ASSESSMENT OF THE BENTHIC ENVIRONMENT FOLLOWING OFFSHORE PLACER GOLD MINING IN NORTON SOUND, NORTHEASTERN BERING SEA

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ABSTRACT

The effects of placer gold mining on the benthic environment of Norton Sound in the northeastern Bering Sea were assessed. Research focused on red king crab *Paralithodes camtschaticus*, a species with commercial and subsistence importance in the Sound and seasonal occurrence in the mining area. The study addressed mining effects on: 1) benthic macroinvertebrates, many serving as food for this crab, 2) crab relative abundance, distribution, and food, and 3) heavy metal concentrations in crabs. Mining on variable substrates in < 20 m water depths occurred between 1986-90 during ice-free months when crabs were further offshore.

Sampling nearly a year subsequent to mining revealed moderate substrate alteration. Benthic community parameters and abundance of numerically predominant families (e.g., owenid, spionid, and capitellid polychaetes and echinarachniid sand dollars) were reduced in mined areas. Many reduced taxa are known crab prey. Although young individuals of opportunistic taxa predominated, taxa were generally smaller at mined areas. Multi-year surveys of a once-mined area showed continued smoothing of bottom relief. Ordination of taxon abundance from mined (1 yr after mining), recolonizing (2-7 yrs after mining), and unmined stations reflected decreasing station disturbance. At least four years were required for benthos to recover from mining.

Mining had a negligible effect on crabs. Crab catches, size, sex, and most prey groups in stomachs were similar between mined and unmined areas. Concentrations of eight heavy metals in muscle and hepatopancreas tissues were generally not different in mined areas. Furthermore, these metals were not different in sediments upcurrent and downcurrent of mining. Concentrations of most metals in tissues showed no temporal trend. Elemental concentrations in muscle tissues were below or within the range of

concentrations in red king crabs from other North Pacific locations. Most metals from Norton Sound crabs were well below federal guidance levels for human consumption.

Effects from mining were apparent for benthic macrofauna with virtually no effects observed for king crabs. Absence of any demonstrable effects of mining on this crab is primarily a result of the high natural dynamics of the Sound and opportunistic feeding behavior and high mobility of the crab.

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INTRODUCTION

The extent of mining in the marine environment at northern latitudes (north of 54° Latitude) is limited, with the bulk of this activity involving the marine disposal of mine tailings from coastal operations in Canada (Ellis, 1987, 1988, 1989; Poling & Ellis, 1993). Most of these operations have resulted in some aspect of environmental assessment, with the most prevalent monitoring components including tailing discharge rates and chemical analyses, acute bioassays, turbidity, tailing deposition, chemical oceanography, stocks and dynamics of intertidal and subtidal organisms, and trace metal bioaccumulation and biomagnification (Ellis, 1988). Marine/coastal mining activity in Alaskan waters has mainly been associated with small, unregulated placer mining at the turn of the century and short-term exploratory endeavors with no associated impact assessments (R. Baer, USDI-Bureau of Mines, Juneau, AK, pers. comm., 1995). Only one major marine mining program with associated environmental monitoring has occurred on the Alaskan continental shelf. An offshore placer gold mining operation was conducted in the shallow waters of Norton Sound in the northeastern Bering Sea, near the City of Nome, between 1986 and 1990 (Jewett *et al.*, 1992). This thesis presents an assessment of some effects of mining activity on segments of the shallow-water benthic community of Norton Sound.

Mining project history

The history of the offshore mining project at Nome dates to 1962 when Shell Oil Company was issued offshore prospecting permits for six tracts of submerged state lands covering approximately 88 km^2 (21,750 acres). The area extended from approximately 1.6 km east to 16 km west of Nome, and offshore for a distance of approximately 4 km (Fig. 1) (Rusanowski *et al.*, 1986). An exploration program (Project Glitter), using the winter

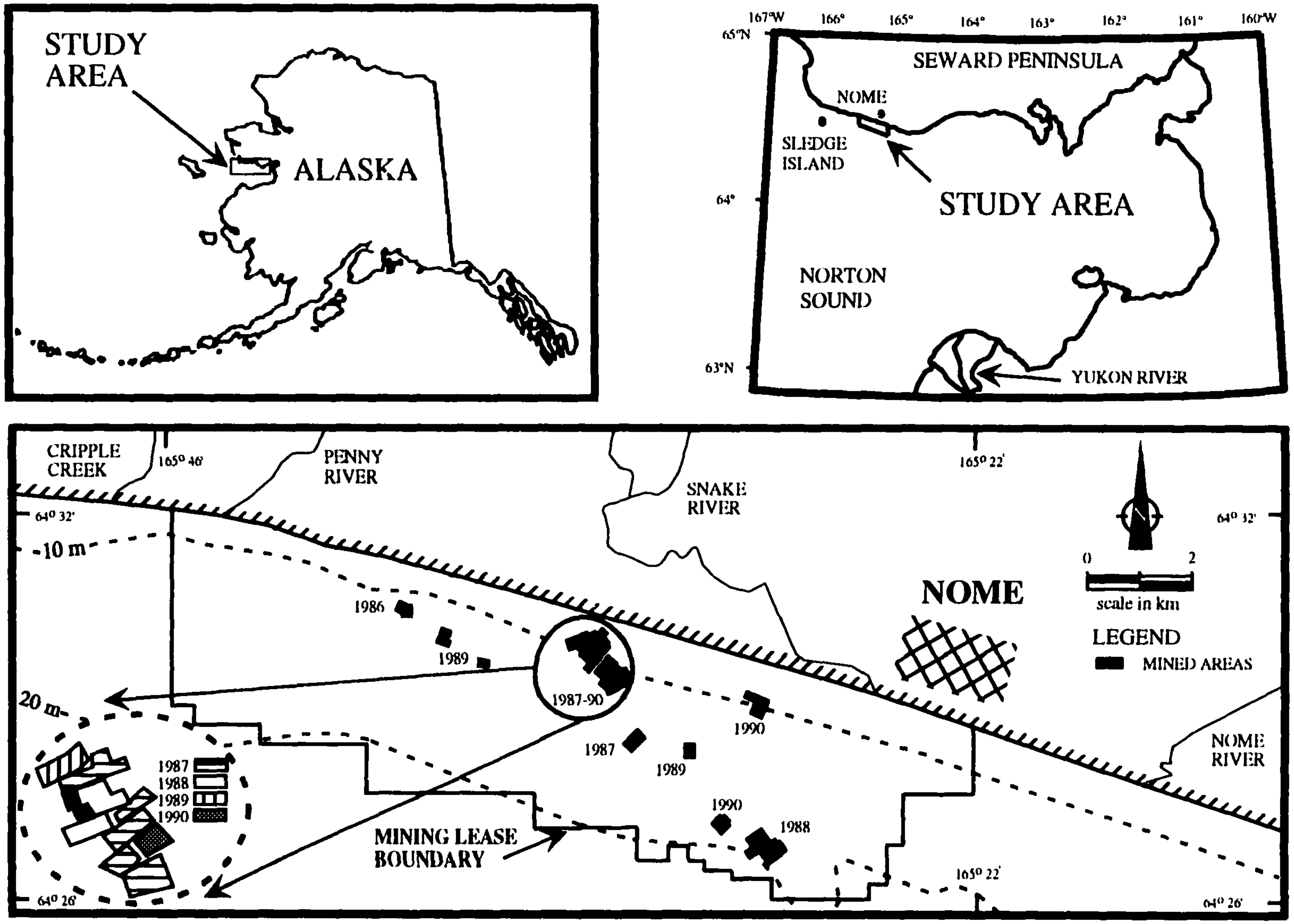

Figure 1. Map of the Nome Offshore Placer Project showing mining lease boundary and areas mined by year.

icesheet as an operating platform, was started by Shell Oil Company in the winter of 1963/1964; 568 test holes were successfully drilled along the coast (Daily, 1969). Although potentially commercial concentrations of gold were delineated in several areas, the project failed to gain further support from the company. In 1967 and 1968, the U.S. Bureau of Mines and U.S. Geological Survey drilled an additional 51 holes, collected 700 bottom grab samples, and conducted a reconnaissance geophysical program in the nearshore area to evaluate heavy metals offshore of the greater Nome area (Tagg & Green, 1973).

In 1969, American Smelting & Refining Company (ASARCO) acquired 50% interest in the Shell Oil leases. ASARCO completed an additional 500-hole exploration program and extensive feasibility studies, including bottom photography, current and wave measurements, offshore bulk sampling, pilot-scale test mining from the beach, and an environmental assessment (Jewett *et al.*, 1990a). Based on the price of gold and the fact that mining could only be done seasonally, ASARCO concluded that the property was not economical at that time.

With the rise in gold prices in 1984, Power Resources Company negotiated an option to purchase the leases from ASARCO. Power Resources subsequently initiated permitting activity to bring the property into production.

In May of 1985, Inspiration Mines, Inc. became a principal in the project as well as the project operator. Permitting was completed on October 3, 1985, and test mining operations began on October 7 from the barge KOKOHEAD using a crane-operated clamshell bucket. The company changed its name to Inspiration Gold, Inc. in 1986 and mining operations resumed in June from the barge BIMA, a large, bucket line, offshore mining dredge. In January 1988, the company's name was changed to Western Gold Exploration & Mining Co., Limited Partnership (WestGold). WestGold used the BIMA off Nome during ice-free months (June-October) until it ceased operations on September

20, 1990. The mining leases, now owned by Nova Natural Resources Corporation, Denver, Colorado, are not being worked at this time (Brian Spillain, Nova, pers. comm., 1996).

The BIMA was approximately 110 m long, 43 m wide, and 45 m high (Fig. 2). During its mining operations off of Nome, it was the world's largest operable bucket line, offshore mining dredge, capable of dredging in depths of 6 to 45 m of water. The bucket ladder was 88 m long and contained 134 buckets, each of which had a 0.85 m^3 capacity. It was capable of digging to a depth of 45 m. For example, in 30 m of water, a sediment depth of up to 15 m could be dredged. The BIMA was designed to dredge nearly 4.6×10^4 m^3 of sediment per day under optimal conditions, with a possible process water discharge of up to 181×10^6 liters d^{-1} (47.8×10^6 gallons d^{-1}); operating rates seldom exceeded 1.6×10^4 m^3 of substrate per day (Jewett *et al.*, 1991). Materials were processed onboard and tailings were returned to the excavation site to restore the seafloor to the approximate pre-mining configuration. A small berm was created on the discharge end of the mining area as well as a small trench on the digging end.

The area (and volume) within the 88 km^2 lease area that was mined annually between 1986 and 1990 ranged from 0.093 km^2 (3.1×10^5 m^3) in 1986 to 0.583 km^2 (2.0×10^6 m^3) in 1988. The total area and volume mined was 1.5 km^2 (371 acres) and 5.5×10^6 m^3, respectively (Howkins, 1992; Jewett *et al.*, 1992). This area amounts to 1.7% of the total lease area available. The approximate locations and extent mined are shown in Figure 1.

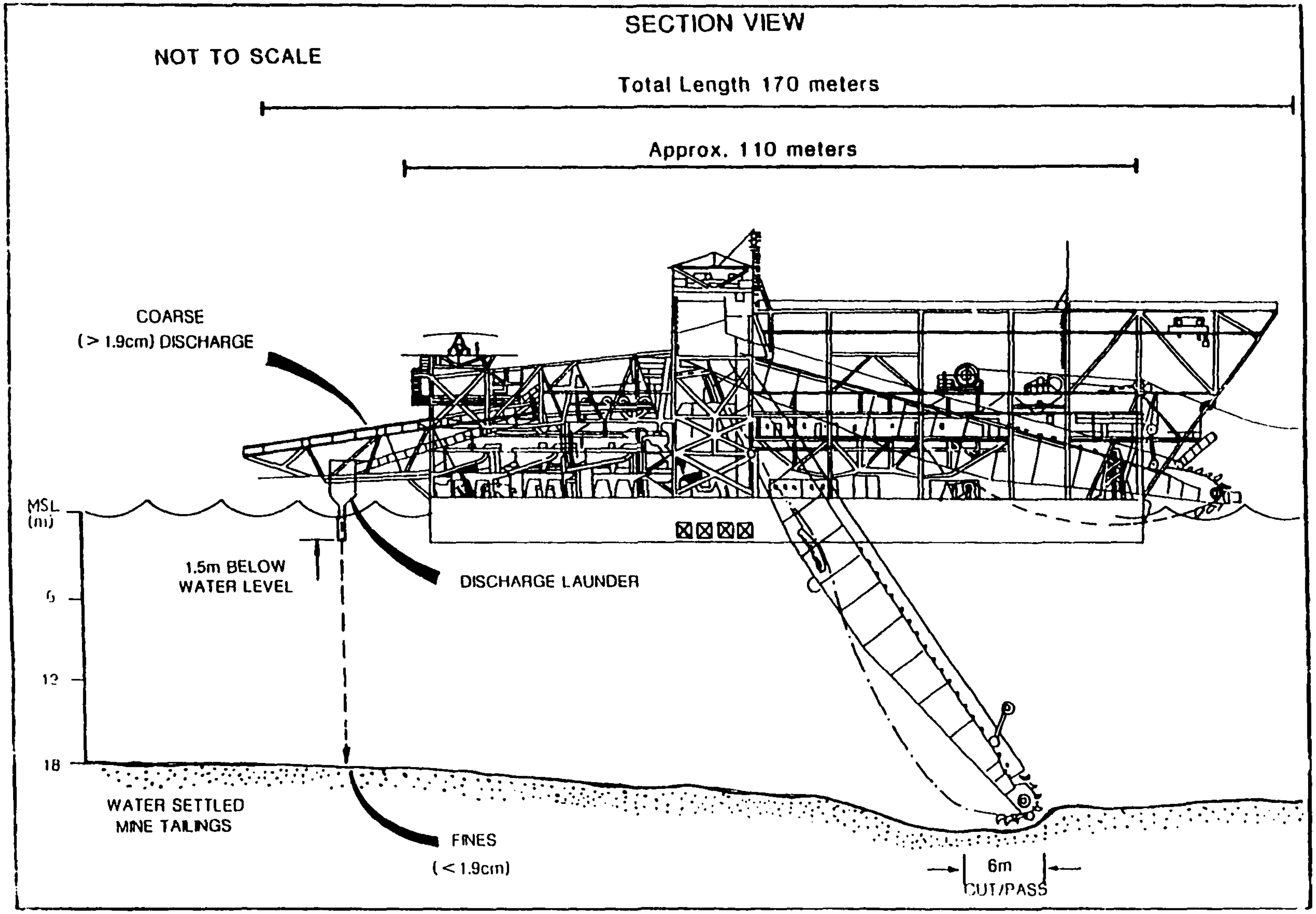

Figure 2. Schematic of typical mining dredge cut showing barge and mining operation in progress.

Impact assessment

As stipulated in the WestGold's National Pollutant Discharge Elimination System (NPDES) permit-to-operate, environmental monitoring occurred annually while in operation and one year after ceasing operation. A long-term environmental monitoring program for the Nome Offshore Placer Project began in 1986 and concluded in 1991 with research on physical and biological characteristics of the mining locations and the Nome vicinity (Rusanowski *et al.*, 1987, 1988; Jewett *et al.*, 1989, 1990a, 1991, 1992). The main environmental concern with this placer gold mining endeavor was the potential effect to the red king crab (*Paralithodes camtschaticus* [Tilesius, 1815]), a species with commercial and subsistence importance in Norton Sound. In general, king crabs occur nearshore in the vicinity of mining only during the ice-covered period, a time when dredging operations were inactive. This monitoring program addressed four areas of concern: 1) changes to the seafloor; 2) biological characteristics of sea floor habitats; 3) king crab distribution, abundance and feeding; and 4) potential for heavy metal accumulation in the marine food chain. The monitoring program was formulated by a Project Review Committee, which was composed of key personnel from state agencies (Alaska Department of Environmental Conservation, Alaska Department of Fish & Game, Alaska Department of Natural Resources - Division of Mining, and Division of Governmental Coordination), federal agencies (U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, U.S. Fish & Wildlife Service, and National Marine Fisheries Service), regional regulatory and special interest groups (Nome Eskimo Community, Kawerak, Inc., Bering Strait Native Corporation, Eskimo Walrus Commission, Bering Sea Fishermen's Association, City of Nome, Trustees for Alaska, and Bering Straits Coastal Resources Management Program), and project groups (WestGold, ENSR Consulting & Engineering, Engineering Hydraulics, Inc., Meacham and Associates, and University of Alaska Fairbanks [UAF] - Institute of Marine Science).

This program was managed by ENSR Consulting & Engineering (Anchorage, AK) with assistance from me and UAF. The benthic biological components of this program were conducted under my direction.

Study area

Physical environment

This study was conducted within approximately 88 km^2 of State of Alaska offshore mining leases in the northwestern portion of Norton Sound. The area is north of 64° 26′ N to the southern coastline of the Seward Peninsula. The southern boundary tends to follow the 5 km [3 mi] State of Alaska marine boundary from shore, which approximates the 20 m depth contour. The eastern boundary is a straight line south, midway between the mouths of the Snake and Nome rivers (165° 22′ W), and the western boundary is a straight line south, midway between the mouths of Cripple Creek and Penny River (165° 46′ W) (Fig. 1). A breached causeway approximately 600 m long extends offshore from Nome in the lease area to a water depth of about 6 m.

Information on the marine environment of Norton Sound, pre- and post-mining, is presented in a number of governmental reports and scientific publications. The primary sources are those relative to the oceanography and resources of the Bering Sea (Hood & Kelly, 1974; Hood & Calder, 1981), the proposed OCS mining lease area (Naidu *et al.*, 1989; MBC, 1990; USDI, 1991), the proposed OCS oil and gas lease area (Feder & Jewett, 1978a,b; USDI BLM, 1982; Zimmerman, 1982; Feder *et al.*, 1985; Truett, 1985; Thorsteinson *et al.*, 1989), the feasibility for the Nome causeway (Tetra Tech, 1980; Ettema & Kennedy, 1982), the Nome offshore lease area (Hood *et al.*, 1974) and those references relative to Norton Sound red king crabs (Wolotira *et al.*, 1977; Powell *et al.*, 1983; Sample & Wolotira, 1985; Stevens & Macintosh, 1986; Stevens, 1989; Otto *et al.*, 1990: Stevens & Haaga, 1992).

Norton Sound is a shallow subarctic embayment that is about 150 km in the north-south dimension, 220 km in the east-west dimension, with a depth to about 30 m (Cacchione & Drake, 1979; Muench *et al.*, 1981). The water properties and circulation within the Sound are primarily affected in the summer by the discharge from the Yukon River, wind transport and mixing, and, to a lesser extent, tidal mixing (Muench *et al.*, 1981). Wind mixing may extend to the bottom. Wind transport may also drive significant currents within the Sound. Salinities range from less than 20 ‰ in summer surface waters to a maximum of about 34 ‰ in winter. Water temperatures range from above 12 °C in summer to -1.85 °C in winter (Hood *et al.*, 1974). In general, water enters the southern part of the Sound and flows out along the northern part. The T-S correlations suggest a northward transport of water past the west end of Norton Sound, an inward flow of Bering Sea water along the bottom of the Sound, and modification of the near surface water by river input. The westward, counter-clockwise flow of water offshore along the south coast of the Seward Peninsula is a common feature that varies in intensity and extent (Hood *et al.*, 1974). This causes the predominant offshore currents at Nome to be directed to the west (Tetra Tech, 1980; Muench *et al.*, 1981). The mean speed of surface currents in the western portion of Norton Sound ranges from about 5 to 20 cm s^{-1}; the maximum velocity is about 50 cm s^{-1}. Bottom-current speeds are about 10 to 20 cm s^{-1} in the western part of the Sound (Muench *et al.*, 1981). Strong coastal currents reaching speeds up to 100 cm s^{-1} have been reported in the vicinity of Nome (Nelson & Hopkins, 1972). Tides in Norton Sound are primarily diurnal (1 high and 1 low d^{-1}) and average about 0.5 m in height between mean higher high water and mean lower low water (Pearson *et al.*, 1981). While the normal tidal fluctuation at Nome is minimal, major storm events can cause dramatic fluctuation in sea level height.

The surficial substrate of northern Norton Sound is heterogeneous, consisting of a mosaic of sediments from silt to boulder, with sand and cobble dominating (USDI, 1991). The surface sediments covering the study area consist of relict gravel and sand along with modern sediments of very fine sand-and silt-size particles from the Yukon River (Hess & Nelson, 1982). The summer sediment load of the Yukon River is generally estimated to be about 20 to 30% very fine sand, 60 to 70% silt, and 10% clay (Drake *et al.*, 1980). These sediments cover the southern to the northeastern portion of Norton Sound. Fine sand/mud substrate, which overlies a more permanent cobble substrate, are somewhat transient in nature and subject to redistribution by storms, ice, and currents. The wave-induced nearshore currents at Nome move the fines in both east and west directions, however, the net nearshore sand transport is in an westerly direction (Drake *et al.*, 1980). Frequent storms that pass through the Bering Sea cause substantial disturbance of surficial sediments to depths of 90 m (Sharma *et al.*, 1972). Long-term measurements of near-bottom velocities off Nome at a depth of 18 m revealed extensive sediment resuspension and transport, particularly during storms (Cacchione *et al.*, 1982; Cacchione & Drake, 1982).

Norton Sound is ice-covered during much of the winter-spring period (November-May). Winter water characteristics are controlled by cooling, thermohaline mixing throughout the water column, and diminution of fresh water input. Some high salinity water observed in Norton Sound may be due to either exclusion of salt during ice formation or to advection of saline waters from the western Bering Sea. Shorefast ice develops in the nearshore region, forming first along the northern shore (Muench *et al.*, 1981). This ice is composed of both bottomfast and floating fast ice and is contiguous with the shore. The thickness of ice is variable, but it often approaches 1.2 m. The seaward edge of the ice generally extends to the 20-m isobath and is often anchored by the keels of ridges in the 10-20 m region (Stringer, 1981). Ice gouges generally occur inside the 20-m isobath and trend east to west. Gouge-incision depth usually ranges from 0.25 to 0.5 m deep, but may be as deep as 1 m (Larsen *et al.*, 1981). Ice-gouge widths of 15-25 m are most common, but range from 5 to 60 m.

Storm surges are common in Norton Sound. Between 1960 and 1981, 19 storm surges hit the Norton Sound area, usually during late summer or early fall (Wise *et al.*, 1981). These storm surges vary in frequency from none to two per year. Two exceptionally large storm events occurred in the past 23 years. In November 1974 maximum sustained winds of about 20 m s^{-1} with gusts to 36 m s^{-1} (80 mi h^{-1}) were recorded in the Norton Sound area (Brower *et al.*, 1977). Wave heights were estimated to be between 3 and 5 m. The worst since 1974 battered the northern coastline in October 1992 with winds to 26 m s^{-1} (59 mi h^{-1}) and caused extensive damage to the community of Nome (Nome Nugget, 1992). Because extensive shoreline alteration occurs during these storms, the disruption of the nearhore subtidal habitat may also be extensive.

