1994

Benthic marine pollution around McMurdo Station, Antarctica : patterns of chemical contamination, invertebrate communities, and toxic responses

Hunter S. Lenihan
San Jose State University

Recommended Citation
Lenihan, Hunter S., "Benthic marine pollution around McMurdo Station, Antarctica : patterns of chemical contamination, invertebrate communities, and toxic responses" (1994). *Master's Theses*. 847.
DOI: https://doi.org/10.31979/etd.h83p-a55f
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Benthic marine pollution around McMurdo Station, Antarctica: Patterns of chemical contamination, invertebrate communities, and toxic responses

Lenihan, Hunter Stanton, M.S.

San Jose State University, 1994

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BENTHIC MARINE POLLUTION AROUND MCMURDO STATION, ANTARCTICA: PATTERNS OF CHEMICAL CONTAMINATION, INVERTEBRATE COMMUNITIES, AND TOXIC RESPONSES

A Thesis Presented to
The Faculty of Moss Landing Marine Laboratories
San Jose State University

In Partial Fulfillment
of the Requirments for the Degree
Master of Science

by
Hunter S. Lenihan
August, 1994

Approved for Moss Landing Marine Laboratories

Ken Johnson

Dr. Ken Johnson

James Nybakken

Dr. James Nybakken

John Oliver

Dr. John Oliver

Approved for the University

Serena W. Stanford

ABSTRACT

BENTHIC MARINE POLLUTION AROUND MCMURDO STATION, ANTARCTICA: PATTERNS OF CHEMICAL CONTAMINATION, INVERTEBRATE COMMUNITIES, AND TOXIC RESPONSES

by Hunter S. Lenihan

This thesis documents the presence and biological impact of anthropogenic chemical contamination in the marine benthic environment at McMurdo Station, Antarctica. Sampling and field experiments were conducted from 1975 to 1991 to test (1) how the structure of benthic invertebrate communities around McMurdo Station varied with levels of chemical contaminants in marine sediments, (2) if similarities existed between communities disturbed by chemicals and those by natural ice phenomena, and (3) if survivorship and behavior of infauna differed when exposed to sediments from around the station.

Benthic communities changed radically along a steep gradient of anthropogenic hydrocarbons, metals, and PCBs. Communities in highly contaminated locations and ice-disturbed areas resembled one another and those observed in oil contaminated areas in temperate latitudes. Results of survival and behavioral bioassay experiments revealed (1) similarities across a suite of species, (2) that contaminated sites were highly toxic, and (3) that behavior (e.g., burial and escape) helped explain patterns of natural community structure.

ABSTRACT

Marine benthic sediments and invertebrate communities were highly modified by human activities at McMurdo Station, Antarctica. Sediment samples for chemistry and physical properties, cores samples for infauna, and photographs for epifauna were taken along a spatial gradient around the station. Changes in infaunal communities patterns along the spatial gradient were compared with those within two natural ice disturbances, anchor ice uplift and iceberg scour. The results of standard toxicity bioassays using amphipods were compared with patterns of survival and behavior exhibited by various invertebrate species in laboratory and field experiments. Abundant and species rich infaunal communities were transplanted to contaminated and uncontaminated sites and exposed for one year. Benthic communities changed radically along a steep gradient of anthropogenic hydrocarbons, metals, and PCBs. Communities in highly contaminated sites and those in ice-disturbed areas contained similar species, all with opportunistic life histories. Amphipods had low survivorship when exposed to highly contaminated sediments in the standard bioassays but field experiments showed no significant pattern. The results of the many survival and behavioral experiments supported those of the standard bioassays and help explain community patterns along the pollution gradient.

INTRODUCTION

This document provides a quantitative analysis of marine pollution and its biological effects at McMurdo Station, Antarctica, the largest human settlement on the continent. The levels and sources of contamination to the marine benthos, the resulting changes in benthic invertebrate communities, and the toxicity of sediments were determined through a sampling and experimental program conducted in 1988-92. Some data were collected by J.S. Oliver in 1974-83. This project was funded by the National Science Foundation as an ongoing effort to document the results of poor environmental management practiced by the United States Antarctic Program and Navy at McMurdo Station over the last 30 years. The results of this research program are presented in three chapters, each representing a separate set of experiments, each to be published in scientific journals as separate manuscripts. The first chapter describes patterns of chemical contamination at McMurdo Station, the second, changes in community patterns along a spatial gradient of contamination, and the third, results of a suite of toxicity bioassay experiments. Chapter one* and two** are published and three*** is in peer review. The abstracts of each manuscript have been condensed into one. Each chapter contains its own introduction, methods, results, discussion, figures, tables, and bibliographies.

* Published in Marine Pollution Bulletin (Volume 21 (9): 422-430, 1990)

** Submitted to Ecological Applications (in press)

*** Submitted to Journal of Experimental Marine Biology and Ecology

ACKNOWLEDGMENTS

I thank my advisor and friend John S. Oliver, the galactic wizard. He taught me to live my dreams, recognize my strengths and weaknesses, and showed me a great deal of this planet. Praises to Peter Slattery, James Oakden, and Rikk Kvitek for their teaching, patience, good humor, and many travels. Much appreciation goes to Ken Johnson for introducing me to marine chemistry and for listening and to James Nybakken for exposing the world of marine invertebrates. A hearty thank you to Michael Foster for many laughs and teaching me to be more thorough and rigorous. Thank you Mark Stephenson for good advice, support, and use of analytic facilities.

A special appreciation to my fellow students at Moss Landing Marine Laboratories who leave the fondest memories, especially but not exclusively; Stacy Kim, Kim Burdett, Cary Bretz, Kim Kiest, Eric Johnson, Dan Bockus, Rusty Fairey, Kim Paulsen, Gary Ichikawa, John Goetzl, Patience Brown, John Mason, Tom Norris, and Tom Oakey. Thank you with love to Cassandra Roberts for support and warmth. Thank you to Fiorenza Micheli for your constructive criticism. The assistance I received from my peers in the field, classroom, and laboratory made work possible and more joyous.

Thanks to the staff of Moss Landing Marine Laboratories who helped me clear the many hurdles of graduate school; Sheila Balderidge, Sandy Yarbrough, Irene Cheung, Gail Johnston, and Sandy O'Niel. You are the most cheerful and competent staff at any institution. Thank you Ralph, Larry, and Aldo for your skills and jokes.

My greatest appreciation goes to my friend Brenda Konar who supported me in work,

through the hardest and best of times, and shared many great adventures. Thank you to my family for love and support. Thank you also to John Martin for laughing with and at me, your spirit will never fade.

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Chapter 1

INTENSE AND LOCALIZED BENTHIC MARINE POLLUTION AROUND MCMURDO STATION, ANTARCTICA

INTRODUCTION

Antarctica is the least inhabited continent and thus the least impacted by human activities. This is certainly true for nearshore benthic habitats and communities. As a result, the source of much chemical contaminants is from atmospheric drift (Risebrough 1977). However, significant chemical contamination of marine environments has been documented around some human settlements (Platt & Mackie 1979; Clarke & Law 1981), as well as observable impacts to benthic communities (Dayton & Robilliard 1971; Dayton 1972). Nevertheless, little is known about how antarctic benthic communities respond to anthropogenic disturbances.

The patterns of benthic contamination and community change have not been quantified from a single Antarctic area, except at South Georgia Island, where the evidence of impacts from past human activities is weak and equivocal (Platt 1978, 1979b). Although a pattern of community recovery is presumed, it is not documented (Platt 1978, 1979). Little sediment contamination is present and no community patterns are clearly related to anthropogenic disturbance (Platt 1978, 1979). Major conclusions of this early work have been seriously questioned (Clarke & Law 1981).

The present study describes the contamination of marine sediments and general changes in benthic communities around the largest human settlement in Antarctica, McMurdo Station. It is part of a companion study of trace hydrocarbons (Risebrough et al. 1990), a larger study of community disturbance (Chapter 2 of this volume), and study of sediment toxicity using bioassay experiments (Chapter 3). Preliminary observations indicate severe nearshore pollution and a steep gradient of contamination and community change from Winter Quarters Bay (Dayton & Robilliard 1971; Dayton 1972). The impacted areas are surrounded by some of the richest (total density and species number) benthic communities in the world (Dayton et al. 1969, 1970, 1974; Dayton & Oliver 1977; Oliver & Slattery 1985). Since recent pollution cleanup and abatement may initiate a unique experiment in community recovery in one of the most extreme environments in the world, the present study also establishes a baseline for exploring the recovery process.

METHODS

Site selection

Nineteen sampling stations were selected in relation to past and present human activities around McMurdo Station (Figure 1). These disturbances were most intense around Winter Quarters Bay (Figure 1), where until 1988 the primary station dump was located, ice breakers and cargo ships dock, and local runoff from the station is highest. The bay is also surrounded by many large fuel tanks, a few of which have leaked small amounts of gasoline which may have reached the bay. The station's only sewer outfall is located at the mouth of the bay (Figure 1), where raw sewage is discharged at the sea surface. A smaller sewage outfall once emptied near the VXE-6 facilities, but it now enters the main sewage system. Other past disturbance activities involve construction at the sea water intake jetty, moving rock on the sea ice to maintain the ice road from the station, and periodic dumping of debris along the entire shoreline bordering the station (Figure 1).

During preliminary dives, a general gradient of human disturbance was observed with the most pronounced disturbance occurring inside Winter Quarters Bay and decreasing with distance from the bay. Human disturbance was indicated mainly by the presence of debris such as leaking 55 gallon drums scattered on the seafloor . Three transects were established along this general disturbance gradient. Two were along the main axis of the bay from the head to the mouth at water depths of 24 and 18 m (Figure 1). Each contained four sampling stations. The 18 m transect was along the top of a submarine ridge bordering the east side of the bay. The 24 m transect was along the floor of the valley formed by the submarine sill and Hut Point. The third transect (18 m depth) was a series of stations along the shoreline from the outfall (nearest the bay) to Cape Armitage (furthest from the bay) (Figure 1). A deep (33.5 m) and shallow (9 m) station were also sampled at the back of Winter Quarters Bay, forming a depth transect (9m-1,18m-1, 24m-1, 33.5 m-1) through the area of greatest human disturbance (Figure 1). Finally, sampling stations were established in three soft-bottom habitats (Reference sites) at much greater distances from McMurdo Station and thus not directly influenced by human activities. Cinder Cones is 9 km, Turtle Rock 15 km, and Marble Point 90 km from the station (Figure 1). These are some of the few soft-bottom habitats in McMurdo Sound that are comparable (similar water depth, sediment, and fauna) to sites around the station.

Field sampling

All sampling was done by divers using SCUBA in November, 1988. Sampling sites were located by drilling a small hole (10 cm diameter) in the sea ice and measuring water depth with a weighted line. At appropriate water depths, a diving hole (1.3 m diameter) was drilled with a mobile drill rig. Divers observed bottom topography, anthropogenic debris, and faunal patterns through exploratory ice holes, and positioned final diving holes over stations along the sampling transects, where physical, chemical, and biological patterns were quantified. Preliminary observations of potential sampling locations are essential to the selection of comparable substrata (i.e., avoidance of gross differences in slope, depth and sediment type) and benthic communities.

Physical and chemical analysis of sediments were determined from haphazardly (sensu Fager, 1968) selected surface scrape samples (top 5 cm). A single sediment sample was used for physical analyses; 3 replicate samples were used for trace metal levels. Due to expensive analytical cost a single sample was used for hydrocarbon levels excluding the 24 m stations where 3 replicate samples were analyzed. Sediments analyzed for grain size and % organic carbon and nitrogen were collected in glass jars (500 ml). Surface scrape samples analyzed for heavy metals and hydrocarbons were collected in Ichem jars (also 500 ml) with teflon lid-liners. Prior to use, all collection jars were washed in HCl and, for organic analysis, with petroleum ether. All sampling jars were taken unopened through the water column, opened at the bottom, filled with sample, resealed, and brought to the surface. Samples for hydrocarbons and heavy metals were frozen at -4 °C upon return from the field. Samples taken for grain size and % carbon and % nitrogen were refrigerated.

Tissue samples for trace metals were taken from fish, Trematomus hansoni and T. bernacchiii, and a nemertean worm, Parbolasia corrugatus. These animals were hand caught on the sea floor, placed in game bags, and brought to the surface. They were immediately placed in aluminium foil that had been ashed for 12 hours at 550 °C. Ashing is conducted to eliminate organic carbon contaminants Tissue samples were then frozen at -4 °C.

Total number of infauna were quantified from core samples (0.0075 m^2) taken from the top 10 cm of sediment. Six infaunal cores were haphazardly selected at each station. Samples were washed over a 0.5 mm mesh screen and residues preserved in a 4% solution of formaldehyde. The percent of anthropogenic debris covering the seafloor was determined in 1 m^2 photographs taken along two 10 m transect lines (calibrated each 1 m) haphazardly placed at each station.

Laboratory analyses

Grain size of sediments was determined with a Sieve/Hydrometer method. For analysis of % organic carbon, 0.1 g subsamples of sediment were burned in a Control Equipment 240 Analyzer to obtain a measure of total carbon. A subsequent 0.1 g subsample was acidified with 6M HCL, allowed to effervesce until completion, and the residue was measured with the elemental analyzer. Organic carbon was estimated as the difference between the unacidified and acidified subsamples and the value reported as % dry weight of sediment. For analysis of % organic nitrogen, 0.1 g subsamples were burned in the elemental analyzer and the values reported as % dry weight of sediment.

Hydrocarbons in sediments were extracted using a purge-and-trap procedure (U.S.E.P.A. Method 5030), and a Hewlet-Packard 5890-5970 Gas Chromatograph/Mass Spectrometer (following U.S.E.P.A. Method 8240). Hydrocarbon values reported here are Total Purgeable Hydrocarbons and represent gasoline, kerosine, and naphthalene compounds (a mixture of C_5 to C_{12} aliphatic and aromatic hydrocarbons) with boiling points below 200 °C.

Sediments analyzed for Ag, Al, Cd, Cu, Pb, and Zn were digested in the following method. Each replicate sediment sample was mixed with a Titanium blade and a 1.0 g (wet weight) aliquot was placed in a 30 ml beaker. This subsample was dried at 60 °C. After 48 hours, 5 ml concentrated HNO_3 (all HNO_3 was quartz distilled) was added and the mixture was heated at 200 °C for 1 hour. This solution was evaporated to 0.5 ml and 20 ml of HNO_3 was added; the extract was transfered to a polyethylene bottle. Levels of mercury in sediments were analyzed using a Flameless Perkin-Elmer 2280 Atomic Absorption

Spectrometer (A.A.S.) (Stainton, 1971). Heavy metals excluding Hg were analyzed using a Graphite Furnace Perkin-Elmer 3030 A.A.S.

Tissue samples were analyzed for trace metals by homogenizing 1.0 g subsamples of fish muscle and liver tissue, and nemertean worm body tissue following the procedures used in the analyses of sediment metals. All glasswear was acid cleaned for a minimum of 3 days in 50% HCl and samples were processed and digested in a positive pressure clean lab. Standard reference materials were analyzed for all elements. National Bureau of Standards Estuarine Sediment (SRM 1646) and National Research Council Canada DOLT-1 and MESS-1. All standard reference materials analyzed were within the specified range.

Organisms sorted from core samples were divided and identified to lowest possible taxa and counted. Total numbers of individuals are given, not including meiofauna, nematodes or copepods. Percent cover of anthropogenic debris was quantified from slides by projecting the 1 m^2 areas over 100 evenly spaced points and counting the number of dots intercepting debris.

Statistics

Differences in mean values between stations for hydrocarbons, trace metals levels, and infaunal were tested by ANOVAs and Student-Newman-Keuls (SNK) multiple range tests. Homogeneity of variances was tested using Cochran's method. Spearman Rank Correlation Coefficient (SRC) was used to test for correlations between biological and chemical parameters, and between sediment and chemical parameters. When samples were replicated from a station, the mean was used in the SRC.

RESULTS

Physical and chemical patterns

Sediments with a smaller medium grain size and poorer sorting coefficients (greater variation in sizes) were generally more abundant in Winter Quarters Bay especially compared to the least disturbed locations at Cape Armitage, Cinder Cones, Turtle Rock, and Marble Point. Stations in the bay usually had a greater percent of silt and clay size particles (muddier) and those further away were sandier (Table 1). The percentage of organic carbon and nitrogen in sediments was quite variable, but also generally highest at stations in or near Winter Quarters Bay (Table 1).

The quantity of visible debris on and in sediments was greatest at stations in the back of Winter Quarters Bay. Large debris was observed by divers. The back bay was littered with a wide variety of large debris including tractors, storage sheds, pipeline, hose, tires, and the ubiquitous 55 gallon drum. Station 18m-1 had the greatest percent cover of debris because it was closest to the former dumpsite. Until 1985, refuse material was left on the ice to eventually sink or float away. This practice has been terminated. Although large debris was common along the front of the station, it was never so abundant as in the back bay. The same qualitative pattern was observed with smaller debris particles on the wash screens from infaunal cores. The pattern was quantified from underwater photographs, which show no debris at undisturbed stations and a generally decreasing percent cover of debris at greater distances from the bay (Figure 2).

The most striking contamination of sediments was by hydrocarbons, probably from oils, gasoline and other fuels (Risebrough et al. 1990). Total purgeable hydrocarbons showed a sharp gradient of contamination, decreasing several orders of magnitude along the three gradients from the back bay stations away from the bay (Table 1). Within Winter Quarters Bay, there was a significantly greater amount of total purgeable hydrocarbons at station 24m-1 compared to stations 24m-2, 24m-3, and 24m-4 (ANOVA, SNK, $p<0.05$ $n=3$). Hydrocarbon levels in the latter three stations were not significantly different. This series of stations was selected for statistical testing because it contained the only replicate samples for hydrocarbons (Table 1). Hydrocarbons values for all stations listed in Table 1 were positively correlated with % organic C in sediments (SRC, $p<0.05$) and were not correlated with the % silt and clay fraction (SRC, $p>0.05$). Although the purgeable hydrocarbons in this study represent a narrow range of compounds, they provide an adequate index of hydrocarbon contamination and coincide with direct observations of oily sediments and with other measures of hydrocarbon abundance (Risebrough et al. 1990).

Metals

There was a greater concentration of most metals (silver, cadmium, copper, lead, mercury, and zinc) in sediments from Winter Quarters Bay compared to outside the bay (Table 2). Sediment levels of nickel were higher at stations outside Winter Quarters Bay. Statistical differences in metals were examined along the most complete contamination gradient from Winter Quarters Bay, including the 18 m bay station, and the outfall, VXE-6, Jetty, and Cape Armitage stations (Figure 1). Metal levels at Cape Armitage, the uncontaminated end of the gradient, were not significantly different or were significantly lower (ANOVA, SNK, $p<0.05$, $n=3$) compared to the three reference stations (Table 2), except for Cd and Ag which were significantly higher at Cape Armitage (ANOVA, SNK, $p<0.05$, $n=3$).

In general, most metals increase inside the bay, but the pattern is complex. Concentrations of Ag, Cd, Cu, Pb, and Zn were significantly greater in sediments from 18m-1 compared to the stations from the Outfall to Cape Armitage (ANOVA, SNK, $p<0.05$, $n=3$). Ag, Cu, and Zn in sediments were not significantly different at the stations from the Outfall to Cape Armitage. Pb levels at the Outfall were significantly higher than VXE-6, the Jetty, and Cape Armitage, while Cd levels at Cape Armitage were significantly higher than stations from the Outfall to the Jetty. The highest values recorded for Ni were found at the Reference stations, Cinder Cones and Turtle Rock (Table 2). For all stations, metals in sediments did not correlate with the % silt and clay fraction (SRC, $p>0.05$, mean of 3 replicate metal values, and 1 replicate sediment sample), while there were positive correlations between Ag, Pb, Cu, and Zinc and % organic carbon (SRC, $p<0.05$, mean of 3 replicate metal values, and 1 replicate sediment sample).

Biological patterns

The total number of infaunal animals increased dramatically with distance from Winter Quarters Bay (Figure 3). Numbers of infauna were significantly higher at Cape Armitage compared to all stations along the gradient from stations 18m-1 to Cape Armitage (For statistical tests see Chapter 2). Total number of infauna from the Outfall to the Jetty were not significantly different, but they were significantly higher than the number of infauna at station 18m-1. The dense assemblage around McMurdo Station harbors large populations of many different species.

For all stations (Table 1), there was a highly significant negative correlation between infaunal abundance and the purgeable hydrocarbons in sediments (SRC, $p<0.0004$). The abundance of sedentary infauna was also negatively correlated with sediment hydrocarbons (SRC, $p<0.005$). The opportunistic polychaete species Capitella spp. and Ophryotrocha claparedii were positively correlated with hydrocarbons in sediments (SRC, $p<0.008$). Trace metals that were least likely to occur at high levels in natural sediments and are common anthropogenic contaminants in other environments had the highest negative correlation with the fauna. These include Ag, Pb, Zn, and especially Cu. However, these correlations were not significant (SRC, $p>0.05$).

Finally, the concentration of trace metals in the tissues of benthic fishes, Trematomus hansoni and T. bernachii, and the nemertean worm, Parbolasia corrugatus, from Winter Quarters Bay completely overlapped the values from Cinder Cones (Table 3).

