Piscivorous predators do not always operate using single types of strategies or behave as single "units" of predation within reef fish communities. Predator strategies can vary based on changes in landscape attributes as well as under variable social contexts. Examples of variation in predator strategies are described for shark mackeral (*Grammatorcynus bicarinatus*) on the Great Barrier Reef, yellowtail snapper *(Ocyurus chrysurus*) on the barrier reef and lagoonal patch reefs off Belize in the Caribbean Sea, coronetfish (*Fistularia commersonii*) off the north coast of Mauritius in the Indian Ocean and, along with observations of leopard grouper (*Mycteroperca rosacea*), at various sites off La Paz in the Gulf of California. Fishes exhibited a range of predation strategies across a gradient of social context (i.e., as individuals, as intraspecific groups, as interspecific groups, and using resting schools of co-occurring predators as cover to stalk and attack prey). In a spatial context, fishes exhibited stationary ambush, short distance stalk and ambush, and long distance rush tactics to capture prey. Variations in landscape formation appeared to mediate variations in predation strategies. A conceptual model integrates these variations in predation tactics to facilitate collection of data (i.e., in response in variations in prey density) on predation success as a function of spatial and social guilds.

Introduction

Predation is an important ecological process structuring communities of coral reef fishes (Hixon and Menge 1991). Empirical studies have demonstrated that the distribution of shelter resources and the abundance of predators mediate reef fish distribution and abundance (Hixon 1991, 1993, Beets 1997, Carr et al. 2002). Observational studies have shown correlations between predator guilds, shelter resources, and species abundance and composition. Experimental approaches, that have produced a mechanistic understanding of the role of predation, have generally been conducted using a limited number of taxa that have small movement rates and limited types of escape responses when compared to the wider diversity of reef fish taxa (Hixon and Webster 2002). Further, observational and experimental studies of predator-induced mortality in fishes generally treated predation as a black box and did not attribute components of mortality to particular predators or predator strategies. Unfortunately, there is a paucity of information in the literature on predation strategies, especially of highly mobile predators (but see Hobson 1968, Parrish 1993, Sancho 2000).

Predators do not have uniform search, stalk, or attack strategies. Further, piscivorous predators have developed behavioral repertoires that vary based on landscape attributes, intra- and interspecific interactions with proximate predators, and the behavior of prey. Attributes of the reef landscape in which predators operate vary at multiple spatial scales (e.g., rugosity, slope angle) and mediate interactions with prey. Predator morphologies also constrain behavior such that predators operate at particular, or across a range of, spatial scales. In order to understand the recruitment patterns of fishes mediated by interactions with a diverse piscivore guild, a reductionist approach seeking to understand how variations in the suite of predator behaviors influence mortality may provide important insights. In this paper I summarize observations of variation in the behavior of four predator species as they relate to reef landscape features and the behavior of proximate predators. In addition, I present conceptual models based on guilds of predators delineated by how they operate in both social and spatial contexts within reef landscapes. Understanding the range of variation in predator tactics, and how such variation is mediated by local conditions, is a step towards predicting the role of particular piscivore guilds in structuring reef fish communities.

Materials and Methods

Observations of four piscivorous reef fish species were made ad hoc while using open-circuit scuba on other projects focused on social foraging behavior in reef fishes. Behaviors were recorded either using video (for post dive analysis) or directly on underwater slates. Observations included number and species composition of individuals participating within foraging bouts; search, stalk, and attack behaviors; landscape attributes; and interactions with co-occurring predators and prey. Observations of shark mackeral (*Grammatorcynus bicarinatus*) were made during dives conducted from 9-18 April 2003 at Ribbon Reef 10 on the Great Barrier Reef; of yellowtail snapper (*Ocyurus chrysurus*) on the barrier reef and lagoonal patch reefs off Belize from 10-14 February 2004; of coronetfish (*Fistularia commersonii*) off the north coast of Mauritius (19-30 June 2001) and, along with observations of leopard grouper (*Mycteroperca rosacea*), at various sites off La Paz in the Gulf of California (15-25 October 2001).

Results

Shark mackeral Grammatorcynus bicarinatus – Coral Sea: Shark mackeral are wide ranging piscivores distributed in the western Pacific and occur near reefs off the east and west coasts of Australia (Randall et al. 1996). Shark mackeral (n=24) were observed along the leeward side of Ribbon Reef 10 and at adjacent features across a depth range of 3-20 m. Observations revealed this species used multiple search and attack strategies that were related to both landscape type and associated piscivorous predators. Shark mackeral exhibited three distinct strategies:

1. Linear search along reef face (n=10) – This strategy was exhibited by individuals swimming singly or in groups. Groups occurred both as individuals swimming in a single line (i.e., with one individual in the lead), in parallel (i.e., with one individual closer to the reef face than the other), or as an aggregation swimming along the reef face (Figure 1a). Red bass snapper (*Lutjanus bohar*) commonly followed shark mackeral short distances along the reef face (ca. 5-10 m; Figure 1b), breaking off their following at discrete landscape features (e.g., tips of reef spurs, large crevices,

other minor promonotories). Mackeral occasionally would break from steady swimming and charge at potential prey. One group of five individuals broke formation swimming and charged schools of fusiliers at the reef crest.

2. Ambush from the seafloor (n=3) – Three individuals that had identified potential prey (i.e., based on eventual directed movements towards groups or individuals) ended their linear search strategy and began station keeping at a position hovering just above the seafloor using "low frequency" movements of pectoral and caudal fins. Station keeping started at locations that were several meters off the end of reef spurs on the downcurrent side (i.e., at the edge of an area with reduced current or eddy feature). Individuals rapidly shifted from their "nominal" color pattern (silver or blue-green upper side and back and silver lower side) to one with alternating vertical bars and stripes on the dorsal side of the body and spots on the ventral side (Figure 1c). On two occasions, "high frequency" tail beats and pectoral fin movements were followed by a rapid charge upward and attack on schooling scissortail fusiliers (*Caesio caerulaurea*) that occurred in shallow water. Both attacks resulted in the successful capture of prey. Slow directed movement using "low frequency" fin movements, after initial station-keeping behavior and color change, were used to stalk an individual surgeonfish for less than 30 s (Figure 1d). However, no attack resulted from this behavior sequence and the mackeral then shifted back to nominal shading and continued a linear search along the reef face.

3. Ambush from resting schools of co-occurring predators (n=11) - Shark mackeral joined resting schools of bigeye trevally (*Caranx sexfasciatus*) and used schools as cover to attack scissortail fusiliers along near vertical reef faces (Figure 1e). Generally only a single mackeral joined a resting school of trevally. However, up to eight mackeral had been observed at one time in a single resting school of bigeye. Fusiliers (Caesionidae species) and other schooling fishes (primarily Anthiinid species) generally did not react to resting schools and exhibited defensive and flight behaviors (coalesence of school or individual flight) only during rushes by single or multiple predators. Shark mackeral also broke away from resting schools of bigeye to join proximate predatory attacks on fusiliers with bluefin trevally (*Caranx melampygus*). In one instance attacks included both bigeye and bluefin focused on the same schools of prey (Figure 1f-g). Unlike other species with coordinated attack strategies, shark mackeral attacked independently of the group of trevally and seemed to take advantage of coordinated movements of the co-occurring predators.

All individuals were initially observed singly or in pairs exhibiting generalized searching while swimming parallel to the sloping face of reef platforms (bommies). Behaviors switched from the simple search to more complex types of strategies when potential prey were in large groups (based on directed stalking or attacks) and local landscape conditions were amenable (e.g., presence of reef spurs, vertical reef faces, resting schools of piscivores). The ambush from the seafloor strategy is similar to one described by Sancho (2000) for bluefin trevally at Johnston Atoll in the central Pacific. In particular, individuals that generally attacked from midwater rapidly adopted a pigmented color pattern and ambushed prey from a sheltered position under corals.

Yellowtail snapper* Ocyurus chrysurus – *Caribbean Sea: Yellowtail snapper are common predators on coral reefs in the Caribbean Sea, feeding on fish and macroinvertebrates (Randall 1967, Bohlke and Chaplin 1993). Yellowtail snapper (n>200) were observed from 1-20 m depth. Observations revealed that group size and landscape attributes were correlated with search behaviors.

- Search by individuals (n>100) - Individual fishes generally searched through the coral landscape on patch reefs and along the reef slope by swimming below the nominal "horizon" of nearfield corals (Figure 2a). That is, individual fishes did not generally swim above the height of proximate corals where visual line-of-sight could identify potential prey at long distances but also expose individuals to larger predators.

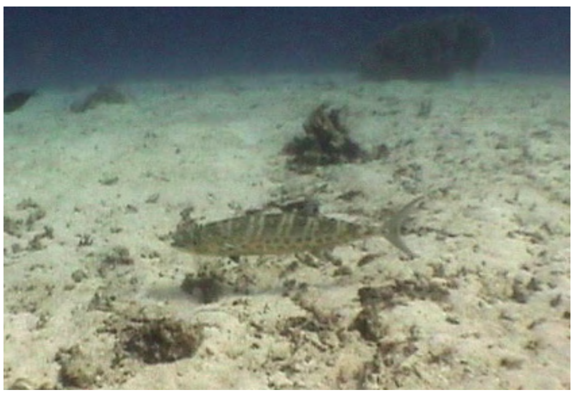
- Ambush strategy (n=3) – Individual fish exhibited ambush predator strategies by "hovering" above or "resting" on the seafloor or against corals alongside crevices where potential prey could swim through a constrained space (Figure 2b).

- Group searching – In contrast to search behaviors of individual fishes, groups of yellowtail snapper exhibited a range of complex search behaviors that included coordinated actions of multiple individuals in particular types of landscapes (Figure 2c). Groups of 3-18 fish searched along the reef slope in loose groups. "Loose" groups were defined as those groups of yellowtail snapper that were searching for prey in a particular direction along a reef but had variable nearest neighbor distances, up to several meters, and reacted to the behavior of conspecifics. There was a clear increase in the number of fishes that swam above the coral horizon when group size increased (Table 1). Group members responded to individuals who exhibited directed swimming towards the seafloor, either in response to perceived threats (e.g., large barracuda, divers) or potential prey (e.g., search the same area where a conspecific captured prey).

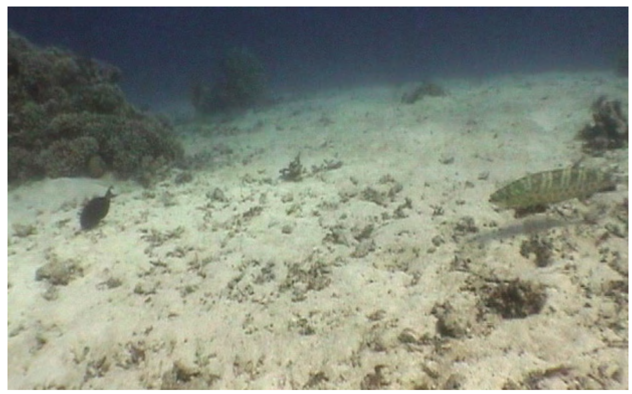
- Group swamping of prey in crevices – Groups of fishes searched in a coordinated manner amongst and above patch reefs. Fishes responded to conspecifics and "swamped" crevices searching for prey with 9 individuals targeting a particular crevice (Figure 2d-f). Not all individuals within a group participated in swamping behavior but those that did returned to searching as part of the larger group.

A. Single shark mackeral searching with parallel swimming along reef face.

B. Red bass snapper following shark mackeral along reef.



C. Shark mackeral station-keeping after breaking off from linear search strategy. Note color shift with vertical bars and stripes on upper side and back with spots on lower side



D. Slow stalking of acanthurid.

E. Shark mackeral swimming with resting school of bigeye trevally.

F. Shark mackeral and bigeye trevally maneuvering to attack fusiliers from under the school

Figure 1

G. Shark mackeral breaks from association with resting school of bigeye trevally and joins bluefin trevally rushing a school of fusiliers. Note resting school of bigeye trevally in the background.

Figure 1

Table 1. Summary of search behaviors by individuals and groups (two or more) of yellowtail snapper based on search height above seafloor. Groups assigned to the "above coral horizon" category had at least one individual swimming above the coral horizon.

Number in Group	Below coral "horizon"	Above coral "horizon"
1	37	5
2	18	4
3	5	1
≥4	5	12

***Leopard grouper* Mycteroperca rosacea – *Gulf of California*:** Leopard grouper occur in a limited range from Bahia Magdalena on the Pacific side of Baja California, throughout the Gulf of California and to southern Jalisco on the west coast of Mexico (Thomson et al. 2000). This species is generally considered a crespuscular predator, preying on schooling fishes (Hobson 1968). However, diurnal observations of fishes from 5-25 m depth showed that individuals exhibited active stalking and ambush behaviors where they altered focal sites based on landscape features and behavior of prey (i.e., primarily scissortail damselfish *Chromis atrilobata* and Cortez rainbow wrasse *Thalassoma lucasanum*).

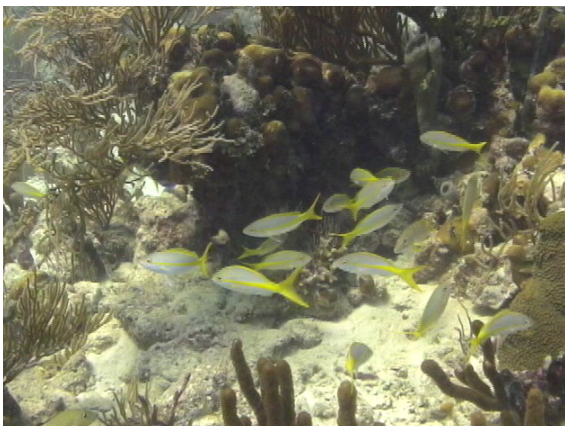
- Linear search along rock reefs (n=25) – Single fishes or those in groups actively searched for prey while moving along reef drop-offs or amongst boulders. Swimming speed varied and when schools or aggregations of prey were located, occasional burst swimming into schools to capture schooling fishes was observed.

- Landscape mediated ambush strategies (n=27) – Leopard grouper exhibited ambush predation behavior along reef edges and along the peaks of large isolated boulders. Individual fishes hovered in mid-water off the edges of reefs or isolated boulders (Figure 3) and faced towards the reef and aggregations of mid-water fishes (n=24). Alternatively, fishes oriented over or on the reef edge at an angle normal to the axis of the reef and faced outward towards planktivorous fishes in mid-water aggregations out and generally above the reef or boulder edge (n=3).

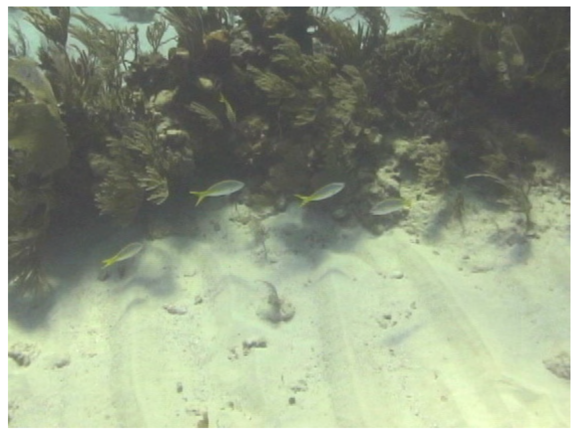
- Mixed species foraging groups (n=4) – Leopard groupers were the focal species in mixed species groups where their foraging activities exposed prey for followers (i.e., coronetfish, graysby *Cephalopholis panamensis*, Pacific mutton hamlet *Alphestes immaculatus*, and Mexican hogfish *Bodianus diplotaenia*).

A. Individual yellowtail snapper searching blow the horizon of nearfield corals.

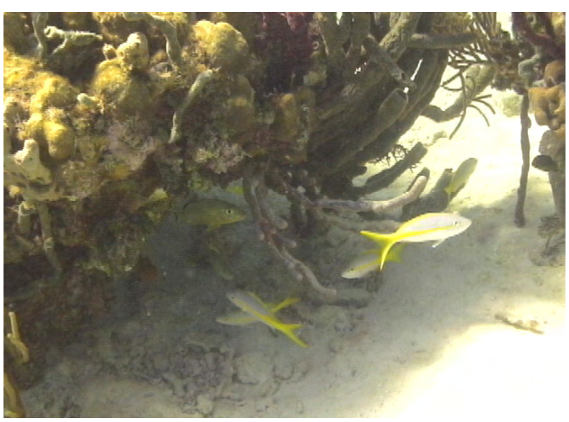
B. Yellowtail holding station behind coral to ambush prey.



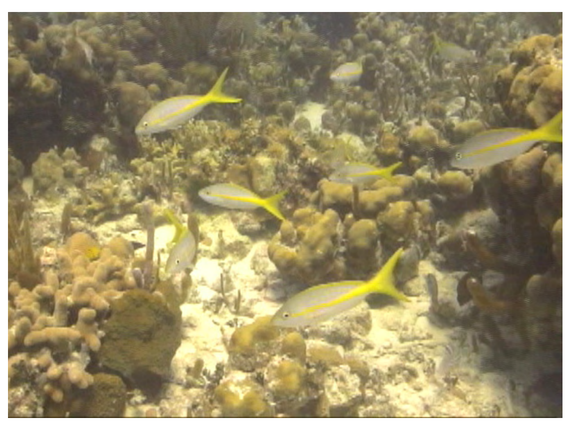
D. Group of yellowtail in a coordinated search for prey amongst patch reefs (i.e., the group targeting particular areas for search).



C. Group of yellowtail searching along boundary of patch reef.



E. Group of yellowtail swamping a crevice in search of prey.



F. Note three yellowtail scanning under crevice while a fourth leaves the area.

Fiure 2

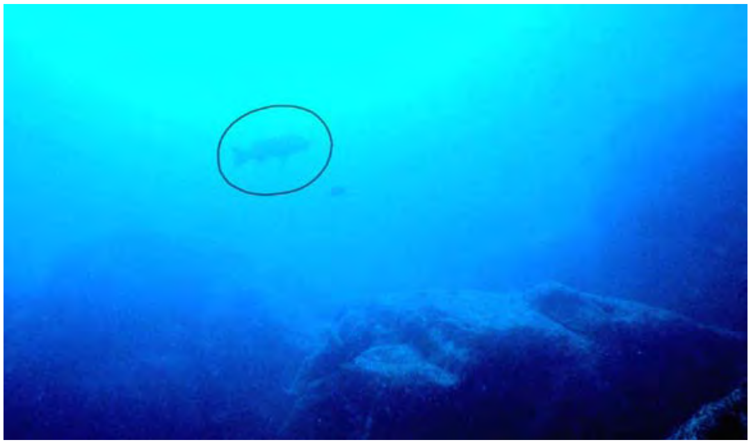


Figure 3 A leopard grouper station-keeping in mid-water and facing towards reef slope. Station-keeping fish were observed to chase or ambush planktivorous fishes foraging off the face of reef slopes and over boulders.

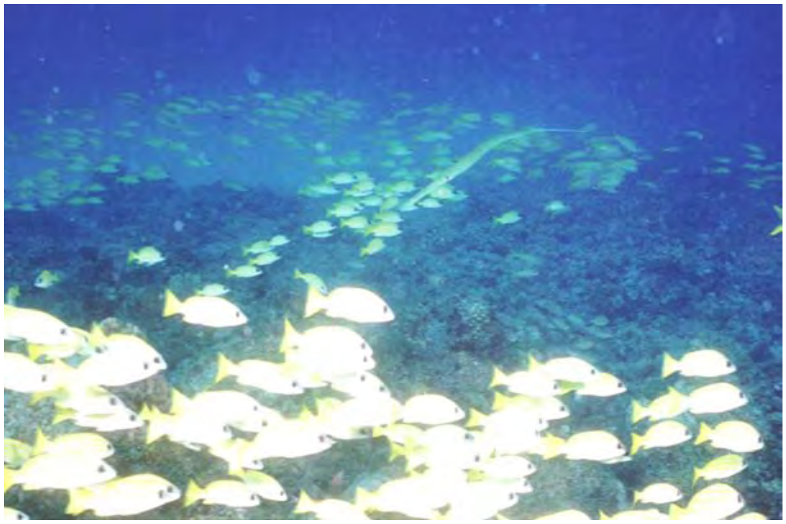
A. Coronetfish searching for prey while swimming parallel to reef axis (Indian Ocean).

B. Coronetfish perpendicular to reef axis oriented to ambush prey in a crevice (Gulf of California).

C. Coronetfish and graysby in a social foraging group (Gulf of California).

D. Group of coronetfish swimming in parallel to aggregate prey (Indian Ocean).

Figure 4



E. Coronetfish in arched posture prior to attempted ambush of aggregating prey fish (Indian Ocean).
Figure 4

Coronetfish* Fistularia commersonii – *Indian Ocean and Gulf of California: Coronetfish occur from the western Indian Ocean to the eastern Pacific including the Gulf of California where they prey upon small fishes (Thomson et al. 2000). Observations showed individuals altered their stalking behavior based on variations in reef landscapes and exhibited cooperative foraging. These behaviors included:

- Landscape mediated stalking strategies (n=48) - Individual coronetfish varied their body angle in relation to the axis of the reef as they stalked potential prey. Coronetfish swam or drifted parallel to the long axis of a reef (Figure 4 a) when reef surfaces were absent of deep crevices (reefs formed by rock outcrops or carbonate ridges and short non-branching corals). In contrast, fish oriented normal to reefs when potential prey aggregated in deep crevices (Figure 4b). Crevices are defined loosely as structures with openings of approximately a single predator body length and deeper than one-half body length. Such spatial constraints appear to limit stalking and capture success when stalking parallel to the reef axis (i.e., limiting detection and strike).

- Mixed species foraging groups (n=19) - Fishes followed other taxa (i.e., Mexican hogfish, leopard grouper, graysby; all in Gulf of California) as they foraged along the reef (Figure 4c). Coronetfish altered orientation to the reef depending on where focal animals searched or captured prey.

- Group stalking behavior (n=5 pairs and 1 group of 4) – On reef patches (surrounded by sand such that movement of reef associated prey was constrained by a landscape boundary) coronetfish were observed to move along the patch reef in a line abreast. As prey avoided one approaching predator, their movements created opportunities for an adjacent predator to ambush individuals or strike at high-density aggregations of prey (Figure 4d-e).

Discussion

Observations of predatory behaviors of four piscivore species demonstrated that strategies for search, stalk, and attack of prey varied within species and were correlated with attributes of the surrounding landscape and the behavior of proximate predators. There are few examples documenting the variability of such behavior in the literature, especially in relation to group foraging behaviors where followers exploit prey exposed by a nuclear or focal individual (Sancho 2000, Auster and Lindholm 2002). Here I provided examples of variations in search and attack strategies for a suite of species under different sets of social and landscape conditions that can lead to some preliminary generalizations about how predators operate within reef landscapes.

Based on these observations, I suggest that one approach for better quantifying the role of predation in mediating survivorship patterns in reef fish communities is to define predators based on behavior guilds linked to landscape features. Table 2 lists guild types based on the diversity of behaviors reported in this paper. This list is not necessarily complete or exclusive and applications in other landscape types or with other taxa should be adaptive. Collecting data on rates of predation success based on predation strategy (the behavior guild) within a particular landscape element may elucidate spatial patterns of survival when habitat types can be mapped across reefs

The observations of fishes from multiple reef types also demonstrate a range of patterns in spatial orientation to landscape features that allow classification of fishes into “spatial” guilds. A conceptual model that integrates the gradient of spatial relationships between predators and prey within reef landscapes is shown in Figure 5. Predators exhibited three general types of attack strategies (i.e., ambush, slow stalk and ambush, and rush). The underlying assumption in terms of the utility of the model is that variation in the orientation of fishes in relation to landscape features, and the range at which predation events are initiated, affects the outcome of predation events.

This model does not specifically integrate variations in social context but categorical behavior treatments (e.g., individual versus various types of group foraging behaviors) within orientation categories will allow comparisons of predation impacts to reef fish communities based on variability in both landscape and social contexts.

The overall objective of this work is to propose a pathway to understanding how the behavior within a diverse predator guild affects population dynamics of fishes within reef landscapes (e.g., Cosner et al. 1999). This paper provides some fodder for developing a pathway towards a mechanistic understanding of the role that variations in predation behavior and landscape variation play in mediating local patterns of species composition and diversity in reef fish communities.

Table 2. List of behavior guilds based on synthesis of observations of search, stalk and attack strategies of reef piscivores.

Behavior guild	Description
Individual	Individual predators operating singly (i.e., independently of other individuals or groups)
Intraspecific group	Groups of two or more of the same species interacting to search and capture prey (link rates of predation success to group size)
Interspecific group	Groups of two or more individuals composed of two or more species interacting to search for and capture single or multiple prey types (link rates of predation success to group composition and size)
Cryptic predator in resting school	Single or multiple predators actively searching and attacking prey from the cover provided by co-occurring in resting schools of fishes (link rates of predation success to number of active foragers)

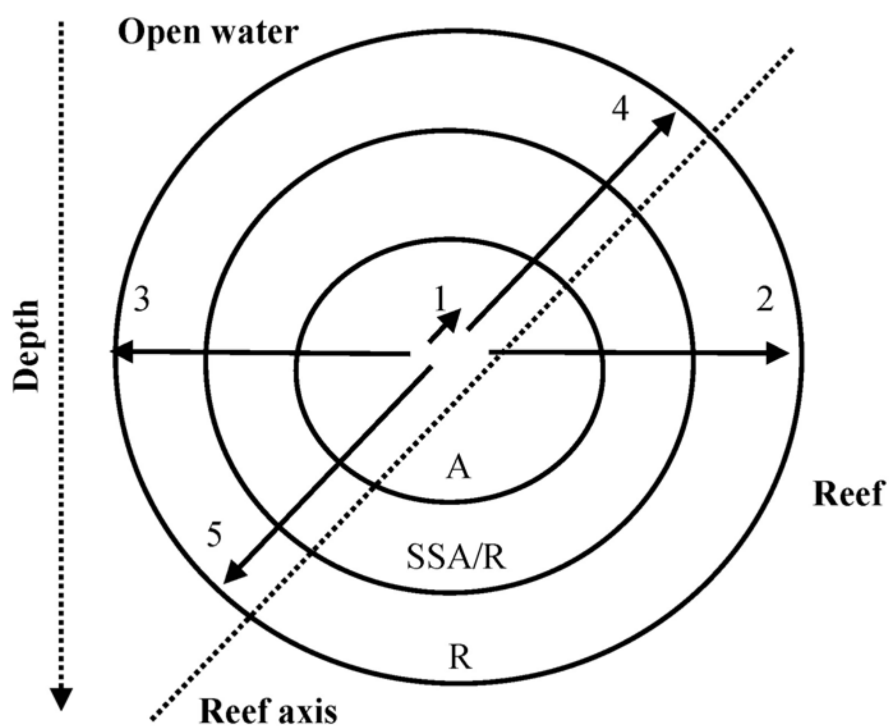


Figure 5. Conceptual model of predator orientation and relative distances to prey. Predators exhibit ambush (A), short distance stalk and ambush (SSA) and rush (R) strategies along a gradient of distances. Classifying predators into such spatial guilds may aid in understanding how diverse predator taxa affect population dynamics of fishes within reef landscapes. Predator strategies also vary in relation to their orientation to the reef. Orientations can be classified as: horizontal and parallel to the reef face (1), horizontal and facing normal to the reef face (2), horizontal and facing normal from the reef face (3), oriented upslope and parallel to the reef axis (4), and oriented down slope and parallel to the reef axis (5).

Acknowledgments

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Baseline Scuba Assessments of Habitat and Fishery Resources in Eight Candidate Marine Reserve Sites in Skagit County, Washington

Andrew J. Weispfenning, Paul A. Dinnel, Nathan T. Schwarck, and Gene McKeen
Shannon Point Marine Center, Western Washington University, Anacortes, WA 98221

Abstract

Continuous human demand for Puget Sound's marine resources has negatively affected the biological richness of this ecosystem. In order to maintain a sustainable fishery and viable ecosystem, the Skagit County Marine Resources Committee is in the process of establishing marine reserves to protect the territorial, long lived, and slow to mature bottomfish brood stock from over harvesting. The objective of this study is to estimate current bottomfish density, fish size, and document habitat complexity and species composition within 8 candidate rocky reef reserve sites. Data were collected using visual band transect scuba surveys and ROV (Remotely Operated Vehicle) cruises to assess 8 target bottomfish species: black, canary, copper, quillback, and yellowtail rockfishes, lingcod, kelp greenling, and cabezon. The number of target species at each survey site ranged from 0-6 and a site within the Rosario area was the most diverse. Average fish size ranged from 0.15 m – 0.55 m and the average size of the observed rockfishes was 0.25 m. Scuba surveys indicate that nearshore bottomfishes tended to be within a 45 ft-65 ft depth range, which suggests the need for ROV surveys at greater depths for more accurate density estimations. Northwest Island, Rosario, and Burrows channel appear to be excellent locations for marine reserves as a result of complex rocky reef habitat, high bottomfish density and diversity, visibility to the public, and proximity to marine research institutions.

Introduction

In the Pacific Northwest, Puget Sound's marine and estuarine waters sustain diverse and valuable natural resources supporting a multitude of human interests (Monaco *et al.* 1992). However, exploitative activities continue to negatively impact the richness of this ecosystem. Human pressure on marine fishes has steadily escalated over the past several decades as commercial, tribal, and sport fishery demands increase, resulting in the lowest bottomfish densities and harvests in more than 50 years (Mills 1994). Furthermore, habitat degradation and chemical pollution have seriously affected Puget Sound resources (Landahl *et al.* 1997). The American Fisheries Society identified Puget Sound as one of the primary geographic "hot spots" in North America with exploited fish stocks at risk of collapse (Musik *et al.* 2000). Puget Sound's bottomfish community includes approximately 200 species and the majority associate with rocky reef habitats. Rocky reef fishes include species such as flatfishes, greenlings, sculpins, and rockfishes, with greater than 30 species targeted. Fishing pressure within North Puget Sound is the main cause of the decreased populations of rockfishes, lingcod, scallops, and urchins (Tuya 2000).

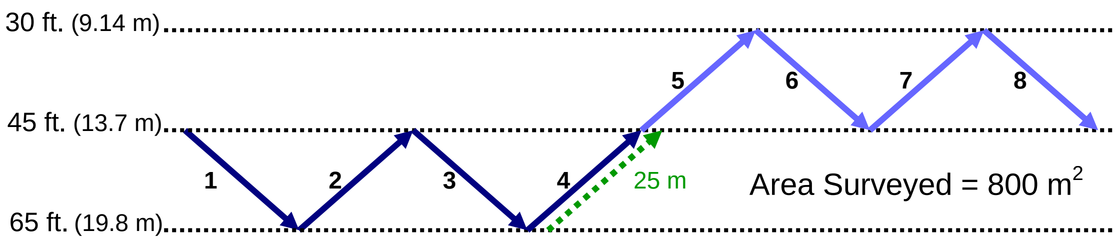
The general ecology of rocky reef fishes makes them vulnerable to the effects of fishing pressure, thus requiring management plans that acknowledge their unique life histories. Many species are long lived, having average life spans of 20-60 years. Rockfishes have particularly long life spans averaging 50-140 years, while the rougheye rockfish (*Sebastes aleutianus*) may be one of the longest-lived fishes on earth, exceeding 200 years of age (Love *et al.* 2002). Consequently, first reproduction occurs much later in life, around 6-12 years of age, in comparison to other exploited fish species. Older and larger individuals are significantly more fecund, however fishing selection tends to remove the most sexually productive fish leaving the least reproductively fit individuals to contribute to subsequent generations (McConnell *et al.* 2001). Many species exhibit a relatively strong homing behavior and reside within specific territories for extensive periods of time. Overfishing facilitates rapid removal of broodstock from local populations, negatively affecting larval production. Rockfishes are particularly vulnerable to the effects of overfishing due to their ease of capture and inability to recover from rapid pressure changes (Starr *et al.* 2002). Rockfish caught from depths as shallow as 10 ft may experience lethal barotrauma; therefore, catch-and-release is not a viable management technique. Conventional fishery management techniques have failed to protect rocky reef fishes from over exploitation (Murray *et al.* 1999). However, recent studies suggest that marine reserves may serve as a useful management tool (Lubchenco *et al.* 2003).

The objective of this study was to collect baseline habitat and fish data within the boundaries of each of the eight candidate marine reserve sites. Although it is probable that only a subset of the eight sites might become marine reserves, the other sites will then serve as unprotected “reference” sites with which to compare population dynamics. If no marine reserves are established, these data will serve as a baseline to monitor changes in Skagit County waters relative to any other management measures that may be adopted by the state resource co-managers (Washington Department of Fish and Wildlife and the Treaty Tribes of Washington) to restore and manage fish species.

Methods

Visual strip transect surveys using scuba, adapted from McCormick and Choat (1987) and Eisenhardt (2001), were used to estimate bottomfish density, fish size, and document habitat complexity at 17 sites located within the eight candidate marine reserve areas (Fig. 1). Scuba surveys were completed during the months of July, August and September, 2003. Survey sites were chosen based on the existence of complex rocky reefs identified by the Washington Department of Fish and Wildlife, previous diving excursions, and the presence of extensive bull kelp (*Nereocystis leutkeana)* beds. Depth soundings also aided in site selection by providing bathymetric profiles of the prospective rocky reef habitat.

Each survey, the sample unit, consisted of eight, 25 x 4 x 4 m transects between two depth strata (45-65 ft and 45-30 ft). The dive profile was parallel to shore despite some variation in reef slope and began with the four deep transects in a stair step like fashion:



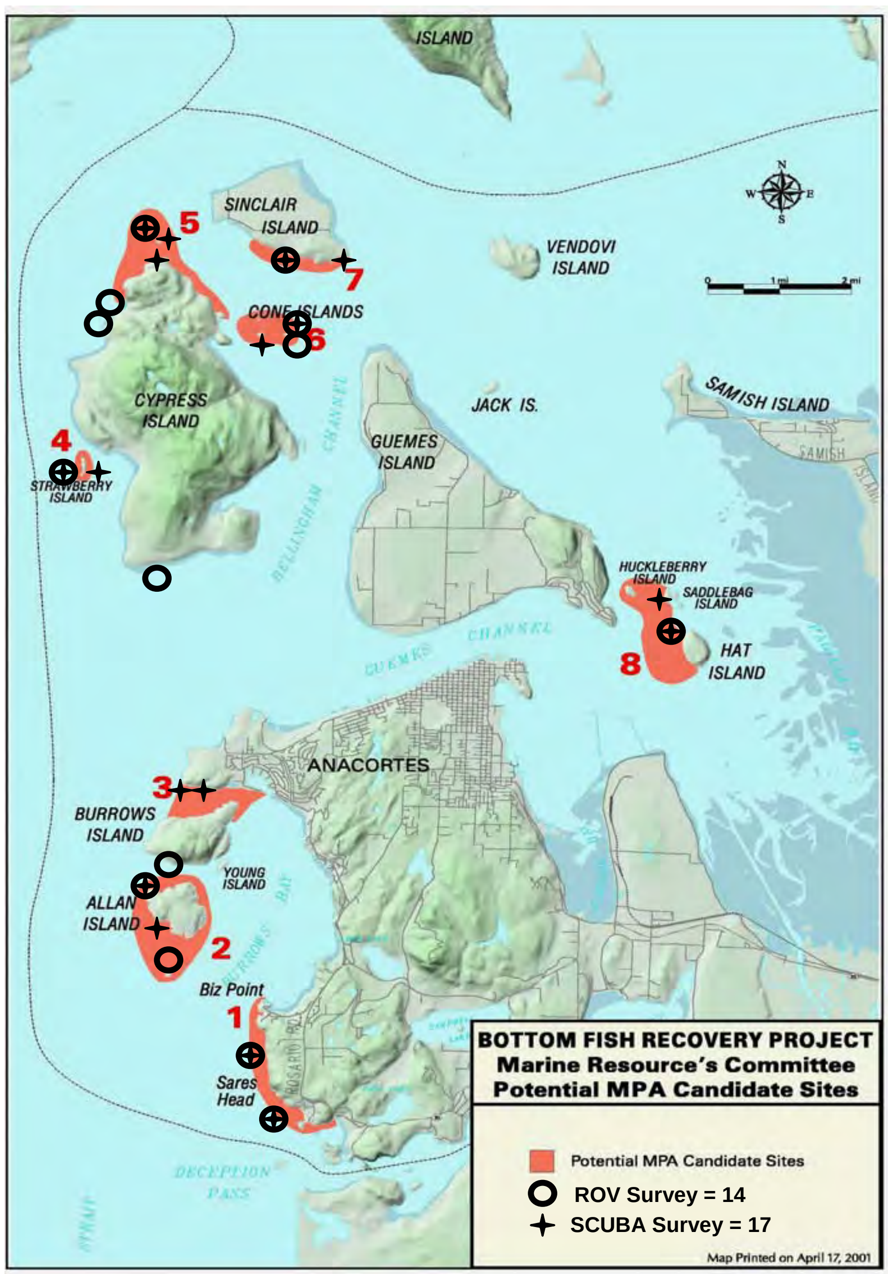


Figure 1. Approximate locations of SCUBA and ROV surveys within the eight candidate marine reserve areas in Skagit County, Washington.