Biological environment

The biotic resources--plankton, benthic invertebrates, fishes, marine mammals, and marine birds--are reviewed below in terms of their location and their ecologic and/or economic importance. I address the salient environmental requirements for their well-being relative to offshore mining.

Phytoplankton and zooplankton are key components of the offshore and coastal ecosystems in Norton Sound because they constitute a major portion of the food base for pelagic and benthic food webs. They influence nutrient dynamics, and the zooplankton includes larval forms of commercially harvested species.

<u>Phytoplankton</u>

In open waters, phytoplankton is a main food resource for zooplankton, which, in turn, is consumed by many other species. The importance of phytoplankton, as well as ice algae, to pelagic food webs of the eastern Bering Sea has been emphasized by many authors (e.g., Cooney, 1981; Feder & Jewett, 1981a; Niebauer *et al.*, 1981; Braham *et al.*, 1982; Cooney & Coyle, 1982). In the outer shelf and oceanic domains (Iverson *et al.*, 1979) of the eastern Bering Sea, zooplankton graze on at least 20 to 30% and occasionally up to 100% of the daily phytoplankton production. Energy is thus transferred mainly to higher trophic levels within the pelagic zone. In contrast, inefficient zooplankton grazers in the middle and coastal shelf regions of the eastern Bering Sea remove less than 10% of the daily phytoplankton production, such that a substantial amount of organic matter settles to the bottom where it is incorporated into benthic food webs (Cooney, 1981; Cooney & Coyle, 1982; Sambrotto *et al.*, 1984).

Few phytoplankton studies have been conducted within Norton Sound. The shortened period available for primary production and the heavy suspended load of river sediments in the southern portion of the Sound may combine to reduce water column productivity. Geological observations, as well as observations on the types and distributions of benthic fauna and the stomach contents of bottom-feeding fishes, corroborate this opinion (Zimmerman, 1982).

The daily rate of primary productivity in Norton Sound in July 1973 (measured by the ^{14}C technique) ranges from 239 mg carbon m^{-3} d^{-1} near Nome to 500 mg carbon m^{-3} d^{-1} south of St. Lawrence Island. Similar rates have been observed in other Bering Sea shelf waters at this time of year (Boisseau & Goering, 1974).

The summer standing crop of phytoplankton near Nome also appears to be similar to values reported for other Bering Sea shelf waters, averaging 1.88 mg chlorophyll a m^{-3} (McRoy *et al.*, 1972, cited in Boisseau & Goering, 1974).

Diatoms, dominated by *Chaetoceros*, *Thalassiosira*, and *Nitzschia*, are the dominant phytoplankters in Norton Sound during spring and summer. Microflagellates are generally dominant at other times of the year. The epontic (under ice) algae, primarily diatoms, are important as a concentrated food source for invertebrates and fishes, and provide a major source of primary productivity prior to the spring water-column bloom. The epontic algae also acts as an inoculum for the spring phytoplankton bloom at the edge of the ice (Sambrotto *et al.*, 1984). Nearly all water-column primary productivity occurs during a spring diatom bloom associated with the retreating ice edge. Because of the shallowness of the area, and underutilization by zooplankton, a substantial portion of this production finds its way into the benthic invertebrate food web (Cooney, 1981; Cooney & Coyle, 1982; Sambrotto *et al.*, 1984).

Zooplankton

Neimark (1979) studied the zooplankton resources in the coastal waters of Norton Sound in the summer of 1976 and 1977. Sampling at the eastern portion of the Sound between Cape Denbigh and Tolstoi Point yielded 66 zooplankton taxa, with three species (the calanoid copepod *Acartia clausi*, and the cladocerans *Podon* sp. and *Evadne* sp.) predominant in abundance and frequency of occurrence. These three species were able to tolerate the widely ranging salinities and temperatures of the coastal waters. The abundance of *A. clausi* was correlated with water temperature, while cladoceran and larval mollusc populations were correlated with salinity. No difference in species composition was detected between stations along the shallow coast. However, the seaward community contained a greater diversity that supported a larger planktonic carnivore biomass.

Sea-surface temperatures decreased and salinities increased in Norton Sound from east to west during June and July, 1977 (Neimark, 1979). Because physical oceanographic parameters are so different between eastern Norton Sound and the nearshore Nome vicinity, the zooplankton communities in these two areas may also be different. The zooplankton community in the project area is presumably a mixture of nearshore and offshore species.

Information on zooplankton predation by fishes was collected in eastern Norton Sound by Neimark (1979). Twenty species of fishes were examined, and 85 different prey taxa were identified. Mysids (*Neomysis* spp.) were the most frequently occurring prey and occupied the largest percentage by volume of stomach contents. Unidentified eggs and the copepods *Acartia clausi* and *Eurytemora* spp. were important because of their abundance and frequent occurrence.

Benthos

Two major studies of the benthic environment were carried out in the Nome area. Feder & Mueller (1974) sampled invertebrates in 1973 in anticipation of mineral leasing offshore of Nome. A total of 83 invertebrate species were collected with a van Veen grab sampler; an additional 62 invertebrate species were collected by trawling. Of the invertebrates collected from sandy-gravel-rock bottom in the mining lease area, echinoderms were the most common organisms and contributed the greatest proportion of the invertebrate biomass. Representative species of other invertebrate groups were also common (e.g., the soft coral, *Gersemia* and some species of shrimps such as the coonstripe shrimp *Pandalus hypsinotus* and crangonid shrimps). Polychaetous annelids appeared to be abundant in the mud-sand areas outside the WestGold mining lease site, but the brittlestar *Diamphiodia craterodmeta* was the most common species in all grab samples within the latter area.

A preponderance of suspension feeders, scavengers, and predators with relatively few deposit feeders were found among invertebrate feeding types adjacent to the WestGold mining area. An increase in deposit feeders with a decrease in scavengers was noted in the grab samples collected in the mud-sand area outside of the lease site. Species collected by trawl within the lease site were similar at all stations sampled. In addition, species reported from areas east and west of the WestGold site in previous studies in 1949, 1968 and 1971, as well as within the site, were similar to those reported by Feder and Mueller (1974).

A demersal trawling study in September and October 1976, occupied 106 stations in Norton Sound, yielding an average epifaunal invertebrate biomass of 3.7 g m^{-2} (Wolotira *et al.*, 1977; Feder & Jewett, 1978a,b) belonging to 13 phyla, 26 classes, 89 families, 124 genera, and 187 species of invertebrates (Feder & Jewett, 1978a,b). Mollusca, Arthropoda, and Echinodermata predominated in species richness with 74, 45, and 27 species, respectively. These three phyla also dominated the invertebrate biomass, but in reverse order, i.e., Echinodermata (80.3% of the total biomass), Arthropoda (9.6%), and Mollusca (4.4%).

The most abundant echinoderm families with regard to biomass were the families Asteriidae, Gorgonocephalidae, and Strongylocentrotidae. Four sea stars of the family Asteriidae -- *Asterias amurensis*, *Lethasterias nanimensis*, *Evasterias echinosoma* and *Leptasterias polaris acervata* comprised 67.4% of the total invertebrate biomass. Wolotira *et al.* (1977) estimated the sea star biomass in Norton Sound at more than 1 x 10^5 mt. The basket star, *Gorgonocephalus caryi*, and the sea urchin, *Strongylocentrotus droebachiensis*, were also predominant echinoderms by weight.

Although *Asterias amurensis* was distributed throughout most of Norton Sound, high biomasses were generally restricted to the inner Sound region. However, an offshore station located near Nome had the highest average biomass, with 14.9 g m^{-2}. *Lethasterias nanimensis* was found mainly in the northern half of Norton Sound. Another station located off Nome had the highest average biomass for this species with 2.5 g m^{-2} (Feder & Jewett, 1978a,b).

Commercially important benthic invertebrates found in Norton Sound include red king crabs (*Paralithodes camtschaticus*), blue king crabs (*Paralithodes platypus*), Tanner crabs (*Chionoecetes opilio*), pink shrimp (*Pandalus borealis*), humpy shrimp (*P. goniurus*), and large gastropods (*Neptunea* spp., *Buccinum* spp.) (Wolotira *et al.*, 1977;

Otto, 1981). Crabs comprised most of the arthropod biomass (86.3%), but comprised only 8.3% of the total invertebrate biomass. The red king crab occurred in less than half of the Norton Sound area stations and were confined to the inner and mid-portions of the Sound. A station adjacent to Norton Bay had the highest red king crab biomass reporting an average of 2.1 g m^{-2} (Feder & Jewett, 1978a,b).

Gastropod mollusks, especially whelks, *Neptunea* spp., were the most abundant invertebrates of potential commercial importance in Norton Sound. *Neptunea heros* was the most abundant species accounting for 75% of the region's snail biomass (Wolotira *et al.*, 1977). This species had an estimated biomass of over 2,788 mt and population of 2.2 x 10^7 individuals within the Sound.

Stations off Cape Nome (at depths of approximately 22 m) reflected an environment where particulate material settles to the bottom. Infaunal species, in decreasing order of density, were the polychaetes *Myriochele oculata* and *Haploscoloplos elongatus* and the amphipod *Ericytonius hunteri*. The species dominant in biomass were the crangonid shrimp *Argis lar* and the deposit-feeding echiurid worm *Echiurus echiurus alaskanus* (Feder *et al.*, 1985).

In the eastern Bering Sea benthic invertebrates are important prey of large decapod crustaceans (king crabs - *Paralithodes* spp., Tanner crabs - *Chionoecetes* spp.), demersal fishes (Pacific cod - *Gadus macrocephalus*, walleye pollock - *Theragra chalcogramma*, Pacific halibut - *Hippoglossus stenolepis*, yellowfin sole - *Pleuronectes asper*, Greenland halibut - *Reinhardtius hippoglossoides*, Alaska plaice - *Pleuronectes quadrituberculatus*, rock sole - *P. bilineatus*, arrowtooth flounder - *Atheresthes stomias*, flathead sole - *Hippoglossoides elassodon*, rex sole - *Errex zachirus*), and marine mammals (gray whale - *Eschrichtius robustus*, bearded seal - *Erignathus barbatus*, walrus - *Odobenus rosmarus*) (Feder & Jewett, 1981a). Since most of these predators also occur in Norton Sound, similar benthic trophic interactions presumably occur there.

Major foods for adult king and Tanner crabs include polychaetes, bivalve mollusks, echinoderms (mainly brittle stars), and crustaceans (Feder & Jewett, 1981b; Jewett & Feder, 1982, 1983; Jewett *et al.*, 1990b). Juvenile crabs utilize benthic diatoms, copepods, and ostracods, and small organisms that have presumably settled from the water column, plus detrital material (Feder & Jewett, 1981b).

The feeding habits of the most abundant demersal fish (starry flounder - *Platichthys stellatus*) and four abundant species of sea stars in Norton Sound was examined from the 1976 trawl study (Feder & Jewett, 1978a,b; Jewett & Feder, 1980). Starry flounder in Norton Sound fed primarily on clams (*Yoldia hyperborea*) and brittle stars (*Diamphiodia craterodmeta*). The four abundant sea star species fed on various infauna and epifauna, but primarily the Greenland cockle (*Serripes groenlandicus*).

Eighteen or more species of marine mammals occur in the Norton Sound area (Frost & Lowry, 1981; Lowry & Frost, 1981), many of which consume benthic invertebrates or fishes (e.g., Pacific cod, walleye pollock) that also consume benthic invertebrates. Among the marine mammals preying directly on benthic invertebrates are gray whales, bearded seals, spotted seals (*Phoca largha*), walrus, and sea lions (*Eumetopias jubata*). Gray whales feed on amphipods, polychaetes, bivalves, and gastropods (Hameedi, 1982; Lewbel, 1983). Bearded seals prey mostly on Tanner crabs, shrimp, and bivalves (Hameedi, 1982; Lewbel, 1983), while spotted seals prey on amphipods, shrimp, and other crustaceans (Lewbel, 1983). Walrus consume polychaetes, bivalves (*Tellina*, *Spisula*, *Serripes*, *Siliqua*), gastropods, Tanner crabs, and echinoids (Hameedi, 1982; Lewbel, 1983); sea lions consume crustaceans (Lewbel, 1983). Sea otters have also been sighted infrequently on St. Lawrence Island and in Norton Sound (Schneider, 1981); they have been found to feed on bivalves, crustaceans, and echinoderms in the northern Alaska Peninsula area (Lewbel, 1983).

Demersal Fishes

Demersal trawling in Norton Sound in 1976 yielded 14 families and 51 species of demeral fishes (Wolotira *et al.*, 1977). The three families that contributed most to numerical abundance were Gadidae, Pleuronectidae and Cottidae. The dominant species were saffron cod (*Eleginus gracilis*), Arctic cod (*Boreogadus saida*), starry flounder, yellowfin sole, Alaska plaice, and plain sculpin (*Myoxocephalus jaok*). Over 90% of the fish biomass is represented by these six species.

Saffron cod (Gadidae) was the dominant species during the fall (September and October) 1976 sampling period representing 60% of the total catch. Saffron cod is an important subsistence resource throughout the area and is harvested primarily during the winter (Wolotira, 1985). From spring through fall this species is an important marine mammal food source (Frost & Lowry, 1981; Lowry & Frost, 1981). They are fall-winter spawners and eggs are deposited on sandy bottoms. Pelagic larvae have been found in the area in early spring (Wolotira, 1985).

Arctic cod (Gadidae) is also an important marine mammal food source during the winter (Frost & Lowry, 1981; Lowry & Frost, 1981). Although distribution and movement patterns of this cod are not well known, saffron cod tend to be distributed more nearshore than Arctic cod (Gillispie *et al.*, 1997). Arctic cod appear to have a deeper-water, offshore distribution during the summer and inhabit the shallower, nearshore waters of Norton Sound during the winter. Generally, they move from offshore to inshore in the fall, spend the winter and spawn nearshore, and then move offshore during summer. Both adults and juveniles are important forage fish (Gillispie *et al.*, 1997).

Starry flounder appears to be the most abundant species of the Family Pleuronectidae in both offshore and nearshore waters. It was the second most abundant demersal fishes, comprising 17% of the catches in Norton Sound in the 1976 survey. It was the only flatfish species found in slightly brackish waters such as Imuruk Basin, the

Unalakleet River Lagoon and the Yukon Delta. Offshore, the largest concentrations of starry flounder were found in outer Norton Sound and the eastern portion of the northern Bering Sea.

Yellowfin sole, the third ranking demersal species in abundance from the same 1976 survey, represented 5% of the catches. This species migrates from winter habitat in deeper outer continental shelf and slope waters to shallower (15 to 76 m) inner shelf waters where spawning occurs in summer (Pereyra *et al.*, 1976). The migratory pattern for flatfishes which have been studied is, in contrast to the cod, an inshore movement in the spring and summer for spawning. Adults move offshore in fall and winter; juveniles remain in shallow, nearshore areas throughout their first few years before dispersing to offshore waters.

Most of the demersal fishes in the 1976 survey were found in greatest abundance in areas where bottom waters were warmer than 3.9°C and shallower than 30 m. Arctic cod were the exception, occurring at all temperatures and at depths greater than 20 m.

Pelagic Fishes

The important groups of pelagic fishes found in Norton Sound include all five species of Pacific salmon and Arctic char (*Salvelinus alpinus*). The most abundant are char, chum (*Oncorhynchus keta*) and pink salmon (*O. gorbuscha*); coho (*O. kisutch*), chinook (*O. tshawytscha*) and sockeye salmon (*O. nerka*) are far less abundant in this area. Pacific herring (*Clupea pallasi*), rainbow smelt (*Osmerus mordax*), Pacific sand lance (*Ammodytes hexapterus*) and capelin (*Mallotus villosus*) are important forage fishes of Norton Sound (Barton, 1978; Wolotira, 1980). The following accounts of these species are mainly taken from Barton (1978) and Wolotira (1980).

Among approximately 20 freshwater, salmon-producing streams that empty into Norton Sound, the three in the Nome vicinity (Nome, Penny and Snake rivers) have relatively small runs (ADF&G, 1983). Adult salmon migrations into Norton Sound coincide with the commercial fishing season, occurring from about mid-June through August. Chinook salmon are the earliest to appear, while coho salmon are the latest. Juvenile chum and pink salmon (fry) outmigrate in the spring from the previous fall spawning areas in freshwater to estuarine and nearshore areas. The fry may remain nearshore for several weeks before moving into ocean feeding areas. This period is believed to be a particularly critical phase for anadromous species as they adjust to the transition from a freshwater to a marine environment. Predation, temperatures and food availability are basic factors influencing survival rates.

Pacific herring (hereafter referred to as herring) movement into the Norton Sound coastal spawning areas appears to be greatly influenced by climatological conditions, particularly the location of the Bering Sea ice pack. Most herring appear near the eastern Bering Sea coast immediately after ice breakup in mid May and early June. Spawning progresses from south to north and continues until July and August along portions of the Seward Peninsula and Chukchi Sea. Peak spawning in Norton Sound usually occurs during the first half of June. Herring spawning is primarily intertidal and shallow subtidal in Norton Sound. Known spawning areas are located in the eastern and southern portions of inner Norton Sound, principally south of Norton Bay. Virtually no spawning occurs in the Nome vicinity. Spawning in intertidal areas occurs on rockweed (*Fucus* sp.), the dominant vegetation, and also on bare rock. In suspected subtidal spawning areas, eelgrass (*Zostera marina*) is the likely spawning substrate. Herring eggs hatch in two to three weeks as planktonic larvae, then metamorphose to juveniles in six to ten weeks. Juveniles have been found in Port Clarence, Grantly Harbor, Imuruk Basin, and Golovnin Basin, but detailed data on distribution of juveniles in Norton Sound are not available.

Inshore herring biomass estimates in Norton Sound are made each season by ADF&G personnel using standardized aerial observation techniques. These observations are made on nearshore spawning and pre-spawning schools of herring in shallow water.

Biomass estimates since 1979 have ranged from 7,000 mt in 1979 to 30,840 mt in 1988 for the Norton Sound region.

Capelin exhibit characteristics very similar to herring in terms of spring spawning, migration timing and utilization of the intertidal zone for spawning. Capelin, however, spawn on sandy beach areas and the eggs remain buried approximately two weeks before hatching. Known and suspected capelin spawning areas in Norton Sound extend from Cape Rodney on the western edge of northern Norton Sound to Cape Nome on the east. Capelin is an important prey species for several species of marine mammals as well as marine birds.

Pacific sand lance is similar to capelin in spawning, migration timing and habitat use (Dick & Warner, 1982). Sand lance are widely distributed in nearshore areas of Norton Sound with the greatest abundance in the northern portion of the Sound in the Golovnin Bay and Bluff areas. Abundance is lowest in the eastern and southern areas of Norton Sound. Sand lance represent a basic and important forage fish for marine birds, particularly kittiwakes (*Rissa tridactyla*), common murres (*Uria aalge*), and common guillemots (*Uria anlge*) (Roseneau *et al.*, 1982; Murphy *et al.*, 1986, 1991).

Rainbow smelt are common throughout Norton Sound. This species represented 2% of the National Marine Fisheries Service (NMFS) demersal trawl survey catches in 1976 (Wolotira *et al.*, 1977). They are important forage fish and also contribute to the Norton Sound subsistence harvest. Known spawning occurs in the fall; eggs adhere to aquatic plants and rocky substrates in freshwater streams and estuarine areas. Rainbow smelt larvae are commonly found throughout the nearshore areas of Norton Sound.

Arctic char is an abundant anadromous species found in streams throughout Norton Sound (Barton, 1978). These fish overwinter in freshwater and outmigrate to estuarine waters in late May or early June with ice break-up. They spend the summer feeding in estuarine areas and re-enter streams in the fall to spawn. Adult char travel the nearshore coastal waters during the summer feeding migration. Migrations usually do not exceed 161 km, so the populations are somewhat localized.

Marine Mammals

Three of the more common marine mammals found in Norton Sound are the spotted seal (*Phoca vitulina largha*), ringed seal (*Phoca hispida*), and beluga whale (*Delphinapterus leucas*). Less common species to Norton Sound are the harbor porpoise (*Phocoena phocoena*), bearded seal (*Erignathus barbatus*), Pacific walrus (*Odobenus rosmarus*) and polar bear (*Ursus maritimus*). Species peripheral to Norton Sound but common to outer reaches of the area include the killer whale (*Orcinus orca*), Minke whale (*Balaenoptera acutorostrata*), ribbon seal (*Phoca fasciata*), bowhead whale (*Balaena mysticetus*), and the gray whale (*Eschrichtius robustus*) (Zimmerman, 1982; Truett, 1985).

Spotted seals are distributed throughout Norton Sound in nearshore waters during the ice-free summer and early fall period. Haul-out areas within Norton Sound include Stuart Island, Besboro Island, Cape Denbigh, Cape Darby, Rocky Point, Safety Sound and Cape Wooley. During the winter, spotted seals are closely associated with the ice edge south of Norton Sound; they follow it northward and landward to rest and feed during the summer. The population estimate ranges from 2×10^5 to 3×10^5 spotted seals. Spotted seals feed mainly on pelagic fishes such as capelin, Pacific herring, and Arctic and saffron cods during the spring through fall period (Zimmerman, 1982; Truett, 1985).

The ringed seal is the most abundant and widely distributed ice inhabiting seal of the Bering, Chukchi, and Beaufort Seas. A conservative estimate of population size is 1.0 to 1.5 million for this species; it is an abundant species in Norton Sound when ice is present (Zimmerman, 1982; Truett, 1985). Ringed seals are migratory and leave their winter habitat zones of land-fast ice in the spring to follow the retreating ice pack northward. Most of the seals spend the summer period in the Chukchi or Beaufort Seas.

Breeding occurs from mid-April through May; pups are born the following year from mid-March through April. Both breeding and pupping occurs in the land-fast ice zone. Predominant diet items include Arctic and saffron cods, sculpins, shrimp, mysids, and amphipods (Zimmerman, 1982; Truett, 1985).

Beluga (Belukha) whales can be found throughout Norton Sound coastal areas during the spring through fall months. They appear nearshore with the onset of herring spawning in early summer and feed on these as well as a wide variety of other fish congregating or migrating nearshore. Two concentration areas in Norton Sound are between Golovnin Bay and Norton Bay and off the mouth of the Yukon River. Not many occur in the nearshore Nome vicinity. An estimated 9,500 beluga whales inhabit the Bering, Chukchi, and Beaufort Seas. An unknown number reside along the edge of the summer pack ice; the total population size is unknown. The winter distribution of these whales is restricted to regions of open water or young ice. Their migration is dependent upon ice conditions. The northward spring migration from southern wintering areas in the Bering Sea usually begins in late March or early April. Calving occurs in June and July and estuarine delta areas seem to be preferred, although calving may occur anywhere in near coastal areas (calving has been reported in Norton Bay). Food habits of beluga can vary considerably by season or location, but some common items include saffron cod, walleye pollock, octopus, capelin, Pacific halibut, and several species of crustaceans (Zimmerman, 1982; Truett, 1985).