DISCUSSION

There are high levels of some heavy metals and extremely high levels of hydrocarbons in the sediments of Winter Quarters Bay. Fortunately, heavily contaminated sediments are largely restricted to the back bay and decrease dramatically from the back bay to the mouth (Tables 1 and 2). The submarine sill probably prevents the transport of much material outside the bay, and plays a major role in limiting the geographic spread of debris and contaminated sediment. Approximately 0.1 km^2 of the bay is heavily polluted. Perhaps 5-10 times this area has been modified by human activities around the station: some anthropogenic debris is present and subtle changes in the fauna, such as the presence of weedy or opportunistic species, suggest human disturbance.

The major contaminants are petroleum hydrocarbons saturating the sediments in the back bay. These materials may have originated from ship bilges that were emptied into the bay while ships were moored at the ice dock, or from fossil feuls and burned oils that were deposited in the old dump (shown in Figure 1). Risebrough et al. (1990) present evidence that the oily material is burned and is not from a spill of fuel or unburned oil.

The sedimentary environment within Winter Quarters Bay is intensely contaminated with pyrogenic hydrocarbons relative to background levels around McMurdo Station and to oil polluted sites at other latitudes. Cinder Cones, Turtle Rock, and Marble Point provide realistic background levels of anthropogenic purgeable hydrocarbons. None were detected. Levels in Winter Quarters Bay are greater than those from the most polluted harbors in temperate and tropical latitudes and even large oil spills. The highest value in Winter Quarters Bay was 4500 ug g^{-1} (Dry Wt in sediment) (Table 1, 9m-1) compared to 834 ug g^{-1} in Forth Estuary, England (Ajayi & Poxton 1987), 2900 ug g^{-1} at the New York Bight dumpsite (Farrington & Tripp 1977), and 123 ug g^{-1} in sediments impacted by the Amoco Cadiz spill (Law 1978). Discharges of oil based drilling muds from North Sea oil platforms contain levels as high as 5000 ug g^{-1} (Davies et al. 1984). Sediment hydrocarbons were as high as 4500 ug g^{-1} almost a year after the West Fallmouth fuel spill (Blumer & Sass 1972). Finally, hydrocarbon levels were as high as 6180 ug g^{-1} in sediments around the largest sewage outfall on the west coast of North America in the Southern California bight (Swartz et al. 1986). Most of these values are of hydrocarbons of higher molecular weight than those quantified in Winter Quarters Bay, which were analyzed with a GC/MS.

Excluding Nickel, metal levels in sediments from the back of Winter Quarters Bay are 2 to 10 times greater than background levels from reference stations (Table 2). Corroding containers of machine shop wastes and solvents, photographic and chemistry laboratory wastes, and metals associated with oil pollution and bilge pumping are likely inputs to back bay sediments. Unlike hydrocarbon contamination, metal levels around McMurdo Station are not as high as the most polluted sites at other latitudes, such as large sewer outfalls in southern California (Katz & Kaplan 1981; Stull et al. 1986; Swartz et al. 1986), and industrial harbors in Narragansett Bay (Goldberg et al. 1978), Australia (Peerzada & Rohoza 1989), and Hong Kong (Phillips & Yim 1981).

There is a striking match between patterns of sediment contamination and benthic communities around McMurdo Station. There are significant negative correlations between purgeable hydrocarbons and some metals and the abundance of infaunal animals along several gradients of anthropogenic disturbance. The abundance of benthic animals is extremely low and community structure is grossly modified inside Winter Quarters Bay. The numerically dominant species are highly opportunistic polychaete worms (Chapter 2). Their presence at stations as far from the bay as the Jetty (Figure 1), suggest significant anthropogenic disturbances here (see Chapter 2).

Our results contrast markedly with those from South Georgia Island, where almost no sediment contamination was documented and no gradient in community patterns was present (Platt 1979b). However, the sources of anthropogenic disturbance were much different here. They were almost entirely from commercial whaling that began in 1904 and ended in 1965, about 13 years before Platt and his colleagues began their studies. The major source of contamination was probably combusted fossil fuels and whale carcasses. In contrast, McMurdo Station has been the major logistic and science center for the United States Antarctic Program for almost three decades. These activities increased dramatically over the years. The station is now a busy town, highly dependent on advanced technology and petroleum products.

McMurdo Station is the largest human settlement in Antarctica. It harbored some of the earliest inhabitants. Scott's first winter hut is located on Hut Point just above Winter Quarters Bay. Until recent years, human wastes and debris were commonly dumped near or into the nearshore habitats around the station. The main dump was located adjacent to Winter Quarters Bay (Figure 1). Station management, maintenance, and construction have gradually shifted from military to civilian control. In recent years, the dump was excavated, moved to an inland canyon, and subsequently removed and the debris retrograted back to the U.S. The cleanup around the station is ongoing. Dumping along the shoreline is no longer practiced. Raw sewage is consolidated into one marine outfall, and there are plans to extend the pipe to deeper water outside the protected waters near the station. Closer monitoring of oil and fuel leakage and ship dumping are essential, and a high priority in the NSF's environmental plans. Therefore, although the history of marine dumping and its legacy of intense, localized pollution are unadmirable, recent cleanup and abatement activities and future plans are encouraging.

Preliminary observations conducted in this study suggest that a major effort to remove contaminated sediments or debris from Winter Quarters Bay could spread contaminated sediments into highly sensitive and relatively undisturbed benthic habitats, especially the unique sponge community which is well developed just outside the bay (Dayton et al. 1969, 1970, 1974). The submarine sill apparently contains the contaminated sediment and larger debris within the bay (Figure 1). Although the breakdown of anthropogenic chemicals and recovery of native habitats and communities may take many decades, contamination of more benthic habitats is highly undesirable.

There is evidence that the impacts of human disturbance have expanded around the station during the last decade. The infaunal communities around the Jetty were sampled during several years and monthly for an entire year during the late 1970's (see Chapter 2). The highly opportunistic polychaetes, Capitella spp. and Ophyrotrocha claparedii, never occurred in the undisturbed dense assemblage. Nevertheless, smaller numbers of both species were present in each sediment core collected in the present study. This difference is statistically (Mann-Whitney U test, $p<0.001$, $N=6$) and ecologically significant; it indicates greater disturbance of the dense assemblage in recent years, probably from the extensive construction and expansion of the jetty during 1983 (see Chapter 2).

The distinct gradient in sediment contamination and the efforts to prevent future marine pollution permit an unprecedented opportunity to explore community recovery in an extreme environment. The recovery process may require many decades. Although the heavily impacted areas are restricted to a small and contained geographic area, the benthic communities around McMurdo Station are unique and an important scientific resource. Little is known about the habitats and communities that were destroyed, but much can be gained by their restoration.

Conclusion

Sediment contamination is extremely high and restricted to a relatively small geographic area around McMurdo Station, primarily Winter Quarters Bay. Except for the British work around the whaling station at South Georgia Island, this is the first extensive examination of sediment contamination and faunal changes around a permanent Antarctic settlement.

Acknowledgements

We are grateful to Peter Slattery and Stacy Kim for field work; Mark Stephenson and his colleagues for metal analyses; Jim Watanabe and Drew Anderson of Monterey Bay Aquarium for carbon and nitrogen analyses; and Ken Johnson, Mike Foster, Ted DeLaca, Robert Sletten, James Nybakken and Bob Risebrough for improving the manuscript. This work was supported by the National Science Foundation Division of Polar Programs (NSF-DPP 8716460) and La Asociacion de Biologos Ambulantes.

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Table 1. Changes in the physical and chemical conditions of sediments around McMurdo Station, Antarctica

Stations	Median Grain Size (phi)	Sorting Coef.	% Silt and Clay	% Org. C	% Org. N	Total Purgeable Hydrocarbons (ppm)
Back Bay Areas						
WQB 9 m -1	5.2	3.1	64.3	0.3	0.9	4500
WQB 18 m-1	2.2	2.5	21.3	1.1	0.1	2400
WQB 24 m-1	4.0	1.2	50.3	0.6	0.01	700 ± 200 *
WQB 33.5 m-1	3.8	2.5	45.9	0.7	0.7	200
Gradients Within Bay						
WQB 24 m-2	4.0	1.2	67.7	0.3	0.02	220 ± 370 *
WQB 24 m-3	4.0	0.3	90.6	0.1	0.01	ND (<1) *
WQB 24 m-4	3.2	2.8	37.9	0.3	0	1.2 ± 1.6 *
WQB 18 m-2	3.0	2.4	28.8	0.4	0.1	5
WQB 18 m-3	2.3	0.9	6.1	0.4	0.03	15
WQB 18 m-4	4.0	1.0	72.3	0.3	0.1	ND (<1)
Gradient From Bay						
Outfall	2.2	1.1	11.4	1.3	0.1	3.5
VXE-6	3.0	0.9	8.7	0.5	0.2	ND (<0.5)
Jetty	3.1	1.4	28.0	0.2	0.01	0.6
Cape Armitage	2.3	1.1	13.2	0.4	0.05	ND (<0.5)
Reference Sites						
Cinder Cones	2.4	0.8	5.9	0.3	0.03	ND (<0.5)
Turtle Rock	1.8	0.6	1.6	0.1	0	ND (<0.5)
Marble Point	2.9	0.7	8.3	0.05	0.02	ND (<0.5)

* Mean and one standard deviation based on N=3.
ND = Not detectable (detection limits in parenthesis).

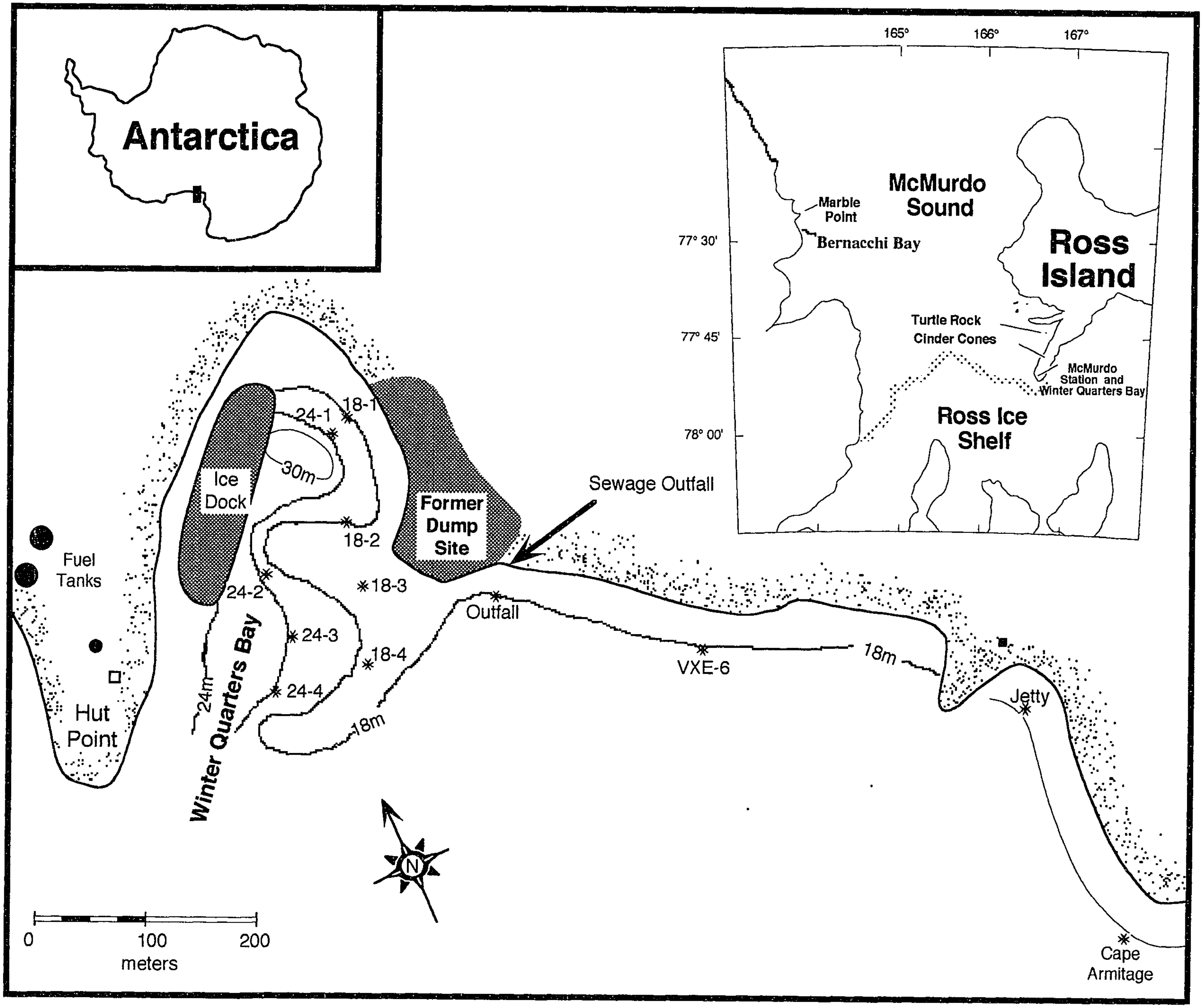
Table 2. Metals in sediments (ppm dry wt.) in the back of Winter Quarters Bay, along two gradients from the back to the mouth of the bay (at water depths of 24 and 18 m), along a gradient away from the bay, and at three reference sites further from the bay. Means and one standard deviation based on three replicate sediment samples per site.

Stations	Cd	Ag	Hg	Pb	Cu	Zn	Ni
Back Bay Area							
WQB 9 m-1	1 ± 0.2	0.4 ± 0.1	0 ± 0	67 ± 5	64 ± 2	115 ± 1	47 ± 4
WQB 18 m-1	10 ± 0.5	1.0 ± 0.4	0.4 ± 0.1	83 ± 9	121 ± 29	117 ± 21	78 ± 5
WQB 24 m-1	10 ± 3.2	0.7 ± 0.3	0.9 ± 0.7	62 ± 11	68 ± 14	98 ± 20	83 ± 15
WQB 33.5 m-1	1 ± 0.2	0.2 ± 0.3	0 ± 0	62 ± 11	99 ± 18	111 ± 14	47 ± 6
Gradients Within Bay							
WQB 24 m-2	8 ± 2	0.6 ± 0.2	0.4 ± 0.3	45 ± 18	66 ± 11	86 ± 15	90 ± 14
WQB 24 m-3	1 ± 0.3	0.0 ± 0.0	0.1 ± 0	12 ± 6	19 ± 2	18 ± 3	22 ± 2
WQB 24 m-4	5 ± 4	1.0 ± 0.5	0.5 ± 0	49 ± 30	35 ± 8	60 ± 15	89 ± 7
WQB 18 m-2	0.2 ± 0.1	0.1 ± 0.1	0 ± 0	11 ± 11	22 ± 11	41 ± 14	29 ± 5
WQB 18 m-3	0.5 ± 0.3	0.2 ± 0.2	0 ± 0	20 ± 15	67 ± 62	86 ± 34	52 ± 20
WQB 18 m-4	0.1 ± 0.1	0.1 ± 0.0	0 ± 0	8 ± 6	19 ± 5	36 ± 7	62 ± 6
Gradient From Bay							
Outfall	3 ± 2	0.6 ± 0.2	0.4 ± 0.2	62 ± 9	40 ± 2	63 ± 4	70 ± 8
VXE-6	0.3 ± 0.1	0.1 ± 0.1	0 ± 0	22 ± 5	27 ± 1	74 ± 9	87 ± 10
Jetty	1 ± 0.3	0 ± 0	0 ± 0	15 ± 1	27 ± 1	49 ± 1	65 ± 2
Cape Armitage	2 ± 1	0.4 ± 0.1	0 ± 0	11 ± 3	10 ± 1	52 ± 5	57 ± 6
Reference Sites							
Cinder Cones	1 ± 0.8	0 ± 0	0 ± 0	18 ± 1	39 ± 4	59 ± 8	127 ± 21
Turtle Rock	0.2 ± 0.3	0 ± 0	0 ± 0	7 ± 0	24 ± 2	31 ± 6	110 ± 10
Marble Point	1 ± 0.3	0 ± 0	0 ± 0	7 ± 2	11 ± 1	32 ± 2	68 ± 3
Detection Limits (ppm)	.05	.05	.05	.05	.05	.10	.10

Table 3. Metals in the tissues of fishes and a nemertean worm from Winter Quarters Bay and Cinder Cones. Means and standard deviations based on three replicate samples per site.

Stations	Cd	Ag	Pb	Cu	Zn	Ni
Back Bay Areas						
WQB 24 m-3						
Fish Liver	5 ± 2	0.2 ± 0.2	0.4 ± 0.3	5 ± 2	110 ± 36	0.5 ± 0.8
Fish Muscle	0.1 ± 0.1	0	0.4 ± 0.3	0.1 ± 0.1	25 ± 9	1.8 ± 0.3
Worm	21	0.3	2	8	163	0
WQB 18 m-4						
Fish Liver	21 ± 9	0.8 ± 0.4	3 ± 2	23 ± 10	140 ± 37	0
Fish muscle	0.2 ± 0.2	0	0.7 ± 0.2	0.3 ± 0	0.4 ± 0.1	0
Worm	21	0.3	7	8	173	0
Reference Site						
Cinder Cone						
Fish Liver	12 ± 4	0.8 ± 0.1	0.8 ± 0.2	14 ± 2	127± 25	1.4 ± 1.2
Fish muscle	0.2	0.2 ± 0	0.7 ± 0.7	0.9 ± 0.8	41± 13	1.2 ± 2.1
Worm	49	1	2	8	170	0

Figure 1. Sampling stations around McMurdo Station, Antarctica. Locations of sampling represented by *.



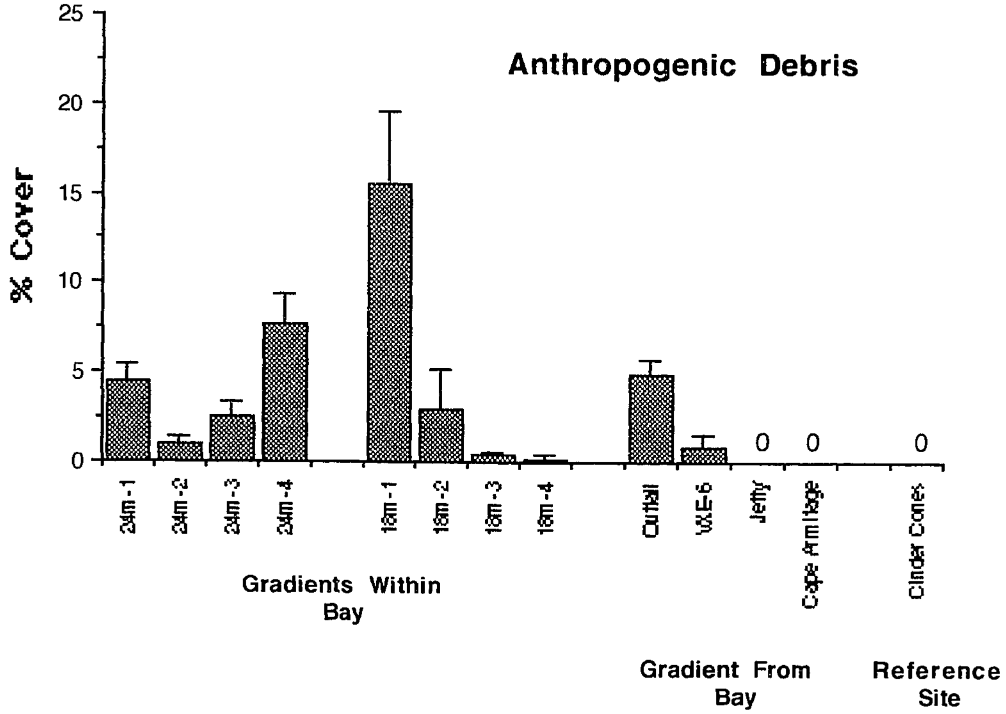


Figure 2. The percent cover of anthropogenic debris observed in underwater photographs (each 1 m^2). Means and one standard error based on 20 photographs per site.

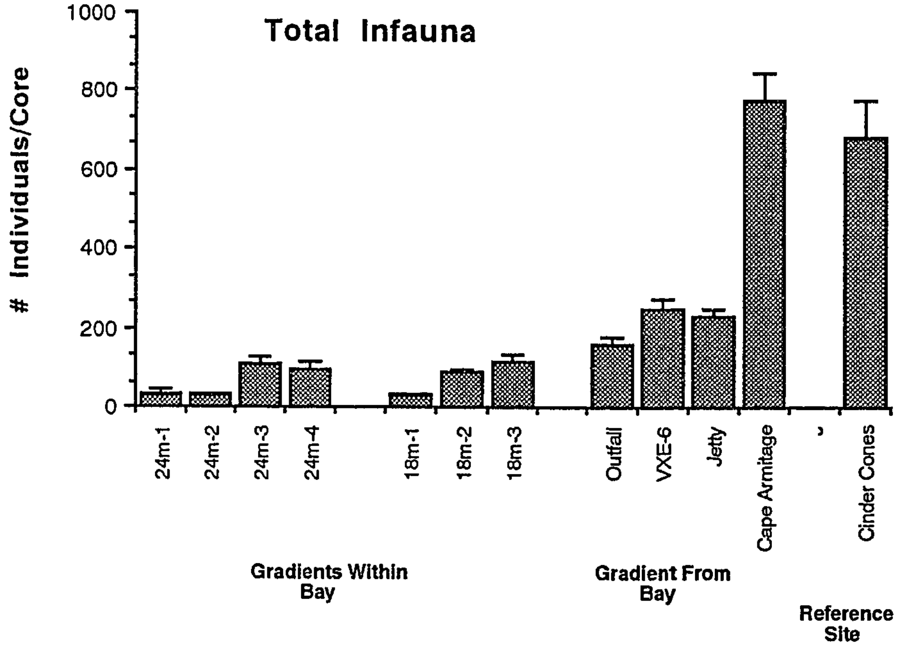


Figure 3. Changes in infaunal invertebrates in relation to human activities around Winter Quarters Bay and McMurdo Station. Means and standard errors based on six core (each 0.0075 m^2) samples per site.