All surveys occurred during the high slack tide period to maintain consistency between sampling dates, avoid the effects of tidal currents on diving safety and fish behavior, and maximize the period of best subtidal visibility. GPS coordinates were recorded at the start and end of the survey, as well as notes regarding current, weather conditions, fishing activity, and derelict fishing gear. Temperature and salinity (Refractometer type 102 Endeco mfg.) were measured at all sites at depths of 30, 45, and 65 ft.

The survey protocol involved a primary observer and support diver connected via a 25 m measuring tape or marked dive reel line. The primary observer swam at a constant rate of approximately 30 fin strokes per minute and changed depth at a relatively constant slope to reach the desired depth by the end of the 25 m transect. Variation in reef slope within the survey site had some effect on whether the entire depth stratum (45-65 ft, 45-30 ft) could be covered by the 25 m transect. While swimming the 25 m transect, the primary observer identified and measured all large nearshore bottomfish (total length estimated using parallel laser pointers spaced at 20 cm) within a four meter cube centered in front of the primary observer. In complex rocky reef areas it was important to search within crevices, behind rocks, and amongst macroalgae for cryptic fish. Potential sampling bias was minimized by focusing only on the immediate 4 m x 4 m x 4 m cube and maintaining a constant course.

Species of interest included all large nearshore demersal fishes: black rockfish (*Sebastes melanops*), canary rockfish (*Sebastes pinniger*), copper rockfish (*Sebastes caurinus*), quillback rockfish (*Sebastes maliger*), yellowtail rockfish (*Sebastes flavidus*), lingcod (*Ophiodon elongatus*), kelp greenling (*Hexagrammos decagrammus*), and cabezon (*Scorpaenichthys marmoratus*). The abundance of other fish species observed was also recorded. Subtidal visibility was determined as the support diver recorded the distance at which the primary observer was no longer visible. The secondary observer signaled transect completion with three sharp tugs on the transect line and proceeded to reel up the line along the same 25 m transect. This cycle was repeated eight times (four in each of two depth strata) and took approximately 30 min. to complete. The secondary observer collected habitat and macroinvertebrate information.

Fish density (fish ha^{-1}) was estimated based upon the 800 m^2 survey area at each survey location. Fish diversity at each survey site was calculated using the Shannon-Weiner Diversity Index (H′) and Pielou's Evenness Index (J′). A substrate complexity index was calculated for each site to assess habitat quality. The "habitat complexity index" was calculated by averaging substrate complexity index values over the 0.08 ha survey area. The assigned "index values" are: 5 = Boulder > 3 m, 4 = Boulder < 3 m & > 1 m, 3 = Boulder < 1 m, 2 = Cobble, 1 = Flat Rock, 0 = Sediment. Combined habitat types were assigned values of intermediate value. It was assumed that areas with high bottomfish density and diversity and complex habitat would be the best candidates for possible marine reserve protection.

The ROV (Remotely Operated Vehicle) surveys were conducted using a Deep Ocean Engineering Phantom model HD-2 ROV system piloted from the University of Washington's RV Centennial. Eleven of the fourteen ROV surveys were conducted within the eight candidate marine reserve areas. Locations within candidate marine reserve areas were selected based on steep depth contours and probable occurrence of rocky habitat. Survey depth ranged from 28 ft to 250 ft depending upon site bathymetry and deployment times ranged from 14 to 59 minutes. ROV surveys were conducted at either high or low slack water during the months of June and November, 2003. Visibility on all ROV surveys was limited to some degree by particulate matter in the water; however visibility was typically at least 10 ft. For each survey, the RV Centennial was anchored at the selected location and the ROV deployed to run a circular survey transect, usually from the boat to inshore and returning to the vessel offshore. Data recorded during each survey were: date, time, ROV GPS locations generating ROV tracklines for each dive, depth, current speed, bottom habitat type at one minute intervals, and number and species of fish observed. The ROV had a 10 cm parallel laser system for estimating fish size. For bottom habitat type, the following five categories were recorded: rock (R), cobble (C), gravel and/or shell (G), sand (S) and mud (M). A simple "habitat complexity index" was calculated by assigning the following values to each category: R = 3, C = 2, G = 1, and S and M = 0. Combination habitat types were assigned values of intermediate values. Habitat type and fish abundances were assessed real time using on-board data sheets and most surveys were video recorded for subsequent detailed analyses of habitat type, fish species identification, fish numbers and fish size.

Results

Of the eight candidate marine reserve areas surveyed, fish density and diversity was highest at Rosario / Northwest Island (reserve area # 1) and Burrows Channel (reserve area # 3) (Table 1 and Table 2). Based upon the habitat complexity index, reserve areas 1 and 3 also ranked highly in comparison to the other reserve areas. The Cone Islands (reserve area # 6) and Cypress Island (reserve area # 5) exhibited complex habitat and comparatively high bottomfish density and diversity. Habitat complexity and the number of observed bottomfish species were positively correlated; however the relationship was not strong (Pearson Correlation with correction; $r^* = 0.500$, $p < 0.05$).

Kelp greenling, lingcod, and copper rockfish were the most abundant and most frequently observed bottomfishes during the SCUBA surveys (Fig. 2). Northwest Island had the largest observed numbers of black rockfish, and yellowtail rockfish as well as the only sighting of canary rockfish (Table 3). Quillback rockfish and cabezon were also rare species, in which only one cabezon was seen at N.W. Allan Island. Copper rockfish were most abundant at Burrows Channel and East Cone Island, while lingcod were most abundant at Burrows Channel. Kelp greenling were most abundant at N.W. Allan Island and were seen during all surveys except at N.W. Hat Island. A total of 251 fishes were counted during the SCUBA surveys, in which 37.5 % were observed along the 45-30 ft transects and 62.5 % were observed along the 45-65 ft transects (Fig. 3). Average size of observed rockfishes ranged from 15 cm to 31 cm (Table 4). Some error in total length measurement can be assumed depending on the angle at which the fish was oriented to the lasers. Measurements were most accurate when the angle between the fish and lasers was 90°. Almost all fish measured oriented themselves at this angle.

Table 1. Summary of habitat complexity index values and associated bottomfish density estimates at each of the 17 survey sites. The "Habitat Complexity Index" was calculated by averaging substrate complexity index values over the 0.08 ha survey area.

Candidate Marine Reserve #	SCUBA Survey Site	Estimated Bottomfish Density (Fish/ha)	Habitat Complexity Index*
1	Northwest Is.	563	2.31
1	Rosario	425	2.54
3	Burrows Channel	363	3.42
5	Tow Head Is.	263	2.13
2	NW. Allan Is.	250	1.63
6	E. Cone Is.	225	1.94
6	Middle Cone Is.	175	3.88
4	E. Strawberry Is.	175	1.88
3	Fidalgo Head	150	2.44
5	Cypress Point	138	2.06
4	W. Strawberry Is.	113	1.69
2	S. Allan Is.	88	2.69
7	Sinclair Is.	75	2.63
7	S.E. Sinclair Is.	63	2.50
5	Cypress Reef	38	2.46
8	Saddlebag Is.	38	1.88
8	N.W. Hat Is.	0	0

Table 2. Observed bottomfish diversity and species richness at each of the 17 SCUBA survey locations.

MPA #	SCUBA Survey Site	Shannon-Wiener Diversity Index (H′)	Pielou's Evenness Index (J′)	Species Richness
1	Rosario	1.432	0.798	6
3	Burrows Channel	1.367	0.849	5
4	E. Strawberry Is.	1.272	0.918	4
1	Northwest Is.	1.156	0.834	4
5	Cypress Reef	1.099	1.00	3
5	Tow Head Is.	1.071	0.975	3
6	E. Cone Is.	1.061	0.966	3
5	Cypress Point	1.036	0.943	3
7	Sinclair Is.	1.011	0.921	3
6	Middle Cone Is.	0.992	0.903	3
2	NW. Allan Is.	0.914	0.660	4
3	Fidalgo Head	0.868	0.790	3
8	Saddlebag Is.	0.637	0.918	2
4	W. Strawberry Is.	0.637	0.918	2
2	S. Allan Is.	0.598	0.863	2
7	S.E. Sinclair Is.	0	0	1
8	N.W. Hat Is.	NA	NA	0

H' = Shannon-Wiener diversity index
H' = 0, when community consists of only a single species. H' increases as species richness and species evenness increase.
J' = Pielou's Evenness Index
J' = H'/H' max

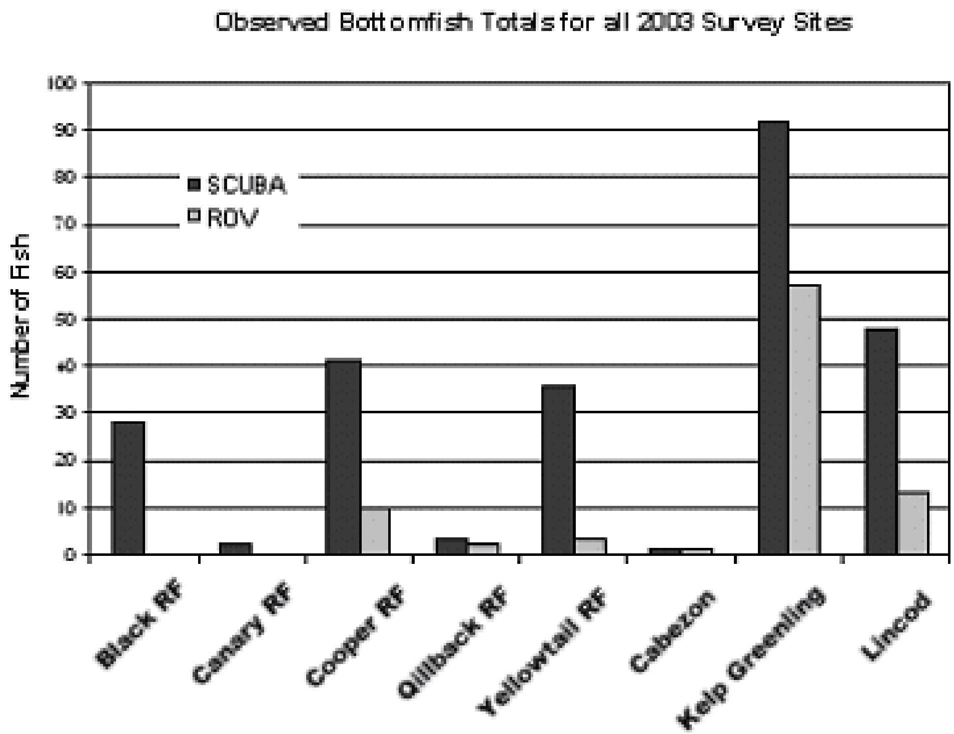


Figure 2. Comparison of total observed bottomfishes during SCUBA and ROV surveys.

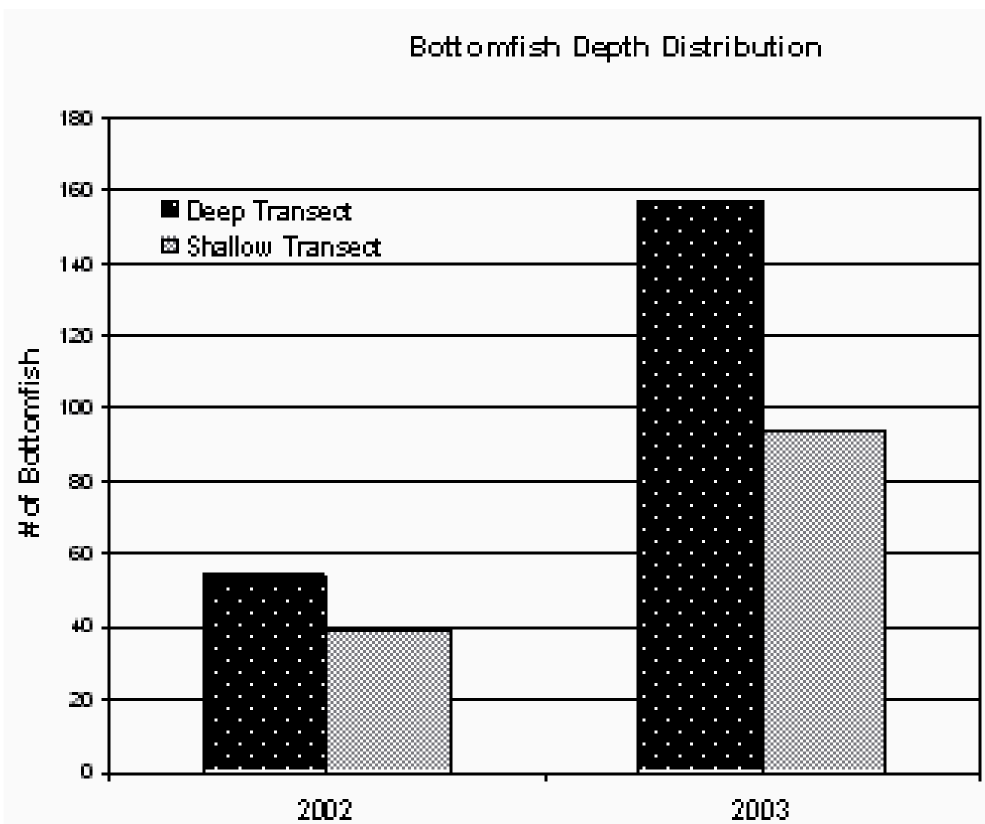


Figure 3. Trend in depth distribution of observed bottomfishes between the deep (45-65 ft) and shallow (45-30 ft) SCUBA survey transects conducted in 2002 and 2003.

Table 3. Bottomfish species composition within the 0.08 ha survey area at each of the 17 SCUBA survey sites.

MPA #	SCUBA Survey Site	Black Rockfish	Canary Rockfish	Copper Rockfish	Quillback Rockfish	Yellowtail Rockfish	Cabezon	Kelp Greenling	Lingcod
1	Rosario	**1**	0	**2**	**2**	**15**	0	**9**	**5**
3	Burrows Channel	**11**	0	**8**	0	**1**	0	**2**	**7**
5	Tow Head Is.	0	0	**7**	0	0	0	**9**	**5**
2	NW. Allan Is.	0	0	**2**	0	0	**1**	**14**	**3**
6	E. Cone Is.	0	0	**8**	0	0	0	**6**	**4**
6	Middle Cone Is.	0	0	**2**	0	0	0	**7**	**5**
4	E. Strawberry Is.	0	0	**5**	**1**	0	0	**4**	**4**
3	Fidalgo Head	0	0	**2**	0	0	0	**8**	**2**
1	Northwest Is.	**16**	**2**	0	0	**20**	0	**7**	0
5	Cypress Point	0	0	**2**	0	0	0	**4**	**5**
2	S. Allan Is.	0	0	0	0	0	0	**5**	**2**
7	Sinclair Is.	0	0	**2**	0	0	0	**3**	**1**
7	S.E. Sinclair Is.	0	0	0	0	0	0	**5**	0
5	Cypress Reef	0	0	**1**	0	0	0	**1**	**1**
8	Saddlebag Is.	0	0	0	0	0	0	**2**	**1**
4	W. Strawberry Is.	0	0	0	0	0	0	**6**	**3**
8	N.W. Hat Is.	0	0	0	0	0	0	0	0

Table 4. Comparison of mean total lengths for all bottomfishes observed during SCUBA and ROV surveys.

Bottomfish Species	**SCUBA**		**ROV**	
	n	**Mean Size (cm) ± SE**	**n**	**Mean Size (cm) ± SE**
Black Rockfish	28	31 ± 0.3	0	0
Canary Rockfish	2	30 ± 0	0	0
Copper Rockfish	41	26 ± 0.9	8	29 ± 2.0
Quillback Rockfish	3	22 ± 1.7	2	22 ± 6.5
Yellowtail Rockfish	36	15 ± 1.6	3	27 ± 0
Cabezon	1	40	1	46
Kelp Greenling	92	30 ± 0.4	36	29 ± 1.0
Lingcod	48	55 ± 2.9	11	42 ± 5.0
Other Species Observed		**SCUBA**		**ROV**
		Puget Sound Rockfish		Puget Sound Rockfish
		Pacific Herring		Red Irish Lord
		Stripped Surfperch		Gunnels
		Painted Greenling		Snake Prickleback
		Buffalo Sculpin		Dogfish Shark
		Starry Flounder		Halibut
		Rock Sole		Unidentified sculpins and small fish
		Tubesnout		
		Dogfish Shark		

Table 5. Summary of "Habitat Complexity Indices" for each ROV survey

Survey Location	**Habitat Complexity Index**	**% Survey Path w/ Rock Bottom**	**Depth Range (ft)**
6 East Cone Island-east	2.96	100	64-200
2 Dennis Shoal	2.94	100	92-206
8 Hat Island	2.68	89.8	43-145
2 NW Allan Island	2.67	79.2	42-114
5 Cypress Reef	2.65	81.8	94-201
* SW Burrows Island	2.31	73.1	75-158
4 Strawberry Island	2.13	56.3	40-190
1 Rosario	1.53	33.3	29-175
* S Cypress Island	1.52	16.1	32-70
6 East Cone Island - south	1.52	6.9	148-250
7 SW Sinclair Island	1.29	4.9	28-113
1 Northwest Island	1.07	30.5	47-230
* Cypress-Eagle Bluff	0.43	0	44-54
* Cypress-Smugglers Cove	0.1	5.6	56-63

* These sites are outside candidate marine reserve boundaries.

The "Habitat Complexity Index" was calculated by averaging bottom type index values for each minute of survey time.

ROV "habitat complexity index" values ranged from a high value of 2.96 to a low of 0.10 (Table 5). Seven of the sites had complexity index values > 2.0, which indicates these sites had predominately rock and/or cobble substrate. Of the survey locations within the candidate reserve sites, Northwest Island, Sinclair Island and the Cone Island #1 locations had relatively low habitat complexity values (< 1.5).

A total of 1,473 fish were observed while monitoring the ROV survey video. The most abundant fish observed on the ROV surveys was the Puget Sound rockfish (*Sebastes emphaeus*). This species accounted for about 67 % of all fish observed. Percentage composition for the other species observed were: rockfish (other than Puget Sound rockfish) = 1.3 %, lingcod = 0.9 %, greenling = 3.7 % and cabezon = < 0.1 %. Mean fish total length was similar between ROV and scuba surveys (Table 4).

Discussion

Less than 1% of the world's oceans and 0.002% of U.S. territorial waters currently receive reserve protection, therefore a large challenge exists to protect biodiversity and targeted species within marine reserves considering the ecological effects of increasing human disturbance (Brailovskaya 1998, Carr *et al.* 2003). Implementation of a state protected marine reserve network in Skagit County would be an important precedent for further conservation of Puget Sound's biodiversity and marine resources. Berger *et al.* (2003) suggests that protecting 20% of the habitat within no-take reserves will benefit 78.8% of the present species, but protection of rare species requires specific management plans coupled with functional reserve networks. Given the present situation of declining rockfish populations, species specific management and marine reserves could aid in rockfish stock rebuilding.

A successful marine reserve network is dependent upon many factors such as size, shape, number, and location of reserve areas, enforcement, life history characteristics of targeted species, and ecological processes. The use of scuba and ROV surveys to explore the eight candidate marine reserve areas yielded useful data to qualitatively compare the sites since no surveys were replicated in 2003. However, six sites (Northwest Island, Rosario, Burrows Channel, N. W. Allan Island, and S. Allan Island) were previously surveyed in 2002 (Weispfenning 2002). There was not much variation in the number of observed bottomfish species, but the estimated fish densities differed between 2002 and 2003 (Fig. 4 and Fig. 5). These trends may be the result of natural variation in fish abundance or the experience of the survey team. The same trend in depth distribution was observed in 2002 as in 2003 (Fig. 3). Bottomfish were more abundant along the deeper scuba transects (45-65 ft), but ROV surveys observed fewer fish than were expected (Dinnel *et al.* 2003). It is believed that the ROV was potentially biasing by scaring the fish prior to seeing them on video. Figure 2 shows the difference in observed bottomfishes for all surveys and it is interesting how the same species abundance pattern is present for both scuba and ROV surveys. Scuba surveys appear to be more accurate in estimating bottomfish density and diversity based upon fish behavior in reaction to a diver versus the ROV. The use of video during scuba surveys may

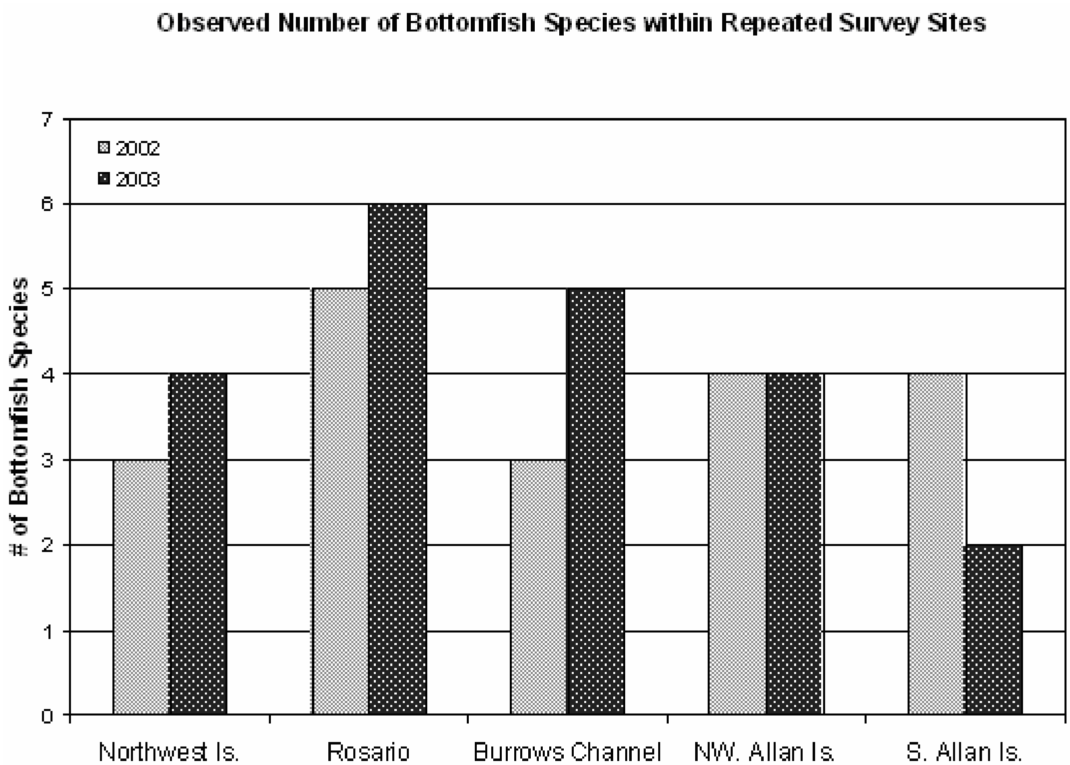


Figure 4. Observed bottomfish species richness at six sites repeatedly surveyed via SCUBA visual band transects during the summers of 2002 and 2003.

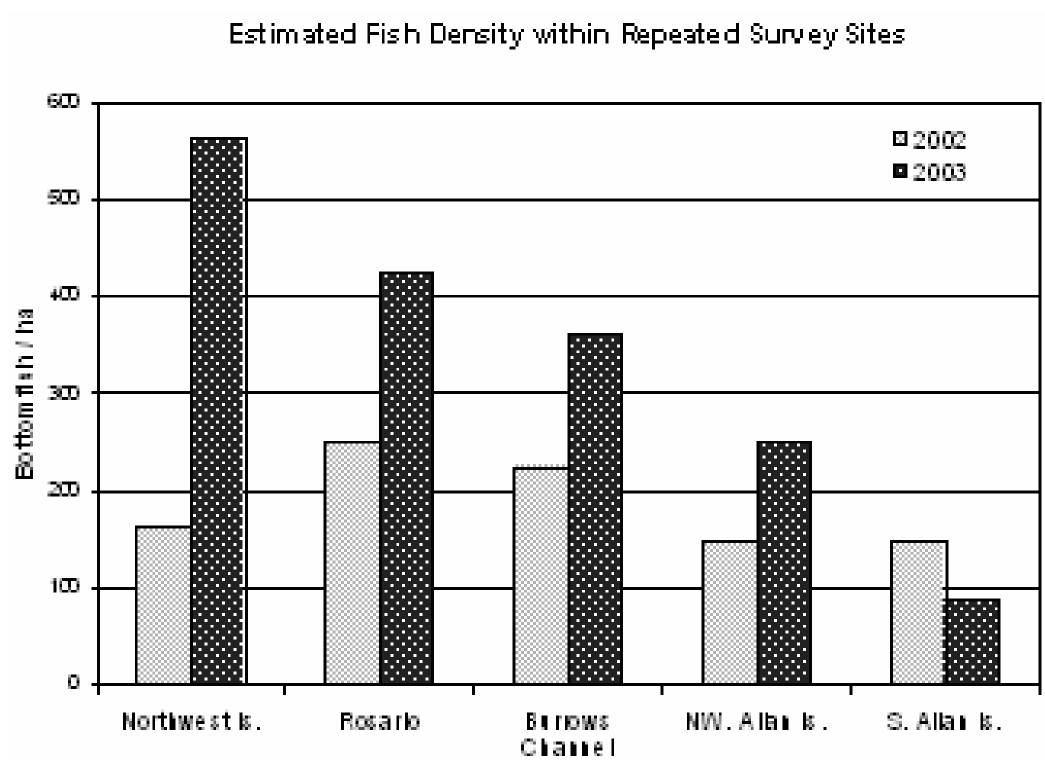


Figure 5. Difference in bottomfish density at six sites repeatedly surveyed via SCUBA visual band transects during the summers of 2002 and 2003.

be used as a tool to reduce observer bias in counting bottomfish, increase accuracy of total length measurements, and to permanently record habitat complexity and benthic species diversity. If camera lights are used, fish density estimates may be biased as a result of some species avoiding the light and possibly attracting other species. Additional research may focus on comparing bottomfish survey results involving the use of scuba and rebreathers.

The results of these baseline SCUBA surveys helped to identify potential marine reserve areas based upon habitat complexity and present bottomfish diversity. Rosario / Northwest Island (reserve area # 1) and Burrows Channel (reserve area # 3) appear to be the best reserve areas based on habitat complexity and the density and diversity of present rocky reef fish populations. Not only do these areas have complex rocky reef habitat and diverse fish communities, but are in locations that would facilitate monitoring and enforcement efforts. Visibility of these reserve areas by the public is an important aspect in preventing illegal activities within reserve boundaries. Burrows Channel receives sufficient boat traffic during summer (approximately one boat every four minutes) and is bordered by Washington Park and the Skyline Community. Both areas are popular recreational diving destinations due to easy access and diverse marine life and may ultimately serve to increase ecotourism to Anacortes. In addition, the Cone Islands (reserve area # 6) and Cypress Island (reserve area # 5) may also serve as suitable marine reserve areas. Further research and monitoring following implementation will be necessary to determine reserve success in meeting the primary objective of protection and conservation of bottomfish, especially rockfish (*Sebastes* spp.).

Acknowledgments

I thank my advisor, Dr. Paul Dinnel, for his assistance with the project and for his admirable work to protect rocky reef bottomfishes in Puget Sound. I would like to thank Gene McKeen, Nate Schwarck, Mike Parker, Western Washington University and Shannon Point Marine Center for making this project feasible. My dive buddies Pema Kitaeff, Rich Hoover, and Jason Hall were always ready to be my measuring tape anchors. Funding was generously provided by the Northwest Straits Commission, PADI Project AWARE Foundation, and the American Academy of Underwater Sciences.

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Scuba Techniques Used In Risk Assessment Of Possible Nuclear Leakage Around Amchitka Island, Alaska

Stephen Jewett[1], Max Hoberg[1], Heloise Chenelot[1], Shawn Harper[1], Joanna Burger[2], Michael Gochfeld,[3]
[1]Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK 99775-7220
[2]Division of Life Sciences, Consortium for Risk Evaluation with Stakeholder Participation (CRESP), and Environmental and Occupational Health Sciences Institute (EOHSI), 604 Allison Road, Rutgers University, Piscataway, NJ 08854-8082
[3]CRESP and EOHSI, UMDNJ-Robert Wood Johnson Medical School, Piscataway, NJ 08854

Abstract

Amchitka Island, in the Aleutians, had three underground nuclear tests (1965 to 1971) ranging from approximately 80 kilotons to 5 megatons. Initial surveys (1960s-1970s) did not report radioactive contamination in the marine environment. The U.S. Department of Energy (DOE) is moving to closure and Long-term Stewardship of Amchitka Island. Therefore, it is necessary for a reassessment of Amchitka's marine environment with respect to possible current or future transfer of radionuclides to marine ecosystems, particularly to sensitive or endangered species, and to foods harvested by Aleut and commercial fishermen. The Amchitka Science Plan was compiled by CRESP, a multi-university consortium of researchers, as a guideline for the reassessment. The overall objective of the Science Plan is to evaluate possible contamination of marine organisms of concern to subsistence hunters and fishers in Native Communities, the U.S. Fish & Wildlife Service, the Alaska Department of Environmental Conservation, DOE as well as other stakeholders, and to provide a baseline for future monitoring.

An assortment of marine organisms was collected at Amchitka and at a reference site (Kiska), including representatives of various trophic levels, sedentary/sessile plants and animals, and subsistence/commercial species in the intertidal and subtidal zones. A team of scuba divers from University of Alaska Fairbanks collected shallow (< 30 m) subtidal organisms during July 2004. This paper details the rationale and methods used by the divers to log nearly 93 hours of bottom time collecting thousands of samples of water, sediment, kelp, invertebrates, and fishes for radionuclide analyses.

Introduction

Amchitka Island, situated in a tectonically and seismically active area in the western Aleutians, was the scene of three underground nuclear test shots: Long Shot (~80 kilotons) in 1965; Milrow (~1 megatons) in 1969; and Cannikin (~5 megatons) in 1971 (Figs. 1 and 2). Amchitka Island is unusual among US legacy sites of the Cold War in a number of ways:

- Underground nuclear explosions of exceptional size including the largest (Cannikin) ever;
- Location within an actively deforming plate boundary characterized by intense earthquake activity;
- Remote location and difficulty of access;

- Proximity to Asia;
- Location within an important international fishery;
- Protected status as a National Wildlife Refuge with endangered species; and
- Part of the marine environment that supports the subsistence lifestyle of indigenous people and significant commercial fisheries.

Figure 1. Location of Amchitka Island relative to the State of Alaska.

Many concerns over earthquakes, pollution, and marine resources were voiced at the time of the testing. Initial surveys did not report evidence of radioactive contamination in the marine environment, and residual radionuclides were considered confined to the test cavities (Merritt and Fuller 1977). At present, the U.S. Department of Energy (DOE) is moving to closure of contaminated sites and longterm stewardship. Therefore, it is necessary to reassess the marine environment with respect to possible current or future transfer of radionuclides and other contaminants to the sea, to foods harvested by Aleut fishers and hunters, foods of commercial interest, and selected representatives of marine food webs. It is also necessary to develop plans for the scope and frequency of the monitoring that will be needed in the long term stewardship program.

The cause for stakeholder concern is that residual radionuclides from nuclear tests may migrate through the fractured and faulted rock, carried by groundwater, and enter the marine food chain causing ecological and human health effects. As a result of this concern, Alaska Department of Environmental Conservation (ADEC) and DOE requested that the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) take the lead role in organizing and implementing the Amchitka Independent Assessment Science Plan (hereinafter referred to as Science Plan) (Burger et al. 2005). CRESP is a multi-university consortium of

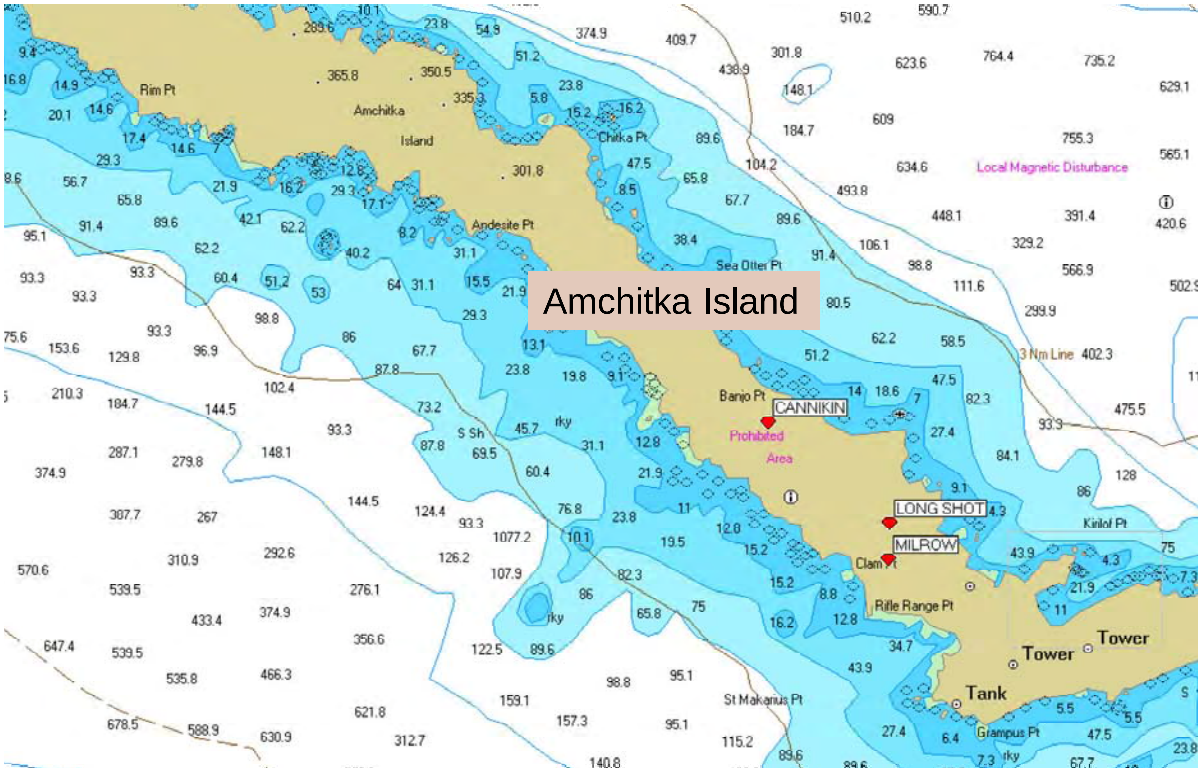

Figure 2. Location of three nuclear test blasts on Amchitka Island: Long Shot (~80 kilotons) in 1965; Milrow (~1 megaton); and Cannikin (~5 megatons) in 1971. Depth is in meters.

researchers dedicated to assisting DOE in the planning and prioritizing of its massive environmental management responsibilities, through the involvement of stakeholders at each step of the risk management process. Members of the Amchitka CRESP team are from U Maryland and New Jersey-Robert Wood Johnson Medical School, Rutgers U., Vanderbilt U., U. Pittsburgh, U. Alberta, and U. Alaska Fairbanks. The Amchitka CRESP team mobilized to implement the Science Plan with a three-phase field expedition in 2004.

Approach and Rationale

Since the potential exists for radionuclides from the test shots to be carried into the marine environment by freshwater through seeps along faults and fractures, research is needed to determine the location where these discharges may occur. To address this need a physical oceanographic survey (Phase I) was conducted from the 49-m F/V Ocean Explorer during June 12-23 by UAF Physical Oceanographer Mark Johnson and a group from the Naval Undersea Warfare Center, Keyport, Washington. Twelve transects were established adjacent to Cannikin and Long Shot and perpendicular to shore at depths ~30-90 m (Fig. 3). These transects covered an area determined in part by the location of fault lines nearest to the blast sites and extending in a parallel direction offshore. Due to the presence of extensive canopy-forming kelp, depths < 30 m could not be surveyed by the Ocean Explorer. The team used a multibeam echosounder to construct the bathymetry, a side scan sonar with sub-bottom profiler to map the substrate, and a Conductivity-Temperature-Density (CTD) instrument to determine whether there is fresher-than-expected water near the ocean floor. Bottom water and sediment samples were also collected for radionuclide analyses. No physical oceanographic transects were established off Milrow due to budgetary constraints. Another task conducted on land simultaneously during Phase I was magnetotulleric and audiomagnetotulleric testing of the subsurface on Amchitka by Physicist Martyn Unsworth, U. Alberta. This task was carried out along the cross-island transects contiguous to the nuclear test shots, to characterize the Amchitka rock mass and to identify the depth and location of the most likely groundwater pathways from the island to the sea.