Marine Birds

The largest seabird colony (4-6 x 10^4 birds) near the Nome area is located on the Bluff Cliffs, east of Cape Nome. Two other sizeable colonies (4-8 x 10^3 birds) are located on Sledge Island (in the study area) and Square Rock. Smaller seabird colonies (1,000 birds or less) are located at Rocky Point, Cape Darby, Bluff, and Safety Sound: Safety

Sound is used by the rare Aleutian tern (*Sterna aleutica*) (Roseneau *et al.*, 1982; Murphy *et al.*, 1986, 1991).

Prime wetland-nesting and feeding habitats of several breeding and migrant waterfowl and shorebird populations exist in the Nome area (Springer *et al.*, 1987). The most abundant seabirds include: common murres (*Uria aalge*) (3.5-7 x 10^4 birds), glaucous gulls (*Larus hyperboreus*) (over 2 x 10^4 birds), black-legged kittiwakes (*Rissa tridactyla*) (1.15-1.5 x 10^4 birds), horned puffins (*Fratercula corniculata*) (1.6-4.5 x 10^3 birds), pelagic cormorants (*Phalacrocorax pelagicus*) (1.5-2.5 x 10^3 birds) and thick-billed murres (*Uria lomvia*) (950-1,250 birds). Small numbers of parakeet auklet (*Cyclorrhynchus psittacula*), tufted puffin (*Lunda cirrhata*), and pigeon guillemot (*Cepphus columba*) also breed in Norton Sound (Drury *et al.*, 1981; Roseneau *et al.*, 1982).

Seasonal seabird occurrence (breeding, nesting, and feeding activities) in Norton Sound is generally from May through September. The most abundant seabird species prey on fish during the nesting season with sand lance, cods (Gadidae), and pricklebacks (Stichaeidae) being important food items (Springer *et al.*, 1987). According to bird census data, the common murre population at Norton Sound's largest bird colony--the Bluff Cliffs--declined markedly (7.5 x 10^4 to about 4 x 10^4 birds) from the late 1970's to the mid 1980's. The decline is attributed to low reproductive success in recent years and low survival in wintering areas in the southeastern Bering Sea (Murphy *et al.*, 1986).

The fact that least (*Aethia pusilla*) and crested (*A. cristatella*) auklets have only a few suitable nesting areas in Norton Sound (and in Alaska) makes this habitat critical (Roseneau *et al.*, 1982). Any adverse effects to their highly concentrated breeding grounds or feeding grounds could have severe consequences for both species.

Norton Sound king krab overview

The red king crab, *Paralithodes camtschaticus*, which belongs to the family Lithodidae, is one of three commercially exploited king crabs in the North Pacific Ocean. It was once the most valuable shellfish resource on Alaska's continental shelf (Otto, 1990). Red king crabs of Norton Sound represents the northern-most commercial fishery for this species (Powell *et al.*, 1983). The stock within the Sound is unique in that 1) it appears to be separate from other stocks in the Bering Sea (Seeb *et al.*, 1989), 2) it lives in the coldest area of its range (bottom water temperatures to -1.8° C; Hood *et al.*, 1974; Muench *et al.*, 1981), under ice for 5-6 months a year (Dupré, 1980), and 3) it is confined to waters less than 30 m in depth. The red king crab population within the Sound is small; estimates from trawl surveys in 1976 and 1979 revealed 4.6 and 1.4 million crabs, respectively (Sample & Wolotira, 1985). The most recent Norton Sound population assessment, conducted by trawl in August 1991, placed the total population of males and females and legal males (≈104 mm carapace length [CL]) at only 4.0 and 1.4 million crabs, respectively (Stevens & Haaga 1992). Migrations of the Norton Sound stock were found by tagging studies to typically follow north-south or northeast-southwest movement patterns (Powell *et al.*, 1983). Although the greatest distance moved in the Sound was reported to be 61 km in 46 days (Powell *et al.*, 1983), they could conceivably traverse the 250 km width of the Sound in a seasonal migration. The longest distance traveled by a crab in a single year was 426 km (Simpson & Shippen, 1968). In contrast, red king crabs in southeast Alaska had significant vertical movement but only small (10-20 km) horizontal movement over two years (Stone *et al.*, 1992).

A commercial summer/fall fishery has been traditionally centered in the northwestern portion of the Sound, south and east of Sledge Island (Wolotira *et al.*, 1977; Powell *et al.*, 1983). The harvest between 1986 and 1995 averaged 92,900 ± 38,900 (±1

SD) males ($\bar{x}$ = 1.36 kg ± 0.01) from an average of 17 ± 16 vessels (no fishing occurred in 1991; Lean & Brennan, 1995). A northeasterly migration of adult and subadult crabs (mainly males) into coastal waters occurs in late fall/winter (Powell *et al.*, 1983), and small commercial and subsistence fisheries exist for this species through the ice adjacent to coastal villages, in particular Nome (Powell *et al.*, 1983; Lean & Brennan, 1995). The average winter commercial (males only) and subsistence (both sexes) harvests between 1986 and 1995 were 3,402 ± 2,729 and 6,220 ± 3,581 crabs, respectively (Lean & Brennan, 1995). The crabs have an offshore migration during nearshore ice breakup (usually May) when temperatures rise and salinities fall (Muench *et al.*, 1981; Powell *et al.*, 1983).

Although little life history information is available for red king crabs from Norton Sound (i.e., Wolotira *et al.*, 1977; Powell *et al.*, 1983; Jewett *et al.*, 1990b; and Otto *et al.*, 1990), it is assumed that red king crabs there behave similarly to populations elsewhere (see McMurray *et al.* [1984] and Jewett & Onuf [1988] for reviews of red king crab life history). In general, there is an offshore-nearshore migration of both sexes. Most reproductive activities (e.g., egg-hatching, female-molting, grasping, mating, and egg extrusion) occur while nearshore, and sexes are somewhat segregated offshore. Population surveys during ice-free months (between late June and early October) in 1976, 1979-81, and 1981 revealed that female crabs generally were found to the north and east of the male crabs (Powell *et al.*, 1983). The crab's reproductive activities are intense while nearshore, particularly from March through June when some ice is still prevalent (Powell *et al.*, 1983; Otto *et al.*, 1990; pers. observ.). Norton Sound female red king crabs mature at smaller sizes than those in populations to the south (Otto *et al.*, 1990), and males are also assumed to mature smaller there, since maturity of both sexes within an area is attained at similar sizes elsewhere (Jewett & Onuf, 1988). The estimated size at 50 % maturity for females in Norton Sound is 71.4 mm CL, in comparison to 88.8 mm CL in Bristol Bay and 102.1 mm CL near the Pribilof Islands (Otto *et al.*, 1990). King crabs from Norton Sound take a wide array of prey items, including polychaete worms, bivalves, gastropods, sea urchins, and fishes (Jewett *et al.*, 1990b).

Objective

The primary objective of this study was to assess the effects of mining activities on the red king crab and their environment within and adjacent to mined areas off Nome. This objective was accomplished by evaluating the effects relative to: 1) the benthos; 2) crab relative abundance, distribution and prey; and 3) heavy metal concentrations in king crabs and surficial sediments. Each of these three major areas of the study will be addressed in an individual chapter.

Hypotheses

The following chapters address the general hypothesis that offshore mining operations had no significant effect on selected segments of the benthic community in the Nome vicinity. The following sub-hypotheses are addressed individually by chapter:

Chapter 1 • Benthic invertebrate community parameters (i.e., total abundance, biomass, number of taxa, taxon richness, diversity, and dominance) at mined areas are not significantly different from these parameters at unmined areas.

Chapter 2 • The relative abundance and sex composition of king crabs at the mined areas are not significantly different from that in the adjacent unmined areas; and

- Prey quantity and composition in king crab stomachs at mined areas are not significantly different from that in stomachs from adjacent unmined areas.

Chapter 3

- Heavy metal concentrations in king crabs at mined areas are not significantly different from concentrations in crabs at adjacent unmined areas; and
- Heavy metal concentrations in surfical sediments downcurrent is not significantly different from concentrations in sediments upcurrent of the mined sites.

CHAPTER 1: ASSESSMENT OF THE BENTHIC ENVIRONMENT FOLLOWING OFFSHORE PLACER GOLD MINING IN NORTON SOUND, NORTHEASTERN BERING SEA - I. BENTHOS[1]

Abstract: The effects of offshore placer gold mining on benthic invertebrates was assessed in Norton Sound of the northeastern Bering Sea. Mining with a bucket-line dredge occurred nearshore in 9-20 m during June-October 1986-90. Sampling nearly a year subsequent to mining revealed moderate alteration of the substrate granulometry, yielding a general pattern of more fines at the surface of the "sand" substrates and more coarse material at the surface of the "cobble" substrates. Benthic macrofaunal community parameters (e.g., total abundance, biomass, diversity) and abundance of numerically predominant families were reduced at mined stations. Although young individuals of opportunistic taxa predominated, selected taxa were smaller at mined stations. Many of the reduced taxa are known prey of the locally important red king crab (*Paralithodes camtschaticus*). Multi-year bathymetric and side-scan sonar surveys of an area mined only in 1986 showed a continued smoothing of ocean bottom relief, decreasing size of tailing footprint, and shoaling of depressions left by mining. An ordination (multidimensional scaling) of taxon abundance data from mined (1 yr after mining), recolonizing (2-7 yrs after mining), and unmined stations showed a configuration that reflected disturbance along its ordinate axis. At least four years were required for benthos in sand and cobble substrates to recover from mining activities. Mining effects are contrasted with local natural disturbances (e.g., currents, storms, ice).

[1]Jewett, S.C. Submitted. Assessment of the benthic environment following offshore placer gold mining in Norton Sound, northeastern Bering Sea - I. Benthos. Mar. Environ. Res. **00:** 00-00.

INTRODUCTION

Numerous studies have addressed marine benthic disturbance effects from activities such as mining (Olsgard & Hasle, 1993), dredging (Kenny & Rees, 1996), fishing (Collie *et al.*, 1997), petroleum production (Boesch & Rabalais, 1987), pulp effluent (Pearson *et al.*, 1986), sewage effluent (Anderlini & Wear, 1992), feeding of marine organisms (Klaus *et al.*, 1990), storms (Dobbs & Vozarik, 1983), ice scouring (Carey & Ruff, 1977), and seasonal hypoxia/anoxia (Tyson & Pearson, 1991). An extensive review of natural and anthropogenic physical disturbance on marine benthic communities in unconsolidated sediments was presented by Hall (1994). Little work has addressed the effects from marine mining (Ellis, 1987).

Only one marine mining program with associated environmental monitoring occurred on the Alaskan continental shelf. That study, known as the Nome Offshore Placer Project, assessed the effects of placer gold mining in the shallow waters of Norton Sound in the northeastern Bering Sea. Mining there occurred in ice-free months of 1986 through 1990; environmental monitoring occurred between 1986 and 1993. The physical and biological characteristics and effects in the mining area were considered, with emphasis on the effect to red king crab (*Paralithodes camtschaticus* [Tilesius, 1815]), a commercially-harvested and non-commercially-harvested (subsistence) species in Norton Sound. The potential effects of mining on this crab are addressed in Chapter 2, which compares crab abundance and prey between mined and unmined areas, and Chapter 3, which examines the concentrations of heavy metals in crabs and surficial sediments relative to mining activity.

This chapter examines the effect of mining activities on the substrate and associated benthic macrofauna and the subsequent recolonization process. Previous investigations of the Norton Sound benthos were carried out, primarily offshore of the current study area (Hood *et al.*, 1974; Wolotira *et al.*, 1977; Feder & Jewett, 1978).

Mining overview

Mining in the Nome Offshore Placer Project was conducted in northwestern Norton Sound in ice-free months (June - November) by Western Gold Exploration and Mining Company (WestGold) using the world's largest bucket-line mining dredge, the BIMA. The BIMA's dimensions were approximately 110 m long, 43 m wide, and 45 m high with a 88 m long bucket ladder that contained 134 buckets, each of which had a 0.85 m^3 capacity. Variable surficial substrate types were mined (targeting residual lag gravel deposits), materials processed onboard, and tailings returned to the excavation site. Mining occurred in 9-20 m water depths. The approximate locations and extent mined from 1986 through 1990 are shown in Figure 3. The area and volume mined within a 88 km^2 (21,750 acres) lease area was approximately 1.5 km^2 (371 acres) and 5.5 x 10^6 m^3, respectively (Howkins, 1992). The area and volume mined annually was 0.093 km^2 and 3.1 x 10^5 m^3 in 1986, 0.218 km^2 and 1.2 x 10^6 m^3 in 1987, 0.583 km^2 and 2.0 x 10^6 m^3 in 1988, 0.320 km^2 and 1.1 x 10^6 m^3 in 1989, and 0.287 km^2 and 9 x 10^5 m^3 in 1990 (Howkins, 1992). The Nome Offshore Placer Project ceased operation on September 20, 1990.

Study area

This study was conducted from 1986 to 1993 within the 88 km^2 of State of Alaska offshore mining leases adjacent to the City of Nome in the northwestern portion of Norton Sound. The lease area is north of 64° 26′ N to the southern coastline of the Seward Peninsula. The southern boundary generally follows the 20 m depth contour. The eastern boundary is a straight line south, midway between the mouths of the Snake and Nome rivers (165° 22′ W), and the western boundary is a straight line south, midway between the mouths of Cripple Creek and Penny River (165° 46′ W) (Fig. 3).

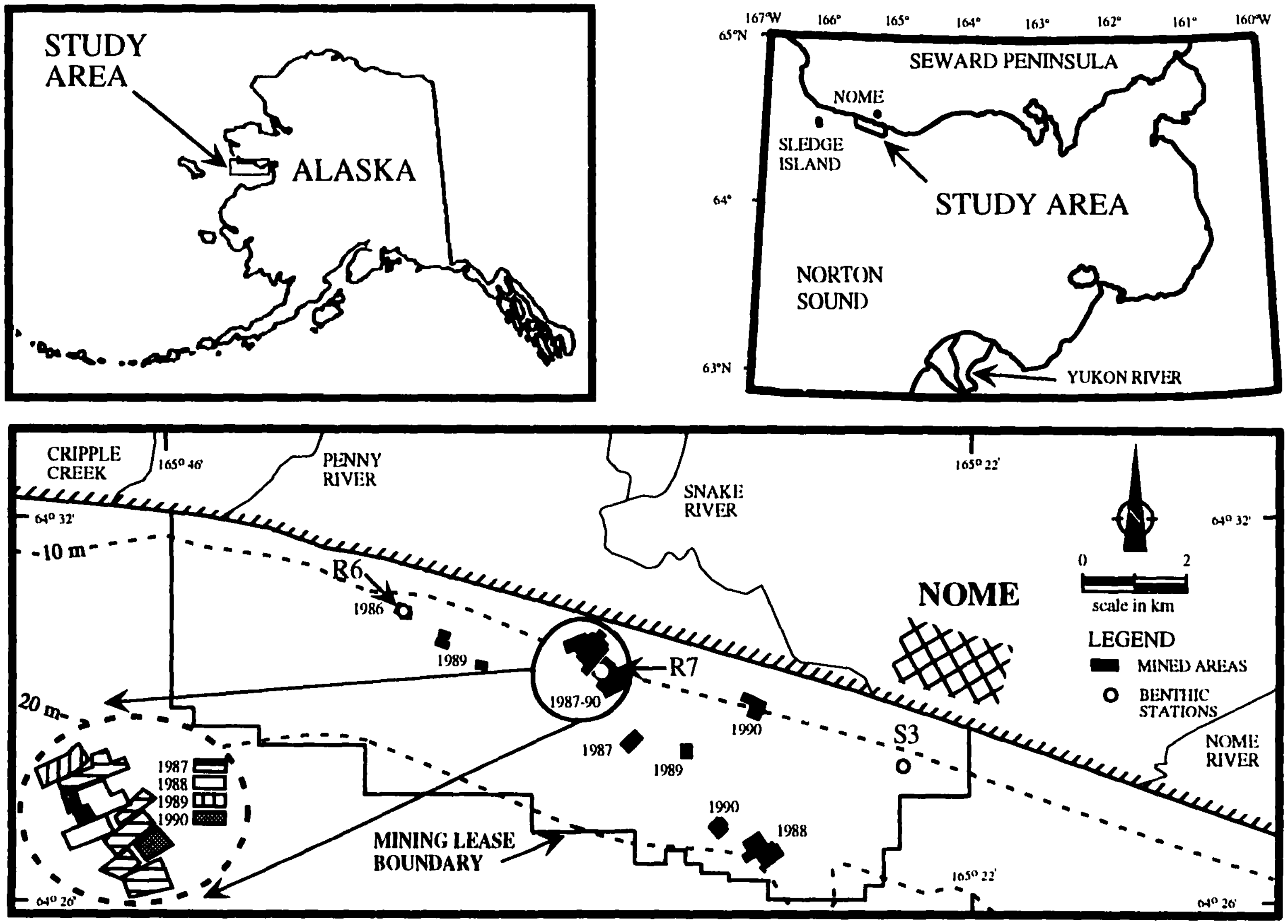

Figure 3. Map of the Nome Offshore Placer Project showing mining lease boundary, areas mined by year, and three stations where the benthos was monitored.

The westward flow of water along the south coast of the Seward Peninsula varies in intensity and extent (Hood *et al.*, 1974; Muench *et al.*, 1981). The speed of surface currents in the western portion of Norton Sound ranges from 5 to 20 cm s^{-1} with a maximum value of 50 cm s^{-1}. Strong coastal currents reaching speeds up to 100 cm s^{-1} may occur in the vicinity of Nome (Nelson & Hopkins, 1972). Bottom-current speeds are 10 to 20 cm s^{-1} in the western part of the Sound (Muench *et al.*, 1981). Tidal fluctuations at Nome are minimal (Pearson *et al.*, 1981) although major storms can cause dramatic fluctuation in sea-level height.

Surface sediments within the study area consist of a mosaic of sediment types, relict gravel and sand from residual lag deposits along with modern sediments of very fine sand- and silt-size particles derived from the Yukon River (Drake *et al.*, 1980; Hess & Nelson, 1982; Naidu, 1988). The fine sand/silt substrate overlying the more permanent cobble substrate is transient in nature and subject to redistribution by storms, currents and ice gouging. Wave-induced nearshore currents move fines in both east and west directions, but the net nearshore sand transport of approximately 5 x 10^5 m^3 y^{-1} is to the west (Drake *et al.*, 1980; Tetra Tech, 1980).

In the ice-free months of June through November bottom water temperatures and salinities typically range from near 0 to 12 °C and 21 to 34 ‰, respectively. During ice-covered months of December through May bottom bottom temperatures and salinities range from -1.8 to 1.5 °C and 32-34 ‰, respectively (Hood *et al.*, 1974; Muench *et al.*, 1981; Jewett, unpubl.).

Norton Sound is ice-covered during much of the winter-spring period (December-May). Ice thickness is variable and may approach 1.2 m. The seaward edge of the ice generally extends to the 20-m isobath and may be anchored by ice keels in the 10-20 m region (Stringer, 1981). Ice gouges generally occur inside the 20-m isobath and trend east to west. Gouge-incision depth usually ranges from 0.25 to 0.5 m deep, but may be as deep as 1 m (Larsen *et al.*, 1981). Ice-gouge widths of 15-25 m are most common but range from 5 to 60 m.

Bioturbation by numerous benthic invertebrates, demersal fishes and occasionally pacific walrus represents another mode of disturbance in the study area (Jewett & Feder, 1980; Nelson *et al.*, 1981; Klaus *et al.*, 1990). These organisms have dual roles as consumers as well as disturbers (Woodin, 1978; VanBlaricom, 1982; Klaus *et al.*, 1990).

METHODS

Field and laboratory

Bathymetry and side-scan sonar

Bathymetric and side-scan surveys were conducted to assess seafloor features at three offshore locations. The areas surveyed included 1) the 1986 mined area, containing Station R6, 2) the contiguous area mined in 1987-90, containing Station R7, and 3) a randomly selected unmined area which encompassed Station S3 (Fig. 3). Bathymetric and side-scan surveys were conducted at R6 in 1987-91. Side-scan surveys were made at R7 in 1987-89 and at S3 in 1985 and 1989. These surveys were conducted to identify possible navigation hazards and define substrate changes attributed to mining and natural events. The surveys utilized an EG&G Model 260, 100 KHz side-scan sonar system. A Del Norte UHF positioning system (accuracy of ± 1 m) was used for navigation and a Ross 6800-4400 digital recorder was used to determine water depths.

Based on side-scan sonar surveys, seafloor substrates were subdivided into four distinct types: Very Coarse (gravel > 64 mm), Coarse (coarse sand/fine gravel - 500 µm-64 mm), Smooth (predominantly fine sand and silts - 2-250 µm), and Sand Waves (waves 5-15 cm in height, mainly 2-250 µm). These substrate types were initially verified by diver observations and sediment sampling. A mosaic of the sediment types was constructed for each survey area from the accumulated data transferred from trackline maps.

The changes in relief of the 1986 mined area, including Station R6, were analyzed by measuring the surface areas at < 6 m water depth which corresponded to eroding mounds (tailing piles) and to areas > 15 m which mainly consisted of shoaling depressions (dredge scars). The percentage of eroding and shoaling areas were calculated using the area of the entire bathymetric diagram, which represented an area somewhat larger than the actual footprint of mining.

Sediment

Three replicate sediment samples for granulometry were collected by divers immediately adjacent to the infaunal sampling location. Samples at two predominant substrate types, fine (mainly sand) and coarse (mainly cobble) materials, were collected within each station area. These two substrates are loosely referred to as "Sand" and "Cobble". Divers using a hand-held, 1-l scoop collected the top 5 cm of each sediment type. The mean grain size was analyzed by the sieve-hydrometer method (Folk, 1980). Sediment samples were collected every year; 1993 samples were lost in shipping.

Macrobenthos

A reconnaissance survey in the study area in September 1985 determined the level of effort needed for long-term monitoring of the benthic fauna. Eight replicate samples were collected at two depths from three randomly selected stations using a diver-operated suction sampler with a 0.1 m^2 surface area. Power analysis (Peterman, 1990) revealed that five or more replicates per station were needed to detect differences in number of taxa or individuals between stations 80% of the time at a significance level of 0.05. Six replicates per station were subsequently taken at each station.

