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ON STABLE REFERENCE AREAS
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INTRODUCTION

Vast quantities of manganese nodules cover the seafloors of the world's oceans. In certain regions, such as the area between the Clarion and Clipperton fracture zones in the eastern Pacific, the deposits appear to consist of sufficient quantities of high-grade nodules (nodules with relatively high concentrations of nickel, cobalt, copper, and manganese) to interest mining companies in the possibility of their commercial recovery. Although studies have been under way for more than a decade, serious investment in seabed mining has awaited the development of a legal system that would provide companies with exclusive rights to a mine site and with the necessary security of tenure. The problem is complicated by the fact that deep ocean nodule deposits are, in general, beyond the limits of jurisdiction of any nation.

The Third United Nations Conference on the Law of the Sea (UNCLOS III) has been attempting to reach agreement on a new international legal system for managing the exploitation of seabed minerals since it convened in 1974. While an impressive consensus has been reached on almost all of the other ocean issues the conference is dealing with, agreement on a seabed regime has so far been elusive.

Before the start of UNCLOS III, domestic legislation had been introduced into the U.S. Congress to license U.S. firms wishing to explore for nodule deposits and ultimately to exploit them commercially. The legislation was based on the concept that nodule mining, like fishing, was a high seas freedom permitted under the 1958 Geneva Convention of the High Seas. After UNCLOS III negotiations began, the legislation was modified to make it interim in nature, pending U.S. ratification of a Law of the Sea treaty and its entry into force.

The seabed mining legislation underwent other changes as well before it was passed by Congress. In early 1979, several months before its enactment, a provision calling for the establishment of "stable reference areas" (SRAs) was added. The impetus for this provision came in part from a resolution passed at the 14th Session of the General Assembly of the International Union for Conservation of Nature and Natural Resources (IUCN), meeting in Ashkhabad, USSR, in the fall of 1978. The resolution stated:

> AWARE that deep sea mining activities are being undertaken by several nations that will disturb or destroy natural systems that have developed without the adverse influence of mankind;
> FURTHER AWARE that such disturbance of the deep sea bed affects adjacent water masses from the sea bed to the surface and relates to the stability of the ocean environment as a whole;
> RECOGNIZING that undisturbed natural systems in the deep sea can provide insight into the processes by which valuable mineralized nodules develop;

> NOTING THAT even incomplete knowledge of deep sea organisms and deep sea ecology confirms great diversity of life and the existence of unique forms of life hitherto unknown;
> CONCERNED because both species and systems have been shown to develop very slowly and thus are especially vulnerable to the impact of mining activity;
> BEARING IN MIND that any meaningful evaluation of the effects of ocean mining on marine life requires comparison with areas in which no mining has occurred;
>
> The General Assembly of IUCN, at its 14th Session, Ashkhabad, USSR, 26 September-5 October 1978:
>
> URGES all nations engaged in, or considering, deep sea mining activities to:
>
> (a) precede commercial mining operations by commissioning a comprehensive ecological survey to determine the impact of such mining activity;
> (b) designate appropriate areas of the deep sea bed as baseline reference and resource zones in which no mining will be allowed;
> (c) designate the size and shape of such area or areas to ensure that their stability will be maintained;
> (d) establish guidelines for scientific research to ensure minimum disruption of the natural state of such areas.

After reconciliation of several different versions, the seabed mining legislation became law when the President signed the Deep Seabed Hard Minerals Resources Act (Public Law 96-283) on June 28, 1980. Section 109(f) of the act states:

> STABLE REFERENCE AREAS
>
> (1) Within one year after the enactment of this Act the Secretary of State shall, in cooperation with the Administrator and as part of the international consultations pursuant to subsection 118(f), negotiate with all nations that are identified in such subsection for the purpose of establishing international stable reference areas in which no mining shall take place: Provided, however, That this subsection shall not be construed as requiring any substantial withdrawal of deep seabed areas from deep seabed mining authorized by this Act.
>
> (2) Nothing in this Act shall be construed as authorizing the United States to unilaterally establish such reference area or areas nor shall the United States recognize the unilateral claim to such reference area or areas by any State.
>
> (3) Within four years after the enactment of this Act, the Secretary of State shall submit a report to Congress on the progress of establishing such stable reference areas, including the designation of appropriate zones to insure a representative and stable biota of the deep seabed.

(4) For purposes of this section "stable reference areas" shall mean an area or areas of the deep seabed to be used as a reference zone or zones for purposes of resource evaluation and environmental assessment of deep seabed mining in which no mining will occur.

Implementation of the legislation was assigned principally to the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce. NOAA established the Office of Ocean Minerals and Energy for this purpose and has begun preparation of the required policy and regulatory framework. Regulations pertaining to exploration licenses were issued in September 1981 (46 Federal Register 45890-45920).

At the time of the issuance of domestic licensing regulations, the U.S. government, represented by NOAA and the Department of State, began negotiating for mutual license recognition with the three other nations (Federal Republic of Germany, France, and the United Kingdom) that had passed similar domestic seabed mining legislation shortly after the United States. Since agreement on the basic reciprocal arrangement dealing with licensing is now near, negotiations regarding stable reference areas could begin later this year.

In preparation for those discussions, NOAA requested that the National Research Council's Ocean Policy Committee (OPC) undertake a short scientific study of the stable reference area provision and its validity and intent in order to provide a basis for NOAA's actions with respect to this portion of the seabed law. The objectives of the OPC study were as follows:

1. To determine the scientific validity of the SRA concept;
2. To define, if the concept is found to be scientifically valid, a cost-effective program to address the major scientific questions involved in establishing SRAs; and
3. To define, if the concept is not found to be scientifically valid, alternative, cost-effective approaches to addressing the scientific issues prompting the insertion of this section into the law.

To undertake the study, the Ocean Policy Committee requested G. Ross Heath, dean of Oregon State University's School of Oceanography, to organize and serve as chairman of a meeting of experts on March 28-29, 1982. This interim report contains the findings arrived at by the participants in that meeting. Additional review and appropriate revision of these findings will take place before the final report is submitted to NOAA in September.