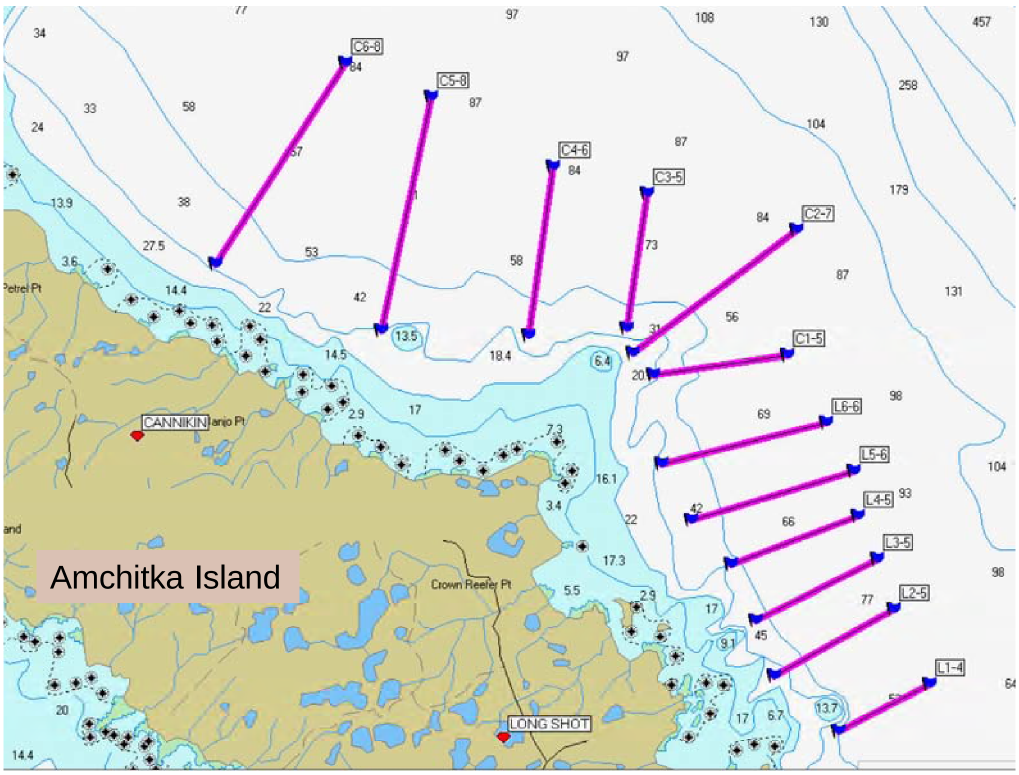

Figure 3. CTD transects established adjacent to Cannikin and Long Shot, June 2004 (Source: Dr. Mark Johnson, UAF). Depth is in meters.

A second survey (Phase II) was carried out from June 29 through July 19 aboard the Ocean Explorer to sample the marine benthic environment inside the 30-m depth by scuba divers. Divers from UAF focused on eastern Amchitka Island and Kiska Island, the Reference site situated approximately 80 km west of Amchitka (Fig. 4). Transects established for physical oceanography off Cannikin and Long Shot were extended to shore and transects established off Milrow and Kiska Island (Figs. 5-7) were sampled by divers. The rationale for positioning the Milrow transects was based on proximity to this test shot and known fault lines. Locations of the Kiska Island transects were based mainly on proximity to shore-based sampling sites on the east and west sides of the island. Divers collected sediment, water, algae and animals at about 5, 9, 18, and 27-m depths along transects. Limited sampling occurred at the 27-m depth due to the need to adhere to no-decompression diving at this remote region. Diving operations were conducted by two teams each consisting of two divers and a tender using an inflatable skiff. Dive sites along transects were determined with the aid of portable depthsounders (Speedtech Instruments Model SM-5) and GPS units (Garmin GPSmap 60CS with BlueChart electronic nautical charts). Dive teams worked adjacent dive sites simultaneously and they were in constant radio contact.

At each dive site divers descended to the anchor and sampled within a ~60-m radius of the anchor. Dive time at each site varied from 20-60 minutes, depending upon the depth. Each diver had a mesh bag ("goody bag") and dive knife for collecting organisms. One diver also had a spear for spearing fishes and octopus and containers for water and sediment. Water and sediment sampling in all shot site areas surrounding Amchitka Island was performed to fulfill the Radiological Health and Safety provisions of the overall Amchitka Expedition, Health and Safety Plan and to supplement the physical and biological data collected on the expedition. Typically two 1-L plastic containers of water were collected within 1 m of the bottom. Containers were filled at the surface and purged at depth and replaced with bottom water. Wherever soft substrate was encountered a 1-L plastic container was filled with surface (to 5 cm deep) sediment by plowing the open jar across the substrate. Digital still and video recordings were made of the diving activities.

Phase III of the CRESP expeditions was carried out in deeper waters around Amchitka and Kiska islands aboard the biennial NOAA Aleutian Islands bottom trawl survey. CRESP researcher, James Weston, collected designated fishes and other marine biota from the F/V Gladiator during July 18 and August 7.

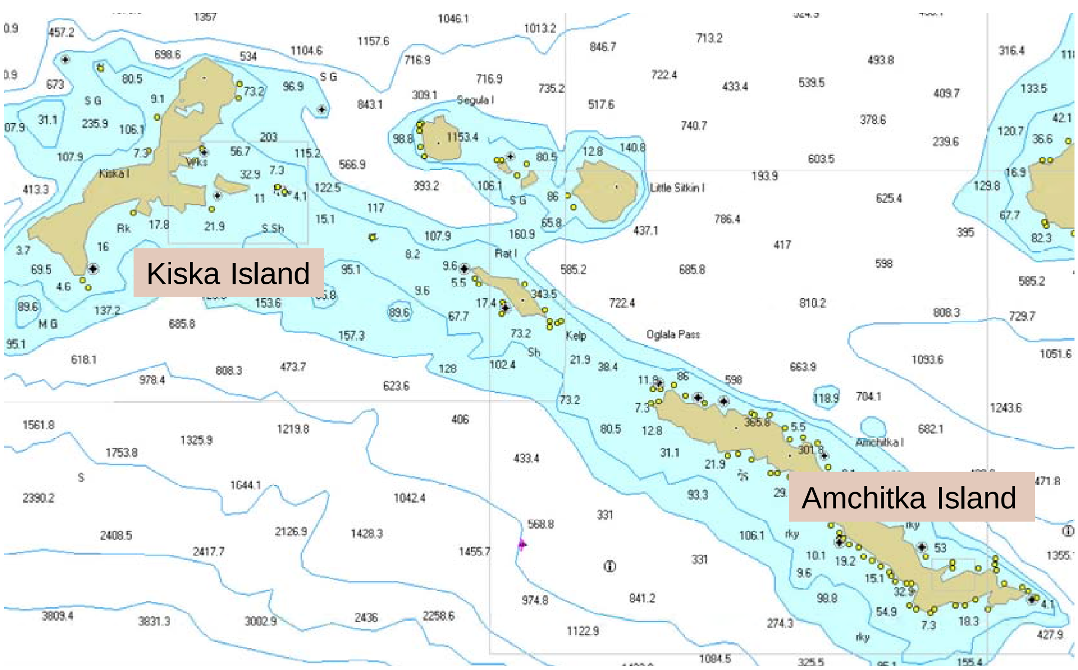

Figure 4. Map showing Amchitka Island and Kiska Island (Reference). Depth is in meters.

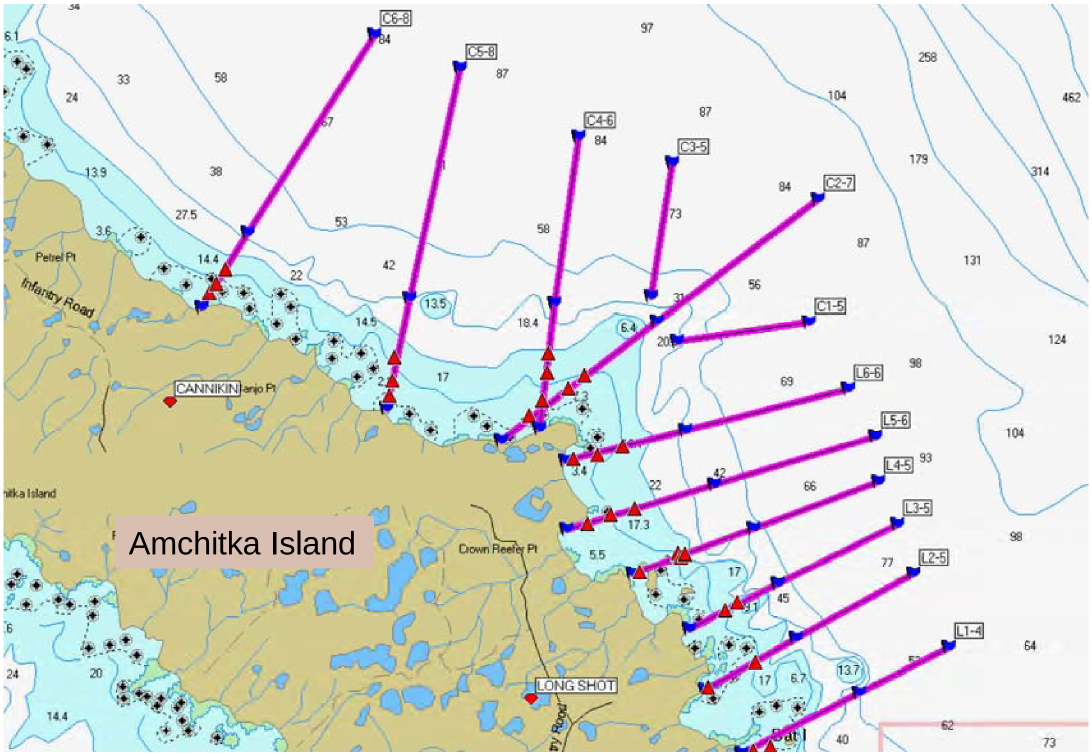

Figure 5. Dive locations (red triangles) adjacent to Cannikin and Long Shot where samples were collected July 2004. Depth is in meters.

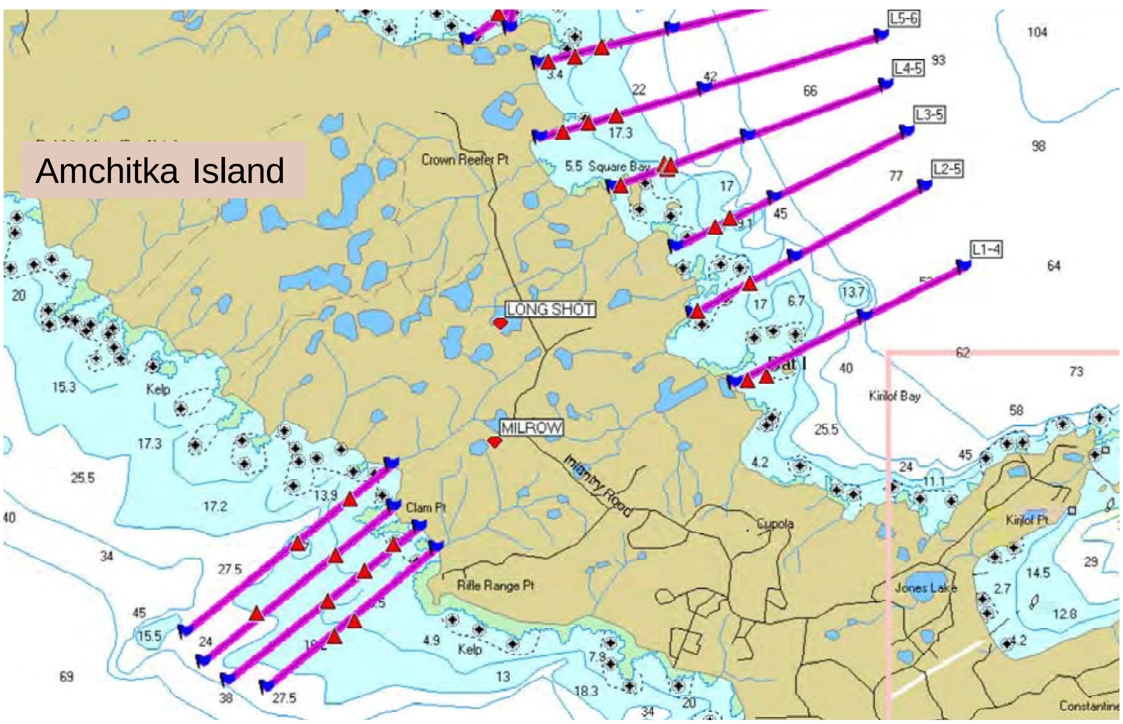

Figure 6. Dive locations (red triangles) adjacent to Milrow and Long Shot where samples were collected July 2004. Depth is in meters.

Figure 7. Dive locations (red triangles) off Kiska Island (reference site) where samples were collected July 2004. Depth is in meters.

Organisms targeted for collection included some subsistence and commercial species (Table 1), species previously tested for radionuclide analyses (Table 2), species trophically important, and species with various modes of mobility, longevity and feeding. Approximately 1500 g wet weight (composited) of each species was targeted per site. All samples including water, sediment and biota were screened for radioactivity in the field to insure that expedition personnel were not exposed to radiation in excess of HASP exposure guidelines. Organisms collected by divers are presented below mainly by feeding mode, but other life-history attributes are presented.

Primary Producers

The dominant primary producers were brown algae (kelp), mainly *Alaria fistulosa*. This canopy-forming subtidal species is an annual and can attain lengths up to 25 m (O'Clair et al. 1996). For kelp collections, 1 m of the plants' proximal (including holdfast and sporophylls) and distal ends were cut off and bagged. Five replicates were collected per site. Other species of brown algae collected less frequently included *A. nana*, *Laminaria bongardiana*, *L. yezoensis*, *L. saccharina*, *Agarum clathratum*, *Cymathere triplicata* and *Fucus gardneri.* The latter species was collected intertidally without diving.

Grazers

The dominant grazer or herbivore collected was the green sea urchin *Strongylocentrotus polyacanthus*. This urchin feeds mainly on kelp, including A. fistulosa, while it is the main food of sea otters, as well as occasionally eaten by Aleut residents of Atka, Alaska. Approximately 12 or more large urchins were bagged from each site. Another grazer included the gumboot chiton or giant Pacific chiton *Cryptochiton stelleri*, the largest chiton (to 33 cm long) in the world. These brick red organisms were typically pried off rocks by hand, unlike smaller chitons of other species that require tools to extract them. This chiton feeds on a variety of young kelps and it is eaten by Aleut residents from Atka. Cryptochiton can live to more than 20 years (O'Clair and O'Clair 1998). Although generally low in density, 2-6 individuals were collected at sites where possible.

Filter feeders

The dominant filter feeder or suspension feeder collected was Jingle Shell or Alaska Falsejingle Pododesmus macroschisma. Much of the carbon of this bivalve is derived from detritus sloughed off the blades of growing kelps (O'Clair and O'Clair 1998). It is mainly eaten by a variety of sea stars. The size of the jungles that were collected approximated 8-12 cm wide. It was pried off rocks using a knife and generally 6-12 individuals were collected per site. Another filter feeder taken was an unidentified spherical tan sponge with a size to ~10 cm in diameter. This sponge was relatively ubiquitous, but low in density. Some sponges are known to be long-lived, perhaps in excess of a hundred years (O'Clair and O'Clair 1998). Generally 6-12 individuals were collected per site. Other filter feeders collected were the Northern Horse Mussel *Modiolus modiolus* and Blue Mussel *Mytilus trossulus*. Modiolus was more common than Mytilus, however, both species were in low densities. Modiolus, which attains a larger size than Mytilus, required much time to dig out of rocky crevasses where they were secured by byssal threads and camouflaged by a variety of epiphytic organisms. Typically 4-6 individuals of each species were collected where possible.

Deposit feeders

The only deposit feeder collected was the sand dollar *Echinarachnius parma*. This organism was taken partially buried within the sand surface;, however, only a few sites had sandy sediment. Because of the low density only 4-6 individuals were taken per site.

Predators/scavengers

The snail known as the Oregon Triton or Hairy Triton *Fusitriton oregonensis* was a common predator/scavenger invertebrate. This snail, which attains lengths up to 12 cm, was typically cryptic with various epiphytic organisms attached to their shell.

Fusitriton feeds on a wide variety of invertebrates (O'Clair and O'Clair 1998). Typically 4-6 individuals of this snail were taken where possible. Another invertebrate predator/scavenger was the Giant octopus *Octopus dofleini*. This species feeds on a variety of benthic organisms and it is taken by sea otters and occasionally by subsistence harvesters at Atka. Although this species is not long-lived (<5 years), it can attain very large size - to 272 kg (O'Clair and O'Clair 1998); specimens collected by divers ranged up to 23 kg. This octopus typically required both divers to subdue by spearing and bag at depth.

Fish predators collected by divers with spears mainly included Rock greenling *Hexagrammos lagocephalus*, Irish lords *Hemilepidotus jordani* and *H. hemilepidotus*, rockfishes *Sebastes ciliatus*, *S. melanops*, Pacific cod *Gadus macrocephalus*, and Rock sole *Lepidopsetta bilineata*. Typically less than six individuals of each of these species were taken at a site. The Rock greenling, known locally as "Pogie", is harvested by subsistence users at Atka; adults as well as eggs deposited on kelp and rocks are taken. This is a very territorial fish and relatively easy to approach and spear. Pacific cod are taken for subsistence and commercial purposes. The only species taken from the less encountered sandy substrate was Rock sole. This species feed mainly on benthic invertebrates, while the other fishes feed on benthic and pelagic invertebrates and fishes.

Table 1. Marine species most commonly harvested for subsistence in Atka, Alaska (source: Bartell et al. 1999) and most commonly harvested commercially near Amchitka Island (source: Kruse et al. 2000; Witherell 2000).

Subsistence Food	Commercial Food
Sea Lion	Atka Mackerel
Pacific Salmon	Pacific Cod
Pacific Halibut	Walleye Pollock
Harbor Seal	Pacific Ocean Perch
Chiton	Sablefish
Pacific Cod	Pacific Halibut
Octopus	Turbot
Sea Urchin	Greenland Turbot
Dolly Varden	Brown King Crab
Rock Greenling (“Pogie”)	

Table 2. Marine plants and animals collected for radiological analyses near Amchitka Island in 1965-75 (source: Merritt and Fuller 1977) and 2004 (present study).

1965-75

Mammals	**Fishes**	**Invertebrates**	**Algae**
Sea otter	Rattail	Sponge	Red - *Corallina*
	Cal. Smoothtongue	Jellyfishes	Red - *Constantinea*
	Dolly Varden	Blue Mussel	Red - *Porphyra*
	Salmon (5 spp.)	Weathervane Scallop	Red - *Halosaccion*
	Lantern Fish	Snails	Brown - *Alaria*
	Northern Lampfish	Squid	Brown - *Fucus*
	Pacific Cod	Octopus	Brown - *Laminaria*
	Walleye Pollock	Mysid	Brown - *Hedophyllum*
	3-Spine Stickleback	Krill	Brown *Thalassophyllum*
	Pacific Ocean Perch	Isopod	Green - *Ulva*
	Dusky Rockfish	Amphipod	
	Rock Greenling	Tanner Crab	
	Atka Mackerel	Horse Crab	
	Red Irish Lord	Red King Crab	
	Sculpin	Brown King Crab	
	Pacific Halibut	Basket Star	
	Turbot	Sea Urchin	
	Rock Sole		

2004

Mammals	**Fishes**	**Invertebrates**	**Algae**
	Pacific Cod	Sponge	Brown - *Alaria*
	Pacific Ocean Perch	Blue Mussel	Brown - *Fucus*
	Dusky Rockfish	Horse Mussel	Brown - *Laminaria*
	Rock Greenling	Rock Jingle	Brown - *Agarum*
	Atka Mackerel	Gumboot Chiton	Brown - *Cymathere*
	Red/Yellow Irish Lords	Oregon Triton	
	Pacific Halibut	Octopus	
	Rock Sole	Brown King Crab	
		Sea Urchin	
		Sand Dollar	

Results

Samples were collected for radionuclide analyses by divers at 50 transect sites, with 17 at Long Shot, 9 at Milrow, 12 at Cannikin and 12 at Kiska Island, the Reference (Table 3).

Opportunistic sampling also was carried out at Constantine Harbor (Amchitka) and Kiska Harbor on days when foul weather prevented sampling on transects. Dive sampling resulted in 136 dives for a total bottom time of nearly 93 hours. Samples included bottom water, sediment, four genera of brown algae, nine genera of benthic invertebrates, and six genera of fishes. Organisms were selected for analyses based on their importance in subsistence and commercial fisheries (Table 1), history of radiological baseline information (Table 2), mobility (Table 4), and life history traits. The CRESP team has initiated the processing of the specimens for testing at Idaho National Engineering and Environmental Laboratory (INEEL) and Vanderbilt U. Isotopes of interest for analysis in this study are the gamma emitters ^{137}Cs, ^{152}Eu, ^{60}Co; alpha emitters $^{238, 239, 240, 241}$Pu, $^{234, 235, 236, 238}$U, ^{241}Am; and beta emitters ^{90}Sr, ^{3}H, ^{99}Tc, ^{129}I. Of these, ^{137}Cs and ^{90}Sr are most likely to accumulate in muscle (soft tissue) and cause human health risks through consumption. The other isotopes that are expected to result from the test shots accumulate preferentially in either skeletal material (bones or exoskeletons) or specific organs, with a lesser distribution in muscle. Details of the sample preparations and radionuclide analytical results will be presented in a report scheduled for Spring 2005.

Table 3. Marine locations around Amchitka and Kiska islands where UA divers collected water, sediment, brown algae, invertebrates and fishes for radionuclide analyses, June 29 - July 19, 2004. X indicates where a sample was collected.

LOCATION	SITE NAME/a	COORDINATE	WATER	SEDIMENT	ALARIA	LAMINARIA	AGARUM	CYMATHERE	SPONGE	BLUE MUSSEL	HORSE MUSSEL	JINGLE SHELL	GUMBOOT CHITON	OREGON TRITON	GIANT OCTOPUS	SEA URCHIN	SAND DOLLAR	ROCK GREENLING	IRISH LORDS	ROCKFISHES	PACIFIC COD	ROCK SOLE
Constantine Harbor	RECON	N 51 24.885 E 179 17.892														X						
Constantine Harbor Doc	CONST DOCK	N 51 24.445 E 179 17.504								X		X										
Long Shot Transect BL1	BL1-15A	N 51 25.388 E 179 13.738														X						
Long Shot Transect BL1	BL1-15B	N 51 25.421 E 179 13.95	X		X											X						
Long Shot Transect BL2	BL2-15	N 51 25.881 E 179 13.10	X													X						
Long Shot Transect BL2	BL2-30	N 51 26.071 E 179 13.698			X											X						
Long Shot Transect BL2	BL2-60	N 51 26.099 E 179 13.75	X													X						
Long Shot Transect BL3	BL3-30	N 51 26.512 E 179 13.36	X		X											X		X				
Long Shot Transect BL3	BL3-60	N 51 26.480 E 179 13.52	X									X	X			X		X	X			
Long Shot Transect BL4	BL4-15	N 51 26.820 E 179 12.261							X	X	X	X	X	X		X		X				
Long Shot Transect BL4	BL4-30	N 51 26.973 E 179 12.766			X							X	X			X		X				
Long Shot Transect BL4	BL4-60	N 51 26.981 E 179 12.91	X						X			X	X	X		X		X	X			
Long Shot Transect BL4	BL4-90	N 51 26.963 E 179 12.84	X	X		X			X			X	X	X		X						X
Long Shot Transect BL5	BL5-15	N 51 27.209 E 179 11.588							X	X	X	X				X		X	X			
Long Shot Transect BL5	BL5-30	N 51 27.278 E 179 11.886			X				X			X	X	X		X		X	X			
Long Shot Transect BL5	BL5-60	N 51 27.331 E 179 12.20	X	X													X					X
Long Shot Transect BL6	BL6-15	N 51 27.729 E 179 11.417							X		X	X	X			X						
Long Shot Transect BL6	BL6-30	N 51 27.760 E 179 11.724			X				X			X	X	X	X	X		X				
Long Shot Transect BL6	BL6-60	N 51 27.831 E 179 12.04	X			X			X			X	X	X		X		X	X	X		
Milrow Transect BM1	BM1-30	N 51 23.638 E 179 09.16	X		X																	
Milrow Transect BM1	BM1-60	N 51 23.524 E 179 08.92	X			X	X		X		X	X		X		X		X	X			
Milrow Transect BM2	BM2-15	N 51 24.193 E 179 09.613				X		X	X			X	X			X		X		X		
Milrow Transect BM2	BM2-30	N 51 23.999 E 179 09.27	X		X	X	X	X	X			X				X						
Milrow Transect BM2	BM2-60	N 51 23.785 E 179 08.84	X			X	X		X		X	X				X						
Milrow Transect BM3	BM3-30	N 51 24.116 E 179 08.93	X		X	X			X		X	X				X		X				
Milrow Transect BM3	BM3-60	N 51 23.696 E 179 08.02	X						X			X		X		X		X	X			
Milrow Transect BM4	BM4-30	N 51 24.527 E 179 09.10	X		X				X			X				X		X				
Milrow Transect BM4	BM4-60	N 51 24.199 E 179 08.50	X	X					X			X				X		X		X		
Cannikin Transect BC2	BC2-15	N 51 28.072 E 179 10.838							X		X	X				X						
Cannikin Transect BC2	BC2-30	N 51 28.289 E 179 11.341			X						X	X	X	X		X		X	X			
Cannikin Transect BC2	BC2-60	N 51 28.393 E 179 11.55	X						X		X	X	X	X	X	X		X	X	X		
Cannikin Transect BC4	BC4-30	N 51 28.197 E 179 11.007							X		X	X	X			X		X	X	X		
Cannikin Transect BC4	BC4-60	N 51 28.418 E 179 11.07	X			X			X		X	X		X	X	X		X				
Cannikin Transect BC4	BC4-90	N 51 28.578 E 179 11.08	X			X			X			X		X		X			X			
Cannikin Transect BC5	BC5-15	N 51 28.236 E 179 09.040		X		X					X					X		X			X	
Cannikin Transect BC5	BC5-30	N 51 28.356 E 179 09.067		X	X							X	X		X	X						
Cannikin Transect BC5	BC5-60	N 51 28.540 E 179 09.10	X	X													X					X
Cannikin Transect BC6	BC6-15	N 51 29.058 E 179 06.712		X	X	X		X								X		X				
Cannikin Transect BC6	BC6-30	N 51 29.136 E 179 06.804			X								X			X		X				
Cannikin Transect BC6	BC6-60	N 51 29.244 E 179 06.91	X						X		X	X	X	X	X	X		X	X	X	X	
Kiska Harbor Dock	KISKA DOCK	N 51 58.708 E 177 32.828								X		X		X		X			X			X
Kiska Transect BK1	BK1-30	N 52 02.252 E 177 30.057			X							X	X			X						
Kiska Transect BK1	BK1-60	N 52 02.259 E 177 29.91	X						X			X	X			X		X	X	X		
Kiska Transect BK2	BK2-15	N 52 01.426 E 177 29.902							X		X	X				X		X				
Kiska Transect BK2	BK2-30	N 52 01.492 E 177 29.742			X	X	X				X	X	X	X		X		X	X			
Kiska Transect BK2	BK2-60	N 52 01.489 E 177 29.68	X						X		X	X		X		X			X			
Kiska Transect BK3	BK3-30	N 51 58.516 E 177 33.925			X	X											X					X
Kiska Transect BK3	BK3-60	N 51 58.342 E 177 33.76	X	X												X						X
Kiska Transect BK4	BK4-30	N 51 59.464 E 177 34.500																				X
Kiska Transect BK4	BK4-60	N 51 59.531 E 177 34.810		X													X					X
Kiska Transect BK5	BK5-15	N 51 59.108 E 177 34.601									X	X	X			X		X	X	X		
Kiska Transect BK5	BK5-30	N 51 59.317 E 177 34.581			X							X	X	X		X						
Kiska Transect BK5	BK5-60	N 51 59.087 E 177 35.06	X								X	X	X			X		X	X			

a = Site name: B=Biological, L=Long Shot, M=Milrow, C=Cannikin, K=Kiska, 1-6=transect #, -15=intertidal to 15 ft (~5 m), -30=30 ft (~9 m), -60=60 ft (~18 m), -90=90 ft (~27 m).

Table 4. Mobility traits influencing selection of screening marine species for radionuclide analyses
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Mobility	Importance	Species
Sedentary	Provides an indication of point exposure	Brown Algae, Sponge, Rock Jingle, Mussels
Locally mobile	Integrates exposure over a few meters of designated site	Gumboot Chiton, Oregon Triton, Sand Dollar, Sea Urchin, Rockfishes, Rock Greenling
Mobile	Provides an indication of local movement within a few km of designated site	Octopus, Brown King Crab, Irish lords
Migratory	Provides an indication of regional exposure	Atka Mackerel, Pacific Ocean Perch, Pacific Cod, Walleye Pollock, Flatfishes

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NOAA's Diving Accident Management Program: A Review of Current Capabilities and Plans for Improvement

David A. Dinsmore[1] and CAPT Michael L. Vitch, USPHS[2]
[1]NOAA Diving Program, 7600 Sand Point Way, NE, Seattle, WA 98115-0070
[2]NOAA Marine And Aviation Operations, 1315 East-West Highway, Silver Spring, MD 20910-3282

Abstract

Since 1989, the NOAA Diving Program has experienced a substantial increase in the number of NOAA divers, number of dives, and hours of bottom time; and this trend is expected to continue. With increased activity, come increased opportunities for accidents and injuries. Diving is an important, yet potentially hazardous activity performed by NOAA personnel; often at great distances away from definitive medical care. Many of the risks associated with diving can be mitigated through comprehensive training; the establishment of, and adherence to, reasonable standards and procedures; and the use of top-quality, well-maintained diving equipment. However, injuries can still occur even if a diver does nothing wrong procedurally. Therefore, adequate and appropriate safeguards must be in place to respond to diving emergencies when and wherever they may occur. Upon review of NOAA's dive accident management program, it was evident that current safeguards did not adequately meet these criteria – therefore, additional policies were required to help ensure adequate and appropriate safeguards. This paper outlines the results of the review and the steps to be taken to improve NOAA's dive accident management capability.

Introduction

NOAA has a variety of programs that require research below the ocean's surface. This research is conducted using a variety of diving methodologies including scuba diving, seafloor habitats, remotely operated vehicles, and manned submersibles.

Scuba diving plays an important role in helping NOAA meet its ocean data acquisition requirements. By physically "being there," divers can interact with their environment and make critical decisions about the work being performed. Despite all the technological advances today, no robotic system (e.g., remotely operated vehicle, autonomous underwater vehicle, manned submersible) can duplicate what humans can do using their hands, their minds, and their senses. It is the human presence that makes the difference. For shallow water applications, diving is a safe, efficient, and cost-effective means of collecting data and performing tasks underwater.

Background

Over the past 14 years, the NOAA Diving Program (NDP) has seen a steady increase in diving activity throughout NOAA's Line Offices. This increase can be attributed to a number of factors, most notably: 1) an increased number of research programs requiring work by divers, and 2) the development of a new "scientific diver" certification.

Since 1989 there has been a 74% increase in the number of NOAA divers (Figure 1). As the number of divers increased, so too have the number of dives performed and hours of bottom time recorded (Figure 2). The NDP has seen a 108% increase in the number of dives performed and a 117% increase in hours of bottom time accumulated in the same time period. Bottom time is significant since it directly correlates to productivity.

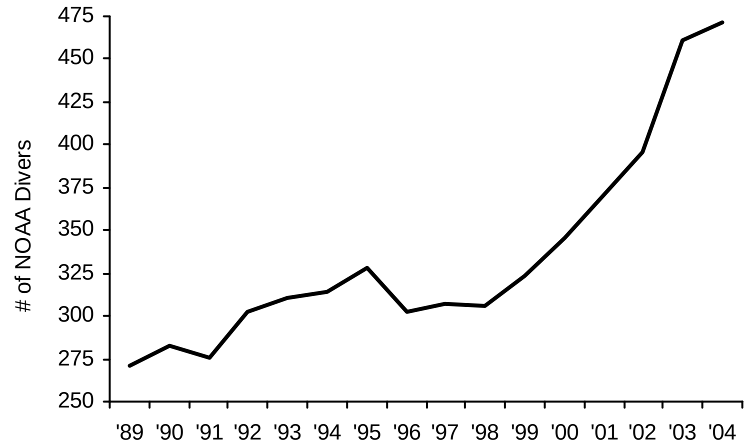

Figure 1: Number of NOAA divers FY 1989 thru 2004

This trend of increased diving activity is expected to continue in the foreseeable future as NOAA establishes new research areas and programs that require the use of diving to collect data and perform work underwater.

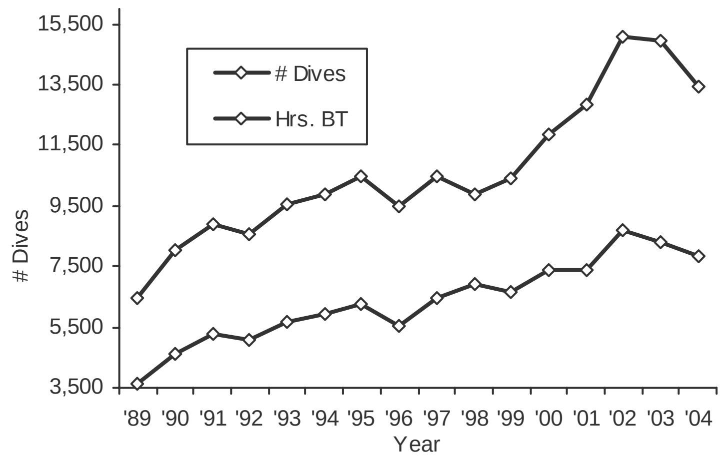

Figure 2: Number of dives & hours bottom time FY 1989 thru 2004.

Hazards of Diving

With increased activity comes increased opportunity for accidents and injuries. During the 2003 field season, a diving-related incident occurred on a NOAA ship while operating in the remote Northwest Hawaiian Islands. Although the incident did not require evacuation and was handled onboard by the ship's crew, had the incident been more serious requiring evacuation, the nearest medical facility was more than 36 hours away.

During the same period a NOAA employee diving off the coast of California experienced undeserved (i.e., the diver did nothing wrong, but still contracted the malady) spinal cord decompression sickness, but did not report the incident for several days. Although the diver was eventually treated in a hyperbaric chamber, the symptoms were not totally resolved – resulting in the diver not being able to work for a full six months. The individual has since returned to work part-time, with continued residual symptoms, and significant medical bills (six figures) that the Agency is covering through OWCP. Such cases can result from any significant delay to recompression therapy. Operating in remote areas without chamber support makes this a distinct possibility for future occurrence, as almost all of NOAA's experiences with DCS have involved 'undeserved' hits.

In FY ’04, there were five (5) documented cases of DCS-Type II (neurologic) - all occurring during training sessions where rapid availability of recompression was present - but all 'undeserved' cases nonetheless. These incidents are a reminder that diving is an inherently hazardous activity and injuries can occur anywhere and at anytime.

As a result of these “near-misses,” the Director, NOAA Marine and Aviation Operations (NMAO) requested a thorough review of NOAA’s diving accident management capability and recommendations for improvements.

Diving Accidents & Injuries

The injuries associated with diving can be divided into two general categories: operational and physiological.

Operational injuries are those that occur as a result of working in and around the water, and are frequently caused by human error. Two examples of such injuries include drowning and trauma. Drowning and/or near drowning can occur from a variety of causes including equipment failure, anxiety and panic, poor diving technique and/or training, lack of experience, and running out of air. According to the Divers Alert Network (DAN 2004), drowning is the number one cause of deaths in divers.[1] Trauma can also result from a variety of activities including problems with entering and exiting the water, being struck by boats, and general cuts and bruises from sharp objects and marine life.

Physiological injuries are those directly or indirectly related to complications of pressure changes to the human body. Barotrauma is the term used to describe “pressure-related injuries,” and is typically caused by a pressure differential between the air spaces in the human body and the ambient (surrounding) water pressure. Such injuries can occur both on descent (increased pressure) and on ascent (decreased pressure). Examples of injuries that can result from increased pressure on descent are ear, sinus, and mask squeezes. Although not life-threatening, these injuries can be painful, and in the case of ear barotrauma, can result in partial or total hearing loss.