Sampling each year occurred prior to commencement of mining operations. In June of 1986-91 and 1993, samples were collected from three areas within the lease boundary, two within mining areas (Stations R6 and R7) and one in an area where no mining occurred (Station S3) (Fig. 3). Station S3 was randomly selected as the reference station in a 1985 preliminary survey. This site had similar gross surficial sediment composition and grain size to the sites slated to be mined in 1986 and 1987. Also, S3 was upcurrent of the priority mining locations, away from any mining-related disturbance. Although many areas were mined and sampled over the five-year mining period (Fig. 3), a post-hoc decision was made to analyzed data from Stations R6 and R7 because they were the first ones mined and represented the longest temporal data sets. Station R6, mined only in 1986, and R7, mined in 1987-90, were monitored annually. Depths at all stations were generally 10-12 m, however, depths in the vicinity of R6 varied from 5 to 17 m soon after mining. The area at each station was 0.04 km^2 or 200 m by 200 m. Stations R6 and R7 were positioned in the middle of each mining area. Samples were collected by SCUBA divers within two predominant sediments at each station, one on fine substrate, mainly sand, and the other on coarse substrate, mainly cobble. Since the substrate was generally heterogenous at each station, divers sampled the first substrate (fine or coarse) encountered within five meters of the buoy anchor marking the station. The remaining substrate was located by swimming in a random compass direction up to 100 m from the buoy until the substrate was found.

Infauna and relatively non-motile epifauna were collected in both substrates using a diver-operated suction sampler. For the soft substrate, divers pushed a circular collecting frame with a 0.1 m^2 surface area into the sediment 10 cm deep. The material within the frame was vacuumed into a conical, 1.0 mm mesh collecting bag with a removable PVC collection cup attached to the suction device. Sampling in coarse substrates necessitated placing a 0.1 m^2 frame on the sediment surface. Attached to one side and perpendicular to the collecting frame was a second frame used to secure a 1.0 mm mesh bag for hand placement of large gravels (> 4 cm in diameter). The portion of the collecting frame in contact with the substrate was open to facilitate hand or suction collection of samples. Material in collection bags and cups was preserved in 5% neutral buffered formalin, stained with 0.1% rose bengal, and taxonomic determinations made at the Institute of Marine Science, University of Alaska Fairbanks. Organisms were identified to at least the family level, but there were a few instances when only higher taxonomic levels could be assigned. The most common organisms were identified to genus or species. All pelagic invertebrates, meiofauna, highly-motile epifaunal invertebrates, large organisms weighing more than 5 g, unidentified animal tissue, and fishes were excluded from analyses. Counts and blotted wet weights to the nearest mg were obtained for each taxon. The abundance (A; individuals m^{-2}), biomass (B; g m^{-2}) and number of taxa (T) were recorded. Fragments of animals were not considered in abundance (density) computations, but were included in biomass estimates. Determination of size of selected dominant organisms were made. Lengths of the bivalve *Tellina lutea* and the cockle *Clinocardium californiense*, widths of the sand dollar *Echinarachnius parma*, and the disc diameter of the brittle star *Diamphiodia craterodmeta* were measured to the nearest 0.1 mm. Abundance and size values in the text are generally presented as means ± one standard error.

Data analyses

Univariate analyses

Possible effects of dredging activities on the benthos were examined by testing the general null hypothesis that a suite of benthic community parameters at mined areas are not significantly different from the community parameters at unmined areas. The parameters measured at each station/substrate included A, B, and T, in addition to indices of taxon richness (R; Margalef, 1958), Shannon diversity (H′; Shannon & Weaver, 1963) and Simpson dominance (D; Simpson, 1949). In the calculations for the above indices, taxa were identified to family level (or above). While these indices are normally applied to species, the overall diversity of a community is comprised of hierarchical components (e.g., family, genus, and species) and the concept can be applied to any of these components (Pielou, 1974; Grebmeier *et al.*, 1989). Diversity values computed using taxon identifications higher than species have been reported by Lloyd *et al.* (1968), Valentine (1973), Ferraro & Cole (1992).

For testing this hypothesis, only the station mined in the previous year (1 yr after mining) was used as the mined station in each yearly comparison. The comparison for 1987 used the station mined in 1986, R6, with unmined Station S3. In the comparisons for 1988 through 1991, mined Station R7 was used in the analyses. Data on faunal and sediment parameters were compared between mined and unmined areas and years using non-parametric Mann-Whitney and Kruskal-Wallis tests. Student's t and ANOVA tests were used in all animal size comparisons. Statistical significance was set at $p \leq 0.05$.

The approach to examine the successional changes in the benthic communities disturbed by mining operations was primarily to compare the faunal changes from a one-time disturbance event, and secondarily to compare the recolonizing state with fauna at a nearby unmined reference location. Since Station R6 was only mined once, it was monitored for benthic recolonization up to seven years after mining (2-7 yrs after mining).

Multivariate analysis

The multivariate technique of nonmetric multidimensional scaling (MDS: Kruskal & Wish, 1978) was employed to assist in the interpretation of potential mining effects. Taxa used in the analyses were at the family level or above (Rosenberg, 1972; Heip *et al.*, 1988; Warwick, 1988). The Bray-Curtis similarity coefficient (Bray & Curtis, 1957) was used to calculate separate similarity matrices for the sand and cobble substrates using *ln* (x+1) abundance data. The MDS ordination technique constructs a "map" of station similarities from the taxon abundance data (Bray-Curtis similarity matrix) where the more similar stations are closer together in space (Gray *et al.*, 1988). The extent to which the data are adequately represented by the two-dimensional map is summarized by the stress coefficient (square root of a normalized residual sums of square: should be ≤ 0.15 [Clark & Ainsworth, 1993]). MDS ordination procedures have been applied widely to abundance data to assess disturbance effects upon marine communities (e.g., Clark & Ainsworth, 1993; Olsgard & Hasle, 1993; Warwick & Clarke, 1993; Olsgard & Gray, 1995; Feder & Blanchard, In press).

RESULTS

Bathymetric surveys

Two-dimensional bathymetric maps of the 1986 mined area, including Station R6, were generated for each year, commencing one year after mining, 1987 through 1991 (See Fig. 4 for examples). The maps illustrate continued smoothing of ocean bottom relief, decreasing size of the tailing footprint, and filling in of the depressions left by the mining operation. Although moderate anomalies in the seafloor relief were observable five years after mining, it is apparent that recovery from the physical disturbance was still taking place. The areas of eroding mounds (i.e., < 6 m water depth) showed a general decrease in surface area following mining until no area < 6 m was apparent in 1991 (Table 1). The depression areas of the mining footprint (i.e., > 15 m) showed a 22% reduction in surface area (or shoaling) from 1987 to 1991; 19% reduction was noted between 1990 and 1991.

Side-scan sonar surveys

Side-scan surveys made in the 1986 mined area, included Station R6, in October 1987, October 1988, September 1989, July 1990, and June 1991. Generally, small changes in dominance of substrate types were apparent over the five-year period. The

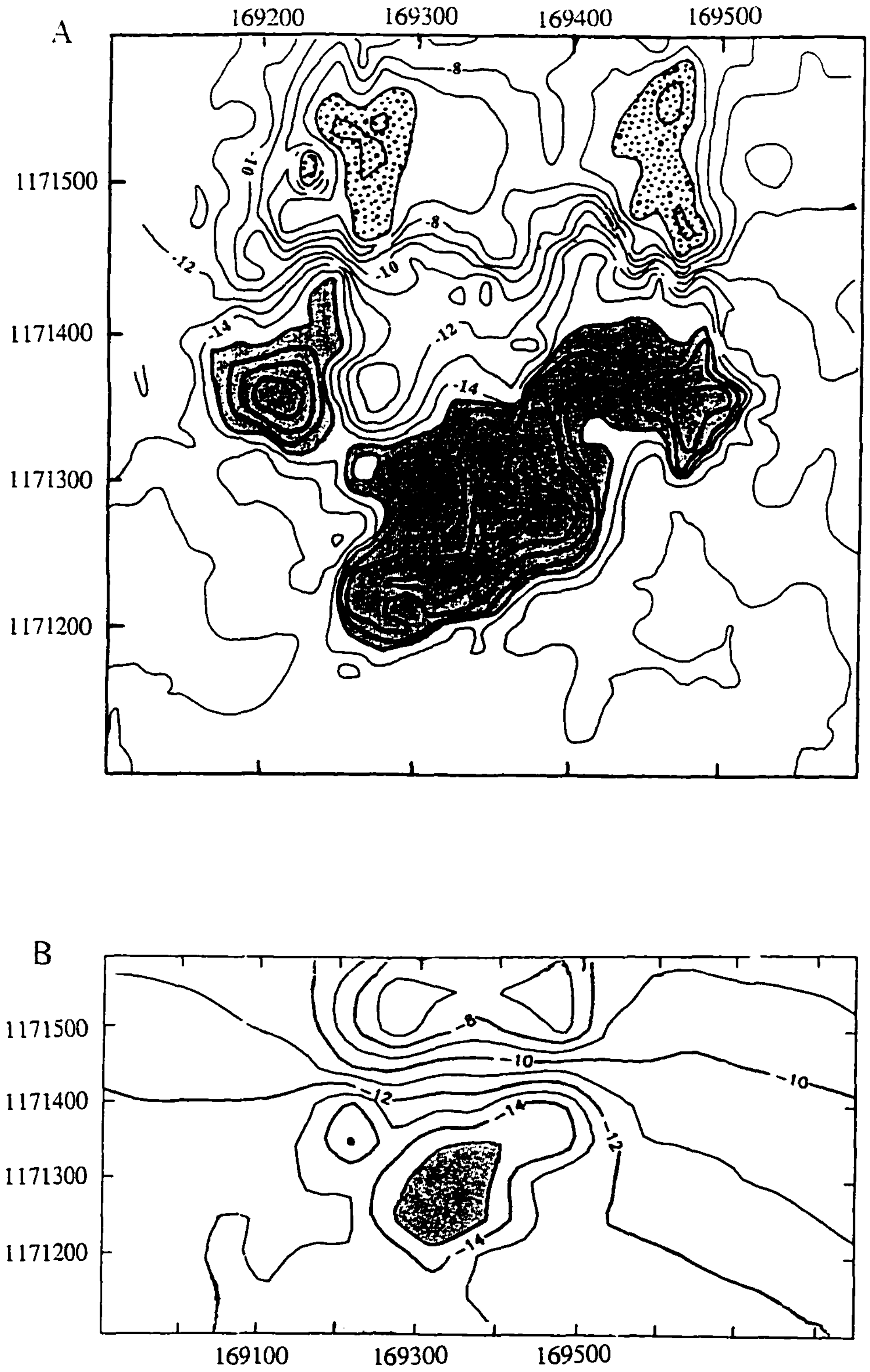

Figure 4. Two-dimensional representation of the 1986 dredge area bathymetry during (A) October 1987 and (B) June 1991. The axes (in meters) correspond to the WestGold coordinate positioning system. Dotted stippling refers to ≤ 6 m water depth; solid stippling refers to ≥ 15 m.

Table 1. Summary of area eroding and shoaling by year at depths < 6 m and > 15 m within the 1986 dredge site.

Year	Surface area < 6 m		Surface area > 15 m	
	m^2	%	m^2	%
1987	9,225	8.1	37,775	32.8
1988	5,100	4.4	35,425	30.7
1989	5,350	4.6	29,550	25.6
1990	3,000	2.6	34,425	29.8
1991	0	0	12,195	10.6

predominant substrate in all years, Smooth substrate (mainly fine sand and silts), decreased from 53% in 1987 to 39% in 1991 (Table 2). Very Coarse (gravel) and Coarse (coarse sand/fine gravel) substrates were the next prominent surficial features; both varied considerably over the five-year period. Sand Waves were always a minor component, except in 1991 when it made up nearly 24% of the surveyed area.

Based on the three years (1987-89) of side-scan surveys of the contiguous area mined in 1987-90, Station R7, the surficial substrates had similar characteristics over the three-year period (Table 2). Smooth substrate generally predominated with about 45 to 65%. Very Coarse substrate and Sand Waves varied from 14 to 50% and 1 to 29%, respectively. Coarse substrate always made up less than 10% of the substrate.

Sonographs of the reference area that included Station S3 generally revealed that Very Coarse (47 to 55%) and Smooth (43 to 50%) substrates predominated in the two survey years (1985 and 1989) (Table 2). Sand Waves and Coarse substrates never accounted for more than 2% of the area.

Comparison between mined and unmined stations

Sand substrate

Comparisons of sediment and community parameters between mined and unmined "sand" stations revealed significant differences (Tables 3 and 4), thus rejecting the null hypothesis of no difference between mined and unmined stations. Sediment granulometric parameters of percent(s) gravel and sand from sand substrates were not different ($p > 0.05$) between mined and unmined stations; however, there was more ($p = 0.04$) mud at mined stations (Table 3). That more mud occurred there was mainly attributed to R7-89 and R7-90 which had high proportions of mud, 23 and 27%, respectively. Benthic faunal community parameters (i.e., abundance [A], biomass [B], number of taxa [T], richness [R], diversity [H'] and dominance [D] indices) differed significantly between mined and

Table 2. Multi-year comparisons of seafloor sediment types (%) from side-scan sonar surveys at mined stations R6 and R7 and unmined reference station S3.

	R6[1]				
Substrate Types	1987	1988	1989	1990	1991
Smooth	53.4	42.1	45.3	45.7	38.9
Sand Waves	0.2	5.4	1.0	8.5	23.7
Coarse	34.8	11.0	24.3	13.2	11.3
Very Coarse	11.6	41.5	29.5	32.6	26.1

	R7[2]		
Substrate Feature	1987	1988	1989
Smooth	65.3	44.7	53.8
Sand Waves	5.8	1.2	28.6
Coarse	8.7	3.7	4.0
Very Coarse	20.1	50.4	13.6

	S3[3]	
Substrate Feature	1985	1989
Smooth	50.1	43.4
Sand Waves	1.6	2.0
Coarse	1.1	0.0
Very Coarse	47.2	54.5

[1] Coinciding area surveyed = 0.36 km^2 (88 ac)
[2] Coinciding area surveyed = 0.38 km^2 (95 ac)
[3] Area surveyed = 1.1 km^2(275 ac)

Table 3. Average sediment and infaunal community parameters in "sand" and "cobble" substrates from mined, recolonizing, and unmined stations within the offshore Nome mining lease area.

SAND SUBSTRATE

Mined	% gravel	% sand	% mud	Abund.	Biomass	# Taxa	Richness	H′	D
R6-87	0.12	94.47	5.41	242	1.03	9	1.52	1.82	0.22
R7-88	0.00	98.94	1.19	398	0.30	15	2.41	2.35	0.13
R7-89	0.00	76.53	23.47	607	1.07	15	2.18	1.89	0.27
R7-90	0.00	73.27	26.72	455	1.27	13	1.88	2.01	0.18
R7-91	54.03	39.27	6.70	118	0.29	9	1.62	2.06	0.13
Recolonizing (2-7 years after mining)									
R6-88	0.00	99.40	0.60	1388	7.41	23	3.07	2.21	0.22
R6-89	0.00	99.42	0.58	1192	13.66	22	2.98	2.43	0.13
R6-90	0.00	98.38	1.61	2127	20.67	27	3.35	2.13	0.25
R6-91	0.57	95.07	4.37	653	6.04	18	2.60	2.36	0.14
R6-93	-	-	-	660	10.34	20	2.94	2.44	0.13
Unmined									
S3-87	9.50	89.05	1.45	2645	61.15	31	3.75	2.72	0.11
S3-88	0.00	99.58	0.42	5962	32.11	43	4.82	2.80	0.12
S3-89	0.00	97.03	2.96	4208	60.31	40	4.74	3.06	0.07
S3-90	0.00	98.66	1.34	7317	14.14	36	3.99	1.44	0.53
S3-91	1.07	95.90	0.03	677	7.84	21	3.10	2.46	0.13
S3-93	-	-	-	1787	11.80	22	2.95	2.37	0.14

COBBLE SUBSTRATE

Mined	% gravel	% sand	% mud	Abund.	Biomass	# Taxa	Richness	H′	D
R7-88	78.80	19.98	1.22	397	0.57	15	2.36	2.39	0.12
R7-90	86.17	13.57	0.26	450	0.62	13	1.96	1.79	0.28
R7-91	73.30	23.87	2.83	247	0.43	10	1.64	1.92	0.18
Recolonizing (2-7 years after mining)									
R6-88	75.38	24.59	0.03	748	1.02	16	2.34	2.29	0.14
R6-89	42.32	56.36	1.31	1295	4.86	19	2.69	2.40	0.13
R6-90	97.60	3.31	0.09	812	104.26	23	3.34	2.40	0.17
R6-91	75.70	22.33	1.97	712	20.57	22	3.21	2.62	0.10
R6-93	-	-	-	1313	39.04	29	3.94	2.71	0.10
Unmined									
S3-87	56.41	43.45	0.14	2840	22.60	36	4.40	2.91	0.08
S3-88	51.82	45.84	2.34	2692	17.32	36	4.43	2.97	0.07
S3-89	57.92	41.08	1.00	1405	1.80	24	3.26	2.49	0.13
S3-90	61.25	37.61	1.14	1777	27.67	32	4.15	2.57	0.13
S3-91	46.70	44.40	8.90	555	10.96	20	2.92	2.40	0.13
S3-93	-	-	-	1122	8.47	29	3.92	2.71	0.10

Table 4. Mann-Whitney test comparisons of community parameters between mined and unmined stations in "sand" and "cobble". The < sign indicates that the value for mined station is significantly less than for the unmined station and > indicates the value for the mined station is greater. NS = not significant; NA = not available.

	SAND				
Mined vs. Unmined	1987	1988	1989	1990	1991
Abundance (A)	<<	<<	<<	<<	<<
Biomass (B)	<<	<<	<<	<<	<<
No. Taxa (T)	<<	<<	<<	<<	<<
Taxon Richness (R)	<<	<<	<<	<<	<
Diversity (H')	<<	<<	<<	<	<
Dominance (D)	>>	NS	>>	<<	NS

< = 0.05 < p < 0.001; << = p < 0.001

	COBBLE				
Mined vs. Unmined	1987	1988	1989	1990	1991
Abundance (A)	NA	<<	NA	<<	<
Biomass (B)	NA	<<	NA	<<	<<
No. Taxa (T)	NA	<<	NA	<<	<
Taxon Richness (R)	NA	<<	NA	<<	<
Diversity (H')	NA	<<	NA	<<	<
Dominance (D)	NA	>	NA	>>	NS

unmined stations (Tables 3 and 4; Fig. 5). In nearly all of the five-year (1987-91) comparisons, A, B, T, R, and H′ were less ($p \leq 0.05$) and D was more ($p \leq 05$) at mined stations than at unmined Station S3 (Tables 3 and 4; Fig. 5).

Mined and unmined stations were characterized by different dominant families, most of which were either motile or discretely motile (sensu Fauchald & Jumars, 1979). Most taxa had lower ($p \leq 0.05$) abundance at mined stations than at the unmined station (Table 5). The ten most abundant families at mined sand stations were Sigalionidae, Nephtyidae, Goniadidae, and Magelonidae (polychaetes); unidentified bivalves; Lampropidae and Diastylidae (cumaceans); Corophiidae and Oedicerotidae (amphipods); and Amphiuridae (brittle stars) (Tables 5 and 6). Most families comprised only one genus and species, although amphipods consisted of 13 genera including tube-dwelling corophiids (*Corophium, Erichtonius, Photis, Protomedeia,* and *Ischyrocerus*) and burrowing oedicerotids (*Acanthostepheia, Aceroides, Bathymedon, Monoculodes, Monoculopsis, Machaironyx, Paroediceros,* and *Westwoodilla*). Amphiurid brittle stars (*Diamphiodia craterodmeta*) represented the most abundant faunal group at mined sand stations (Tables 5 and 6).

The ten dominant families at unmined sand Station S3 were Goniadidae, Spionidae, Capitellidae, and Oweniidae (polychaetes); Tellinidae (bivalves); Diastylidae (cumaceans); Corophiidae and Oedicerotidae (amphipods); Echinarachniidae (sand dollars); and Amphiuridae (brittle stars) (Tables 5 and 6). These families, with the exception of spionids, were represented by one or two genera and species. Spionids comprised eight genera (*Polydora, Prionospio, Spio, Boccardia, Spiophanes, Pygospio, Scolelepis,* and *Marenzellaria*), with *Spiophanes* predominating. Oweniid polychaetes represented the most abundant family. Oweniids ($\bar{x}$ = 1,368 ± 1017 m^{-2}; mainly the tube-dwelling *Myriochele oculata*), were approximately 273 times more numerous ($p < 0.001$) than at mined stations

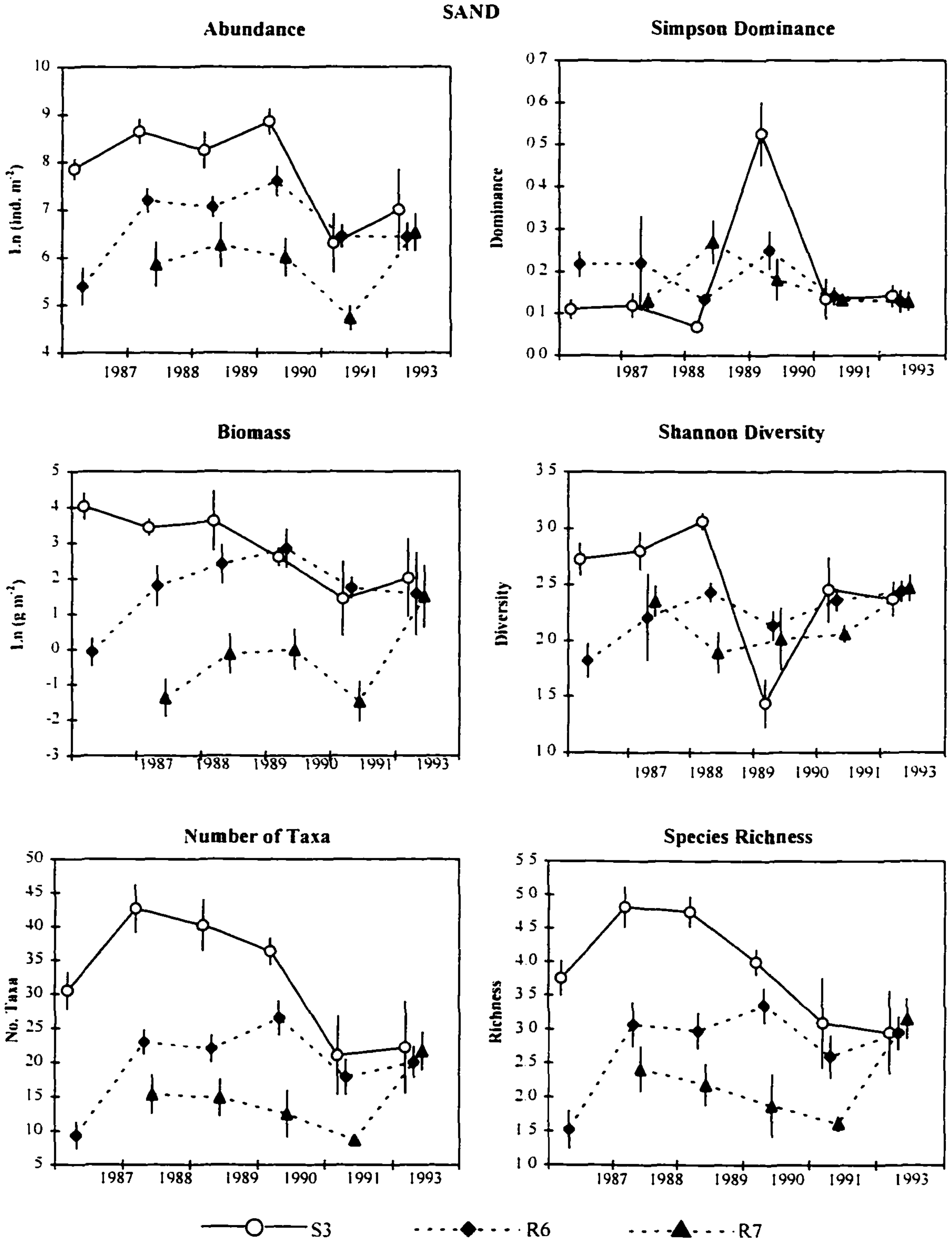

Figure 5. Plots of means and 95% confidence intervals of benthic community parameters in the sand substrate at mined stations R6 and R7 and unmined station S3.

