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Review of Deep-Sea Ecology and Monitoring as They Relate to Deep-Sea Oil and Gas Operations

R.K. Kropp

Battelle Marine Sciences Laboratory
Sequim, Washington

January 2004

Prepared for the U.S. Department of Energy
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Executive Summary

This review summarizes available information concerning deep-sea benthic ecology and how that information might be used to monitor and eventually reduce the potential impacts resulting from oil and gas production activities. The paper provides a brief overview of deep-sea ecology and benthic faunal groups and summarizes some of the physical and biological features that may be important in evaluating potential impacts. In addition, presented is a synopsis of issues related to the design of a sampling program and a discussion of analytical considerations related to the uncertain knowledge of deep faunas. Also included is an overview of some of the variety of sampling techniques and equipment available to study the deep sea. The review concludes with management considerations and recommendations.

The deep sea is a dynamic biological environment, where rare species are known to exist under extraordinary conditions of tremendous pressures, low oxygen, cold temperatures, total darkness, and periodic storms. The review describes some of the adaptations necessary to exist under these extreme conditions. Impacts associated with exploration activities generally result from physical and biological disturbances. Impacts can also result from new habitat creation (e.g., the placement of a platform creates new habitat that can be colonized by a variety of organisms).

Habitat assessments generally include acquiring information on the physical and chemical properties of the sedimentary environment, including grain size, availability of organic matter, and oxygen levels. Pros and cons are outlined of various methods of monitoring the density, diversity, and rarity of different benthic faunal groups, as are means of minimizing impacts to and preserving these species.

Most studies of ecological communities in the sea have focused on defining community structure; however, the study of ecosystem functions, and especially the effects of anthropogenic activities on these functions, is also an important part of a benthic study. Structure is usually determined by obtaining a sample of the community and determining its constituent taxa. Measurements of function may include estimates of growth, reproduction, and development, or community processes, such as respiration and nutrient flux.

Various considerations relevant to the design of a monitoring program are summarized, including aspects of sample collection, visual observations, manipulative experiments, and issues of spatial and temporal scales, particularly as they relate to statistical planning and analysis. Emphasized is the importance of clearly establishing goals in the planning stages, as well as practical considerations, such as maintaining the quality and comparability of data.

Species-level analyses contain useful data about life-history patterns, reproductive strategies, and dispersal capabilities that can be used to anticipate impacts to communities, but more importantly, to gain insights into the potential for recovery from disturbance. Although achieving high quality and consistent taxonomic data can be difficult, it is cautioned that restricting taxonomic identifications above a species level cannot provide the same knowledge about community structural and functional changes in response to disturbance.

Other means of assessing impacts to deep-sea organisms are also addressed. For example, although the study of biomarkers in deep-sea animals is in its infancy, it certainly holds promise for use in detecting exposures to foreign compounds.

Field sampling equipment used on studies of the sea floor involve either tethered collection devices or non ship-linked techniques, such as submersibles. Examples of both of these primary types of data collection techniques are discussed, including sample collection and preservation techniques, sediment profile imagery, acoustic monitoring, remotely operated and autonomous underwater vehicles, and various sensor systems.

Also considered are factors that affect the management of ecosystem monitoring programs, one of the most important of which is change. Understanding the effects of change is inherently complex, because change can be gradual or abrupt (e.g., in response to a catastrophic event), and the adaptability of ecosystems under widely fluctuating conditions can vary considerably. Given the dynamic, unpredictable nature of ecosystems, the integration of human activities and ecosystem conservation is difficult. Because there is often considerable uncertainty about how and when a system will change, an adaptive management approach is recommended to provide the flexibility required to manage effectively deep-sea resources.

Recommendations to support a more effective monitoring program are outlined in the final chapter. Included are the importance of clearly stating objectives, designing a statistically relevant sampling and analysis plan that provides answers to the questions being asked, elements of structure and function, considerations of taxonomic identification of organisms, the potential use of alternative technologies, and the importance of disseminating the results to the broader community.

Contents

1.0 Introduction

Reliance on oil and gas products in the U.S. continues to be very high. About two-thirds of the total energy demands in the U.S. are met by oil and gas. Almost all of the transportation-related energy consumption in the U.S. is met by refined oil and gas products. Demand for refined oil products will grow 35% between 1996 and 2020 as consumption increases from about 18 million barrels to almost 25 million barrels per day (USDOE 1999). As demand increases and supplies dwindle, new sources of oil and gas need be found and developed.

Oil and gas resources in the deep sea are beginning to be used to help meet the growing demand for energy. The number of deepwater projects in the Gulf of Mexico increased from 16 in 1997 to 51 by the beginning of 2002 (Baud et al., 2002). In 2001 alone, 14 new deepwater projects began production. Deepwater production is also occuring off the coasts of Brazil, West Africa, and the Shetland Islands. As activities in deep water increase, there is also growing concern for the impacts that these might have on sensitive deep-sea benthic environments. Although studies of the deep sea have burgeoned in the last 20 years, much is still unknown, especially as relates to the impacts of activities surrounding human resource use.

The purpose of this review is to summarize some information that is available concerning deep-sea benthic ecology and how that information might be used to monitor and eventually reduce the potential impacts resulting from oil and gas production activities. The summary cannot be used as a "cookbook" for the design of a specific monitoring program, because each program will have specific goals and, therefore, specific design requirements. Sections 2 through 4 of the report briefly summarize what is known about the kinds of impacts that might be expected from production activities, provide a brief overview of deep-sea ecology and benthic faunal groups, and summarize some of the physical and biological features that may be important in evaluating potential impacts. Section 5 provides an overview of issues related to the design of a sampling program and a discussion of analytical considerations related to the uncertain knowledge of deep faunas. Section 6 presents some of the variety of sampling techniques and equipment available to study the deep sea, and Section 7 outlines a few management considerations. A complete listing of the references used for this study is also included.

2.0 Potential Impacts

Many of the potential impacts of oil and gas exploration, drilling, and production activities on benthic environments are well known, especially for relatively shallow waters. The impacts of oil industry activities on the benthos have been particularly well studied for the North Sea and coastal U.S. waters. Impacts may result from all phases of oil and gas operations, from the evaluation of the sea floor (seismic surveying) through the development and production phases (Neff et al. 1987).

Impacts associated with exploration activities may be ameliorated by the energy regime in which the activity occurs. Neff et al. (1989) studied oil and gas exploration activities on benthic communities of Georges Bank, a relatively high-energy open ocean bank off Massachusetts. The study found that the amounts of drilling muds that accumulated on the sea floor were small, most likely because they were dispersed over a wide area by the active currents at the bank. Concurrent with this finding was the observation that there were no benthic community changes that could be related to the exploratory activities. A similar finding might not be occur in deep-sea environments, which typically are relatively quiescent.

Peterson et al. (1996) reviewed the findings of the many studies performed in the vicinity of three platforms in the Gulf of Mexico as part of the interdisciplinary GOOMEX study (Kennicutt et al. 1996). They concluded that sediment around platforms showed effects of drilling activities, that the effects evident in the benthos to distances of 100 m to 200 m from the platforms were probably attributable to toxicity and organic enrichment, and there were no detectable impacts to fish or large invertebrates.

2.1 Physical Disturbances

Peterson et al. (1996) discussed four primary impacts of oil and gas operations on the physical environment around platforms that were principally expressed as alterations of the sediment. Close to the platforms, the predominant texture of the sediment was modified from the relatively fine-grained material found at background locations to sands. The probable causes of this change were the sand blasting of the platforms and discharges of drill cuttings. The concentration of hydrocarbons in the sediment was slightly increased near platforms. The concentrations of several metals increased in the sediment as far as 200 m from the platforms. Trace metals were present at concentrations greater than those known to induce biological effects. In addition, there was evidence of organic enrichment near the shallower platforms. Many of these effects have been observed in sediments close to platforms in other seas ranging from the North Sea (Kingston 1992) to the Gulf of Thailand (Kelly et al., 1998).

2.2 Biological Disturbances

Peterson et al. (1996) reported that the primary biological effects related to oil production activities were manifested as changes in the invertebrate animals inhabiting the sediment around platforms. Most notable was an increase in animal densities near the platforms, which was attributable to an increase in worms in those sediments (Montagna and Harper 1996). Crustaceans and echinoderms were less abundant near platforms than farther away. Increased toxicity and organic enrichment near the platforms were the two primary factors thought to contribute to these observations. Similar benthic responses have been documented in the North Sea (Kingston 1992) and the Gulf of Thailand (Kelly et al., 1998), although the distances at which the effects occurred differed among the areas. The distance that effects may reach is related to the type of drilling fluid used at the platform. Where oil-based drilling fluids are used (North Sea), impacts are detected much farther from platforms (up to 10 km) (Kingston 1992) than where water-based muds are used (e.g., Gulf of Mexico, 200 m) (Peterson et al., 1996).

Carr et al. (1996) documented that toxicity was a probable causative factor in determining the changes in the faunal community near the platforms. Porewater toxicity tests demonstrated that toxicity generally followed a pattern similar to that of chemical contamination, but occurred only at stations located within 100 m of a platform. Metals were suspected as the cause of the toxicity. In the North Sea, toxicity to amphipods was detected in sediments as far as 600 m from a platform and was attributed to high concentrations of hydrocarbons rather than to metals, sulfides, or ammonia (Grant and Briggs 2002).

McDonald et al. (1996) did not detect significant differences among various biomarkers (e.g., EROD activity, P450IA activity, CYP1A mRNA levels, polycyclic aromatic hydrocarbons [PAHs] in bile) from fish collected close to or far from the GOOMEX platforms. Thus, there probably was no sublethal effect of platform activities on highly mobile fish (Peterson et al., 1996).

2.3 New Habitat Creation

Placement of a production platform and its associated support infrastructure (e.g., pipelines or other structures on the sea floor) in an otherwise open-water area creates new habitat that can be colonized by a variety of epifaunal organisms. A platform can provide about 1 hectare of novel habitat for sessile organisms to colonize (Bull 1989, as cited by Montagna et al., 2002). This novel community can contribute to increased organic content of sediment near platforms as community members slough shells and other materials that fall to the sea floor. This organic enrichment has been described as a “reef effect” (Rowe and Kennicutt 2001) and was observed in the GOOMEX study (Peterson et al., 1996). The potential impacts of this phenomenon on deep-sea sediment are unknown. Peterson et al. did not observe organic enrichment at the deepest platform in the GOOMEX study, and it is possible that the falling material disperses more in deeper than in shallower waters.

Montagna et al. (2002) attempted to parse platform contaminant effects on meiofauna from the organic enrichment, or reef effects, attributable to platforms. The key finding of this study was that habitat, not contamination, was more important as a factor affecting the meiofaunal community.

Hall (2001) offered an interesting, although unusual, idea that oil production activities might be beneficial to the conservation of some critical animal species. He argued that oil platforms actually offered some degree of protection to the deep-water coral, *Lophelia pertusa*, by reducing the potential for disturbance from fish trawling and providing a hard substrate for corals to colonize.

3.0 Deep Sea Overview

The first step in evaluating the deep-sea environment is to establish its limits. The critical boundary is the depth at which shallow waters can be separated from deep waters. That boundary has been variously set at a variety of depths. Carney (2001), in a recent review of the deep-sea environmental and biological factors that are applicable to the management of oil and gas production efforts, cited 200 m as the upper boundary of the deep sea. This depth coincides with that set by the Deepwater Oil and Gas Royalty Relief Act. Carney mentioned that the depth at which the physical environment of the deep sea becomes relatively homogeneous is about 1000 m and considered this upper region to be one of transition from surface waters to those at depth. Habitats in this transitional region likely differ substantially from those deeper, because it is here that the oxygen concentration in the water becomes low, physical conditions such as salinity and temperature stabilize, and light from the upper waters disappears.

3.1 Physical Environment

Largely by virtue of the great distances between surface waters and the sea floor in deep regions of the oceans, the physical environment of the deep sea naturally differs substantially from that in shallow waters. Some of the main deep-sea environmental factors expected to have the most profound effects on the biota, which were discussed in more detail by Carney (2001), are summarized in the following sections.

3.1.1 Pressure, Temperature, and Light

Probably the most obvious factor is that pressure increases with depth, effectively increasing at a rate of one atmosphere for every 10-m increase in depth. Pressure exerts opposing effects on chemical reactions, depending on how that reaction affects volume. Reactions that tend to reduce volumes are enhanced under pressure, whereas those that increase volumes become more difficult. The main implication of this property is that many enzymatic reactions from various metabolic pathways are inhibited as depth increases (Somero 1998). Thus, the enzyme systems of deep-sea organisms differ from those inhabiting shallow waters and, therefore, studies of the effects of various stressors on shallow-water organisms are not likely to be extendable to those of the deep sea.

Pressure also affects the solubility of calcium carbonate. Below a certain depth, which varies throughout the sea (in the north Atlantic, it is about 4000 m), the sinking calcium carbonate shells of small unicellular animals (foraminiferans) dissolve before they reach the sea floor and accumulate in the sediments. Carney (2001) stated that this has some implications for management, because the nature of the sediments above and below the depth differ, and therefore, the communities inhabiting them are likely to differ also.

Deep-sea waters are characterized by cold temperatures, ranging from about 10ºC at 200-m depth down to about 2ºC at depths beyond 3000 m (Carney 2001). Temperature differences form important natural boundaries that are major factors in determining organism distributions (Somero 1998).

Sunlight gradually disappears in the transition zone, such that darkness is one of the main features of the deep sea. Yet, as Carney (2001) points out, light may be of critical importance to animals in the deep sea. Some may be able to detect the little sunlight that penetrates to depths of 1000 m. Beyond this depth, bioluminescence may be very important to organisms. Activities that change the optical properties of the water, such as increased turbidity resulting from pipeline placement, may have important effects on deep-sea organisms. Also of concern is that light introduced during deep-sea monitoring or other surveys (e.g., by the bright lights mounted on remotely operated vehicles) could have adverse impacts on organisms. Kochevar (1998) reviewed the scientific literature on light adaptations in deep-sea organisms to evaluate these potential impacts. Although stating that there is not enough information available, or likely to be available, to perform a risk analysis, he concluded that there was no compelling reason to stop the use of submersibles, in part because the localized impact would be quite small relative to the global deep-sea area.