Injuries that occur on ascent are generally more serious in nature than those occurring on descent. The two major injuries associated with decreasing ambient pressure are lung overpressurization and decompression sickness.

Lung overpressurization injuries result from the expansion of air in the lungs during ascent. If the excess gas is not vented, via exhalation, the lungs will continue to expand to the point of rupture, inducing gas into various body areas. The physiological consequences (pathophysiology) of these bubbles depend on where they come to rest in the body. In the most severe case, the bubbles are forced into the arterial blood supply via the alveoli sacs and arterioles of the lungs. The bubbles often travel from the lungs to the brain where they become lodged in ever decreasing sized arteries, eventually occluding blood flow. The signs and symptoms of such an insult, referred to as an "arterial gas embolism or 'AGE'," frequently mirror that of a cerebral blood thrombosis, better known as a "stroke." Such symptoms may range from numbness, to partial or total paralysis, to unconsciousness or death. As with a stroke, time to treatment is critical and may make a difference between life and death for the patient.

The most common cause of lung overpressurization in diving is holding one's breath during ascent. Proper breathing technique is one of the most basic and fundamental skills taught in all dive training classes. With proper training, lung overpressurization injures are normally preventable.

Decompression sickness, also known as the "bends," is the second major type of barotrauma that can occur on ascent. This malady is caused by a rapid ambient pressure reduction during ascent which allows dissolved inert gas (typically nitrogen) to come out of solution in the blood and other aqueous tissues of the body in the form of bubbles. As with lung overpressurization injuries, the final resting place of these bubbles will determine the physiological insult experienced by the diver. Signs and symptoms of decompression sickness (DCS) range from pain in joints, to numbness, to partial or total paralysis. Should a bubble lodge in the portion of the brain that controls breathing or heart function, the results could be fatal. Like lung barotrauma, time to treatment is critical. However, unlike lung barotrauma, DCS is not totally preventable - that is, a diver can still contract DCS even if they do not exceed their maximum allowed bottom time or the prescribed ascent rate to the surface. This fact emphasizes the perplexing and difficult task of preventing DCS.

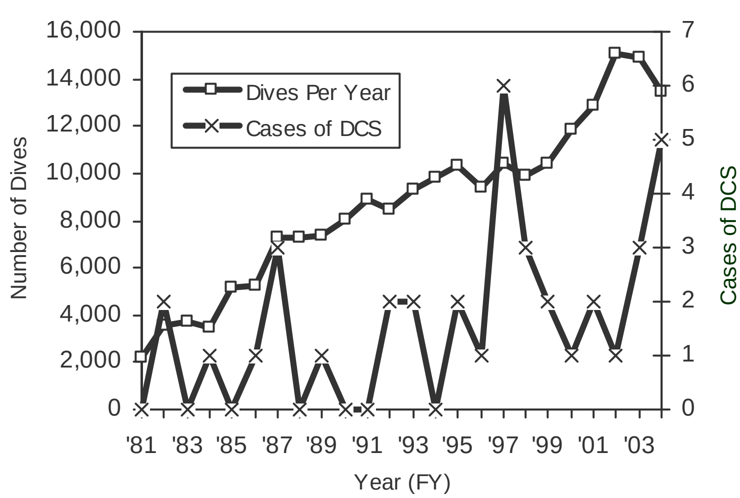

Figure 3: Number of dives and cases of DCS FY 1981 thru 2004.

From 1981 through 2004, NOAA divers conducted 208,459 dives. During this time there were 38 cases of decompression sickness reported and treated using recompression therapy (Figure 3). These statistics correlate to an incident rate of .018% or 1 case per approximately 5,500 dives. All of these cases of DCS were undeserved. Experts in the field of decompression attribute such occurrences to the physiological differences between humans.

The formation of bubbles within the human body has a number of detrimental affects on an individual. As mentioned, if bubbles are formed within the vascular system, they may disrupt or totally block blood flow, thus depriving vital organs and systems of life-sustaining oxygen. Bubbles in the circulatory system can also stimulate blood clotting which further obstructs normal blood flow. Extravascular bubbles; that is, outside the circulatory system such as in muscles tissue, tendons, ligaments, or bones, can press on nerves and other body parts disrupting normal functioning and creating pain. Finally, there are data that bubbles in the body are perceived as foreign bodies, thus triggering the formation of chemical processes to surround and attack the bubbles. It is still unclear what effect such processes have on the initial or final outcome of the insult.

Recognition and Treatment of Diving Maladies

Pathophysiology of AGE and DCS

The physiological affects of Arterial Gas Embolism and Decompression Sickness are the direct and indirect result of bubbles in the body. The treatment, therefore, for these maladies focuses on the elimination or reduction in the size of the bubbles. The most effective way to accomplish this is through recompression. By subjecting the bubbles to increased ambient pressure, the same gas law that allows bubbles to increase in size with an ambient pressure decrease, reduces the volume of gas in the bubbles with increased pressure.

There are two means of achieving increased ambient pressure: 1) recompression in a hyperbaric chamber, and 2) recompression in the water. Although in-water recompression has been used successfully in certain situations, the problems associated with returning the victim to the water (e.g., hypothermia, seasickness, inadequate air supply, inability to closely monitor the diver) outweigh the potential benefits from such practices. It is for these reasons that both the US Navy and NOAA do not endorse this method of recompression.

Hyperbaric Oxygen Therapy

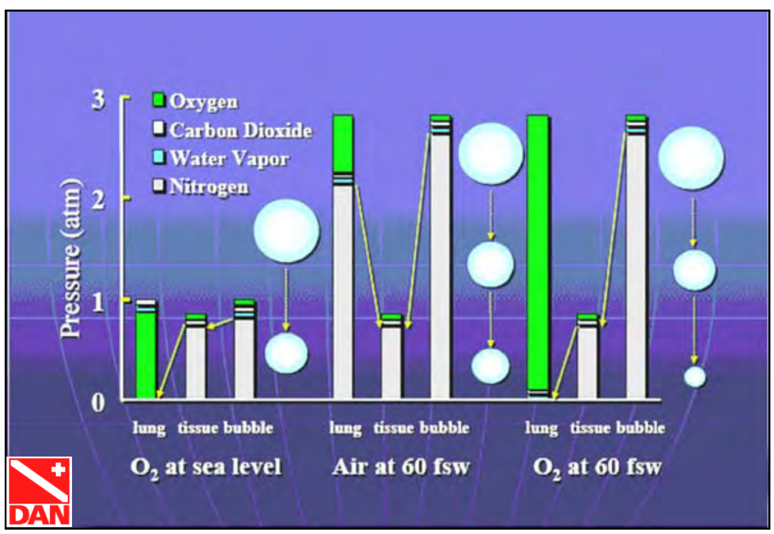

Figure 4: Effects of increased pressure & PO2 on bubble size.

"Hyperbaric Oxygen Therapy" (HBO) is the term used to describe the comprehensive program utilized in recompression treatment. Hyperbaric means "above normal pressure" - which at sea level is 14.7 pounds per square inch. The definition of HBO therapy is: "The inhalation of 100% "medical-grade" oxygen by a patient exposed to elevated ambient pressure." There are five elements to HBO: 1) raised atmospheric pressure, 2) raised inspired oxygen pressure, 3) time, 4) fluid management, and 5) drug therapy.

Raised atmospheric pressure reduces the size of the bubbles, thus restoring blood flow and relieving pressure on vital nerves and tissues and organs (Figure 4). It also increases the pressure differential between the gas in the bubble and that in the blood which forces the gas in the bubble back into solution for elimination via normal respiration.

Raised inspired oxygen pressure is achieved by breathing 100% oxygen while exposed to increased ambient pressure in a hyperbaric chamber. Breathing oxygen creates a pressure gradient in the body which reduces the amount of excess inert gas in the bloodstream and in the tissues (Figure 4). Lowering the inert gas level in the lungs lowers the level in the blood, then the tissues, and finally in the bubbles themselves. The greater the pressure gradient (i.e., the higher concentration of inhaled oxygen), the faster the inert gas is eliminated from the body. There are several secondary benefits of oxygen: 1) reduced edema (swelling) produced by the blockage of small blood vessels thus, restoring function of affected nerve tissue, and 2) reduced blood sludging and platelet aggregation which occur as bubbles form in the bloodstream.

Time under pressure, or time of exposure to elevated oxygen partial pressures is a critical element of HBO therapy. Sufficient time with appropriate levels of pressure and oxygen is necessary for the latter to achieve the desired results. Standard treatment tables generally provide appropriate pressure/oxygen/time relationships for successful therapy, (Wells,. 2000).

Fluid management involves ensuring adequate hydration of the patient via ingestion or invasive medical procedures. Appropriate types and amounts of fluids help reverse hemo-concentration (blood thickening), enhance micro-profusion, and limit edema duration.

Drug therapy may serve in an adjunctive capacity with the other elements of HBO therapy. Appropriate types and amounts of drugs help to reduce edema, reduce blood and tissue response to gas surface tension, and enhance micro-profusion.

Early diagnosis and prompt treatment

The signs and symptoms of AGE typically occur within 5 - 10 minutes after a diver surfaces, therefore, recovery from such an injury demands immediate hyperbaric treatment rendering a full-time, ready chamber the optimum choice, (DAN 1992). A gas embolism is a minute-to-minute emergency transfer, and the chances of full recovery decreases with each minute lost in returning to pressure, (Joiner, 2001)

The signs and symptoms of DCS may occur even before reaching the surface or may not manifest for many hours after surfacing (Figure 5, DAN 2004). According to the DAN, slightly more than 50 percent of all decompression sickness cases that received hyperbaric oxygen therapy for DCS in 2002, were successfully treated without residual symptoms (Figure 6, DAN, 2004). In general, recurrence of symptoms can occur, but this is not necessarily normal. In many cases of decompression sickness, the response to therapy is related to the time between symptom onset and chamber recompression. Divers must do everything they can to assure rapid first-aid measures including the use of 100 percent oxygen and evaluation leading to chamber therapy, (DAN 1992).

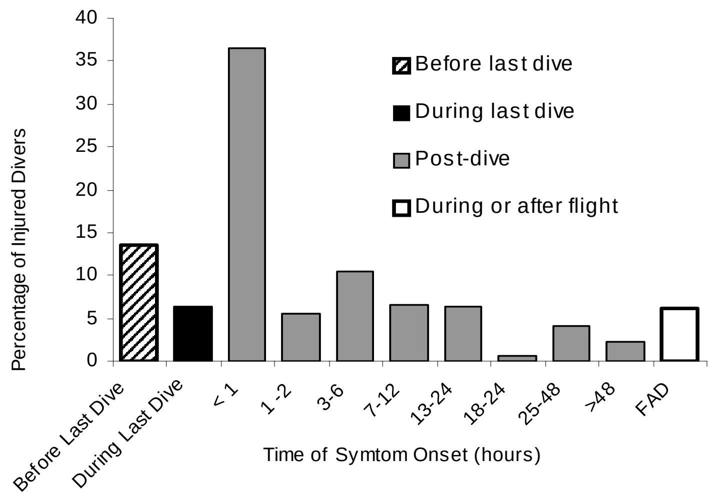

Figure 5: Onset of first symptoms of

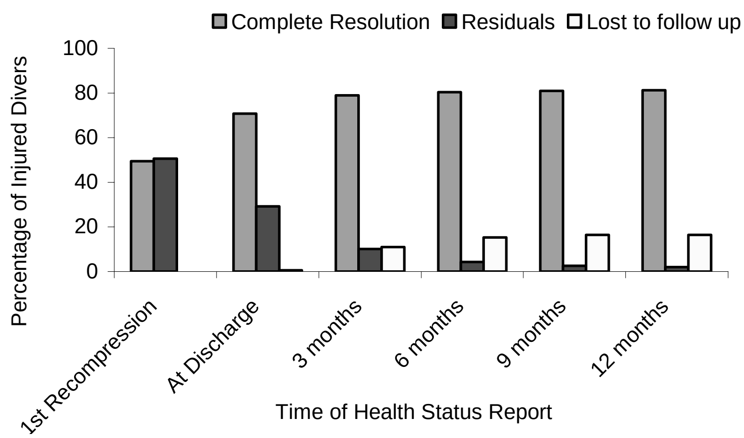

Figure 6: Relief of symptoms after HBO therapy.

At the first signs or symptoms of AGE or DCS, divers should begin breathing 100% oxygen via a tight-fitting, oral-nasal mask and continue to do so until the patient is recompressed in a hyperbaric chamber. The numerous benefits of oxygen for suspected barotrauma injuries are well documented. There is also evidence that breathing oxygen at the surface may actually relieve symptoms of DCS without recompression treatment, (Thalmann, 2003). Although not universally accepted, such findings further support the rationale for the immediate and sustained administration of oxygen for suspected DCS and AGE. NOAA regulations require that an oxygen resuscitator that is capable of ventilating a non-breathing person be immediately available at the dive site during official duty dives. (NOAA 2003).

Prompt treatment of AGE and/or DCS with hyperbaric oxygen therapy is directly correlated with success of treatment as measured by its ability to reduce or totally resolve symptoms (Buzzuto, 1999). HBO therapy for AGE and DCS involves pressurization of the individual in a recompression chamber to a depth of 60 fsw (18 msw) while breathing 100% oxygen via a built-in-breathing system (BIBS) mask. The patient breathes oxygen in 20-minute cycles followed by short (5 mins) air breaks. After a specified number of oxygen/air cycles, the chamber is depressurized to 30 fsw (9 msw) and the breathing cycles continue according to a specified schedule, followed by a slow, gradual depressurization of the chamber back to the surface. In the United States, the procedures of choice for treatment of AGE and DCS are those developed for use by the US Navy and designated USN Treatment Tables 5 & 6. Both utilize oxygen/air breathing cycles at 60 and 30 fsw - the main difference being the number of cycles performed at each depth - the TT 6 being longer in duration.

Recommended time to treatment

The time to begin HBO treatment for signs and symptoms of AGE and DCS is critical. For AGE and severe DCS, the patient should be recompressed within 10 minutes of onset of symptoms. In less severe cases of DCS, this time may be expanded to a somewhat longer period.

In a recent poll of the members of the NOAA Diving Medical Review Board concerning a recommended maximum time for initiation of HBO treatment, Dr. Richard Moon indicated that, "Within the first 4-6 hours, there is no incontrovertible evidence that time to treatment of DCS affects outcome, although for severe cases there is not unanimity of opinion on this issue. Thus, for 'low risk diving,' a 4-6 hour transport time should be acceptable, provided this is unlikely to be affected by weather, etc. For other types of diving (i.e., decompression, mixed gas, technical), on-site availability of recompression should be the aim." Dr. Carolyn Fife, another member of the NDMRB, wrote that, "One assumes that the risk of injury will increase as your depth of operation and number of divers, as well as, individual dives increases. In general, one assumes that the window for significant impact on treatment of a neurological DCS begins to close after 4-6 hours."

Thus, it appears that six (6) hours is the maximum recommended time for commencement of HBO treatment for DCS. Certainly this time is too long for an AGE - however, as mentioned, with proper training AGE is considered a preventable malady. Further, AGE occurs much less frequently than DCS as indicated in Figure 7, (DAN, 2004).

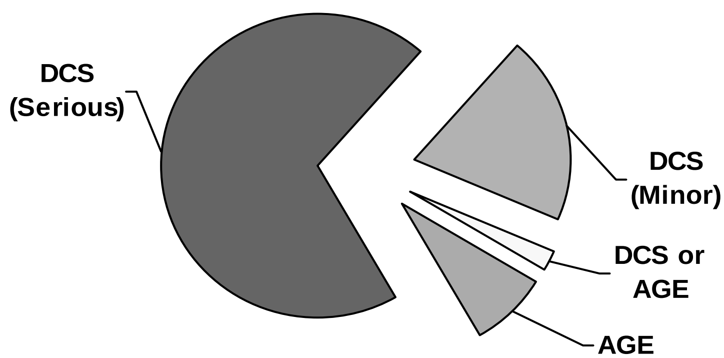

Figure 7: Final diagnosis of cases of injured divers.

Evacuation time to the nearest chamber

NOAA diving regulations do not specifically address evacuation of injured divers to a hyperbaric chamber or stipulate a maximum transport time to a chamber in an emergency. The regulations merely state that, "The locations, means of accessibility, and telephone numbers of all accessible and operable recompression chambers shall be available to all participating divers and support personnel before each diving operation.", (NOAA 2003). Additionally, the regulations require that all diving activities that involve "in-water" decompression be pre-approved by the NOAA Diving Safety Board (NDSB). Several activities of this nature have occurred over the past 10 years including dives to the Monitor National Marine Sanctuary, and in the Northwest Hawaiian Islands Ecosystem Reserve. To date the NDSB has required a recompression chamber be accessible within a 2-hour window for decompression diving operations. No such requirement is currently mandated by the NDP for dives that fall within the no-decompression limits.

By comparison, the commercial diving industry is required by federal regulations (OSHA and USCG) to have a chamber "on site" whenever performing 'non-exempt' dives: 1) deeper than 100 feet (OSHA) or 130 feet (USCG), and/or 2) outside the no-decompression limits. The NDP falls under the OSHA Commercial Diving Regulations (29 CFR 1910), but is exempt from USCG diving regulations (46 CFR 197).

In September, 2003, a survey was conducted of all NOAA diving units to determine: 1) the maximum time, in hours and minutes, required to transport an injured diver from all dive sites to the nearest hyperbaric chamber, and 2) the quantities of oxygen available on-site to support injured divers.

The survey indicated that 71% of the units could reach a hyperbaric chamber in six (6) hours or less (Figure 8). Those units unable to meet the 6-hour window were NOAA Ships (7), NMFS (5), and NOS Marine Sanctuaries (3) and CO-OPS Pacific Regional Office (1). Most of the diving related to these units is remote in nature.
It should be noted that several of the units responding to the survey based their evacuation times on the availability and use of a commercial airliner. The problem with such aircraft is that the cabin pressure is maintained at the equivalent of 8,000 feet elevation or 10.92 pounds per square inch (psi). This is a 3.78 psi reduction in pressure from that at sea level which further expands any bubbles that may be present, thus exacerbating the symptoms of DCS. Thus, the use of pressurized aircraft is not the ideal option for evacuating a diver with DCS or AGE. If evacuation is conducted using aircraft, the flight crew should be instructed to fly or pressurize the aircraft below 800 feet (244 m) altitude.[4]

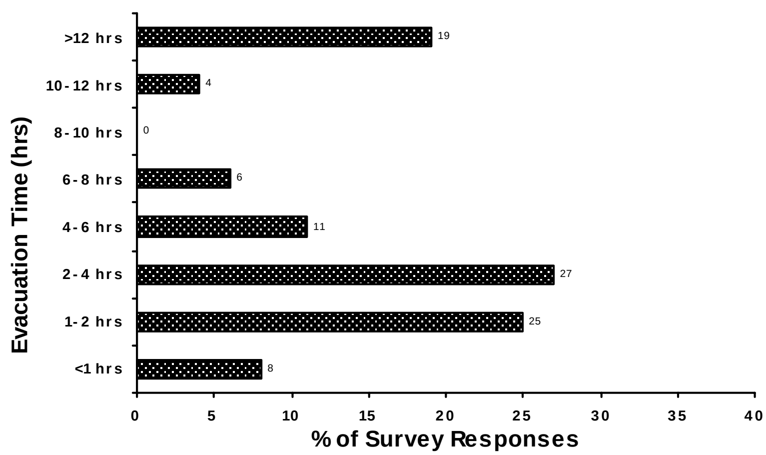

Figure 8: Evacuation time to closest hyperbaric chamber.

Figure 9 shows the results of the survey question regarding the availability of oxygen at the dive site. Correlating maximum evacuation times with oxygen supplies indicates that 17% of the units do not have sufficient oxygen to last throughout the evacuation period or twelve (12) hours whichever is shorter.

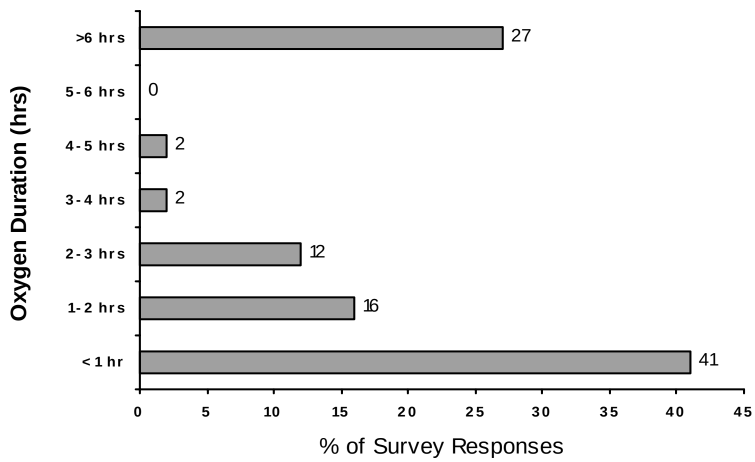

Figure 9: Duration of available medical oxygen.

Recommendations

On November 1, 2003, the NOAA Diving Safety Board and the Chairman of the NOAA Diving Medical Review Board discussed NOAA's diving accident management program in detail. Although the group felt that the current plan was equivalent to those used by other similar research-oriented diving organizations, the group felt that the plan could and should be improved, especially in light of new research initiatives being undertaken by NOAA involving intensive diving activities. Specifically, the group discussed improvements in three areas: 1) access to recompression chambers for HBO therapy, 2) access to oxygen at the dive site, and 3) review of dive plans and accident management instructions.

The following recommendations were submitted to the Director, NMAO in September 2004 for consideration and were approved for implementation a month later:

Recommendation #1: Access to recompression chambers

- That NOAA require a recompression chamber be on-site for all dives conducted deeper than 130 feet, or when diving is conducted outside of the U.S. Navy no-decompression limits.

- Unplanned dives associated with emergency situations where death, serious physical harm, total loss of property, or major environmental damage would be exempt from this requirement. Recognizing that there may be situations that warrant actions contrary to this requirement, it is recommended that exceptions to this requirement be considered on a case-by-case basis by the Director, NMAO with recommendations from the Director, NOAA Diving Program.

Recommendation #2: Availability of on-site oxygen for emergency first aid

- That NOAA require the availability of sufficient quantities of oxygen at the dive site for the sustained management of a diving incident for the duration of time required to transport the diver to a medical facility or twelve (12) hours whichever is less.

- NAO 209-123 currently requires the availability of an oxygen delivery system capable of ventilating an unconscious victim at the dive site.

Recommendation #3: Review of Dive Plans

- That the Director, NOAA Diving Program, or his/her designee approve of all planned diving operations involving: 1) dives conducted more than six (6) hours from a recompression chamber, and/or 2) dive accident management plans utilizing rotary or fixed-wing aircraft as the primary means of evacuation.

- NAO 209-123 currently requires the formulation of a Dive Accident Management Plan for all operational areas prior to diving.

One of the primary concerns expressed by the NDSB during the development of the above recommendations was the potential impact the new requirements would have on the science programs – either financially or operationally. The goal therefore, was to implement additional safety measures to protect the health and welfare of the divers without detracting or interfering with ongoing research efforts or imposing unfunded mandates.

Implementation of Recommendations

Recognizing that the implementation of the new dive accident management requirements cannot be accomplished overnight and will require additional funding, an implementation plan is being developed that will outline the resources and time needed. The plan will be submitted to the Director, NMAO in FY ’05 for consideration.

However, several steps have already been taken to begin implementation of the requirements. To address the need for recompression chambers to support decompression diving activities, the NOAA Diving Center has obtained two chambers to support field operations: a 2-person, mono-place Drager Duocom and a 54” diameter, double-lock recompression chamber housed in an 8’ x 20’ climate-controlled container (Figure 10). Additionally, an SOS Emergency Evacuation Hyperbaric Stretcher (EEHS) has been purchased for use as a transport chamber or for use on smaller vessels that do not have adequate deck space for either of the other two chambers. A full-time chamber supervisor/operator position has also been created and filled to support these and future chambers yet to be developed. All three of these NDC chambers have been used to support remote and/or advanced diving operations in the past year.

It is anticipated that the implementation plan will include funding for additional oxygen cylinders for those units with insufficient quantities. The plan will also include funding for the investigation of new technologies, (e.g., oxygen generators combined with oxygen rebreathers), to supply oxygen to divers in remote locations where oxygen is not readily available.

Figure 10: Containerized recompression chamber

The implementation plan will also address the issue of reviewing dive plans for all operations conducted at locations more than six (6) hours from a hyperbaric treatment facility, as well as all dive accident management plans that call for the use of a rotary or fixed-winged aircraft as the primary means of evacuating an injured diver. Depending on the type, location and intensity of the diving operations (e.g., multi-day, multi-dive and/or repetitive dives >100 feet), a recompression chamber may be required at the dive site.

Conclusion

Diving is an important, yet potentially hazardous, activity performed by NOAA personnel. Many of these risks are mitigated through extensive training, the establishment of, and adherence to, reasonable standards and procedures, and the use of top-quality, well-maintained diving equipment. However, injuries can still occur even if a diver does nothing wrong procedurally. Therefore, adequate and appropriate safeguards must be in place to respond to diving emergencies when and wherever they may occur.

Once fully implemented these new safety measures will be a positive step towards ensuring that appropriate accident management procedures are established for NOAA diving operations.

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The Risk of Decompression Sickness (DCS) is Influenced by Dive Conditions

Richard D. Vann[1,2*], Petar J. Denoble[1] , Donna M. Uguccioni1[1], Neal W. Pollock[2], John J. Freiberger[1,2], Carl F. Pieper[2], W.A. Gerth[3] and Robert Forbes[4]

[1]Divers Alert Network, 6 West Colony Place, Durham, NC 27705
[2]Duke University Medical Center, DUMC 3823, Durham, NC 27710
[3] Navy Experimental Diving Unit
[4] Orkney Hyperbaric Trust Orkney, UK

[*]Corresponding Author

Abstract

DAN's Project Dive Exploration (PDE) gathers data on dive profiles, conditions, and outcomes to assess DCS risk and risk factors. This report investigated the DCS risk in three dive groups: 51,497 PDE warm-water dives; 6,527 PDE cold-water dives; and 2,252 Navy chamber dives. First, DCS risk was predicted for all dives by a probabilistic decompression model that had been calibrated to Navy data. Next, predicted risk and observed incidence were compared for the groups. Finally, predicted risks were recalibrated to all dives combined. Mean observed DCS incidences were 2, 28, and 311 cases per 10,000 dives for warm-water, cold-water, and Navy dives, respectively. Original predictions overestimated observed incidences for warm and cold-water dives but not for Navy dives. With recalibration, mean predicted risk and mean observed incidence were the same. Navy dives had higher predicted risks than warm or cold-water dives, but even for a given dive profile, the groups differed significantly in both recalibrated risk and observed incidence. We conclude: (a) probabilistic models are useful for estimating risk; (b) models may not extrapolate accurately beyond their calibration data; and (c) dive conditions, in addition to dive profiles, may significantly affect risk.

Introduction

Brief sojourns at elevated pressure while breathing compressed gases are relatively safe, but extended exposures can lead to unacceptable risk of decompression sickness (DCS). The limits of safe exposure are particularly difficult to determine for multi-level, repetitive, and multi-day dives. Besides exposure, the conditions and circumstances of a dive may also affect risk. We investigated the influence of exposure and conditions on DCS risk in three groups of dives.

Project Dive Exploration

Investigation of safe diving limits requires knowledge of depth-time profiles and medical outcomes. This is the objective of Project Dive Exploration (PDE) which became possible when recording dive computers were introduced by Suunto and Orca in 1989. Seven brands of dive computer and recorder are now PDE-compatible including those made by Suunto, Uwatec, Dive Rite, Cochran, Sensus, Oceanic, and Delta P Technologies.

PDE divers are asked to describe any symptoms noted during or after a dive series. When the series is complete, the diver submits a report that reviews his or her medical condition at 48 hrs after the last dive or altitude exposure. The 48 Hour Report admits or denies symptoms, indicates whether recompression occurred, and provides information about flying after diving. If the diver was recompressed, DAN contacts the treating chamber for a case report. The report is evaluated by a diagnostic algorithm to classify the case as not all recompressed divers have DCS, (Vann 2004b).

PDE began in 1995 as a pilot study (Project Dive Safety) that was designed to develop procedures and software for collecting dive profiles from open water divers (Figure 1). Formal PDE data collection began in 1998, and to date, over 100,000 raw dive profiles have accumulated. All dives are reviewed and error checked before analysis. The 58,024 dives that have undergone this process so far are discussed below.

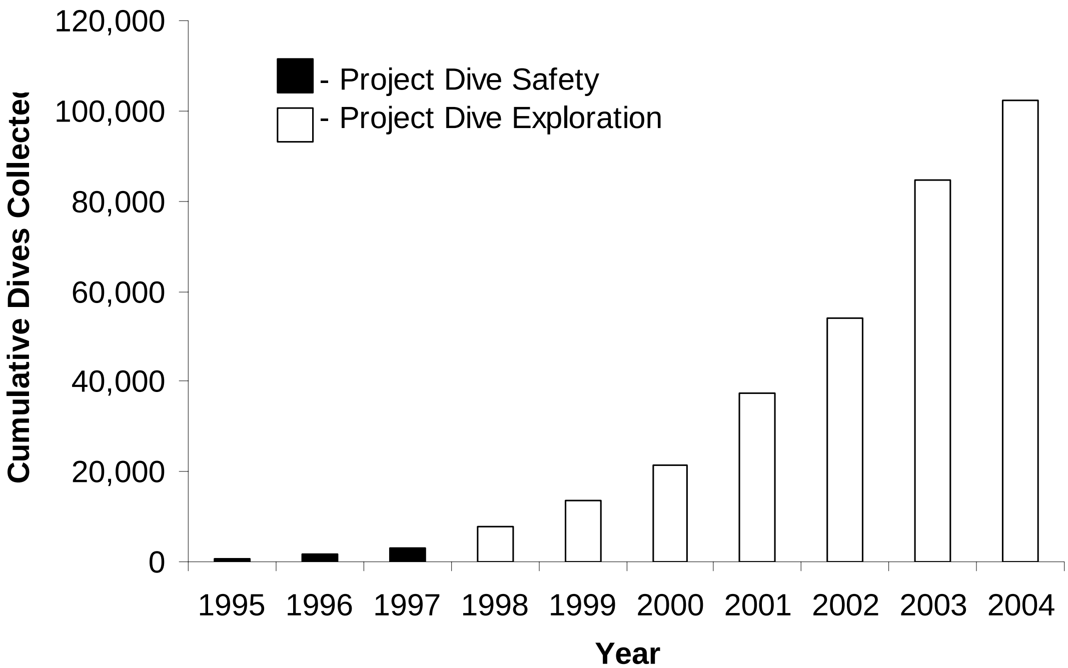

Figure 1. History of PDE data collection.

Methods

Dive Groups

Table 1 describes three dive groups with known depth-time profiles and medical outcomes. Two were from PDE, and one was from U.S. Navy chamber dive trials for developing decompression procedures. The first PDE group included live-aboard dive boats, day boats, and shore dives in warm water locations. The second PDE group was from cold water wreck divers in Scapa Flow, Scotland. The U.S. Navy group included experimental dives conducted in hyperbaric chambers during which the divers were usually immersed and exercising.

Table 1. Dive population samples.

Dive Group	# DCS Cases	# Dives	DCS per 10,000 Dives
PDE Warm Water	8	51,497	2*[+]
PDE Cold Water	18	6,527	28[+]
USN Chamber	70	2,252	311

* - significantly different from Cold Water
[+] - significantly different from Navy trials

Statistics

DCS incidences between dive groups were compared by Fisher's exact test. Differences between observed incidence and DCS risk predicted by a probabilistic decompression model were evaluated by Chi-square test.

Predicting the DCS risk of a particular dive can be accomplished with a probabilistic decompression model if the depth-time profile and breathing gases are known. A probabilistic model is a mathematical rendering of a decompression theory. The parameter values of the model are statistically calibrated to empirical decompression data for which the dive profiles and medical outcomes are known. We used a probabilistic model of bubble growth and resolution calibrated to a dataset that included the Navy chamber dives of Table 1 (Gerth and Vann, 1997).

Each dive group of Table 1 was divided into sub-groups, and the mean predicted risk and mean observed incidence were computed for each of the sub-groups. Trendlines to the sub-groups were determined by linear regression. Logistic regression was used to investigate the relationship of predicted DCS risk to observed DCS incidence based on the individual dives.

A p-value of less than 0.05 was accepted as an indication of statistical significance for all tests.

Results

The mean DCS incidence for each dive group was significantly different from the other groups (Table 1).

For each group, the mean DCS risk predicted by the model was compared with the mean observed DCS incidence. The difference between predicted and observed was not significant for the Navy dives, as might be expected since these dives were part of the model calibration data, but the predicted means were significantly greater than the observed means for both PDE groups (Table 2).

Table 2. The observed DCS incidence and the DCS incidence predicted by the probabilistic model of reference (1) for the three dive groups of Table 1.

Dive Group	Mean Observed Incidence (DCS per 10,000 Dives)	Mean Predicted Risk (DCS per 10,000 Dives)
PDE Warm Water	2	51*
PDE Cold Water	28	75*
USN Chamber	311	351

*observed and predicted differ significantly

The Navy dives were sorted in order of predicted DCS risk, divided into six equal sub-groups of 375 dives, and the mean risk and mean observed incidence were determined for each sub-group. The observed incidences were plotted against the predicted risks in Figure 2. If the predictive model were perfect, the points would fall exactly on the line of identity. The model under-predicted slightly at high risks and over-predicted slightly at low risks, but with an R-square of 0.98, the trendline indicated a good simulation of the Navy dives.

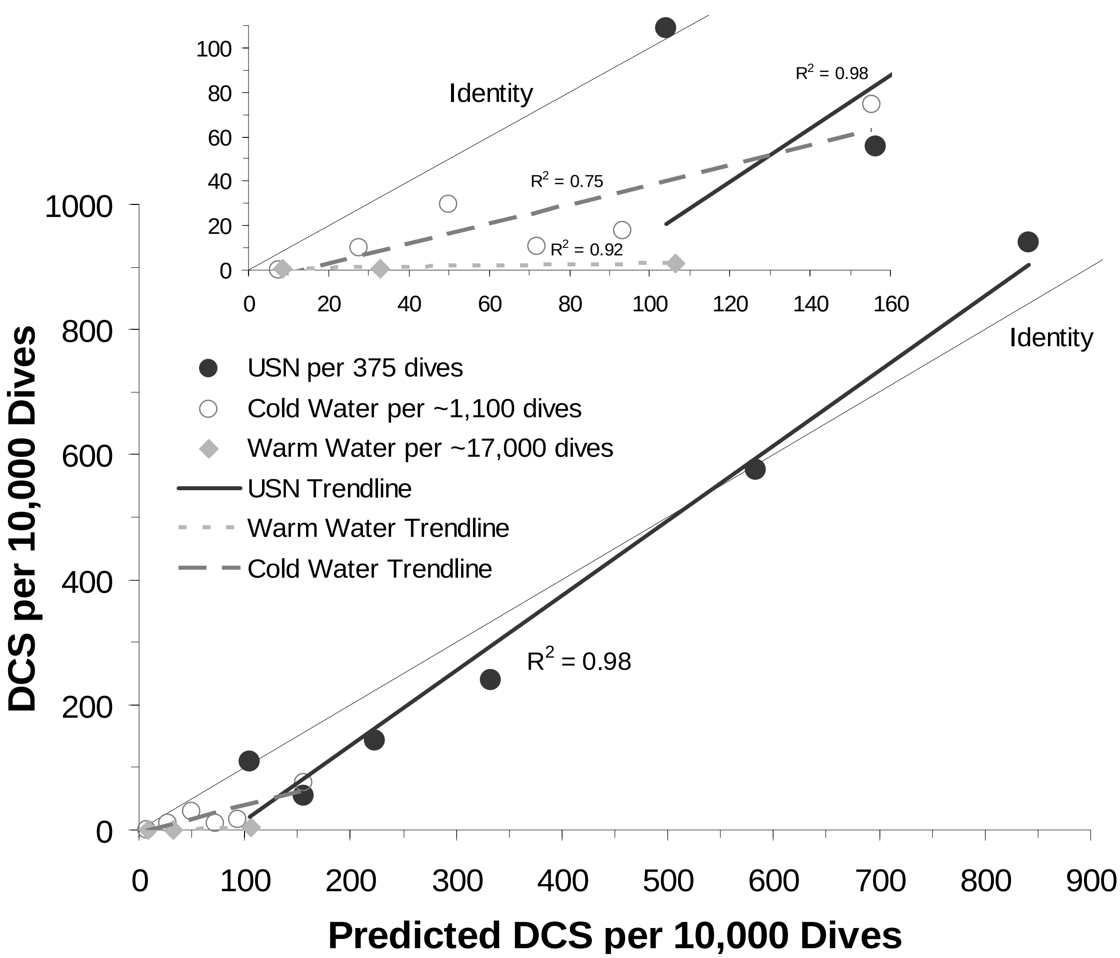

Figure 2. Observed DCS incidence and predicted DCS risk for the Navy and PDE dives. The inset shows the lower left corner of the main plot.