FINDINGS

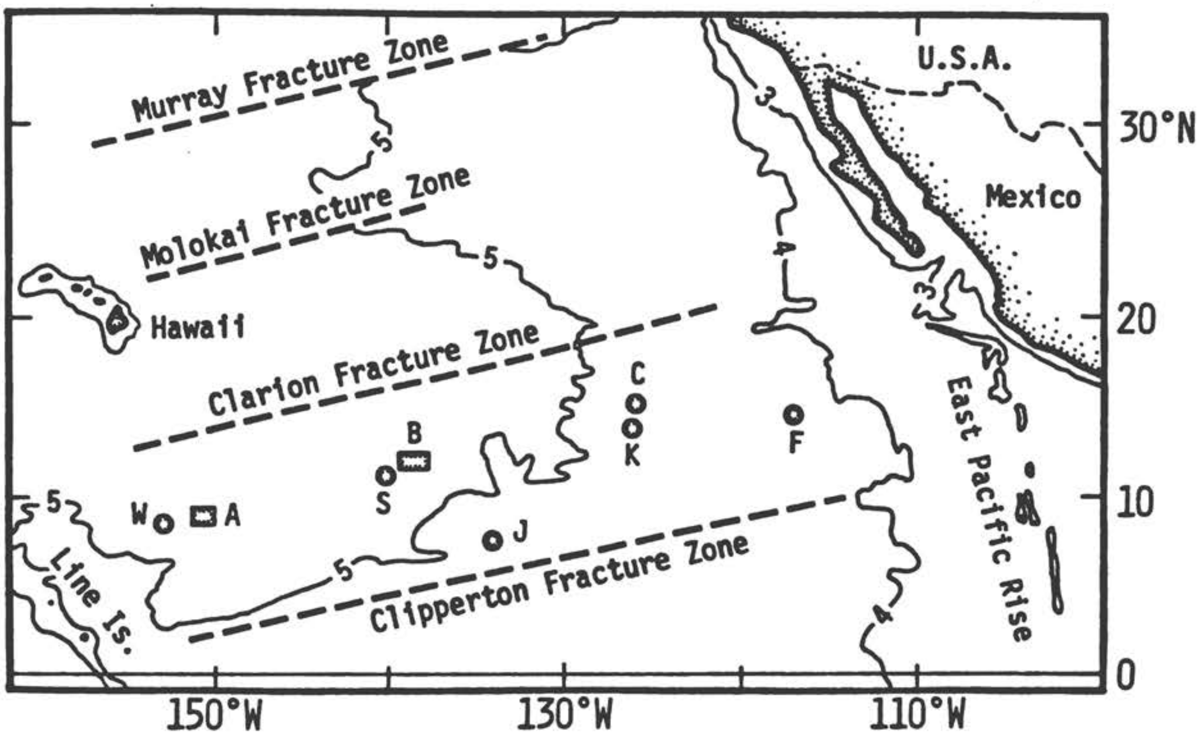
The findings that follow represent a consensus of the participants in the March meeting, but not all the findings were supported unanimously.

1. The concept of stable reference areas (SRAs) as outlined in P.L. 96-283 is scientifically valid. With the current state of knowledge, however, the goals of P.L. 96-283 (designation of appropriate zones "to insure a representative and stable biota of the deep seabed" and "to be used as a reference zone or zones for purposes of resource evaluation and environmental assessment of deep seabed mining") can be met only by designating two types of SRAs. One type, the "preservational" reference area (PRA), must be sufficiently distant from mining sites to ensure that the biota is not affected by mining activities. These areas should also be protected from other anthropogenic impacts, such as dumping of wastes. The other type, the "impact" reference area (IRA), must be close enough to a mining area to minimize inherent environmental differences and thereby allow statistically valid assessments of the impact of mining activities.
2. Development of a cost-effective program to address the major scientific questions involves several technical and institutional considerations and could follow this possible sequence of actions:

   (a) A panel of deep-sea ecologists would design an economical means of measuring the gross temporal and spatial variability of benthic communities in areas for which the variability of the physical environment is relatively well known. A comprehensive biotic-abiotic description is needed to select SRAs that meet the requirements of the legislation. Measurements will be needed to examine community processes, such as oxygen consumption, bioaccumulation, and sediment mixing, as well as community structure. Although total faunal inventories during this early stage would not be cost effective and might well be impossible, this shortcoming could be minimized by concentrating on the distribution of a small number of sentinel organisms. These organisms, which might reflect overall faunal patterns, should be reliably sampled and should be organisms for which ecological expertise exists. Further, the current search for field methods for measuring pollutant-induced stress in coastal marine organisms should be monitored closely to ascertain whether any techniques are transferable to the deep-sea environment.

   (b) A panel of experts would develop a U.S. position on the initial number and locations of PRAs in the region covered by pre-enactment exploration license applications. There should be at least one such PRA per "characteristic environment," and it should be large enough to remain significantly unaffected by the sediment plume from a mining operation. The term "characteristic environment" would be defined by the panel on the basis of such parameters as water depth, primary productivity, surface and deep currents, topography, and substrate character/nodule coverage. PRAs should be located to incorporate and make maximum use of existing intensively studied benthic areas (such as DOMES sites, MANOP sites, WAHINE areas, and Deep-Tow sites) whenever possible (Figure 1).

   (c) Negotiation of an international (reciprocating states regime) agreement on the number and locations of the provisional



A = DOMES Site A (Bischoff and Piper, 1979)

B = DOMES Site B (Bischoff and Piper, 1979)

C = DOMES Site C (Bischoff and Piper, 1979)

*F = BENTHIFACE area (Johnson, 1974)

*J = D. Johnson's area (Johnson, 1972)

*K = Deep-Tow area K (Johnson, 1972)

*S = MANOP Site S (Karas, 1978)

W = WAHINE area (Calvert et al., 1978; Moore, 1970; Moore and Heath, 1967)

* Near-bottom (deep-tow) bathymetric survey available

FIGURE 1 Locations within the Clarion-Clipperton region that have been studied in detail. Depths (isobaths) are in kilometers.

PRAs and on the need for IRAs should occur in conjunction with and prior to the award of the pre-enactment licenses. The agreement should be considered interim in that it could provide an opportunity for other nations to join in the agreement and participate in its further development once a Law of the Sea treaty enters into force.

(d) Preliminary environmental characterization of the provisional PRAs should make use of the most economically effective techniques so that the greatest number of areas can be assessed. Approaches could include Seabeam surveys of selected portions of PRAs; coordinated time-series measurements of near-bottom currents, particle fluxes, and particle concentrations; and discrete determination of the spatial and temporal variability of the parameters mentioned in paragraph (2a) above.

(e) Assessment, by an international panel of experts, of the provisional PRAs should take place before the award of commercial recovery permits. Such an assessment could result in the continuation, discarding, modification, or addition of PRAs, with the expectation that agreed upon PRAs would no longer be treated as "provisional."