3.1.2 Oxygen Minimum Zone

Another important characteristic of the deep-sea environment is that at some depth, the concentration of dissolved oxygen in the water reaches a minimum. The depth of this oxygen minimum zone varies among the oceans, for example, generally occurring between 200 m and 750 m depth in the Gulf of Mexico (Carney 2001). Oxygen enters surface waters via photosynthesis or diffusion from the atmosphere. As decaying biological material sinks through the water column, it is degraded by bacteria that eventually consume oxygen faster than it can be replaced (Somero 1998). At these depths, dissolved oxygen concentrations often fall below 3 mL/L, which means that benthic habitats in this zone might be considered hypoxic as described by Diaz and Rosenberg (1995). The oxygen content of the water begins to increase below the oxygen minimum zone as deep water from downwelling zones at the poles brings oxygenated water to an area. Within the oxygen minimum zone, the likelihood of any anthropogenic perturbation that increases biological oxygen demand of the waters should be minimized (Carney 2001).

3.1.3 Benthic Boundary Layer

Boundary layers occur wherever water (or air) flows over a stationary object or surface (Vogel 1994). In the boundary layer, there is gradually decreasing flow as the surface of the stationary object is approached. Boundary layers have considerable importance in many biological habitats and have proven to be very important in the deep sea. An important feature of the benthic boundary layer (BBL) in the deep sea is that it limits contact between the water column above and the benthos below (Carney 2001). The BBL, which is often called the benthic nephloid layer, varies considerably in thickness. The layer is typically thin where the bottom topography is flat, and thick where the topography is complex (Kontar and Sokov 1997). The nephloid layer is rich in suspended material that includes the detrital material that has descended from the upper layers of the sea. Descending particles become trapped here for a time before being deposited on the sea floor. The amount of material trapped in the layer depends on the flow speed of the current (Kontar and Sokov 1997). About 10% of the benthic carbon consumption occurs in the BBL. The link between the BBL and the sea floor is so strong that Carney (2001) stated that this area forms a unified system that should be studied together. A monitoring program of the benthos in the vicinity of oil and gas production structures should include the BBL.

3.1.4 Benthic Storms

Historically, deep-sea environments have been considered fairly stable and quiescent. Studies beginning in the latter half of the 20th century disproved that notion. Some deep sea floor areas are now known to be swept periodically by very strong currents or "storms." Current speeds during benthic storm events may average about 15 cm/sec (Kontar and Sokov 1997) and reach a peak velocity of about 50 cm/sec (Carney 2001). Benthic storms can disturb bottom sediments such that particles can be picked up in the nephloid layer and transported long distances.

3.2 Biological Environment

As might be expected in a region that is characterized by high pressure, cold temperatures, and darkness, the biological environment in the deep sea is very different from that in shallow waters. Some of the adaptations necessary for individuals to exist in the deep sea were mentioned in the previous sections. In the following sections, some of the broader scale properties of deep biological environments are summarized.

3.2.1 Benthic Faunal Groups

Most of the sea floor in the deep sea is comprised of soft sediment and most deep-sea animals are well-suited to living in and on them (Carney 2001). Animals living within the sediments are referred to as infauna, whereas those living on the sediment surface are called epifauna. Descriptions of the basic faunal components are often based on size (e.g., Carney 2001; Gage 2001), although the precise definitions sometimes vary. With respect to the deep-sea fauna, animals that are retained on a 0.3-mm-mesh sieve are termed the macrofauna. For shallow water faunas, often a sieve mesh size of 0.5 mm or even 1.0 mm is used to "define" the macrofauna. The macrofauna is a diverse category that includes annelid worms, a variety of crustaceans, molluscs, and echinoderms as the principal members. Animals that pass through a 0.3-mm-mesh sieve but are retained on a 0.063-mm-mesh sieve are called meiofauna. Principal meiofaunal animals include harpacticoid copepods (small benthic crustaceans) and nematode worms (round worms). Animals much larger than the macrofauna (usually larger than 1 cm) (Gage 2001) are termed megafauna and include larger crustaceans (e.g., crabs, squat lobsters), echinoderms (sea stars, sea cucumbers, brittle stars), some mollusks, and some sea anemones. Megafaunal animals are not often very abundant and are poorly sampled by the usual infaunal sampling methods (Section 6.1.1.). The microfauna is characterized as single-celled animals, such as protozoans, that primarily live attached to sediment particles (Gage 2001). The macrofauna and meiofauna typically receive most of the focus during studies of benthic communities. Both groups bring similar advantages and disadvantages to a monitoring program (Carney 2001). Advantages include that they reveal the high diversity of the deep sea and can be sampled by standardized, quantitative methods. Disadvantages, on the other hand, are that they are not well known, studies require high processing costs, and results are not well-translated to those addressing larger, popularly-known animals, such as fish. As mentioned in Section 2.2, oil production activities have been found to exert significant impacts on both types of faunal communities.

3.2.2 Diversity and Rarity

Benthic community studies typically include some measure of the numbers of individuals and species in collected samples. Simply put, the relationship between the two is an indication of the diversity of the sample. One sample has a higher diversity than another if it has more species for a given number of individuals. Benthic samples from the deep sea are well known to show high diversity (e.g., Grassle and Maciolek 1992, Carney 2001, Gage 2001, among many others). The high diversity reflected in the deep-sea macrofauna and meiofauna has been well documented and discussed, although there is not yet a consensus about the underlying processes that contribute to this diversity. Carney (2001) summarized some of the current hypotheses advocated to explain high diversity in the deep sea and concluded that support for any particular notion is not overwhelming. Still, as Carney points out, a basic understanding of the underlying processes regulating diversity is important to environmental managers and industries interested in using deep-sea resources to be able to determine more efficient guidelines for reducing disturbances.

It is widely accepted that macrofaunal communities in the deep sea are characterized by many rare species (Gage 2001). Because of this, sediment samples collected from the depths have many species represented by one or just a few individuals (Grassle and Maciolek 1992). The large number of rare species in the deep sea has important ramifications for sampling designs and protocols. Gage emphasized the point made by Cao et al. (1998) that disturbance influences the numbers of rare species present in a community. He further argued that studies of the deep sea should use methods that will accurately include rare species, because small changes in rare species could be one of the early effects of a disturbance on a community (Gray et al., 1990).

The high diversity and prevalence of rare species presents a dilemma for the protection of deep-sea benthic communities (Carney 1997). Because it is difficult to know how to protect diversity without an adequate understanding of its underlying mechanisms, Carney offered that protecting rare species might be a reasonable approach. He then examined the two main aspects of rarity: species having low numbers of individuals in a sample and species that do not have a high frequency of occurrence among samples. Carney compared rarity in deep-water samples from the Mid-Atlantic with that in samples from Texas shelf waters. He found that the number of species with a single individual in a sample was directly related to the number of species in the sample, regardless of whether the sample was from deep water or the shelf. One facet of rarity in the deep sea that Carney uncovered was that most rare species in a sample were common elsewhere, which may indicate that the deep sea has larger regions and species pools than shallow water. The acceptance of localized impacts in the deep sea as inconsequential because of the vastness of the sea is inappropriate without knowing the effects of localized impacts on region-level processes. Carney argued that proper protection of diversity in the deep sea should recognize the deep-sea sediments are not homogeneous and that different areas of the sea floor may differ in their contribution to local and regional processes. Carney suggested that impacts to benthic diversity could be lessened by reducing disturbance of environmental characteristics that contribute to habitat diversity. Specifically, changes in near-bottom hydrodynamics, the nature of the sediment-water interface, biological activity patterns, and detrital inputs to the sea floor should be avoided.

4.0 Habitat Assessment

4.1 Physical Environment

Information about several physical or chemical properties of the sedimentary environment is necessary to be able to understand the nature of infaunal communities inhabiting soft substrates in the sea. Some of these factors, especially grain size and organic carbon content, have often been described as causative mechanisms that control infaunal organism distributions. However, a thorough review by Snelgrove and Butman (1994) of many benthic community studies showed that this description is not necessarily valid and the observed relationships may simply be correlative.

4.1.1 Grain Size

The sediment grain-size distribution is probably the factor that is most frequently offered as determining the distribution of infaunal organisms. Grain size is determined by methods designed primarily for geological studies. Typically, a subsample is collected and passed through a series of wet and/or dry sieves of different size mesh. The amount of material left on each sieve is dried and weighed. The sieve fractions are variously translated into verbal descriptions such as sand, silt, or clay and often expressed as a percentage of dry weight. The resulting sediment data are then correlated with infaunal community parameters in an attempt to establish a relationship between them. Snelgrove and Butman (1994) found little evidence supporting the idea that sediment grain size alone was a causative factor in determining species distributions. Part of the reason for the lack of evidence relates to the dissociative manner in which grain size is determined. The sample being analyzed probably bears little resemblance to that encountered by infaunal animals. Any apparent relationship between grain size and animal distributions could be strictly correlative rather than causative. Sediment grain-size measurements will continue to be taken, but they are most useful if taken from the same sample that houses the animals in the community and it is remembered that the relationship between grain size and community parameters is possibly just correlative.

4.1.2 Organic Matter

One factor that might be more likely to contribute to the determination of animal distributions is the organic content of the sediment because of its potential role as a food source for deposit-feeding organisms (Snelgrove and Butman 1994). Twenty years earlier, Johnson (1974) expressed a different view on the role of organic matter, stating that it isn't the only "value" sediments provide to animals and emphasizing that the amount present in the sediment is generally too low (2% to 3%) to be an important factor. Watling (1991) stated that much of the organic carbon in sediment is bound into refractory humic polymers and that bulk measurements of organic content were not really useful in determining nutritional value. Watling contended that measuring the dry weight of carbon (or nitrogen) in the sediment is not indicative of its value as food to deposit feeders and suggested that the development of techniques that could separate organic matter into digestible fractions, such as protein, amino acids, and lipids, would be useful. Watling even suggested that time should not be spent trying to correlate benthic data with the organic carbon or nitrogen content of the sediments. Nonetheless, Snelgrove and Butman, although they did not discuss Watling's ideas, emphasized that animals do respond to organic matter, but did state that it was premature to consider that infaunal distributions were primarily determined by organic matter.

4.1.3 Oxidation-Reduction (Redox) Potential Discontinuity Depth

The oxidation-reduction (redox) potential discontinuity (RPD) depth is the depth at which the sediment becomes anoxic. This depth depends on several factors, including diffusion from the surface of the sediment and the activities of burrowing organisms. Diffusion alone usually cannot transport oxygen much deeper than 1 cm to 2 cm into the sediment. Deep-burrowing animals can transport oxygen much deeper into the sediment. The approximate RPD depth can be determined visually by observing the change in color from the brown hue of oxidized sediments to the dark gray or black of anoxic sediments. Microelectrodes inserted into the sediments can measure the RPD depth directly by measuring a vertical profile of the redox potential (E_H) of the sediment porewater. Davis et al. (1998) suggested that measurement of E_H, because it is related to many activities of infaunal organisms, can be used as surrogate measure of benthic conditions. This E_H measurement is much easier and less costly than traditional sampling and analysis methods. However, Watling (1991) cautioned that E_H might not be an indicator of oxygen distribution in the sediment because that distribution is probably independent of factors that determine E_H. Still, the measurement of E_H, by direct or indirect means, is often included in monitoring programs and is probably most useful if interpreted in concert with other parameters.

4.2 Biological Environment

Some environmental factors that can affect the deep-sea benthos are biological features that may originate away from deep habitats. Also, benthic organisms themselves often exert a considerable effect on their environment. Some examples of each as they relate to monitoring the deep sea are discussed in the following sections.

4.2.1 Feeding and Food Availability

The energy available for use by deep-sea animals generally must be supplied by organisms in the euphotic zone, often thousands of meters above the sea floor. Of course, there are exceptions, such as hydrothermal vents and cold seeps where chemosynthetic bacteria supply energy for diverse communities. Animals that don't live near vents or seeps ultimately depend on food arriving from above. Food availability is often low and not supplied continuously. The periodic influx of food from the surface waters contributes to a type of seasonality in the deep sea that was previously not thought to exist (Gooday 2002). The material sinking from the surface water forms aggregates, termed phytodetritus, that accumulate on the sea floor. Patchy deposits of phytodetritus arrive on the sea floor in late spring or early summer and gradually vanish throughout the summer (reviewed by Gooday 2002). Phytodetrital layers have been observed in most regions of the deep-sea realm. The exact composition of the phytodetritus depends on season, geography, and processes on the sea floor. The responses of benthic microfaunal (bacteria, protozoans) populations to the periodic influx of phytodetritus have been demonstrated and are typically fairly rapid (Gooday 2002). Population responses have been harder to document, however, for meiofauna and macrofauna, probably because both groups have longer generation times. Gooday (2002) also emphasized that these seasonal influxes of organic material create spatial heterogeneity on the sea floor, which may in turn increase species diversity.

Because the deep-sea benthos depends on food influx from surface waters, it could be impacted by population changes of the organisms in the euphotic zone. During a seven-year study, Smith and Kaufmann (1999) found that there was a decrease in particle flux to the bottom and that there was similar decline in primary productivity in the surface waters. However, they also found that the demand for food (as measured by respiration rates) did not change. It is possible that the effects of decreased food were reflected in some process not measured (e.g., reproduction) or that the animals were slowly starving. It is also possible that animal groups (megafauna) not included in respiration measurements were affected. Because of the potential impact of decreased particle flux to the benthos, monitoring programs should consider monitoring particle flux.