Trendlines were found in a similar manner for the PDE Cold Water dives (six sub-groups of ~1,100 dives each) and PDE Warm Water dives (three sub-groups of ~17,000 dives each).

The trendlines showed that the Navy dives had higher predicted risks than either PDE group. This is best seen in the inset that expands the low risk corner of Figure 2 where the PDE dives were concentrated. Over-prediction of the Navy DCS incidence was small, but the Cold Water DCS was over-predicted by a factor of about two, and Warm Water DCS was over-predicted by a factor of about 30. The R-square values for PDE trendlines were lower than for the Navy trendline, but the observed DCS incidences for the PDE dives were ordered reasonably well by the predicted risks, and most so for the Warm Water dives.

Although predicted risk was a poor measure of observed DCS incidence for the PDE dives, the trendlines of Figure 2 suggested that there might be a functional relationship between predicted and observed DCS. We tested this hypothesis by applying logistic regression to the combined PDE and USN data. This recalibrated the relationship of predicted to observed DCS, in effect, by treating predicted risk as a decompression stress rather than an absolute risk. Individual adjustments were made for each dive group to represent possible (but not necessarily known) differences in dive conditions between the groups.

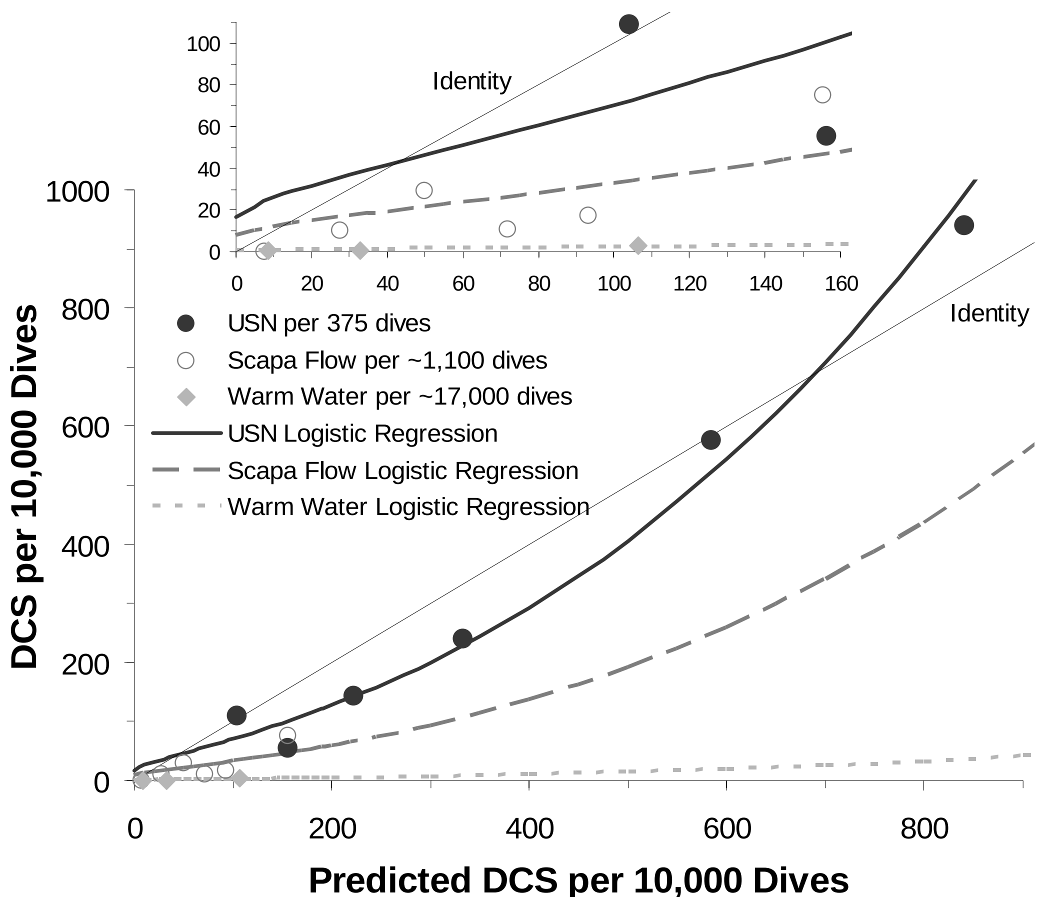

Figure 3. Logistic regression model of the Navy, Cold Water, and Warm Water dives. The inset shows the lower left corner of the main plot.

Predicted risk was significantly associated with DCS, and Warm Water dives were significantly different from Cold Water dives and from Navy dives. Recalibration brought the mean observed and predicted DCS into agreement for each dive group at 8, 18, and 70 cases for the Warm Water, Cold Water, and Navy dives, respectively (Table 1). Figure 3 is similar to Figure 2 but shows the logistic regression model of observed DCS after recalibration. The inset in Figure 3 expands the low risk corner of the main figure.

Discussion

What are the implications of this analysis for a familiar dive such as a no-decompression exposure on air to the U.S. Navy limit of 60 min at 60 fsw? After recalibration by logistic regression, a 60 min no-decompression dive to 60 fsw had an estimated DCS risk of 4 DCS per 10,000 dives for Warm Water, 59 DCS per 10,000 dives for Cold Water, and 132 DCS per 10,000 dives for Navy trials.

If these estimates are correct, the conditions and circumstances of a dive may have important effects on DCS risk even for dives of identical depth-time profile. While we refer to “Warm Water,” “Cold Water,” and “U.S. Navy” dives, these are better described as labels for the entire set of conditions that apply for each dive group. The conditions may be unmeasured or unknown and might include water temperature, thermal protection, and pre-, during, and post-dive exercise.

Our analysis demonstrated a significant effect for each dive group by assigning a separate parameter value to each group in the logistic regression. While we cannot confirm the underlying causes for differences between groups, exercise and temperature are known to have profound effects on inert gas exchange and bubble formation (Vann 2004a and 2004b), with magnitudes that vary according to the phase of the dive (pre-dive, at depth, during decompression, or post-dive), and recent evidence has demonstrated that thermal stress is an important determinant of decompression risk (Ruterbusch *et.al*., 2004). One might speculate that long, cold, decompression dives put the Navy divers at higher risk than short, no-decompression Warm Water dives. The difference was smaller for the Cold Water dives at Scapa Flow (for which most divers wore drysuits) that involved thermal stress and some decompression diving.

A final conclusion is that probabilistic decompression models should be calibrated to the type of diving for which they are to be used. While the probabilistic model that was calibrated to the Navy trials did well at predicting the high risk Navy dives (Gerth and Vann, 1997), there were few low risk dives under conditions of low thermal stress in the Navy calibration data. The ideal approach would be to calibrate probabilistic models to a dataset that included both high and low risk data. This could be achieved by calibration data that included both the Navy and PDE dives.

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The Pacific Islands Fisheries Science Center Dive Program: Meeting the Challenges of the Pacific Region

Raymond Boland
Pacific Islands Fisheries Science Center, NMFS
2570 Dole St. Honolulu, HI. 96822

Abstract

The National Marine Fisheries Service, Pacific Islands Fisheries Science Center is the largest dive unit in the National Marine Fisheries Service. Over 40 divers from five programs use working and scientific dive operations to address protected species, fisheries, coral reefs and anthropogenic issues.

Much of the diving is in remote locations and involves specialized techniques that require additional training beyond the basic NOAA Scientific/Working Diver certifications. PIFSC in consultation with NOAA Dive Center (NDC) has developed training curriculums that ready new divers and retrain experienced divers for the various tasks they are assigned. Curriculums exist for marine debris survey and removal, SCUBA towboarding and mooring installation and service. Upon completion of the curricula the diver's certification receives a Specialized Task Endorsement (STE) for the specific operation.

Due to the remoteness of dive sites, or decompression operations a chamber is required by NOAA. Fielding the chamber and necessary support staff is a challenge to the center. Collaborative expertise pulled from the Navy, Army, NOAA, and PIFSC staff is often how this requirement is met.

Introduction

The Pacific Islands Fisheries Science Center (PIFSC) dive program operating area is the Pacific Ocean. The center operates from Honolulu, Hawaii with its jurisdiction extends west to Guam and the Northern Marianas Islands, south to American Samoa, and east to the equatorial islands. Deep water is quickly found near these islands, with water being 1000's of feet deep within 2-3 miles of the shoreline. Because of their mid-ocean location, these small islands are affected by open ocean currents and sea states. Frequently the sites are remote, usually days away from any major medical support. Often the food webs of these remote sites are dominated by large sharks and jacks. Immediate dive support is primarily provided by small craft (17-20 feet) with a large research vessel (220-240 feet) acting as a mother ship. The mother ship is the major support platform, and has a hyperbaric chamber with trained medical personnel, large compressors and banks for filling SCUBA tanks and in some cases the capability to blend gases for nitrox and trimix. Because the archipelagos are large and remote, research cruises are a minimum of 20 days and may last as long as 3 months.

The PIFSC dive program is nested within the NOAA Diving Program (NDP) and adheres to the NDP regulations. In the NDP, there are two types of diving: Scientific and Working. The Scientific Diver rating is given to divers that meet the basic standards set forth by the NDP and is limited to the gathering of data through diver observation that is noted by hand or is recorded using photography or videography. Working Divers have to attend the NOAA Working Diver class, which is conducted by the NOAA Dive Center, or be a graduate of a military or commercial dive school, or have substantial experience in the performance of working dives. Working divers use tools to accomplish a task underwater such as hull inspections, lifting heavy objects with lift bags, coring and other light commercial dive projects.

PIFSC Diving Program

The PIFSC dive program has been supporting research needs in the Pacific Basin since the 1980s when it was called the Honolulu Laboratory. The current diving staff consists of 43 biologists and technicians who have met the NOAA requirements for Scientific or Working diving and conduct dives in support of their primary duties. A dive supervisory group consists of NOAA divemasters and a Unit Diving Supervisor (UDS). The UDS oversees all diving operations conducted at the center, maintains all records, conducts training, and petitions for reciprocities with other dive programs. There are several research programs at PIFSC that employ diving for their projects (Table1).

Table 1: List of Programs and their projects that employ diving.

Program	Scientific Diving	Working Diving
Fisheries and Oceanography Programs	Fish observations and handling.	Oceanographic instrument support.
Ecosystems and Oceanography Division	Benthic habitat surveys, ecosystem surveys.	Archival instrument support.
Protected Species Division	Hawaiian Monk seal forage base surveys. Turtle surveys and tagging	Archival instrument support.
Coral Reef Ecosystems Divisions	Biological surveys, bottom topography surveys and marine debris surveys.	Oceanographic instrument support and marine debris recovery.

In addition to these projects, PIFSC has also evaluated dive equipment in cooperation with NDC. Divers have evaluated dive computers, technical dive equipment, and software decompression and gas mixing.

The technical dive program at PIFSC has developed technical dive protocols (Parrish, F.A. 1999), conducted comparative studies between closed circuit systems and open circuit systems (Parrish, F.A. 2000. and Parrish, F.A. and Pyle. 2002) and support future advanced diving initiatives.

Nearly all of the research diving at the PIFSC is conducted from large NOAA research vessels and contract vessels at remote sites that are often deep and usually far from both emergency and diving support centers. A primary challenge to these operations has been crafting dive accident management contingencies.

When PIFSC began using SCUBA at the limits of conventional diving (90ft-130ft) in 1990 on remote banks in the NWHI, NDC provided training and equipment for in water oxygen recompression to provide treatment options in the event a diver became bent. With the advent of technical/mixed gas diving at PIFSC in 1998, NDC provided decompression tables, and assisted in creating decompression dive protocols. Initially hyperbaric chamber support from the US Navy was used and later, NDC refurbished a monoplace hyperbaric recompression chamber.

The number of divers and dives conducted on research cruises tripled from 1999 to 2000. Routine cruises expanded to include Guam, the Northern Marianas Islands, American Samoa and the equatorial islands. Recognizing the need for treatment facilities, NDC began to provide portable multilock chambers to the research vessels for emergency treatments. Presently NDC has one portable multiplace chamber system which is completely containerized. A second containerized system is being fabricated for cruises occurring later this year.

Development of Diving Techniques and Training

In order to accomplish studies or gather data, PIFSC has developed, refined and employed unique diving techniques. Divers who wish to employ these techniques must first meet the prerequisites and undergo the required training (Table 2). One of the first projects that employed divers and new techniques was a study conducted on juvenile snappers.

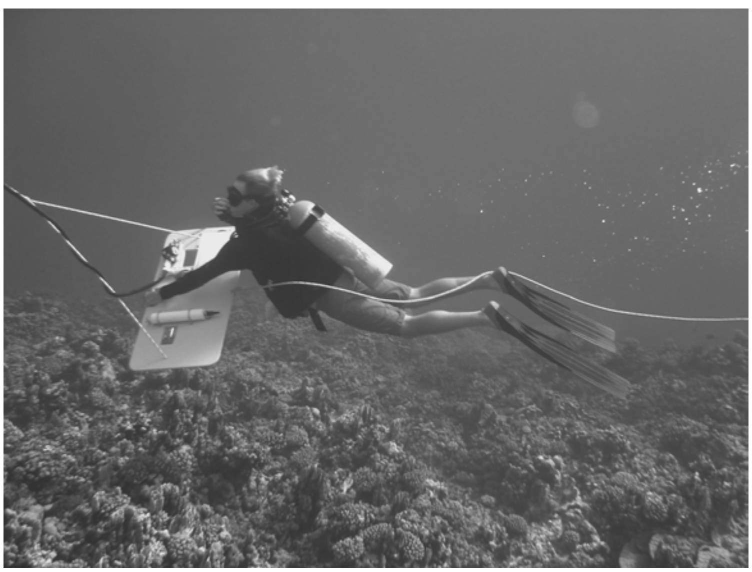
Table 2: Dive Operations and their training requirements.

OPERATION	PRE-REQUISITES	TRAINING	LIMITATIONS
Marine Debris STE	40+ dives Advanced SCUBA Certification	20 hours classroom 1 week field training/water work	Depth <30 feet
Buoy STE	50+ dives NOAA Scientific Diver for one year	2 hours of class 4-6 dives	Depth <100 feet
Towboarding	50+ dives. 10 dives deeper than 100 feet -NOAA Scientific Diver for one year	2 hours of class 1-2 dives	Depth <120 feet
Technical diving	Certification through recognized technical agency	work up dives previous to project or cruise	Depth <240 feet Hyperbaric Chamber on site

In 1989, a study to track juvenile deepwater snapper: *Pristipomoides filamentosus* was faced with a unique problem: as the fish were pulled from depth on hook and line, their swim bladders would expand and force their stomachs out of their mouths. While it was possible to deflate the swim bladder with a hypodermic needle and reinsert the stomach at the surface, the survivability of the fish was less than 50%. A technique was developed to use divers at depth to intercept the hooked fish, insert the acoustic pingers for tracking, observe the fish and then release the fish (Parrish, F.A. and Moffitt, 1993.).

A "tagging array" consisting of a surface buoy with a line to a T-Bar at a depth of 55 feet to a wire cage at 100 feet was built. The array was connected at the T-bar to the boat conducting the fishing operations. Hooked fish were reeled to a pre-marked position on the fishing line. A carabiner was then connected to the fishing line and the line connected to the tagging array T-bar which brought the fishing line to the divers. Divers then followed the fishing line down to the hooked fish, where the acoustic transmitter was inserted, the fish unhooked and then placed in the cage. The fish were observed for a short period of time to determine their hardiness. Fish that survived the tagging operation were released. All of these fish immediately swam toward the bottom with no apparent ill effects. The acoustic tracking portion of the project was a success.

This same type of method was later used for a gut content study on the same species of fish. When fish were hooked and brought to the surface, the everted stomachs would empty the gut contents that were needed for the study. Divers were used to intercept the fish at 110 feet and place the hooked fish into bags. The fish were then pulled to the surface and their gut contents would be trapped within the bags. (DeMartini, E.E., et. al., 1996)



Scuba diver on towboard surveying reef.

A primary survey technique employed by divers at PIFSC is towboarding using either snorkel or SCUBA. Towboarding or "Manta Tow" is used to survey large areas rapidly for large features and this technique has worked well for several studies. (Boland, R.C., and Donohue, 2003; Donohue, et. al., 2001; Parrish, F.A. and Kazama, 1992; Parrish, F.A. and Boland, 2004; and Parrish, F.A. and Polovina, 1994.)

Divers grasp onto boards that are towed behind small craft on towlines between 50 and 200 feet long. The boards allow divers to "fly" through the water, descend, ascend and steer either to the left or right. Snorkel towboarding has been used most recently to survey marine debris in water less than 30 feet.

SCUBA Towboarding has existed at PIFSC since 1990 when it was first used to survey bank habitats between 90 and 130 feet. It has since been used to survey marine debris, coral reefs and large fish to depths of 120 feet. A large board, nearly the size of an average desktop, is towed behind a small craft. Early SCUBA towboarding used film cameras and video-8 cameras to record benthic habitat and compare to diver observations. Modern day towboards use digital imaging and may even included a mini-CTD (Conductivity, Temperature and Depth recording device).

SCUBA towboarding is a specialized tool with unique hazards. Because of this specific protocols have been developed to maximize data collection and minimize danger. The primary danger related to SCUBA towboarding is a hyperbaric pressure injury. Because the divers are being towed at speeds between 1 and 2 knots, control loss of the board could cause a rapid ascent possibly leading to a decompression illness. Divers are taught how to control the board through hand placement and practice. Divers must also be able to clear their ears without the use of their hands, and be able to deal with flooded masks while towing. Other problems associated with towboarding include the danger of fouling within one's own lines, loss of regulator, and loss of mask.

Separation of the diver from the board is also a danger. Two features of towboards negate this: a tail line that trails from the board back past the diver and a telegraph device to communicate with the tow vessel. If a diver falls off a towboard, the diver normally recovers the board via the tail line.
The telegraph allows divers to control the speed and direction of the boat. Divers send an "okay" signal on the telegraph every five minutes and the boat will stop if more than five minutes have elapsed from a signal. This minimizes the area to be searched if divers are indeed lost. This protocol also alerts the towboarding team to malfunctions in the telegraph itself. Leaks in the cable or switch or a battery dying in the middle of a tow have led to tows being stopped and surveys ended early. Because only one diver has the telegraph, both divers must be able to communicate with each other through standardized hand signals. Divers must also be able to recover lost boards for their buddies and in the event of the diver with the telegraph board is separated, it is imperative that the other diver be able to recover the empty board and send a stop signal to the tow boat.

The danger of predators being attracted to a towed diver does exist. One of the original names given to this survey method was called "trolling for sharks." While predators have followed towed divers, they tend to lose interest after a few minutes. In some cases, predators ignore the divers completely and only in rare instances has aggressive behavior forced the divers to abandon the survey. While there is not much a diver can do if a predator becomes aggressive, the trail line gives the diver a "tail" that most curious predators approach first. Divers are trained to observe for predators, especially predators that are tailing them, by conducting a quick turn to the left or right allowing them to momentarily see what is behind them. This maneuver is referred to as the "Crazy Ivan". Divers also eventually get a feel for what is aggressive behavior and what is simple curiosity.

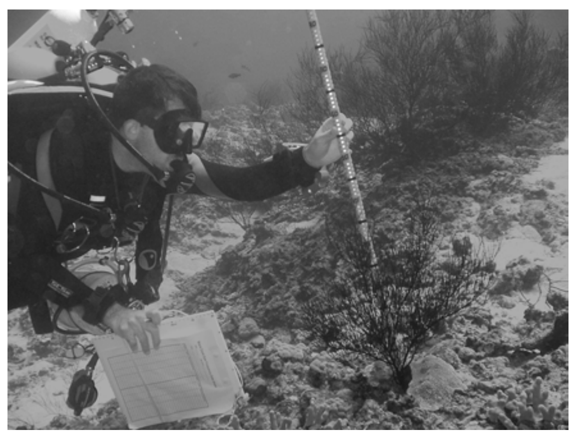
Technical diving began in 1998 at the center in response to data that indicated Hawaiian Monk seals were foraging in depths between 150 to 300 feet. (Parrish, F.A., et. al. 2000) Divers were trained through recreational instructors to open-circuit trimix level. Technical SCUBA gear was assembled, a gas mixing system built and a computer program capable of calculating gas mixing was created. NDP dictated which gas mixtures to use and provided decompression tables. During the research cruise, the US Navy provided hyperbaric chamber and medical support. After 2001, the hyperbaric chamber and Diving Medical

Technician (DMT) were provided by NDC. Personnel from PIFSC were trained as hyperbaric technicians to run the chamber to fill in the gaps. In 2004, NDC began to provide a hyperbaric technician, DMT and hyperbaric physician.

The monk seal project surveyed both the habitat and fauna at these depths. The data gathered was invaluable in providing information on the forage diet of these endangered and endemic mammals. Archival equipment was also deployed and recovered to determine the visitation rate of seals to specific sites.

Another project utilizing technical diving between depths of 160 to 240 feet monitors the black coral industry. Black coral divers visit these depths to harvest black coral, the official gem of Hawaii. The harvesters typically use a single tank, cut legally sized coral off of the bottom and send them up tied to a lift bag. The diver then decompresses. Many of these divers have died in this practice. PIFSC conducted surveys of black coral stock and the associated fish assemblage surveys in the waters off of Lahaina, Maui (Boland, R.C. and Parrish. 2005). This is the only source of fishery independent data available to manage the black coral fishery. Current studies are now focused on habitat parameters and monitoring possible damage from an invasive species of soft coral.

A technical diver deploys from a Research Vessel.



Technical diver measures a black coral tree.

The demand for divers trained as a NOAA Working Diver is high within NOAA, and classes conducted at NDC are always full and dive candidates are turned away. Two tasks at PIFSC require a NOAA Working Diver certification: Marine Debris and support of Oceanographic Buoys. Because the Working Diver class is conducted on the mainland and it can be difficult to gain access to this class, the NDP and the PIFSC have developed a Specialized Task Endorsement (STE) which allows divers at PIFSC to conduct specific tasks for which they are trained.

The Marine Debris Program originally utilized working divers from both PIFSC and the NOAA Research Vessel Townsend Cromwell to conduct pilot surveys and efforts, which indicated that a larger effort would be required to make any progress on the debris. From 1998 to 2000, the debris program enlisted the help of several agencies to expand the effort. In 2001, the Debris Program hired nearly 20 personnel for the sole purpose of a large scale, long term survey and removal effort in the NWHI. Because of the impossibility of training 20 new divers at the NDC without impacting other NOAA program dive needs, an agreement was made with the NDP that eventually evolved into the first STE.

This initial STE allowed divers with Scientific Diver ratings to remove debris from the shallow waters of the NWHI using lift bags and other tools. Candidates first had to obtain a NOAA Scientific Diver rating and then complete two additional weeks of dive training and water work. Divers were taught and drilled in the specialized skills of snorkel towboarding, lift bag use, recovery of debris, surf operations and small boat piloting in shallow waters and through surf. The divers also received additional training in Remote First Aid and Medicine Training. Due to divers moving to other tasks or divisions, there has been annual debris training for replacement divers since its inception in 2001 and has continued to this year.

Diver entangled in debris during training.

Divers recover debris in the field.

The second STE was created for the "Buoy Program" because of the extensive use of liftbags to deploy and recover moorings and instrumentation. To qualify for the Buoy STE divers must have a minimum of one year as a scientific diver at PIFSC and have a minimum of 50 dives. The STE consists of 2 hours of classroom work covering applicable physics (Archimedes principle, Boyles law), equipment use and safety guidelines. Divers then conduct a minimum of 4 dives to familiarize themselves with the use of lift bags ranging from 250 to 2,000 lbs of lift and at depths between 30 - 90 feet. All STEs are valid for one year and divers must complete a yearly refresher training to renew this rating.

Diver practices with lift bag during training.

Diver working on a buoy in the field.

Most of the diving conducted through PIFSC is from small craft. Because most new divers rarely have experience in piloting small craft, basic small craft handling was incorporated within the Debris STE from 2001 to 2003. Divers piloted inflatable craft through surf breaks and passes in reefs, conducted fast rescues and even righted flipped inflatables.

In 2003, a mandate within NOAA required all personnel who coxswain small craft to participate in specialized training that qualified them as official NOAA coxswains. Because training programs were already in place the divers, PIFSC was able to transition quickly to meet this requirement. In 2004 it became known as the PIFSC Small Boat Program. Today PIFSC is one of the few groups in NOAA that has a recognized coxswain course.

Divers practice a pivot turn in an inflatable boat.

Divers attempt to right flipped inflatable boat in surf.

Reciprocities

PIFSC projects span the Pacific and necessitate cooperation with other agencies and academic institutions from the various regions. The PIFSC sponsors three reciprocities with other AAUS accredited programs: the Hawaii State Division of Aquatic Resources (HDAR), Guam Department of Wildlife and Aquatic Resources (GDWAR) and Confederation of the Northern Marianas Islands Department of Environmental Quality Costal Resources Management (CNMI-DEQCRM). PIFSC has also cooperated with divers from the USFWS, National Undersea Research Program (NURP), University of Hawaii (UH), University of Florida, US Coast Guard, Federal Bureau of Investigation, University of Guam and Bishop Museum.

These reciprocities have been instrumental in promoting cooperation on projects, especially projects conducted in waters local to the agencies. Reciprocities encourage the participation of scientific divers with local knowledge, and enhance data collection and safety. Finally, it increases the number of divers available for projects in distant areas.

Reciprocities also allow for groups to respond to large scale events, such as coral bleaching or ship groundings. The recent grounding of a freighter hauling concrete, the Cape Flattery, on a reef off Honolulu Hawaii; required the cooperation of PIFSC, HDAR and UH. Individually the dive programs did not have enough divers to finish the various tasks. Divers were needed to survey the large swath of damage created by both the ship grounding and its removal from the reef. Divers were also needed to install reference transects for follow-up surveys and participated in habitat restoration. Because reciprocities were already in place between the dive programs, divers were deployed the day after the ship was removed and were able to seamlessly cooperate together for two weeks. Had only one program responded, the goals would have taken longer to accomplish or never would have been accomplished.

Conclusion

Scientific Diving in the Pacific associated with NOAA and PIFSC will continue to grow. The proposed creation of a NOAA campus within Hawaii will concentrate dive programs from National Marine Fisheries Service, National Ocean Service, National Weather Service, NOAA vessels and possibly Ocean Exploration; increasing housing and equipment needs. Scientific Diving within standard depths will continue and increase in divers, projects and dive sites. This will lead to increasing demands for reciprocity agreements. There is already a demonstrated need for technical diving on new projects that would require support from NDP. NDP and PIFSC will continue to grow, creating support, training and reciprocities to meet these needs.

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University of South Florida College of Marine Science Divers Get Put On a "Shelf"

Rick Cole, Robert Weisberg and Jason Law
Oceanographic and Diving Operations, University of South Florida, College of Marine Sciences 140 Seventh Ave. South, St. Petersburg, FL 33701

Abstract

This overview describes the diving operations and a brief summary of the University of South Florida's (USF) coastal ocean monitoring program in the Gulf of Mexico using oceanographic and meteorological instrumentation along the west Florida shelf (WFS). The Ocean Circulation Group (OCG) manages the *in-situ* physical oceanographic measurements and modeling on the west Florida shelf not far from USF's College of Marine Science (CMS) campus. In 1993, the OCG initiated a pilot mooring program in the Gulf that has grown into a more complete air-sea interaction processes and coastal ocean monitoring study called the Coastal Ocean and Monitoring Prediction System (COMPS). The array now supports basic research as well as providing data needed for management issues such as more accurate predictions of flooding by storm surge, safety and efficiency of marine navigation, search and rescue efforts and fisheries management. The overall goal of this work is to improve the understanding of how the physical processes affect material property distributions on continental shelves.

Introduction

Dr. Robert Weisberg, OCG Director (front, center) with Dave English, Pete Wenner, Monica Wolfson, CharlieCullins (CMS divers), Rick Cole (OCG Divemaster) and Bill Dent (USF Diving Safety Officer and AAUS Pres.) finish up a day on the west Florida shelf aboard Florida Institute of Oceanography's R/V BELLOWS.

The University of South Florida's (USF), Ocean Circulation Group (OCG), College of Marine Science (CMS) in St. Petersburg, Florida, has had an active diving program since beginning research in the Gulf of Mexico in 1993. Under the direction of Dr. Robert Weisberg, the OCG manages the *in-situ* physical oceanographic measurements and modeling on the west Florida shelf (WFS), along the eastern Gulf of Mexico. The shelf spans from the Florida Keys to the Mississippi River and is an excellent natural laboratory for studying continental shelf processes. Data are acquired by deploying a variety of ocean instrumentation on the seafloor and in the water column as well as meteorological sensors at the surface (air-sea interaction). As knowledge of the ocean continues to improve along with new technologies, our understanding of the coastal zone is still lacking an adequate observational baseline. Dr. Weisberg along with founding members and students of the OCG drew upon experiences in the tropics, with equatorial Atlantic and Pacific Ocean studies such as SEQUAL, TOGA-TAO, TIWE, and COARE, funded by NOAA and NSF, to begin a field program on the WFS.

Recognizing that knowledge of the coastal zone requires a complete understanding of the shelf-wide circulation and its response to seasonal winds and buoyancy forcing, the OCG initiated a pilot-mooring program in the Gulf called the "West-Central Florida Shelf Hydrography and Circulation" project in collaboration with the United States Geological Survey (USGS) Center for Coastal Geology, St. Petersburg in the early 90's. This research was aimed at improving the description and understanding of the physical processes that control shelf circulation and hydrography. Three separate programs have been integrated since: NOAA's "Ecology and Oceanography of Harmful Algal Blooms" (ECOHAB), an Office of Naval Research (ONR) initiative "Hyperspectral Coupled Ocean Dynamics Experiment" (HyCODE) and The State of Florida's "Coastal Ocean Monitoring and Prediction System" (COMPS, Fig.: 1). Data from this array will lead to a better understanding of the responses of the inner shelf to forcing by tides, winds, seasonal heating and cooling, fresh water inflows, and the interactions with the adjacent deep Gulf of Mexico.

The array now supports basic research as well as providing data needed for management issues such as more accurate predictions of flooding by storm surge, safety and efficiency of marine navigation, search and rescue efforts and fisheries management. In the wake of the 1993 no named extra-tropical "Storm of the Century" and after severe Atlantic Ocean and Gulf of Mexico hurricanes, Principal Investigators from USF approached state legislature for support of a real-time "Coastal Ocean Monitoring and Prediction System". A precedent for this system already existed in the form of the Tampa Bay "Physical Oceanographic Real-Time System" (PORTS), a program initiated by NOAA. COMPS consists of an array of instrumentation both along the coastline and offshore, combining sites initiated and maintained by USF with other sites maintained by federal, state and local agencies and serves these data in real-time on the Internet.

Dr. Mark Luther and his Coastal Modeling and Prediction Laboratory (OMPL) direct the coastal component of COMPS. Program Director is Clifford Merz. The URL is: (http://comps.marine.usf.edu). Future buoys, bottom mounts and towers are planned as the program expands. Compared with other continental shelf regions, little is known about the west Florida shelf circulation. There is an immediate need to make more effective use of existing resources and new technologies to provide a more timely detection and prediction of the coastal environmental conditions from changes in weather and sea state to changes in habitat and living marine resources.

Measurements

The offshore array presently consists of ten moorings: six surface sites and four subsurface sites. All mooring sites use acoustic Doppler current profilers (ADCP) for water column velocity measurements in either upward looking or downward looking mode. ADCP technology allows current velocity and direction to be determined using the Doppler effect by transmitting sound at a fixed frequency and listening to echoes returning from scatterers in the water. Temperature and salinity recorders are spaced on the moorings as well as on the bottom mounted sites (Fig. 2). The most complete system provides surface meteorological sampling (i.e.: wind speed and direction, air temperature, barometric pressure, relative humidity, precipitation, short and long wave radiation and sea surface temperature), water column currents, temperature and salinity at three depths all telemetered in near real-time hourly intervals via NOAA's Goestationary Operational Environmental Satellite (GOES), (Fig. 3).

USF's Center for Ocean Technologies (COT) designed and integrated various components of the buoy system into a data logger for transmission over the GOES network. All data are acquired, processed, archived and disseminated by the OCG systems administrator and COMPS data manager. COMPS field operations are supported by the Florida Institute of Oceanography (FIO) research vessels; SUNCOASTER and BELLOWS, the USGS R/V GILBERT and the CMS's R/Vs PRICE and SUBCHASER. Cruises depart quarterly for regular servicing of the array as well as emergency trips offshore as various issues arise.

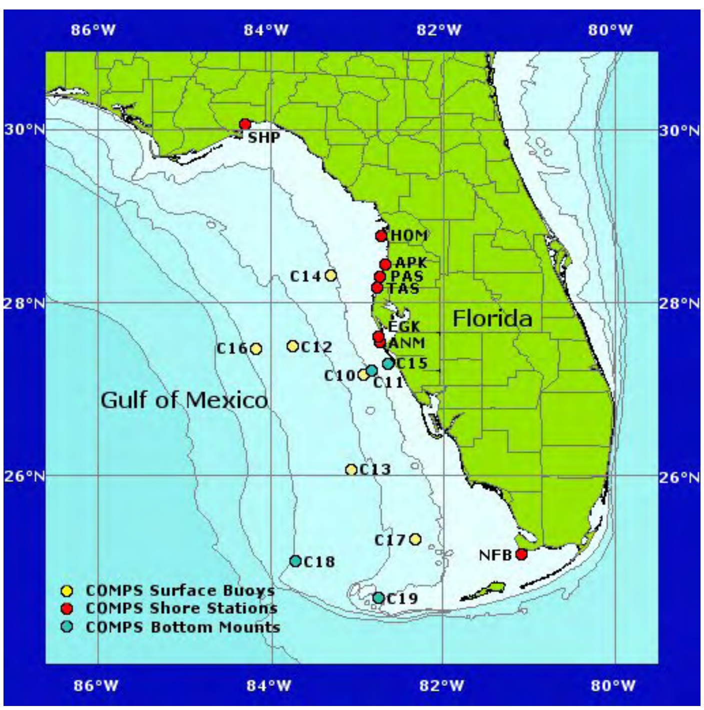


Figure 1 The COMPS Array

Figure. 2: Rick Cole prepares a bottom mount with ADCP and SeaGauge for deployment)

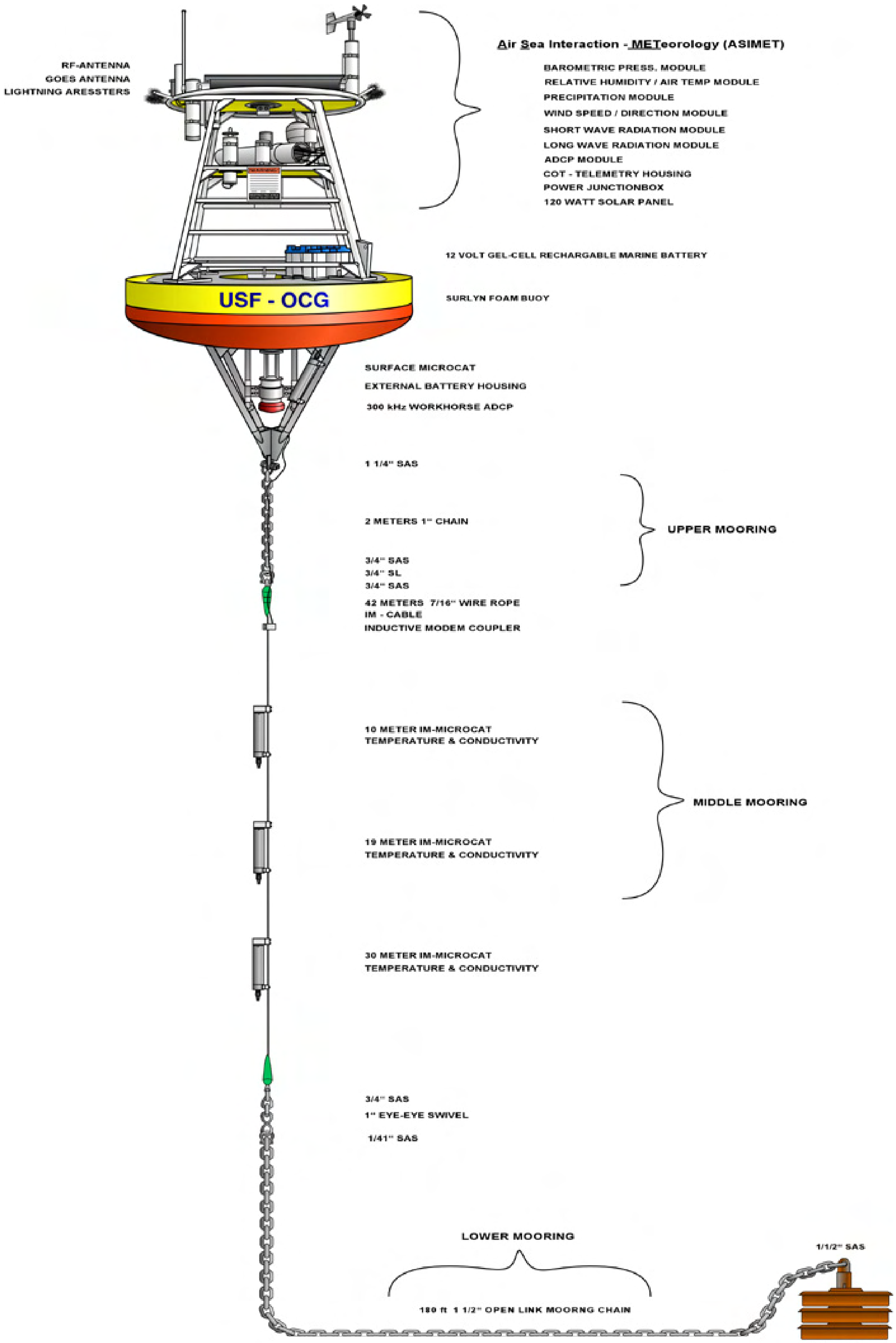


Figure 3: Complete Air-Sea Interaction System)

The Dives

USF is an active AAUS Member Organization that follows a set of standard guidelines and regulations provided by the Academy on all diving projects. This allows the University's Diving Safety Program to ensure safe and effective diving practices and to properly educate and support underwater researchers within the ocean sciences community as well as collaboration on research projects with other AAUS member organizations. The program operates under the Office of Research, Division of Research Compliance. USF's Diving Safety Officer (DSO) is William Dent, also President of AAUS, Assistant DSO is Ben Meister, both very active in OCG diving and a essential asset to all of us at USF where diving is a component on CMS research programs.