(f) A course of research should be developed to seek specific ecological bases for the number, location, and size of preservational areas needed to maintain deep-sea communities. This research might involve the development and testing of theories of population maintenance and life history adaptation. High cost or constraining scientific factors may limit such follow-on studies to a subset of PRAs.

(g) One IRA per mining site should be designated simultaneously with the issuance of commercial recovery permits. Studies in these areas should be modeled on paragraph (2d) above and should form part of the monitoring program to be carried out by the permit holder. To the extent that IRAs within areas covered by commercial recovery permits are mined within 20 to 30 years, they will not have the permanence sought for PRAs. Studies of the type described in paragraph (2f) should begin as soon as a sound theoretical basis is developed. IRA studies should be continued long enough to assess both short-term and possible long-term impacts of mining activities. Shapes and locations of the IRAs should be designed to minimize the likelihood of null experiments (i.e., those detecting no impact).

DISCUSSION AT THE MEETING

Following introductory remarks by R. Heath, who suggested that the participants concentrate on scientific issues rather than questions of policy, organization, or specific research activities, R. Wicklund and S. Earle described the evolution of the SRA concept (see Introduction). Subsequent discussion made it clear that both the "preservational" and the "impact" aspects of SRAs are important. Formal international acceptance of the concept (even within the reciprocating states regime) does not yet exist, and it has been discussed only in the context of broader environmental questions (see Center for Law and Social Policy, 1981). There is a sense that other nations are waiting to react to a U.S. proposal.

M. Wimbush emphasized the need for effective integration of international scientific work to support the credibility of the SRA concept and to help control costs to individual countries. R. Knecht felt that the framework for such work exists in the current wording of the Draft Convention on the Law of the Sea.

Scope. P.L. 96-283 concerns the mining of deep-sea nodules. The act will have to be amended to cover polymetallic sulfides or nodules on the Blake Plateau.

As the meeting progressed, concerns over the apparent incompatability of the preservational and impact aspects of SRAs led the participants to the conclusion that the goals of P.L. 96-283 could be met only by the designation of two types of SRAs.

Preservational reference areas (PRAs). Preservational reference areas are SRAs that are far enough from mine sites to be unaffected by mining activities. In addition to preserving an area of the seabed, PRAs would provide sites for study of deep ocean processes to guide study design and data interpretation in impact reference areas. R. Carney emphasized the need to work with modelers in choosing the PRA size required for population maintenance. Models can also guide sampling strategy and allow subsets of taxa from the total fauna to be used for characterization.

M. Wimbush supported long-term current measurements as well as bottom photography (long time series) if erosion is suspected. J. Dymond added nephelometry and flux measurements to Wimbush's suggestions. J. Dymond also suggested the use of metabolic data (oxygen consumption and ATP activity) to help assess spatial and temporal variability of biological activity. J. Dymond and R. Heath both proposed the use of natural short-lived and fallout radionuclides to quantify near-surface bioturbation. R. Carney expressed concern that field surveys not place too much emphasis upon direct or indirect measures of community processes because of an inability to relate such findings to questions about specific animal populations. However, because a total faunal survey on the necessary spatial scale might prove impossible, it was suggested that a limited set of taxa might be studied. These "pet beasts" would be species that were reliably sampled and might reflect overall faunal patterns.

S. Earle emphasized the need for comprehensive biological studies (as described, for example, by P. Jumars in Appendix B). Because of their cost and the need for a stronger theoretical framework for such studies, most participants favored a measured rather than crash implementation of this approach.

Impact reference areas (IRAs). Because of the "control" aspect of IRAs, the participants felt that IRAs should adjoin or even overlap commercial recovery permit areas to minimize the effect of inherent spatial variability. C. Morgan indicated that many, if not most IRA studies might well be included in the monitoring activities that will accompany mining. R. Carney pointed out the need to assess both immediate impacts, where cause-effect relationships are likely to be obvious, and delayed (or long-term) impacts, where the chain of cause and effect may be obscure and may depend on understanding developed in PRAs for its interpretation.

M. Wimbush, J. Dymond, and C. Hollister suggested that because of initial uncertainties in plume dispersal, annular IRAs may be required around some sites to avoid the possibility of a null experiment. In general, the IRA studies should follow those proposed for PRAs.

C. Morgan expressed concern over early distinction and designation of PRAs and IRAs. He suggested deferring decisions on these issues and on size as long as possible (perhaps until the commercial recovery permit phase) so that environmental data developed by the consortia during their explorations could be used to better define SRAs.

Rationale. S. Earle pointed out that the need for SRAs extends far beyond scientific studies or mining controls. Stable reference areas should serve as "bank accounts" for the future. P.L. 96-283 provides a rationale and focus to get the designation process started. S. Earle also pointed to the rapid development of small submersibles that should greatly enhance the accessibility of the abyssal seafloor in the next decade. C. Curtis reiterated the need to protect portions of abyssal environments, which are now poorly understood.

The participants felt that the concept of limited "exploited" areas in a matrix of "preserved" ocean floor (rather than the reverse implied in P.L. 96-283) was an ideal that would be difficult to maintain in practice. The tendency would be toward continuous erosion of preserved areas.

Size of SRAs. As is clear from the Jumars paper (Appendix B), there is too little information or too few tested concepts about the deep sea to provide a sound scientific basis for choosing an optimum size for an SRA at this time. Based on an intuitive sense of the area needed to ensure protection from a mine site plume (M. Wimbush) and on the concept that SRAs should approximate commercial recovery permit areas, there was some support for initial designation of an area in the range of 20,000 km^2. This figure should be reassessed as knowledge of population theory and spatial variability of deep-sea biota expands. R. Carney pointed out that determination of an ecological basis for designating the size of SRAs should be a high-priority topic for research. Similar problems are being addressed in terrestrial ecology, and the conceptual framework might be similar. The upper bound on size is likely to be determined by a balance between environmentalist desires for the largest possible SRA and the requirement under P.L. 96-283 that "substantial withdrawal of deep seabed areas from deep seabed mining" be avoided.

Number of SRAs. Suggestions centered, arbitrarily, on either a total of ten SRAs or one SRA per commercial recovery permit area. Subsequent discussion led to a preference for at least one per "characteristic environment" in the Clarion-Clipperton region. The lack of benthic biological data will require that the number and location of provisional PRAs be specified on the basis of surface productivity and physical, geological, and geomorphological properties. C. Morgan emphasized the importance of calling on environmental expertise in the mining consortia because of the huge pool of unpublished data that they hold.