Table 5. Mann-Whitney test comparisons of the most abundant (avg. indiv. m^{-2}) benthic families from mined and unmined stations on "sand" and "cobble" substrates. Ranks of the ten most abundant taxa in each treatment are presented in parentheses. * = significant difference ($p \leq 0.05$).

	SAND		COBBLE	
Taxa	Mined[1]	Unmined[2]	Mined[3]	Unmined[4]
Rhynchocoela				
Lineidae	6	40 *	8 (7.5)	114 (7) *
Annelida				
Polychaeta				
Polynoidae	7	35 *	29 (5)	52
Sigalionidae	20 (6)	47 *	32 (4)	108 (8) *
Syllidae	1	2	3	120 (6) *
Nephtyidae	8 (9.5)	43 *	4	5
Goniadidae	24 (3.5)	165 (6) *	4	75 (10) *
Spionidae	3	220 (4) *	2	124 (5) *
Magelonidae	9 (8)	75 *	1	3
Cirratulidae	1	33 *	1	145 (3) *
Capitellidae	3	156 (7) *	3	31 *
Oweniidae	5	1368 (1) *	4	166 (2) *
Ampharetidae	1	35 *	0	86 (9) *
Mollusca				
Bivalvia				
Nuculanidae	4	30 *	8 (7.5)	25
Cardiidae	6	10	78 (1)	45
Tellinidae	5	142 (8) *	2	10 *
Myidae	5	9	6 (10)	5
Unid. bivalve	18 (7)	15	4	5
Arthropoda				
Cumacea				
Lampropidae	8 (9.5)	30 *	6	9
Diastylidae	24 (3.5)	81 (10) *	4	45 *
Amphipoda				
Dexaminidae	1	0	7 (9)	1
Corophiidae	22 (5)	282 (2) *	36 (3)	45
Oedicerotidae	48 (2)	269 (3) *	22 (6)	138 (4) *
Echinodermata				
Echinoidea				
Echinarachniidae	1	209 (5) *	0	1
Ophiuroidea				
Amphiuridae	86 (1)	131 (9) *	53 (2)	248 (1) *

1 = R6-87; R7-88 - R7-91
2 = S3-87 - S3-91
3 = R7-88 - R7-91
4 = S3-87 - S3-91

Table 6. Dominant benthic taxa, in terms of abundance (indiv. m^{-2}), at mined, recolonizing, and unmined stations on "sand" substrates. A = amphipod, B = bivalve, BS = brittle star, C = cumacean, G = gastropod, N = nemertean, P = polychaete, SD = sand dollar, T = tunicate.

STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.
MINED (1 YEAR AFTER MINING)																	
R6-87	Oedicerotidae A	82	R7-88	Sigalionidae P	93	R7-89	Amphiuridae BS	295	R7-90	Oedicerotidae A	110	R7-91	Lineidae N	15			
	Diastylidae C	58		Bivalvia B	43		Corophiidae A	48		Amphiuridae BS	90		Amphiuridae BS	14			
	Lampropidae C	20		Corophiidae A	37		Bivalvia B	33		Goniadidae P	68		Bivalvia B	12			
	Goniadidae P	15		Amphiuridae BS	25		Goniadidae P	32		Diastylidae C	43		Ascidiacea T	7			
	Corophiidae A	10		Myidae B	22		Mytilidae B	22		Magelonidae P	28		Lampropidae C	7			
	Amphiuridae BS	8		Polynoidae P	22		Oedicerotidae A	22		Oweniidae P	22		Sigalionidae P	5			
	Campylaspidae C	7		Nephtyidae P	22		Hiatellidae B	22		Tellinidae B	10		Oedicerotidae A	5			
	Nephtyidae P	7		Oedicerotidae A	20		Magelonidae P	13		Corophiidae A	10		Corophiidae A	5			
	Oweniidae P	5		Cardiidae B	18		Molgulidae T	13		Cardiidae B	8		Molgulidae T	5			
	Trochidae G	3		Nuculanidae B	18		Polynoidae P	12		Capitellidae P	7		Magelonidae P	3			
RECOLONIZING (2-7 YEARS AFTER MINING)																	
			R6-88	Cirratulidae P	417	R6-89	Mactridae B	238	R6-90	Oweniidae P	1032	R6-91	Magelonidae P	180	R6-93	Spionidae P	162
				Oweniidae P	227		Magelonidae P	223		Oedicerotidae A	180		Haustoridae A	93		Oedicerotidae A	112
				Lineidae N	105		Tellinidae B	213		Magelonidae P	135		Spionidae P	50		Lampropidae C	70
				Corophiidae A	99		Goniadidae P	72		Goniadidae P	128		Goniadidae P	47		Nephtyidae P	38
				Capitellidae P	80		Spionidae P	48		Amphiuridae BS	73		Orbiniidae P	35		Cumacea C	30
				Goniadidae P	55		Lineidae N	43		Orbiniidae P	73		Tellinidae B	33		Corophiidae A	30
				Nuculanidae B	45		Oedicerotidae A	40		Apistobranchidae P	53		Oedicerotidae A	27		Tellinidae B	20
				Spionidae P	32		Nephtyidae P	38		Opheliidae P	50		Nephtyidae P	25		Goniadidae P	20
				Amphiuridae BS	30		Orbinidae P	28		Tellinidae B	47		Oweniidae P	22		Orbinidae P	18
				Diastylidae C	30		Corophiidae A	26		Spionidae P	42		Amphiuridae BS	20		Haustoridae A	17
UNMINED																	
S3-87	Spionidae P	513	S3-88	Oweniidae P	1030	S3-89	Oedicerotidae A	607	S3-90	Oweniidae P	5378	S3-91	Amphiuridae BS	90	S3-93	Oedicerotidae A	397
	Oweniidae P	280		Corophiidae A	992		Corophiidae A	465		Oedicerotidae A	238		Magelonidae P	73		Spionidae P	325
	Capitellidae P	275		Echinarachnidae SD	512		Tellinidae B	385		Spionidae P	225		Oedicerotidae A	73		Lampropidae C	278
	Oedicerotidae A	173		Capitellidae P	342		Echinarachnidae SD	308		Goniadidae P	143		Bivalvia B	48		Echinarachnidae SD	157
	Magelonidae P	157		Goniadidae P	327		Amphiuridae BS	249		Tellinidae B	138		Orbiniidae P	47		Tellinidae B	137
	Echinarachnidae SD	123		Oedicerotidae A	255		Goniadidae P	233		Amphiuridae BS	122		Lineidae N	35		Lineidae N	65
	Diastylidae C	113		Amphictenidae P	207		Scaphandridae G	228		Echinarachnidae SD	102		Molgulidae T	25		Goniadidae P	62
	Phoxocephalidae A	108		Spionidae P	172		Spionidae P	173		Haustoridae A	100		Oweniidae P	23		Haustoridae A	47
	Goniadidae P	105		Cirratulidae P	157		Diastylidae C	143		Orbiniidae P	85		Capitillidae P	23		Magelonidae P	35
	Tellinidae B	105		Sigalionidae P	155		Oweniidae P	130		Magelonidae P	77		Haustoridae A	20		Diastylidae C	33

($\bar{x}$ = 5 ± 3.4 m^{-2}).

Amphiurid brittle stars (i.e., *Diamphiodia craterodmeta*) ranked first and ninth at mined and unmined stations, respectively. Nevertheless, abundance of *D. craterodmeta* was less ($p = 0.013$) at mined stations ($\bar{x}$ = 86 ± 24.2 m^{-2}) than at unmined Station S3 ($\bar{x}$ = 131 ± 24.2 m^{-2}) (Table 7). Abundance was significantly different between years at mined stations but not at the unmined station (Table 7). Highest and lowest abundance values at mined stations were in 1989 and 1991, respectively. The size of *Diamphiodia*, which ranged between 0.4 and 6.6 mm disc diameter, was smaller ($p < 0.001$) at mined stations ($\bar{x}$ = 0.8 ± 0.02 mm) than at the reference station ($\bar{x}$ = 1.5 ± 0.06 mm) (Table 8). Individuals < 2 mm comprised nearly 100% and 77% of the brittle stars at mined and reference stations, respectively. Less than 1% at S3 were ≥ 6 mm.

Bivalves in the Family Tellinidae, a dominant group readily amenable to size analysis, was more ($p < 0.001$) abundant at the unmined station ($\bar{x}$ = 142 ± 27.6 m^{-2}) compared to mined stations ($\bar{x}$ = 5 ± 1.6 m^{-2}). *Tellina lutea*, the predominant representative of this family, accounted for nearly 85% of the tellinid abundance. There were significant differences in abundance (Table 7) and size (Table 8) of *T. lutea* at unmined Station S3 over the 1987-91 study period. Abundance of *T. lutea* ranged from a high of 333 ± 53.9 m^{-2} in 1989 to only 7 ± 4.2 m^{-2} in 1991. The size of *T. lutea* over the study period ranged from 1.5 to 38.8 mm and averaged 3.0 ± 0.12 mm. Approximately 97% of the individuals (n = 348) were ≤ 6 mm long; nearly 68% were ≤ 3 mm.

Echinarachniidae (the sand dollar, *Echinarachnius parma*), also a dominant group selected for size analysis, ranked fifth in abundance at unmined Station S3 ($\bar{x}$ = 209 ± 61.5 m^{-2}), but was virtually absent at mined stations. Significant differences in abundance

Table 7. Comparison of abundances of four benthic species from mined and unmined stations. Between-year comparisons were made with the Kruskal-Wallis test; between-treatment comparisons were made with the Mann-Whitney test.

			Mined		Unmined		
Species	Years	N[1]	# m^{-2} Mean (se)	Between-year comparisons	# m^{-2} Mean (se)	Between-year comparisons	Between-treatment comparisons
Tellina lutea [2]	1987-91	30	12 (9.8)	p<0.001	121 (24.2)	p<0.001	p<0.001
Clinocardium californiense [3]	1988,90,91	18	78 (21.0)	p<0.001	45 (10.0)	p=0.001	p=0.740
Diamphiodia craterodmeta [2]	1987-91	30	86 (24.2)	p<0.001	131 (24.2)	p=0.06	p=0.013
Echinarachnius parma [2]	1987-91	30	<1	p<0.001	209 (61.5)	p<0.001	p<0.001

[1] N = number of 0.1 m^2 samples
[2] from "Sand" substrate
[3] from "Cobble" substrate

Table 8. Comparison of sizes of four benthic species from mined and unmined stations.

		Mined				Unmined					
Species	Years	N	Size, mm Mean (se)	Between-Year Comparisons	Statistic	N	Size, mm Mean (se)	Between-Year Comparisons	Statistic	Between-Treatment Comparisons	Statistic
Tellina lutea [1]	1987-91	*				348	3.0 (0.12)	p<0.001	F=8.3		
Clinocardium californiense [2]	1988,90	148	1.7 (0.03)	p<0.001	t=13.7	74	2.0 (0.07)	p<0.001	t=7.5	p<0.001	t=-4.2
Diamphiodia craterodmeta [1]	1987-91	171	0.8 (0.02)	p<0.001	F=13.6	352	1.5 (0.06)	p<0.001	F=34.7	p<0.001	t=-7.6
Echinarachnius parma [1]	1987-91	*				550	3.1 (0.08)	p<0.001	F=272.5		

* = Too few for comparison
[1] from "Sand" substrate
[2] from "Cobble" substrate

(Table 7) and size (Table 8) occurred at S3 over the 1987-91 period. Sand dollar abundance ranged from 512 ± 257.6 m^{-2} in 1988 to zero in 1991. Their size ranged from 0.5 to 17 mm and averaged 3.1 ± 0.09 mm diameter. Approximately 88% of the sand dollars (n = 550) were ≤ 6 mm; nearly 50% were ≤ 2 mm.

Cobble substrate

Sediment granulometry and community parameters in "cobble" substrate differed between mined and unmined areas (Tables 3 and 4), thus rejecting the null hypothesis. There was more ($p \leq 0.05$) gravel at mined stations and more ($p \leq 0.05$) sand at unmined reference station S3; there was no difference ($p > 0.05$) in percent mud (Table 3). In general, A, B, T, R, and H´ were lower and D was greater at mined stations than at the unmined station (Tables 3 and 4; Fig. 6).

Of the ten most abundant families at mined and unmined stations, only four were in common between the two areas. Most of the dominant taxa were motile motile. Most taxa generally had lower ($p \leq 0.05$) abundance at mined stations than at the unmined station (Table 5). The ten most abundant families at mined cobble stations were Lineidae (nemertean worms); Polynoidae and Sigalionidae (polychaetes); Nuculanidae, Cardiidae, and Myidae (bivalves); Dexaminidae, Corophiidae, and Oedicerotidae (amphipods); and Amphiuridae (brittle stars) (Tables 5 and 9). The most abundant family was cardiid cockles (i.e., *Clinocardium californiense*).

The ten most abundant families at unmined cobble Station S3 were Lineidae (nemertean worms); Sigalionidae, Syllidae, Goniadidae, Spionidae, Cirratulidae, Oweniidae, and Ampharetidae (polychaetes); Oedicerotidae (amphipods); and Amphiuridae (brittle stars) (Tables 5 and 9). Amphiuridae (i.e., *Diamphiodia craterodmeta*) represented the most abundant family. *Diamphiodia* ($\bar{x}$ = 248 ± 22.0 m^{-2}) was more ($p \leq 0.001$)

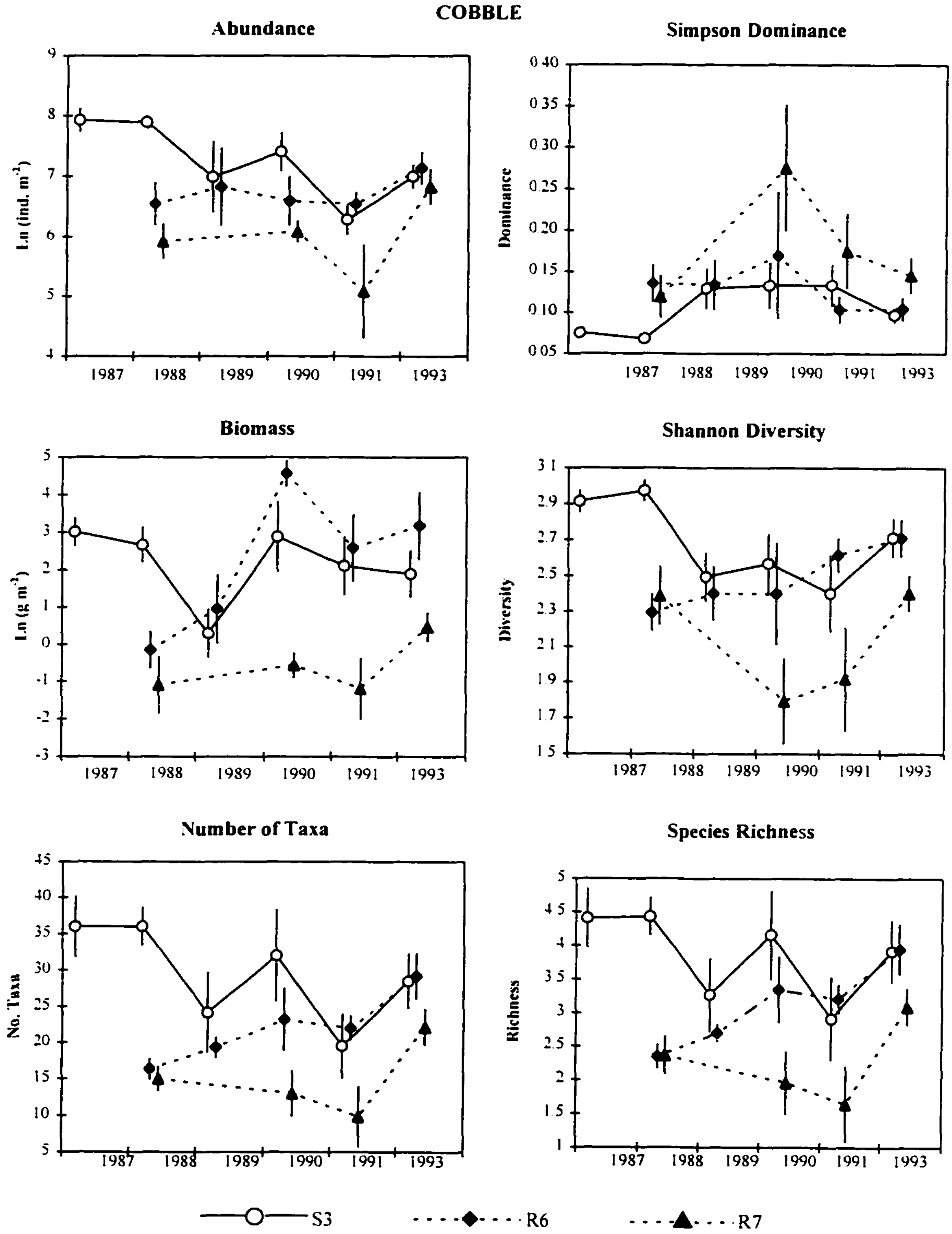

Figure 6. Plots of means and 95% confidence intervals of benthic community parameters in the cobble substrate at mined stations R6 and R7 and unmined station S3.

Table 9. Dominant benthic taxa, in terms of abundance (indiv. m^{-2}), at mined, recolonizing, and unmined stations on "cobble" substrates. A = amphipod, B = bivalve, BS = brittle star, C = cumacean, E = echiurid, I = isopod, N = nemertean, NU = nudibranch, P = polychaete, SD = sand dollar, SS = sea star, SU = sea urchin, T = tunicate.

STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.	STA.	TAXON	ABUND.
MINED (1 YEAR AFTER MINING)																	
R6-87	NO DATA:		R7-88	Sigalionidae P	75	R7-89	NO DATA:		R7-90	Cardiidae B	197	R7-91	Corophiidae A	64			
	COBBLE			Polynoidae P	67		COBBLE			Amphiuridae BS	87		Amphiuridae BS	37			
	NOT			Cardiidae B	37		NOT			Oedicerotidae A	32		Oedicerotidae A	28			
	FOUND			Amphiuridae BS	36		FOUND			Dexaminidae A	18		Polynoidae P	17			
				Corophiidae A	28					Corophiidae A	15		Sigalionidae P	17			
				Nuculanidae B	23					Oweniidae P	10		Lineidae N	17			
				Myidae B	15					Mytilidae B	8		Munnidae I	7			
				Lampropidae C	12					Rhynchocoela N	8		Caprellidae A	7			
				Bivalvia B	10					Goniadidae P	7		Lampropidae C	5			
				Nephtyidae P	10					Leuconidae C	5		Syllidae P	5			
RECOLONIZING (2-7 YEARS AFTER MINING)																	
			R6-88	Corophiidae A	143	R6-89	Syllidae P	278	R6-90	Amphiuridae BS	272	R6-91	Oweniidae P	97	R6-93	Sigalionidae P	278
				Amphiuridae BS	110		Corophiidae A	147		Oweniidae P	108		Amphiuridae BS	90		Lineidae N	118
				Nuculanidae B	103		Caprellidae C	128		Oedicerotidae A	72		Corophiidae A	90		Amphiuridae BS	113
				Polynoidae P	93		Mytilidae B	117		Cirratulidae P	38		Syllidae P	55		Oweniidae P	110
				Cardiidae B	68		Oedicerotidae A	95		Cardiidae B	25		Lineidae N	35		Syllidae P	73
				Sigalionidae P	42		Onchidoroidae NU	83		Lineidae N	22		Polynoidae P	33		Oedicerotidae A	67
				Echiuridae E	35		Amphiuridae BS	53		Strongylocentrotidae SU	22		Ascidiacea T	33		Cirratulidae P	65
				Spionidae P	32		Hiatellidae B	45		Serpulidae P	22		Mytilidae B	28		Capitellidae P	55
				Bivalvia B	17		Polynoidae P	43		Goniadidae P	20		Serpulidae P	25		Ascidiacea T	55
				Oedicerotidae A	13		Asteriidae SS	27		Capitellidae P	17		Rhynchocoela N	23		Spionidae P	32
UNMINED																	
S3-87	Cirratulidae P	322	S3-88	Cirratulidae P	285	S3-89	Spionidae P	420	S3-90	Amphiuridae BS	353	S3-91	Amphiuridae BS	120	S3-93	Oedicerotidae A	220
	Amphiuridae BS	317		Amphiuridae BS	253		Amphiuridae BS	195		Oweniidae P	293		Lineidae N	82		Lampropidae C	132
	Syllidae P	313		Sigalionidae P	225		Oweniidae P	145		Oedicerotidae A	267		Syllidae P	70		Spionidae P	107
	Oweniidae P	230		Lineidae N	207		Lineidae N	68		Goniadidae P	147		Sigalionidae P	45		Lineidae N	100
	Ampharetidae P	213		Ampharetidae P	197		Cirratulidae P	52		Lineidae N	65		Oweniidae P	43		Goniadidae P	53
	Sigalionidae P	197		Oedicerotidae A	192		Diastylidae C	48		Cirratulidae P	63		Oedicerotidae A	20		Orbiniidae P	52
	Oedicerotidae A	170		Polynoidae P	187		Polynoidae P	45		Syllidae P	52		Rhynchocoela N	13		Corophiidae A	46
	Lineidae N	148		Syllidae P	122		Corophiidae A	45		Cardiidae B	48		Goniadidae P	10		Diastylidae C	43
	Spionidae P	117		Oweniidae P	117		Syllidae P	42		Sigalionidae P	38		Caprellidae A	8		Nephtyidae P	33
	Cardiidae B	83		Goniadidae P	115		Oedicerotidae A	40		Tellinidae B	38		Opheliidae P	8		Amphipoda A	22

abundant at S3 than at mined Station R7 ($\bar{x} = 53 \pm 18.2\ m^{-2}$). Although detailed measurements of *Diamphiodia* were not made, random measurements revealed a size structure similar to amphiurids in sand (i.e., most were < 2 mm disc diameter).