OCG Oceanographic and Diving Operations Coordinator is Rick Cole, long time Senior Scientific Diver with AAUS, PADI Divemaster, NOAA and EPA Working and Scientific Diver. Rick has been overseeing OCG diving since they began working on the shelf in the early 90s. Dr. Weisberg and Jason Law are the other two resident OCG divers. New divers continue to become involved as new students and postdoctoral candidates join the group.

Diving is a critical component to the mission of the OCG on the WFS. Cruises are usually split up into full mooring recovery and deployment trips with minimal diving involved or are planned with diving as priority, with a minimum of three and on some cruises, eight divers onboard. Due to mechanical wear and tear on wire, shackles and buoys, and instrument power, the moorings are turned around every six months with new mooring components and recently calibrated instrumentation. Once a new mooring is set a full underwater inspection is conducted. All components of the mooring from the anchor to the buoy, including the instrumentation, are carefully examined to ensure the array will remain secure over the course of a long deployment. (Fig.: 4 & 5)

Figure 4 Authors Cole, Weisberg and Law prepare for a dive to set an ADCP in the Dry Tortugas

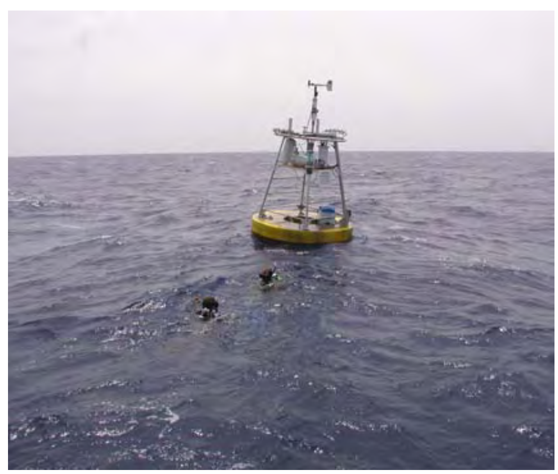


Figure 5 Mooring Inspection

The bottom-mounted ADCP racks must be initially located using pingers and a diver held acoustic receiver. The instruments are marked on the surface with floats for research vessel positioning and recovery operations. Since three divers are a required on all USF dive trips and in most cases all three OCG divers cannot make every cruise together, the offer goes out to the list of CMS certified divers to attend the trip offshore. Four divers is the best option. This allows dive teams to work alternate dive sites which saves time waiting for safe surface intervals as well as reducing ship time costs.

COMPS dive sites range in depth from ten to fifty meters. Cruise tracks are planned to hit the fifty-meter sites first, working east into the shallows as the day progresses. An example of a deep site was an ADCP system in a depth of 242 feet where the acoustic release failed to fire and bring the instrument pod to the surface. Bill Dent and fellow USF diver Dr. James Garey, who are Tri-Mix trained, were able to drop down on the rack and secure a winch cable for a successful lift aboard, rescuing nearly $75K worth of instrumentation. Cruises are planned around evening departures putting the divers on site and in the water at first light. Night dive operations are also conducted when necessary. Figures 6-13 depict the variety of diving and instrumentation used within the program.

The Future

As coastal monitoring projects continue to evolve new programs will come online. In May of 2000, the Chief of Naval Research, the Administrator of NOAA, and the President of the Consortium for Ocean Research and Education announced the formation of OCEAN.US, an organization dedicated to the formation of an integrated and sustainable ocean observation system. The Southeastern Atlantic Coastal Ocean Observing System (SEACOOS) was formed and is to be one of the regional systems ringing the U.S. to form the coastal component of the Integrated Ocean Observing System (IOOS); a collaborative university partnership that collects, manages, and disseminates integrated regional ocean observations and information products for the coasts of North Carolina, South Carolina, Georgia, and Florida. The Office of Naval Research has provided funding for this effort. The vision for this ocean observation system requires that observing systems around the country cooperate to collect and disseminate data and data products to serve the critical and expanding needs of environmental protection, public health, industry, education, research, and recreation. SEACOOS is to be a part of this larger IOOS system. USF's COMPS program will continue to evolve as coastal monitoring nationally and internationally continues to expand.

Figure 6 Successful recovery with new ADCP system ready to deploy

Figure 7 HOBILabs Divers from Santa Cruz, CA prepare to recover optical sensors on one of the buoys. Harbor Branch Oceanographic Institute's R/V SEADIVER in the background

Figure 11 Acoustic Wave Gauge deployment

Figure 9 Science party and divers with recovered mooring anchor from a 20-meter site

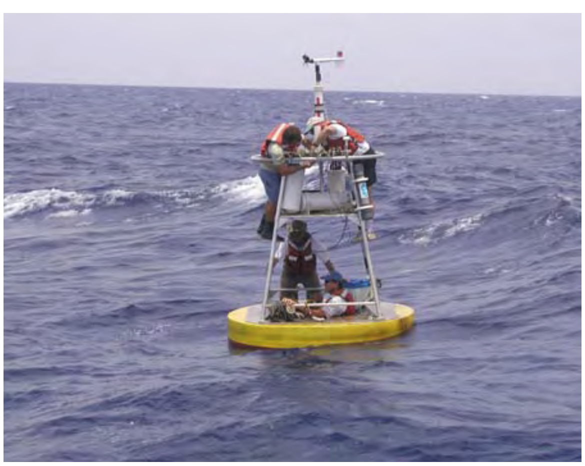
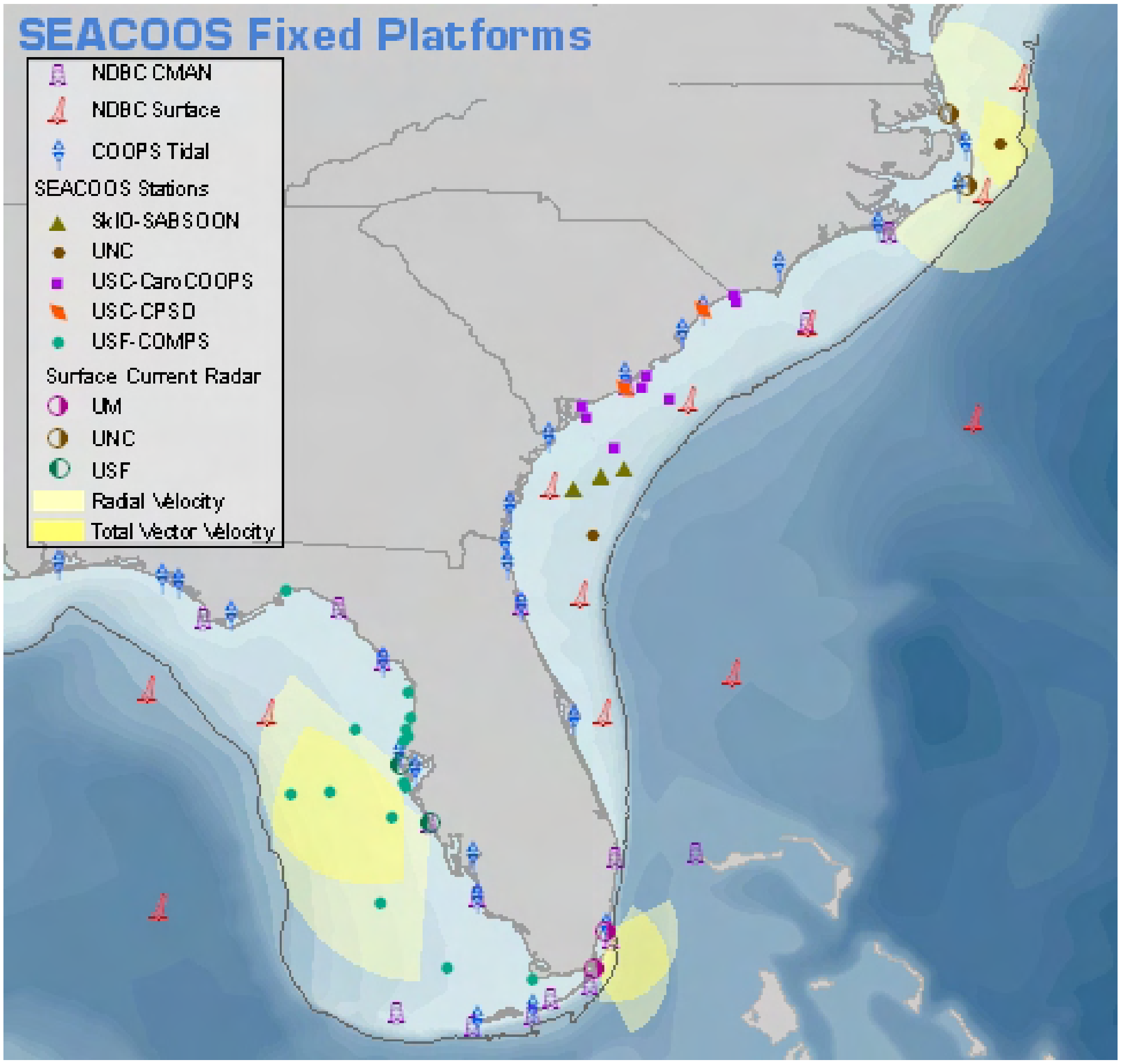


Figure13 Pre dive buoy and electronics servicing

Figure. 12 RV SUNCOASTER Loaded for sea



(Figure 14 SEACOOS Domain and Array)

Acknowledgments

The author's wish to thank all involved over the past eleven years when work began on the WFS. These projects would have never left the lab, or pier if not for the hard work, work ethic and determination of everyone in and involved with Dr. Weisberg's Ocean Circulation Group, all COMPS personnel, USF DSO Bill Dent and Asst. DSO Ben Meister. In addition, we thank Dr. Mark Luther and the Ocean Modeling and Prediction Lab, Randy Russell and the Center for Ocean Technologies of USF, Florida Institute of Oceanography, Captains and crews of R/V SUNCOASTER, R/V BELLOWS, R/V PRICE, USGS and R/V GILBERT, The Harbor Branch Oceanographic Institution and R/V SEA DIVER, Paul Coenen and crew from HOBILABS, The National Data Buoy Center, Aquatic Obsessions Dive Shop, St. Petersburg and the countless number of graduate students and divers involved in all OCG research on the WFS

Community Science – Recruiting, Training & Leading Scientific Dive Teams: Transects, Quadrats, Lift Bags and Science to "Save the Bay"

Richard B. Carey & Richard V. Ducey
Scientific Dive Team
Magothy River Association
Severna Park, Maryland

Abstract

Community science is what results when citizen volunteers undergo training, adhere to protocols and perform service to assist scientists and advance scientific interests and local outcomes. One example of a community science program that has achieved notable recognition is the volunteer scientific dive program run by the Magothy River Association (MRA). Originally formed to assist the oyster restoration research efforts, it has grown to encompass many other areas. The Magothy River is one of the Chesapeake Bay's many tributaries. The volunteer divers recruited into our program are specially trained and led by certified scuba instructors, professional biologists and scientists, and scientific dive leaders to perform specific scientific diving projects define "community science." Training, motivating and providing project leadership requires a unique set of resources, management skills and programs, many of which the Magothy River Association has pioneered. We offer our perspective on community science largely by describing the goals, methods and procedures used in our research projects and the training programs we have developed.

Introduction

We discuss community science and provide examples of projects involving the scientific dive team of the Magothy River Association (MRA) which is based in Severna Park, Maryland which is part of the Chesapeake Bay watershed. Community science leverages the contributions of trained volunteers under the direction of professional scientists. In the case of the MRA, a volunteer scientific dive team trained and supported by the Association, conducts and support research programs designed to foster oyster population restoration among other ecological goals. We will address our perspective on community and describe the training program we use to prepare volunteer divers to assist scientists who would otherwise face more limited resources for conducting their research agendas.

Community Science

Carr defines community science as "the interaction between conventional (institutional, professional) and community-based scientific knowledge systems", (Carr, 2003). Carr, also argues that like other science traditions, community science techniques and protocols are subject to careful and critical peer review. Community science offers advantages to the institutional and professional scientist by providing access to volunteers with intellectual, political and financial capitol including local knowledge, factual and anecdotal.

Cornell University's Laboratory for Ornithology relies extensively on community science for the collection of field data. A major advantage has been the ability of community science to extend the collection of data sets across boundaries of space, time and size. While Stevenson and Morris, (2004) have credited Cornell's Ornithology laboratory with pioneering the use of citizen scientists, it is Wilderman, (2004) who noted that it was the U.S. Weather Bureau who first used trained volunteers in this country during the late 19th century to collect weather data and man weather station.

Wilderman notes that community science depends on a partnership between the community and the scientific community. While Wilderman, found there are many reason citizens become involved in scientific research, it depends in a large measure with whom they work. Further. She offers several models of community science such as "community workers model", "consulting model" and the "community-based participatory model". Her models are based on answers to five basic questions:

1. Who defines the problem?
2. Who designs the study?
3. Who collects the samples?
4. Who analyzes the samples?
5. Who interprets the data?

Against this backdrop we present our models for community science which are based on a unique wealth of diversity and community resources.

Chesapeake Bay and Magothy River Association

The Chesapeake Bay is the largest estuary in the United States, (Chesapeake Bay Program, www.chesapeake.net). It is the most biological diverse estuary containing over 3,600 species of flora and fauna. The Chesapeake Bay covers 2,500 square miles. Its watershed drains 64,000 square miles in six states and the District of Columbia. The largest river is the Susquehanna River. Over 60% of the "fresh water" entering the Bay comes from this river by discharge through the Conowingo Dam. This discharge is drainage from about one-third of New York (upstate) and one-half of Pennsylvania. These once rural areas are becoming more developed and runoff has significantly increased over the past few years. The increase in fresh water flow has had both a beneficial and a detrimental effect on oysters; Low salinities protect oysters from disease but adversely affect growth and recruitment. Perhaps even more environmental destructive is the periodic scouring of sediments, caused by weather events, of new and legacy sediments accumulated behind the dam. These sediments carry high levels of attached phosphates, smother grasses, cause algae blooms, destroy habitat and eventually result in dead areas in the Bay. Regrettably, the Magothy River by virtue of its location is not immune to this insult.

The Magothy River is located in the Upper Western Shore Watershed of the Chesapeake Bay Watershed. Physically it is located midway between Annapolis and Baltimore roughly bound by MD route 50 on the south, MD route 2 on the west, MD route 100 on the north and Chesapeake Bay on the east. The Magothy River is 6 miles long and covers 9 square miles of the 36 square mile watershed. Most of the land area is fully developed except for a portion of the north shore which is held in a land trust. Water circulation in the Magothy River is extremely poor. Water input to the river from natural sources is very low.

The Magothy River Association (MRA) was formed in 1946 by the residents of the watershed to prevent the river from becoming a Navy seaplane base. The organization has grown to represent 46 communities. It is very active in land use including zoning and land trusts, submerged aquatic vegetation, oyster reef restoration, water quality monitoring, fish habitat and reforestation programs.

In 2001, the dive program became a formal and active group with the addition of a volunteer dive coordinator and dive professional to its dive program. Volunteers divers come from Northern Virginia, District of Columbia, Maryland, West Virginia and Pennsylvania. By virtue of its location in the Washington, DC metropolitan area, the MRA has many Federal employees who volunteer to assist in projects. These volunteers include well trained and experienced personnel from the National Oceanic and Atmospheric Administration (NOAA) headquarters in Silver Springs, Maryland and the Chesapeake Bay Office in Annapolis, Maryland. The dive team provides a venue where NOAA divers can interact with MRA divers and other groups such as the U. S. Naval Academy and Capitol Hill Divers on an informal basis.

Volunteer Diver Qualifications

Members of the MRA Scientific Dive Team are all volunteers. They are certified by nationally recognized dive training agencies. We also conduct our own training for which our instructors offer volunteers PADI or NAUI specialty certifications. All divers must file a statement of health or have a dive medical examination periodically. Additionally, appropriate waivers and emergency notification forms are completed. These documents are maintained on file, reviewed periodically and updated. Most of our divers are college graduates and about 25% hold doctorates in various fields. This blend of talent results in a combination of ideas and skills easily applied and practical in application.

Community Science – U. S. Naval Academy Workshop

As part of our community science outreach program we conduct workshops where we can train divers in basic scientific diving, evaluate their skills, recruit new divers and inform these groups about the Chesapeake Bay and the Magothy River ecology. The format varies with the group. We work with community colleges, dive clubs and other groups. We will provide details for the training work we do with the U.S. Naval Academy.

Each year we do an Earth Day Project with the U.S. Naval Academy Oceanography Club. This begins in February when we go to the Academy to conduct a workshop and culminates on Earth Day with a dive in the Magothy River where the Midshipmen perform an environmental survey. This task may require sampling an oyster reefs, site investigation or positioning reef balls to increase fish habitat in the river.

Our training program consists of multiple tasks – Skill Assessment, Entanglement Net, and Point Sampling Method. Spat-on-Shell Planting Method, Reef Ball Positioning. Our workshop has been observed by NOAA and the University of Maryland. The training exercises we conducted in the Naval Academy workshop are summarized below.

Figure 1 Skill Assessment Exercise

Skill Assessment Exercise:(Figure 1) This exercise is requires a diver to demonstrate several basic skills which are standard to diver training. Our evaluation requires a diver to enter the pool and demonstrate these skills.

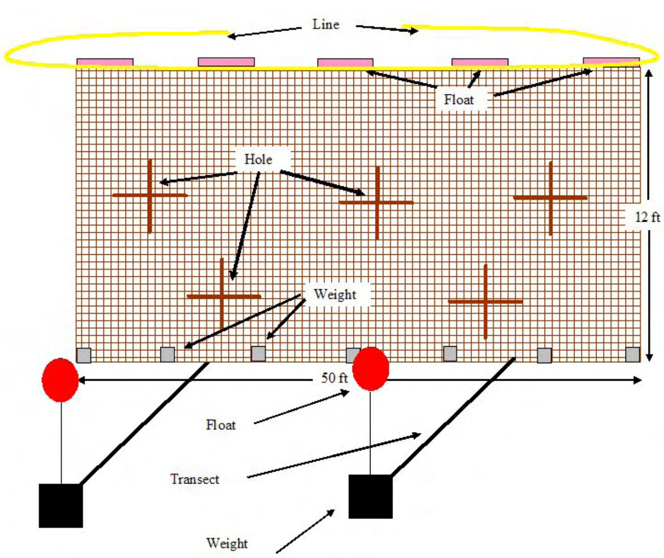


Figure 2 Entanglement Net Exercises

Entanglement Net: (Figure 2) This exercise requires a diver to operate in a hazardous environment without visibility. With a darkened mask, the diver descends down a line to a transect which leads to a net. A diver must locate an opening in the net, swim through the opening and then reverse their track returning to the starting point. If the diver becomes entangled along the route then they must work free of the entanglement.

Point Sampling Method: This exercise instructs the divers in the approved sampling protocol for our oyster reefs. A weighted float is pre-positioned on the reef to be surveyed. The weight is rectangular and allows the divers to locate themselves in low visibility. The surface float identifies the location of the sample and the divers. In the pool a basket with shell (tokens) is positioned one meter from the weight at 0^{o}, 90^{o}, 180^{o} and 270^{o} relative to the indexed weight. Divers collect four quadrats, one quadrat at each point one meter from the weight.

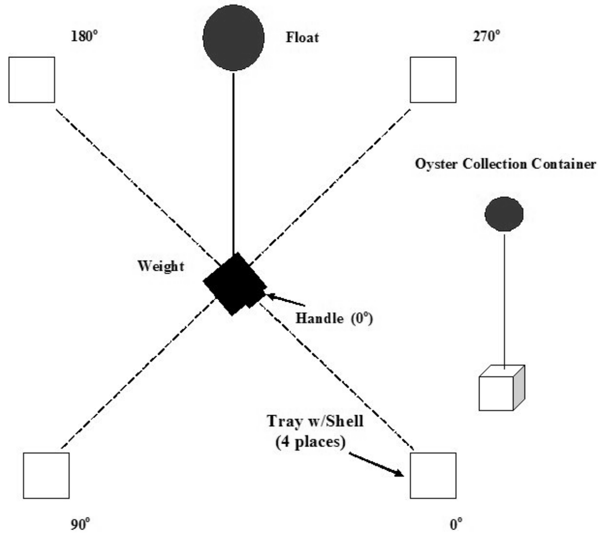


Figure 3 Point Sample Method

Spat-on-Shell Planting Method: (Figure 4) This exercise instructs divers in a method of uniformly planting oysters. A transect line with a quadrat strung on it is positioned between two weighted floats. A diver with a darkened mask moves along the transect line properly positioning the quadrat and placing a shell (token) to mark each location.

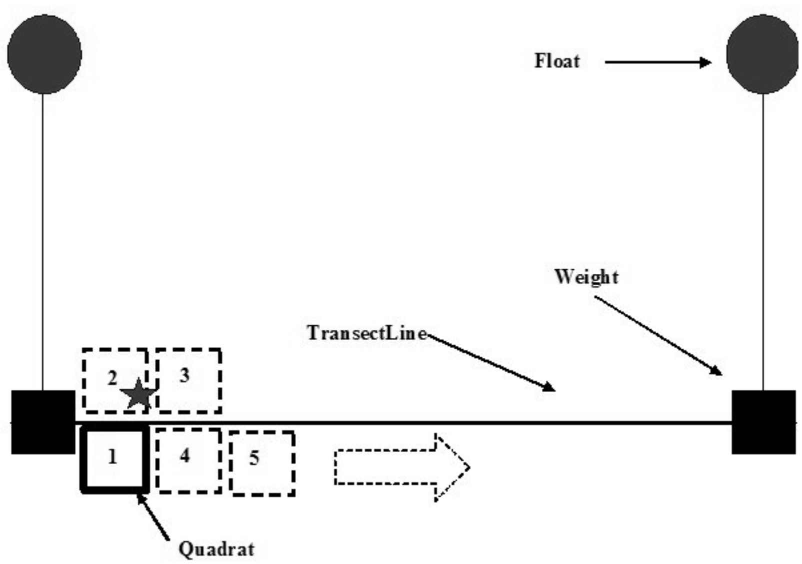


Figure 4 Spat-on-Shell Method

Reef Ball Positioning: (Figure 5) Corp of Engineers and State permits governing the positioning of reef balls for fish habitat requires a minimum water depth to provide adequate clearance for vessels. The skill instructs divers in the proper use of lift bags and the movement of small reef balls so diver can reposition the balls if necessary.

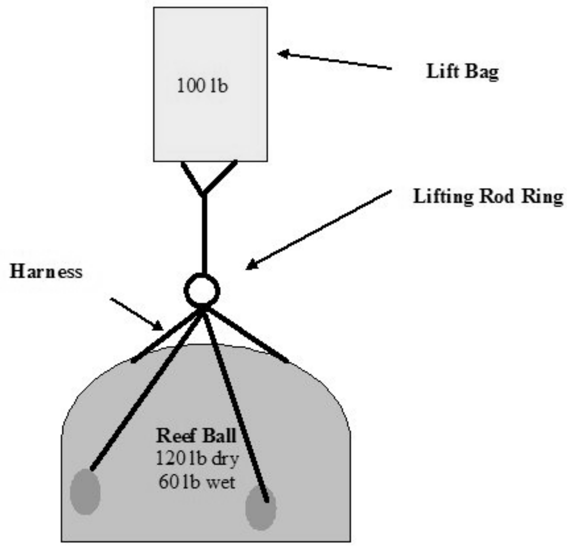


Figure 5 Reef Ball Positioning

Open Water Experience:

In conjunction with our workshops an open water dive is offered. As part of our 2002 Earth Day Project we introduced a system of transects radiating from a central location (Figure 6). This method was used again with the Capitol Hill Dive Club work shop in 2005 to survey an old oyster site. The number of transects emanating from the central anchor can be varied and allows good control of a group of divers while investigating a specified area. A modification of this system can be useful in reducing in-water exposure during winter months.

In our 2003 Earth Day Project we practiced reef ball positioning and sampled a reef using the Point Source Sample Method. Samples were collected in baskets and then placed in buckets (Figure 8) for transport to shore for processing. After measuring and recording oyster data (Figure 9) a portion of our sample was sent to the University of Maryland and to Virginia Marine Institute for disease testing. The remaining oysters are returned to the reef of origin.

While the workshops are fun in and of themselves, volunteers want to be put to work to feel useful, gain experience and learn more about their environment. Here we will provide details about several such projects in which our training graduates were eligible to participate.

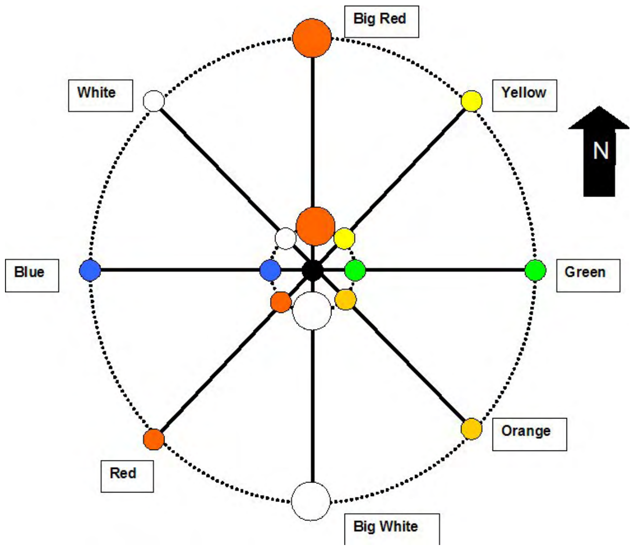


Figure 6 Radial Transect System

Figure 7 Support Vessels

Figure 8 Samples Prepared for Transport to

Figure 9 Sorting, Measuring and Recording

Community Science – Projects

Recruitment Study: Our first organized project was in 2002. The salinity in the Magothy River had been increasing as the result of a drought in the northeast. The fresh water entering the Bay was at a minimum. Conditions for oysters to reproduce were favorable, dissolved oxygen (DO), greater than 2 milligrams per liter, salinity of 8 parts per thousand or higher and temperature greater than 17 degrees Celsius (Figure 11). Oysters exposed to conditions below these levels for extended periods require several months to ripen once their habitat recovers.

A test plan was developed and submitted to the Maryland Department of Natural Resources (DNR) and Dr. Paynter, University of Maryland Center for Environmental Science (UMCES). MRA members traveled to the State operated Piney Point Hatchery (now closed) to pick up 100 mess bags containing oyster shell. This shell was our spat collector. The

Magothy River has 5 restored oyster reefs (Figure 12), Chest Neck Point (CNP)(1), Rock Point (ROCP)(2), Ulmstead Point (ULMP)(3), Dobbin Hill (DOBH)(4) and Persimmon Point (PERS)(5). Three reefs were selected, PERS at the mouth of the river, DOBH mid-river and CNP located at the upper recruitment line.

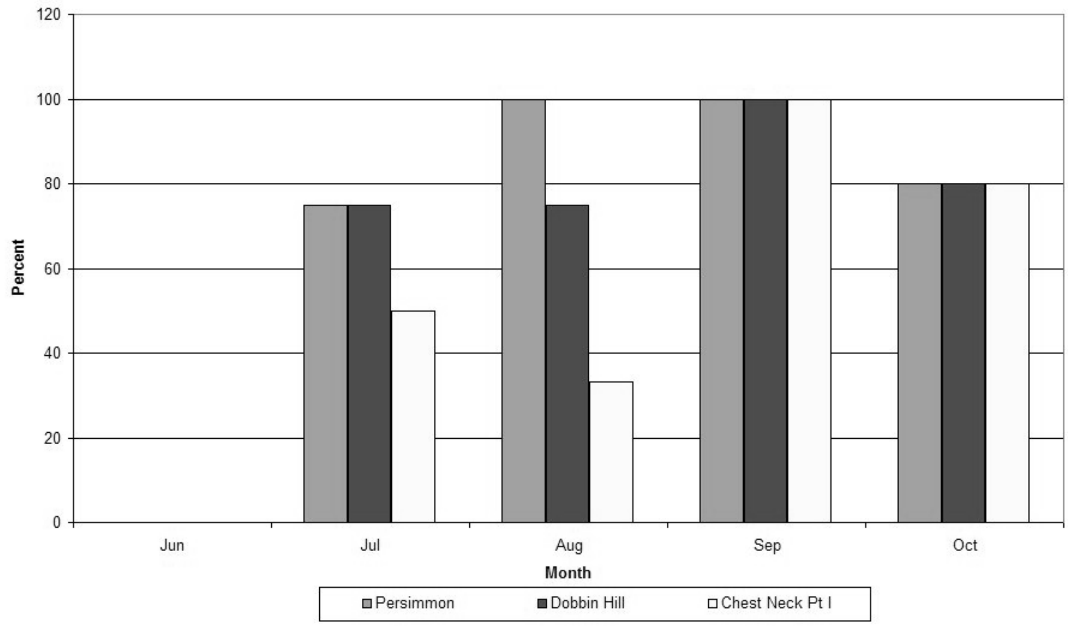


Figure 11 Frequency of Days with Temperature, Dissolved Oxygen and Salinity Exceeding Minimum Critical Recruitment Criteria, (Site Data at 0.1 meters).

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A transect line was laid across each of the selected reef (Figure 13) and a total of 21 bags were placed on each reef. Water quality was measured weekly over the season (Figure 11).

During November the bags were recovered. The recovery rate was 76% PERS, 86% DOBH, and 95% CNP. A total of 10,918 individual oyster shells were inspected for spat. Spat sets were PERS, 3.0 spat per 1000 shell, DOBH, 4.5 spat per 1000 shell and CNP, 4.0 spat per 1000 shell.

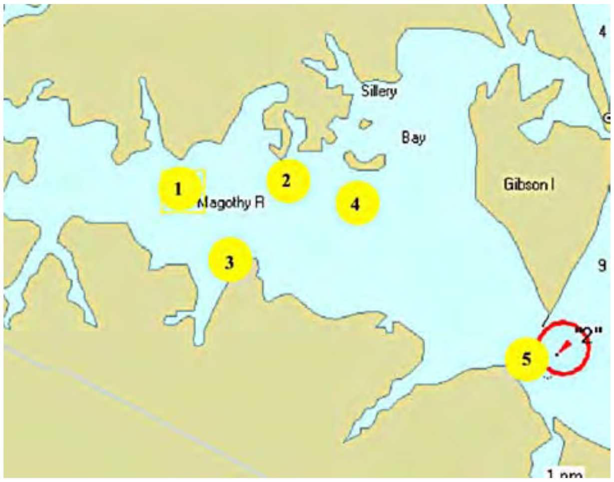

Figure 12 Magothy River Active Oyster Reefs (numbers refer to text)

Figure 13 Shell Bag Spat Collector on Reef

Brood Stock Study: During 2003 the MRA Board of Directors authorized a brood stock study. The dive team recovered oyster remnants off an old oyster lease. Although these oysters were not native to the river, it was estimated they survived in the river for up to 10 years (the last date the lease was active). Working with DNR and UMCES Hatchery at Horn Point these oysters were bred. The hatchery provided 285 bags of brood oysters and 50 bags of regular hatchery stock for comparison testing.

A portion of this stock was given to oyster gardeners in a blind growth study and the balance was planted by the dive team on ROCP reef. Oysters given to oyster gardeners became overgrown with up to 2 inches of the dark false mussel (DFM). Although native to Chesapeake Bay, this growth of DFM had never been experienced before in the river. Oyster gardener samples were lost as their cages became too heavy for most to remove from the water to collect data. Where possible the dive team recovered these oysters and planted them at ROCP. The remaining brood oysters and hatchery stock oysters were planted on ROCP at the rate of one bag per square meter. A test area was set aside where the remaining hatchery oysters could be compared to the brood stock. ROCP is especially suited for this test as the base is 3-7 inch stone and all oyster shell was placed on site. Although DFM was found on this reef, the higher salinity seems to have retarded reproduction and only low levels were experienced. When planted the brood stock had 8 spat per shell and the brood stock had 5 spat per shell. During our 2005 survey, both stocks had a survival rate of 3 spat per shell but the hatchery stock had grown almost twice as fast as the brood stock.

Oyster Reef Monitoring: Annually we sample our oyster reefs. This requires a permit from DNR and approval of our sampling method by Dr. Paynter, UMCES. Often we are asked to retain our sample for disease testing. Our standardized methods and diver training simplifies this approval process. The data we collect is available to interested parties. The results of out survey taken in 2004 are in Table 1.

Table 1. Active Reef Survey 2004

Reef Identification	Year Planted	Base Material	Mean Size Mm	Mortality %
PERS	1998	DSH	97.9	98.9
PERS (BSA)	2000	DSH	82.8	57.3
DOBH	1999	DSH	107.9	27.7
ROCP (MR)	2003	3”-7” Stone	17.0	24.8
ROCP(STD)	2003	3”-7” Stone	18.8	23.0
ULMP	1999	DSH	84.1	90.8
CNPI	2000	DSH	67.3	24.8
CNPII	2001	DSH	45.1	14.7

Summary

In this paper, we have presented some of our community outreach projects, some of our scientific projects, and training methods employed in our practice of community science. In our discussion of the MRA team diver we find although a project may fit one community science model, each of the projects described are different, leading to a different model. Our divers are volunteers and have developed a unique and collaborative relationship with our local science partners, both professional and amateur. We have demonstrated, given ready access to the support of institutions such as NOAA, DNR colleges and the support of highly qualified citizens volunteers, a collaboration results called community science.

We hope this information will be useful to others either currently undertaking their own community science projects or those planning these programs in their own communities. Our expectation is that each community will offer its own special resources that will lend itself to different implementations of community science.

Acknowledgments

Photographs – Sally Hornor, Peter Bergstrom, Rick Ducey, Scott Hagedorn, Richard Carey
Illustrations – Richard Carey

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Chesapeake Bay Program, www.chesapeake.net

Diving in two Marine Lakes in Croatia

Eric Klos[1], John H. Costello[2], Sean P. Colin[3] and William M. Graham[4]
[1]Graduate School of Oceanography,University of Rhode Island, Narragansett, RI 02882
[2]Providence College, Providence, RI 02918
[3]Roger Williams University, Bristol, RI 02809
[4]Dauphin Island Sea Lab, University of Alabama, Dauphin Island, AL 36528

Abstract

We describe the diving methods used for *in-situ* observations of the scyphozoan medusa, *Aurelia* sp., in two marine lakes on the island of Mljet, Croatia. Both lakes have a strong pycnocline at approximately 15 m. During this study (May, 2004) surface temperature was about 20^{o} C; bottom temperature about 10^{o} C. Visibility was 15 m to 30 m. Tide and currents were negligible. A dense resident population of *Aurelia* sp. and a predictable environment made this an ideal study site. *Aurelia* was most abundant in mid-water around the pycnocline. There were several dive objectives: specimen collection for laboratory analysis, population census, discrete plankton tows and direct observation of flow around swimming medusae. We used several methods for maintaining our orientation underwater including working from an anchor line, towing a tethered buoy, and use of a blue water rig. Because the environment was relatively benign we allowed the rig to drift free while the boat was standing by at a short distance. Often a tether was not required. This plan allowed the most freedom and provided an excellent reference throughout the dive.