Several participants emphasized the benefits of incorporating existing detailed study sites into PRAs, if at all possible. Such sites represent a major investment of field and laboratory effort, and in some cases they provide initial data for time-series studies that go back a decade or more.

Still unclear is the extent of funding that will be available for SRA studies. To get around the difficulty of creating realistic scientific plans in such a vacuum, the participants favored development of a minimum-cost credible program to determine gross environmental, temporal, and spatial variability, as well as a comprehensive, model-based program to be focused, as it is perfected, on a few SRAs.

Because there is a statistical chance that provisional PRAs will coincide with commercial recovery permit areas based on pre-enactment license applications, a large enough number of provisional PRAs should be defined to ensure the long-term survival of at least one per characteristic environment.

Timing. Suggestions regarding the timing of SRA designations ranged from immediate designations at arbitrary locations to designations a decade or more in the future. Possibilities include the initial designation of more sites than necessary, with culling as a data base is developed. The participants preferred the position outlined by C. Curtis, which would tie PRA designations and agreement on the IRA concept to the initial negotiations of pre-enactment exploration licenses (so that the the SRA concept would be embedded in the reciprocating states regime from the start) while tying IRA designations to the award of commercial recovery permits.

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APPENDIX A: LIST OF PARTICIPANTS

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APPENDIX B

Limits in Predicting and Detecting Benthic Community Responses to Manganese Nodule Mining*

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Abstract There are severe problems both in predicting and in detecting the responses of benthic communities to manganese nodule mining. Predictions are hampered by the basic lack of natural history information for deep-sea organisms; in all but a few instances, crucial data on dietary habits, population dynamics, modes and rates of dispersal, food-web relationships, and natural successional sequences and rates are lacking. Detection is further impeded by sampling problems. Besides the obvious logistic problems encountered in sampling under miles of water, the extremely low areal densities at which most deep-sea species live enforce wide confidence limits about their estimated mean abundances. The rarest species in any deep-sea community have yet to be sampled.

Nonetheless, some predictions can be made. Animals in the path of the nodule collector will suffer high mortalities. Populations dependent upon manganese nodules as attachment substrata will be very slow to recover ($> 10^3$ yr), as will food-web members dependent on this encrusting epifauna. Mobile scavengers (i.e., fishes, amphipods,

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and shrimps) will find a new, temporary food source in the form of injured and displaced animals, but they may be forced to switch to carnivory when a given mining effort ceases. Suspension and surface deposit feeders will be most heavily impacted by mining-induced resuspension and redeposition, the extent of this effect depending on the (unknown) food value of the resuspended material. Substantial narrowing of uncertainty in mining effects, however, will require continuing iteration among predictive ecological modeling, *in situ* experimentation, and carefully designed monitoring of actual, full-scale mining operations.

The aim of this paper is, within the realm of conceivable impacts of manganese nodule mining, to identify the somewhat smaller region of likely responses within deep-sea benthic communities. From the outset, I will set the limits of resolution at the level of effects leading to the appearance or disappearance of individuals, to actual changes in community composition. Physiological changes that are not likely to lead to altered population birth or mortality rates will not be addressed. I hope to make two problems apparent: one is the shortage of verified theory concerning deep-sea community structure, and the other is the imprecision with which deep-sea community spatial structure and changes in it have been and can be measured. To accomplish these goals within a limited space, I will draw freely upon several recent, more specialized, yet more comprehensive reviews. Rather than redescribing the biota of the DOMES area, I will rely on the extensive baseline of Hecker and Paul (1979). Pertinent theory regarding the mechanisms controlling deep-sea community structure will be abstracted from Jumars and Gallagher (1981), while conclusions about spatial structure and sampling variability within deep-sea communities will be extracted from Jumars and Eckman (1981). Comments on conservation strategies largely will reflect the landmark collection on this topic by Soulé and Wilcox (1980), although opinions on optimal procedures are far from unanimous.

While the lack of verified theory and of data on deep-sea community structure is serious, it does permit straightforward presentation of this chapter. In a "connect-the-dots" approach to outlining the likely outcomes of mining, I will simply present contrasting scenarios of likely results. Following the more detailed, and less specific to manganese nodule mining, approach of Jumars and Gallagher (1981), I will choose dots or pairs of dots at the individual, population, and community levels of ecological organization. I sincerely hope that neither member of the respective pairs will be extracted from context and considered alone. If the approach is sound, it will serve to box in the effects that require controlled experimentation and monitoring as mining proceeds. The size of the box alone attests that monitoring and experimentation will be needed to determine where (hopefully) within this figure the truth will lie.

I will endeavor not to make value judgments, but policymakers may find it difficult to form such evaluations without familiarizing themselves with the kinds of organisms that frequent the deep sea. Contrary to the plates in volumes describing early voyages of discovery, the numerically dominant members of the deep-sea benthic community are tiny (a few millimeters or less in length) nematode and polychaete worms and test-building protozoans (Foraminifera) of varying sizes (but again mostly smaller than a few millimeters in diameter). Most of these animals inhabit the uppermost centimeter of deep-sea sediments. More thorough and less diminutive illustrated descriptions can be found in Gage (1978), Grassle (1978), Hessler (1972), Hessler and Jumars (1974), and Jumars and Gallagher (1981). Many of the surprisingly numerous species are as yet not even described, much less well known; so that it clearly is impossible to estimate how valuable these organisms might someday become, for example as sources of natural pharmaceuticals (e.g., the once nearly worthless horseshoe crab) or as model systems for addressing scientifically and medically important questions (as sea urchins have been in studying fertilization and early embryonic development). Because the smaller species (meiofauna and microbiota) are so poorly known, I will limit my discussion to those species that are (if only barely) visible to the naked eye (i.e., macrofauna and megafauna).

Because the questions of tightness of organization and interdependency of the various components of communities are still matters of debate, even for much more accessible communities (e.g., Levin, 1975), it is worth attempting prediction of several levels of ecological organization. The truth falls somewhere between the extreme view that a community can be understood simply by summing the behaviors of its smallest component parts (individuals, at the aforementioned level of resolution) and the opposing view that the interactions among these parts are so strong that communities can be understood only by studying the whole. Numerical abundances given below, unless otherwise stated, are quoted from the extensive baseline studies of Hecker and Paul (1979) in the DOMES region. Mining rates are taken from Ozturgut *et al.* (1981, Appendix).