The deposition of large animal carcasses on the sea floor constitutes not only a novel source of organic material, but also represents a fairly major, albeit localized, disturbance (Smith et al., 1998). Such whale falls are largely unpredictable for any specific location on the sea floor, however, may be estimated by knowing whale migration patterns that may be somewhat seasonally predictable for particular regions (Gooday 2002). The impact of a whale carcass on the sea floor creates an initial disturbance by resuspending bottom sediments. The carcass also deposits a very large amount of organic material in a fairly small spot on the sea floor, attracting large numbers of scavengers (Smith et al., 1998). Opportunistic macrofauna also colonize the carcass. The decay process releases sulfides from the carcass, and it was recently found that a carcass can support sulfide-based communities similar to those found on hydrothermal vents. The soft tissue components of the carcass remain on the sea floor for years to decades, but eventually only the skeleton remains. The skeleton may continue to affect the benthos by disrupting water flow along the bottom.

4.2.2 Sediment Modification

Benthic animals modify sedimentary habitats in several ways. Bioturbation is the movement of sediment materials by animals as they build structures, feed, and burrow. Bioturbation changes many of the physical properties of the sediment by redistributing particles, modifying grain-size distributions, and mixing surface-born materials into the sediment (Smith et al., 2000). This biogenic sediment mixing affects the burial of nutrients, organic carbon, and contaminants (Smith and Rabouille 2002). It is the main process affecting particle movement in near-surface sediments. Smith and Rabouille found that the depth to which sediments are mixed varies in different deep-sea environments and is related to the flux of particulate organic material from the surface. High particle flux supports large deposit-feeding animals that mix sediments to deeper depths than do small animals. Although not studied yet, biogenic mixing may also increase habitat diversity, thereby helping maintain species diversity (Carney 2001).

4.2.3 Succession and Recovery

Since the late 1970s, the notion that shallow-water, soft-bottom benthic communities pass through well-defined stages of recovery after a disturbance (Pearson and Rosenberg 1978, Rhoads et al., 1978) has become so accepted in marine ecology that sometimes a community is characterized in reference to a particular recovery stage even when the purpose of the study was not related to disturbance. Faunal groups are often described by the same general set of successional stage terms. After disturbance, high densities of small opportunistic species, typically polychaete worms, rapidly colonize a disturbed patch. As succession proceeds, these Stage I animals are replaced by Stage II infaunal deposit feeders, such as small shallow-burrowing clams, or suspension feeders, such as some tube-dwelling amphipod species. The final equilibrium, or Stage III, community is comprised primarily of deposit feeders that obtain food from deep in the sediment. Animals in this stage play a significant role in oxygenating deep sediment layers and mixing particles in the sediment. Little is known about how such a successional model would apply to deep-sea communities, if at all. If the successional paradigm is followed in the deep sea, it might progress at a much slower rate than in shallow water. For example, Young and Richardson (1998) considered the effects of waste disposal on abyssal communities and predicted that initial colonization would take years and that an equilibrium community might not develop for hundreds of years or more.

Several studies of disturbance and recolonization in the deep sea have been conducted. Some have studied the process at fairly small scales, for example, experimental colonization trays (Grassle and Morse-Porteous 1987), whereas other studies have focused on controlled disturbances of large (~11 km^2) patches of deep-sea floor (Thiel et al., 2001). Grassle and Morse-Porteous concluded that the species that colonize an area and the rate at which they respond depend on the characteristics of background populations near the disturbance and the type of disturbance. Their study probably reflects the response to most biogenic disturbances, which typically occur at relatively small scales.

However, disturbances by industrial activities, such as deep-sea mining or oil and gas operations, have the potential to occur at larger scales. A large-scale disturbance experiment was conducted off the coast of Peru to mimic the potential impacts resulting form deep-sea mining. Known as the DISCOL (DISturbance and reCOLonization) experiment, this study involved mechanical disturbance (plowing) of about 11 km^2 of the sea floor (Thiel et al., 2001). Samples were collected a few months, three years, and seven years after the disturbance. The results from this study contrasted with the previous studies of small-scale recolonization in that infaunal abundances quickly recovered in the plow tracks and that there were no differences in the taxonomic composition of major infaunal groups between disturbed and undisturbed habitats (Borowski and Thiel 1998, Borowski 2001). Results indicate that recolonization was likely facilitated by the lateral transport of sediment from nearby regions and that migration is probably more important than larval settlement in the recovery of disturbed deep-sea sediments (Borowski 2001). Most ecological metrics in the area showed recovery seven years after the disturbance. By that time, large epifaunal animals (megafauna) differed in abundance and composition from predisturbance conditions, although the differences were relatively small (Bluhm 2001).

Several studies have also shown that communities recover from disturbances related to oil production activities in relatively shallow waters. Recovery from impacts associated with low-toxicity drilling muds in the North Sea can occur within several years (e.g., Mair et al., 1987,; Kroncke et al., 1992). A study of several platforms in the Gulf of Thailand showed significant differences in biological communities that were linked to differences in drilling histories of the platforms (Kelly et al., 1998). These differences were interpreted as indicating potential recovery from the drilling impacts.

5.0 Biological Community Assessment

5.1 Structure and Function (Process)

Ecological features of biological communities usually are separated into structural and functional, or process, elements. Until relatively recently, most studies of ecological communities in the sea have focused solely on defining community structure. Many monitoring programs still consist only of sampling and analyzing structural elements. Certainly, at least part of the reason for this focus is that structure is relatively easy to measure. Gradually, it has become clearer that studying ecosystem function, and especially how anthropogenic activities might affect it, is an important part of a benthic study. Key properties of community structure and function are briefly described in the following two sections.

5.1.1 Structure

The structural elements of biological communities include the living animals and plants of the community. Structure is usually determined by obtaining a sample of the community and determining its constituent taxa. Several metrics are used to characterize a community's structure. Abundance is typically estimated simply by counting the number of individuals in the sample. The number and composition of identifiable species in a sample is also determined. Biomass, essentially the weight of the community members, is sometimes also included in estimates of community structure. Biomass is often estimated by determining the wet weight of the community constituents, most frequently as grouped into major taxonomic categories. Wet weight is not an accurate biomass measure because all organisms do not have the same ratio of water to organic material. Dry weight is a preferable measure of biomass, but is still somewhat inaccurate because some organisms contain relatively high amounts of inorganic materials (e.g., mollusk shells). Biomass is most accurately measured by obtaining the ash-free dry weight of an organism. This latter technique removes all of the water and inorganic material from the estimate and provides a measure of only the organic material comprising an organism. Neither of the dry-weight methods is typically used in a monitoring program because both destroy the sample.

The structural elements mentioned above are summarized by several calculated metrics. In marine studies, sample sizes often vary. The abundance of organisms determined for a sample is extrapolated to estimate the number that would be present in one square meter of the sea floor in the community. The number of species in a sample is tallied. However, the number of species is often related to abundance such that one sample might contain more species than another simply because it is larger. To make this indication of species richness more equitable among samples having different sizes, many diversity indices have been proposed and used. Probably the most common of these is the Shannon-Weiner Index (H'), which estimates the uncertainty associated with predicting the species identity of an organism randomly selected from a sample. A more diverse sample has greater uncertainty in predicting the identity of any individual in the sample. This index and many others were reviewed by Washington (1984).

5.1.2 Function

Study of function is an attempt to determine how a community works. Measurements of function may include estimates of organismal metrics, such as growth, reproduction, and development (Rowe and Kennicutt 2001), or community processes, such as respiration and nutrient flux. Growth is often measured only for selected species by measuring changes in a physical dimension of individuals, such as body length or changes in weight. Reproductive parameters are measured by counting the number of mature and juvenile individuals in the sample or by counting the numbers of egg-bearing individuals. Measurement of body length and the subsequent calculation of length-frequency graphs, which plot the numbers of individuals comprising various size classes, are useful in analyzing growth and reproduction patterns.

Community process measurements are more difficult to obtain because they must be obtained by enclosing a small portion of the sea floor or by completely enclosing a sediment sample and returning it to the laboratory. Measures of benthic metabolism, such as respiration and the flux of carbon and nitrogen across the sediment:water interface, are indicative of the rates of the decomposition of organic matter in the sediment. Several benthic metabolism parameters are important in coastal ecosystems (Hopkinson et al., 2001) and can be used to estimate the proportion of primary productivity decomposed by the benthos. The role of such processes in deep-sea benthic systems is not as well known.

5.2 Observations and Experiments

In this section, various issues relevant to the design considerations of a monitoring program will be summarized. Many articles concerned with various aspects of monitoring program designs have been written, and the intent here is to summarize some of the more important points as they relate to monitoring benthic communities in the deep sea.

Most, if not all, of the articles on monitoring design stipulate that the most important aspect to establishing a monitoring program is to clearly and concisely state the questions that are being addressed. This clear statement of a monitoring program's goals needs to be made before any of the other concerns can be addressed. Once the questions and goals are clearly formulated, an appropriate design that will provide the data to answer the questions being asked must be determined. Included in the design will be the kinds of data to be collected, the equipment to be used, and the spatial and temporal frequency of sampling that needs to be used. Question formulation and design are the most important considerations for a monitoring program (Green 1979; Underwood et al., 2000; Vos et al., 2000; Carney 2001; Solan et al., 2003).

Information about marine communities is gathered by making observations or conducting manipulative experiments. There is a proper place for both types of data collection in a well-designed monitoring program.

5.2.1 Observations

The value of observations to a monitoring program cannot be overstated. The generation of theories or explanations starts with observations of patterns or the lack of patterns (Andrew and Mapstone 1987; reemphasized by Underwood et al., 2000; Solan et al., 2003). Understanding patterns leads to models about processes (Underwood et al., 2000). Underwood et al. also stated that observations provide data that test hypotheses about patterns. Observational tests of pattern hypotheses have been termed mensurative experiments (Hurlbert 1984).

Solan et al. (2003) pointed out another aspect that observations bring to a monitoring program. Solan et al. stated that throughout most of the history of marine community science, most of the data collection has been accomplished without the scientist directly observing community. Often it is very difficult to get direct observations of many habitats. Soft-bottom community ecology has been based on collection of samples by grab samplers and other collection devices, which has also essentially limited descriptions to the structural parts of communities. This sample-based analysis often places an emphasis on numerically dominant organisms, often ignoring less abundant animals that may be very important ecologically. This emphasis is still evident in most current monitoring projects. Visual input is a very important factor in allowing the perception of reality and order, and the lack of direct observation has often led to misinformation (Solan et al., 2003). The development of acoustic and optical imaging techniques has greatly enhanced scientists' ability to understand ecosystem properties and processes over what could be learned by just collecting samples. Some of these methods, which are described in Section 6.0, have been developed to collect information over relatively long time periods. The ability of scientists to observe communities, especially over longer time scales, has led to new understanding of systems and organisms, especially concerning the functionality of organisms, which now is known to change under different environmental circumstances (Solan et al., 2003).

The collection of samples traditionally has been the primary means of obtaining data about benthic communities, and this is not likely to change substantially in the future. However, a monitoring program should consider using one or more of the visual data collections methods, if doing so will contribute positively to answering the questions the program is evaluating.

5.2.2 Manipulative Experiments

As described above, one way to test the hypothesis resulting from the observation of a pattern is to conduct more observations. Another approach, which follows naturally from the observation of pattern, is to design and conduct a controlled, manipulative experiment to test the hypothesis (Underwood 1997). Such controlled experiments have contributed substantially to the development of marine community ecology during the last 20 years. Experiments are designed primarily to test the primary effects of a manipulation, but can also detect indirect effects. Indirect effects result when the interactions of two species in a community affect the abundance or function of a third (Menge 1997). It is beyond the scope of this review to discuss all of the facets of proper experimental designs. Books (e.g., Underwood 1997) have been written about design and statistical issues. However, manipulative experiments should be considered for inclusion in a monitoring program if they can be designed to help explain some of the patterns that are observed early in the program. Also of interest are experiments on how some of the potential effects of offshore operations might affect deep-sea animals. Most, if not all, of what is known about such impacts today is based on shallow-water organisms. It may be possible to extend some of these findings to deep-water animals, but there are physiological differences between deep and shallow organisms, and impacts might also differ. The inclusion of experiments in a monitoring program should be dictated by the goals of the program.

5.2.3 Spatial and Temporal Scale Issues

The issues reviewed in this section speak directly to monitoring program design concerns, but it is paramount to remember that the specific questions or goals of a program need to be defined before an appropriate design can be devised. Among those involved in the design of a monitoring program, a statistician with experience in ecological communities should be involved. Involving a statistician will help prevent the question, "What can we do with the data?" that is sometimes raised during the analysis phase of a program.

The various components of survey design are discussed in many articles. In this section, the discussion by Dungan et al. (2002) provides the basic information. The article primarily discusses concepts of spatial scale, but also includes some discussion of temporal issues. Features of spatial scale can be applied to three general categories: the phenomenon being studied (the structure of the community), the sampling units used to collect data, and data analysis. Dungan et al., defined several terms that are useful ways to express some of the features associated with scale-related issues. These are presented below, along with notes of how these might be considered in a deep-sea monitoring program.

Sampling Unit Size—The size of the sampling unit is simply the size of the individual sample. It should be larger than the "objects" being sampled (e.g., an individual or individuals) so that count data rather than presence-absence data can be obtained. The sampling-unit size should also be smaller than the size of the process (e.g., patch) that one is trying to evaluate. Because of the relative rarity of deep-sea infaunal organisms, the sampling unit should cover the largest bottom area feasible (Gage 2001). At present, the equipment that provides the largest area for the collection of a quantitative benthic sample is a large box corer (Section 6.1.1). Dungan et al. point out that this concept also applies to temporal issues in which the shortest time period that can be compared is twice the time interval between successive samplings. In other words, to compare one sampling year with another, each year must contain more than one sampling time. This important temporal component of design and analysis is often not adequately expressed in monitoring programs (Morrisey et al., 1992).