Introduction

Croatia is located on the eastern shore of the Adriatic Sea across from Italy. This study took place in the region known as the Dalmatian coast which is characterized by hundreds of islands and rugged terrain. The bedrock of the region is limestone and the resulting weathered karsted topography has produced a complex and intricate shoreline with numerous bays, shoals, rocky headlands, and coves with crescent beaches.

In May 2004, an international group of about 14 scientists and students, hosted by the Croatian Institute of Fisheries and Oceanography, gathered on the island of Mljet to study the biology of the scyphozoan jellyfish *Aurelia* sp. This workshop was coordinated by Dr. Jack Costello, Providence College, and was funded by the National Science Foundation and the US State Department. The four authors of this article constituted the US dive team. The site selected for study was a system of two marine lakes (called Big Lake and Small Lake) on the northern end of the island Mljet. This site was chosen because *Aurelia* was known to be consistently abundant in the lakes and the lake waters were known to have relatively good visibility (> 15 m) and stable conditions.

Study area

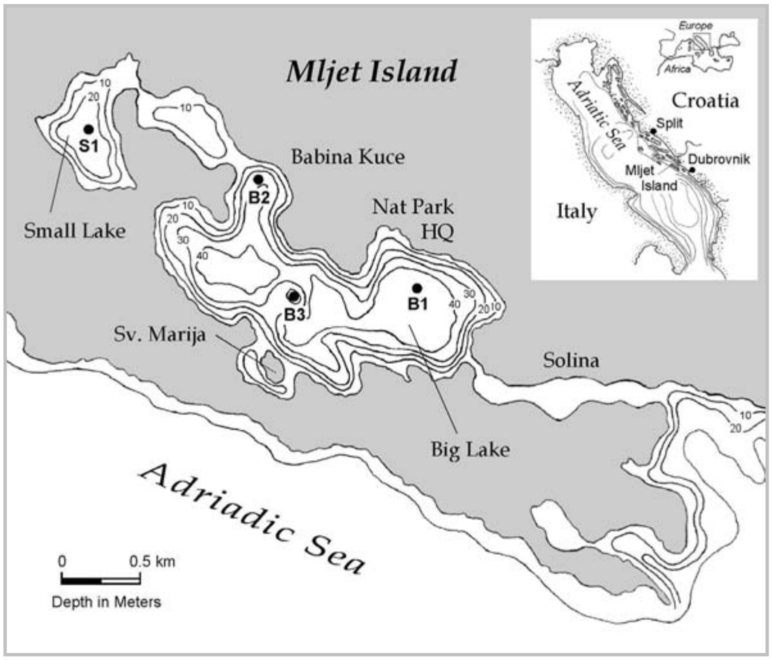

Figure 1. Mljet Lakes Site Map. B1, B2, B3, and S1 indicate the location of the different dive stations. (Adapted from Vanicek, et. al., 2000.)

Mljet is the southernmost major island in the Dalmatian archipelago and is located about 30 km off the coast of Dubrovnik, Croatia. It is oriented NW-SE and is roughly 35 km long by 3 km wide. The northern end of the island has been established as a national park. The main attractions of the park are the two marine lakes known in Croatian as Veliko Jezero and Malo Jezero or Big Lake and Small Lake, respectively in English (Figure 1). Big Lake is about 145 ha and is connected to the adjacent Adriatic Sea through a narrow shallow channel. Small Lake, about 30 ha, is connected to Big Lake through an even narrower channel and has no connection to the Adriatic Sea (Dabelic, 2001). Although there are a few notable shoals and outcrops, both lakes are 25 m to 40 m deep (Figure 2). The lakes are stratified throughout much of the year with a sharp pycnocline at about 15 m from April through October. During this study, which took place in May 2004, water temperature was near 20^{o} C at the surface and 12^{o} C below the pycnocline. Salinity varied from around 34 ppt at the surface to 38 ppt at the bottom. Tidal exchange, while nominal, drove gentile laminar currents at mid-water. Water visibility was good to excellent – 15 m to 30 m – on all dives.

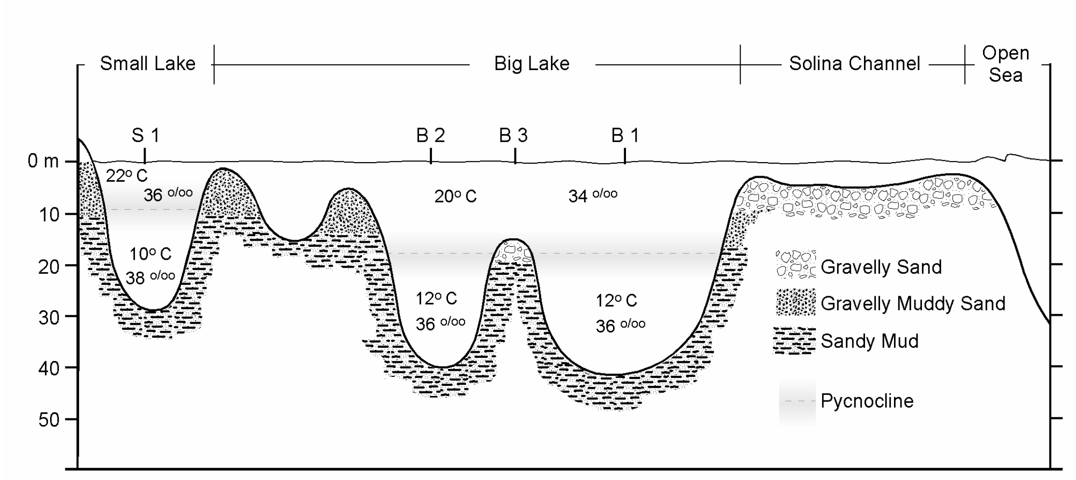

Figure 2. Mljet Lakes schematic profile. (Adapted from Vanicek, et. al., 2000.)

Aurelia sp.
Scyphozoan medusae, including those of the genus *Aurelia*, are one of the first evolved and simplest motile multicellular organisms. *Aurelia*, like many scyphozoans, is a voracious predator, feeding on a range of zooplankton species (Matsakis & Conover 1991). In order to better understand how *Aurelia* feeds, there is interest in understanding the relationship between body form, swimming motion, and prey capture (Costello and Colin 1995; Colin and Costello 2002). The bell of *Aurelia* is blunt and oblate shaped and causes considerable drag to act on the medusae as it swims. Consequently, as *Aurelia* swims it pulses vigorously but moves slowly through the water. However, large vortex rings are generated by each pulse which draw water through the tentacles located along the bell margin. This serves as a feeding current and enables *Aurelia* to capture prey organisms entrained in the fluid.

In the lakes on Mljet, *Aurelia* is highly abundant and found primarily below the pycnocline. It is likely that the population of *Aurelia* in the lakes has been isolated from the main body of the Adriatic Sea for tens of thousands of years (Benovic, et. al., 2000). There is compelling evidence that as a consequence of this isolation a new species of *Aurelia* has evolved in the lakes (Dawson and Jacobs, 2001).

Logistics

Our base of operation was located in an eleventh century Benedictine monastery, Sv. Marija, located on an island within Big Lake. Tanks and compressors were made available by our Croatian hosts and were set up in a make-shift dive locker situated in the cavernous chambers of the monastery. Laboratory space was also located in similar chambers. Small boats were provided by the National Park and we used a long wharf on the island as our dock for boats.

In a worst case scenario, emergency plans called for helicopter evacuation to Split, Croatia, 30 km distant, to an available decompression chamber. All contingency arrangements and contacts were confirmed prior to arrival. All divers possessed DAN international membership. It was our good fortune that our work concluded without incident, but it was impressive that plans existed to deal with any contingency, even in such a remote area.

Dive Methods

We used standard recreational gear and techniques. All dives were on air and limited to no-decompression excursions. On all dives each diver wore a dive computer to monitor their dive and safety diver was designated to manage contact and communication. Most dives were mid water, 10 m to 20 m, typically around the pycnocline where the medusan population was most abundant. Expert buoyancy control skills were essential for our planned tasks.

We used several methods for maintaining our orientation underwater and contact with the support boat. Since most of our work was within the water column, we used a blue-water rig for the dives. The blue-water rig was provided by DISL and, when fully rigged, was constructed similar to the designs recommended by Heine (1989). It was used for these dives because the rig provided an excellent frame of reference for mid-water work. These types of dives can be quite disorienting since divers are suspended in the water column with the surface and bottom out of sight. Orientation was facilitated by the large plastic tabs attached to the downline that indicated the depth. There tabs provided a strong vertical cue and produced a sense of perspective that is simply not achievable with a wrist mounted depth gauge.

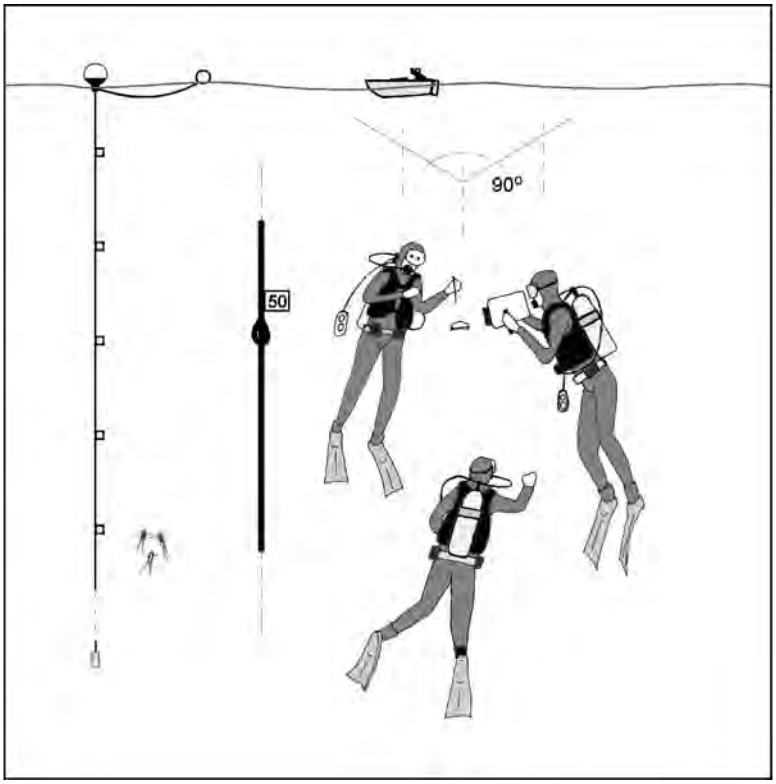

Figure 3. Dive method used for a majority of dives. Divers drifting on gentle tidal current along with blue water rig. The support boat stands off, unattached to the surface buoy, so as not to drag the rig with the wind.

As a result of the benign conditions in the lake we adapted typical blue-water procedures (Figure 3). First, visibility was generally high in the lakes (> 20 m) and currents were slow, therefore, the divers did not tether themselves to the blue-water rig. This enabled the divers to move more than the 10 m tether distance while still using the rig for visual orientation. Second, while conditions were quiescent, we often encountered nominal horizontal advective currents moving in different directions than the winds. Therefore, we did not tether the surface buoy of the blue-water rig to the support boat. Independence from the support boat allowed us to drift gently with these currents rather than being dragged by the boat in the wind. These modifications facilitated working with the drifting medusae by permitting more freedom for movement and enabling the divers to drift with the medusae (Figure 3). These are critical factors when attempting to get long-term and highly focused video sequences of individual jellyfish. Divers were instructed to keep the downline of the blue-water rig in their sight as one would keep an eye on their buddy. Further, depending on visibility, currents and decompression limits the divers agreed upon a maximum depth and a maximum allowable distance to drift from the downline. These limits were further maintained by the safety diver.

Underwater Research Methods

The primary goals of the project were to gather direct *in-situ* observations of the kinematics and flow of swimming medusae and to collect samples for determining prey diversity and abundance. Divers performed a number of sampling and data collecting tasks. Some of the sampling was as straightforward as recording observations onto underwater slates. Individual jellyfish were routinely collected into plastic bags for further examination in the laboratory. Plankton samples were collected at discreet depths using a diver-controlled plankton net. In that case, the diver was tethered to the blue-water rig and would swim out horizontally to the length of the tether, turn 180°, swim to the limit of the tether in the opposite direction and return. The safety diver would tug the tether as the end of the line was approached. At the end of each run the nets were closed by hand and the cod end jar removed and capped.

A novel approach to obtaining a dynamic view of swimming was employed by using dye to visualize the flow around swimming medusae. Specifically, a small amount of fluorescent dye was released either just outside or inside the bell of a swimming medusa (Figure 4). The vortices generated by the swimming medusa – now clearly defined by the swirling dye – were video recorded. Two divers were involved in these sequences – one to release the dye, one to video the medusa. The divers would orient themselves in the water column at 90° to a medusae and gradually move close to a single selected individual. A Sony digital video in an Amphibico housing was used to record the event. All dye studies were done with natural lighting so as not to affect the behavior of the jellyfish.

Figure 4. Dye release around swimming *Aurelia*. Divers are positioned at a 90° orientation to each other. Fluorescent dye was released close to a swimming medusa with great care so as not to disturb the fluid surrounding the medusa.

Conclusion

The marine lakes of Mljet are fascinating ecosystems ideally suited to the study of *Aurelia*. A predictable population of the species in consistently calm environmental conditions allowed us to collect significant amounts of data under replicable circumstances in a relatively short period of time; a condition sometimes difficult to realize when working in the field. The facilities made available to us were equally ideal. Proximity to the dive sites and available space for lab, dive locker and meals was unparalleled. Incorporating this area into a National park will – one hopes preserve this natural wonder for generations.

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Scientific Diving Techniques Applied to the Geomorphological and Geochemical Study of some Submarine Volcanic Gas Vents (Aeolian Islands – Southern Tyrrhenian Sea – Italy)

G. Caramanna,[1] N. Voltattorni,[2] L. Caramanna,[3] D. Cinti,[2] G. Galli,[2] L. Pizzino,[2] And F. Quattrocchi[2]
[1] Via A. Sogliano n. 79 00164 Roma (Italy)
giorgiocaramanna@yahoo.it
[2] Fluid Geochemistry Laboratory - Italian National Institute of Geophysics and Volcanology
[3] Interuniversity Consortium – l.caramanna@caspur.it

Abstract

The Panarea Island lies few miles south of the active volcano of Stromboli (Aeolian Islands, Italy) in a very active hydrothermal area. On November, 4th, 2002 a huge submarine volcanic-hydrothermal gas burst was detected near the shore line of Bottaro, an islet at around 1, 5 miles east of Panarea. The INGV Scientific Diving Team began the underwater surveys of the area from 5 to 40 meters below the sea surface locating a large field of gas vents. In two cases the high-pressure gas rising created sinkholes with the collapse of the seafloor. Scientific divers surveyed the area, took pictures, and collected samples of gas, hydrothermal springs water, and new-formation minerals. Customised SCUBA techniques were exploited and refined to collect these samples. Free and dissolved gases and water samples were analyzed by gas and liquid chromatographic techniques. The minerals, mainly of neogenic hydrothermal formation, were identified by X ray-diffraction and by SEM. We deployed two data loggers to collect the hot vents temperature in long term period. The data collected suggest a correlation between the gas/water vents location/evolution and the main local and regional fault systems. The main component of the gas mixture is CO_2 (up to 98 %) with presence of H_2S, H_2, CO, CH_4 and He. What is still ongoing (September, 2004) has had a strong negative influence on the marine ecosystem. Discussed are the state of art of the methods, key-lines and the limits of the actual sea-bottom geochemical sampling as well as the possible future developments.

Underwater hydrothermalism in the Mediterranean Sea and Tyrrenian Sea

The Mediterranean Sea area is a geological active region with the subduction of the African plate under the European plate. Deep subduction basins (i.e. Marsili Basin) and volcanic arcs (i.e. Aeolian Islands arc) lie in the south Tyrrenian Sea as clues of the tectonic and volcanic activity. The active volcanism is believed to have begun in the Oligocene (Bellon, Jarrige et alii, 1979; Savelli, 1988). Actually active volcanoes are found along the Tyrrenian shore (Vesuvio), in Sicily (Etna) and in the Aeolian Islands (Stromboli and Vulcano islands). The volcanic districts are located on the Benioff plane around 100- 350 km above the focal depth of earthquakes (Ninkovich & Hays, 1972). Near the basins and the volcanic regions there is an increase of heat flow (up to 200 mW/m^2 in the Tyrrenian abyssal plain) that coincides with gravity and magnetic anomalies (Dando et alii, 1999).
Close to the volcanoes there are geothermal active zones with gas vents (mainly CO_2) and hot water springs both sub aerial and underwater (i.e. Naples Bay, Aeolian Islands). The total CO_2 flow from the Mediterranean Sea gas vents is around $10^7 – 10^8$ Kg/d comparable,

as magnitude order, with the total mid-ocean ridge vents that is 2.5 10^8 kg/d (Butterfield et alii, 1990; Italiano and Nuccio, 1991; Dando et alii, 1999).

The submarine vents detected are mostly in shallow water (less than 200 m depth) and bubble plumes are visible to divers, ROV and by echo sounder. In the neighboring areas bacterial mats and polymetallic sulfide deposits have been found (Marani et alii, 1997; Dando et alii, 1999).

There is a direct correlation between earthquakes, volcanic crisis and increasing of gas vents as numbers and flow. A reverse correlation has been detected between the gas flow and temperature and the sea tides (Dando et alii, 1999).

Morphology of the hydrothermal field around the island of Panarea

The Panarea Island lies few miles south of the active volcano of Stromboli (Aeolian Islands, Italy) in a very active hydrothermal area (Fig 1). Geochemical investigations around the island have revealed the presence of a large field of gas vents and warm water springs on the seafloor since the 1980's (Italiano and Nuccio, 1991).

On November, 4th, 2002 a huge submarine volcanic-hydrothermal gas burst had been detected near the shore line of Bottaro, an islet 1,5 miles east of Panarea (Fig. 2).

An extensive survey of the new developed vents has been conducted by the Italian National Institute of Geophysics and Volcanology since then and is still on going.

The area delimitated by the islets of Dattilo, Bottaro, Lisca Bianca, Lisca Nera (Fig. 3) is characterized by a flat seabed, (lava layers, pebbles, gravel and sand) covered by Posidonia mats. The morphology is distinguished by banks, dykes and sub-circular depressions of some meters in diameter. There is a widespread presence of gas vents, often correlated with bacterial mats, aligned along the main regional and local faults (SW – NE, NW – SE, N-S). We suppose that the origin of the depressed circular shaped areas within the Posidonia mat, covered by sand, is associated with collapses of the seafloor due to ancient gas bursts. This opinion is supported by the actual presence of such phenomena other surveyed points (Fig. 4).

Figure 1 Panarea and the gas vents area. In the background the Stromboli volcano

Figure 2 The main gas eruption of November 2002 from the shore line of Bottaro. On the background Dattilo islet and Panarea island

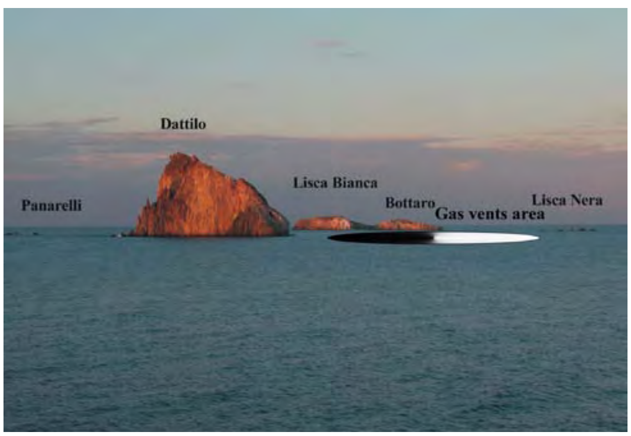

Figure 3 The islets around the gas vents area

Figure 4 The sinkhole with sulphurbacteria

Near the islet of Dattilo, off the eastern shore, the seafloor lies at about 25 meters of depth with Posidonia matte. There are several closed circular areas with a sandy bottom and little gas vents. In one of these areas there is the Black Point vent. The name comes from the black colour of the fluids, due to the presence of metal sulphurs. Fluids came out from a fracture aligned NNE – SSW and covered by an outcrop of black metal sulphurs (Fig. 5). This is the hottest vent (130 °C) measured (Fig. 6). After March 2003 the black emission decreased and the fluid emission is mainly of gas and hot water.

Few hundreds meters away from the north point of the islet of Bottaro the seafloor, at 16 m of depth, is characterized by a flat sandy surface with some dykes. The gas rises through several linear emission sections aligned with a SW – NE trend (main group) and NW – SE with bacterial mats along the gas emission lines (Fig. 7). The gas emission is characterized by 3 – 5 second impulses of warm water. The maximum temperature of the fluids is around 35 – 40 °C (Fig. 6).

Figure 5 The "Black point" vent

On the north of this area, at a distance of about 30 m, there is a collapsed sinkhole on the seafloor (Fig. 4). In this zone the seabed is represented by sand and big boulders. We suppose that the genesis of the sinkhole is due to the gas rising and consequent forming of a sort of cave just below the boulders. The collapse of the roof of the cave generated the sinkhole. The horizontal shape is sub-elliptical with the main axis aligned NNE – SSW and 7,5 m long. The secondary axis is NW – SE, 5,2 m of length. The seafloor of the area is 17 m deep, the sinkhole itself is 3 m deep. Around the boundary there is a cave about 2 m high and 3 m wide. On the bottom of the cavity lies a bacterial carpet. Bacteria filaments hang from the ceiling of the cave (Fig. 8). The structure is still in evolution and increasing in dimensions, due to the step collapse of the boundaries. Warm fluids rise from the bottom. From June 2003 to July 2004 the temperature increased from 34 °C to 90°C just few centimetres below the sandy bottom of the sinkhole (Fig. 6).

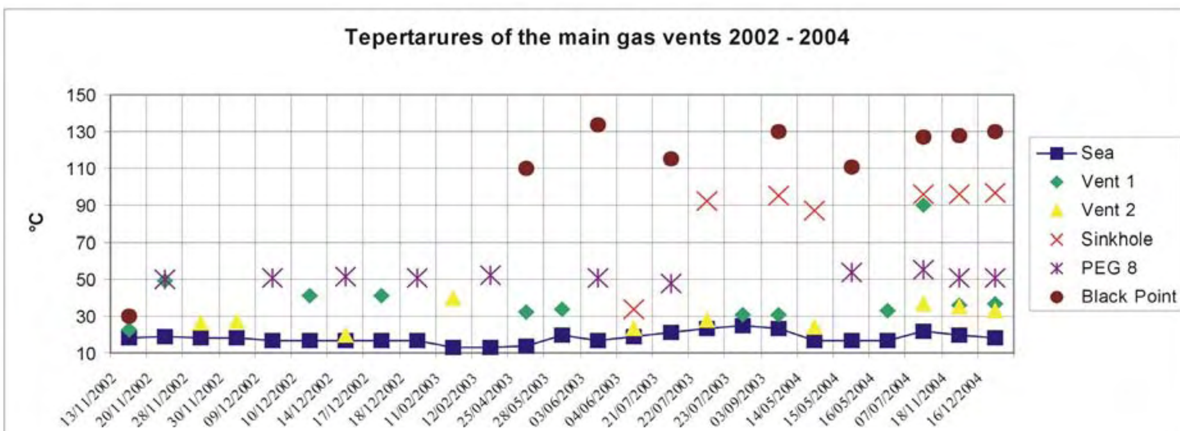

Figure 6 Chart of the temperatures of the main gas vents studied

Geochemistry of the gas vents

More than 120 samples (both water and gas) have been collected from November 2002 up to December 2004. We performed an analysis in order to determine major and minor elements (liquid chromatography), trace elements (ICP-MS), dissolved gases in water and gases in the free phase (gas chromatography).

Obtained results were compared with data from literature (Italiano and Nuccio, 1991): water chemical composition showed an enrichment in Na-Cl and in trace elements (i.e., Li, As and Sr especially in the "black point"). This comparison suggested the hypothesis that sea water is locally affected by acid, reducing and more saline fluids that circulated at high temperatures in volcanic rocks. Figure 9 shows the Na-Cl enrichment in comparison with sea-water content: in particular, samples from May and July 2004 have the same content of samples collected just after the Panarea "crisis" (December 2002).

Figure 7 Gas emission in the area north of Bottaro islet

Figure 8 The cave in the sinkhole with the sulphurbacteria hanging from the ceiling

During the first months of Panarea "activity", some vertical logs were performed: they showed the presence of convective cells with a mix of water and gas from the vents. Furthermore, they revealed a modification of pH from 8.0 to 5.0 and the redox variation from +80 mV to -200 mV probably due to the presence of H_2S.

Results from gaseous composition (mean values) is summarized in table 1: 98% of gases is composed by carbon dioxide. All the emission points have a methane content around 10 ppm excepting the "Black point" whose mean value is around 600 ppm. Figure 10 shows the direct relationship between temperature and CH_4 content in the "Black point" confirming the thermogenic origin of the methane. Discrete contents of helium (11 ppm) were found in every point. He isotopic analysis were carried out over 32 samples in order to define the origin of helium: the helium isotopic range is 4.1-4.5 suggesting a magmatic origin. Figure 11 shows the contemporaneous content variations of H_2 and H_2S inferring fractionation of gases by partial dissolution in water.

Gaseous composition of Panarea emission points is very different from literature. Data collected before November 2nd, 2002 have values typical of hydrothermal field while samples collected after the recent gaseous emission have concentrations typical of volcanic field suggesting an evolution of the system controlling Panarea emissions(Figure 12).

Study methods

Due to the presence of water we developed special techniques to adapt the usual sampling methods to the undersea environment.

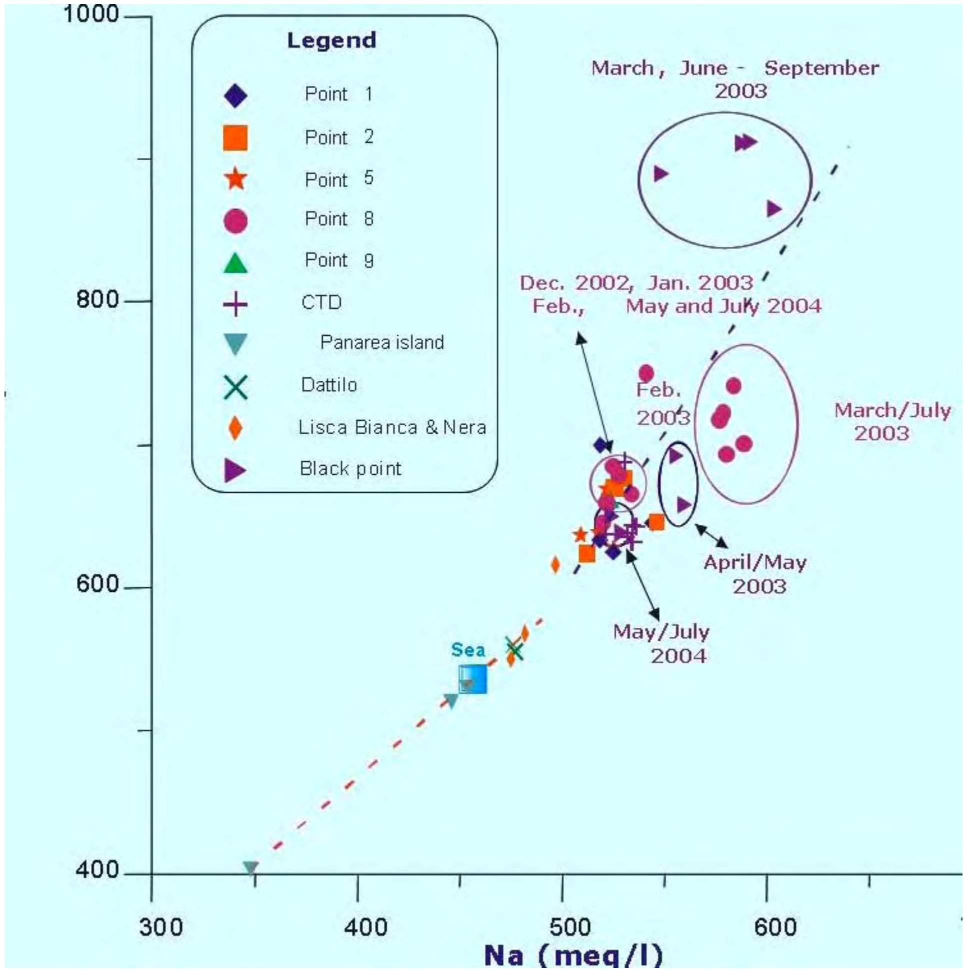

Figure 9 Na/Cl chart in the water samples

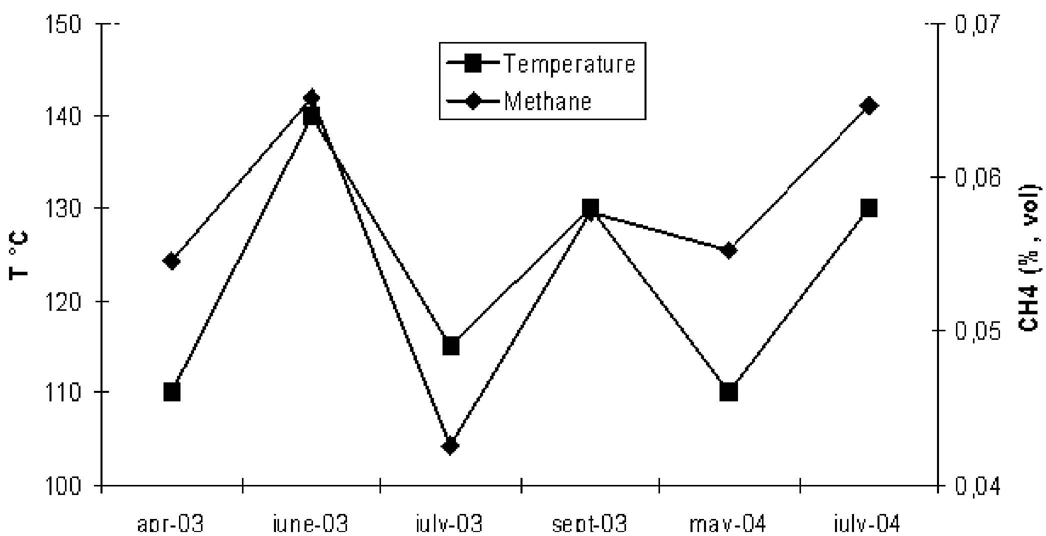

Figure 10 CH_4/T in the "Black Point"

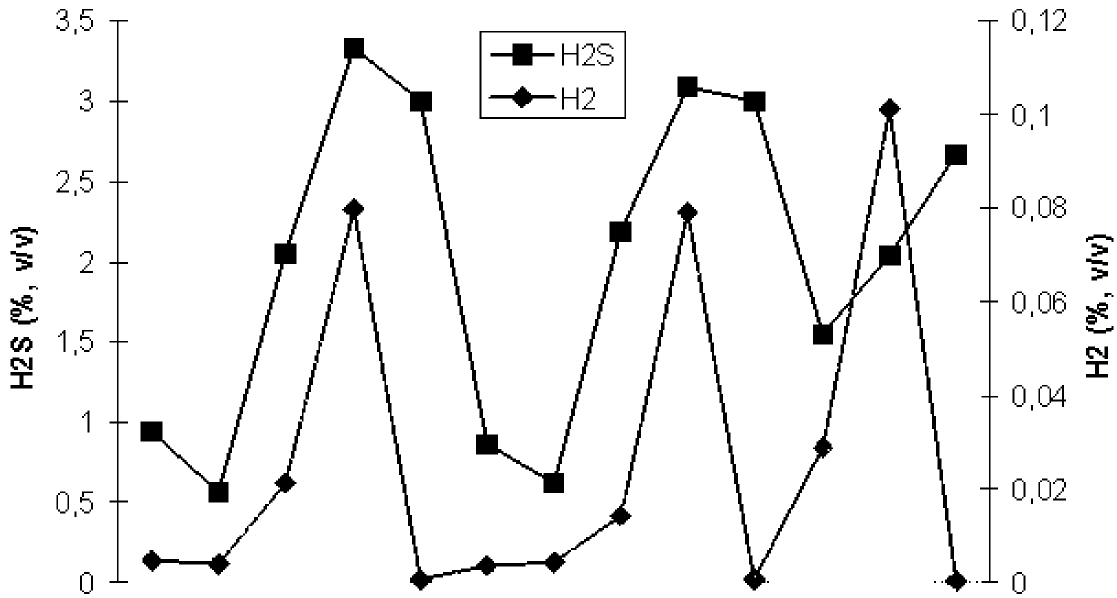

Figure 11 Variations of H_2 and H_2S inferring fractionation of gases by partial dissolution in water

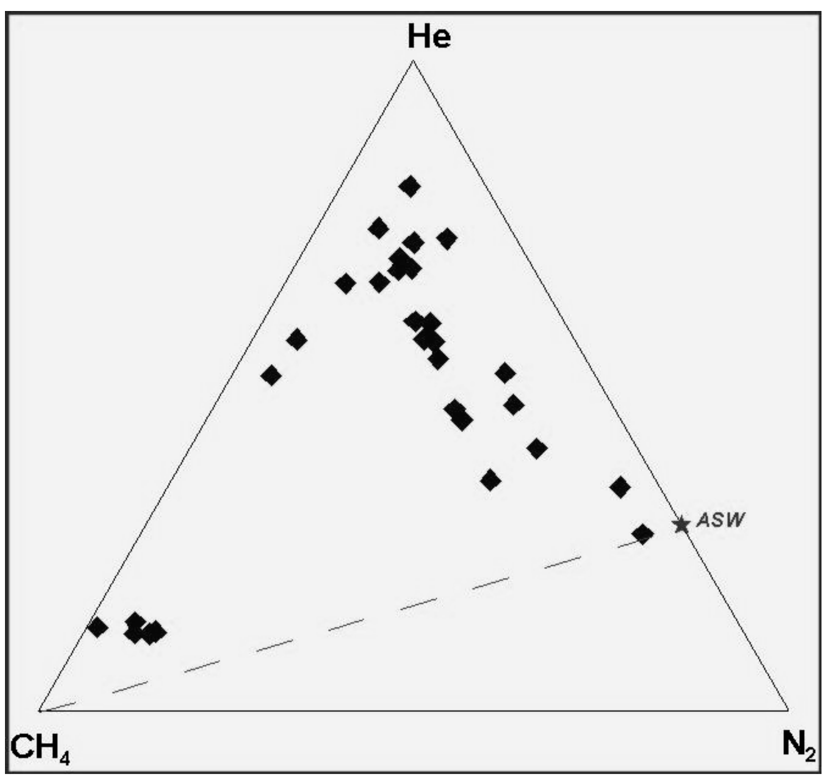

Figure 12 Ternary chart showing the volcanic composition of the gas samples in the area after the November 2002 crisis.

Table 1
Mean gasses composition

Gas	Mean value
CO_2	98 vol. %
CH_4	10 ppm
N_2	0.4 vol. %
He	11 ppm
H_2	1100 ppm
H_2S	2.2 vol. %

Fluids sampling

To collect free/dry gas samples we placed a plastic funnel upside-down (30 cm diameter with 12 kg ballast around the lower ring) exactly on the gas vent to be sampled. All the samplers are stored in a plastic box carried underwater by the divers (Fig. 13). The funnel is connected, through a silicon hose, to a Pyrex glass flask with twin valves. This flask has been previously filled with air, at a pressure higher than the hydrostatic pressure expected at the sampling depth, to avoid the sea water entering in the sampler. With this system we can change the flasks underwater to collect more samples at each vent. The same device is also used to collect the gas samples in NaOH 4 M filled flasks. In this case we fill the external section of the flask valve with distillated water to avoid sea water contamination.

Figure 13 Underwater equipment used for the fluids sampling

For the dissolved gas we used the traditional glass sampler filled with the water close to the vent. Radon gas is collected by the funnel linked to a cylindrical plastic sampler. In this case we fill the sampler with water and then we replace the water with the gas by placing the sampler upside-down on the gas stream coming out from the funnel.