Since *Clinocardium californiense* predominated at mined cobble stations and was readily amenable to size analysis, abundance and size comparisons were made between stations and years. No difference ($p = 0.74$) existed in abundance between mined ($78 \pm 21.0\ m^{-2}$) and unmined ($45 \pm 10.0\ m^{-2}$) stations; however, differences were apparent between years (Table 7). Lowest abundance values were observed in 1991 at mined ($2 \pm 1.6\ m^{-2}$) and unmined stations ($5 \pm 2.2\ m^{-2}$). Nearly 99% of the cockles at mined and unmined stations were < 3 mm. Cockles at R7 ($\bar{x} = 1.7 \pm 0.03$ mm length) were smaller ($p < 0.001$) than those at S3 ($\bar{x} = 2.0 \pm 0.07$ mm) (Table 8).

Recolonization

Sand substrate

In 1987, one year after R6 was mined, abundance (A), biomass (B), number of taxa (T), richness (R), and Shannon diversity (H') were significantly less and Simpson dominance (D) was significantly more there than at unmined Station S3 (Table 4; Fig. 5). Organisms that dominated R6 were motile oedicerotid amphipods and diastylid and lampropid cumaceans (Table 6). Polychaete families (spionids, oweniids, and capitellids) dominated at unmined Station S3 in 1987.

By 1988, two years after mining, there were significant increases in all community measures, except D (Fig. 5); however, most community parameters were still lower at R6 than S3. Crustaceans decreased from 75% of the total abundance in 1987 to 12% in 1988. Polychaetes accounted for most of the abundance. The predominant polychaete families were Cirratulidae (mainly *Tharyx secundus*), Oweniidae (mainly *Myriochele oculata*), and Capitellidae (mainly *Heteromastus filiformis*) (Table 6). An increase in biomass at R6 (Fig. 5) was mainly attributed to nemertean worms (Lineidae: *Cerebratulus* sp.) and cirratulid and oweniid polychaetes.

Three years after mining, in 1989, R6 exhibited few signs of recovery; there were no significant changes in any of the community parameters since 1988. Also, most parameters were still less than at S3 (Fig. 5). The predominant families in 1988 (Cirratulidae and Oweniidae) were absent in 1989 (Table 6). Instead, bivalve mollusks (Tellinidae: *Tellina lutea* and Mactridae: *Spisula polynyma*) and magelonid (*Magelona sacculata*) polychaetes predominated numerically (Table 6). Tellinid and mactrid bivalves were also present in appreciable quantities at unmined Station S3 (mactrid abundance was 130 m^{-2}; not shown in Table 6). There was no difference ($p = 0.57$) in size of *T. lutea* between R6 ($\bar{x} = 2.4 \pm 0.09$ mm) and S3 ($\bar{x} = 2.5 \pm 0.06$ mm). Also, there was no difference ($p = 0.79$) in size of *S. polynyma* between R6 ($\bar{x} = 1.6 \pm 0.04$ mm) and S3 ($\bar{x} = 1.6 \pm 0.02$ mm).

In 1990, four years after mining, the community parameters of A, B, T, and R had no ($p > 0.05$) changes from the previous year, and A, T, and R were still less ($p \leq 0.05$) than at S3 (Fig. 5). Changes in the dominant taxa were most apparent. Densities of the bivalves *Tellina* and *Spisula* decreased sharply at R6, as well as at S3. The oweniid polychaete *Myriochele oculata* became the most abundant organism at R6 with more than 1,000 individuals m^{-2}. This polychaete was also predominant at S3 (5,387 m^{-2}), resulting in significantly higher D and lower H′ than at R6.

In 1991, five years after the 1986 mining event, significant decreases in all community parameters, except H′, occurred relative to 1990 (Fig. 5). The same pattern was generally noted for S3. There were no differences in community parameters between

R6 and S3. The family that predominated at R6 and S3 in 1990, Oweniidae, was only represented by few individuals at both stations in 1991 (Table 6). The magelonid polychaete, *Magelona sacculata*, was the predominant polychaete in 1991 at R6, as well as at S3 (Table 6).

At R6 in 1993, seven years after the initial mining disturbance, there were no differences in the community parameters relative to 1991 and unmined Station S3 (Fig. 5). Spionid polychaetes (mainly *Polydora* spp.), oedicerotid amphipods and lampropid cumaceans predominated the benthos at R6 and S3 (Table 6).

Cobble substrate

No cobble was located at R6 in 1987, therefore no samples were collected. In 1988, two years after mining, cobble was sampled and R6 had values of A, B, T, R, and H′ significantly less than unmined Station S3 (Fig. 6). Corophiid amphipods (mainly *Protomedeia* sp.) and amphiurid brittle stars (*Diamphiodia craterodmeta*) predominated in abundance at R6 (Table 9). In comparison, the most abundant organisms at S3 were cirratulid polychaetes and amphiurid brittle stars.

In 1989, the fauna at R6 had no significant changes in community parameters from the previous year (Fig. 6). In contrast, significant declines in A, B, T, R, and H′ and an increase in D were noted at S3 relative to 1988. As a result of the convergence of these two stations there were no differences in any community parameters between stations R6 and S3. However, faunal differences were apparent with syllid polychaetes (mainly *Autolytus* sp.) and corophiid and caprellid amphipods dominating at R6 and spionid polychaetes (mainly *Polydora* sp.), amphiurids, and oweniids (mainly *Myriochele oculata*) predominating at S3 (Table 9).

In 1990, four years after mining at R6, there was still no significant change in most community parameters from 1989. The exception was an increase in biomass. This was also the pattern at S3. The predominant taxa at both stations were amphiurid brittle stars and oweniid polychaetes (Table 9). The increase in biomass at R6 from less than 5 g m^{-2} in 1989 to 104 g m^{-2} in 1990 (Fig. 6) was mainly attributed to the green sea urchin *Strongylocentrotus droebachiensis* (Strongylocentrotidae). A similar increase in urchin biomass was not observed at S3.

In 1991, there was still little change in most community parameters at R6 relative to 1990. Also, no differences were revealed in these parameters between R6 and S3 (Fig. 6). The most abundant taxa at R6 were oweniid polychaetes, amphiurid brittle stars, and corophiid amphipods (mainly *Ischyrocerus* spp.) (Table 9). Amphiurids predominated at the unmined station.

In 1993, seven years after the initial mining disturbance, R6 demonstrated increases in A, T, and R from 1991; no changes were noted in the other parameters (Fig. 6). No differences were observed in any of the community parameters between R6 and S3. In 1993, both stations had different dominant taxon groups; sigalionid polychaetes at R6 and oedicerotid amphipods at S3.

Multivariate analysis

Sand substrate

Sand stations were positioned in ordination space (MDS plot) with decreasing disturbance from left to right. The most disturbed stations, the five mined (1 yr after mining; R6-87, R7-88 - R7-91), were not closely associated to each other, but were separated to the left of all other stations (Fig. 7A). The least disturbed stations, multiple years of unmined Station S3, generally were to the right. Recolonizing stations (2-7 years after mining; R6-88 - R6-91) had intermediate disturbance by the position between mined and unmined stations. Stations closest to the mined stations were those from 1991 (R6-91

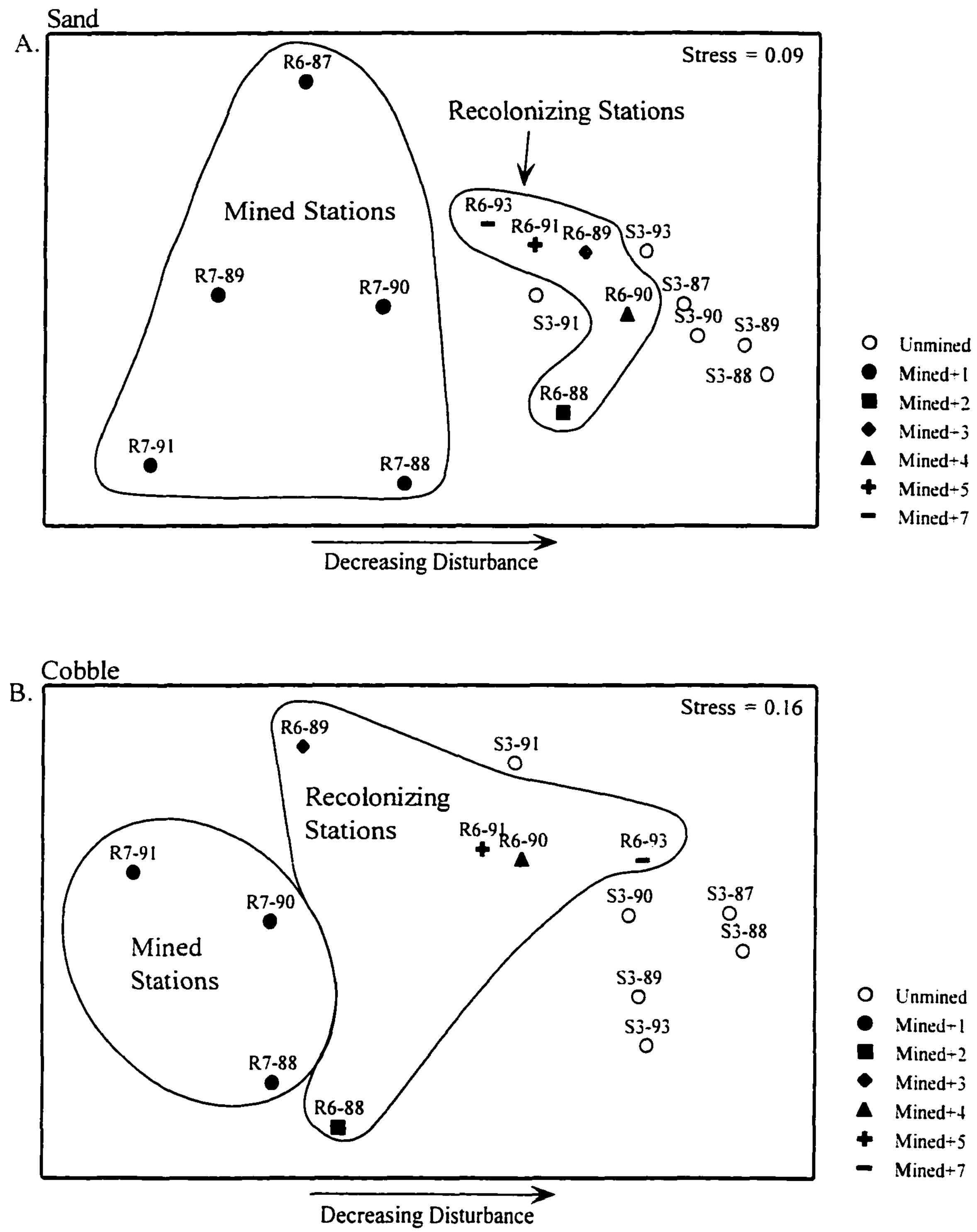

Figure 7. MDS ordination of *ln*-transformed abundance from stations on (A) sand and (B) cobble substrates. Mined and recolonizing stations are encircled as a visual aid, but do not imply statistical groupings.

and S3-91) and 1993 (R6-93 and S3-93). The closest proximity of recolonizing Station R6 and unmined Station S3 in the same year was in 1990, four years after mining. Recolonizing Station R6-91 and unmined Station S3-91 were also relatively close together, but they were more disturbed than 1990.

Cobble substrate

Benthic data from the cobble substrate revealed a pattern in ordination space similar to the sand substrate, although the pattern in cobble had less dimensionality (greater stress [0.16]) than in sand. MDS (Fig. 7B) also portrayed stations decreasing in disturbance from left to right, with the recently mined stations (R7-88, R7-90, R7-91) to the left, the unmined stations (S3-87 - S3-93) generally to the right, and recolonization stations (R6-88 - R6-93) generally between mined and unmined stations. Recolonization stations R6-88 and R6-89 closest to the mined stations. One unmined station, S3-91, was closely associated with the recolonization stations (Fig. 7B). The year in which recolonizing Station R6 and unmined Station S3 were close in ordination space and had the least disturbance was in 1990, four years after mining. Stations R6 and S3 were actually closer together in 1991, but displayed greater disturbance than 1990.

DISCUSSION

Inherent in interpreting the effects of mining on the benthos are some limitations that cannot be overlooked. The investigation mainly relied on one station for each of the mined (mainly R7), reference (S3) and recolonization (R6) categories. The bulk of the mined (1 yr after mining) versus unmined comparisons used R7, although R6 in 1987 was also included in the mined category. Other randomly selected reference stations, besides S3, were infrequently sampled over the study period, but because of the lack of continuous sampling they were not included in the analyses. Also, since the substrate at S3 was similar to R6 and R7, and S3 was well upstream of any anticipated mining activities, it was an appropriate reference location. The statistical inference for tests made with respect to stations sampled are not intended to apply to similar depths elsewhere within Norton Sound but only to the mining area.

There was initial concern that the prevalence of sporadic natural perturbations might interfere with the detection of mining effects. A key element that facilitated the separation of mining disturbance from natural disturbance is the relatively short time that transpired between the annual termination of mining and subsequent sampling (approxiately eight months). Disturbance from natural events was assumed to be minimal during this abbreviated period when ice cover mitigates storm events. Conversely, mining effects were more prone to be masked by natural disturbances over longer periods of time (years), as in the examination of the recolonization station.

The northwest coast of Norton Sound is subject to a suite of natural disturbances that appear to maintain communities in early successional modes (e.g., Rachor & Gerlach, 1978; Kenny & Rees, 1996). Offshore mining activity represented an additional source of disturbance to the benthos of this region, although limited temporally and localized in its effects.

Natural disturbances

The benthic fauna in the study area is subject to constant natural disturbance from episodic storms, current scouring, ice gouging, and bioturbation. Organisms living here have adopted strategies enabling them to exist under these disturbances. Numerous storms occurred in the study area between 1986 and 1993, particularly during the fall months. For example, during October and November 1989 and 1990, peak easterly winds over 13 m s^{-1} (30 mi h^{-1}) were observed at Nome for 9 and 24 days, respectively (NOAA, Local

Climatological Data Monthly Summary). A severe storm battered the northern Norton Sound coastline on October 5, 1992 with winds to 26 m s^{-1} (59 mi h^{-1}) (Nome Nugget, 1992) and disrupted the nearshore habitat to at least 12 m (pers. observ.). The idea of pervasive disturbances in the area is supported by measurements of near-bottom wave-induced current velocities off Nome over an 80-day period at 18 m that resulted in extensive sediment resuspension and transport, particularly during storm events (Cacchione & Drake, 1982). Another indication that the region is highly dynamic is the prevalence of sand waves generated by longshore currents (e.g., Clifton *et al.*, 1971; Oliver *et al.*, 1983a; Nelson *et al.*, 1981). Side-scan sonar imagery revealed that sand waves constantly changed in form and extent. For example, at unmined stations sand waves varied from less than 1% of the surveyed substrate in 1986 to 7% in 1988 (Table 2). Even greater annual variations in proportions of sand waves occurred at mined stations where unconsolidated sediments were more amenable to transport. For example, a three-fold increase in sand waves was noted at R6 from 1990 to 1991, presumably due to turbulent conditions in the fall of 1990 (Table 2).

Storms in the fall of 1990, and to a lesser extent the single storm in October 1992, disturbed the benthic environment at stations R6, R7, and S3. The intensity of the storms of late 1990 was evident at the granulometric level where the greatest amount of shoaling of mining depressions (> 15 m) occurred from 1990 to 1991, a 19% change (Table 1). Additionally, considerable sand erosion apparently occurred at R7 in 1991 because only a veneer of sand overlaid a gravely substratum. The high gravel content at this "sand" location was the greatest proportion of gravel in all sampling years (Table 3). Many benthic community parameters, especially in sandy substrates, also declined from 1990 to 1991, indicating increased disturbance from the storm events (Figs. 5 and 6). Declines were especially evident for the clam *Tellina lutea*, the sand dollar *Echinarachnius parma*, the brittle star *Diamphiodia craterodmeta* in the sand substrate and the cockle *Clinocardium californiense* in the cobble substrate. All four species had their lowest densities in 1991, subsequent to the late 1990 storms. These storm-related disturbances are reflected in the MDS plot of sand stations for 1991 and 1993 (Fig. 7A), where unmined Station S3-91 and recolonizing Station R6-93, were closely associated with the mined stations. Among the mined stations, sand Station R7-91 reflected greatest disturbance, presumably due to the 1990 storms. Similar findings were noted in the cobble substrate relative to stations S3-91 and R7-91 (Fig. 7B). Comparison of MDS plots from sand and cobble suggest that the storm of 1992 had less effect on cobble benthos than on sand, since recolonizing cobble Station R6-93 was closer to unmined stations and sand Station R6-93 was closer to the mined stations. The effects of storms on the benthos elsewhere resulted in considerable disturbance to shallow-water (< 20 m) benthic fauna by burial or excavation, with such disturbances also serving as mechanisms of faunal dispersal (e.g., Boesch *et al.*, 1976: McCall, 1977, 1978: Rees *et al.*, 1977; Oliver *et al.*, 1980; Dobbs & Vozarik, 1983). Areas of the seafloor subject to sporadic but chronic natural disturbance (e.g., current scour, ice gouging, or sedimentation typical of the study area) typically contain the most resilient members of benthic ecosystems (Boesch & Rosenberg, 1981).

Bottom-current speeds in the western part of Norton Sound are typically 10 to 20 cm s^{-1} (Muench *et al.*, 1981). Under such conditions there is a constant movement of fine surficial sediments and detrital material in a westerly direction during ice and ice-free periods (pers. observ.). High suspended sediments (~6 mg l^{-1}) in surface waters near the 10-m contour off Nome (Hood *et al.*, 1974) reflect the prevalent high currents. Inferences into the strong current nearshore are available from the biota. One of the predominant epifaunal organisms in the study area, the sea urchin *Strongylocentrotus droebachiensis*, usually had at least one rock and/or shell on its aboral side which appeared to prevent transport by the currents (pers. observ.). Removal of these weights usually initiated transport of the urchin in the current direction. Also, Oliver *et al.* (1983a) observed the infaunal tunicate *Rhizomogula* sp., presumably dislodged by recent walrus (*Odobenus rosmarus*) feeding activities in the Sledge Island vicinity, rolling across the sediment surface in strong current.

The benthic fauna in the study area is also subject to disturbances by sea ice. Ice gouges ranging from 0.25 - 0.5 m deep and 5 - 25 m wide were extensive throughout the study area (Larsen *et al.*, 1981; pers. observ.). This disturbance is similar to the effects that occur within gray whale (*Eschrichtius robustus*) and walrus feeding excavations adjacent to the study area where the benthic community is maintained in an early successional mode (Oliver *et al.*, 1983a,b; Oliver & Slattery, 1985).

Bioturbation by benthic invertebrates and demersal fishes represents an additional disturbance on the bottom in the study area. All of the dominant infaunal organisms present in the study area (Table 5) disrupt substrate particles, whether as a consequence of their tube-building activities, locomotion through the sediment, or feeding on organic material associated with the sediment. The largest epifaunal component of the study area (Jewett & Feder, 1981), the red king crab, utilizes the inshore region during ice-covered months (Powell *et al.*, 1983; Chapter 2), and feeds on numerous subsurface organisms (e.g., polychaetes, bivalves, amphipods, and brittle stars), many of which require extensive excavation. Turbid conditions occur where king crabs actively forage (pers. observ.). Similar digging activities occur with other predatory crabs elsewhere (e.g., Hall *et al.*, 1991). Sea stars, another important large epifaunal component within the Sound (Feder & Jewett, 1978a), excavate for bivalves throughout the year (Fukuyama & Oliver, 1985). The dominant fishes, the starry flounder (*Platichthys stellatus*), yellowfin sole (*Pleuronectes asper*), and Alaska plaice (*P. quadrituberculatus*) and, to a lesser extent walrus, forage within the substrate (Wolotira *et al.*, 1977; Jewett & Feder, 1980; Oliver *et* *al.*, 1983a; Lang, 1992). The consequence of extensive bioturbation is that sediments (and associated fauna) are more easily suspended (Rhoads, 1974). Further, the digging activities of crabs, sea stars and bottom fishes would be expected to bring infaunal species to the sediment surface where they are vulnerable to predation and subject to lateral transport by the high-velocity currents and storms typical of the study area.

Mining disturbance

As expected, annual mining activities altered the substrate granulometry, yielding a pattern of more fines at the surface of "sand" substrate areas approximately a year after each mining disturbance (Table 3). A pattern of more fines at mined sand stations was also evident in the side-scan sonar imagery at Station R6, which showed fine sand/silt (Smooth substrate) as the predominant substrate type nearly a year subsequent to mining (Table 2). A steady decline in the fine sand/silt component was evident in the sonographs up to five years after the one-time mining disturbance. Dredging operations in soft substrates elsewhere resulted in variable effects on the bottom with little alterations in surficial granulometry (McCauley *et al.*, 1977; Poiner & Kennedy, 1984; Eleftheriou & Robertson, 1992), an increase in fines (Jones & Candy, 1981), and a decrease in fines (López-Jamar & Mejuto, 1988). Generally, changes in fine substrates were short-term with a return to predredged conditions within a year of the last disturbance (e.g., López-Jamar & Mejuto, 1988; Swartz *et al.*, 1980). Relative to "cobble" substrates, more coarse material appeared at the surface of the mined station. Similar findings were reported by Kenny & Rees (1994) in an experimental gravel-dredging operation off the coast of England. They found that the gravel content of dredged surficial sediment (> 2 mm; < -1Ø) increased up to 20% after dredging, and related this to dredging into the subsurface layers with a greater proportion of gravel. Apparently mining in surficial cobble off Nome occurred with similar coarse material at subsurface depths and any fines associated with the cobble were winnowed away when the tailings were redeposited.

Although there were only moderate changes in sediment granulometry at mined stations, faunal differences were extensive, with virtually all community parameters and abundance of dominant families reduced nearly a year after mining (Tables 4 & 5). These effects are consistent with post-dredging responses observed elsewhere (e.g., McCauley *et al.,* 1977; Swartz *et al.,* 1980; Jones & Candy, 1981; Poiner & Kennedy, 1984; López-Jamar & Mejuto, 1988; Eleftheriou & Robertson, 1992; and Kenny & Rees, 1996).