Spatial (Sampling) Lag—Spatial lag is the interval between nearby sampling units. This is related to the number of samples collected, which is often determined by the effort permitted by the study. The number of samples collected helps determine the ability, or power, of the study to detect the differences in patterns. The spacing between units should be smaller than the hypothesized pattern (patch). Sampling lag is directly concerned with replication issues. As Carney (2001) mentioned, many monitoring programs have specified a number of replicates (very often the number is 3) without appropriate consideration of whether or not that number is sufficient to answer the questions being asked. Replication in ecological studies provides information about variability within an area so that variability among areas can be evaluated (Carney 2001). As Green (1979) stated, "Differences among can only be demonstrated by comparison to differences within." Replicates provide the only information about variation in sampling, and in practice, many replicates are needed and are analyzed separately. Including many replicates in monitoring design is especially important for the deep sea because of the relative rarity of the fauna (Gage 2001), but Carney (2001) cautions that trying to collect enough samples to obtain adequate representation of very rare species will result in having so many samples that these species will be so rare in the data as to have no effect on the analyses.

Sampling Extent—The sampling extent for a benthic monitoring program is the total size of the area that is to be studied. Although the typical benthic sample actually encompasses a volume by including all of the material down to a specified depth in the sediment, the data are only expressed in terms of the sample area. The extent of a sampling program should be as large as the area covered by the patterns being evaluated. Sampling beyond the expected boundaries of the patterns will enable the extent of the phenomenon to be understood more clearly. One primary reason for extended sampling during deep-sea monitoring studies is that the actual extent of the pattern may surpass its expected boundaries. Such was the case in the monitoring around oil platforms off Norway, where platform effects were not expected to extend beyond 1 km from the platform but were later found to be detectable 3 km away (Gray et al., 1999). Another reason to sample beyond the expected extent of an activity is that data from a more regional perspective can be used to evaluate whether or not local changes were likely the result of a platform activity or the consequence of some larger-scale event. This ability to be able to evaluate local change in the broader context is very important to an effective monitoring program.

Determining Appropriate Sampling Parameters—How can the appropriate sample size, sampling frequency, lag, and extent for a monitoring program be determined? Green (1979), among many others, strongly advocates conducting some preliminary sampling in the intended area of study. This approach will provide the information (e.g., numbers, size, and approximate distributions of the organisms comprising the community) that will allow selection of appropriate sampling parameters. If such a survey is not possible, there are two alternatives, although they are less preferable. One is to use any previously collected data from a potential study area. The other, which in practice may be more useful, is to consider that the early survey or surveys in an area are essentially preliminary surveys, and the data from them can be used to adjust the sampling design if necessary.

5.2.4 Regional and Local Monitoring

The discussion here, although not completely independent of the spatial scale issues mentioned in Section 5.2.3, focuses more on practical aspects, such as maintaining the quality and comparability of the data collected in a monitoring program and improving the cost efficiency of monitoring. Gray et al. (1999) described the offshore monitoring history in Norway from its inception to its current status. When monitoring around oil platforms in Norway was first required, each oil company was required to monitor its own field (local monitoring) following certain guidelines. Problems arose as new fields were developed close to existing ones and some of the monitoring stations overlapped. The use of different consultant companies that used similar, but not identical methods, lead to differences in the quality of the reports produced and the lack of directly comparable data among relatively close sites. Control sites for certain platforms were located too far away to function as appropriate controls and were eventually affected by the development of new fields.

In the mid 1990s, Norway adopted a regional monitoring approach, one that should be considered by oil companies seeking to develop deep-sea oil fields. The Norway coastline is divided into regions and all monitoring within a region is performed by one consultant company. All of the oil companies working in the region develop the proposal and set up joint financing for the monitoring. Monitoring within the region covers all fields and several reference areas. The new monitoring provides industry and regulators with a regional perspective on oil production activities. Data quality improved and larger-scale trends in animal populations became easier to recognize. Importantly for the oil companies, substantial yearly cost savings resulted form the streamlined monitoring approach. A similar cooperative monitoring approach could be a very cost-effective way to conduct monitoring at deep-sea fields, because individual survey costs are likely to be relatively high.

5.2.5 Notes on Oil and Gas Monitoring Studies

Monitoring programs conducted at fields around the world employ relatively similar sampling designs that are essentially variations on the same theme. The basic approach is to collect samples at varying distances from a platform along two axes placed at right angles to each other (or five radii as in the GOOMEX program). The distances between sampling locations usually increase at a specific rate. For example, samples might be located 50 m, 100 m, 250 m, 500 m, and 1000 m from the platform. Replicate samples are typically collected at each location. This general sampling pattern has been used in Norway (Gray et al., 1999), the North Sea (Kingston 1992), the Gulf of Mexico (Kennicutt et al., 1996), and the Gulf of Thailand (Kelly et al., 1998). The studies based on this design often have two basic objectives: to determine the direction and distance of the impacts from a point source (the platform) and to establish general impacts of point sources (Green and Montagna 1996). However, Green and Montagna pointed out that the two purposes require different sampling designs. The determination of impact patterns around a platform requires a relatively large number of samples, and the radial design meets the requirement fairly well. However, the relatively intense sampling is costly, and therefore, few platforms are typically included in a study, thereby rendering the second objective almost impossible to meet. Green and Montagna calculated that the probability of obtaining a perfect rank correlation by chance variation alone with three platforms included in the comparison (as used in the GOOMEX study) is 0.17, which is not statistically significant. The probability decreases as the number of platforms included in the analysis increases. Green and Montagna concluded that to be able to make general statements about the effects of platforms, the design should include more platforms (e.g., 12 or more) with fewer sampling locations at each (e.g., at 50 m and 3000 m along each radius). This design would allow near-versus-far comparisons based on a sample size of 12 platforms. Green and Montagna recommended 12 or more platforms because having 10 degrees of freedom makes the test robust, and the power of the test to detect differences will be higher than with fewer platforms.

5.3 Species Identification Issues

One of the most significant problems facing any study of marine environments is ensuring that the data used in any analysis are as complete and accurate as possible. Ranasinghe et al. (2003) listed the major concerns as undercounting the numbers of organisms and species present in a sample by not removing all organisms during the sorting process and incorrectly identifying the organisms that were removed.

In the study of deep-sea environments and their associated benthic communities, ensuring accurate identification of the constituent fauna is very difficult. Certainly one of the primary contributing factors is the very high diversity of the deep-sea benthos. Many species in the deep sea, especially those in relatively unexplored areas (e.g., West Africa, Brazil), are poorly known. Efforts to resolve the taxonomic uncertainties associated with the deep-sea fauna have not been well-supported, and competent taxonomists are becoming increasingly rare. For example, in the 1980s, the U.S. Department of Interior, Minerals Management Service (MMS) sponsored a series of pioneering studies of Atlantic Slope and Rise in advance of oil and gas exploration activities (Blake et al., 1985, 1987; Maciolek, et al., 1987a, b). These extensive studies, conducted at depths of about 255 m to 3500 m, found that about 58% of the species collected were undescribed (Grassle and Maciolek 1992; Gage 2001). To date, some 15 years after the last of the surveys was completed, most of the undescribed species remain so (N.J. Maciolek, personal communication, 2002).

The difficulty in achieving high quality and consistent taxonomic data for deep-sea faunas arises from the high diversity of organisms in an underexplored marine habitat and the dearth of competent taxonomists to study it. Despite recent implementation of a funding program for systematic and taxonomic studies in the U.S. (the Partnerships for Enhancing Expertise in Taxonomy [PEET] program funded by the U.S. National Science Foundation) and recommendations for increased funding to such activities (House of Lords 2002), there are still not enough taxonomists to study the world's flora and fauna (Blackmore 2002; House of Lords 2002), let alone the fauna of the deep sea.

5.3.1 Provisional Species Concept

One approach to provide accurate species-level calculations when analyzing data from benthic communities for which the constituent species are poorly known is to use "provisional" species identifications. With this approach, a taxonomist working on a faunal component identifies specimens that belong to an undescribed taxon to the lowest practical level, then assigns a species designator to the taxon if it can be recognized at species level. For example, when specimens of an isopod can be identified to the genus *Prochelator*, but cannot be confidently assigned to any described species, the taxonomist can then apply an artificial descriptor, usually a letter or Arabic numeral, to the taxon. Thus, the isopod specimens in the above example could become known as *Prochelator* sp. A. This provisional species name does not replace a valid scientific name and has no valid standing in terms of the International Code of Zoological Nomenclature (ICZN 2000). Provisional species names have been used by many large exploratory surveys (e.g., Blake et al., 1985, 1987; Maciolek et al., 1987a, b) or monitoring programs (e.g., Steinhauer and Imamura 1990; Kropp et al., 2002). However, implementation of this approach does have a potential weakness in that provisional species very often are not supported by adequate documentation or by voucher materials, and material is not deposited in recognized institutions, but left with individual taxonomists or disappears altogether. Therefore, standardization among taxonomists is very difficult to attain, as is achieving taxonomic consistency in a long-term program during which multiple taxonomists are employed. The potential problem is rectified relatively easily by requiring any taxonomist that uses provisional names to support those names by documenting the key features used to recognize the taxon and by comparing the taxon to other taxa, especially described taxa, if appropriate. The taxonomist also should be required to set aside several examples of the provisional taxon in a collection that can be made available to other taxonomists for study and that can eventually be deposited in an established national or regional museum (e.g., U.S. National Museum of Natural History, Santa Barbara Museum of Natural History). Publication of taxonomic studies should be encouraged and supported.

5.3.2 Voucher Collections

One of the most important tasks a funding entity can include in a survey or longer-term monitoring program is the establishment of a well-documented and properly prepared voucher collection. A voucher collection is a collection of "scientific specimens preserved to support the results of a particular piece of research" (Huber 1998). Voucher specimens document that a species was found at a specific location at a specific time and permit reexamination to verify or reject the identification that was made at the time the collection was studied. This ability to reexamine examples of the material identified during a particular study helps ensure the repeatability of the study, which is one of the primary tenets of science (Huber 1998).

The value of the voucher collection must be ensured by following several procedural guidelines (Huber 1998). Specimens to be included in the voucher collection should be clean, complete, and adequately portray the degree of morphological variation present in the population sampled. Several sizes of individuals should be included, as should examples of both genders and juveniles. The material should be properly fixed to allow key morphological features to be preserved (Section 6.1.1).

Voucher materials should be clearly and appropriately labeled (Huber 1998). Information on the label must include the name of the taxon, detailed information about the collection location including geographic references as appropriate, latitude and longitude, depth of the collection, the date the collection was made, habitat data, name of the collector, and the collection method. Other information that may be included to help relate the material back to the collection program are the name of the program and a program-specific sample identification number.

The steps necessary to adequately establish and document a voucher collection involve costs that must be included in the planning of a monitoring program. In addition to the cost associated with the preparation of the collection by the original scientists, museums often require compensation for receiving, processing, and maintaining the collection. Most museums have established guidelines specifically outlining the requirements for the submission of voucher collections (e.g., Hochberg and Scott 2002) and require approval before the collection is submitted. Therefore, the museum should be contacted early in the planning process. Museums may require that all final reports and publications associated with the voucher collection also be submitted to provide more complete supporting documentation for the collection (Hochberg and Scott 2002).

Recently, there has been an increased interest in the study of the population genetics of organisms exposed to stress. If such studies are to be included in a deep-sea monitoring or survey program, measures should be instituted to ensure that samples are adequately preserved for DNA or other molecular analyses. Some DNA and molecular studies can be performed on formalin-fixed materials, but formalin is not the best fixative for these analyses. It would be advisable to allow for the collection of samples dedicated towards these studies, thereby ensuring that proper preservation techniques would be followed (Dawson et al., 1998).

5.3.3 Taxonomic Resolution

The study of infaunal communities provides many advantages over the study of other communities in the investigation of anthropogenic effects (Bilyard 1987), but it is a very labor-intensive activity that requires a considerable amount of time and expense to process samples (Warwick 1988a; Carey and Keough 2002). In addition, the identification of the organisms comprising them requires taxonomic expertise that may be difficult to obtain. Therefore, there has been considerable interest in the development of alternative ways of analyzing infaunal communities. After a long history of identifying collected organisms to species, the notion that this level of detail was necessary to demonstrate the effects of pollution was first challenged in the mid 1980s. Ellis (1985) introduced the concept of "taxonomic sufficiency," which maintains that the level of the taxonomic identifications conducted for a study needs to be appropriate for the biological questions being addressed. Taxonomic sufficiency for studies investigating the impacts of human activities has been interpreted as the level necessary to detect a change in the community (Warwick 1988b). Investigations about the possible use of taxonomic levels other than species (e.g., genus, family, etc.) started in the late 1980s, primarily with the work of Warwick (1988a, b). Warwick developed several rational arguments for using higher taxonomic levels for infaunal community studies that included practical and possible theoretical justification. Practical considerations include the high cost of processing samples and expertise required in obtaining high-quality species-level identifications. If successful in examining human-caused perturbations, using taxonomic levels other than species could obviate these two concerns. Warwick (1988a) also argued that there might be theoretical reasons for not using species-level identifications, primarily involving the reduction of "nuisance" variables, such as sediment particle-size distribution and water depth, both of which can affect infaunal community structure. Other possible theoretical advantages to using higher taxonomic levels include the possible reduction of the natural variability inherent in infaunal patterns (Ferraro and Cole 1990) and that increasing levels of stress become expressed at increased taxonomic levels (Pearson and Rosenberg 1978; Ferraro and Cole 1990).

Several of the early studies that examined the effect of using increasing taxonomic levels on the detection of impacts to infaunal communities focused on visual comparisons of the plots resulting from ordination analyses and found that plots based on aggregated data were similar to those based on species-level data and that little information was lost by using aggregated data (Warwick 1988a, b; Gray et al., 1990). Later studies, by using correlation comparisons, took a more objective approach at examining the effect of data aggregation on the ability to detect community changes. These showed that there was good correlation between analyses performed at taxonomic levels up to family (Vanderklift et al., 1996; Olsgard et al., 1997), but that each level had a certain degree of unique information. Olsgard et al. (1997) also determined that the type of data transformation used during the analysis had more effect on the results than did the aggregation of the data, and recommended using intermediate transformations. Few studies have attempted to estimate the cost savings by using higher taxonomic levels for community analyses, and it is very difficult to generalize from one study to another, because each has very different constraints related to its target community. However, Ferraro and Cole (1990) estimated cost savings of 23%, 55%, 80%, and 95% for genus-, family-, order-, and phylum-level identifications, respectively, over the costs of species-level identifications of the infaunal community off southern California.