Likely Impacts

Individual Level

It is hardly worth arguing about the fate of individuals directly in the path of the nodule collector. Those that are not killed outright by the fluid shear produced in the dredge or by the combination of abrasion and temperature rise in traveling up the pipe will be ejected helter-skelter with sediments in the near-bottom plume. Technical difficulties, including ones of experimental design, would argue against attempting to monitor whether mortality amounts to 95% or 99.999% of the total individuals taken. With 168 (macrofaunal) individuals per m^2 and assuming 100% mortality, that amounts to 3.36×10^3 individuals per second, 2.9×10^8 per day, or 1.06×10^{11} individuals per mining ship per year. At roughly 0.3 g of wet weight per m^2, that equates with 1×10^8 g per year.

From this point, predictions become decidedly less precise. Impacts on individuals outside the collector zone surely will depend upon the guild to which they belong—upon their life-styles. (An ecological guild is defined as a group of species that utilizes the same resource in similar ways.) Specifically, impacts on swimming scavengers, walking–crawling scavengers, surface deposit feeders, subsurface deposit feeders, and suspension feeders are likely to differ.

The scavengers are the most active lot, and the fishes, shrimps, and larger lysianassid amphipods are likely to be able to avoid local regions of high redeposition rates and high turbidity. The non-swimming scavengers observed to date are among the larger benthos, so we might expect them to be relatively immune from mortality due to burial. Both kinds of scavengers are likely to experience a short-term increase in rate of food supply in the form of animals injured by mining, with the swimming forms obviously being first to arrive at the windfall.

Subsurface deposit feeders are likely to be the least affected of all feeding guilds on the short term because of their relative isolation from resedimentation effects. Presumably they are dependent upon continued bacterial growth for their food, and it is not known how subsurface bacterial growth will vary as a function of time and thickness of the overlying resedimented layer. Because of the low standing stocks of animals, the scavenger activity, and the high concentration of oxygen in bottom water, there seems to be little opportunity for anaerobic conditions to develop, even for the subsurface dwellers; no mass mortality due to anoxia is anticipated.

Surface deposit feeders and suspension feeders, on the other hand, will be affected much sooner and perhaps in similar ways. The rate of supply of surface deposits and of suspended material certainly will be increased, but its net food value is likely to be altered substantially over the normal surface deposit and suspended load. Very little is known about the organic chemistry of deep-sea clays under deep-sea conditions, but adsorption of materials onto suspended clays may be a major effect (e.g., Moore, 1977). If the average food value of these resuspended and redeposited particulates is still lower than that of their normal supplies, then the net rate of energy gain to members of surface deposit-feeding and suspension-feeding guilds is likely to fall. It is conceivable, alternatively, that the net rate of energy gain within these guilds might be increased if, during resuspension, the clays chemically scavenge sufficient organic matter from the overlying water.

Assuming no fatality beyond the collector path, Figure 1 summarizes these predictions of net rates of energy gain by individuals within various guilds. How likely is fatality? If net rate of energy gain falls below maintenance levels for an appreciable period, mortality would result. I find little basis for predicting the actual time scales in Figure 1, except that suspension feeders will be affected only so long as the cloud of resuspended material remains in their vicinity or so long as their feeding mechanism remains affected. Deep-sea suspension feeders are likely to be especially sensitive to clogging of their filtration apparatus, which after all has evolved to operate at ambient suspensate levels of a few micrograms per liter; even 20 km from the mining site, suspensate levels may rise by two orders of magnitude (Ozturgut *et al.*, 1981).

Burial under a few centimeters of sediment may seem and be innocuous enough to one accustomed both to the large amounts of sediment transport and to the strong burrowers often seen in the intertidal. Most

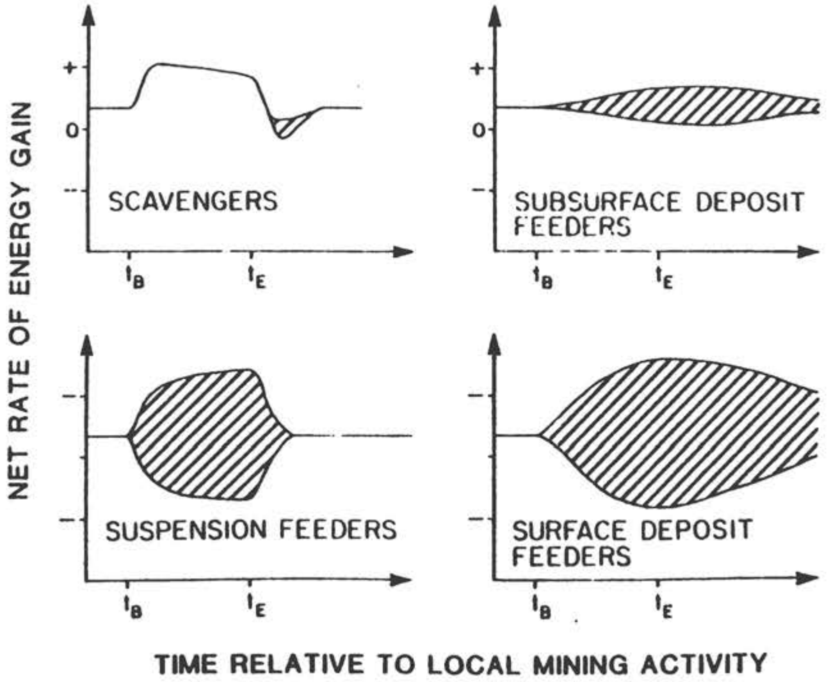

FIGURE 1. Crude predictions of net rate of energy gain as a function of time by feeding guild for those individuals (as opposed to populations) not suffering immediate mortality from mining effects. t_B: local mining begins; t_E: local mining ends; shaded area: major region of uncertainty in predictions. Predictions at the level of numerical responses of populations are more difficult.

deep-sea animals living near the sediment–water interface of nodule fields have limited burrowing abilities, however, because sedimentation proceeds at rates of millimeters per 10^3 yr. In an accidental burial of a small region (~ 10 m^2) of a bathyal community living at 1,200 m (where sedimentation rates are roughly 10 cm per 10^3 yr), for example, I have observed substantial mortality (unpublished observations of an unsuccessful particle tracer experiment attempted during Expedition Quagmire; Thiel and Hessler, 1974) of numerous sedentary animals after only one day's burial. Suspension feeders were too rare to be censused with adequate statistical precision, but most of the mortality was evident (as autolysis or bacterial decay) in surface deposit feeders. Although linear extrapolation is hazardous at best, these results suggest that burial depths of millimeters may cause substantial mortality among the faunas of the DOMES area. For animals adapted to feeding at the sediment–water interface, it is conceivable that burial of their normal food resources under a millimeter or less might be critical, depending on the time scale over which these food resources recover. The sessile suspension feeders attached to nodules are likely to be the most severely affected, however, even by an exceedingly thin veneer of sediments.