Chapter 2

ANTHROPOGENIC AND NATURAL DISTURBANCES TO MARINE BENTHIC COMMUNITIES IN ANTARCTICA

INTRODUCTION

The Ross Sea and McMurdo Sound provide the most southerly access to marine bottom communities in Antarctica, where the benthos has been explored beyond 78° S latitude (Littlepage and Pearse 1962, Dayton and Oliver 1977). Exploration in this area is facilitated by the presence of McMurdo Station, a U.S. scientific installation. Located on Ross Island, McMurdo Station, with over 1,000 people in the summer season, is the largest settlement on the continent. Around the Station, over 30 years of human activities have contaminated the nearshore sediments with high levels of hydrocarbons, PCBs, and metals, leading to a steep, localized gradient in marine pollution (Lenihan et al. 1990, Risebrough et al. 1990, Table 1). The most contaminated habitats are within Winter Quarters Bay, where levels of hydrocarbons are as high as the most polluted harbors in the world; yet dense and species rich Antarctic bottom communities are well developed less than 1 km away (Dayton et al. 1970, 1974, Dayton 1989, Oliver and Slattery 1985).

Responses of benthic invertebrate communities to human disturbances are best known for organically enriched sediments around sewage and industrial discharges in temperate latitudes (Pearson and Rosenberg 1978, Boesch 1982, Swartz et al. 1986, Gray et al. 1990). In general, organic enrichment causes predictable shifts in community structure, including the loss of some resident species and increases of opportunistic species (with short generation times, high proportions of ovigerous females in the population, high larval availability, and rapid colonizing ability) (Grassle and Grassle 1974, McCall 1977, Pearson and Rosenberg 1978). Shifts in community structure around organic loadings which lack toxic contaminants are largely due to reduced oxygen concentration in water and increased redox potential in sediments (e.g., Pearson and Rosenberg 1978, Swartz et al. 1984). Not only is oil contamination a form of organic enrichment with negative and stimulatory effects

(Baker and Griffiths 1984) but it also has direct toxic effects on benthic species (e.g., Varanasi and Gmur 1981, Plesha et al. 1988). Nevertheless, changes in the structure of marine benthic communities associated with chronic oil contamination are often similar to those around sources of non-toxic organic loading (Davis and Spies 1980, Sanders et al. 1980, Swartz et al. 1986, Spies et al. 1988, Gray et al. 1990, Howarth 1991).

The ecological impacts of oil spills are often investigated in temperate latitudes and several of these studies describe the resulting habitat and community changes in soft-sediments (Sanders et al. 1980, Fleeger and Chandler 1983, Davies et al. 1984, and see Foster et al. 1988 for review). Fewer studies of organic enrichment or oil spill disturbances are available for tropical (Raman and Ganapati 1983, Jackson et al. 1989, Agard et al. 1993) and polar environments (Cross and Thompson 1987). Understanding the ecological consequences of human disturbance to marine benthic communities in Antarctica is important in managing our domestic, shipping, and scientific activities there (Dayton and Robilliard 1971, Dayton 1972, and for non-benthic disturbances see Barinaga and Lindley 1989, Epply and Rubega 1990).

To demonstrate that biological changes are caused by pollution and not by natural variations in biological interactions or the physical environment, it is desirable to sample in many locations several times before and after a chemical discharge or an experimental chemical spill (Underwood 1991, Cross and Thompson 1987). Multiple regressions may also be used to assess the functional relationships between important environmental variables, levels of contaminants, and biological responses if these parameters are not perfectly confounded. Unfortunately, chemical contamination at McMurdo Station already exists and to conduct simulated oil spills in Antarctica would be environmentally undesirable and politically impossible. We relied on a post-impact sampling program to evaluate community changes potentially caused by pollution. We compared the resulting patterns to those described along pollution gradients in other latitudes to infer causality.

Community responses to anthropogenic disturbances are rarely compared to patterns of recovery after natural disturbances. Such comparisons increase our ability to predict the responses of organisms to future disturbances (Lissner et al. 1991), and help place the human activity in a more realistic perspective of natural history. Chemical contamination and physical disruption of the seafloor and benthic communities are common forms of anthropogenic disturbance in the marine environment. The potential for chemical contamination in Antarctica is inherent in transportation activities, energy needs, scientific inquiry, and waste disposal. Physical disruption of the seafloor may result from dredging, demolition, mooring, installation of pipelines, and construction of piers and jettys. We provide predictions of the biological responses to human perturbations by evaluating changes caused by three existing forms of disturbance: chemical contamination around McMurdo Station, iceberg grounding, and anchor ice formation and uplift. Iceberg grounding and anchor ice formation are common natural physical disturbances of the seafloor which dramatically impact benthic communities in polar regions (e.g., Ellis and Wilce 1961, Dayton et al. 1969, 1970, Heine 1989).

The primary goal of our study was to describe changes in marine bottom communities along a well defined gradient of contamination in Antarctica. We characterize community changes and use the results from previously unrelated manipulative experiments to explore the recovery of disturbed communities. We test the hypotheses that relative rates of recovery of disturbed communities are (1) dependent on the initial structure of the community and (2) are much slower in eutrophic habitats compared with oligotrophic habitats. Based on the results of these tests, we derive predictions of the impacts of future anthropogenic disturbances in different oceanographic conditions of McMurdo Sound. We also test the hypothesis that community responses to anthropogenic chemical contamination are similar to those around natural physical disturbances (those caused by icebergs and anchor ice). We accomplish this test by qualitatively comparing data collected along the pollution gradient to those taken around ice disturbances. The result of this comparison provides a better assessment of the environmental risks of human activities in Antarctica.

METHODS

Study sites

The nearshore marine environment around McMurdo Station is heavily contaminated with anthropogenic chemicals, especially hydrocarbons dumped with ship ballast near an ice dock or leaked from a former waste disposal area (Figure 1 of Chapter 1). Physical and chemical changes in the sedimentary environment along the contamination gradient extending from Winter Quarters Bay to stations outside of the bay are described by Lenihan et al. (1990, and see Chapter 1) and Risebrough et al. (1990) (see Table 1). Sampling in this study along the pollution gradient was conducted at the same stations established by Lenihan et al. (1990, and see Chapter 1). Two sampling transects were located within Winter Quarters Bay, one at 18 m water depth and another at 24 m (Figure 1 of Chapter 1); each contained four sampling stations. A third transect consisted of five stations placed along the 18 m contour paralleling the front of the station from the sewage outfall to Cape Armitage (Figure 1). A final station was selected at 18 m water depth at Cinder Cones 9 km north of McMurdo Station. Cape Armitage and Cinder Cones are defined as "gradient ends". The primary water depth of stations was 18 m because the dense infaunal assemblage is best developed here (Oliver and Slattery 1985), ice gouging and anchor ice formation disturb the shallow benthos, and a sponge spicule community begins in deeper water (33 m, Dayton et al. 1970, 1974, Dayton 1989). However, the one transect was established in Winter Quarters Bay at 24 m water depth along a submarine valley where deposition of contaminants was relatively high (Figure 1 of Chapter 1, Lenihan et al. 1990, and see Chapter 1).

In addition to sampling along the contamination gradients, two types of natural disturbances were sampled in this study and a previous study: the first was a zone of anchor ice formation (at Cinder Cones; Figure 1 of Chapter 1), and iceberg gouges (see below). Anchor ice is a dense aggregation of ice platelets growing on the sea floor. Ice forms around protruding rocks and animals and lifts them off the bottom producing a distinct zonation of invertebrate communities to water depths of at least 30 m (Dayton et al. 1969, 1970). In an experiment conducted in 1977, we sampled along a gradient of water depth and anchor ice disturbance at Cinder Cones, in eastern McMurdo Sound, where there are no impacts of human activities and minimal changes in sediment grain size (Oliver et al., unpublished data) from water depths of 3-20 m. We use these unpublished data for our present comparison.

We sampled communities in gouge marks made by grounded icebergs in 25-40 m of water along the western side of McMurdo Sound, at Marble Point (in 1988) and Bernacchi Bay (in 1990), and along the eastern side, at Cinder Cones (in 1992) to compare patterns of infaunal abundance and composition with those in contaminated locations (Figure 1 of Chapter 1). The results of unrelated sampling around an iceberg gouge at Marble Point in 1977 are included in this study. Icebergs displace large amounts of sediment and benthic communities. This area is not influenced by human disturbances (Lenihan et al. 1990) and contains the highest concentration of grounded icebergs in McMurdo Sound (Oliver 1984).

Descriptive sampling

All sampling was done by SCUBA divers under shore-fast sea ice from tidal cracks and drilled holes. Sampling along the pollution gradient was conducted in November 1988 and 1990 and the data presented here are from the same set of samples described in Chapter 1. Defaunated sediment experiments were started in 1974 and sampled for infauna in 1975-77. Additional defaunated sediments (five replicates) were established at the Jetty (Figure 1) in 1977 and sampled in 1983. Defaunated sediment experiments originate from an unrelated study designed to examine patterns of colonization in oligotrophic, eutrophic, and chemically disturbed sedimentary habitats. All sampling was conducted in austral summer during November through early January. Infaunal samples (usually six cores/station) were taken haphazardly (sensu Fager 1968) with a diver-held core (0.0075 m^2; 10 cm deep), washed through a 500 μm screen, and fixed in a 10% solution of formaldehyde. Macrofaunal invertebrates were sorted and identified to the lowest identifiable taxon. The density of epifaunal invertebrates and siphons of large bivalves along the contamination gradient were counted from photo-transects taken from the same transect. Our siphon counts represent an index of total bivalve abundance because the method we used underestimates actual bivalve abundance (Authors, unpublished data). Photographs of 1-m^2 quadrats were taken along haphazardly placed 30-m transect lines marked at 1 m intervals; two transects were deployed at each station along the same depth contour and spaced about 15 m apart. A total of 20 photographs were randomly selected and analyzed from the 60 photographs at each station. Sediments analyzed for grain size were collected in polyethylene cores (4 cm^2; 12.5 cm deep).

The relative intensity of anchor ice uplift as it changed with depth was estimated by placing stakes at various depths (4 m, 7 m, 10 m, 13 m, and 21 m) and counting the number remaining after one year of exposure (one season of anchor ice formation). Two groups of eight stakes were haphazardly placed upright 5 cm into the sediment with 10 cm protruding above the sediment water interface along each depth contour. Groups of stakes at each depth were separated by 5 m and individual stakes were separated by at least 15 cm.

Field experiments

In defaunated sediments experiments, natural sediment and fauna were excavated from 0.25 m^2 areas within a round cylinder and the holes were refilled with defaunated sediment. This produced a patch of azoic substrate surrounded by undisturbed sediment and native infauna. Sediment was defaunated by washing through a 500 μm screen and allowed to sit in freshwater at room temperature for 72 hours. The sediment was collected from 18 m water depth around the Jetty. Defaunated areas were established in environments with different levels of natural (Dayton and Oliver 1977) and anthropogenic organic enrichment (Dayton and Robilliard 1971): nine replicates at 18 m water depth at the Jetty (eutrophic and un-enriched), six at 24 m in Winter Quarters Bay (eutrophic and enriched), and six at 30 m at New Harbor (oligotrophic and un-enriched; Figure 1). An additional five replicates were established at the Jetty in 1977. One replicate core (0.0075 m^2; 10 cm deep) was taken at all three stations from each of three randomly selected defaunated areas in each year from December 1975 to 1977 . No defaunated area was resampled.

Statistics

Differences in mean values among stations for infauna, epifauna, experimental treatments, and numbers of anchor ice stakes were tested by single factor model 1 ANOVAs (Zar 1984) and Student-Newman-Kuels (SNK) or Tukey-Kramer multiple comparisons (Underwood 1981, Day and Quinn 1989). Homogeneity of variances were tested using Cochran's method and, where variances were heterogeneous (a >0.05), the data were square root or log transformed and homogeneity was retested. Most variances were homogenous. However, transformed data which retained heterogeneous variances were subsequently tested using a Kruskal-Wallis nonparametric ANOVA and a Joint-Rank Ryan multiple comparison test (Day and Quinn 1989). Other tests are presented in the results. All values of infauna densities given in the text are for the area 0.0075 m^2 and all values for epifauna for the area 1 m^2.

RESULTS

Community patterns along contamination gradients

There were significant differences in the density of infaunal individuals (ANOVA, $F_{7,40}=34.18$, $p=0.0001$, $n=6$) and number of species (ANOVA, $F_{7,40}=32.24$, $p=0.0001$, $n=6$) at stations along the 18 m depth contour (Table 1). Infaunal density and number of species were higher outside of Winter Quarters Bay and were significantly lower at station 18m-1, at the back of the bay, compared to all stations (SNK, $p<0.05$). The densities of infauna were higher at Cape Armitage and Cinder Cones compared with all stations ("Treatment" vs. "Control" stations; Dunnett's test, $p<0.05$). There were significantly greater densities of total infauna at the gradient ends than along the station front (Outfall, VXE-6, and Jetty) and within the bay (18m-1, 18m-2, and 18m-3) when data were pooled amongst these three groups (ANOVA, $F_{2,45}=131.52$, $p=0.0001$, $n=18$, 18, and 12, Tukey-Kramer, $p<0.05$). The station front had a significantly greater density of total infauna compared to the bay (Tukey-Kramer, $p<0.05$). Winter Quarters Bay had fewer numbers of species compared with the station front and the gradient ends, Cape Armitage and Cinder Cones (ANOVA, $F_{2,45}=78.30$, $p<0.05$, $n=6$, SNK, $p<0.05$). Along the 24 m transect, numbers of infauna were not different between stations 24m-3 and 24m-4 (ANOVA, $F_{3,20}=7.05$, $p<0.001$, $n=6$, SNK, $p>0.05$) but both stations were greater than 24m-1 and 24m-2 (SNK, $P<0.05$).

The same patterns are reflected in the total number of crustaceans and polychaetes along the contamination gradients (Figure 1). Epifaunal populations also showed the same general trend as the infauna, with lower densities at the contaminated end of the gradient and higher densities at the gradient ends (Table 1).

Polychaete worms with opportunistic life histories (rapid colonizing ability, high proportions of ovigerous females, and rapid generation times; sensu Oliver 1980), *Capitella* spp.(Capitellidae), *Ophryotrocha claperedii* (Dorvillidae), and *Gyptis* sp. (Hesionidae) numerically dominated infaunal communities within Winter Quarters Bay. The total density of opportunistic polychaetes, *Capitella* spp., *O. claperedii*, and *Gyptis* sp., were significantly greater at stations within the bay compared with those with along the station front and at Gradient ends (Figure 2; Bay > Station front > Gradient ends; Kruskal-Wallis, H=33.59, p=0.0001, n=18, 18, and 12, J-RR test, $p<0.05$). Very few *Gyptis* sp., and no *Capitella* spp. or *O. claperedii* were found at gradient ends . The infauna at stations 18m-1 and 24m-1 consisted almost exclusively of *Capitella* spp. and *O. claperedii*.

The densities of polychaete species with intermediately opportunistic life histories were high within Winter Quarters Bay and along the station front (Figure 2). Intermediate opportunistic species, e.g. *Tharyx* sp. (Cirratulidae), have moderate colonizing ability, proportions of ovigerous females, and generation times relative to opportunistic species (Oliver 1980). Numbers of *Tharyx* sp. were greatest at stations from the Outfall to the Jetty (ANOVA, $F_{2,45}=90.43$, p=0.0001, n=6, SNK, $p<0.05$) and at station 24m-4 along the 24 m contour in the bay (ANOVA, $F_{2,20}=40.46$, p= 0.0001, n=6, SNK, $p<0.05$). The density of *Haploscolopus kerguelensis* (Orbiniidae) was highest at VXE-6 (ANOVA, $F_{7,40}=25.452$, p=0.0001, n=6, SNK, $p<0.05$), was high at the Jetty, and at several stations within Winter Quarters Bay (data available from H.S.L.). Stations along the station front and within Winter Quarters Bay contained another species, the infaunal anthozoan Edwardsia meridionalis,with an intermediate opportunistic life history.

The gradient end stations of Cape Armitage and Cinder Cones harbored a dense assemblage of infauna (Table 1) numerically dominated by Spiophanes tcherniai (Spionidae) and Myriochele cf. heeri (Oweniidae), sedentary tube-dwelling polychaetes , Nototanais dimorphous, a tube building tanaid, and Edwardsia meridionalis (Data available from H.S.L.). The most abundant motile fauna were the crustaceans Heterophoxus videns and Monoculodes scabriculosus (Gammerid amphipods), Austrosignum grande, (Isopoda), Heptathrix spp. (Ostracoda), and Gromia sp., a large protista. These species were extremely rare at stations within the bay and relatively few were found at stations from the outfall to the jetty.

The density of total infauna, number of species, opportunistic polychaetes, and Tharyx sp., an intermediate opportunistic polychaete, were also compared between stations along another potential pollution gradient extending away from the sewage outfall. This gradient consisted of three stations, the Outfall, 18m-3, and 24m-3 (Figure 1 of Chapter 1). Density of infauna was significantly higher at the Outfall compared to the other two stations, where density did not differ (ANOVA, $F_{2,15}=4.97$, $p<0.05$, $n=6$, SNK, $p<0.05$). Number of species at the Outfall was greater than 18m-3 and 24m-3 (ANOVA, $F_{2,15}=7.89$, $p<0.05$, $n=6$, SNK, $p<0.05$). Numbers of opportunistic polychaetes were significantly higher at stations 18m-3 and 24m-4 compared to the Outfall (ANOVA, $F_{2,15}=4.81$, $p<0.05$, $n=6$, SNK, $p<0.05$). Numbers of Tharyx sp. per core were greatest at the Outfall (ANOVA, $F_{2,15}=56.38$, $p<0.001$, $n=6$, SNK, $p<0.05$).

Densities of sedentary fauna were significantly different between all 18 m stations (Kruskal-Wallis, H=42.10, p=0.001, n=6) and increased dramatically with distance from Winter Quarters Bay (Figure 3). The highest density of sedentary individuals was found at Cape Armitage (J-RR test, $p<0.05$), where the spionid polychaete, Spiophanes tcherniai, formed a thick tube mat. Large numbers of sedentary animals were also present at Cinder Cones, and both areas harbored dense beds of the large infaunal, suspension feeding bivalve, Laternula elliptica (Laternulidae). Bottom communities at all stations except Cape Armitage contained greater numbers of motile fauna (Figures 3). In Winter Quarters Bay, most of the motile species were surface dwelling, opportunistic polychaetes species. The ratio of motile to sedentary infauna (total motile individuals:sedentary individuals) was significantly different among stations (ANOVA, $F_{7,40}=23.48$, p=0.001, n=6) with a higher ratio at station 18m-1 compared to all other stations (SNK, $p<0.05$). The ratio motile:sedentary at the Outfall was higher than all other stations except 18m-1 (SNK, $p<0.05$).

The densities of the large suspension feeding bivalve Laternula elliptica were significantly different between stations along the 18 m gradient (ANOVA, $F_{7,40}=40.352$, p=0.0001, n=10). There were generally fewer clams at uncontaminated stations within the bay (Table 1). No L. elliptica were found at 18 m within Winter Quarters Bay but a relatively high density was found near the sewage outfall. Although relatively low densities of L. elliptica were found at Cape Armitage, we observed dense beds throughout that region at shallow water depths where current speeds were greater. A large number of L. elliptica shells were found at, and near, station 18m-1 (Figure 3) indicating that a large suspension feeding population once lived there.

Anchor ice gradient

We were unable to measure the cover of anchor ice because much of the ice had melted by November, the beginning of our field seasons. However, we estimated variations in anchor ice uplift with experimental stakes which provided surfaces for ice growth and potential for uplift and removal. The stakes did not mimic any specific organism. Stake removal was significantly greater at 4 m than all other depths (7 m, 10 m, 13 m, and 18 m: ANOVA, $F_{4,6}=14.89$, $p<0.05$, n=2 groups per depth, SNK, $p<0.05$). After one year in the field, no stakes remained at the 4 m site and there was evidence of removal by ice gouging. Six to eight stakes per group remained at the four other depths.