Restricting taxonomic identifications to a level higher than species needs to be viewed with caution. Vanderklift et al. (1996) point out that arbitrarily selecting a taxonomic level for data analyses may change the risk of making an error, yet there is no guarantee of whether that risk is increased or decreased by selecting one level over another. Olsgard et al. (1997) and Gage (2001) point out that using higher taxonomic levels to detect impacts probably works best when there is a strong contaminant gradient and the habitat *per se* is generally homogeneous. Gage (2001) further stressed that, with respect to studies of the deep sea, analyses done at higher taxonomic levels are premature, and that before any such approach is implemented, testing against baseline species-level data is necessary. Carney (1997) essentially agreed, arguing that to learn how important processes in the deep sea (resource partitioning, recruitment, species movements) relate at local and region scales, the "highest quality taxonomy" must be employed. Rumohr and Karakassis (1999) stressed that the information contained by macrofaunal analyses includes more than that used in ordination analyses. Species-level analysis of faunal communities provides knowledge about community structural and functional changes in response to disturbance that is more biologically informative than that provided by higher-level analyses. Species-level analyses contain useful data about life-history patterns, reproductive strategies, and dispersal capabilities that can be used to anticipate impacts to communities, but more importantly, to gain insights into the potential for recovery from disturbance.

5.3.4 Sample Compositing

Other approaches that have the potential to reduce the cost and effort associated with the study of infaunal communities include subsampling sediments in the laboratory and using various floatation and elutriation techniques to remove organisms from sediments. However, subsampling may not provide unbiased results if the infauna are not distributed randomly in the main sample. Floatation techniques may exclude certain dense or oddly shaped taxa that can't effectively be floated out of the sediment. Recently, Carey and Keough (2002) described and advocated a method of compositing (i.e., thoroughly mixing) infaunal samples from several field locations and subsampling that composite for laboratory processing and analyses. They used a modification of coning and quartering, a sedimentological technique (Twenhofel and Tyler 1941, cited by Carey and Keough 2002). Carey and Keough gently implemented this technique with the sediments submerged to prevent the organisms from drying out and to lessen the likelihood of physical damage to them. Carey and Keough tested this procedure and found that the mixing process randomly distributed organisms before subsampling and produced subsamples that were comparable with traditional "replicates" collected from the same study site. Carey and Keough found that the power of the subsampling protocol to detect a 50% change was greater than that for samples processed traditionally. As with alternative taxonomic resolution schemes, sample compositing and subsampling may be a promising way to reduce the costs of a benthic study. However, critical assumptions regarding the distribution of the organisms in the composite and the lack of damage to those animals need to be evaluated and compared with traditional samples before the approach is implemented in studies of deep-sea communities. Furthermore, the Carey and Keough study was directed towards a very specific purpose that does not require some of the fine-scale information (e.g., small-scale differences in the distribution of organisms) that are still desirable during early studies of deep-sea communities in particular areas.

5.3.5 Ancillary Special Studies

Funding entities have very high stakes in the quality of the data generated by their community-based monitoring programs. As a substantial investment is made in the collection and analysis of such data, relatively small additional investments can be made to ensure the reliability and repeatability of taxonomic data. When the taxa comprising the infaunal community of interest are poorly known, special taxonomic studies can be planned to help resolve some of the uncertainties of the fauna. There are several very good examples of such programs. In the 1980s, the MMS funded several studies of infaunal and hard-bottom communities in the Santa Maria Basin north of Point Conception, California. These studies generated the traditional types of survey and analytical reports (e.g., SAIC 1986; Steinhauer and Imamura 1990) and publications (Hyland et al., 1991; Montagna 1991) that included many provisional species. Later, MMS funded a follow-on study whose intent was to examine and document the fauna collected during the programs. The results of this latter study were published in a 14-volume Taxonomic Atlas that included formal scientific descriptions of many of the study's provisional species (Blake and Scott 1993–1997).

Another type of special study also could document, albeit somewhat less formally, the fauna encountered during a study. Unocal Thailand, Ltd., funded the preparation and written documentation of a large voucher collection established during a series of short-term surveys conducted at its exploration and production fields in the Gulf of Thailand (Battelle 1991). The predominant species identified during the studies were selected for description and illustration in a series of one-page notes that were bound into a single reference volume (Kropp 1994). Voucher collections were prepared and delivered to a major university in the host country and to major natural history museums in the U.S. These actions have led to the publication of new species descriptions, which validated several provisional species identified during the studies (Scott 1995; Fitzhugh 2002).

Though relatively small and focused primarily on individual sets of studies conducted in restricted areas, both types of special studies are examples of what monitoring entities can do to help ensure the validity of data collected during their programs and also to enhance scientific understanding of the fauna inhabiting the study areas.

5.4 Potential Use of Biomarkers

Although analyses of biological communities are inherently important in monitoring programs, there are some disadvantages relative to the assessment of potential pollution or human-caused disturbances (e.g., Clarke and Warwick 1994; Attrill and Depledge 1997). The primary disadvantage may be that communities may respond slowly to disturbance (and community analyses are time consuming), such that by the time a community change is detected, it may be too late to ameliorate the disturbance (Attrill and Depledge 1997). Other methods may be more appropriate as "early warning" indicators. A hypothetical model describing the effects of a stressor on biological communities is that the effects first occur at lower levels of organization before they become manifest at the community or ecosystem level (Adams 1990).

The general model asserts that first effects of a stressor can be detected at molecular levels as cellular defense systems are activated in response to exposure (Schlenk 1999). Damage at higher levels of organization, for example, to tissues, can occur as cellular defense systems fail. If this damage occurs at critical times in an organism's life cycle, the effect may translate into population-level and eventually community-level alterations (Schlenk 1999).

Several biomarkers that mark the exposure of marine animals to hydrocarbons are known. Many of these have been directly related to exposures to oil spills. Harvey et al. (1999) found elevated levels of DNA adducts in three species of fish exposed to the *Sea Empress* oils spill in 1996. (DNA adducts are addition products that form when DNA molecules are attacked by certain chemicals, and may lead to the development of cancers [Harvey et al., 1999]). However, DNA adducts were not induced in two species of invertebrates studied, a sponge and the blue mussel, *Mytilus edulis*. The animal populations did show recovery by 17 months after the spill. Cytochrome P450 enzymes are important biomarkers that may be used to indicate the exposure of animals to PAHs derived from oil and gas production activities. These enzymes, which function in the oxidation of foreign organic compounds, become activated when vertebrates are exposed to dioxins, furans, coplanar polychlorinated biphenyls (PCBs) and some PAHs (Anderson et al., 1995; Anderson et al., 1999). Three biomarkers in fish that are associated with exposure to hydrocarbons were measured in greenling and gunnel 10 years after the *Exxon Valdez* oil spill (Jewett et al., 2002). Studied were cytochrome P4501A (CYP1A); liver fluorescent aromatic compounds (FAC), which are short-term indicators of recent hydrocarbon exposure; and ethoxyresorufin *O*-deethylase (EROD) activity, which is a measurement of CYP1A induction (Jewett et al., 2002). The study found elevated biomarker levels in fish collected near mussel beds that still had oil from the spill, and also found evidence of hydrocarbon exposure at sites that were within the original spill boundaries, but no longer contained oil. Thus, 10 years later, fish were still being exposed to oil from the spill.

Although the study of biomarkers in deep-sea animals is in its infancy, it certainly holds promise for use in detecting exposures to foreign compounds. Because biomarkers can indicate the exposure of shallow-water animals to hydrocarbons, the utility of such indicators in detecting the exposure of deep-sea animals should be investigated. Use of biomarkers could provide useful information regarding the exposure of animals to hydrocarbons from offshore oil and gas operations.

6.0 Equipment and Techniques

Studies of the sea and the seafloor involve two basic approaches. One deploys various collection devices connected to the research vessel by a wire (also called a tether or umbilicus). The second involves the use of equipment that is not directly attached to the ship (Bachmayer et al., 1998). Ship-linked techniques, which provided the earliest method of deep-sea data collection, are still the predominant field-sampling methods in use today. They offer a relatively cost-effective way to gather information, especially over fairly large areas. Some of the obvious limitations of these methods include the length of time it takes to deploy devices to the deep sea, which often necessitates long cruises to collect the desired number of samples, and the inadequacy of information about the location on the seafloor at which samples are collected, which precludes making a direct link between the samples and the bottom geology.

Non ship-linked techniques provide some advantages over the other methods. Deep-sea submersibles can carry scientists to depths, thereby allowing them to make direct observations of the seafloor and its biota. Within the last several years, devices have been developed that allow for long-term data collection that is not possible by using ship-linked methods. One of the chief disadvantages of these methods is that their development costs are often high.

Some examples of both of these primary types of data collection techniques are discussed in the following sections. The list of techniques is not exhaustive and is focused primarily on methods useful in sampling benthic habitats and biota. In each section, there is a discussion of the general method, types of data collected, the potential utility to deep-sea monitoring, the limitations of the device, and future developments that may be forthcoming.

6.1 Ship-linked

6.1.1 Sediment Sampling

Sample collection—The typical methods for quantitatively sampling the infaunal community include grab samplers and box corers of various sizes (Blomqvist 1991; Somerfield and Clarke 1997). Among the more common grab samplers used are the Smith-McIntyre and van Veen grab samplers that typically have an effective sampling area of 0.1 m^2 or smaller. Several researchers have expressed concern over the quality of the sample taken by grab samplers (e.g., Blomqvist 1991). One of the disadvantages of a grab sampler is that it collects a relatively small sample, usually preventing a subsample for chemical or other analyses to be taken synoptically with the infaunal sample. This particular disadvantage was overcome by the use of a large box corer such as the U.S. Naval Electronics Laboratory (USNEL) sampler (Hessler and Jumars 1974), which has a sampling area of 0.25 m^2. The internal volume of the box corer is often subdivided into several 10- by 10-cm cores that can be assigned to different analyses (Jumars 1975). For example, 10 of the subcores are usually dedicated to infaunal analyses, whereas others provide samples for analyses of chemistry, grain-size, and meiofauna. One major concern with the use of a box corer (and grab samplers) is that the device will push a significant bow wave in front of it as it descends that will blow away some of the surface sediment before it can be sampled (Blomqvist 1991). Andersin and Sandler (1981) found that the efficiency of a van Veen grab sampler could be improved if it were equipped with mesh-covered windows on its upper side to reduce this potential bow wave. Blomqvist stated that the box corer needs to have an open upper side to reduce the bow wave and also needs a locking door that seals the compartment during the retrieval of the box. Somerfield and Clarke (1997) evaluated four sampling methods, including a van Veen grab sampler and a USNEL box corer. Although they didn't find substantial differences among methods, Somerfield and Clarke pointed out that the particular requirements or constraints (water depth, weather) of a project need to be considered in selection of the equipment used in a sampling program.

Although a seemingly minor concern in the planning of a sampling program, the choice of the mesh size of the sieve used to separate the animals from the bulk of the sediment is as important as the selection of the device that collects the sediment sample. Considerable discussion over the effect of the sieve mesh size has punctuated the literature on sampling. The sieve mesh size is often used to define, somewhat artificially, categories of infaunal animals, although the actual biological boundaries between groups are more diffuse than the physical ones set by the sieves. The typical mesh sizes of the sieves used in most marine sampling programs ranges from 1.0 mm down to 0.3 mm (300 μm) or 0.25 mm (250 μm), with a 0.5-mm-mesh (500 μm) sieve probably being the most commonly used. Within the last few years several studies have examined the effect of sieve mesh size on the description of infaunal communities (Bachelet 1990; James et al., 1995; Schlacher and Wooldridge 1996a, b). All concluded, albeit not surprisingly, that sieve mesh size has a tremendous effect on interpretation of community data. The general conclusion of these studies is that the larger mesh sieves often underestimate the macrofaunal assemblage present in an area.

Gage (2001) specifically addressed sieve mesh size in relation to deep-sea community studies, pointing out that many of the organisms comprising deep-sea infaunal communities are much smaller than their shallow-water counterparts. Recall that disturbance affects the numbers of rare species present in a community and that the deep-sea fauna has many rare macrofaunal species. Gage argued that deep-sea studies should be designed to accurately sample rare species. This is especially important in studies that monitor the potential effects of human activities, such as oil and gas production, on the benthos. Gage suggests that the smallest practical sieve size be used in deep-sea monitoring studies. This size most likely will involve the use of 250-μm- to 300-μm-mesh sieves.

Another factor that may have important ramifications on the description of an infaunal community is whether or not the sample is rinsed over the sieve before or after it is fixed. Typically, samples are rinsed over the sieves to remove excess fine sediment material before they are fixed to keep the amount of material that must be handled to a minimum. However, some animals will pass through the openings of a sieve more easily before they are fixed than after. Some polychaete worms may easily crawl through sieve openings and be lost from samples that are not fixed before being rinsed on a sieve (Ohwada 1988). Ohwada recommended fixing samples before rinsing them to reduce this particular bias, although at times this may not be a practical solution.