Most of the predominant families in the study area showed great temporal variability and were opportunistic or stress-tolerant taxa (i.e., rapidly respond to open or unexploited habitats), found in dynamic, shallow (< 20 m) regions elsewhere (e.g., McCall, 1978; Oliver *et al.*, 1980; VanBlaricom, 1982). Ellis & Hoover (1990a) found that opportunistic tubiculous oweniids and spionids, burrowing capitellids, and surface-dwelling cirratulids and goniadids were common on mine tailings in coastal British Columbia. However, in the present study these opportunist polychaete families were common at both mined and unmined stations off Nome, indicating area-wide disturbances. The extremely abundant oweniid *Myriochele oculata* at unmined sites in this study was also one of the most abundant early colonizers within areas disturbed by dredge-spoil disposal in British Columbia (Ellis & Hoover, 1990a). This polychaete constructs long flexible tubes that it probably works up and down in the sand to rebury itself, as observed for another oweniid, *Owenia fusiformis* (Dales, 1957). This is a desirable feature for an organism living in the turbulent nearshore environment of northwestern Norton Sound where scouring and shoaling is common at shallow depths (Drake *et al.*, 1980). The high density of *M. oculata* tubes in the study area, $\approx 5{,}000\ m^{-2}$, may stabilize the substrate, as shown for other tube-dwelling polychaetes (Fager, 1964; Rhoads & Young, 1970; Eckman *et al.*, 1981). High densities of *M. oculata* were also observed in dynamic nearshore environments in the eastern Bering & Chukchi seas (e.g., ≈ 25,000 indiv. m^{-2}: Feder *et al.*, 1985). Most of the spionid polychaetes in the study area are known opportunists (Grassle & Grassle, 1974; Pearson & Rosenberg, 1978). Capitellids are characteristic of highly disturbed environments (Grassle & Grassle, 1974; McCall, 1978; Pearson & Rosenberg, 1978; Zajac & Whitlatch, 1982). Cirratulids live in a variety of habitats (e.g., Nicolaidou *et al.*, 1989) and can be common in disturbed benthic environments (Ellis & Hoover, 1990a; Gray, 1979). Goniadids (e.g., *Glycinde* spp.) are secondary colonizers of disturbed areas and as predator/scavengers (Fauchald & Jumars, 1979) feed on settled larvae and young of the early colonizers (e.g., Pearson *et al.*, 1982).

Among the predominant bivalves in the study area, members of Tellinidae are secondary or tertiary colonizers of disturbed regions (McCall, 1978). Since fewer and smaller (97% ≤ 6 mm long) *Tellina lutea* were present at mined sand stations, mining activity is the suspected cause. Nevertheless, the predominance of small individuals throughout the study area indicates that the region is dynamic and typically precludes the establishment of populations of large, older individuals. Most *T. lutea* were probably one year of age since the smallest ones measured by McDonald *et al.* (1981) in the southeastern Bering Sea were 8 mm long and estimated to be two years old. The most abundant bivalve group (cardiid cockles) at cobble stations is not considered to be an early colonizer. Although cockle abundance did not differ between mined and unmined stations, smaller individuals were at mined stations, suggesting mining effect. However, the presence of only small individuals (99% ≤ 3 mm long) at all stations is further evidence that the entire region is sufficiently dynamic to prevent these bivalves from attaining a large size. Cockles of the size found in this study are probably less than a year old (e.g., see Hancock, 1967; Quayle & Bourne, 1972 for size of cockles elsewhere).

The ophiuroid *Diamphiodia craterodmeta* is one of the most ubiquitous and abundant species in mainly sandy-silt substrates throughout the Bering Sea shelf (Hood *et al.*, 1974; Feder *et al.*, 1980; Feder *et al.*, 1985). Their predominance in cobble off Nome was unexpected, but presumably sufficient fines were present in the interstices of the cobble to enable them to become established there. While little is known about the biology of *D. craterodmeta*, a similar shallow-water cogenus in European waters, *Amphiura filiformis*, has many similar opportunistic traits. *Amphiura* resides in semi-permanent burrows in fine sandy-silt, is fast-growing, relatively short-lived (5-6 years), and has a high metabolic rate (Buchanan, 1964; Woodley, 1975; Ockelmann & Muus, 1978; Muus, 1981). The greatest density of *A. filiformis* occurs in disturbed areas (Gray, 1979; Pearson *et al.*, 1985; Josefson & Conley, 1997). *Diamphiodia craterodmeta* exhibited dominance and temporal variability in both substrates and treatment locations off Nome, suggesting adaptation to area-wide disturbance. Although mining activities undoubtedly resulted in their reduced abundance and size, the overall small size (< 2 mm in disc diameter) in both areas reflects unstable conditions. A size of 2 mm approximates the age of two years for *A. filiformis* (Muus, 1981). Few *Diamphiodia* in the study area were of adult size; only about 1% approximated the size at maturity of *A. filiformis*, i.e., 4 mm disc diameter (Muus, 1981).

The sand dollar *Echinarachnius parma* was another organism with lower abundance at the mined sand station. Although echinoids are not considered opportunists, they occur in high-energy sandy regions where opportunists usually dominate. In California, the sand dollar *Dendraster excentricus* is mainly present in highly turbulent inshore areas (Davis & VanBlaricom, 1978; Oliver *et al.*, 1980) where it demonstrates great annual variability in abundance (VanBlaricom, 1978). Species with pelagic larvae, such as echinoids, can rapidly recruit to a disturbed habitat after abatement of stress (Boesch & Rosenberg, 1981) which may, in part, explain the temporal variability noted above. Mean annual growth rates of *E. parma* from the Middle Atlantic Bight is 3.5 to 6 mm yr^{-1} for the first five years

(Steimle, 1990). If this growth is similar to the Norton Sound population where the mean size was 3.1 mm, then most individuals were no more than a year old. Thus, no *E. parma* approached the size of sexual maturity (27 mm: Ruddell, 1977) in the study area. Sand dollar populations may persist at some locations for long periods of time because their larvae settle preferentially in existing beds in response to an adult-produced cue (Pearce & Scheibling, 1990; Highsmith & Coyle, 1991). Therefore, the absence of adult sand dollars in the mined area precluded preferential settling there.

Another possibility as to why this species never increased in the mined area may be attributed to predation pressure. Highsmith & Coyle (1991) demonstrated ampeliscid amphipod predation on juvenile *E. parma* and reasoned that benthic amphipods play a significant role in structuring benthic communities.

The main environmental concern about mining activity off Nome was its impact on the red king crab, a commercially harvested and subsistence species in Norton Sound. Most of the predominant benthic organisms in the region are utilized as food by this crab (Feder & Jewett, 1981a; Chapter 2), and these organisms were less abundant and, in some cases, smaller in the mined area. However, comparisons of crab food items taken by crabs between mined and unmined stations indicated that mining had no effect on feeding activity of the crabs (Chapter 2). This finding was presumably a result of the high mobility and opportunistic feeding habits of the crabs.

In summary, this investigation revealed unequivocal mining disturbance to the benthos of sand and cobble substrates, as demonstrated mainly by the reduction of most community parameters and the reduction abundance of dominant families at mined sites relative to the reference site. The predominance of small opportunistic individuals throughout the study area indicates that the region is dynamic and typically precludes the establishment of populations of large, older individuals. Selected taxa were smaller at mined sites than at unmined sites, indicating a response to mining activities.

Recolonization

Following disturbance to the benthos, recolonization and long-term community composition depend on numerous factors such as stability of dredged areas, changes in local oceanographic regimes, tolerance of organisms to physical changes, and availability of recruits (e.g. Pearson & Rosenberg, 1978; Boesch & Rosenberg, 1981; Thistle, 1981; Poiner & Kennedy, 1984; Hall, 1994). Within the study area, relative to physical data, multiyear bathymetric and side-scan sonar surveys of once-mined Station R6 revealed progressive smoothing of substrate relief, decreasing size of the tailing footprint, filling in of mining depressions, and little change in surficial granulometry. Moderate evidence of disturbance was still visible five years after the single mining event (Fig. 4), indicating that the mined area had not yet stabilized physically.

The best portrayal of the long-term recolonization process is evident in the MDS plots which show a decrease in disturbance from first-mined to recolonizing to unmined stations (Figs. 7A and 7B). The position of recolonizing sand Station R6 from 1988 through 1990 becomes progressively closer to unmined Station S3, with R6 closest (most similar) to S3 in 1990, four years after mining. A similar temporal faunal progression is apparent for R6 in the cobble substrate. The series of storms in Norton Sound prior to the collections of 1991 greatly affected the study area. Changes in all community parameters for R6 and S3 were generally similar that year for both substrates (Figs. 5 & 6), a reflection of an area-wide disturbance. Dredging studies elsewhere demonstrate that recolonization of infaunal populations is a fairly rapid process, especially in shallow, highly dynamic environments (McCauley *et al.*, 1977; Oliver *et al.*, 1977; Swartz *et al.*, 1980; López-Jamar & Mejuto, 1988; Hall, 1994). Assessment of the effects of repeated dredging operations reveal that infaunal communities on soft bottoms < 20 m in depth returned to pre-dredging levels from 28 days (McCauley *et al.*, 1977), to six months

(López-Jamar & Mejuto, 1988), to approximately a year (Oliver *et al.*, 1977; Swartz *et al.*, 1980) following cessation of dredging. Few investigations examined recolonization in shallow, coarse substrates. However, Kenny & Rees (1996) did not observe a return of the macrobenthos to pre-dredge conditions in the North Sea two years after gravel extraction, although the predominant species quickly recolonized. Assemblages with the least complex community structure recovered most rapidly and were dominated by early successional species adapted to physical disturbances. The longer recolonization process in the present study (at least 4 years) compared to other shallow-water investigations probably resulted from the interaction of mining and severe natural disturbances in Norton Sound. Within deeper, more stable environments, anthropogenic disruptions appear to require a longer time for the benthos to recover (Boesch & Rosenberg, 1981). For example, benthic recovery at a mine site in British Columbia (100 m) revealed that biological differences still existed after 12 years (Ellis & Hoover, 1990b). However, benthic recolonization of tailings from three mines in British Columbia was variable, and appeared related to depth differences (Ellis & Hoover, 1990a).

Although recolonization of sand and cobble substrates at mined Station R6 was apparent, as reflected by taxonomic changes observed, the prevalence of sporadic high recruitment of opportunistic species at recolonizing and unmined sites made it difficult to interpret the recovery process. Opportunistic species are typically found during early stages of succession within a disturbed area (e.g., Grassle & Grassle, 1974, McCall, 1977; Pearson & Rosenberg, 1978; Zajac & Whitlatch, 1982). The predominance of ephemeral and mostly opportunistic crustaceans (amphipods and cumaceans) in the study area in 1987 is consistent with other disturbance-related studies that found peracarid crustaceans as the first colonizers of disturbed substrates (e.g., Oliver *et al.*, 1977, 1980; Swartz *et al.*, 1980; VanBlaricom, 1982; Oliver & Slattery, 1985; Klaus *et al.*, 1990; Kenny & Rees, 1994). Areas of the seafloor subject to chronic natural disturbances are among the most resilient of benthic systems (Rhoads *et al.*, 1978; Boesch & Rosenberg, 1981), and it is apparent that the Norton Sound benthic system falls into this category.

VanBlaricom (1982) found that organic carbon accumulated in the sediments within pits excavated by rays (Order Rajiformes). He initially observed large numbers of peracarids within these pits, apparently a result of the temporary increase in organic carbon as a food source. Once the organic matter was exploited by the peracarids, other organisms, primarily subsurface feeders, outcompeted and replaced the crustaceans in the ray pits. In the present study, by 1988 the opportunistic peracarids on sand were replaced by the opportunistic Cirratulidae (mainly *Tharyx secundus*) and Oweniidae (mainly the tube-dwelling *Myriochele oculata*) polychaetes, thus suggesting that recovery was underway. These polychaete families are known as second- or third-stage colonizers (e.g, Grassle & Grassle, 1974; Addy *et al.*, 1978; Rhoads *et al.*, 1978).

By 1989, an area-wide recruitment of tellinid and mactrid bivalves replaced the dominant polychaetes at R6. This recruitment was short-lived because bivalve numbers decreased greatly by 1990. *Tellina* spp. are documented as secondary or tertiary colonizers to disturbed regions elsewhere. For example, *T. agilis* was a secondary colonizer on disturbed soft sediments at < 20 m in Long Island Sound (McCall, 1977) and *T. modesta* was among the third phase of colonization in ray pits 4-6 weeks after disturbance in California (VanBlaricom, 1982). In 1989, within the study area, the magelonid polychaete, *Magelona sacculata*, was the only burrowing polychaete in appreciable numbers (223 m^{-2}) at the recolonizing station. This species is a good burrower in sands and muds (Fauchald & Jumars, 1979). The relatively high abundance of *Magelona* following the 1990 and 1992 storms (180 m^{-2} at R6-91, 73 m^{-2} at S3-91 [Table 6] 130 m^{-2} at R7-93 [unpubl. data]) is consistent with the behavior of this genus elsewhere. *Magelona papillicornis* had the highest survival among infauna subjected to a series of storms along the shallow North Wales coast (Rees *et al.*, 1977). Oliver *et al.* (1980) determined that *M. sacculata* was the most abundant polychaete found along a subtidal high-energy beach in California where it was present from 9-24 m, but its greatest abundance (1,174 m^{-2}) was at 18-24 m. They determined that the depth of *Magelona* burrows increased with water depth, and even though this polychaete settled into the shallower zone (< 14 m), they rarely survived to adult size. Apparently the prevalence of polychaetes, like *Magelona*, in shallow water is influenced by seasonal changes in wave-induced substrate movements. It also appears that the large fluctuations in the abundance of *Magelona* at both the recolonizing and reference stations in the present study are due to natural disturbances in relatively shallow water.

The tube-dwelling *Myriochele* was not present in appreciable quantities at stations mined annually (R7), but did occur in large numbers two or more years after mining was discontinued at Station R6. The absence of *Myriochele* in 1989 is perplexing, since it was one of the predominant taxa in 1988 and 1990. Since no major storm events occurred in 1989 and ice gouging would have precluded the presence of other non-motile forms, a more likely explanation is that the species is disjunctly distributed within the study area. Their reduced abundance in 1991 and 1993 at recolonizing Station R6 and unmined Station S3 was presumably due to the storms that preceded the latter two samplings.

The data demonstrate that fauna within sand and cobble substrates at the once-mined (1986) Station R6 became most similar to that at the unmined reference site approximately four years after dredging. However, this interpretation may lead to an underestimate of recovery time following a disturbance since continued recolonization in the fifth year was interrupted by severe storms. Thus, a longer period for recovery from a benthic disturbance in Norton Sound is to be expected than that reported for other shallow-water disturbance investigations. It is apparent that the recolonization process in Norton

Sound is affected by episodic natural disturbance events that maintain a highly resilient benthic community that is often in an early mode of succession.

CONCLUSIONS

Based on a series of yearly assessments of sand and cobble substrata and associated benthos following mining operations, it is concluded that mining affected the sediment environment and the benthic community. Mining altered the surficial substrate granulometry, yielding a general pattern of more fines at the surface of the "sand" substrates and more coarse material at the surface of the "cobble" substrates. Mining activity reduced macrofaunal community parameters (e.g., total abundance, biomass, diversity) and the abundance of dominant taxa. The recovery of an area mined once and subsequently monitored for seven years revealed a progressive smoothing of ocean bottom relief, decreasing size of tailing footprint, and shoaling of depressions left by mining. As for the biota, recovery was well underway in both substrates after four years, but this process was interrupted in the fall of the fourth year (1990) by several severe storms.

Although local mining activites affected the benthos in Norton Sound, the effects were minor in comparison to the consequences of the natural disturbances that typically occur there. These disturbances, some of which are unique to the area, are the major forces that structure the resilient benthic community within the Sound.

CHAPTER 2: ASSESSMENT OF THE BENTHIC ENVIRONMENT FOLLOWING OFFSHORE PLACER GOLD MINING IN NORTON SOUND, NORTHEASTERN BERING SEA - II. THE RED KING CRAB *PARALITHODES CAMTSCHATICUS* [1]

Abstract: A four-year study was conducted to assess potential impacts of offshore placer gold mining on red king crabs (*Paralithodes camtschaticus*) in the northeastern Bering Sea near Nome, Alaska. Mining with a bucket-line dredge occurred nearshore in 9-20 m during June-October 1986-90; 1.5 km^2 and ≈ 5.5 x 10^6 m^3 of substrate was mined. All crabs were offshore of the study area when mining occurred. Information on crab abundance and prey was mainly obtained during the ice-covered months of March and April when crabs were in the mining vicinity. Comparisons between mined and unmined stations revealed that mining had a negligible effect on crabs. Crab catches, size, sex, quantity and contribution of most prey groups in stomachs were similar between mined and unmined areas. However, crab abundance, based on a few ROV observations was less in mined areas. Also, plants (mainly eelgrass) and hydroids, which accumulated in mining depressions, were more common in crab stomachs from mined areas. A preponderance of unidentified fishes were consumed by crabs throughout the mined and unmined regions. Mining affects are presented in the context of the small area disturbed, the dynamic nature of the benthic habitat in the region, and the opportunistic feeding habits of the crabs.

[1]Jewett, S.C. Submitted. Assessment of the benthic environment following offshore placer gold mining in Norton Sound, northeastern Bering Sea - II. The Red king crab *Paralithodes camtschaticus.* Mar. Environ. Res. **00:** 00-00.

INTRODUCTION

Marine/coastal mining activity in Alaskan waters has been mainly associated with small, unregulated placer mining at the turn of the century and more recent short-term exploratory endeavors (R. Baer, USDI-Bureau of Mines, Juneau, AK, pers. comm., 1995). Only one marine mining project with associated environmental monitoring has occurred on the Alaskan continental shelf. That project, known as the Nome Offshore Placer Project, assessed the effects of placer gold mining in the shallow waters of Norton Sound in the northeastern Bering Sea. Mining occurred between 1986 and 1990; monitoring occurred between 1986 and 1991. Monitoring components relative to marine mining/dredging programs are varied, but often include tailing discharge rates, chemical analyses, turbidity, and trace metal bioaccumulation and biomagnification (Ellis, 1988). Additionally, most environmental monitoring programs associated with marine mining/dredging have used benthic organisms as a tool to assess the effects of mining. Infaunal invertebrates are the organisms most frequently sampled (e.g., Swartz *et al.*, 1980; Jones & Candy, 1981; Poiner & Kennedy, 1984; Ellis & Hoover, 1990a,b; Kenny & Rees, 1996). Few investigations utilized large motile epifauna such as crabs in their monitoring studies (Stevens, 1981; also see Poling & Ellis, 1993; Ellis *et al.*, 1994 for review of monitoring programs associated with submarine tailings disposal). The red king crab (*Paralithodes camtschaticus* [Tilesius, 1815]) supports commercially-harvested and non-commercially-harvested (subsistence) fisheries in Norton Sound, inclusive of the mining area off Nome. Consequently, this crab was a logical choice to evaluate the effects of mining on marine benthos. The potential effects of mining on this crab are addressed in Chapter 1, which examines the benthos that serves as food for the crab, and in Chapter 3, which examines the concentrations of eight heavy metals in crabs and surficial sediments relative to mining activity.

This chapter examines the potential effect of mining activity on the crab's relative abundance, distribution and prey in northwestern Norton Sound near Nome. Potential prey availability for crabs in the area is also considered.

Mining overview

Mining in the Nome Offshore Placer Project was conducted in northwestern Norton Sound in ice-free months (June - October) by Western Gold Exploration & Mining Company (WestGold) using the world's largest bucket-line mining dredge, the BIMA. The BIMA's dimensions were approximately 110 m long, 43 m wide, and 45 m high with a 88-m long bucket ladder that contained 134 buckets, each of which had a 0.85 m^3 capacity. Variable substrate types were mined, targeting residual lag deposits, materials processed onboard, and tailings returned to the excavation site. Mining occurred in 9-20 m water depths. The approximate locations and extent mined from 1986 through 1990 are shown in Figure 8. The area and volume mined within an 88 km^2 (21,750 acres) lease area was 1.5 km^2 (371 acres) and 5.5 x 10^6 m^3 m^3, respectively (Howkins, 1992). The area and volume mined annually was 0.093 km^2 and 3.1 x 10^5 m^3 in 1986, 0.218 km^2 and 1.2 x 10^6 m^3 in 1987, 0.583 km^2 and 2.0 x 10^6 m^3 in 1988, 0.320 km^2 and 1.1 x 10^6 m^3 in 1989, and 0.287 km^2 and 9 x 10^5 m^3 in 1990 (Howkins, 1992). The Nome Offshore Placer Project ceased operation on September 20, 1990.