Hot water sampling from the underwater springs is more difficult because of the low water flux and the need to avoid external seawater contamination. After several experiments our choice has been a glass flask with twin valves and vacuumed connected to a steel hose. Once the hose is fixed in the spring outlet we use a 60 cl syringe, connected by a 3 way valve, to expel the seawater from the hose and then fill the vacuumed flask just with the geothermal water. In this case there is less risk for seawater contamination.

Helium hysotopes

To collect gas for the helium hysotopes analysis we used a copper hose. On the extremities of the hose there are two steel clips designed to be closed by bolts and nuts. Once one of the extremities of the hose is connect to the funnel and the gas flows through we start closing the free extremity with a wrench. Then, just before disconnecting the sampler from the funnel, we close the other extremity. The use of a copper sampler assures that there is no lack of helium from the gas sample.

Temperature and sea level loggers

For a long term temperature-sea level data acquisition we deployed some STS data loggers near the main hot water springs. The logger is a full submergible cylindrical device (26 cm h, 2 cm diameter). The temperature range of the probe is -5 + 70 °C and the memory size is enough to store up to 130.000 measures. Scientific divers moored it on the seafloor by two steel sticks. To protect the sensor from the aggressive fluid we placed the logger in a plastic bag filled with fresh water and then in a plastic hose for mechanical protection. The data acquisition frequency is one measure per hour to correlate these data to the sea tides. Temperatures have also been collected by divers in each sampled vent by digital encased and glass thermometers.

Biological sampling

Close to the hydrothermal springs there are several mats of bacteria. To collect the bacteria we used 60 cc syringes with the needle section cut. With this device we aspirate the bacteria mat and, once in the boat, put the biological material in the refrigerator for further analysis.

Special diving techniques

The presence of aggressive fluids in the water (with a pH dropped from the usual 8 value of the sea to 5 or less closer to the vents) creates several problems.

The diver should not stay with their skin exposed to the gas for a long time. To avoid this in the longer sampling procedures we used full-face masks and dry suits to reduce the direct contact with the aggressive environment.

The metal parts of the diving gear (i.e. first stages of regulators, valves, cylinders, BCD connectors, zips etc.) undergo to a severe oxidation and need replacement or maintenance after few dives.

For extra safety and to improve data collecting we often used acoustic underwater communicators between the divers and the surface team.

Conclusions

The Panarea's hydrothermal field shows clear correlations between the vents location and the local and regional faults setting. The system is still evolving with modification of temperature, gas composition and seafloor morphology.

The influence of the toxic gasses on the sea ecosystem is very strong with the disappearing of many benthonic life forms (i.e. death and dissolution of shells due to the low pH fluids), serious damage to the Posidonia mat and development of "anomalous" life forms like the sulphurbacteria.

The possible hazard is correlated to gas explosions on the seafloor and strong toxic gas emissions on the sea surface. The island of Panarea in summer is a very crowded holiday place and this can enhance the consequences of a volcanic crisis in the area.

Actually (December 2004) the whole system is still evolving but there are no signs of a dangerous increasing of the gas burst.

The aim of our survey is to create a model of the hydrothermal/volcanic system evolution.
The data acquired by the data logger moored on the bottom of the sinkhole from 1st September 2004 to 17th November 2004 show a correlation between the warm water spring flow and the sea tide.

The *Bravais Pearson linear correlation coefficient* highlights a reverse correlation between daily sea tide and daily temperature of 0,95C. The explanation of this kind of correlation is that during the high tide the cold sea water is injected through the sand cover of the seafloor reducing the thermal flow of the vents.

The *simplified linear regression model* applied to the mean daily temperature data shows an increase of the temperature from September to October of 4,67 Celsius degree. In November there is a decrease of the temperature that should be correlated to the seasonal sea water temperature variation.

Other data will be necessary for an exhaustive study of the phenomenon but these first results show an evolution of the thermal field in good accordance with the geochemical outcomes.
The development of special underwater fluid sampling techniques by scuba divers is another important result of this research project.

Acknowledgments

Dr. Alessandra Esposito that helped me in several dives. Thanks also to the National Italian Fire Brigade and the Italian Coast Guard

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Diving for Science: Teaching Divers with Disabilities or Adaptive Needs

Debra Greenhalgh[1] and Robert Brousseau[2]
[1]ScubaMadeEasy, PO Box 5034, Newport, RI 02841
[2]Simply Scuba, LLC, PO Box 5138, Newport RI 02841

Extended Abstract

The US Census Bureau's Current Population Study (March 2001) stated there are 21 million disabled in today's American workforce from the ages of 16 to 76 years old. This number represents more than 10 percent of the working population. Many physically challenged individuals demonstrate through their involvement in daily activities, work and recreational activities, that they are not limited and certainly not handicapped. The Americans with Disabilities Act, provides civil rights protection for those who have disabilities in the same way people cannot be discriminated against based on race, color, sex, national origin, age or religion. The act is designed to accommodate accessibility for all people with disabilities in five major areas: employment, public accommodations, public services, transportation, and telecommunications.

SCUBA diving activities and organizations that provide training, instructional services and or supervision to individuals with disabilities are in and of themselves defined as a public accommodation as defined by Title III of the ADA, 42 U.S.C. paragraph 12182 (a). The ADA requires that reasonable accommodations must be made for the disabled if the individual does not pose a direct threat to others and making the accommodations would not fundamentally change or alter the services that are rendered.

Scientific diving programs allow research diving under the exemption from the Occupational Safety and Health Administrations (OSHA) commercial diving regulations. However, scientific diving is not exempt from the American's with Disabilities Act and should work to include scientists with adaptive needs. Many University diving programs do not have training standards for divers with disabilities or adaptive needs but there are organizations that exist to promote the reality that people with disabilities can learn to SCUBA dive through proper education and training. With training and appropriate consideration for accessibility issues more disabled divers, can use diving as a tool for conducting science and research.

Many SCUBA certifying agencies provide dive professionals the additional training they require to safely teach people with disabilities and adaptive needs, and introduce a safe means to deal with potential student diver limitations. The basic premise of these organizations are:

- Disabled and non disabled students all have the right to demonstrate their ability to SCUBA dive
- "Standards of Practice" are upheld
- A Medical survey is conducted and medical requirements are met with physician's approval

- Diving limitations are solely based on the students demonstrated abilities
- For each category of certification restriction, appropriate levels of mitigation are addressed and must be upheld
- Medical planning addresses students particular physical limitations with adaptive measures
- Site planning addresses wheelchair accessibility, adaptive equipment needs
- Instructors and staff are trained
- Low student/instructor & staff ratios are upheld
- Medical staff is onsite (minimum EMT). This is not dictated as a requirement but is practiced.

Divers with disabilities or adaptive needs that adhere to the training requirements, pass the medical requirements and demonstrate their ability to perform the academic, confined water and open water skills are awarded a SCUBA certification. An individual not able to meet all the requirements for full certification as an independent diver may qualify for the adaptive SCUBA diver recognition program in which the students training record documents the restrictions and limitations imposed on the diver solely based on their demonstrated abilities. Table 1 lists the certification restrictions used by National Instructors Association for Divers with Disabilities (NIADD). In all cases for safety, divers with an identified disability must dive along side a unrestricted diver. The severity of the disability dictates the level of restriction as well as the number of qualified diving assistants required to accompany the restricted diver.

Training and Diving Considerations

Before training a medical survey should be included and instructors should complete a risk assessment which considers the nature of the disability as it pertains to a possible threat to others. If there is none and reasonable accommodations can be made for the individual, then the disability should not be a basis for not admitting the person for training. During training and diving activities special considerations need to be addressed which include.

- Medication – The increased ambient pressure may increase or decrease the effects of certain medications.
- Temperature regulation may be diminished and divers need to be monitored more closely for affects of hypothermia and hyperthermia
- DCS Risk may be increased
- Skin and tissue breakdown; increased risk of injury due to reduced circulation, lack of sensation or lack of movement.
- Pulmonary conditions can affect air trapping, heart conditions and even convulsive disorders.
- Buoyancy Control
- Autonomic dysreflexia is a life threatening condition. It is caused when the body detects an injury (even slight) and the pain signals to the brain are blocked. In divers with spinal cord injuries, even a bent toe or an area of the body constricted by wet suit materials can set off this condition.

- Bowel and Bladder Control
- Equipment and Facility Accessibility

Conclusions

It is possible for many divers with disabilities or adaptive needs to use diving as a tool for conducting science and research. However instructors and staff require specialized training to address the need of disabilities or adaptive divers. The following SCUBA certifying agencies, (table 2) give dive professionals the additional training required to safely teach and supervise people with disabilities and adaptive need.

Table 1 NIADD Basic Open Water Certification Levels with Diver Restrictions Based on the Divers Demonstrated Abilities
.

Categories	Demonstrated Requirements	Restrictions
Unrestricted	• Meets all academic requirements • Demonstrated all water skills • Demonstrated all in water SCUBA skills • Successfully met medical requirements with doctor's approval	Dive with buddy
Level 1	• Meets all academic requirements • May need assistance putting on dive gear or with water transfers • Successfully met medical requirements with doctor's approval • Demonstrated all water skills • Demonstrated all in water SCUBA skills except: • Demonstrated self rescue but not able to perform buddy rescue	Must dive with 2 unrestricted certified divers. Strongly recommended that dive buddies are trained with NIADD to dive with people with disabilities/adaptive needs

Level 2	• Meets all academic requirements
	• Successfully met medical requirements with doctor's approval
	• May Need Assistance putting on dive gear or with water transfers
	• Demonstrated all water skills except not able to do self rescue
	• Demonstrated in water SCUBA skills with some assistance such as:
	  • Clearing ears or mask
	  • Basic propulsion
		Must dive with at least 2 unrestricted certified divers; one of which has a minimum of rescue diver certification. Strongly recommended that divers are trained with NIADD to dive with people with disabilities/adaptive needs

Table 2. SCUBA Agencies with Certification Standards of Practice for Divers With Disabilities/Adaptive Needs

Handicapped Scuba Association International (HSA) www.hsascuba.com (949)498-4540	National Association of Underwater Instructors www.naui.org (813)628-6284
International Association for Handicapped Divers www.Iahd.org 0031-227503631	National Instructors Association for Divers with Disabilities (NIADD) (408)379-6536
Open Waters (800)640-7200 www.alpha.one.org	YMCA of the USA (800) 872-9622 www.ymcascuba.org

Further information can be found in the following sources.

Diving Alert Network (DAN) website www.diversalertnetwork.org or by calling DAN at 800-446-2671.

Information on accessibility issues - ADA Website http://www.usdoj.gov/crt/ada/ or by calling the ADA at 800-514-0301.

Frank Degnan, Best Publishing Company 1998, A Guide for Teaching SCUBA Divers with Special Needs.

L Jankowski and I. Barocas, Accessibility vs. Handicaps for Divers with Disabilities, Sources, The Journal of Underwater Educ

Scientific Diving and ROV Techniques Applied to the Geomorphological and Hydrogeological Study of the World's Deepest Karst Sinkhole, (Pozzo del Merro – Latium – Italy)

G. Caramanna
Via A. Sogliano n. 79 00164 Roma (Italy)

Extended Abstract

The "Pozzo del Merro" (Lat. 42° 02' 14'' N - Long 12° 40' 52'' E) is located in the "Macchia di Gattaceca" Natural Park, 130 meters above sea level on the Cornicolani Mounts near the village of Sant'Angelo Romano just 30 km east of Rome. This is a 452 meters deep karst sinkhole, 392 meters are water filled creating a challenging environment for the study of this natural phenomenon.

The Cornicolani Mounts represent the western boundary of the Latium Apennine. They are made predominantly by Lias limestone. These calcareous outcrops are close to the ancient Volcano Albano structure named the "Albani Hills". The last volcanic activity here ended about 30.000 years ago.

In the area there are regional and local faults with main directrixes NW-SE, NE-SW, N-S. These tectonic displacements favored a spread karst erosion creating imposing hypogean and epigeous structures, (Facenna et al, 1994; Mattei et al, 1986; Maxia, 1948).. The diameter of the sinkhole varies from 150 meters at the top of the dry section to 30 meters on the water surface of a small lake hosted in the sinkhole (Fig. 1). The lake is the link to a deep flooded karst shaft that reaches 392 meters of depth below the water surface (Fig. 2).

Direct study of the underwater morphology showed a sub vertical karst chimney with clear evidences of high chemical erosion. The limestone outcrops in the area: the Cornicolani Mounts, the Lucretili Mounts and the Tiburtini Mounts are recharging areas of the regional aquifer. The main flows are from north to south towards the Aniene River (Fig. 3). The aquifer feeds some high mineralized springs hosted in small sinkholes, the Acque Albule (White Waters) ponds, in a travertine plate close to the city of Tivoli (Fig. 4). The Merro's water surface oscillations reflect changes in the level of the deep aquifer. This oscillation correlates with local rainfall but with a delay of some months due to the inertia of the regional acquifer response (Fig. 5).

Geochemical parameters (pH, TDS, temperature) have been collected by the use of a multi probe carried by an underwater robot (ROV) down to 95 meters (Fig. 6). The direct investigations were made by the author and some others volunteer cave divers with the collaboration of the National Fire Brigade Scuba Team (Fig.7). For deeper exploration some ROVs have been used. A ROV is an underwater device equipped with electric thrusters, a video camera, a compass and a depth meter. The control unit is on the surface and power is supplied to the robot trough a cable. The ROVs have no limits as to their diving time; the only limit is the maximum operative depth. (Caramanna, 2001; Caramanna et al, 2001; Caramanna, 2002) (Fig. 8-9).

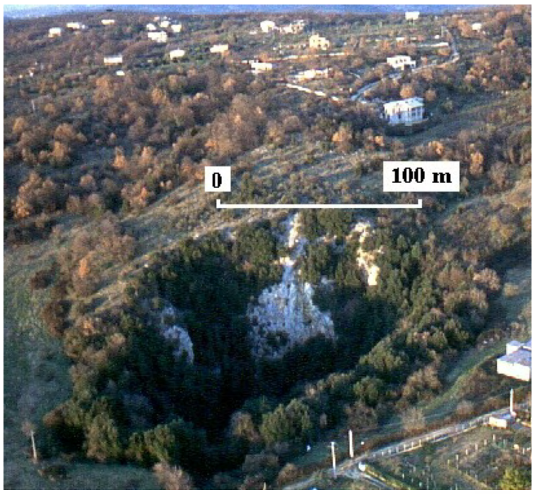

Figure 1 Air view of the "Pozzo del Merro"

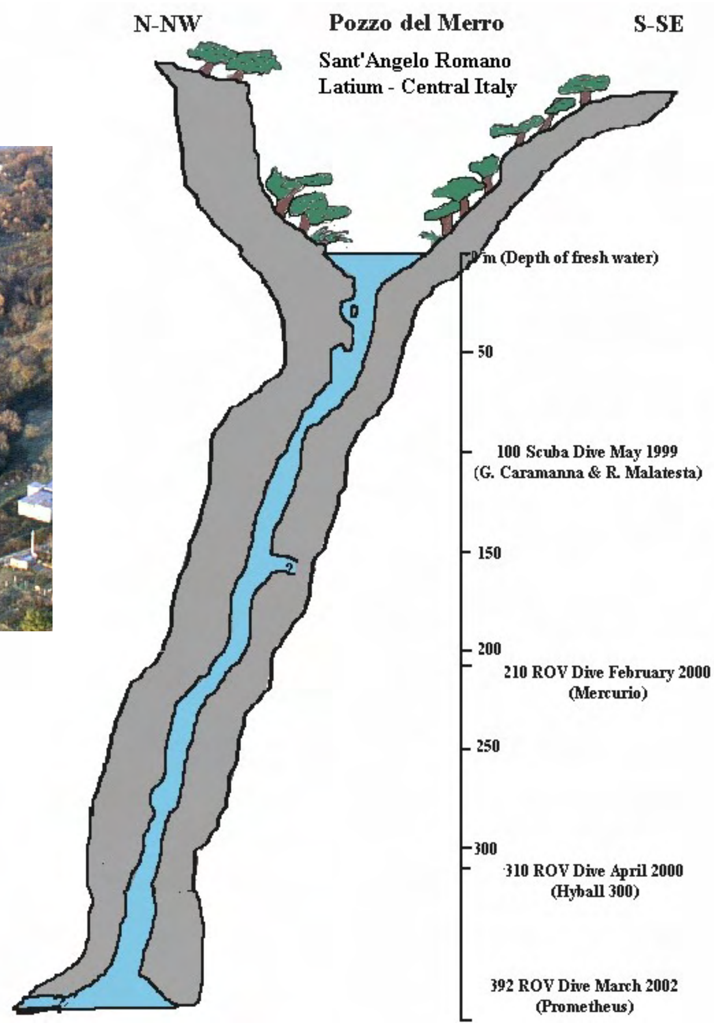

Figure 2 Vertical sketch of the "Pozzo del Merro"

(Facenna et alii, 1994. Mattei et alii, 1986. Maxia , 1948.).

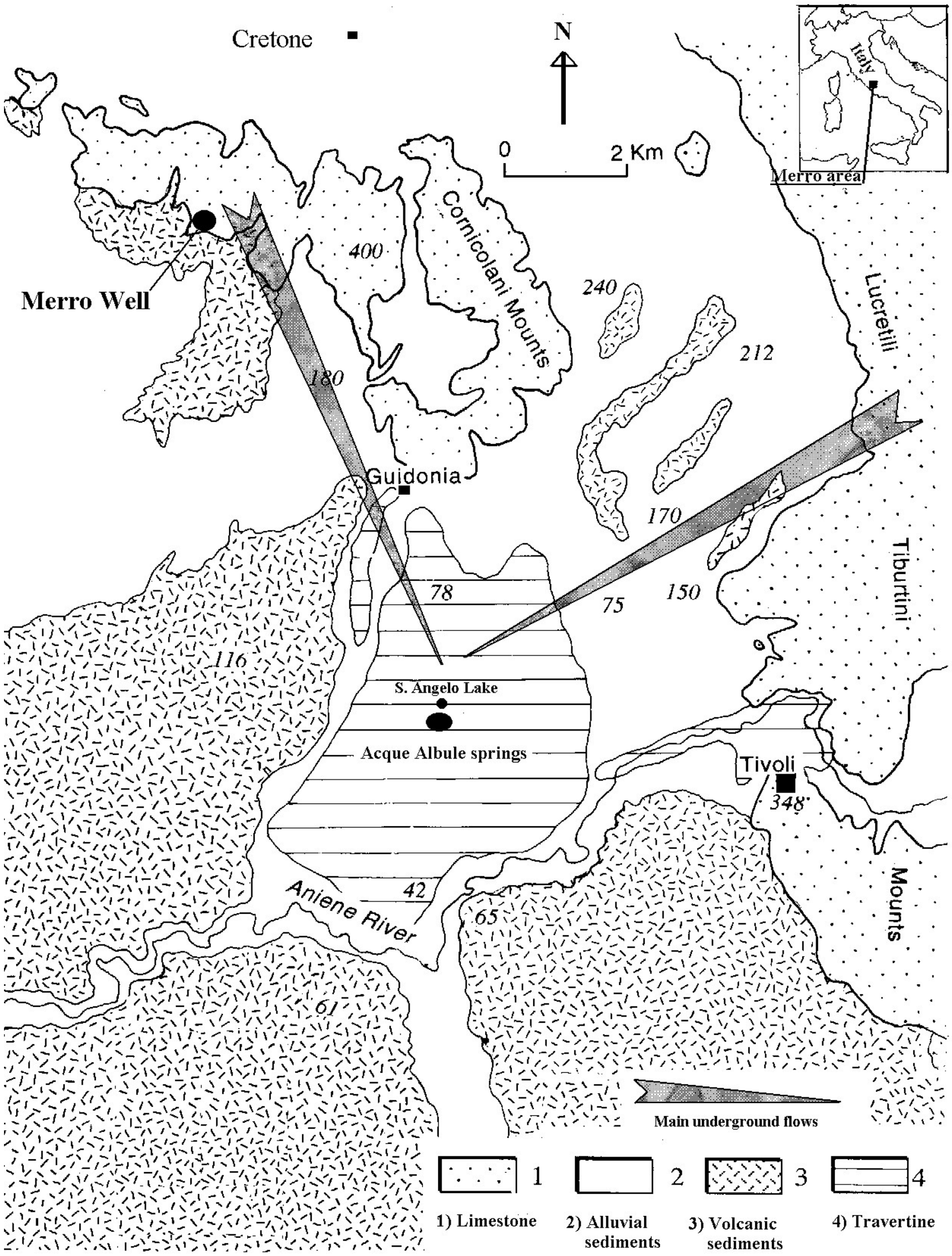

Figure 3 Simplified geological map of the Cornicolani Mounts area.

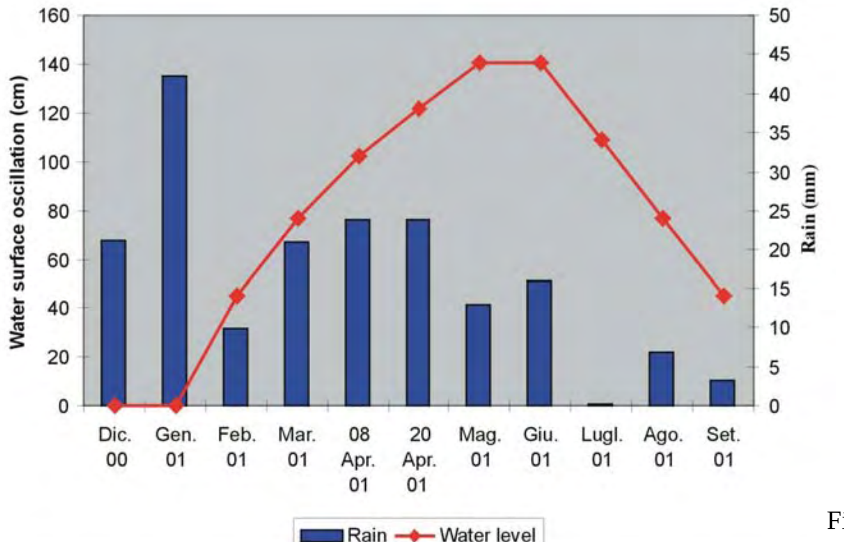

Figure 5 Lake surface oscillation in the “Pozzo del Merro” versus rainfall

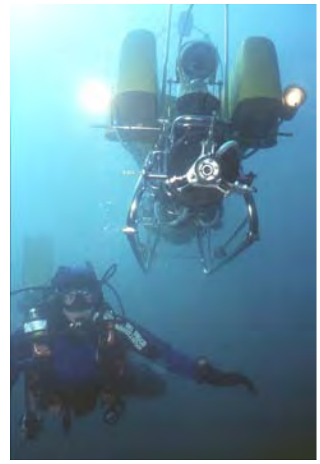

Figure 7 A scuba diver of the Fire Brigade and ROV “Mercury” (picture courtesy of Fire Brigade)

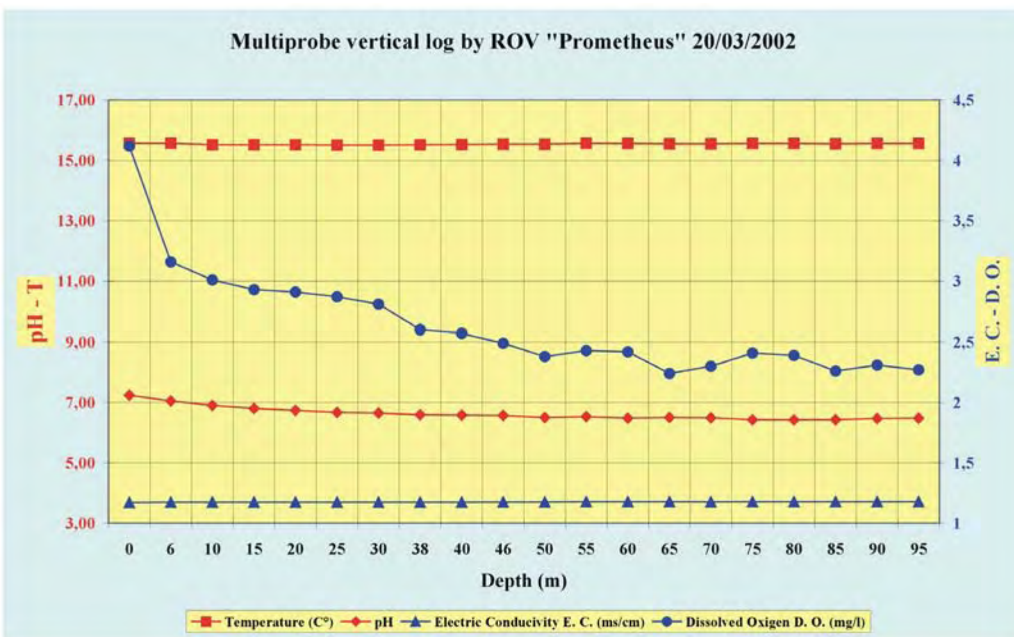

Figure 6 Vertical log made by a multiparametric probe carried by ROV “Prometheus”

Figure. 8 The author and ROV “Hyball 300”

Figure. 9 The ROV “Prometheus” with the multiparametric probe

This study has shown a direct correlation between sinkhole development, faulting and geothermal fluids. In the studied area we have a regional karst water acquifer that in some locations shows the influence of geothermal and mineralized fluids. The dissolution of calcareous rocks is increased by the action of these aggressive fluids, mainly CO_2, rising trough faults and cracks. This erosion is a “reverse type” because the main chemical action is not due to rain water dropping but to the rising of deep and highly mineralized fluids mixed with the regional karst water. Regarding the origin of the “Pozzo del Merro” the evidences indicate that this is a dissolution sinkhole in which the karst erosion has been increased by the presence of aggressive fluids rising through faults and tectonic displacements. The origin of these hydrothermal solutions is in all likelihood be the ancient “Volcano Albano” structure.

Scientific cave diving and ROV techniques for the study of flooded karst features are new tools that will certainly increase our knowledge of underwater environments. This study is just a small first step in a new style of research which allows the direct presence of scientists in places studied before only by remote probing.

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The Southern California Regional Kelp Restoration Project

Dirk Burcham
California Coastkeeper Alliance
C/o Southern California Marine Institute
820 South Seaside Avenue, Room 108
Terminal Island, CA 90731

Extended Abstract

The Waterkeeper Alliance is an international non-profit organization dedicated to promoting clean water and strong communities. The Waterkeeper Alliance sponsors a network of local Waterkeepers which focus on water issues at the community level. The California Coastkeeper Alliance (CCKA) is a coalition of local Waterkeeper chapters located in California. The Alliance takes the lead on issues and projects that are regional or statewide in scope and are of interest to the constituent Waterkeepers of the Alliance.

In 2001, the National Oceanic and Atmospheric Administration's Community-based Restoration Program awarded a three year grant to CCKA for The Southern California Regional Kelp Restoration Project.

Giant kelp forests are often called rainforests of the sea. Dominated by the macroalgae *Macrocystis pyrifera*, giant kelp forests rise from rocky reefs growing up through the water column ultimately reaching the surface spreading out into a dense canopy. Kelp forests are habitat for over 800 species of plants and animals (McPeak et al. 1988). Many species that rely on kelp forests are of value in terms of sport and commercial fisheries. Giant kelp occurs in both the Northern and Southern Hemispheres. It is found along the coasts of Australia, New Zealand, South Africa and South America. In the Northern Hemisphere, giant kelp is found along the western coast with the most dense stands occurring from Central California to northern Baja California (Abbott and Hollenberg 1976). Surveys of California's kelp beds date back to 1911. Studies by the California Department of Fish and Game have shown that over the past century there is a net decline in the area covered by kelp forests in Southern California (CDFG 2000).

Human impacts to the near shore environment can affect giant kelp survival. Sewage discharges (Dayton et al. 1998), sediments from coastal development and urban runoff (Devinny and Volse 1978), and thermal effluents from power plants (Ambrose 1994) will reduce growth and survival in kelp. By removing key predators that keep kelp grazing species, most notably urchins, in check over fishing further compounds impacts to kelp forests, (Tegner and Dayton 1981). It is generally believed that the effects of human impacts combined with natural disturbances such as El Nino events and severe storms are the most likely causes of the observed decline of kelp forests in Southern California (Wilson and North 1983; McPeak et al. 1988; Bedford 2001).

Giant kelp can overcome these perturbations and over time naturally reforest areas where conditions are favorable (Dayton et al. 1992; Tegner et al. 1997).

The Southern California Regional Kelp Restoration Project was formed in 2001 in an effort to restore historic kelp beds in Southern California. Currently participating in the Project are Santa Barbara Channelkeeper, Santa Monica Baykeeper, San Diego Coastkeeper and the California Coastkeeper Alliance.

The Southern California Regional Kelp Restoration Project has two main goals:

1) Restoration of historic kelp beds along the Southern California coast including monitoring of those restoration sites.

2) To educate the public about giant kelp forests and teaching people the importance of this resource to California's marine environment. Our efforts are evenly split between the restoration and education elements.

Restoration

Work on restoring kelp beds along California's coast began in the early 1960's. In the years that followed, a number of techniques have been developed to reforest sites with giant kelp (McPeak and Barilotti 1993; CDFG 2000). This accumulated knowledge benefited our efforts by enabling us to focus on techniques showing the most promise given the Project's set of circumstances.

Outplanting of Giant Kelp:
This method uses juvenile giant kelp which is planted directly onto the restoration site. The stock for planting is grown in a laboratory. Sporophylls, the reproductive blades of the plant, are collected from a number of different adult giant kelp located as close as possible to the restoration site. The sporophylls produce spores which settle out onto a growing media. The kelp is grown on a media which provides a suitable surface for the kelp to attach and which can be secured to a rocky reef. The spores pass through several stages maturing into juveniles. Once the juveniles reach 2 – 4 centimeters in length they are ready for outplanting. Each planting unit has at least 10 juvenile kelp attached.

Unglazed ceramic tile and natural fiber rope are used as culture media. Ceramic tile is cut into strips measuring about .5 centimeter thick by 1.5 centimeters wide by 11 centimeters long. Our best results for rope have been with cotton rope about 1 centimeter in diameter.

The outplanting process is fairly straightforward. A diver searches for overhangs and protrusions on the rocky reef to which the planting media can be secured. If rope is used, it is cut into lengths of about 20 centimeters. The media which is covered with juvenile kelp is secured to the reef using latex rubber bands. If successful, the juvenile kelp develops into an adult growing a holdfast that envelops the culture media and making a firm attachment to the reef. All cultivated kelp is planted in the same region from which the parent sporophylls were collected.

Transplants:
Drift kelp is intact adult giant kelp that pulled away from the bottom. Drift kelp is collected on the open ocean usually in the vicinity of the restoration site. The transplant is attached to the reef using a combination of latex rubber bands and natural fiber rope. If successful, the plant will survive growing a holdfast that makes a secure attachment to the reef.

Sporophyll Bags:
This technique provides a concentrated source of giant kelp spores on the restoration site. Reproductively active sporophylls are collected from nearby adult giant kelp. The sporophylls are put in a mesh bag. The bag is held to the reef by a rope and suspended about one to two meters above the reef using small buoys. In providing a spore source where none exist, the goal is to “seed” the area resulting in colonizing giant kelp.

Urchin Removal:
Where urchin populations reach high concentrations, they effectively eliminate all algae from an area. Such sites are called urchin barrens. In order for the methods described above to be successful, urchin populations need to be at a level that giant kelp has a reasonable chance to survive grazing by urchins. The Project’s permits allow for urchins to be collected from restoration areas and relocated to a site which is far enough away that the urchins will not likely return. The Project does not engage in eradicating urchins as a control method.

Monitoring:
Each restoration site is monitored for the relative abundance of selected algae, invertebrates and fish (protocols). Monitoring includes surveys on control and reference sites as well. The methods and species selection used in monitoring was patterned after other long term kelp forest monitoring studies of the Northern Channel Islands (Davis et al. 1997) and Catalina Island (Burcham 2004). Surveys on the restoration, control and reference sites have accumulated a considerable amount of data. We did not see any direct evidence that sporophyll bags made a difference in establishing new kelp. Work on data analysis is in progress with the goal of documenting the effects of our restoration activities.

Table 1 presents a summary of restoration activities from August 2001 through August 2004. We found that the communities of San Diego and Santa Barbara had reasonably good stands of kelp forests, whereas Santa Monica and Orange County were in the most need of restoration work.

Table 1. Summary of restoration activities by Keeper 2001 - 2004.

Organization	Total Area Restored in Square Meters	Total Number of Outplants	Total Number of Transplants
San Diego CK	1,500	688	0
Orange Co. CK	4,500	4,411	66
Santa Monica BK	3,000	2,000	Unknown
Santa Barbara CK	1,500	700	0
TOTAL	10,500	7,799	66

We were successful in establishing kelp at 8 restoration areas covering about 1 hectare in total. We found that outplants of laboratory cultured kelp and transplanted drift kelp to produce adult giant kelp. Once established, the adult kelp should contribute a natural source of spores which should further spread the front of kelp.

Education and Community Outreach

The cornerstone of our classroom education program is the eco-Kart. An eco-Kart is a self contained kelp culture system on wheels. Eco-Kart gives students the opportunity to grow giant kelp in their classroom with the goal of having it planted on the restoration sites. We have placed eco-Karts in traditional public and private classroom settings, programs for at risk youth and programs for developmentally disabled students. The program generally appeals to grades 4 through 12. Our staff biologists conduct sessions on marine ecology and conservation tailoring the content to the specifics needs of the class. There is no one set curriculum. The staff biologist works with the students' teacher to build a program that is a fit with the overall science instruction for that class. Eco-Karts have drawn favorable response from educators. The biggest challenge to the Eco-Kart program is that of maintenance.

Community outreach for the Project is doing whatever it takes to inform the public at large about giant kelp forests and their importance to California's marine waters. To reach the public we use news media (radio, newspaper and magazines), public venues such as aquariums and interpretive centers, presentations to organizations, festivals and special events. The volunteer program is another form of outreach in that our volunteers have gone through training sessions on The Southern California Regional Kelp Restoration Project and kelp forest ecology. Volunteers then act as ambassadors further informing the public about giant kelp forests. Our volunteer program has exceeded our expectations as well. We believe is that we fill a unique niche especially for divers. The Southern California Regional Kelp Restoration Project is one of the few opportunities where a non-scientist diver can be a part of field data collection and restoration work. There seems to be a demand for such opportunities. Table 2 gives a summary on the numbers of people who participated in or were a part of our education and community outreach programs.

Table 2. A summary of the numbers of people engaged by the Education and Community Outreach Programs by Keeper 2001 – 2004.

Organization	Total Number of Students Participating in Classroom Kelp Cultivation	Total Number of People Who Came in Contact with the Community Outreach Program
San Diego BK	1,175	15,000
Orange County CK	1,000	50,000
Santa Monica BK	3,500	65,000
Santa Barbara CK	1,150	20,000
TOTAL	6,825	150,000

Conclusion

Essentially starting with little more than a concept, the Project is a case study of a grass roots effort that has grown to involve hundreds of volunteers, engage thousands of people in education and outreach activities and make progress towards restoration of California's giant kelp forests. Community involvement has been the key to the Project's success. In the first three years of the Project, approximately 180 volunteer divers have planted kelp and conducted site monitoring and an estimated 10,500 square meters of reef has been successfully restored. The Project's community outreach program has educated about 150,000 people about the importance of kelp forests to California's coastline and over 6,800 students throughout Southern California have participated in the school program learning about kelp forests and how to grow kelp in the classroom.

What makes this project different from other attempts at giant kelp restoration is that most of the work is done by volunteers. Volunteers are a part of all facets of the program from diving to working in classrooms. The Project itself could not continue without the contribution of our corps of volunteers. Table 3 summarizes the level of involvement that volunteers had in the Project.

Table 3. A summary of Volunteer participation in the Regional Kelp Restoration Project by Keeper 2001 – 2004.

	Volunteer Hours Diving	Volunteer Hours non-Diving	Number of Dive Volunteers	Number of non-Dive Volunteers
San Diego BK	559	99	27	21
Orange County CK	2,595	568	70	30
Santa Monica BK	1,680	867	68	10
Santa Barbara CK	768	150	22	15
TOTAL	5,602	1,684	187	76

Future Work

The Project is planned to continue until 2007. Thus far, we have secured funding from NOAA and the California Coastal Conservancy.

We will expand the education and outreach programs reaching many more thousands of people.

Restoration will include 6 new restoration areas in Los Angeles and Orange Counties. We will continue to conduct maintenance restoration on existing sites as needed.

To support the restoration effort, we will be increasing our production of outplanting materials. We will accomplish this by adding kelp culture tables and improving the efficiency of the Laboratory operation.

Our monitoring work will continue on the existing sites and include any new restoration areas. Here too, we are looking at ways to improve efficiency and still accomplish our goals. More emphasis will be given to analysis of the data collected.

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