Population Level

Two extreme views are tenable at the population level. One of them may prove true generally, or each may hold for some subset of the populations encountered. The most optimistic view would hold that little mortality would ensue outside the collector tracks, so that in a year some 170 km^2 of the 30-km by 30-km mining claim would remain inhabited by members of the population. If they were not completely sessile, these survivors would begin to diffuse to produce something like 80% of their initial areal density. (A majority of abyssal species seem to be slowly moving deposit feeders; Hecker and Paul, 1979; Hessler and Jumars, 1974.) If this density is high enough for reproductive success, recruitment will complement the diffusive recovery. If, on the other hand, the population were completely eliminated within the mining claim and for some distance outside it, recruitment to the center of the site would require either many generations of slow, diffusion-like movement or some more rapid means of adult, juvenile, or larval dispersal. Given the seemingly low dispersal abilities of the majority of deep-sea species, this case likely would resemble the slow healing of a deep wound, while the more optimistic first case would be more like the healing of a series of scratches.

To carry this metaphor perhaps too far, both cases are likely to result in "infection" by opportunistic species. Within months, azoic sediments placed on the sea floor in the deep sea are colonized by populations with high dispersal abilities. In the two experimental programs whose results have been published to date (Grassle, 1978; Desbruyères *et al.*, 1980), the most spectacularly successful initial colonists are species that are either absent or very rare in the ambient, undisturbed community.

It is thus reasonable to anticipate a strong, mining-produced selection for high dispersal abilities, coupled with relatively rapid reproductive rates, to fill the gaps produced by the tracks or by the combination of tracks plus resedimentation. In essence, one expects a suite of weed species to recruit to, and to evolve with, the mining activity. Beyond the edges of the mining site, however, selection may favor rather different life-history tactics. Suppose, for example, that the resedimentation near the periphery causes greater or more variable mortality in larvae and juveniles than in adults. Jumars and Gallagher (1981) summarize a simple stochastic model which suggests that, under such circumstances, selection will act to lengthen the less susceptible adult life stage and to lead toward multiple reproductive events (iteroparity), features normally not associated with populations of stressed or disturbed habitats.

Besides varying with proximity to the disturbance, population responses probably will also depend on the feeding guilds under consideration. I already have mentioned the rapid functional response of scavengers to deep-sea windfalls. Especially because of the relative continuity of this new food resource, mining is likely to result in a numerical (reproductive) response as well. Given the high motility of many deep-sea scavengers, though, this numerical response may be especially difficult to resolve from pure attraction. But what will these locally elevated (in abundance) populations do when mining ceases? For energetic reasons suggested by Jumars and Gallagher (1981), this guild is likely to be comprised of generalists which may survive by a combination of dispersal and carnivory when mining ceases.

Much less likely to be so malleable are the populations dependent on nodule-associated microhabitats for their existence (e.g., Bernstein *et* *al.*, 1978). Most obviously, the fouling community of nodule surfaces will probably suffer most and longest. Simply because of the slow growth rates of deep-sea manganese nodules and the fact that nodules will be both removed and buried, these populations are unlikely to recover to natural levels in less than 10^4 yr. Time scales for recovery of other populations cannot be predicted because generation times of nearly all deep-sea species are unknown.

Community Level

Implicit in many of the above population-level effects is the potential for interpopulation interactions. Will the scavengers have substantial predatory impacts on particular prey populations after the source of easier game is removed? Will subsequent invasion of the newly opened territory be facilitated, unaffected, or impeded by the initial colonists (Connell and Slatyer, 1977)? If populations of suspension and surface deposit feeders are reduced, will burrowing deposit feeders encroach on food resources that would have been taken by these two guilds? Very basic natural history information is needed to answer these questions regarding the precise nature of the resources now used by suspension and deposit feeders and the identity of existing predatory–prey links. These data are missing for all deep-sea areas.

The value of this lacking information can be seen by analogy with the diverse communities of tropical rain forest, where at least part of such information has been collected. Gilbert (1980, p. 32), for example, finds that "The system consists of many parallel, structurally similar but taxonomically different, food webs based on particular groups of plants." Similar organization also seems likely in the deep sea, and while it may seem reasonable to predict that predators dependent upon nodule-associated prey will be impacted seriously, this prediction is vitiated because the predators have not been identified, and thus their abilities to utilize alternate prey are completely unknown.

A theme reiterated throughout the anthology by Soulé and Wilcox (1980), *Conservation Biology*, is the need to know the sources, rates, and intensities of natural disturbances in order to predict and manipulate the effects of anthropogenic disturbances. Further, the less similar are these two types of disturbances (if the more frequent and severe type is anthropogenic), the more severe will be the effects of the man-made variety. No natural disturbance of the magnitude to be produced by full-scale mining has been identified for communities of geologically stable mid-ocean regions; all conceivable natural disturbances are much smaller in spatial scale (Jumars and Eckman, 1981) and presumably are less intense.

There is no validity whatsoever, then, in examining community structure and life-history tactics of communities that are exposed relatively frequently to major disturbances such as turbidity flows and using them (Gerard, 1976) to predict the short-term consequences of nodule mining. The comparison is just as ludicrous as suggesting that tropical rain forest will respond to a blizzard in the same way as will tundra. If mining continues at an appreciable rate, selection may lead in the direction followed in areas where turbidity flows are frequent and severe, but this would be a long-term (evolutionary time scale) prediction. Even on this longer time scale, the analogy is imprecise because any one mining plot likely will be mined only once and because the native sediments of nodule areas and continental margins (where turbidity flows are more common) differ substantially.

The events following mining also are difficult to put into the context of the most recent synthesis of successional theory (Connell and Slatyer, 1977). Beyond the suggestion (above) that opportunists will recruit to the mined region within one or a few months, neither the time scales nor the specific directions of succession can be predicted. The initial colonists may alter environmental conditions (e.g., effective sediment porosity and permeability), either accelerating or impeding subsequent colonization, and the initial colonists may be removed via predation, competition, or their own modifications of the sediments. No deep-sea colonization experiments reported have yet shown close approach to the ambient community composition. Given the apparently long lifetime of some deep-sea, sediment-dwelling species (e.g., Turekian *et al.*, 1975), such nearly complete recovery would take decades to tens of decades. Again, simply because of the slow growth rates of nodules, any community components dependent directly or indirectly upon nodules would take more than 10^3 years to begin approaching natural abundance levels in the area of the collector track.