Sample Preservation— In general, fixation procedures for marine invertebrates call for specimens to be immersed in 10% buffered formalin solution (Knudsen 1966; Fauchald 1977). The material remaining on the sieve after rinsing is transferred to a suitable container, and it is recommended that a narcotizing agent be administered before the fixative is added. This agent relaxes the organisms in the sample, thus reducing the possibility of a reaction to the fixative that could cause animals to fragment. Fauchald recommends adding a solution of 7.5% magnesium chloride in seawater to the sample and letting it sit for about 30 minutes before adding the fixative. The standard fixative agent recommended is a 10% buffered formalin solution in seawater. Technical grade borax ($Na_2B_4O_7$) is a very common buffering agent. Fauchald stresses that the sample container should not be filled to more than one-third by the sample and that the jar should be completely filled with the fixative solution. The sample container should be capped and inverted several times to thoroughly mix the fixative into the sample. Samples need to remain in the formalin solution for at least 24 hours. Formalin is acidic and, despite being buffered, may eventually erode arthropod cuticles and etch or dissolve mollusc shells and other calcium carbonate structures. Therefore, samples that have been fixed in formalin are placed onto a sieve and rinsed thoroughly in freshwater. The rinsed sample is placed back into a container into which a preservative, usually 70% ethanol or isopropanol, is added. The preservative should be changed once to ensure that it is full strength when the sample is stored. Generally, the sample should not remain in formalin for more than about a week. In some cases, attempts may be made to fix specimens and place them into the proper storage medium at the same time by placing them into ethanol immediately after collection. Fauchald (1977) strongly argues that this is not an appropriate treatment for annelid worms. Other fixative protocols may also be used, depending on the ultimate use of the organisms collected.

Dawson et al. (1998) tested several methods for preserving tissues of marine invertebrates for DNA analyses. Although they recognized that cryopreservation (temperatures less than −80°C) is probably the best technique, they pointed out that it is often very difficult to use, especially in remote areas. Dawson et al. found that the primary factors that affected tissue preservation were the type of tissue and the preservation solution used. Sturdy tissues, such as muscle, that were not susceptible to degradation preserved well regardless of the solution used. Weaker tissues that were susceptible to degradation preserved best in the solution DMSO-NaCl. Because of the differing susceptibilities of tissues to degradation, Dawson recommended that, if possible, several tests using different preservation techniques be done before undertaking field collections, or that multiple preservation methods be used. If neither is possible, they recommend that DMSO-NaCl be used as the preservative.

6.1.2 Sediment Profile Imagery

Sediment profile imagery is a technique pioneered in studies of benthic soft-bottom habitats in the early 1970s by Don Rhoads, then at Yale University (Rhoads and Young 1970; Rhoads and Cande 1971). The principal purpose of the approach was to document through the collection of sediment profile images (SPI) the relationship between infaunal organisms and their sedimentary habitat. The primary advantage offered by the technique over traditional grab sampling was that information could be gathered *in situ*, without major disruption of the sediment. Though promising, sediment profile imagery did not gain popularity until the mid 1980s after the description of the Remote Ecological Monitoring of the Seafloor (Remots™) System (Rhoads and Germano 1982, 1986), which provided appropriate theory that could be used to interpret the SPI.

SPI are captured through the ship-board deployment of a camera housed in a wedge-shaped prism that penetrates the sea floor to a depth of about 20 cm and captures an image of a relatively undisturbed profile of the sediment (Rhoads and Germano 1982, 1986). The system can house a still camera that captures images in 35-mm slide or high-resolution digital format, or a video camera that can be linked to the deck of the research vessel to provide for real-time data collection. SPI provide much information about benthic habitat conditions (see Rhoads and Germano 1982, 1986). Physical characterization of the sediment is possible through the description of a variety of parameters, including particle-size distribution, sediment-surface relief, and the presence of methane-gas voids. Biological features measured include the presence of epifauna or infauna and feeding voids and an estimation of the successional stage of the community. One of the more informative parameters is the depth of the apparent redox potential boundary in the sediment. The redox potential (E_H) provides a general indication of the biological (i.e., metabolic) activity within the sediment (Davis et al., 1998). The redox depth is estimated by observing the depth at which the color of the sediment changes from dark gray (indicating reducing conditions) to brown (indicating oxygenated conditions). Analyses of SPI are accomplished in the laboratory by examining scanned images with readily available image-analysis software (Viles and Diaz 1991).

Sediment profile imagery was developed to gather data about benthic processes occurring in the sea and has been used around exploratory drilling rigs (Rumohr and Schomann 1992). Data collection is limited to the relatively shallow depth of the sediment into which the camera penetrates (~20 cm). The technique provides data that can be used to map benthic habitat conditions (Rhoads and Germano 1982, 1986; Valente et al., 1992) and was not designed to replace the use of traditional benthic sample collection methods (e.g., grab samples) for study of infaunal communities. Rumohr and Karakassis (1999), through the use of ordination techniques, compared SPI-generated data with traditional grab sample data. Not surprisingly, they found little correlation between the two types of data and concluded that SPI data could not be used as a replacement for traditional infaunal community analyses.

Since the 1980s, several advances in sediment profile imagery have been made to enhance the utility of the technique. Although video images were proposed as a method of providing real-time data about the sea floor (Rhoads and Germano 1982), still images have been the principal data collection method. In the 1990s, Robert Diaz, Virginia Institute of Marine Sciences, pioneered the use of video images to provide a "Quick-Look" analysis of benthic conditions (Diaz 2000). The analysis examines critical SPI parameters (e.g., apparent redox potential discontinuity depth) and allows for very rapid evaluation of benthic conditions. Diaz (2000) showed that the technique is robust, comparing favorably with detailed laboratory analyses. Although informative, typical SPI collection provides a snapshot of benthic conditions at the time the photograph was taken. Recently, time-lapse SPI collection was described (Solan and Kennedy 2002). The system used by Solan and Kennedy remained in place in the sea floor for about 24 hours and captured an image every 30 minutes.

Until very recently, SPI collection has been restricted to relatively shallow coastal areas. However, it is very possible to use sediment profile imagery in the deep sea, and the technique will no doubt prove to be useful in studying deep habitats. Two studies are now being conducted in the Gulf of Mexico at depths of 1500 m, examining the effects of drill cutting on benthic habitats (R.J. Diaz, personal communication 2002). The camera has also been successfully deployed at a depth of 5210 m in the Scotia Sea off the Antarctic Peninsula (R.J. Diaz, personal communication 2002).

Other than the advance mentioned above, the general SPI technology has changed relatively little since its inception. However, an effort is now underway to considerably improve the technology and bring it into the digital age. The development of two new SPI systems is progressing at the Ocean Laboratory of the University of Aberdeen in the United Kingdom that will make the technology readily deployable in the deep sea (M. Solan, personal communication 2002). The system will be fully digital, capable of being used to depths of 6000 m, and will be able to store 3000 images per deployment. The system will be able to function as a "free-vehicle" (Section 6.2.3), capable of being deployed without a direct connection to the research vessel. The second system being developed will be deployable from a remotely operated vehicle (ROV) and can be used to depths of about 12,000 m.

6.1.3 Remotely Operated Vehicles

The first modern ROV, the POODLE, was built in 1953, although the concept of an underwater vehicle dates from the 1860s (ROV Committee 2002). During the early stages of development, advances in ROV technology were related to military activities, primarily by the U.S. Navy. Later, commercial concerns took the lead in advancing the technology, primarily to support the offshore oil industry (ROV Committee 2002). The most recently developed ROVs incorporate technological advances in robotics and fiber optics. Data transmission via fiber optic cables provides scientists of different disciplines the opportunity to view real-time data simultaneously and, therefore, to interact and alter survey plans to better meet the survey's objectives (Bachmayer et al., 1998). This latter capability has proven useful in gathering data that can be used to modify a survey design without requiring the ship to return to port to have samples analyzed.

Bachmayer et al. (1998) described three qualities that successful ROV programs share: design engineers and oceanographers work together to create systems capable of performing many tasks; ROVs are used primarily to perform impractical, expensive, or otherwise unfeasible operations; and feedback systems are employed to use information gained during field operations to improve system designs. ROVs are often used to estimate the abundances of epifaunal organisms, although those estimates are qualitative or, at best, semi-quantitative because the area photographed or observed is difficult to consistently determine (Parry et al., 2002). Parry et al. compared diver-collected data with data from an ROV equipped with an automated benthic image scaling system (ABISS) that permits the collection of quantitative data. ABISS uses aligned lasers to project the four corners of a square of known size onto the substrate and another laser to calculate the distance from the camera to the subject. Imaging software analyzes the spot pattern and calculates the camera's orientation, which permits true measurement of the subjects.

ROVs vary in size from small units that house television systems for making observations to very complex, multitasking work platforms (ROV Committee 2002). Equipment can include a variety of cameras (television, still photograph, video), manipulators that enable the placement of objects on the seafloor and the collection of samples (including organisms), and other equipment. The larger systems are capable of collecting data from some of the ocean's deepest environs. Several can reach depths of 4000 m to 6000 m, and the Japanese ROV *KAIKO* reached the deepest part of the Marianas Trench at depth of about 11,000 m (ROV Committee 2002). Examples of some familiar deep-water ROV systems and their varying capabilities are highlighted in the descriptions that follow.

Medea/Jason—Built by the Woods Hole Oceanographic Institute (WHOI), the *Medea/Jason* is a dual vehicle system in which the *Medea* is a tether management system that allows *Jason* to be isolated from motion of surface waters during its operation (WHOI 2002b). The system can operate at depths as great as 6000 m (Bachmayer et al., 1998; WHOI 2002b) and is virtually neutrally buoyant at depth. A very controllable platform, the *Medea/Jason* system carries video, still-photograph, and electronic cameras. The Jason also has a 5-axis robotic arm that enables the operator to collect a variety of samples (Bachmayer et al., 1998).

ARGO II—Also operated by WHOI, the *ARGO II* was built in 1994 using the frame of the original ARGO as its foundation (Bachmayer et al., 1998). The new version was equipped with several cameras, all of which can be seen in real time by the operators. Capable of providing accurate position and altitude data, the *ARGO II* is towed about 10 m above the sea floor and is used to create sea-floor mosaics. The ROV also carries a conductivity-temperature-depth (CTD) sensor, a transmissometer, a 3-axis magnetometer, and sonar systems (Bachmayer et al., 1998).

***Tiburon*—**Owned and operated by the Monterey Bay Aquarium Research Institute (MBARI), the *Tiburon*, whose name was taken from the Spanish word for shark, has reached a depth of 4000 m (MBARI 1997). The vehicle, which is the size of a compact car, has a variable buoyancy system and can be moved precisely over the sea floor. *Tiburon* contains several types of sensors, an acoustic navigation system, imaging sonar, and a manipulator arm. Custom instrument packages, explicitly built for specific functions, can be easily attached to the platform to give the system a high degree of scientific capability. The *Tiburon* has been used to capture animals and return them live to the surface to be used in educational displays and research at MBARI.

One of the concerns with the operation of ROVs in the deep sea is that their operation has the potential to negatively disrupt the daily behavioral patterns of the organisms sought for study. Modern ROVs are designed to operate with minimal noise and water disturbance. However, to be able to photograph features of the deep sea, or to operate at all, ROVs need to carry and use strong artificial light sources. As described in Section 3.1, Kochevar (1998) studied the likelihood that the use of strong lights on submersibles could damage the vision of deep-sea animals and concluded that there was no compelling reason to eliminate or reduce the use of ROVs.

6.1.4 Organism Sampling

Included in this section are several types of equipment that are primarily used to capture specimens of organisms for study rather than to quantitatively sample the benthos. Many have been mainstays in deep-water sampling programs.

Trawls—A variety of trawls have been used for study of the deep-sea fauna. Among the most commonly used are otter trawls, beam trawls, and Agassiz trawls. The selection of trawling gear is often subjective. Otter trawls vary in size, but typically consist of a large net connected to the vessel by two long wires or warps. The warps are attached to two doors or otter boards at the front of the net. As the net is towed through the water, it is held open by the outward forces on the doors. A disadvantage inherent with the otter trawl is that although the actual width of the net opening may be known, the actual size of the opening while the net is being towed is not known (Carney 2001). A special type of otter trawl, the semiballoon trawl, manufactured by the Marinovich Brothers net company (Carney 2001), is relatively efficient at sampling epibenthic crustaceans, often including amphipods. Trawling is known to cause considerable damage to the seafloor, its communities, and to benthic processes (Watling and Norse 1998; Thrush and Dayton 2002). Considering that these trawls are semi-quantitative at best, the damage they cause probably does not justify their use.

Epibenthic Sledges—Although the epibenthic sledge has been a common tool for sampling the deep-sea epibenthos, its performance has rarely been investigated (Christiansen and Nuppenau 1997). Some studies have examined the replicability of tows, but have not studied how consistently the sledge operates on the sea floor, determined the optimal tow-wire attitude, examined the effects of obstacles in front of the sled, and observed how animals respond to the sledge. To study these, Christiansen and Nuppenau mounted a television camera on a sledge that provided real-time transmission to the ship. The sledge also was equipped with a still camera. When the sledge was towed at a ship's speed of 2 knots, Christiansen and Nuppenau found that the performance of gear depended on having the correct wire-out length: too little and the sledge reflected the ship's movements on the surface; too much wire out and the wire and bridle stirred up the mud in front of the sledge. They also found that the sledge did not tow well on slopes. The television photos showed that larger fish avoided the trawl and also that some crustaceans could escape.

Lewis (1999) developed a new epibenthic sledge, the CSIRO-SEBS sled, that could be used over rough terrain, especially on seamounts. The innovation that provided this capability was a modification of the typical weak-link system used on sleds to allow them to be freed from obstacles or to flip over an obstacle. However, the older weak-link systems sometimes caused the bridle to become tangled when the sled flipped over. The new system allowed the sled to encounter and separate from obstacles without the entanglement. This capability allowed the sled to tolerate greater loads than other designs. The new sled was deployed to a depth of 2100 m.