The densities of individuals and numbers of species of infauna increased along a gradient of increasing water depth and decreasing anchor ice disturbance at Cinder Cones (Table 2). Total infaunal abundance was highest within the dense assemblage at 21 m water depth compared to the anchor ice zone at 3 m and 5.4 m (ANOVA, $F_{3,8}=85.79$, $p<0.001$, n=3, SNK, $p<0.05$). Total numbers of polychaetes and crustaceans increased generally with water depth as did the abundance of sedentary species. The most abundant species in the tube mat were Spiophanes tcherniai, Nototanais dimorphous, and Edwardsia meridionalis, all sedentary animals. In contrast to sedentary species, motile individuals decreased at 21 m, below the anchor ice zone (Table 2). The most abundant species at 3 m, 5.4 m, and 6.4 m was Polygordius sp. (Archiannelidae), a motile polychaete. A high number of S. tcherniai accounted for the abrupt increase in sedentary species at 6.4 m, near the seaward edge of the zone where anchor ice covers most of the sea floor during the winter months (J.S. Oliver, personal observation). Ice gouging may also reduce there numbers above 6.4 m. Abundance of opportunistic polychaetes (Capitella spp., Ophryotrocha claperedii, and Gyptis sp.) was greatest within the anchor ice zone (3-6.4 m) compared to the dense assemblage (21 m) (Table 2; Kruskal-Wallis, H=8.74, $p<0.01$, n=3, J-RR test, $p<0.05$).

Thus, the shallow zone of heavy anchor ice uplift was inhabited by motile infauna with opportunistic life histories.

Iceberg gouges

Infaunal communities were reduced within iceberg gouges along the western McMurdo Sound compared to the surrounding undisturbed habitat (Figure 4). Densities of total infauna were lower inside gouges compared to outside at Marble Point in 1977 (1-tailed t-tests, t=3.419, $p<0.05$, n=5). The infaunal community surrounding that scour was a moderately dense tube mat numerically dominated by the polychaete Myriochele cf. heeri (106.0±71.1/0.0075 m^2). Total species and total individuals outside of the gouges were dominated by polychaetes; polychaete abundance was 221.8±80.4 compared to 87.8±26.8 for crustaceans. Within the gouge in 1977, the species with the greatest numbers of individuals were crustaceans, especially the ostracod, Philomedes sp., the cumacean Eudorella splendida, and an unidentified isopod; all motile species.

nfaunal densities were also low within an iceberg gouge sampled at Marble Point in 1988 (Figure 4; 1-tailed t-test, t=3.23, $p<0.05$, n=6). The species composition and numerically dominant species outside the scour in 1988 were similar to those in 1977.

Infaunal densities within a gouge at Bernacchi Bay in 1990 were significantly lower compared to the surrounding undisturbed community (Figure 4; t-test, t=4.55, $p<0.001$, n=5). In 1980, the undisturbed bottom in this area contained the most densely populated benthic community observed in western McMurdo Sound (Oliver 1980). Infauna in undisturbed areas in 1990 included high numbers of Edwardsia meridionalis (137.0±50.0/0.0075 m^2), and relatively high numbers of the polychaetes Polygordius sp., Tharyx sp., and Haploscolopus kerguelensis as well as the amphipod, Orchomene penguides (Lyssianasidae). The fauna within the scour contained a few ostracods, Tharyx sp., and Polygordius sp. All are motile species.

An apparently recent iceberg gouge was sampled in November 1992 south of Cinder Cones along the more eutrophic eastern McMurdo Sound. The gouge was surrounded by the same dense tube mat community sampled at the undisturbed ends of the anchor ice and chemical contamination gradient (total infauna sorrounding gouge: 797.7± 99.1 animals/0.0075m^2). The gouge contained 46.7± 10.2 total infauna, 11.8±8.3 Capitella spp., and 2.7±2.0 Ophryotrocha claperedii per 0.0075 m^2 core.

Colonization of defaunated sediment

The dense infaunal assemblage surrounding the defaunated sediments at the Jetty has been described (Oliver and Slattery 1985) as a community physically structured by tubes of the polychaetes Spiophanes tcherniai and Myriochele cf. heeri, and the tanaid Nototanais dimorphous. The tube mat harbors a high density of motile amphipods, ostracods, cumaceans, isopods, copepods, and errant polychaetes. After one year of exposure at the Jetty, crustaceans were the major colonists of defaunated sediments (Table 3). The most abundant crustacean species, N. dimorphous. (8.0±3.6/0.0075 m^2), Eudorella splendida (5.3±2.1), and Austrosignum grande (7.0±5.3), occurred in very low numbers compared to the surrounding assemblage (69.6±26.4; 58.9±35.4; 55.7±23.5, respectively). They are relatively motile animals that brood their young in ventral marsupia. After three years, the colonizing crustaceans remained the major infauna but the total number of individuals was only 28% of the number within the surrounding assemblage (Figure 5: 1-tailed t-test, t=4.68, p<0.001, n=3 and 11; 222.0±30.5 vs. 785.0±185.2). During all three years, the relative abundance of motile species was higher in defaunated sediments compared to the undisturbed dense assemblage (Table 3).

By six years, the abundance of infauna in the defaunated sediments and the dense assemblage were not different (Figure 5: 2-tailed t-test, t=1.23, p=0.252, n=5). The species composition, ratio of sedentary to motile individuals, and number of species per core were similar in the experimental and natural sediments (Table 3).

During the 13 year period of sampling around the Jetty (1977-1990), there was a general decline in the total numbers of infauna in the natural assemblage (Figure 5 and Table 3). The decrease in crustaceans between 1977 and 1983 reflected a decline in Austrosignum grande and Eudorella splendida (Data available from H.S.L.). An increase in Gyptis sp. and Tharyx sp. resulted in an increase in total polychaete density over those six years. There was a precipitous decline in numbers of Myriochele cf. heeri and Edwardsia meridionalis by 1988; Tharyx sp. became numerically dominant and numbers of Gyptis sp. greatly increased. The abundance of crustaceans and sedentary animals increased in 1990 compared to 1988 because of a greater number of Nototanais dimorphous.

Unlike the Jetty dense assemblage, communities within defaunated sediments in Winter Quarters Bay and New Harbor recovered within two years (overall numbers were reduced in Winter Quarters Bay but within the range of natural population fluctuation, Table 4). The infaunal communities in Winter Quarters Bay were numerically dominated by the opportunistic polychaetes, Capitella spp. and Ophryotrocha claperedii. They were also the major colonists to defaunated sediments during both years. By the second year, moderate numbers of Gyptis sp. also colonized the experimental sediments. The same three worms were the most abundant species in unmanipulated substrate when the bay was sampled in 1988 (see Figures 2) and 1990 (data available from H.S.L.).

The natural infaunal community in New Harbor was numerically dominated by polychaete worms and relatively motile species (Table 4), maintaining much smaller populations than the animals in the dense assemblage along the eastern side of McMurdo Sound (Jetty, Cape Armitage, and Cinder Cones; Dayton and Oliver 1977, Oliver and Slattery 1985). The primary colonists into defaunated sediments were the same species found in the surrounding bottom; these included the polychaetes Chaetozone sp. (Cirratulidae), Haploscolopus kerguelensis, and the bivalve Laternula elliptica. The New Harbor fauna did not include the highly opportunistic species found in Winter Quarters Bay.

DISCUSSION

Benthic marine communities changed dramatically along the pollution gradient from highly contaminated Winter Quarters Bay to natural Antarctic environments just outside the bay. The dense infaunal assemblages along the eastern shore of McMurdo Sound have been present for many thousands of years (Oliver 1984, Dayton 1989) and are relatively undisturbed by natural physical processes (Dayton et al. 1974, Dayton and Oliver 1977, Oliver and Slattery 1985). In Winter Quarters Bay, bottom communities were dominated by polychaete worms with relatively opportunistic life histories, Capitella spp., Ophryotrocha claperedii, and Gyptis sp. These genera are common in polluted habitats throughout temperate waters (Grassle and Grassle 1976, Pearson and Rosenberg 1978, Aschan and Skullerud 1990). At the uncontaminated gradient ends, bottom communities had higher total abundance and species number2, and species with less opportunistic life histories dominanted numerically. The most abundant species were tube-dwelling spionid and oweniid polychaetes, and suspension feeding infaunal anemones and bivalves. Numbers of polychaetes, crustaceans, and larger epifaunal animals increased away from the bay.

There was a distinct transition community between Winter Quarters Bay and the uncontaminated gradient ends. Communities at the Outfall, VXE-6, and Jetty included several species with intermediately opportunistic life histories: the polychaetes Tharyx sp. and Haploscolopus kerguelensis and the anthozoan Edwardsia meridionalis. Communities at the Jetty and VXE-6 had similar faunas with moderate numbers of suspension feeders and amphipods and relatively high numbers of intermediate opportunistic polychaetes. The Outfall was ecologically distinct from Jetty and VXE-6 because of lower total infaunal abundance and larger populations of Capitella spp., Ophryotrocha claperedii, and H. kerguelensis.

There was no apparent gradient of community structure away from the Outfall consistent with that station being a major source of chemical contamination. The Outfall had higher levels of total infauna and number of species but lower numbers of opportunistic species than two stations extending away into Winter Quarters Bay, 18m-3 and 24m-3. The community structure at Outfall fit the pattern of a intermediately disturbed site along the larger pollution gradient. This may have resulted because the sewage effluent was discharged above sea level during and before our study.

The most important changes in community structure along the pollution gradient were the increases in polychaete worms with relatively opportunistic life histories and the decreases in sedentary (and suspension feeding) groups as chemical contamination increased. The opportunistic species that dominated Winter Quarters Bay, Capitella spp., Ophryotrocha claperedii, and Gyptis sp., are relatively small animals with short generation times, high proportions of ovigerous individuals, high larval availability, and good colonizing ability (see Oliver 1980, p. 260). The numerically dominant species at uncontaminated Cape Armitage and Cinder Cones, Spiophanes tcherniai and Myriochele cf. heeri, possess opposite life history patterns. Three of the most abundant species along the middle of the pollution gradient, Tharyx sp., Haploscolopus kerguelensis, and Edwardsia meridionalis, have intermediate life history patterns (Oliver 1980).

There has also been a gradual change in the structure of benthic communities related to habitat degradation at the Jetty. The Jetty was expanded in 1983 increasing its size nearly 100%. Over the past 13 years, total infaunal abundance declined while populations of opportunistic species increased in number, including Tharyx sp., Gyptis sp., Edwardsia meridionalis, and Capitella spp. The structure of the Jetty community has shifted towards that of the more contaminated end of the gradient.

The proportion of sedentary species increased dramatically with increasing distance from Winter Quarters Bay. The heavily contaminated sites were dominated by more motile and surface-active worms. Many of the sedentary animals were suspension feeders. Laternula elliptica, a suspension feeding infaunal clam, was abundant on both sides of McMurdo Sound and is always found in association with dense infaunal communities of crustaceans and polychaete worms in sandy bottoms (Dayton and Oliver 1977, Oliver and Slattery 1985). Dense beds of L. elliptica apparently once lived in Winter Quarters Bay, where large numbers of dead shells were counted on the sediment surface. There is no apparent mechanism for transport of shells from outside the bay.

If Laternula elliptica was common in the bay, dense infaunal communities like those at the Jetty, Cape Armitage, and Cinder Cones were probably present as well. The bay has been heavily contaminated with anthropogenic chemicals since at least the late 1960's (Dayton et al. 1969, Dayton 1972). The native communities were therefore destroyed two to three decades ago and replaced by the polychaete "weeds". In addition, anthropogenic disturbance increased along the front of McMurdo Station during the last decade. Abundances of opportunistic polychaetes increased as tube worm and clam beds declined. Consequently, the community structure at the Jetty shifted towards that of the contaminated end of the gradient.

The structure of communities along the pollution gradient are similar to those along many organic enrichment gradients (Rosenberg 1976, McCall 1977, Reish et al. 1980, Sanders et al. 1980, Raman and Ganapati 1983, Stull et al. 1986, Swartz et al. 1986, Weston 1990, Aschan and Skullerud 1990, see review in Pearson and Rosenberg 1978); after oil spills in temperate environments (Gassle and Grassle 1974, Elliot and Griffiths 1987, Gray et al. 1990, see review in Teal and Howarth 1984); as well as within experimental organic enrichments and natural oil seeps (Spies et al. 1988). Community patterns around McMurdo Station generally fit the model developed by Pearson and Rosenberg (1978). Infaunal abundances and numbers of species increased along the contamination gradient; peak abundances of Capitella spp. and other opportunistic polychaetes were greatest with maximum contamination; and there was a transition zone between the highly modified and natural communities. The most striking similarity between polluted benthic environments in Antarctica and those in temperate latitudes is the presence of opportunistic polychaete worms, especially Capitella spp., Ophryotrocha spp., Gyptis spp., and Tharyx spp. Consequently, we predict that these genera of annelids will be early colonists of organically enriched and contaminated sediments throughout temperate and polar latitudes if resident populations are present.

Although other environmental conditions vary along the gradient of chemical contamination at McMurdo Station, none of these factors appear to explain the dramatic changes in marine bottom communities from Winter Quarters Bay through the transition area. The influence of natural environmental variables on community structure along the spatial gradient have not been directly tested. Current patterns are highly complex in the region (Littlepage 1965, Barry 1988) and pelagic production is advected along the entire gradient from ice-free waters many miles north (Bunt 1964a, Dayton and Oliver 1977). Although local inputs of freshwater and sediment decrease with increasing distance from the bay (Lenihan et al. 1990), there is no evidence that these inputs have important impacts on community structure except in quite shallow water and around large melt ponds on the sea ice (DeLaca et al. 1980, Berkmen 1990).

Community responses to natural disturbances

We sampled two natural ice disturbances and compared the structure of communities to those along the pollution to provide a relative assessment of the ecological impacts of human activities in Antarctica. Anchor ice formation and uplift and iceberg grounding commonly disrupt the seafloor and benthic communities within McMurdo Sound (e.g., Dayton et al. 1969, Oliver 1984), and most closely mimic anthropogenic disturbances associated with dredging, excavating, and construction. Anchor ice and iceberg grounding disturb bottom communities over vast geographic areas. Animals are picked up, removed, suspended, buried, and crushed by ice. We sampled a gradient of anchor ice in the eutrophic eastern section of McMurdo Sound and iceberg gouges primarily in the oligotrophic western sound; undisturbed bottom communities are strikingly different between these regions (Dayton and Oliver 1977). These natural disturbances produced patterns of community change similar to one another and to those along the McMurdo Station pollution gradient.

The severely disturbed shallow benthos at Cinder Cones (3 m and 5.4 m) was low in total infaunal abundance and colonized by motile species with highly opportunistic life histories.

Areas of intermediate disturbance (6 m) were dominated by species with intermediate life history patterns: undisturbed communities (21 m) had high infaunal abundance and species density. Along with anchor ice, the shallow benthos at Cinder Cones receives a relatively high input of organic matter from the deposition of phytoplankton (Rivkin 1991) and has high benthic primary production (Dayton et al. 1986).

Changes in total infaunal density, species number, and composition of communities along the anchor ice gradient were similar to those along the contamination gradient at McMurdo Station. Similar groups of opportunistic polychaete worms, relatively motile worms, and crustaceans dominated the highly disturbed sites. Communities at the shallowest depth at Cinder Cones (3 m) and those within the back of Winter Quarters Bay (compare Tables 2 and Figure 3) contained high numbers of Capitella spp. and Ophryotrocha claperedii. Unlike Winter Quarters Bay, the most abundant species at Cinder Cones was Polygordius sp., another small, motile polychaete. Therefore, the greatest similarity in areas of chemical and physical disturbance were those experiencing high levels of disturbance.

Iceberg gouging is the most disruptive and widespread physical disturbance to marine bottom communities in polar waters (Reimnitz et al. 1972, Reimnitz et al. 1977, Mathieson et al. 1982, Robertson and Mann 1984, Keats et al. 1985, Wethey 1985, Hodgson et al. 1988, Wilson 1988). Local icebergs originate from the Ross Ice Tongue and Ice shelf, glaciers along the western shore of McMurdo Sound, and the open ocean. The frequency of iceberg grounding varies considerably along the Antarctic shoreline. In McMurdo Sound, the largest number of icebergs ground around Marble Point (Oliver 1984, and see Figure 1) along the western side of the Sound.

Changes in infaunal communities inside and outside iceberg gouges shared several similarities with community patterns along the gradients of anchor ice formation and chemical contamination. There were large reductions in population sizes and species numbers within scours compared to surrounding communities. The fauna within gouges were motile species of crustaceans (ostracods and cumaceans), and polychaetes with intermediately opportunistic life histories, such as *Tharyx* sp. and *Haploscolopus kerguelensis* .

There were striking differences between community responses to iceberg gouging between the oligotrophic west and eutrophic east sides of McMurdo Sound. Recent gouges on the east side contained large numbers of the highly opportunistic polychaete worms, *Capitella* spp. and *Ophryotrocha claperedii*, which were not found in gouges from the western sound. Only a few *Gyptis* sp. were found in the west sound ice gouges. Populations of these opportunistic species are uncommon along the western sound (Dayton and Oliver 1977) where the availability of larvae for settlement into experimental sediments is very low (Oliver 1980).

Recovery in Winter Quarters Bay

Early colonization of defaunated sediment experiments involved motile species and those with relatively opportunistic life histories. These are the same groups living in highly contaminated areas of Winter Quarters Bay and naturally disturbed bottoms. Motile isopods and cumaceans were the first to colonize defaunated sediments at the Jetty and New Harbor, while opportunistic polychaetes colonized experimental sediments in Winter Quarters Bay. The time to recovery (return to a faunal composition resembling the surrounding community) also varied with geographic location and the surrounding community structure. It took six years for the dense infaunal community to recover at the Jetty.

The infaunal community at New Harbor, along the oligotrophic western sound, was dominated by relatively motile infauna with much smaller population sizes compared to dense assemblages (Dayton and Oliver 1977). The New Harbor community recovered more rapidly, within two years. The highly opportunistic species dominating Winter Quarters Bay colonized defaunated sediments within a year and were still the only major groups after two years.

The eventual recovery of bottom communities within Winter Quarters Bay may require many decades if chemical contamination and toxicity persist. The pre-contamination communities were probably similar to those at the less or uncontaminated ends of the gradient, especially the Jetty. The results from colonization experiments indicate that dense populations of infaunal crustaceans and polychaete worms could develop within a decade. However, large suspension-feeding bivalves may require more than a decade to recover in both number and size structure. No information is available on the potential decrease in sediment toxicity and return to a more natural sedimentary environment.

We predict that recovery of the rich benthic communities in the eutrophic eastern sound following future chemical disturbances will take longer than similar disturbances in the oligotrophic western sound because undisturbed communities have greater numbers of infauna and species, and have greater structural complexity. Initial colonists to disturbed sediments in the eastern sound will be opportunistic polychaete worms; they will be replaced by intermediate opportunistic polychaete and anthozoan species, and highly motile crustaceans; these species will be replaced by sedentary polychaetes, bivalves, and predatory crustaceans.

Recovery from physical anthropogenic disturbances

The impacts of physical anthropogenic disturbances on benthic communities may be predicted by community responses to natural ice disturbances. Anchor ice and iceberg gouging produced similar changes in infaunal community patterns but changes were highly dependent on the local community and oceanographic region in which they occurred. In general, recolonization of disturbed sediments in McMurdo Sound appeared to be highly dependent on surrounding populations of motile invertebrates; many colonists were adult and juvenile immigrants. The structure of local communities and the availability of colonists depended on location within McMurdo Sound. Motile crustaceans and intermediately opportunistic polychaetes were colonists in the western sound because they were abundant in surrounding communities and there was low availability of highly opportunistic polychaetes. Development of late successional communities following physical anthropogenic disturbances are likely to follow patterns described for ice disturbances, take longer to develop in highly productive areas, and depend on the absence of heavy natural ice disturbance.

CONCLUSION

This study provides a background description for documenting the path and rate of community recovery after pollution abatement in one of the most extreme physical environments in the world. Compared to the major natural disturbances to shallow water Antarctic habitats, marine pollution around McMurdo Station covers a small area of the seafloor. However, recovery of native communities will require a much longer time if rates of hydrocarbon degradation and natural sedimentation are as low as expected (Scherrer and Mille 1989, Leahy and Coldwell 1990, Delille and Vaillant 1990). Recovery at any rate will depend upon abatement of past dumping and disposal of anthropogenic chemicals and other wastes. If this abatement and cleanup are accomplished, waste management at McMurdo Station will become a model for other polar stations. Finally, this study will be useful in predicting impacts of waste disposal in the deep water marine benthos.

ACKNOWLEDGMENTS

We thank T. DeLaca for his rapid and effective response to environmental problems at McMurdo Station. We thank D. Bockus, P. Dayton, S. Kim, B. Konar, J. Levitt, J. Oakden, and P. Slattery for assistance in the field, and J. Barry, P. Dayton, A. De Vogelaere, K. Grove, J. Heine, D. Kline, R. Kvitek, C.H. Peterson, James Nybakken, and two anonymous reviewers for suggestions on the manuscript. Thanks also to A. Brown, S. Dragon and J. Rastafari for logistical support. This project was funded by NSF grant DPP 8914858 awarded to J.S. Oliver.

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Table 1. Changes in infaunal individuals and species, a large infaunal bivalve, and epifauna along two contamination gradients within Winters Quarters Bay and along a third gradient from the bay. Means and one standard deviation based on six replicate core samples (0.0075 m^2) and twenty replicate photographic quadrants (1 m^2) per site.