A wide variety of theories dealing with succession and (dynamic) equilibrium community composition lead to similar predictions (Figure 1) concerning the relation of species diversity with the frequency and intensity of disturbance. Both of the two extreme Markov models presented by Jumars and Gallagher (1981), for example, predict a relationship like that of Figure 2. While it seems likely, especially given removal of the nodule microhabitat, that mining at the proposed levels will drive the curve toward the lower diversities of its right-hand tail, the position of the natural community along the abscissa is unknown. Extant theories (Jumars and Gallagher, 1981) differ substantially in the importance, frequency, and intensity they ascribe to such natural disturbances as predation and windfalls of food.

It is possible, then, that some low level of mining activity might actually increase species diversity on an appropriately measured spatial scale. The simplest such scenario is that in which opportunistic species (new to the local community) take up residence in the tracks of the dredge, and the community outside the tracks is unaffected, increasing local community diversity by the difference between the number of new opportunistic community members and the (small) number of species that chanced to be present locally only in the path of the dredge. Considering the magnitude of the disturbance (relative to natural ones), a much more likely scenario, however, involves a dramatic local decrease in species diversity. Besides the obvious disturbance effect (viz., Figure 2), a correlate and possible cause of high deep-sea species diversity is small-scale environmental heterogeneity (e.g., tubes and burrows) created by the animals themselves (Jumars and Gallagher, 1981). The net effect of nodule removal and burial of the surrounding bottom of resedimenting clay would almost surely be to make the new environment more homogeneous on these smaller spatial scales.

Extrapolation to Multiple Mining Sites

Implicit in all the above predictions is their limitation to a single mining site approximately 30 km by 30 km in area, mined for a topical mining year (estimated at 300 days). The impossibility of extrapolating these predictions with any set accuracy to multiple mining sites needs to be pointed out. The ability to make analogous extrapolations is just now being approached in the obviously much better known forest ecosystems through successional models (summarized by Shugart and West, 1980). Such models are heavily dependent upon detailed autecological information—detail unavailable in the deep sea.

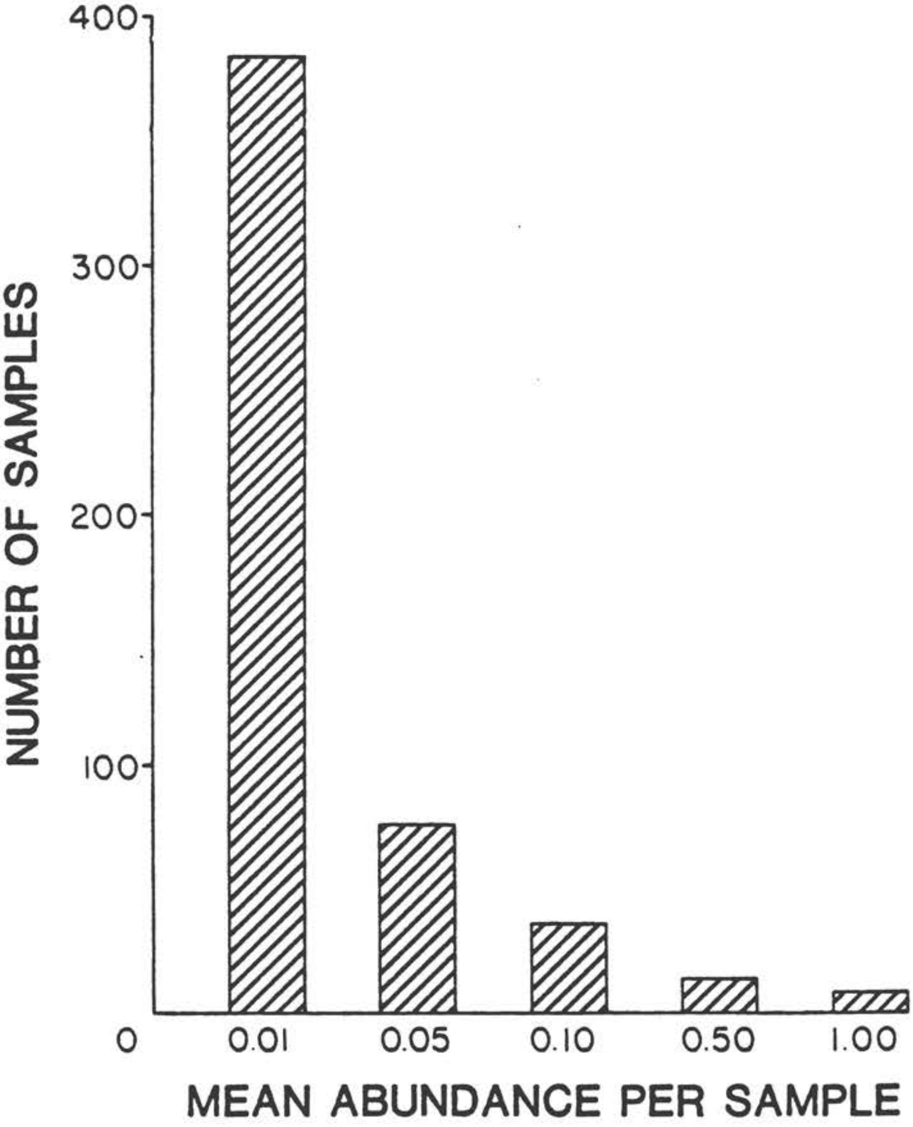

FIGURE 2. General predictions from a wide diversity of models (e.g., Horn, 1975; Huston, 1979; Levin and Paine, 1975) concerning the species diversity likely to result from different rates of mortality-causing disturbances. Without manipulations (cf. Paine, 1977) such as carefully monitored mining, the position of natural deep-sea communities along the abscissa will remain unknown.

One concern that already has surfaced is over the potential extinction of deep-sea populations and species at some (perhaps unrealistically high, but unknown) level of mining activity, and the suggestion has been made that some spatial and temporal patterns of mining would minimize the likelihood of extinction. Terborgh and Winter (1980), in their review of the causes of extinction in better studied systems, point to fragmentation, isolation of one part of a population from others, as a major cause of extinction. Assuming that a mined area does form an appreciable barrier for normal dispersal of at least some populations, the worst mining pattern would thus be one that would cut a more or less continuous, wide swath through the deep-sea habitat. Without more autecological information (e.g., on dispersal abilities of deep-sea species), however, the ecologically optimal mining pattern defies prediction.