Collection devices that sample a small section of the bottom may not be very effective at catching small animals, such as peracarids (small crustaceans), because they are very patchily distributed. Epibenthic sleds may provide better data if it can be shown that the sample is quantitative. Brandt and Barthel (1995) described a modification of the Rothslisberg-Pearcy (RP) sledge that has been used much in Scandinavia. The modification added a net above the main sledge body to better capture animals that live in layers just above the bottom. During deployments to depths of about 2700 m, the upper net caught about 25% of the animals that the main net caught. Brandt and Barthel found that the upper net added useful information about the fauna. It was still difficult to determine the distance traveled by the sled, although a global positioning system was used to fix the locations of the ship at start and end of tow. As is typically done, the tow distance was estimated from these positions and then multiplied by width of opening to determine the area sampled. The modified sledge allowed Brandt and Barthel to determine that mysid crustaceans feed in the benthic boundary layer, about 40 cm above the bottom, where particulate organic carbon is higher. The sledge was used to a depth of about 2700 m.

Pressurized Traps—The high hydrostatic pressure characterizing deep-sea habitats makes it difficult to study the physiology of its inhabitants and their physiological responses to an influx of contaminants.

The traditional collection methods, epibenthic trawls, sleds and box cores, or grab samplers, do not shield animals from physical damage or the lethal effects of rapid decompression as the device is returned to the surface (Yayanos 1978). In the late 1960s and through the 1970s, pressure-retaining traps were developed that allowed animals to be collected from deep waters and returned to the surface under pressure (Phleger et al., 1979). Animals could then be kept in the traps themselves or placed into pressurized aquaria for observation and experimentation (Yayanos 1978). Early pressure-retaining traps were built of heavy-duty polyvinyl chloride pipe (Brown 1975), whereas later models were constructed of titanium (Yayanos 1977) or aluminum (Phleger et al., 1979). Pressure-retaining traps can be deployed by themselves as free vehicles (Section 6.2.2) or as one component of another instrument package. The trap is baited to attract an animal, but may be more effective in attracting fish if a chemiluminescent light is attached to the trap (Phleger et al., 1979). Traps are designed to close automatically in response to the capture of an animal (Phleger et al., 1979) or just before the trap is retrieved (Yayanos 1977). Yayanos (1978) used a pressure-retaining trap to capture amphipods from depths of almost 6000 m and return them to the surface. Although some pressure was lost (the trap retained ~85% of the calculated *in situ* pressure) (Yayanos 1977), the amphipods were kept alive and studied for nine days (Yayanos 1978). Phleger et al. (1979) successfully used a pressurized trap to capture rattail fish (*Coryphaenoides acrolepis*) and sablefish (*Anoploploma fimbria*) from a depth of 1200 m and use them to study biological membrane structure and function.

Pressurized Aquaria—Recently, a new aquarium system was developed that would allow the collection of deep-sea animals and maintain them under high hydrostatic pressure (Koyama et al., 2002). The system can be operated from a submersible, using a suction device to capture animals. The 20-L aquarium is capable of maintaining a pressure equivalent to that at a 2000-m depth and is designed to allow seawater exchange through a high-pressure pump system. A feed box permits feeding of captured animals during the study. In Koyama et al., researchers successfully kept deep-sea fish alive under pressure for 64 days. Such a system could be used to study the effects of byproducts from oil drilling and production activities directly on deep-sea animals.

6.1.5 Acoustic Monitoring

Echosounders equipped with single or multiple frequency transducers are often used to map physical features of the sea floor, including portions of the deep sea. Mapping the sea floor is a necessary step prior to exploiting an underwater resource. Recently, statistical techniques were developed to improve the interpretation of the backscatter data received by echosounders for classifying the seabed (Legendre et al., 2002) or monitoring benthic animal activity (Jumars et al., 1996). Additional studies using the echosounder approach have been able to detect differences in benthic habitats that might be useful in evaluating potential distributions of benthic animals (Freitas et al., 2003). Acoustic techniques can also be used to study the impacts of certain anthropogenic activities, such as fish trawling, on benthic communities (Schwinghamer et al., 1996, 1998). However, these monitoring studies have taken place primarily in relatively shallow waters having depths less than 150 m. Echosounders have also been used to monitor fish populations at depths of about 600 m (Kloser et al., 2002). Kloser et al. identified three acoustic groups based on the size of the fish and the swimbladder type. Such species, or species group, identifications are important, not only for fisheries studies, but also for any attempts to evaluate benthic communities. Acoustic techniques apparently have not yet been successfully used to monitor benthic communities in the deep sea. Acoustic methods, should they eventually be applicable to studies of the deep-sea benthos, would provide a noninvasive method of monitoring the benthos over relatively large areas in a relatively short time period.

6.1.6 Laser Line Scan Systems

Developed in the 1990s, a laser line scan system (LLSS) is an optical survey technique that uses a narrow wavelength laser to scan the sea floor, providing high-resolution habitat images and allowing accurate monitoring of epibenthic organisms (Carey et al., 2003). A rotating mirror focuses the laser on the sea floor and moves the beam perpendicular to the long axis of the equipment. A photoreceiver tracks the light beam as it moves across the bottom. The system detects the boundaries between objects well because of its sensitivity to reflectance angles. The system requires that tow speed and the scan rate be synchronized and that the tow direction, altitude, and attitude be held constant. The system has been used at depths up to 1500 m (Carey et al., 2003), but very likely can be deployed at deeper depths. Recent developments in the technology have added three-dimension and three-color capability. In Carey et al., the system was used to survey sections of the seafloor in Massachusetts Bay and was able to gather images of such quality, that the legs of a lobster and the spots on a winter flounder could be distinguished. Carey et al. recommended that LLSS be used in situations where information about habitats, water depth, and substrate type are available, because the system works best in straight-line surveys conducted at consistent depth.

6.2 Non ship-linked

6.2.1 Autonomous Underwater Vehicles

An autonomous underwater vehicle (AUV) is an unmanned, underwater, data-gathering system that contains its own power supply and uses a variety of sensors to gather data. The AUV does not require any communication with researchers to carry out its mission and can collect data by performing predefined tasks. However, some models do provide a communication link to the surface via an acoustic modem, allowing for transmission of data in real time and providing scientists an opportunity to modify data collection based on information recently received (George et al., 2002). AUVs have several advantages over ship-tethered systems. The lack of tether reduces survey time and costs and increases quality of the data collected (George et al., 2002). AUVs have the ability to navigate a curved line, which also reduces survey time. Data collection is virtually devoid of interference from weather or sea state. With towed systems, corrections in course or depth must be made by changing the ship's position or by changing the length of the cable extending from the ship. This cable winching takes several minutes to translate change to the towed vehicle. AUVs can change course or depth almost instantaneously. An AUV can maintain a constant speed during deployment, which allows consistent, high-quality data gathering. New AUVs incorporate very accurate internal guidance systems that are based on those developed to position precision guided missiles (George et al., 2002). During a recent survey of the Gulf of Mexico, the error in post-processed data was ±5 m.

Despite these and other advantages, AUVs are not yet widely accepted commercially (Flanigan 2002), partly because of production costs, training, and some technical problems that must be overcome. One of problems is that there are limits to the power supply. An AUV must carry all of the power it will need for a deployment. A recently built commercial AUV can be run continuously for 45 hours (George et al., 2002). New low-cost systems are being developed that will reduce the power demands on AUVs (Schofield et al., 2002). A Webb Slocum Electric Glider has been used at the Long-term Ecosystem Observatory located off the coast of New Jersey. Gliders are designed to change buoyancy and use wings to convert the resulting vertical motion to horizontal (Glenn et al., 1999). In the deep sea, large temperature differences can be used to drive the changes in buoyancy required to power the gliders. Gliders are being built for long duration missions that require low power, but that don't require that a precise survey path be followed.

The development of an AUV for monitoring environmental effects during offshore oil and gas operations is in progress, with a goal of performing cost-effective monitoring in the deep sea (Sadiq et al., 2002). Initially, such a system will most likely be deployed in shallow waters, but eventually will be useful in monitoring environmental issues (effects of produced waters and cutting discharges) and operational situations (inspecting pipelines and other subsea structures) in deeper waters.

Although AUVs have most frequently been used in mapping the sea floor, the development of various new types of sensors will expand this role. Though not an exhaustive list, some of the types of sensors that can be used on AUVs are described in the following paragraphs.

Mapping Sensors—Mapping sensors may include a variety of acoustic and optical devices. The recent high-resolution mapping of part of the Gulf of Mexico was performed by using an EM2000 multibeam system that collected data from an area of the seafloor about 220 m wide by receiving input from 111 beams per "ping" (George et al., 2002). Sidescan sonar is also used on AUVs. An LLSS (Section 6.1.6), which is a high-resolution optical scanning method, has not yet been used on an AUV, but could eventually be an effective data gathering system that could be used to map deep-sea epibenthic organisms.

Chemical Sensors—Within the last few years, there have been significant advances in the development of sensors or other systems that can be used to gather data on contaminants in the water column. Although not yet applied to deep-sea situations, both show promise and are indicative of the kinds of new technological innovations that will be useful in monitoring the waters (and perhaps the sediment) around platforms.

Short et al. (1999) described their efforts to develop a mass spectrometry (MS) system for use underwater. MS is a powerful analytical technique, but its use in underwater systems must overcome several difficulties. The primary issue is that MS must occur in a vacuum, and maintaining the vacuum requires continuous pumping during the analysis. Because most vacuum pumps compress gases and vent them to the atmosphere, maintaining a vacuum underwater is particularly difficult. Nonetheless, as described in Short et al., researchers designed and built an underwater MS system that could be fit into an AUV having an external diameter of 0.52 m. The MS system was tested on volatile organic compounds in the laboratory and found capable of achieving detection limits of 1 ppb (for toluene). Unfortunately, the system is presently limited to use in very shallow waters (~30 m or less), but holds promise for use at greater depths as part of an integrated AUV system.

Mizaikoff (1999) approached the problem of detecting contaminants underwater by developing an optical sensor system capable of directly measuring chlorinated hydrocarbons. This system involves fiber-optic evanescent wave sensors that operate in the mid-infrared region and that are coupled to a Fourier transform infrared spectrometer. Laboratory tests showed that the concentrations of six chlorinated hydrocarbons could be determined simultaneously. Mizaikoff used a modular approach in the design of the sensor system that will allow the approach to be adapted to other situations.

Biological Sensors and Biosensors—Many types of biological information, such as data on bacteria, viruses, and plankton, are difficult to measure by remote underwater techniques (Glenn et al., 1999). Sensors capable of measuring many of these biological parameters are being developed. For example, optical systems are capable of identifying and counting phytoplankton and zooplankton.

Biosensors, however, do not necessarily measure properties, but use a biological detector to measure targeted parameters (Kröger et al., 2002), chemical or biological. As described by Kröger et al. (2002), biosensors use biological material or biologically-derived material in conjunction with a microelectronic transducing system to detect analytes. Biological materials that have been used include enzymes, organelles, microorganisms, and tissues. Turner (2000) mentioned other detectors, including antibodies, cell receptors, nucleic acids (DNA chips), and biomimetic molecules (synthetically produced molecules that mimic biological receptors). An important advantage that biosensors have over traditional chemical analyses is that they can detect classes of compounds that are known to be toxic, mutagenic, carcinogenic, or toxic to cells, and yet be designed to be very specific and sensitive (Kröger et al., 2002). Biosensors for many contaminants have been developed, including a molecular imprinting device that successfully detected PAHs (Dickert et al., 1999).

6.2.2 Free Vehicles

A free vehicle is a device that consists of an instrument package with disposable ballast that is deployed from a research vessel to collect data or samples. The device also has a release mechanism that jettisons the ballast when the data collection is complete, allowing the package to float back to the surface (Phleger and Soutar 1971). First developed in the 1930s, typically to deploy relatively small data collection devices, many advances were made through the 1960s and 1970s, and now the use of free vehicles involves much more sophisticated instrument payloads. Early systems connected the ballast to the instrument payload with a magnesium rod, which dissolved slowly when exposed to seawater. The mechanism usually worked, but the length of time required for the wire to dissolve was often unpredictable. This unpredictability eventually led to the development of the time-release and acoustic-release mechanisms in use today. Examples of some modern free-vehicle packages are described in the following paragraphs.

Free Vehicle Grab Respirometer (FVGR)—Developed in the laboratory of Dr. K.L. Smith, Jr. at the Scripps Institution of Oceanography (SIO), the FVGR is designed to measure benthic community respiration and collect sediment samples. The FVGR can be deployed to depths of 6000 m for 2 to 3 days (SIO 2002a). Iron plates serve as the disposable ballast, which is released by a "burnwire" mechanism activated by an electronic controller. Glass floats (protected in plastic containers) provide enough buoyancy to pull the FVGR out of the mud and return it to the surface. The FVGR has four independent respirometers, each containing a data logger mounted on top of the grab chambers.

ROVER—The *ROVER* is a free-vehicle system developed at SIO that permits long time-series measurements of sediment community oxygen consumption (Smith et al., 1997; SIO 2002b). The system, which resembles a small forklift, is almost 3 m long, weighs 40 kg on the sea floor, and operates autonomously as a free vehicle. *ROVER* can be deployed to depths of about 6000 m and crawls across the sea floor to minimize impact to data collection sites. It can measure oxygen consumption at 30 sites per deployment. *ROVER* also has time-lapse still and video cameras to monitor operations and can collect a water sample for analysis at the end of deployment. It is deployed with disposable ballast and an acoustic-release mechanism.

Camera Tripod—The *Camera Tripod* can remain below for as long as one year and take photos of a ~20-m^2 area of sea floor (SIO 2002c). The film camera, a Benthos 377, originally used when the system was developed, could take about 3200 images. The system will use a digital camera when the required resolution and storage capacity are cost-effectively achievable. The tripod carries its own strobe lights. Ballast is released by a time-release mechanism, and glass floatation spheres bring the tripod back to the surface. Two releases are arranged in tandem, so if one fails, the other can still release the ballast. An acoustic release also can be used. Data collected from the *Camera Tripod* have been published in several papers (e.g., Kaufmann and Smith 1997).