	#/Core (0.0075m2)		#/Photographs (1 m2)	
Stations	**Infaunal Individuals**	**Infaunal Species**	***Laternula elliptica***	**Epifauna**
Gradients within bay				
18m-1	29.7 ± 11.6	4.7 ± 1.6	0	2.8 ± 2.4
18m-2	115.2 ± 51.7	9.3 ± 2.0	0	0.8 ± 4.3
18m-3	92.5 ± 19.3	10.3 ± 2.9	0	0.8 ± 1.3
18m-4	NA	NA	0	3.8 ± 5.6
24m-1	34.8 ± 22.3	6.3 ± 2.6	2.3 ± 1.4	3.0 ± 2.6
24m-2	28.7 ± 5.0	10.0 ± 1.1	0	1.8 ± 1.9
24m-3	105.3 ± 55.8	11.3 ± 6.3	7.2 ± 10.3	11.1 ± 26.5
24m-4	101.3 ± 34.7	9.2 ± 5.0	2.2 ± 2.0	0.4 ± 0.6
Gradient from bay				
Outfall	156.3 ± 50.5	18.8 ± 4.5	15.1 ± 6.5	2.2 ± 1.8
VXE-6	264.0 ± 75.6	20.3 ± 5.7	26.0 ± 11.6	8.4 ± 7.6
Jetty	230.5 ± 45.0	17.2 ± 2.0	28.2 ± 10.6	2.4 ± 3.4
Gradient ends				
Cape Armitage	774.5 ± 177.0	18.1 ± 3.3	2.6 ± 1.0	27.4 ± 9.4
Cinder Cones	681.8 ± 235.7	22.3 ± 1.5	11.8 ± 1.3	10.0 ± 6.6
Water depth=18m (excluding 24m stations)	n=6	n=6	n=20	n=20

NA = not analyzed because samples destroyed

Table 2. Density of total infauna individuals, species, and opportunistic polychaetes within and below a zone disturbed by anchor-ice formation and uplift. Means and one standard deviation based on three replicate samples (0.0075 m^2) per water depth.

Cinder Cones	**Water Depth**			
	Anchor ice zone			**Dense Assemblage**
Water depth	**3 m**	**5.4 m**	**6.4 m**	**21 m**
Opportunistic species				
Capitella spp.	17.3 ± 2.5	4.7 ± 2.5	14.0 ± 9.6	0
Ophryotrocha claperedii	9.3 ± 5.1	0.7 ± 1.2	2.3 ± 4.0	0
Gyptis sp.	7.7 ± 2.5	5.0 ± 2.0	3.3 ± 4.2	0.7 ± 1.2
Total infauna	113.3 ± 38.0	604.7 ± 21.5	1070.7 ± 159.2	1212.3 ± 85.9
Polychaetes	69.0 ± 34.0	459.7 ± 19.5	770.3 ± 144.7	458.3 ± 76.2
Crustaceans	35.0 ± 11.5	46.7 ± 15.9	163.0 ± 26.5	645.3 ± 32.2
Motile species	98.0 ± 29.5	586.0 ± 21.8	671.3 ± 213.9	442.3 ± 24.5
Sendentary species	15.3 ± 8.5	18.7 ± 13.3	399.3 ± 54.7	770.0 ± 92.3

n=3

Table 3. Recruitment in defaunated sediment after one to six years of exposure at the Jetty. The experiment began in 1974 and the surrounding dense assemblage was sampled four times during 1977-1990. Means and one standard deviation based on *n* core samples (0.0075 m^2). Also see Figure 5.

	Defaunated Sediment				**Dense Assemblage**			
	1975	1976	1977	1983				
Individuals	**1 year**	**2 years**	**3 years**	**6 years**	**1977**	**1983**	**1988**	**1990**
Crustaceans	25.0 ± 12.3	195.0 ± 48.4	192.0 ± 76.1	185.1 ± 45.6	409.5 ± 79.7	233.1 ± 67.2	111.0 ± 27.5	181.0 ± 45.6
Polychaetes	2.0 ± 1.7	33.0 ± 4.4	25.7 ± 3.2	120.2 ± 34.4	182.5 ± 111.9	203.2 ± 47.4	60.0 ± 28.8	153.7 ± 26.6
Capitella spp.	0.5 ± 0.1	0	0	0	0	0	0	2.5 ± 1.7
Ophryotrocha claperedii	1.0 ± 0.6	0.7 ± 0.5	0	0	0	0	0	5.2 ± 1.6
Sedentary individuals	11.3 ± 4.6	107.0 ± 26.3	79.0 ± 20.7	470.5 ± 45.1	403.3 ± 175.3	538.8 ± 36.8	84.5 ± 26.6	273.2 ± 73.2
Motile individuals	19.0 ± 8.5	167.0 ± 71.3	153.0 ± 73.2	215.3 ± 52.0	374.1 ± 64.2	218.3 ± 79.6	146.0 ± 30.8	144.0 ± 15.6
Number Species/Core	9.0 ± 1.0	16.3 ± 1.2	11.0 ± 1.0	19.0 ± 3.5	NA	18.0 ± 2.0	17.2 ± 2.0	20.2 ± 1.6
	n=3	n=3	n=3	n=5	n=11	n=5	n=6	n=6

Water depth=18m
NA = not analyzed

Table 4. Colonization of defaunated sediment after one (1974-75) and two years (1974-76) of exposure in Winter Quarters Bay (WQB) and at New Harbor (NH). Means and one standard deviation based on *n* core samples (0.0075 m^2).

	Winter Quarters Bay			**New Harbor**		
	Defaunated sediments		**Undisturbed**	**Defaunated sediments**		**Undisturbed**
Individuals	**1 year**	**2 years**	**2 years**	**1 year**	**2 years**	**2 years**
Total infauna	53.3 ± 31.5	168.0 ± 44.1	367.1 ±301.5	17.0 ±4.6	59.0 ±32.5	51.0 ±3.0
Crustaceans	0	1.7 ± 1.5	0.8 ±0.4	3.0 ±0.6	6.7 ±6.4	0
Polychaetes	48.0 ± 28.0	155.0 ± 40.9	364.0 ±301.4	11.3 ±3.2	30.7 ±11.0	27.7 ±9.4
Sedentary individuals	2.0 ± 0	4.3 ± 1.2	1.7 ±1.8	6.0 ±3.0	28.0 ±25.5	11.0 ±6.1
Motile individuals	51.3 ± 31.5	164.0 ± 45.2	366.0 ±301.5	11.0 ±3.6	31.0 ±7.0	27.7 ±9.4
Number Species/Core	6.7 ± 0.6	10.3 ± 1.5	NA	9.3 ±2.5	13.3 ±1.2	NA
	n=3		n=3	n=3		n=3
Water depth	24m		24m	30m		33.5m

NA = not analyzed

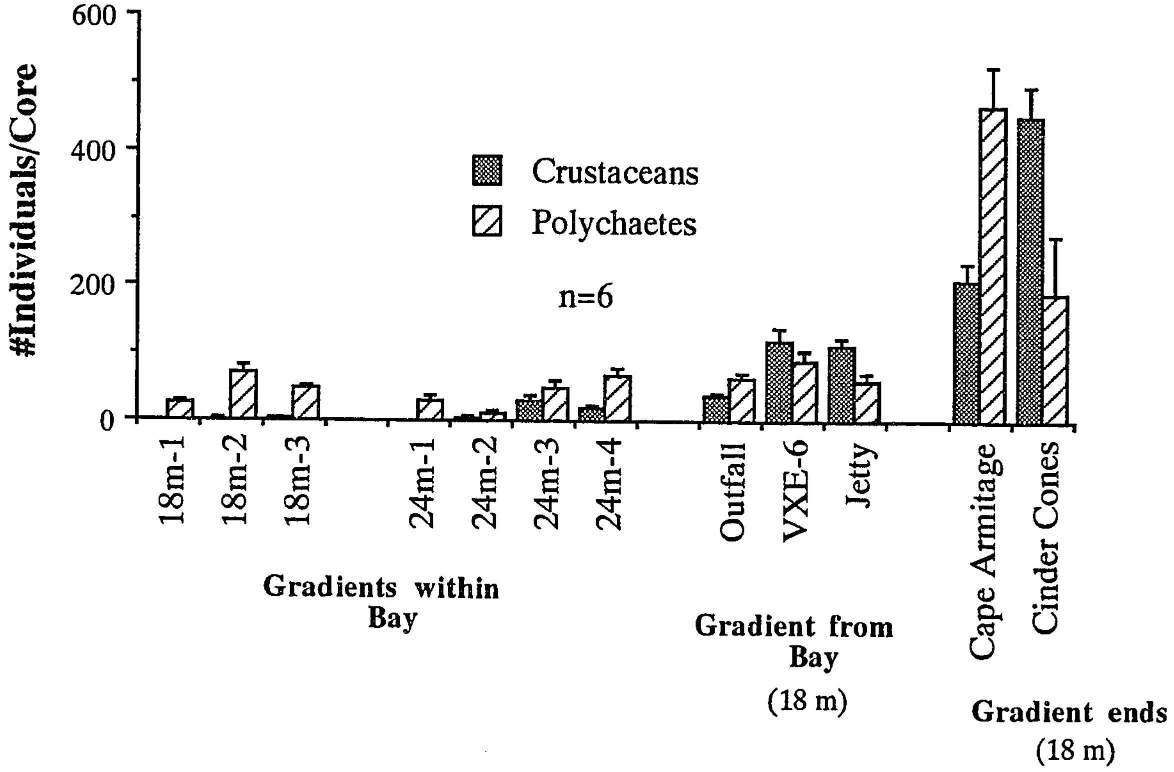

Figure 1. Total numbers of crustaceans and polychaete worms along several contamination gradients around McMurdo Station. Means and one standard error based on six replicate core samples (0.0075 m^2) taken at 18 m and 24 m water depth.

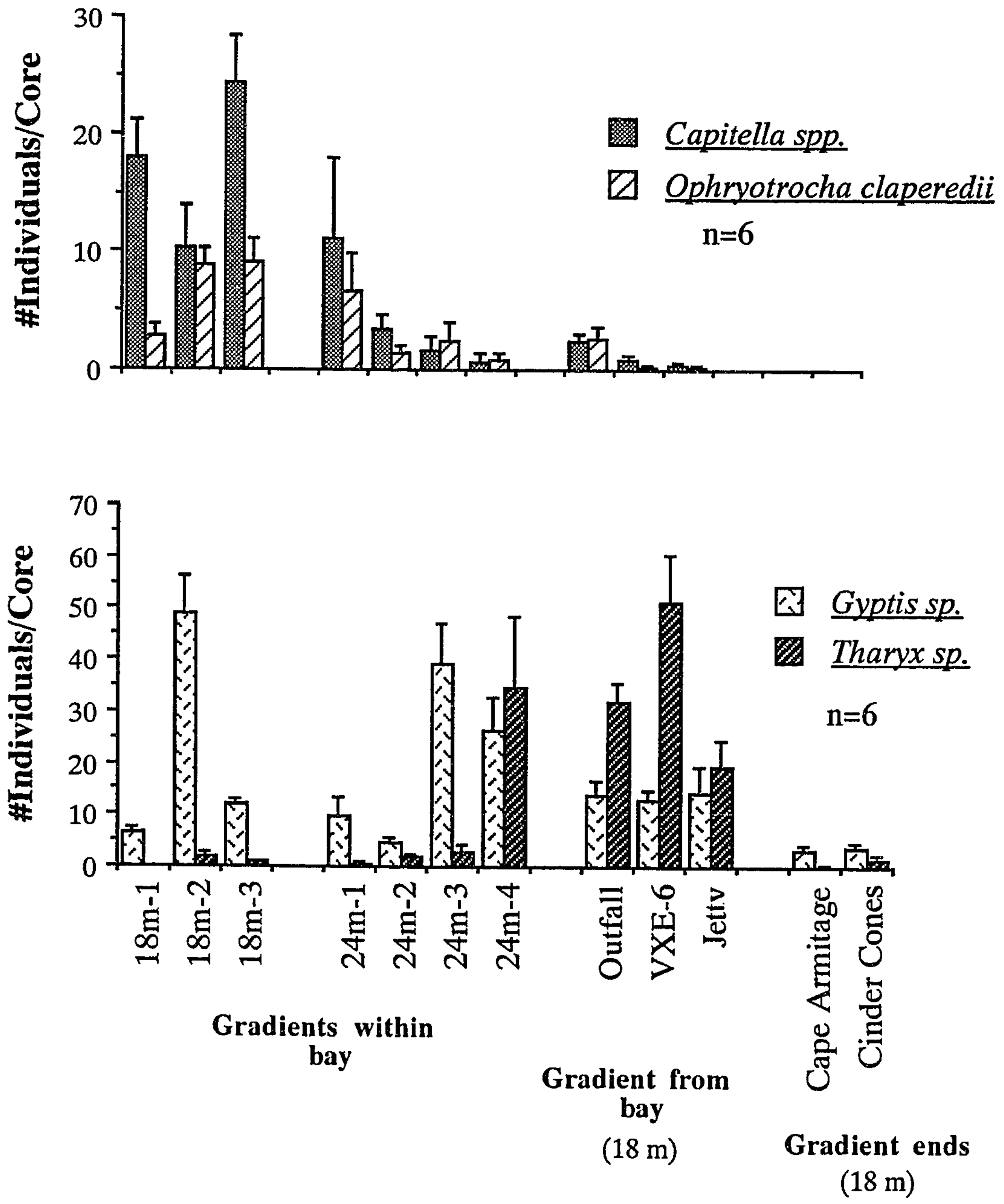

Figure 2. Total numbers of the opportunistic polychaete worms Capitella spp., Ophryotrocha claperedii, and Gyptis sp. and the intermediate opportunistic polychaete worm Tharyx sp. along several contamination gradients around McMurdo Station. Means and one standard error based on six replicate core samples (0.0075 m^2) per site at 18 m and 24 m water depth.

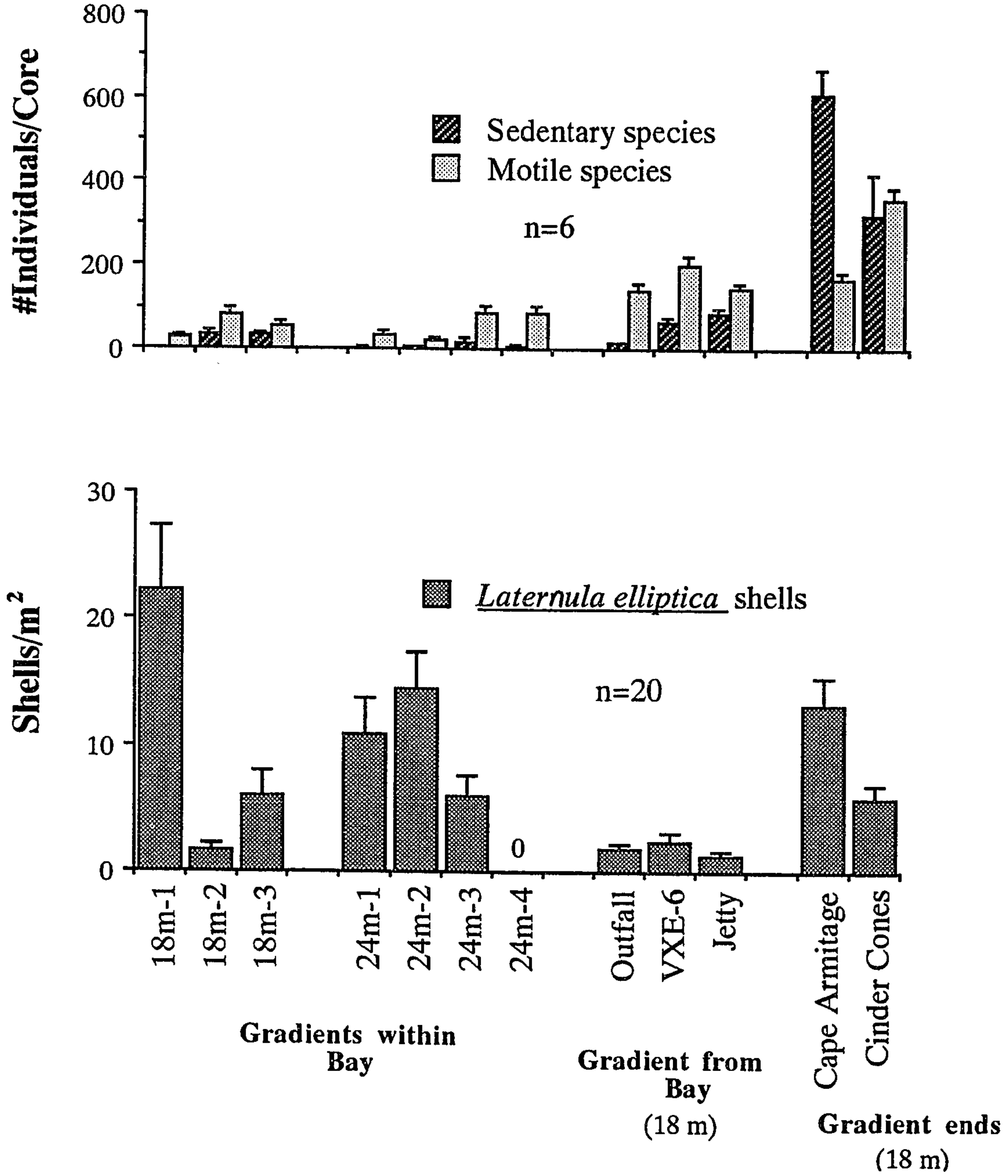

Figure 3. Total numbers of sedentary and motile infauna, and numbers of empty clam shells (*Laternula elliptica*) on the seafloor along several contamination gradients around McMurdo Station. Infaunal means and one standard error based on six replicate core samples (0.0075 m^2). Shell means and one standard error based on twenty replicate photographs (1 m^2). All samples collected at 18m and 24m water depth.

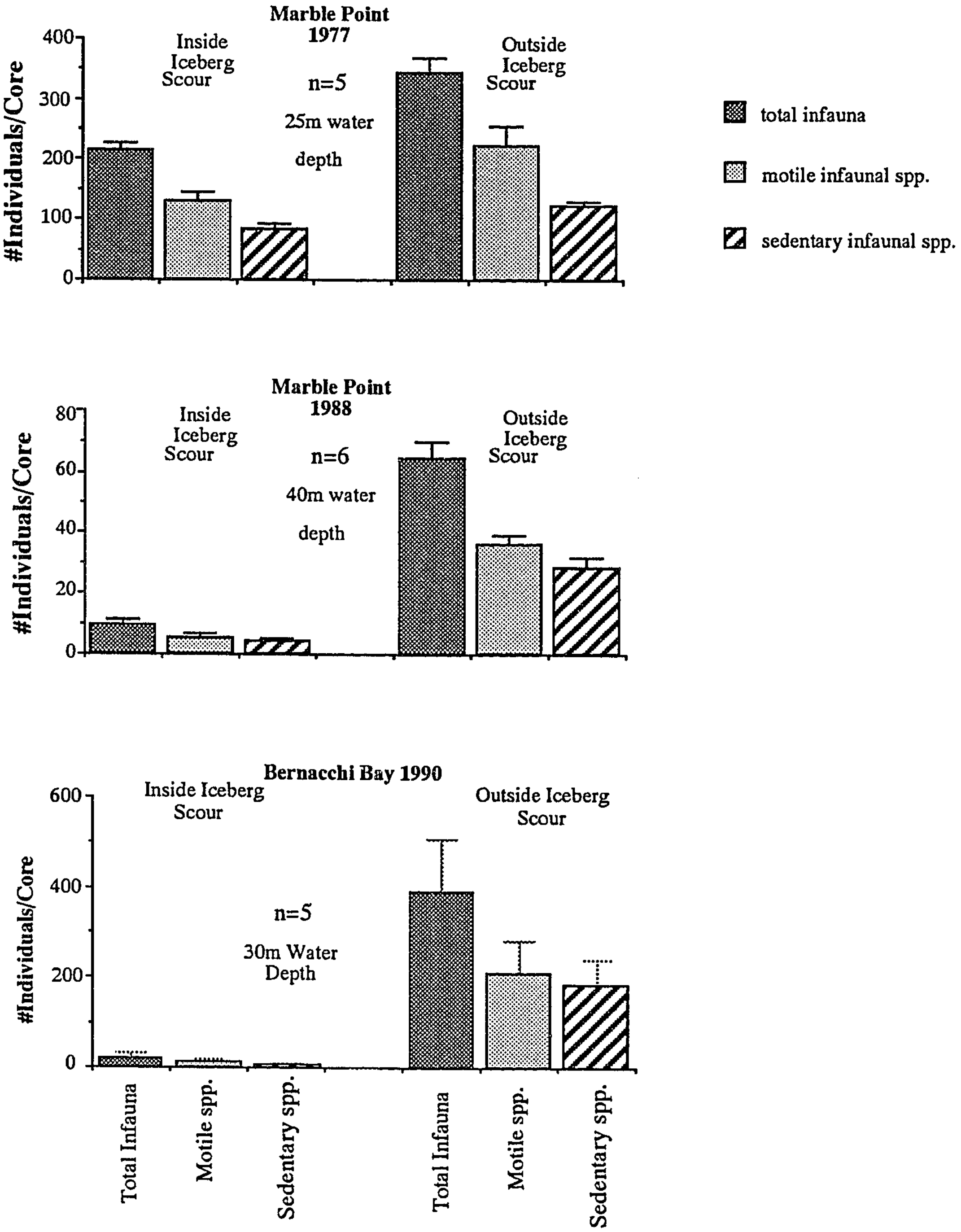

Figure 4. Changes in infaunal communities inside and outside areas gouged by icebergs. Means and one standard error based on _n_ replicate core samples (0.0075 m^2) per site. Note differences in scale between graphs.