Detection of Impacts

The specter of extinction of deep-sea populations carries with it its own "Catch 22" insofar as detection is concerned. Despite extensive and intensive sampling at the various DOMES sites (Hecker and Paul, 1979; Jumars and Self, unpublished), the point at which further sampling would yield few additional species has not been reached at any site within the DOMES region. It is precisely those species that have not yet been sampled which would be predicted to be most extinction prone since, "Rarity proves to be the best index of vulnerability" (Terborgh and Winter, 1980, p. 132). These rare species and their changing abundances with time and with mining activity could not be detected without monumental increases in sampling effort.

Nor will reductions even in those populations that have been sampled be easy to detect. The largest practicable, quantitative samples now taken from the deep sea are 50 cm by 50 cm (0.25 m^2). Once the samples are retrieved and processed on shipboard, it requires roughly one person-month of microscopic sorting just to separate the animals from residual sediments in a single sample. Assuming (optimistically) a random (i.e., Poisson) distribution of individuals among samples, Figure 3 shows how many samples would be required to give reasonable certainty ($P \geqslant 0.95$) of detecting the most severe impact possible—complete mortality of the local population. It is virtually certain (Hecker

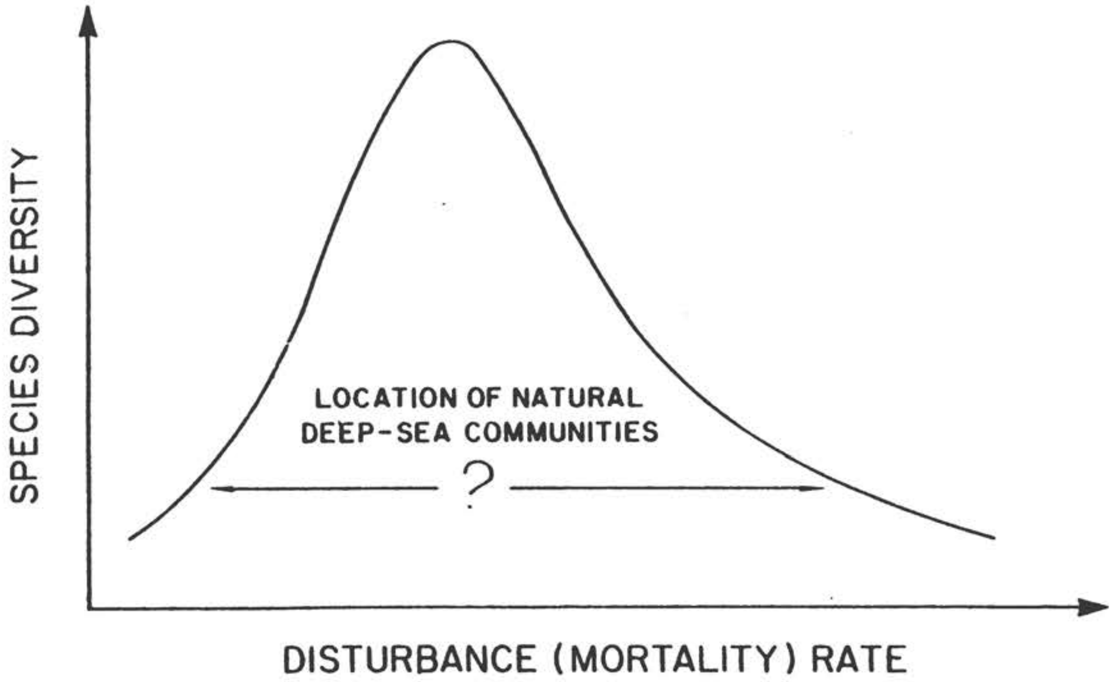

FIGURE 3. The number of 0.25-m^2 samples required to be reasonably certain of detecting any effect when the population has been decimated entirely (i.e., no individuals are found in any sample) versus natural mean abundance per sample. The χ^2 test of goodness-of-fit to a theoretical Poisson distribution with the specified mean was used to generate the figure, so that the estimates provide reasonable minima (cf. Jumars and Eckman, 1981). Most abyssal populations have mean densities below 0.05 individuals per 0.25-m^2 sample, making monitoring at the single population level generally impractical.

and Paul, 1979; Jumars and Self, unpublished) that most species in the DOMES region have mean abundances of fewer than 0.05 individuals per sample (< 0.20 individuals per m^2).

With the outlook so bleak for detecting impacts at the single-species level, monitoring will be practical only at the level of guilds or larger groupings, and one might ask what magnitude of impact could be detected for the fauna as a whole (i.e., the best case). Using total observed faunal abundance per sample within a 20-km by 20-km area at DOMES site A and employing the actual variance observed in that parameter (Jumars and Self, unpublished), the question can be answered relatively precisely. With a (manageable) sample size of 20 0.25-m^2 cores, total faunal abundance changes in excess of 50% over the entire sampling region would be necessary to assure ($P \geq 0.95$) detection of the impact, even in this grossest indicator of community condition.

Conclusions

These figures argue against placing great expectations in the results of routine monitoring efforts aimed at evaluating mining impacts. Even relatively large impacts can easily go undetected via traditional before–after comparisons based on random sampling via a surface vessel. This imprecision in sampling estimates is further coupled with the additional imprecision (and potential inaccuracy) of the above predictions; the theories used to make those predictions have not yet been verified in a deep-sea context.

The major reasons behind these problems are easier to identify than are the solutions. First, organisms are extremely sparse, aggravating the already major difficulties in the sheer mechanics of retrieving reliable bottom samples from several kilometers of water. This rarity sets definite limits on sampling precision (cf. Figure 3). Secondly, crucial data are lacking for the DOMES region as well as for other deep-sea areas. For example, generation times, predator–prey relationships, and both qualitative food requirements and feeding rates of deposit and suspension feeders are all but unknown for the animals living on this major fraction of the earth's surface.

No one approach is likely to bring deep-sea ecology quickly to the point where impact predictions can be as accurate and precise as they are in the longer, more thoroughly studied, and more accessible terrestrial ecosystems (e.g., Shugart and West, 1980). However, the most rapid and sure approach to this sort of knowledge is through iteration between theories and manipulative experiments (Paine, 1977); an accelerated program to couple the collection of essential natural history information with controlled experimentation in an accessible deep-sea environment is surely needed. Because of the low population densities, high species diversities, and low population growth rates which characterize the deep sea, however, this coupling will not be complete before full-scale manganese nodule mining begins. The obvious challenge, then, is to develop both theories and monitoring schemes which make efficient use of the manipulative experiment provided by manganese nodule mining itself.

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