AUDOS II Lander—This free-vehicle lander, developed by Aberdeen University, can be deployed from days to years without intervention from a research vessel. *AUDOS II* has been used to study movements of deep-sea fish *in situ* (Bagley et al., 1999). The system is interesting in that it uses ingestible microprocessor-controlled code-activated (CAT) tags that allow the onboard 77 kHz sonar system to provide a two-dimensional track of the fish movement in relation to currents and other factors. The CAT tags are suspended in bait packages and are readily ingested by deep-sea fish, such as the grenadier (*Coryphaenoides armatus*). Tags are usually retained for about 4 weeks before being regurgitated. Data are stored on board the lander.

6.2.3 Benthic Landers

An important advance in free-vehicle technology was the development of benthic landers. These devices are autonomous research vehicles that are deployed to the sea floor as free vehicles (Black et al., 2001). Benthic landers carry a variety of sensors and instrument packages to the sea floor to permit investigation of environmental features including fish behavior, benthic activity, and community metabolic processes, such as nutrient and oxygen flux (Black et al., 2001). Benthic landers can remain on the sea floor for extended periods of time, permitting long-term data collection not otherwise possible.

Parker et al. (2003) stated that benthic landers are very useful in measuring benthic processes, especially those involving the sediment:water interface. However, they cautioned that several features of landers must be considered when planning a study program involving landers. The manner in which the lander contacts the sea floor, its weight, and the alteration of the flow regime from its presence on the bottom can each affect movement of porewater deeper into the sediment, thus changing some of the very features that are to be measured. Parker et al. suggested that knowledge of the study area before deployment of the lander is highly desirable. Brief descriptions of some types of benthic landers follow.

BENBO Benthic Lander—Designed for use in a large, multidisciplinary investigation of the benthic boundary layer (the BENBO Programme funded by the UK Natural Environment Research Council), this lander has several interchangeable components that enable it to measure benthic community respiration, determine porewater concentrations with a high degree of spatial resolution, and measure trace-metal fluxes and major ion concentrations at very fine spatial scales (Black et al., 2001). During the BENBO study, the lander was used successfully in the Rockall Trough at depths of about 1100 m to 3600 m.

Autonomous Fish Respirometer (FRESP 3)—FRESP was developed by the University of Aberdeen specifically to study deep-sea fish metabolism (Bailey et al., 2002). The particular advantage of this lander is that the metabolism of deep-sea fish can be studied *in situ*, obviating the problems associated with bringing fish to the surface for study. The FRESP lander consists of a relatively simple aluminum tube frame that holds the respirometer, a controller, and a video camera. Bait, loaded prior to deployment, attracts fish into the respiration chamber. The chamber consists of 12-mm thick PVC and polycarbonate walls and a transparent, 6-mm thick polycarbonate lid. The lander has been deployed at a depth of 4000 m and has collected data on respiration for the grenadier *C. armatus* (Bailey et al., 2002).

Autonomous Benthic Explorer* (*ABE)—Operated by WHOI, ABE is a true robot that differs from other landers in that it can move along the sea floor on its own without a pilot or a direct connection to ship (WHOI 2002a). ABE is programmed to perform a predetermined set of maneuvers, during which it takes photographs and collects other data and samples depending on the particular requirements of the research program. During a deployment, ABE covers an area of about a city block. The lander can "sleep" at a docking station between excursions to conserve power. Future enhancements will likely involve use of underwater acoustic transmission systems that will allow scientists to interact with it from virtually anywhere. ABE can operate at depths down to 6000 m with dive durations ranging from 6 h to 1 yr (with 4 to 100 active hours).

6.3 Cabled Underwater Monitoring: A Paradigm Shift

Cabled underwater systems represent the future of monitoring in the sea. Monitoring has traditionally used an expeditionary approach to gather information about the sea and its ecosystems (Delaney et al., 2002). This approach, which generally involves relatively short, periodic surveys, gives scientists mere snapshots of conditions in the sea that do not allow some of the observations that need to be fully explored. The time for change is rapidly approaching. Recent developments in computer and communication technology, robotics, sensors, and power systems have placed modern and future students of the ocean on "the threshold of a scientific revolution" (Delaney et al., 2002). These systems will provide for continuous, long-term monitoring of the sea and will allow scientists and managers to interact directly with the deep-sea environment and to respond opportunistically to unpredicted events.

6.3.1 The Potential

Cabled underwater systems consist of a network of fiber-optic/power cables extending from shore or from some other fixed platform well out onto extensive areas of the sea floor. The cables are connected via a series of nodes that house various sensors and other equipment that can be used to monitor environmental conditions in four dimensions (3-D and time).

Cabled monitoring systems have tremendous potential for advancing the understanding of deep-sea communities and, in particular, how they respond to anthropogenic disturbances. Three critical deep-sea ecological topics that also apply to oil and gas activities (maintenance of diversity, successional patterns, and community structure dynamics) can be studied via a cabled system (K. Smith et al., no date). These studies will rely on many of the methods described in Section 6.2. Experiments can be designed and conducted, then quickly modified as necessary in response to new data to provide new directions for research.

Specifically relevant to oil and gas operations, cabled systems can be used to study how deep-sea communities are affected by human activities. The use of rovers and other underwater devices will permit sections of the deep-sea floor to be manipulated in controlled, process-oriented experiments over fairly long time periods. Such experiments likely would not be possible via other means. A cabled system will allow essentially continuous monitoring of the area around a platform as various production activities occur. Sensing systems placed on AUVs or other devices can be designed to monitor for specific chemical compounds, thus enabling rapid detection of a spill or other discharge. Future visions for cabled systems include the real-time collection and analysis of sediment and water samples, real-time investigations of important ecosystem processes, such as community respiration and bioturbation, and the collection of individual deep-sea animals for study.

The potential utility of a cabled system for monitoring oil and gas operations should be considered and studied further. Offshore oil and gas operations already have many of the infrastructural systems required by a cabled system in place, importantly including a stable power source. A cabled system designed specifically for monitoring a platform or production field need not be as extensive as the one being planned to study plate-level phenomena (e.g., Neptune, see Section 6.3.3), and therefore would not be as expensive. To keep costs reasonable, the system should be designed with a very specific focus that would replace expeditionary-style monitoring surveys. A well-focused cable system would provide better answers to key monitoring questions for the cost than would traditional surveys. Better information provides better answers to tough questions, which is likely to ultimately result in cost savings.

6.3.2 Issues to Overcome

Glenn et al. (1999) described some issues that the development of cabled underwater systems must overcome:

Support—The value of collecting long-term data sets is sometimes not readily apparent to the entities that provide funding because long-term data are not often available to provide evidence for it.

Calibration—Instruments must maintain calibration over the duration of the measurement period; otherwise, it is not possible to differentiate between natural variation and instrument drift. Also calibration is necessary to be able to compare data from different locations or data collected from the same location, but at different times.

Biofouling—Some systems, acoustic and physical, can be coated with material to resist fouling. Others, such as conductivity and optical systems, have serious fouling problems in shallow waters. Fouling may not be as big a problem in the deep sea, because plants won't colonize equipment, although animals probably could.

Power—A reliable power source is the primary factor limiting underwater systems. Cable systems can provide power link, but are expensive to install. Fuel cells are being considered as power sources.

Data Management—Quality Control of data is a concern because it is likely that each project will develop its own cabled system. Raw data and supporting metadata need to be delivered to a national repository.

None of the problems is insurmountable, and the potential benefits of cabled systems outweigh these difficulties.

6.3.3 Example Systems

Long-term Ecosystem Observatory (LEO)—Established in 1996, LEO is located in shallow waters off the coast of New Jersey (Schofield et al., 2002). LEO is intended to provide a rapid, real-time environmental assessment in shallow waters. It uses observational data collected from a variety of sources, including ships, satellites, moorings, and underwater vehicles. LEO has been used to study the seasonal upwelling that occurs along the New Jersey coast associated with a weather system known as the Bermuda High. Data collected by LEO helped determine that local upwelling caused increased water-column turbidity that was related to increased phytoplankton concentrations.

Neptune—Neptune is a large-scale project designed to establish an extensive undersea monitoring system on the Juan de Fuca tectonic plate off the northwest coast of the United States (Delaney et al., 2002). The system will consist of a series of underwater monitoring stations linked by fiber-optic cables through a network of connecting nodes to scientists based on land. The system will allow scientists to rapidly receive and evaluate data and then respond by modifying data-collection protocols, if necessary, to gather specific types of data. The plate-wide collection of data in real time is designed to allow scientists to rapidly respond to sudden events such as volcanic eruptions on the plate that would otherwise go undetected. Other large-scale phenomena that can be studied interactively are fish and mammal migrations, sediment transport, and deep-sea ecological processes.

7.0 Ecosystem Management Considerations

The demands placed on ecosystems for various commodities increased substantially in the 1990s. It also became clear that ecosystems cannot withstand these increased demands indefinitely (Christensen et al., 1996). Resources and ecosystems must be monitored and managed so that future generations will have access to them. In developing management approaches, certain features of ecosystems need to be considered. One of the most important of these is change, which is discussed below. Also, a potentially beneficial approach to managing ecosystem resources that logically follows this ecosystem feature is briefly presented.

7.1 Ecosystem Change and Management

Probably the prime ecosystem feature that is extremely relevant to management considerations is that all ecosystems change. Ecosystems are dynamic, and management efforts to constrain them to a particular form will eventually fail (Christensen et al., 1996). Many of the conditions that affect ecosystems change gradually over time, and ecosystems, too, may change in an even, gradual manner. However, ecosystems can respond in other ways, and these responses have particular importance to management. One response is that the system will remain relatively consistent over some range of conditions, but then will change substantially as these conditions reach a certain point (Scheffer et al., 2001). A third, more complicated, response occurs when an ecosystem has more than one condition in which it can exist in a relatively consistent form. In this case, the system is said to have “alternative (or multiple) stable states,” and the change between them cannot occur smoothly (Scheffer et al., 2001). These “catastrophic” changes from one state to another usually occur without warning. Also, once a system has switched from one state to another, simply restoring the environment to the conditions present before the switch is not enough to reverse the state change. Ecosystems, even those in the deep sea, exist under ever-changing environmental conditions, yet do not necessarily switch from one state to another. Ecosystems have a certain capacity to accept fluctuating environmental conditions, even those that may be more severe (e.g., storms) without switching states. This capacity is termed “resilience” (Scheffer et al., 2001). Any decrease in resilience makes an ecosystem more susceptible to catastrophic change. The implication for management is that efforts should focus on the smaller, gradual alterations of a system that may affect resilience, rather than trying to reduce disturbance *per se* (Scheffer et al., 2001).

7.2 Two Approaches to Consideration of Change

In what is probably the traditional way of approaching the dynamic nature of ecosystems, change is thought to occur in a predictable way. In this case, prior knowledge of the system and the deterministic processes directing the change permits prediction of the final state of the ecosystem (Simpson 2002). This approach to change is manifested most prominently in successional theory under which an ecosystem is considered closed with finite boundaries and low complexity. A contradictory approach considers change as a complex sequence of events that is dependent on the initial ecosystem state and the particular factors driving the change (Simpson 2002). The ecosystem here is considered open without defined boundaries and high complexity. The final ecosystem state is not predictable. Simpson argued that succession theory can provide labels for communities and their constituent species (pioneer, climax), but doesn't allow an understanding of how ecosystem change occurs. Simpson contended that what is normally considered typical successional change after a disturbance actually depends on the local conditions at that time, and that if repeated several times, would yield different communities.

With the open approach, change is influenced by the local conditions and history of change in the ecosystem and follows no prescribed course (Simpson 2002). Interruptions to the changing ecosystem affect the response of the system in the future. Of particular utility to monitoring programs is that a study of the initial ecosystem conditions provides the historical perspective necessary to understand and manage change in response to disturbance and assists in setting goals to minimize impacts or restore the system after disturbance has stopped (Simpson 2002).

7.3 Adaptive Management

Given the dynamic nature of ecosystems and that they can change without warning and in ways that are not easily predictable, the integration of human activities and ecosystem conservation is difficult. Because change is inherent and there is often considerable uncertainty about how and when a system will change, management needs to be able to adapt its approach as conditions change and new information becomes available (Christensen et al., 1996). An adaptive management approach, or learning by doing (Thom 2000), provides the flexibility required to manage deep-sea resources effectively. This approach uses information derived during an assessment program to decide what course of action to take in the future. An effective adaptive management program must set appropriate goals for managing a resource and monitor progress towards those goals. Thom (2000) listed three actions that adaptive management programs can take after evaluating progress towards goals. One is to do nothing (wait and see) or do something (take corrective action). The third option is to change the management goal, something that is often not easy to do. As applied to a deep-sea program, as more is known about the relationship between ecosystem processes and how they relate to structure, regulation of impacts to certain structural elements may need to be strengthened or lessened, rather than proceeding with a program that either does not provide enough protection for the ecosystem, or conversely, is excessive.

8.0 Recommendations

Several recommendations mentioned in this review are summarized here.

- The first step in the establishment of a monitoring program is to clearly state the questions that the program will try to address.
- Design the program to answer the questions being asked. Involve an ecological statistician in the design. Conduct a pilot survey in the study area if possible, and use the information to establish the appropriate sampling parameters.
- Consider measuring community features other than structural elements and including experiments if they contribute to answering the questions being asked by the program. Consider the potential utility of biomarkers in the program.
- When analyzing the benthic samples, use the best available taxonomy and analyze entire, discrete samples. Attempts at cost cutting here will prove to be unwise.
- Consider using alternative technologies (e.g., SPI) in the program if they will help answer the questions being asked.
- Ensure that the information gained during the monitoring is available to the broader scientific community. For example, establish a voucher collection of the organisms collected and deposit it in an established natural history museum.
- Investigate how new and developing technologies (e.g., cabled monitoring systems) might be used or fostered to provide more useful, cost-effective data for the monitoring program.
- Support publication of the results from the program in peer-reviewed scientific or trade journals. Not only will publication be of general benefit to the scientific community, it will help enable offshore operations to be conducted in an environmentally sound manner by disseminating what is learned by one program to others.

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