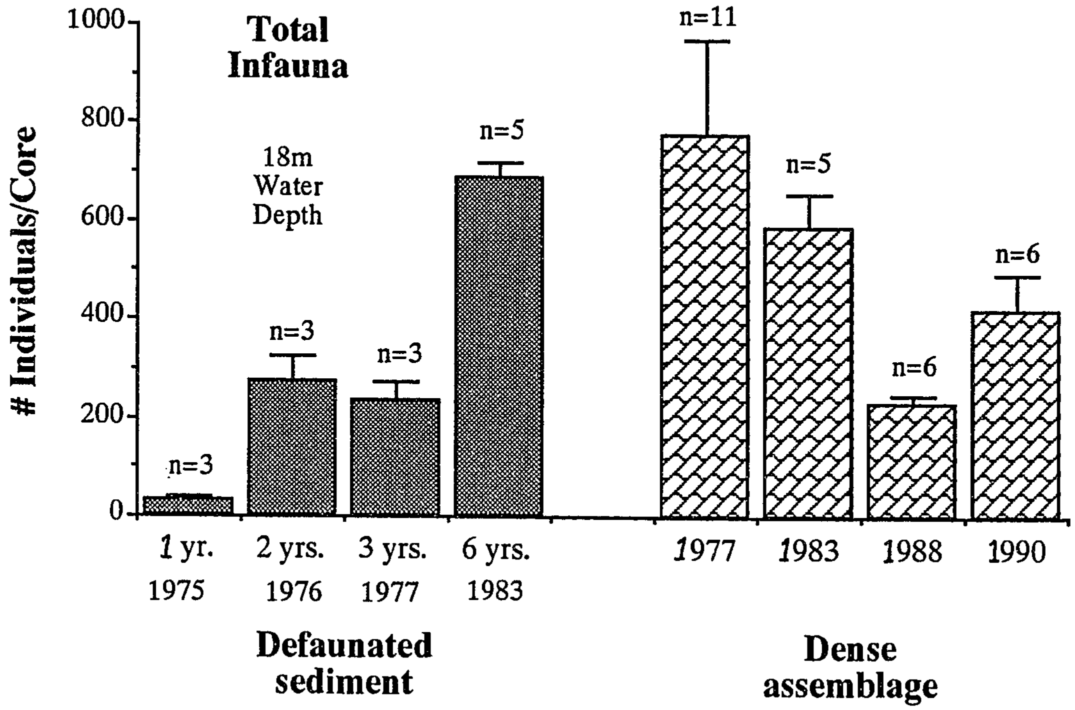

Figure 5. Colonization of infauna to defaunated sediments after one to six years of exposure at the Jetty. Experiments began in 1974 and were placed at 18 m water depth. The surrounding dense assemblage was sampled four times during 1977-1990. Means and one standard error based *n* core samples (0.0075 m^2).

Chapter 3

PATTERNS OF SURVIVAL AND BEHAVIOR IN ANTARCTIC BENTHIC INVERTEBRATES EXPOSED TO CONTAMINATED SEDIMENTS: FIELD AND LABORATORY BIOASSAY EXPERIMENTS

INTRODUCTION

In recent years, single species laboratory bioassays have emerged as a widespread and standardized indicator of biological stress associated with waste discharges into aquatic environments (e.g., EPA 1990). The most widely used bioassays compare survival patterns of test animals in contaminated and uncontaminated habitats. In the marine benthic environment, amphipod crustaceans are often used as test animal to determine the level of chemical stress placed on sedimentary habitats (Swartz et al. 1979, 1984, 1985). However, these tests are rarely related to natural populations or community patterns in nature (Kimball and Levins 1985, but see Swartz et al. 1986). Furthermore, if animals are not killed in short-term (usually 10 to 30 days) laboratory bioassays, this does not address longer-term survival patterns or potential non-lethal impacts of pollution to reproduction or behavior which may be equally important to the survival and persistence of populations and communities (Underwood and Peterson 1988). Thus, although laboratory bioassays have become a tool for regulating and evaluating the impacts of marine pollution, their relation to field conditions and natural chemical and biological patterns is poorly explored.

Our goal was to determine if standard laboratory bioassays are valuable as tools in evaluating and predicting the impacts of contaminants on the biological structure of natural communities. We use as a model system the infaunal species, communities, and sedimentary habitats located along a steep and well-defined pollution gradient at McMurdo Sation, Antarctica (Chapters 1 and 2, Lenihan et al. 1990, Risebrough et al. 1990, Lenihan 1993, Lenihan and Oliver, in press). We compared the patterns of survival of amphipods in laboratory bioassays to patterns of cytological and histopathological measures, reproduction, survival, and behavior exhibited by a suite of infaunal species used in a wide range of laboratory and field experiments. We also compared the patterns of amphipod survival to patterns of community change occurring in a long-term field transplant of whole, intact infaunal communities. Herein, we report our results excluding those concerning cytology, histopathology, reporduction and sexual behavior of amphipods exposed to contaminated sediments from McMurdo Sation.

Our main test animal was the amphipod Heterophoxus videns K.H. Barnard (Gammaridea: Phoxocephalidae) which is an important predator of smaller crustaceans, polychaetes, and newly settled larvae in soft-sediment communities in McMurdo Sound (Oliver and Slattery 1985). This species is similar to Rhepoxynius abronius (J.L. Barnard) another phoxocephalid amphipod, commonly used in sediment bioassays conducted in temperate latitudes (Swartz et al. 1984, 1985). These species are similar with respect to morphology, reproduction, escape behavior, and feeding ecology (Oliver et al. 1982, Oakden et al. 1984a,b, Slattery 1985, and Oliver and Slattery 1985). These similarities yield a comparability between the results of our study and those from bioassays conducted in temperate latitudes. An important difference between the two species is that Heterophoxus inhabits areas that contain fewer infaunal predators, less structural complexity, and lower levels of physical disturbance than temperate latitudes (Dayton et al. 1971). Consequently, there may be fewer direct and indirect interactions between infaunal species in Antarctic systems (Strauss 1991, Scheoner 1993). If the results of our bioassays using Heterophoxus do not provide a reasonable method for evaluating the effects of pollution in Antarctic benthic communities, it is very unlikely that similar tests using Rhepoxynius are useful in temperate, more complex ecosystems.

We tested two general hypotheses that (1) spatial variation in the survival of amphipods is attributable to sediment contamination, and (2) that the spatial differences in survival are related to the concentrations of pollutants. We also tested the hypotheses that (3) patterns of survival in a suite of laboratory and field survival and behavior experiments reflect the results of standard bioassay experiments and (4) that rich and abundant infaunal communities transplanted along the pollution gradient and exposed for a full year will have fewer total individuals and species at contaminated sites compared with uncontaminated sites.

METHODS

Study Sites

We have recently documented changes in the physical and chemical characteristics of marine sediments and benthic community patterns around McMurdo Station in several papers (Chapters 1 and 2, Lenihan et al. 1990, Risebrough et al. 1990, and Lenihan and Oliver, in press). We found that a steep gradient of chemical contamination began in Winter Quarters Bay (Figure 1 of Chapter 1) where hydrocarbon concentrations in sediments were as high as 4500 $\mu g \cdot g$ sediment^{-1}. Contaminant levels fell sharply outside of this small bay and were undetected at stations located 1 km and 9 km away (Chapter 1, Lenihan et al. 1990). Concentration of PCBs (Risebrough et al. 1990) and several metals (e.g., Zn, Cu, and Pb; Lenihan et al.1990) were also high in Winter Quarters Bay and exhibited gradients of contamination similar to hydrocarbons (Lenihan et al. 1990).

Patterns of benthic invertebrate communities along the pollution gradient appeared to be strongly influenced by chemical disturbance (Chapter 2, Lenihan and Oliver, in press). In the highly contaminated back portion of Winter Quarters Bay only a few species of polychaete worms with opportunistic life histories were found in low abundances. Stations near the sewage outfall with intermediate levels of contamination supported communities of intermediate opportunistic polychaetes, crustaceans, and anthozoans. Uncontaminated sites such as the Jetty station (Figure 1 of Chapter 1) supported densely populated infaunal assemblages with high species diversity. Heterophoxus videns is found most commonly in chemically undisturbed habitats but a few individuals can be found in all areas along the pollution gradient (Chapter 2 and Author, personal observation).

Sediment collection

We collected sediments from stations that were highly, moderately, and uncontaminated with hydrocarbons and heavy metals and exposed invertebrates to them in standard laboratory bioassay experiments (e.g., Swartz et al. 1985). In November 1990 and 1991, we collected sediments in Winter Quarters Bay, near the sewage outfall, and at the seawater intake jetty and Cape Armitage (Figure 1 of Chapter 1). All sediment collections were made at 18 m water depth by divers who scraped the sediment surface to a depth of 5 cm with HCl-cleaned polyethylene buckets. Sediments were brought to the surface, transported to the laboratory, and passed through 0.25 mm mesh screen to remove infauna. Sediments were homogenized and allowed to settle in a cold room (-1.0°C) for 24 hrs., after which, the surface water was carefully decanted and aliquots were dispensed into test containers using an HCl-cleaned teflon trowel. These sediments were used in laboratory experiments.

Invertebrate collection

Heterophoxus videns was the main species used in our standard laboratory bioassays, field bioassays, and behavioral experiments. In areas adjacent to Winter Quarters Bay, the density of H. videns ranges from 1500 to 2500 animals per m^2 but it is rarely found in chemically or physically disturbed habitats.

Patterns of survival and behavior were also studied for another predaceous and burrowing amphipod, Monoculodes scabriculosus K.H. Barnard (Oedicerotidae), a tube dwelling tanaid crustacean, Nototanais dimorphous Beddard (Tanaidea: Tanaidae), and a surface active, surficial burrowing cumacean crustacean, Eudorella splendida Zimmer (Cumacea). An additional set of behavioral experiments was conducted with the infaunal heart urchin, Abatus shackletoni Koehler (Echinodermata: Echinoidea). Divers collected most species near Cape Armitage by excavating sediments and passing it through 500 um mesh in the laboratory. A. shackletoni was collected at Cinder Cones (Figure 1 of Chapter 1) where it was most abundant. All animals were placed in flow-through holding aquaria containing defaunated clean sediment.

In December 1990, whole and intact infaunal communities from the Jetty were transplanted along the pollution gradient to compare changes in community structure. These communities contained the crustaceans used in the bioassays, other crustaceans (including several species of isopods and copepods), polychaetes, oligochaetes, protozoans, molluscs, and a priapulid.

Laboratory experiments

We measured the survival of crustaceans exposed to sediments collected along the pollution gradient in laboratory bioassay experiments similar to those conducted in pollution assessment studies in temperate latitudes. In standard U.S. Environmental Protection Agency sediment bioassay experiments amphipods, usually Rhepoxynius, are placed within 1 L glass beakers containing static seawater and 2 cm of sediment collected from the test site and the number of survivors are counted after 14-28 days.

We conducted three experiments to measure survival of three infaunal invertebrates exposed to various sediments; two pilot studies of 14 and 21 days, and a 28 day experiment with Heterophoxus videns, Monoculodes scabriculosus, Nototanais dimorphous, and Eudorella splendida. All of our laboratory experiments were performed in flow-through aquaria. Cylindrical polyethylene containers (10 cm wide; 16 cm deep) were first washed with microclean detergent, soaked in 15% HCl for 24 hrs, and rinsed with deionized water. They were then fitted with a 0.25 mm mesh screen cylinder, filled with a 2 cm layer of the prepared sediment, and placed within aquaria (40 cm x 60 cm or 90 cm x 90 cm by 25 cm deep) which remained at a constant -1.5°C temperature throughout all experiments. Tops of the fitted screens extended above the surface of the water to prevent animals from escaping. Water flow ranged from 0.15 to 0.20 L per sec. and was 34.7‰ salinity. Animals were then added by hand to each container. At the end of the test period containers were removed from the aquaria and the sediment was passed through 0.5 mm mesh to collect the animals.

In the 14 day pilot study in November 1990, we placed 20 Heterophoxus videns together with 10 Eudorella splendida and 10 Nototanais dimorphous in each of four replicate containers filled with sediment from either heavily contaminated Winter Quarters Bay, the moderately contaminated Transition zone (Figure 1 of Chapter 1), near the sewage outfall (Outfall), or two uncontaminated stations, the Jetty and Cape Armitage. We ran a similar 21 day pilot experiment in December 1990 using 20 H. videns together with ten E. splendida exposed to sediments from Winter Quarters Bay and Cape Armitage (n=4). The percentage of living amphipods, cumaceans, and tanaids was recorded at the end of each test.

In November-December 1991, we conducted a 28 day experiment with Heterophoxus videns only. Twenty animals were placed in sediment from Winter Quarters Bay, the Transition, the Outfall, the Jetty, and a fine fraction of Jetty sediment (texture corresponding to that of Winter Quarters Bay) (n=6). The majority of Winter Quarters Bay sediment (by weight) is within a size range below 64 µm in diameter (Chapter 1, Lenihan et al. 1990). To compare the effect of grain size on tests, a fine fraction of Jetty sediment was produced by washing it through 64 µm mesh screen. During the same time period, we ran similar 21 day tests for both adult and juvenile Monoculodes scabriculosus.

Burrowing behavior of amphipods

The number of burrowing Heterophoxus videns in the 28 day bioassay experiment was recorded twice daily to compare changes caused by sediment contamination. Animals not on or above the sediment surface were considered buried. This was an accurate method of measuring burrowing because dead animals were always found on the sediment surface and were usually discolored.

Sediment choice experiments

We compared the preference in the laboratory of Heterophoxus videns, Monoculodes scabriculosus, Eudorella splendida, and Nototanais dimorphous for sediments collected along the pollution gradient. Animals were able to choose between two sediments during three days in containers designed to hold equal amounts of two sediment types. In November 1990 and 1991, polyethylene containers similar to those used in bioassays were fitted with stainless steel dividers vertically positioned to produce two chambers. Enough sediments in various combinations were placed into the chambers to form 2 cm thick layers. The dividers were removed carefully to avoid mixing sediments. The containers were placed into aquaria and animals added to one side. In contrasts of contaminated and clean sediment, 5 to 10 animals were placed first into the contaminated side. To determine if animal movements were an artifact of the experimental method, we ran the same test using clean sediment from Jetty and Cape Armitage placed together (i.e., Jetty vs. Jetty and Cape Armitage vs. Cape Armitage). To test for grain size preferences, we compared the natural Jetty to a fine fraction of Jetty sediments. Oakden et al. (1984) successfully used these methods for Rhepoxynius abronius. Sediment combinations and levels of replication are given in the results.

Escape behavior of Nototanais

The escape response of Nototanais dimorphous exposed to contaminated sediments was assessed in the laboratory. In the choice experiments we noticed the tendency of N. dimorphous to swim away or climb container walls away from toxic sediments but burrow into cleaner sediments. Therefore, in December 1991 we compared this behavior in containers holding sediment from Winter Quarters Bay and the Jetty. Twenty animals were placed in each sediment type (n=5) and their behavior was recorded twice daily for five days.

Burrowing behavior of Abatus

The burrowing behavior of the heart urchin, Abatus shackletoni, was compared in the laboratory in sediments from two stations located along the pollution gradient. In December 1991, sediments from Winter Quarters Bay and North Jetty (Figure 1 of Chapter 1) were placed in plastic containers (441 cm^2 x 8 cm deep; sediment 6 cm in depth; n=4). Containers were placed into an aquarium and four urchins were added to each replicate. The number of urchins buried or remaining on the sediment surface was recorded once a day for seven days. An urchin was considered buried if more than one half of its test was below the sediment surface.

Field experiments

Bioassays

We tested the survival of Heterophoxus videns and Eudorella splendida exposed to contaminated sediments in Winter Quarters Bay in two field experiments. We modified 1 L plastic nalgene bottles to produce two types of mesocosms: one with the bottom removed to allow direct exposure to the seafloor, and the other to hold a 2 cm thick layer of clean sediment. Both types of containers had large openings cut into their sides which were fitted with 0.25 mm mesh screen to allow water flow through. Replicate containers (n=4 or 6) were placed at 18 m water depth in Winter Quarters Bay in the following three treatments. One group without bottoms was placed directly on the undisturbed seafloor while another group without bottoms was placed on areas of the seafloor where a diver had gently removed the top 2 cm layer of sediment with a teflon trawl. This was done to eliminate other benthic animals and to remove potentially the most toxic layer of sediment (Chapter 1, Lenihan et al. 1990, Fairey et al., unpublished data). Containers were haphazardly interspersed in a 16 m^2 area. After the containers were placed in position, H. videns and E. splendida were added to each by divers for a 10 day bioassay. Only H. videns was used in a 28 day bioassay. These animals do not inhabit Winter Quarters Bay (Chapter 2, Lenihan and Oliver, in press). Animals collected several days before at Cape Armitage were taken from containers in the laboratory and placed in 250 ml glass jars containing a sprinkle of Jetty sediment 1 mm in depth. A glass jar containing the appropriate number of animals was fitted to each bottle and left in place, effectively capping them. All animals immediately swam down to the seafloor or sediments provided.

Twenty Heterophoxus videns and 10 Eudorella splendida were used together in a 10 day experiment in January 1991 and 20 H. videns were used alone in a 28 day experiment in December 1991. Containers were hand collected by divers who capped the open-bottomed treatments, returned them to the laboratory, and removed the animals by passing sediments through 0.25 mm mesh screen. For each container, we recorded the number of living, moribund, or dead individuals

Community transplants

Whole communities from the dense infaunal assemblage at the Jetty were transplanted in highly contaminated Winter Quarters Bay, at the intermediately contaminated Transition area, and at the clean Jetty to compare changes in infaunal abundances and species composition at these locations. In November 1990, divers excavated replicate 441 cm^2 areas at 18 m water depth and placed them underwater in cleaned plastic containers (Rubbermaid ^{TM}) with snap-on lids. The containers were brought to the surface and transferred to transplant sites. The containers were placed on the seafloor so that the sediment surface within them sat flush with the seafloor. Four replicates were placed at each station. A set of replicates was then returned to the Jetty and placed in position in the same manner. In November 1991, divers retrieved the containers and sampled them and the undisturbed Jetty community with cores (0.0075 m^2, n=4). The cores were sieved through 0.5 mm mesh screening and the animals preserved in 5% formalin. The animals were later sorted, identified to species, and counted.

Burrowing behavior of Abatus in the field

The burrowing behavior of Abatus shackletoni was measured in the field by placing urchins collected at Cinder Cones within corrals placed on the seafloor in Winter Quarters Bay, at North Jetty, and at Cinder Cones (10 urchins per corral; n=4). All corrals (1 m^2) were circular enclosures made of Vexar 1 cm plastic mesh 85 cm in height. Divers placed them on the seafloor by driving the edges 35 cm into the sediment to prevent the urchins from escaping or entering. The urchins were unable to climb the Vexar mesh. All corrals were placed in 36 m^2 areas at 15 m water depth. Only healthy, active urchins which had been collected 48 hrs. prior to the experiment were used. The number buried was recorded every 24 hrs. by divers for five days using the same criteria developed in the laboratory. There was no mortality of urchins in either treatment.

Statistical analysis

We tested the differences in mean numbers of animals surviving in laboratory and field bioassay experiments with one way model 1 ANOVAs (Underwood 1981). Homogeneity of variances were tested with Cochran's method and where variances were heteroscedastic they were were transformed by square root or natural log. We used Student-Newman-Keuls'*post hoc* multiple comparisons tests to find significant differences between individual treatments. We tested the mean number of exposed Heterophoxus videns in burying behavior experiments, mean number of Abatus shackletoni burying in field and laboratory experiments, and mean number of tanaids climbing the sides of containers with one way model 1 ANOVAs using only the values from the final count. For sediment choice experiments, we tested mean percent of animals on the side not initially receiving animals with a one way model 1 ANOVA. Mean percents were converted to proportions and transformed using the arcsin of the square of the value. When variances remained only slightly heteroscedastic after transformation, they were re-tested in a one way ANOVA at the alpha level of 0.01 (Underwood 1981). Finally, we tested mean differences in total abundance, numbers of several taxonomic groupings, key species, and total number of species in the community transplant experiment with one way Model I ANOVAs.

RESULTS

Standard laboratory bioassays

After 28 days exposure in the laboratory in 1991, the survival of Heterophoxus videns was greatly reduced in sediments from Winter Quarters Bay and near the sewage outfall (Figure 1). Percent survival of H. videns was significantly less in sediments from contaminated Winter Quarters Bay and the sewage outfall (ANOVA; $F_{4,25}= 6.698$, $p=0.0008$, $n=6$; SNK $p<0.05$) compared with survival in uncontaminated Jetty and less contaminated Transition sediment. There was no significant difference in the percent survival of animals placed in natural and the fine fraction of Jetty sediments (SNK $p>0.05$) and these treatments did not differ from the Transition (SNK $p>0.05$).

Results from the 28 day laboratory bioassay differed from those from similar 14 day and 21 day experiments conducted in 1990. After 14 days, survival of 20 Heterophoxus videns across all treatments was 97.5±3.2% and was not different in sediments collected from along the pollution gradient (ANOVA; $F_{4,15}=0.75$, $p=0.575$, $n=4$). Survival of the cumacean Eudorella splendida and the tanaid Nototanais dimorphous exposed with H. videns in the same containers was nearly as high as for the amphipods. In a 21 day experiment comparing animals in sediments from Winter Quarters Bay and Cape Armitage, percent survival of H. videns (68.7%±20.0% for Winter Quarters Bay vs. 100% for Cape

Armitage; 20 animals; n=4) was not significantly different at the alpha level 0.01 (ANOVA; $F_{1,6}=5.87$, $p=0.517$, $n=4$) but showed a trend of lower survival in contaminated sediments with increasing time of exposure.

The pattern of survival of the amphipod Monoculodes scabriculosus after being exposed to Jetty and Winter Quarters Bay sediments for 21 days in the laboratory in 1991 was similar to that in 28 day tests with Heterophoxus videns (Figure 2). Both adults and juvenile M. scabriculosus had a significantly higher percent survival in Jetty than Winter Quarters Bay sediments (ANOVAs; $F_{2,12}=8.234$, $p=0.005$, $n=5$ for adults, and $F_{2,6}=11.454$, $p=0.001$, $n=3$ for juveniles, SNKs $p<0.05$). There was no significant difference in survival between Jetty and Jetty fine sediments (SNK $p>0.05$). Patterns of activity of surviving M. scabriculosus were similar to that seen in H. videns.

Laboratory behavior experiments

Heterophoxus videns consistently avoided contaminated sediments in habitat choice experiments run for three days in the laboratory in 1991 (Table 1; ANOVA; $F_{4,15}=5.935$, $p=0.0045$, $n=4$). A greater percentage of surviving amphipods chose uncontaminated Jetty sediments (natural and fine fraction) over contaminated Winter Quarters Bay and Outfall sediments (SNK $p<0.05$). There were no significant differences in the percentage of animals found on either side of the Jetty-Jetty or Jetty-Jetty fine sediment control treatments ($P>0.05$). Overall mortality of amphipods was low. This group of habitat choice experiments for H. videns included Monoculodes scabriculosus and Eudorella splendida; ten of each species of animals were placed with the 20 H. videns in each container. M. scabriculosus showed no preference between sediment treatments (ANOVA; $F_{2,9}=2.742$, $p=0.068$, $n=4$, tested at alpha level 0.01) Mortality of M. scabriculosus and E. splendida was generally high and the cause of this pattern is unknown.

Heterophoxus videns and Eudorella splendida chose uncontaminated Cape Armitage sediment over Winter Quarters Bay sediment in experiments run in 1990 (Table 2; ANOVA for H. videns; $F_{1,4}=37.95$, $p=0.0035$, $n=3$, E. splendida; $F_{1,4}=38.72$, $p=0.0034$, $n=3$). In tests without a control treatments, H. videns, E. splendida, and Monoculodes scabriculosus all chose Jetty over Winter Quarters Bay sediments (Table 2). Overall survival of animals varied but was generally lower than in 1991. Mortality of H. videns was always lower than for other species when the animals were tested together.

More Heterophoxus videns burrowed below the sediment surface in Jetty sediments than animals in Winter Quarters Bay and Outfall sediments during the 1991 28 day laboratory bioassay experiment (Figure 3). A significantly greater number of living H. videns were buried in Jetty sediments (ANOVA; $F_{2,15}=25.991$, $p=0.0001$, $n=6$) compared with those buried in the two contaminated sediments (SNK $p<0.05$) when behavioral recordings were terminated on day 24 of the experiment. All animals counted in this experiment were alive. If these results are compared with the percent surviving in the 28 day bioassays (Figure 1), it is evident that much of the mortality in contaminated sediments occurred during the last four days of the experiment.

In a similar laboratory experiment conducted in 1991, every heart urchin, Abatus shackletoni, burrowed completely or partially within uncontaminated sediments from the North Jetty (Figure 4). In contrast, several animals were found on the surface of Winter Quarters Bay sediment at each daily recording. A greater percentage of urchins were positioned with 1/2 or more of their tests above the sediment-water interface in Winter Quarters Bay sediment than in North Jetty sediment on the final day of the experiment (50.0±10.2% vs. 0%). All animals survived this test.

In our final laboratory behavioral experiment, we found that a greater percentage of tanaids, Nototanais dimorphous, had climbed or swam away from the sediment water interface when exposed to Winter Quarters Bay sediment than when exposed to the fine fraction of Jetty sediment (Figure 5). At the end of the five day experiment, 35.0±7.4% of the tanaids in Winter Quarters Bay were found on the screen material while all living animals were buried in Jetty sediment. There was a greater than 95% survival rate of tanaids in both treatments.

Field Bioassays

Survival of Heterophoxus videns and Eudorella splendida in a 10 day field bioassay experiment was similar in pattern to that seen in the 28 day laboratory bioassay (Figure 6 and compare to Figure 1). Percent survival of H. videns was slightly higher in Jetty sediment (87.5±2.5%) placed in closed containers on the seafloor in Winter Quarters Bay compared with survival in the Winter Quarters Bay sediment. The difference was not statistically comparable because of heteroscedasticity of variances. Survival was also slightly lower in undisturbed surface sediment (37.5±18.9%) than in sediments with the top two cm removed (60.0±10.0%). All experimental animals were recaptured and counted. The surviving animals in surface and surface-scraped treatments appeared moribund while those in the control treatment appeared healthy.

No Eudorella splendida survived in surface sediments in Winter Quarters Bay. A greater percent of cumaceans survived in controls compared with the surface-scraped sediment treatment (ANOVA; $F_{2,9}$=14.486, p=0.0015, n=4, SNK p<0.05). All animals were accounted for at the end of the experiment.

In 1991, survival of Heterophoxus videns in contaminated Winter Quarters Bay was also low in a 28 day field bioassay conducted under the same conditions as those used in 1990.

There was relatively high mortality of amphipods in uncontaminated Jetty sediments (40.0±12.6%). Consequently, there was no significant difference in survival between contaminated and uncontaminated treatments (ANOVA; $F_{2,15}=0.226$, $p=0.800$, $n=6$, 20 amphipods per treatment). Jetty sediment used in the 28 day field and in laboratory bioassays appeared to be richer in organic matter in December than in January and smelled of sulfides.

Community transplants

Total numbers of infauna in the community transplant experiment after one year of exposure at the Jetty were greatest in the unmanipulated natural community compared with the transplanted communities (Table 3). The differences in infaunal abundances across all treatments, however, were not statistically significant (ANOVA; $F_{3,12}=0.42$, $p=0.7432$, $n=4$; SNK $p>0.05$). The relatively narrow range of numbers of total infauna indicated that the experimental containers provided an adequate habitat for infaunal life.

In contrast to the similarity in total infaunal abundance, numbers of species differed greatly amongst transplant treatments.Those placed in Winter Quarters Bay contained the fewest number of species after one year compared with the other transplants and the undisturbed Jetty community (Table 3; ANOVA; $F_{3,12}=10.62$, $p=0.001$, $n=4$; SNK $p<0.05$). Differences in the number of species in transplants placed at the Transition, Jetty, and the undisturbed Jetty community were not significantly different (SNK $p>0.05$).

There were no significant differences in the total numbers of polychaetes among transplant treatments (ANOVA; $F_{3,12}=2.109$, $p=0.1524$, $n=4$). Within transplants to Winter Quarters Bay, polychaete worms accounted for nearly 94% of the total abundance (Table 3) and the most abundant was Ophryotrocha claperedii (Dorvilleidae). This species has an opportunistic life history (see Chapter 2 and Oliver 1980), is found within the natural and depauperate Winter Quarters Bay community, and is common in polluted soft-sediments throughout temperate latitudes (Chapter 2). Numbers of O. claperedii were greater within transplants to Winter Quarters Bay than in transplants to other locations (ANOVA; $F_{3,12}=52.52$, $p=0.0001$, $n=4$, SNK $p<0.05$).

Two species of polychaetes with intermediate opportunistic life histories, Gyptis sp. (Hesionidae) and Tharyx sp. (Cirratullidae), were most abundant in transplants placed at the intermediately contaminated Transition (Table 3). Species with intermediate opportunistic life histories have moderately short generation times, moderate proportions of ovigerous individuals, larval availability, and good colonizing ability (see Chapter 2, and Oliver 1980, p. 260). Numbers of Gyptis sp. in transplants to the Transition were significantly greater than in all other treatments except those placed at the Jetty (ANOVA; $F_{3,12}=14.08$, $p=0.0003$, $n=4$, SNK $p<0.05$). Numbers of Tharyx sp. did not differ significantly between transplants and the undisturbed community (ANOVA; $F_{3,12}=2.888$, $p=0.795$, $n=4$).

The most abundant polychaete species in the natural Jetty community was the tube building Myriochele cf. heeri (Oweniidae). There were significantly fewer numbers of M. cf. heeri in transplants to Winter Quarters Bay (ANOVA; $F_{3,12}=176.216$, $p=0.001$, $n=4$) compared with all stations (SNK $p<0.05$). Numbers of M. cf. heeri in the undisturbed Jetty community and Jetty transplants were not different (SNK $p>0.05$) but numbers in both were greater than in transplants to the area (SNK $p<0.05$).

There were greater numbers of crustaceans in the transplants to the Jetty and in the undisturbed Jetty community than in transplants to Winter Quarters Bay and the Transition area (Table 3). There was a significantly lower number of total crustaceans in transplants to Winter Quarters Bay than to transplants to other areas (ANOVA; $F_{3,12}=11.34$, $p=0.0008$, n=4, SNK p<0.05). Jetty transplants had greater numbers of crustaceans than Transition transplants (SNK p<0.05). The most abundant crustacean in all treatments was Nototanais dimorphous, which is a common tube building predator of soft-bodied polychaetes in shallow subtidal benthos around Ross Island (Oliver and Slattery 1985). The greatest numbers of N. dimorphous were found in transplants to the Jetty transplants and in the undisturbed Jetty community compared with transplants to Winter Quarters Bay and the Transition (ANOVA; $F_{3,12}$=12.266, p=0.0006, n=4, SNK between Jetty treatment and control not significant at p>0.05). Very few tanaids were found within transplants to Winter Quarters Bay.

Another common crustacean in undisturbed and intermediately disturbed benthic communities was the isopod Austrosignum grande (Lenihan and Oliver, in press). This species was significantly less abundant in transplants to Winter Quarters Bay compared to all other treatments and the control (ANOVA; F3,12=12.388, p=0.0006, n=4, SNK p<0.05), but abundances were not different in stations outside of the bay (SNK p>0.05).

The most important crustacean predator in dense assemblages, Heterophoxus videns (Oliver and Slattery 1985), is not found in the natural Winter Quarters Bay community (Chapter 2, Lenihan and Oliver, in press) and none were found in transplants to Winter Quarters Bay after one year (Table 3). H. videns was most abundant in the undisturbed Jetty community but differences in abundance between all stations outside of the bay were not significant at the alpha level 0.01 (ANOVA; $F_{2,9}$=3.35, p=0.08, n=4).

Field behavioral bioassay

A greater number of Abatus skackletoni buried in the seafloor at uncontaminated North Jetty and Cinder Cones than in Winter Quarters Bay (Figure 7; ANOVA, $F_{2,9}$=19.807,

$p=0.0005$, $n=4$, SNK $p<0.05$). There was no difference in the number burying in the two uncontaminated sites (SNK $p<0.05$). All animals were alive at the end of the experiment.

DISCUSSION

The patterns of amphipod survival in standard laboratory bioassay experiments appeared to be attributable to the spatial patterns of sediment contamination along the McMurdo Station pollution gradient. Furthermore, the patterns of amphipod survival strongly corresponded with patterns of survival and behavior in field and laboratory bioassays which used amphipods or other species common to the shallow subtidal benthos of McMurdo Sound. The amphipods and other infaunal species we tested had low rates of survival and altered behaviors when exposed to sediments from or within Winter Quarters Bay, an area with extremely high levels of hydrocarbons and other anthropogenic chemicals (Chapter 1, Lenihan et al. 1990, Risebrough et al. 1990). The same species had moderate changes in survival and behavior in sediments from intermediately contaminated sites and most survived and behaved normally in uncontaminated sediments. This pattern was documented in the standard laboratory bioassay; in the similar field bioassay; in the laboratory behavioral bioassays involving habitat selection, burrowing, and swimming; in the field behavioral bioassay; and in the one-year community transplant experiment in the field.

The laboratory and field results clearly reflected the dramatic changes in the structure of bottom communities along the pollution gradient. Amphipods are not found in sediments which produced high rates of mortality in field and laboratory experiments nor in sediments that amphipods and other species actively avoided. The similarities between experimental results and community patterns are most striking within the community transplant experiment. After one year of exposure on the seafloor, most of the jetty animals transplanted to Winter Quarters Bay disappeared, probably through emigration or death.

These transplanted communities lost nearly all crustaceans and became numerically dominated by the opportunistic polychaete, Ophryotrocha claperedii, a poor competitor for resources but one of the few species living in the highly contaminated Winter Quarters Bay sediment. Transplants exposed at the intermediately polluted Transition station changed in composition to a community with relatively high abundance of the opportunistic O. claperedii, and the intermediately opportunistic polychaetes Gyptis, and Tharyx. These species of polychaetes, along with the infaunal anemone, Edwardsia meridionalis, dominate the Transition community. By comparison, overall abundance and species composition of control transplants to the Jetty, the least polluted site, changed very little over one year. Therefore, animals in transplants died and were replaced with local species in Winter Quarters Bay and the Transition area.

The mortality of Heterophoxus videns in laboratory bioassays was high in Outfall sediments, a station which is near the Transition zone and also at the edge of Winter Quarters Bay. Amphipods are not abundant at this station (Chapter 2, Lenihan and Oliver, in press). Two forms of anthropogenic disturbance occur there. The local sewage outfall releases over 300,000 liters of untreated effluent daily during the summer when the human population reaches its maximum of 1250 people. The sediment around the outfall contains high concentrations of particulate organic matter and some metals (Chapter 1, Lenihan et al. 1990). The subtidal region around the outfall is also fouled with a substantial amount of debris from the former dumpsite. Machinery, scrap metal, and numerous barrels containing human waste and unidentified materials lay on the seafloor around the outfall. This debris was dumped on the seafloor during 28 years of station operation until the practice was terminated in 1988.

A logical conclusion from our study is that the single species laboratory bioassay provided an adequate tool for predicting the effects of contamination on infaunal communities. In fact, our bioassay results only helped to explain differences in community structure across the pollution gradient. We do not believe our results preclude the need to assess larger ecosystem-level effects. The primary problem is extrapolating from laboratory tests to field conditions. Our laboratory survival experiments alone taught us little about interactions between pollution stress, the effects of predators, variations in the physical environment, and amphipod survival. It was the addition of our behavioral observations that allow us to predict something about predator-prey interactions. We still know little about how changes in physical factors, e.g. current flow, influences contaminant sensitivity. Causal relationship between contamination and variations in community composition not could not be inferred from any laboratory experiment but rather by combing a benthic sampling program (Chapter 2, Lenihan and Oliver, in press) and the transplant experiments. Therefore, only by pooling the results from a hierarchy of experiments, conducted across various levels in this ecosystem, were we able to conclude that chemical contamination is the likely agent causing the dramatic changes in communities around McMurdo Station.

The power to interpret and predict the direct and indirect effects of natural perturbations in ecological communities decreases with the level of ecological complexity (e.g., Strauss 1991 and Schoener 1993). If benthic environments in temperate latitudes are generally more complex than our model system in Antarctica, we conclude that standard sediment toxicity bioassays using Rhepoxynius abronius are inadequate for determining community-wide effects. Instead, we agree others (Kimball and Levins 1985, Underwood and Peterson 1988) that a mixture of various sampling programs (including measurements of chemical contaminates and community composition) and experimental manipulations (including bioassays, mesocosms, and field experiments) will improve our ability to evaluate and predict the effects of pollution in marine systems.

ACKNOWLEDGMENTS

We thank the staff of McMurdo Station's Biological Laboratory and Steve Kottmeier for his excellence and organization. Special thanks to R. Kvitek, D. Carney, J. Oakden, J. Levitt, and to B. Lopez for help in the field and laboratory.. Thanks to G. Skilleter for advice on statistical analyses. Special thanks also to J. Rastafari for moral support. This project was funded by NSF grant DPP 8914858 awarded to J.S. Oliver.

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Table 1. Percentage of surviving Heterophoxus videns, Monoculodes scabriculosus, and Eudorella splendida individuals found in sediments of paired habitats after three days exposure in the laboratory. Animals were placed on the sediment surface of the "starting side" and chose to burrow in either of two sediments. Mean percents and one standard error of surviving animals and total mortality for each test based on 20 Heterophoxus, 10 Monoculodes, and 10 Eudorella placed together in each paired habitat (n=4).

Stations	*Heterophoxus videns* % ± se	*Monoculodes scabriculosus* % ± se	*Eudorella splendida* % ± se
Winter Quarters Bay vs starting side	16.3 ± 9.0	0	4.2 ± 4.2
Jetty	83.4 ± 9.2	100	95.7 ± 4.2
% total mortality in test	17.5 ± 4.2	85.0 ± 6.4	80.0 ± 4.0
Winter Quarters Bay vs.	6.7 ± 6.7	0	0
Jetty (Fine fraction)	93.3 ± 7.1	100	100
	12.5 ± 7.5	85.0 ± 6.4	57.5 ± 36.9
Outfall vs.	13.0 ± 7.2	6.2 ± 6.2	4.2 ± 4.2
Jetty	86.9 ± 7.2	93.7 ± 6.2	95.7 ± 4.2
	10.0 ± 7.0	72.5 ± 6.2	52.5 ± 7.5
Jetty vs.	61.0 ± 20.3	51.2 ± 13.1	79.2 ± 12.5
Jetty	38.9 ± 20.3	48.7 ± 13.1	20.8 ± 12.5
	22.5 ± 6.3	42.5 ± 7.5	67.5 ± 10.3
Jetty vs.	50.7 ± 12.9	45.0 ± 7.4	60.0 ± 18.2
Jetty (Fine fraction)	49.2 ± 12.8	55.0 ± 7.4	40.0 ± 18.2
	17.5 ± 7.5	60.0 ± 6.3	52.5 ± 2.5

Table 2. Percentage of surviving Heterophoxus videns, Monoculodes scariculosus, and Eudorella splendida individuals found in sediments of paired habitats after three days exposure in the laboratory. Animals were placed on the sediment surface of the "starting side" and chose to burrow in either of two sediments. Mean percents and one standard error of surviving animals and total mortality for each test based on various combinations of species, numbers of animals, and numbers of replicate containers.

	Starting side			**Total mortality**
	Winter Quarters Bay		**Jetty**	**in test**
Species	% ± se	vs.	% ± se	% ± se
Heterophoxus videns 10 animals/container, n=5	12.3 ± 7.4		87.7 ± 7.4	15.2 ± 6.4
Eudorella splendida 25 animals/container, n=3	2.8 ± 4.5		97.2 ± 2.8	40.0 ± 12
H. videns	6.3 ± 6.3		60.3 ± 30.7	33.3 ± 33.3
Monoculodes scabriculosus 10 animals of both species/container, n=2	3.3 ± 3.3		97.0 ± 5.8	38.3 ± 19.2
	Winter Quart. Bay	vs.	**Cape Armitage**	
H. videns	1.4 ± 1.4		98.6 ± 1.4	1.3 ± 1.3
E. splendida 25 animals of both species/container, n=3	4.5 ± 0.3		95.5 ± 0.3	13.3 ± 6.7
	Cape Armitage	vs.	**Cape Armitage**	
H. videns	61.6 ± 5.8		38.4 ± 5.8	5.3 ± 5.3
E. splendida 25 animals of both species/container, n=3	73.3 ± 7.2		26.7 ± 7.2	9.3 ± 1.3

Table 3. Numbers of total infauna, polychaete worms, and crustaceans, number of species, and numbers individuals in the natural Jetty community and transplanted communities after one year of exposure on the seafloor at three stations along the McMurdo Station pollution gradient. Communities were transplanted in containers 441 cm^2 x 8 cm. Means and one standard error based on cores taken from four replicate containers per location (1 per container; 0.0075 m^2). All transplants were placed at 18 m water depth.

	Not transplanted	Transplanted		
	Jetty	**Jetty**	**Transition**	**Winter Quarters Bay**
	x ± se	x ± se	x ± se	x ± se
Total individuals				
Infauna	674.0 ± 103.4	520.8 ± 62.1	537.5 ± 76.8	568.5 ± 157.1
Polychaetes	347.3 ± 49.9	223.8 ± 12.5	355.8 ± 46.7	533.5 ± 147.9
Crustaceans	154.5 ± 42.5	220.3 ± 50.1	87.5 ± 15.5	31.0 ± 12.1
Number of species	22.2 ± 1.5	20.7 ± 2.2	17.3 ± 2.5	9.2 ± 0.8
Opportunistic species				
*Ophryotrocha claperedii**	7.0 ± 2.5	2.5 ± 0.9	107.7 ± 23.1	454.8 ± 130.8
Intermediate opportunistic species #				
*Gyptis sp.**	5.8 ± 1.5	10.5 ± 2.1	20.0 ± 2.7	1.8 ± 0.9
*Tharyx sp.**	120.8 ± 20.4	68.0 ± 8.4	128.5 ± 21.1	72.5 ± 21.3
Dense assemblage species #				
*Myriochele cf. heeri**	184.8 ± 29.5	120.8 ± 13.6	92.8 ± 8.8	0
*Heterophoxus videns***	19.8 ± 0.9	13.8 ± 4.9	9.5 ± 1.8	0
*Edwardsia meridionalis****	150.3 ± 15.1	63.3 ± 20.3	80.8 ± 19.9	27.3 ± 1.2
*Nototanais dimorphous*****	66.3 ± 27.6	107.0 ± 31.8	13.8 ± 3.8	1.3 ± 0.6
*Austrosignum grande******	42.3 ± 8.8	50.0 ± 17.3	35.3 ± 7.4	1.0 ± 1.0

* Polychaete worms

**Amphipod crustaceans

*** Infaunal anemone

****Tanaid

*****Isopod

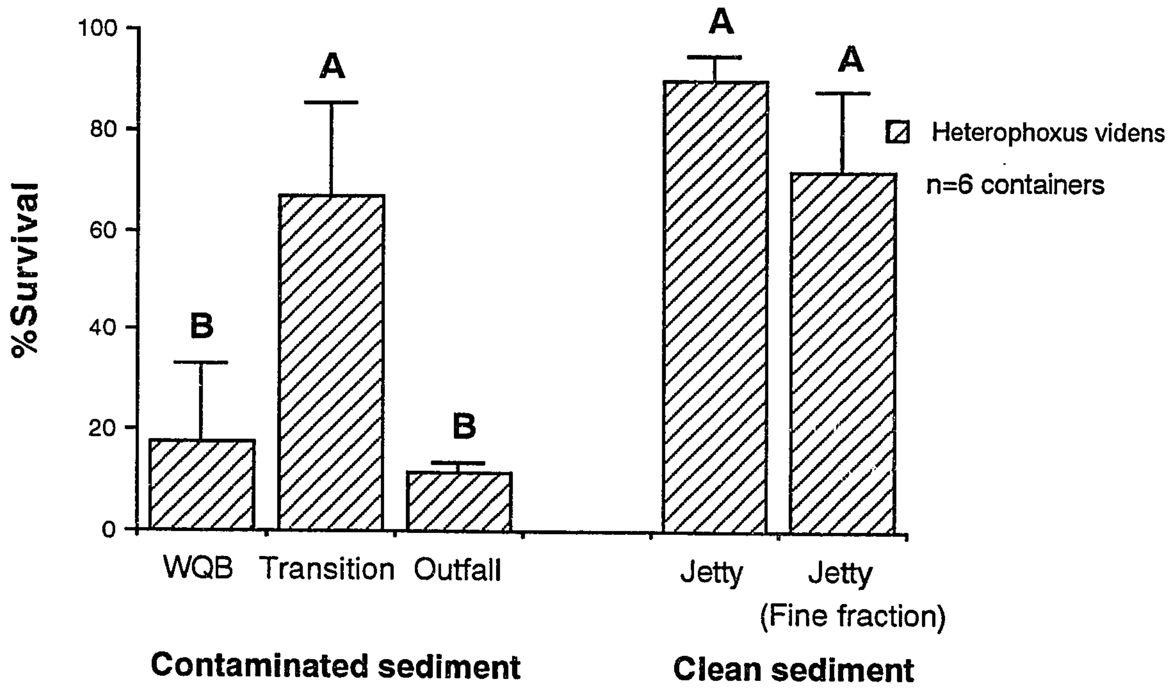

Figure 1. Percent survival of Heterophoxus videns (amphipod) after 28 days exposure in the laboratory to sediments from along the McMurdo Station pollution gradient. Jetty sediment was screened through 64 μm mesh to produce the fine fraction. Mean percents and one standard error based on 20 amphipods placed in six containers of each sediment type.

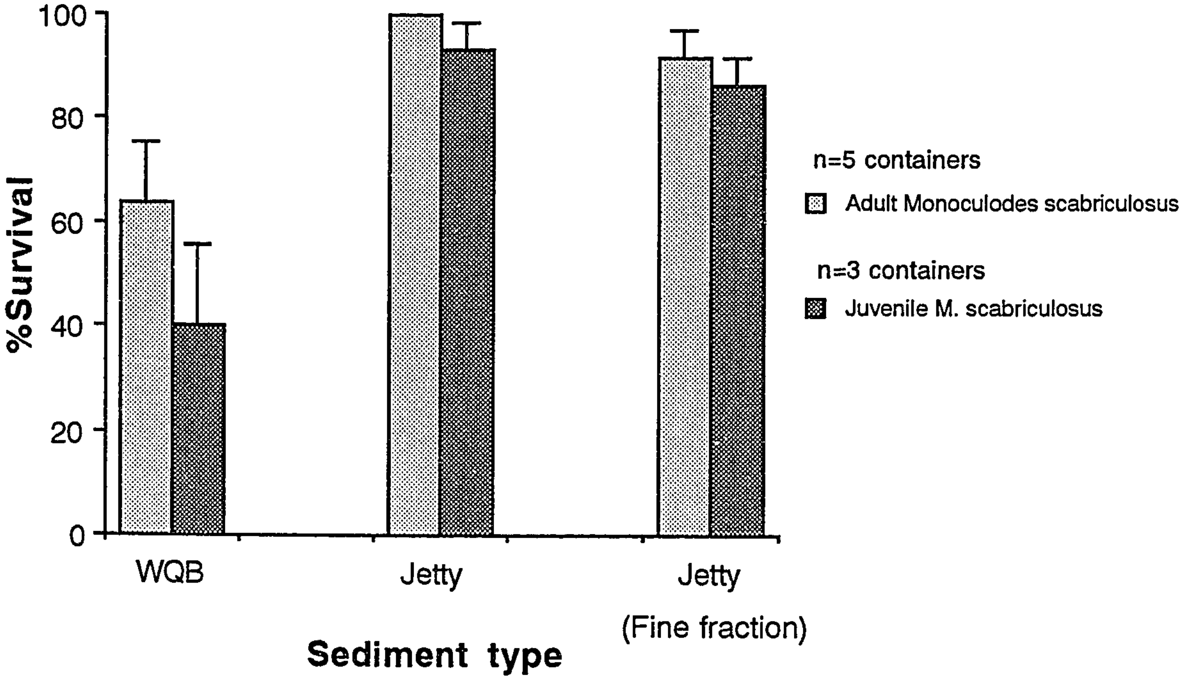

Figure 2. Percent survival of Monoculodes scabriculosus (amphipod) adults and juveniles after 21 days exposure to sediments from Winter Quarters Bay (WQB) and the Jetty in the laboratory. Jetty sediment was screened through 64 µm mesh to produce the fine fraction. Means and one standard error based on five amphipods in each container (n).

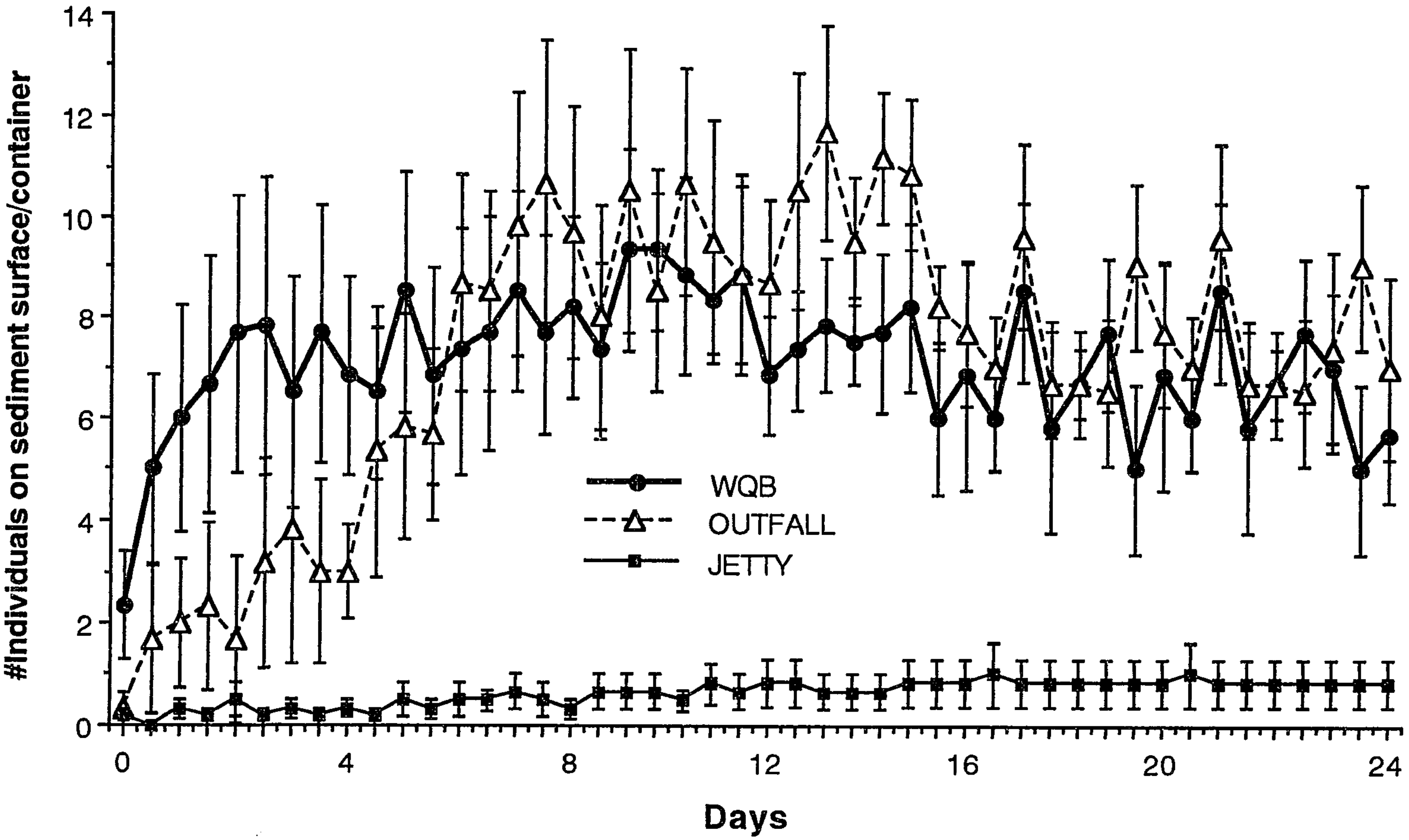

Figure 3. Numbers of living Heterophoxus videns on the surface of sediments from Winter Quarters Bay (WQB), the sewage outfall, and the Jetty over 24 days in the laboratory. Means and one standard error based on 20 amphipods in containers of each sediment type (n=6).

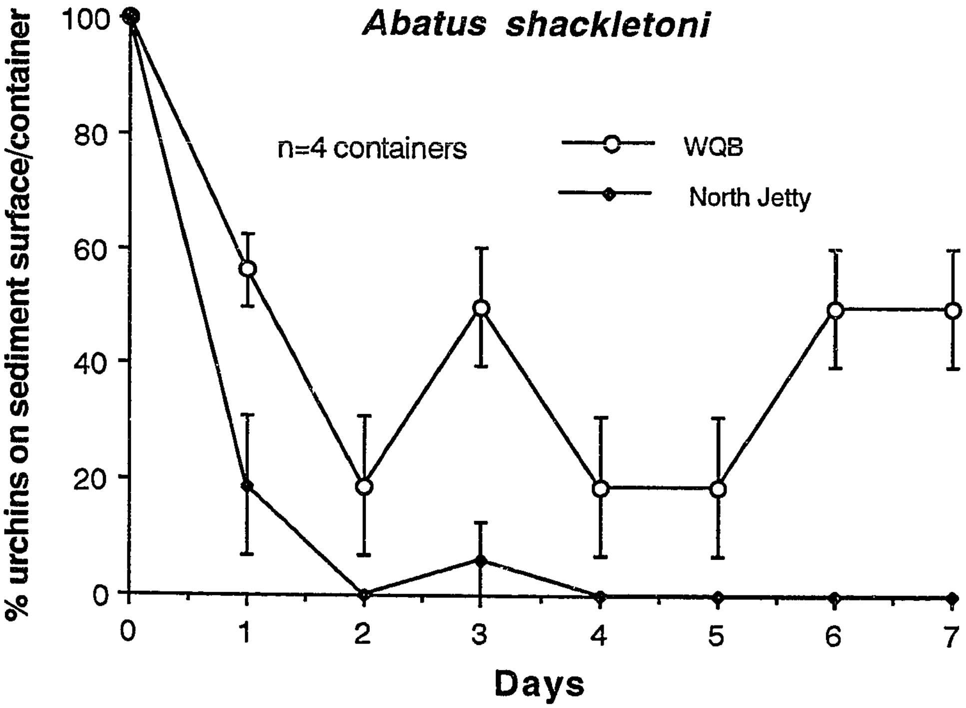

Figure 4. Percent of total Abatus shackletoni (echinoid) individuals remaining on the surface of sediments from Winter Quarters Bay and North Jetty over seven days exposure in the laboratory. Animals with less than 1/2 body height exposed above sediment-water interface were considered buried. Mean percents and one standard error based on four urchins placed in each of four containers of each sediment type.

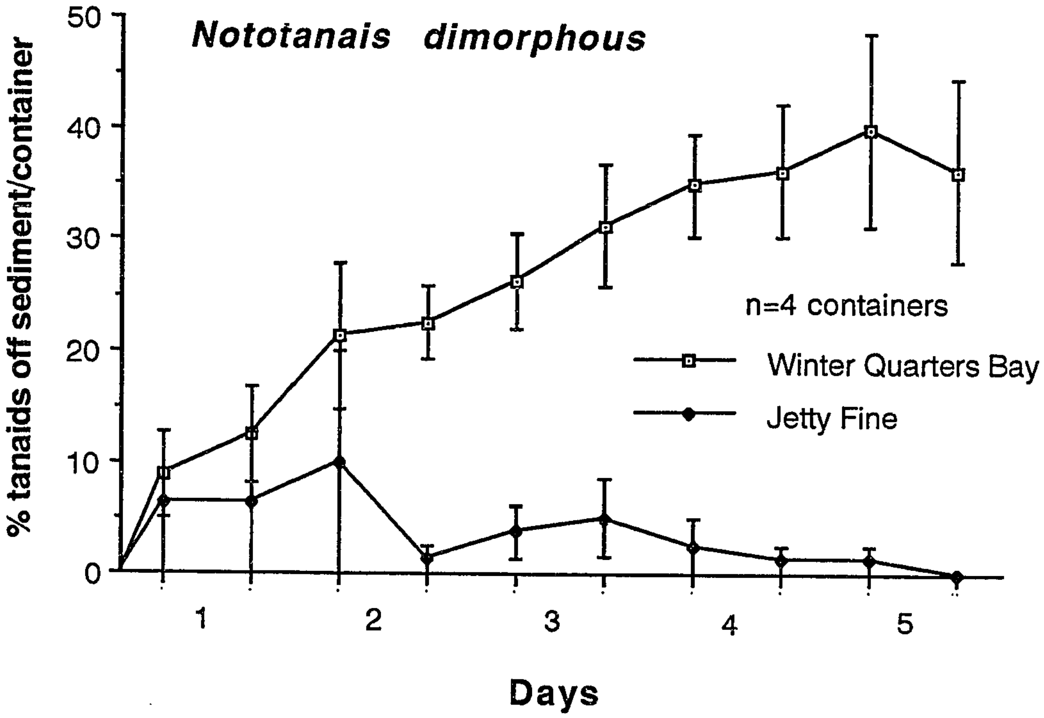

Figure 5. Percent of total Nototanais dimorphous (tanaid) individuals climbing away from sediments from Winter Quarters Bay and the Jetty over five days of exposure in the laboratory. Mean percents and one standard error based on 20 tanaids placed in containers (n=4) of each sediment type.

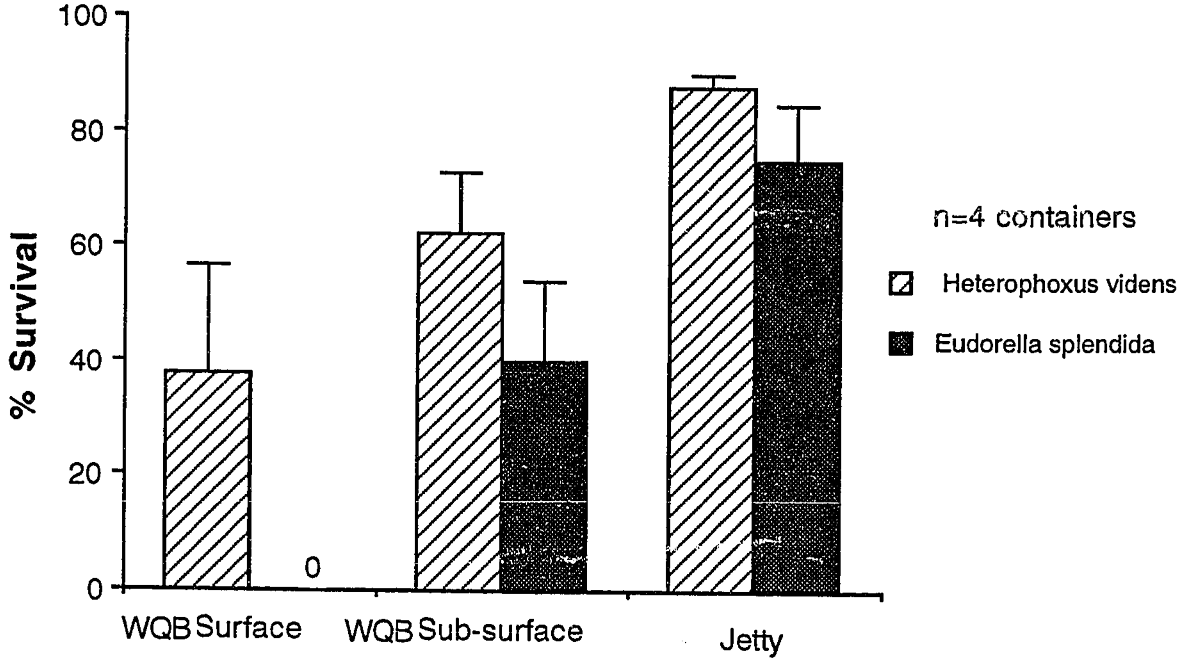

Figure 6. Percent survival of Heterophoxus videns and Eudorella splendida after 10 days exposure in Winter Quaters Bay in three sediment types: natural surface sediment; natural sediment with the top 2 cm removed; and clean Jetty sediment. Mean percent surviving and one standard error based on ten H. videns and five E. splendida Containers were placed at 18 m water depth in the back of the bay (see Figure 1).

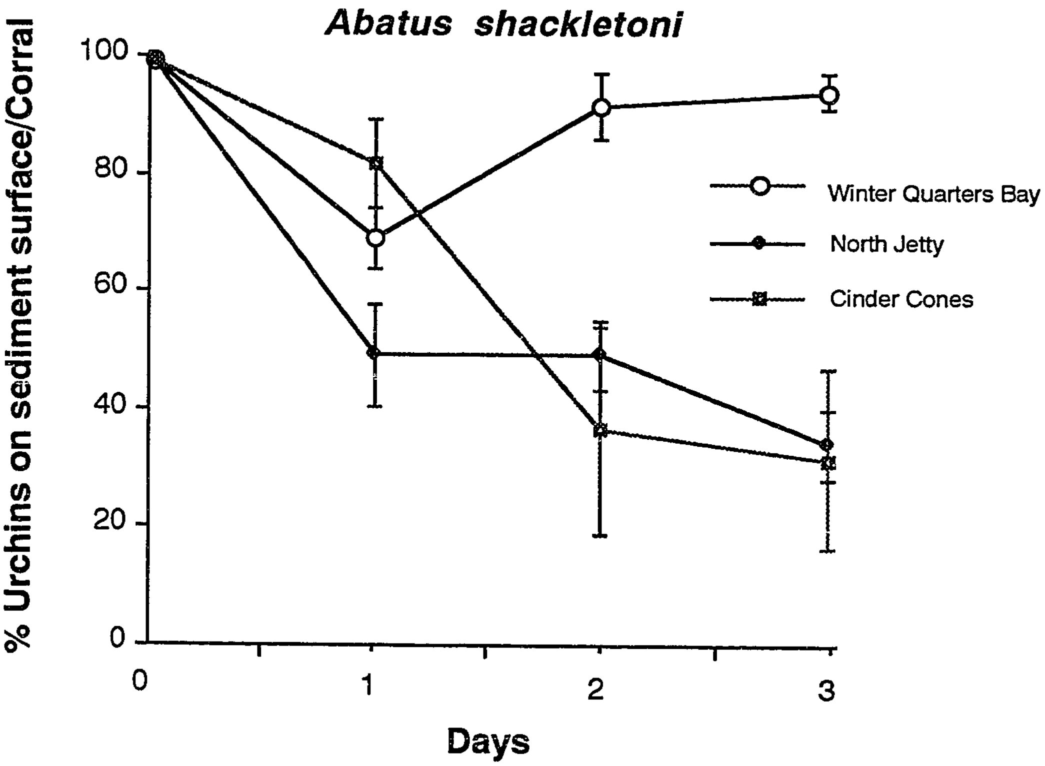

Figure 7. Percent of total Abatus shackeltoni (echinoid) individuals remaining on the surface of sediments in Winter Quarters Bay and at North Jetty and Cinder Cones over three days exposure. Animals with less than 1/2 body height exposed above sediment-water interface were considered buried. Mean percents and one standard error based on 10 urchins placed in corrals (n=4) at 18 m water depth at each location.