Norton Sound red king crab overview

The red king crab (*Paralithodes camtschaticus*), in the family Lithodidae, is one of three commercially exploited king crabs in the North Pacific Ocean. It was once the most valuable fishery resource on the Alaskan continental shelf (Otto, 1990). Norton Sound supports the northern-most commercial and subsistence fisheries for this species (Powell *et*

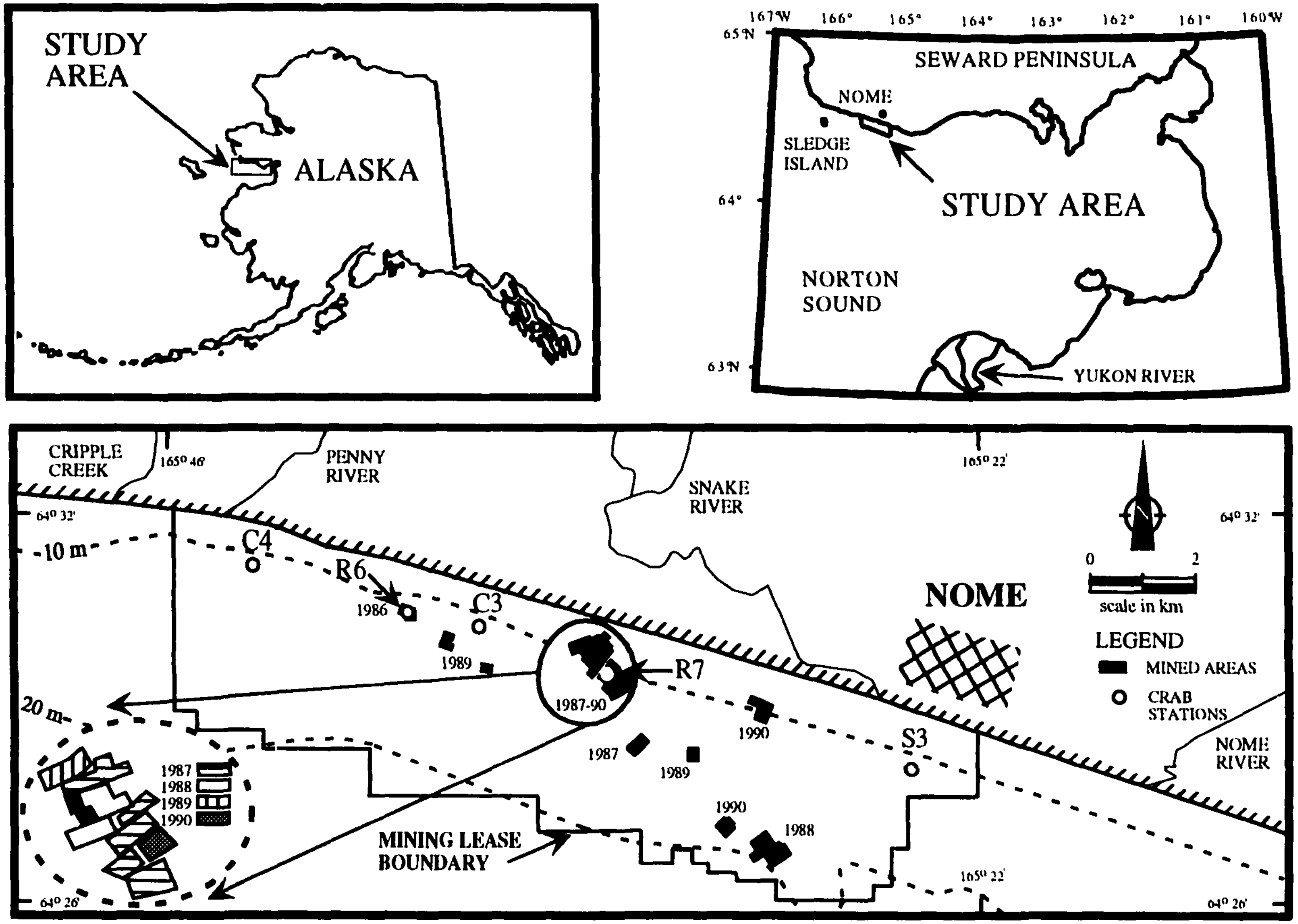

Figure 8. Map of the Nome Offshore Placer Project showing mining lease boundary, areas mined by year, and five stations surveyed for red king crabs.

al., 1983; Lean & Brennan, 1995). The stock within the Sound is unique in that it: 1) is separate from other stocks in the Bering Sea (Seeb *et al.*, 1989), 2) lives in the coldest area of its range (bottom water temperatures to -1.8° C; Hood *et al.*, 1974; Muench *et al.*, 1981), 3) lives under ice for 5-6 months a year (Dupré, 1980), and 4) is confined to waters less than 31 m in depth. The crab population within the Sound is relatively small. A population assessment in August 1991 placed the total number of both sexes and legal males (≈104 mm carapace length [CL]) at 4.0 and 1.4 million crabs, respectively [Stevens & Haaga, 1992]). Migrations of the Norton Sound crabs typically follow north-south or northeast-southwest movement patterns (Powell *et al.*, 1983). Although the greatest distance moved was reported to be 61 km in 46 days (Powell *et al.*, 1983), the crabs could conceivably traverse the 250 km length of the Sound in a seasonal migration. Red king crabs in the southeastern Bering Sea were reported to travel up to 426 km in a year (Simpson & Shippen, 1968). In contrast, red king crabs in southeast Alaska had significant vertical movement but only small (10-20 km) horizontal movement over two years (Stone *et al.*, 1992).

Commercial and subsistence fisheries for king crabs occur in summer/fall and winter. The commercial summer/fall fishery is traditionally centered in the northwestern portion of the Sound, south and east of Sledge Island (Wolotira *et al.*, 1977; Powell *et al.*, 1983). The open-water harvest between 1986 and 1991 averaged 96,000 ± 18,036 (± 1 SE) males ($\bar{x}$ = 1.4 ± 0.02 kg) from an average of 6 ± 1.6 vessels (no fishing occurred in 1991; Lean & Brennan, 1995). In winter, a small commercial and large subsistence fisheries exist through the ice adjacent to coastal villages, particularly at Nome (Powell *et al.*, 1983; Lean & Brennan, 1995). The average winter commercial (males only) and subsistence (both sexes) harvests during this study, from 1986 through 1991, were 1,910 ± 627 and 6,865 ± 1,253 crabs, respectively (Lean & Brennan, 1995).

Limited life history information on king crabs within Norton Sound (Wolotira *et al.*, 1977; Powell *et al.*, 1983; Jewett *et al.*, 1990b; Otto *et al.*, 1990), indicates that the species behaves similarly to populations elsewhere (see Jewett & Onuf, [1988] for reviews of red king crab life history). A northeasterly migration of adult and subadult crabs into coastal waters of Norton Sound occurs in late fall/winter (Powell *et al.*, 1983). Reproductive activities (i.e., egg-hatching, female-molting, grasping, mating, and egg extrusion) are intense while nearshore, particularly from March through May when some ice is still prevalent (Powell *et al.*, 1983; Otto *et al.*, 1990). The crab migrate offshore during nearshore ice breakup (usually May) when temperatures increase and salinities decrease (Muench *et al.*, 1981; Powell *et al.*, 1983). Thus, most crabs were offshore when mining occurred off Nome. Trawl surveys in Norton Sound in August 1985 and 1988 found most adult males widely dispersed between 18-31 m, where bottom temperatures were 2.8-9.5 °C (Stevens, 1989; Stevens & Haaga, 1992). The optimal range of temperatures and salinities for king crabs are -1.8-9.5 °C and 26-34 ‰ (Jewett & Onuf, 1988). Female crabs in Norton Sound mature at smaller sizes than in populations to the south (Otto *et al.*, 1990). The estimated size at 50% maturity for females in Norton Sound is 71.4 mm CL, in comparison to 88.8 mm CL in Bristol Bay and 102.1 mm CL near the Pribilof Islands (Otto *et al.*, 1990). Males are also assumed to mature smaller, since maturity of both sexes is attained at similar sizes elsewhere (Jewett & Onuf, 1988). King crabs elsewhere utilize a wide array of food (see Jewett & Feder [1982] for review) with no differences in feeding between sexes (e.g., Kulichkova, 1955; McLaughlin & Hebard, 1961; Jewett & Feder, 1982).

Study area

This study was conducted within approximately 88 km^2 of State of Alaska offshore mining leases adjacent to the City of Nome in the northwestern portion of Norton Sound. The area is north of 64° 26′ N to the southern coastline of the Seward Peninsula. The southern boundary tends to follow the 20 m depth contour. The eastern boundary is a straight line south, midway between the mouths of the Snake and Nome rivers (165° 22′ W), and the western boundary is a straight line south, midway between the mouths of Cripple Creek and Penny River (165° 46′ W) (Fig. 8).

The westward flow of water offshore along the south coast of the Seward Peninsula is a common feature that varies in intensity and extent (Hood *et al.*, 1974; Muench *et al.*, 1981). The speed of surface currents in the western portion of Norton Sound normally ranges from 5 to 20 cm s^{-1} with a maximum velocity of 50 cm s^{-1}. Strong coastal currents reaching speeds up to 100 cm s^{-1} are reported in the vicinity of Nome (Nelson & Hopkins, 1972). Bottom-current speeds are 10 to 20 cm s^{-1} in the western part of the Sound (Muench *et al.*, 1981). Tidal fluctuations at Nome are minimal (Pearson *et al.*, 1981); major storm events can cause dramatic fluctuation in sea level height.

The surficial substrate of northern Norton Sound is heterogeneous, consisting of a mosaic of sediments from silt to boulder, with sand and cobble dominating (USDI, 1991). Surface sediments within the study area consist of relict gravel and sand along with modern sediments of very fine sand-and silt-size particles derived from the Yukon River (Drake *et al.*, 1980; Hess & Nelson, 1982). Fine sand/silt substrate, overlying the more permanent cobble substrate, is transient in nature and subject to redistribution by storms, currents and ice gouging. The wave-induced nearshore currents at Nome move the fines in both easterly and westerly directions, but the net nearshore sand transport of approximately 5 x 10^5 m^3 y^{-1} is in a westerly direction (Drake *et al.*, 1980; Tetra Tech, 1980).

In the ice-free months of June through November bottom temperatures and salinities in the study area typically range from near 0 to 12 °C and 21 to 34 ‰, respectively. During ice-covered months of December through May bottom temperatures and salinities range from -1.8 to 1.5 °C and 32-34 ‰, respectively (Hood *et al.*, 1974; Muench *et al.*, 1981; Jewett, unpubl.).

Norton Sound is ice-covered during much of the winter-spring period (December-May). Shorefast ice develops in the nearshore region (Muench *et al.*, 1981). This ice is composed of bottomfast and floating fast ice attached to shore. Thickness of ice is variable but often approaches 1.2 m. The seaward edge of the ice generally extends to the 20-m isobath and may be anchored by ice keels in the 10-20 m region (Stringer, 1981). Ice gouges generally occur inside the 20-m isobath and trend east to west. Gouge-incision depth usually ranges from 0.25 to 0.5 m deep, but may be as deep as 1 m (Larsen *et al.*, 1981). Ice-gouge widths of 15-25 m are most common, but range from 5 to 60 m.

METHODS

Field

Crab sampling and observations were made at two mined (R6 and R7) and three unmined stations (S3, C3 and C4) (Fig. 8; Table 10) for determining crab abundance and food. Although numerous sites were mined over the five-year mining period, only R6 and R7 were monitored because they were the ones mined initially. R6 and R7 were mined in 1986 and 1987-90, respectively. C3 was located between R6 and R7, C4 was located west of R6, and S3 was located east of R7 and off Nome. Crab abundance was determined by *in situ* observations and captured crabs in baited pots. Underwater documentation at R6, R7, S3, and C3 was accomplished, using high density color videotape in March 1986-88 and June 1988. Pots were deployed at R6, R7, C3 and C4. Water depths at all stations were 10-12 m. Positioning was obtained with a Motorola Mini-Ranger III and a portable Loran C unit. Videotape recording was accomplished with remotely operated vehicles

Table 10. Stations where king crabs were assessed in the Nome Offshore Placer Project, 1986-90. Unmined stations are S3, C3, and C4; mined stations are R6 and R7.

Stations	Survey Method	Latitude	Longitude	Depth, m
S3	ROV, SCUBA	64° 29′ 25″	165° 24′ 67″	10-12
C3	Pots, ROV, SCUBA	64° 30′ 47″	165° 36′ 35″	10-12
C4	Pots	64° 31′ 03″	165° 45′ 00″	12
R6	Pots, ROV, SCUBA	64° 31′ 03″	165° 38′ 40″	10-12
R7	Pots, ROV, SCUBA	64° 30′ 19″	165° 33′ 16″	10-12

(ROV); a Benthos Mini-Rover was used in 1986 and a Deep Ocean Engineering Phantom 300 was used in 1987-88. Ice operations were supported by all-terrain vehicles, snowmachines, a Weatherport shelter, and a 1.8 KW portable generator. At each station, a hole large enough to accomodate the ROV was cut through the ice. The Weatherport shelter was set up to house the electronic and ROV control equipment. ROV observations were also made in open water June 11 and 12, 1988 using a support vessel. In both periods the ROV was used to count crabs on four transects generally along the four main compass headings (N, S, E, and W) for a distance of up to 140 m. Occasionally the target compass heading and maximum transect distance could not be obtained because of the presence of grounded ice. In cases where this happened a different heading or shorter distance was surveyed. Width of visibility along transects approximated 2 m. Videotape records and a log of physical and biological observations were maintained along each transect. Crab sex could not be determined.

Crab abundance was also determined by divers in open water during June 1986 and 1987. Divers counted crabs along four 50-m transects generally along the four main compass headings. Positioning was obtained with a Motorola Mini-Ranger III and portable Loran. Each station was marked by a buoy. A transect line was attached to the buoy's anchor and set and retrieved from the dive vessel. The transect line was marked at one-meter intervals to provide accurate seafloor positioning during observations. Water visibility generally permitted observations of a transect width of 4 m (two meters on either side of the transect center line). Divers recorded substrate type, water depth and crab sightings relative to the position along a transect. No crabs were collected.

Crabs were collected by pots through the ice at mined and unmined stations during March and early April. Crabs for determination of abundance were caught in 1987-90; crabs for assessing food in stomachs were caught in 1987-89. A subset of crabs caught for the abundance determination was used in the food study. Collections were made with conical, top-loading commercial pots (1.5 m base diameter) or rectangular, side-loading commercial pots that were generally pulled within 12 to 24 hours of setting to minimize the crab's digestion. Pots were baited with chopped, frozen herring (*Clupea pallasi*) within two 9-l plastic perforated containers and the bait changed approximately every 48 hours. A slip knot was tied to each pot line as a mechanism to detect disturbance or pot tampering at all fishing stations. Where disturbance occurred, catch data were not included in the data set. Typically one ice hole was fished at each station. However, in 1987 and 1990 two holes were fished approximately 200 m apart in a north-south orientation at stations R6, R7, and C3. This ensured that two pots were fished at each mined and unmined location in 1987 and 1990. The stations at the mined areas were positioned in the middle of the areas. Stations from the unmined area were randomly selected from a sampling grid. Bottom temperature and salinity were recorded with a YSI Model 33 S-C-T meter the first time a pot was fished at each station over the two-week period in each year.

All crabs were measured (carapace length from the eye orbit to the median posterior margin of the carapace), weighed, and sexed immediately after capture. Exoskeletal condition was recorded to identify molt condition of crabs. Individuals that molted during the past year had exoskeletons with few abrasions and little attached epifauna (termed new shell) (Gray & Powell, 1966). Crabs that failed to molt during the last year had exoskeletal abrasions and larger attached epifauna (old shell). Observations on reproductive stage of the females were also noted. Crab sex ratios in mined and unmined areas were compared. Crabs caught for determination of abundance were marked with a rubber band or a colored wire around the base of a rear appendage and released. Crabs subsequently captured in pots were examined for mark identifications.

Laboratory

Crab stomachs were preserved in 10% buffered formalin and shipped for processing at the Institute of Marine Science, University of Alaska Fairbanks. Stomach contents were sorted and identified to the lowest practical taxon. Most of the eyed eggs in stomachs contained unidentified fish embryos. It is assumed that all eyed eggs were from fishes rather than king crabs or other crustaceans, based on the relatively large size of the eggs. Measurements of these eggs ranged from 1.6-2.0 mm diameter. King crab eggs do not exceed 1.2 mm diameter in the most advanced stage of development (Matsuura & Takeshita, 1985). Detailed examination of fish remains took place in 1988 to determine the frequency of eggs and bones with tissue. Prey taxa from each stomach were identified and weighed (blotted wet weight) to the nearest mg. Counts of each taxon were not made in most cases because of the triturated condition of stomach contents. The percent frequency of occurrence was calculated as the proportion of stomachs containing various food items relative to the total number of stomachs examined. A food index [FI] was calculated for each prey group using frequency of occurrence and weight (FI = % frequency of occurrence x % weight x 100). Most studies on crustacean feeding rely on frequency of occurrence and/or weight of prey items as the method of assessment (e.g., Elner, 1981; Jewett & Feder, 1982; Pearson *et al.*, 1984; Comoglio *et al.*, 1990). Frequency of occurrence analysis provides a qualitative view of the extent to which a group of animals feed on a particular item. The method tends to favor taxa with easily recognizable hard parts, long residence time in stomachs, and small organisms which contribute little food value. Gravimetric or volumetric analyses provide a quantitative approach to the importance of various prey, but also favor items which are resistent to digestion. A similar approach to the FI, which incorporates multiple measures, was used by Stevens *et al.* (1982) with Dungeness crabs, *Cancer magister*.

Statistical analyses

Crab catch-per-unit-effort (CPUE) was standardized to a 24-hour period. CPUE and feeding data were used for testing various hypotheses concerning the effects of mining activity on crabs. Data were compared between mined and unmined areas. Feeding data from male and female crabs were combined in all statistical analyses since previous studies did not reveal differences in feeding (McLaughlin & Hebard, 1961; Jewett & Feder, 1982). All sizes of crabs were combined in the feeding analyses since the range of sizes was small and most were of adult size. Possible effects of dredging activities were examined by testing the following null hypotheses:

- the relative abundance and sex composition of king crabs at the mined areas are not significantly different from that in the adjacent unmined areas; and
- prey quantity and composition in king crab stomachs at mined areas are not significantly different from that in stomachs from adjacent unmined areas.

Parametric analysis of variance (ANOVA) was applied to the CPUE data. Due to heterogeneity of variances nonparametric rank tests were used for comparing the total biomass of stomach contents, FI values and biomass of predominant prey groups, and catches of male and female crabs. Averages are presented with ± one standard error. Determination of statistical significance was set at $p \leq 0.05$. In multiple nonparametric tests, the Bonferroni corrected significance level of $\alpha* = \alpha/n$ was used (Rice, 1995) to ensure all tests simultaneously had a confidence interval of 95% ($\alpha = 0.05$). Statistical procedures were performed mainly with the use of STATISTICA software (StatSoft, 1994). The bootstrap technique (Efron & Tibshirani, 1993) was used to simulate the distribution of the FI values. The bootstrap distribution of FI values was simulated using 1000 resamplings with replacement of the crab feeding database. Confidence intervals were calculated using 95% quantile values. The similarity between prey groups from mined and unmined areas was thus determined by the overlap or no overlap of confidence intervals ($\alpha = 0.05$) between treatments. The power of the parametric tests is presented (Peterman, 1990).

RESULTS

Relative abundance of crabs

ROV and SCUBA surveys

Surveys by ROV and SCUBA divers revealed few crabs. In the three years of March ROV surveys, 19 crabs were observed in 6,539 m^2 of area surveyed. In the unmined areas this represented 13 crabs in 3,435 m^2 or 0.0038 individuals m^{-2} and in the mined areas 6 crabs in 3,104 m^2 or 0.0019 individuals m^{-2} (Table 11). Observations of crabs from ROV surveys were too sparse to allow statistical comparison. In the June surveys with SCUBA and ROV, only two crabs, a grasping pair, were encountered in 9,588 m^2. Of the 21 crabs observed in the underwater surveys, 16 (nearly 76%) were located on coarse substrates of cobble to boulder with the remainder on sand or mud (Table 11). Many of these crabs were feeding.

Crab-pot surveys

Throughout the crab-pot surveys in March and April of 1987-90 bottom temperature ranged between -1.8 and 0 °C and salinity between 28.4 and 31.5 ‰. Over the four-year period, 228 pot retrievals were made with 121 in the mined area and 107 in the unmined area. The standardized (and actual) number of crabs captured at mined and unmined stations totalled 571 (492) and 646 (554), respectively. Average crab catches at mined and unmined areas were 4.7 ± 0.47 and 6.0 ± 0.47, respectively. Of 768 crabs marked none were recaptured over the one-to-three-week period. Two-way ANOVA comparisons, using year and mining treatment (mined or unmined) as factors, were made to test the null hypothesis that there was no difference in crab abundance between mined and unmined areas. Test results using CPUE values (Table 12) revealed that year, treatment and interaction (effects between year and treatment) were not significant (p >

Table 11. Abundance of king crabs in mined and unmined areas off Nome as determined from ROV and SCUBA surveys.

MARCH ROV SURVEYS

	Mined				Unmined			
Date	Station	Area (m^2) Surveyed	Crabs Sighted	Substrate[1]	Station	Area (m^2) Surveyed	Crabs Sighted	Substrate[1]
1986	-	-	-	-	S3	1480	5 [2]	Coarse [3]
							1	Mud
1986	-	-	-	-	R6 [4]	640	0	
1987	-	-	-	-	S3	362	1	Mud
							2	Cobble
1987	-	-	-	-	C3	485	0	
1987	R6	881	1	Cobble				
1987	-	-	-	-	R7 [4]	468	4	Cobble
1988	R6	1081	1	Cobble	-	-	-	-
1988	R7	1142	1	Sand	-	-	-	-
			3	Cobble				
Totals		3104	6			3435	13	

JUNE SCUBA (1986-87) & ROV (1988) SURVEYS

	Mined				Unmined			
Date	Station	Area (m^2) Surveyed	Crabs Sighted	Substrate[1]	Station	Area (m^2) Surveyed	Crabs Sighted	Substrate[1]
1986	-	-	-	-	S3	1600	0	-
1986	-	-	-	-	C3	800	0	-
1986	-	-	-	-	R6 [4]	800	2 [2]	Sand
1987	-	-	-	-	S3	1600	0	
1987	-	-	-	-	C3	800	0	
1987	R6	800	0	-	-	-	-	-
1987	R7	800	0	-	-	-	-	-
1988	R7	560	0		-			
1988	-	-	-	-	S3	560	0	-
1988	-	-	-	-	C3	1268	0	-
Totals		2160	0			7428	2	

[1] Substrate on which crabs were found.
[2] Includes grasping pair.
[3] Coarse = cobble to boulders
[4] Before area was mined.

Table 12. Average catch-per-unit-effort (CPUE) of red king crabs through the ice at mined and unmined stations in the offshore Nome vicinity.

	Stations		Pot	Average (± 1 SE) Crab CPUE [2]		
Date	Mined	Unmined	Retrievals [1]	Males	Females	Both Sexes
3/27-4/9/87	R6a	-	15	4.3 (0.92)	0.3 (0.13)	4.6 (0.95)
"	R6b	-	15	6.2 (1.02)	0.2 (0.14)	6.4 (1.08)
"	-	C3	10	5.3 (1.36)	0.5 (0.27)	5.8 (1.30)
"	-	R7 [3]	14	4.2 (1.44)	<0.1 (0.04)	4.3 (1.44)
3/22-31/88	R6	-	14	3.8 (0.86)	0.1 (0.11)	3.9 (0.87)
"	R7	-	15	4.5 (1.45)	0	4.5 (1.45)
"	-	C3	15	3.4 (0.84)	0.2 (0.15)	3.6 (0.86)
"	-	C4	9	9.2 (1.97)	0	9.2 (1.97)
3/23-4/5/89	R6	-	18	2.8 (0.94)	0.6 (0.28)	3.4 (1.03)
"	R7	-	18	7.7 (1.81)	<0.1 (0.07)	7.8 (1.81)
"	-	C3	18	6.6 (0.87)	<0.1 (0.05)	6.6 (0.89)
"	-	C4	17	8.4 (1.39)	0	8.4 (1.39)
3/21-4/10/90	R7a	-	14	1.6 (0.55)	0.5 (0.38)	2.1 (0.84)
"	R7b	-	12	4.1 (1.71)	0.4 (0.19)	4.5 (1.79)
"	-	C3a	14	5.2 (1.10)	0.1 (0.10)	5.3 (1.12)
"	-	C3b	10	5.4 (1.58)	0.1 (0.10)	5.5 (1.54)

[1] Number of times a pot was fished at a particular station.
[2] Catch standardized to 24-hour effort.
[3] Before R7 was mined.

0.05) (Table 13), thus accepting the null hypothesis.

The overall male to female ratio of the catches approximated 25:1. The number of males and females caught at mined and unmined stations was 538 and 33, and 632 and 14, respectively. Testing revealed no significant difference in catches of male and female crabs between mined and unmined stations ($p = 0.171$; Mann-Whitney U Test), thereby the null hypothesis of similar sex ratios in mined and unmined areas was accepted. There was no significant difference in catches of male and female crabs between years ($p = 0.427$; Kruskal-Wallis ANOVA).

Prey composition of crabs

A total of 278 crabs, 264 males and 14 females, were collected for stomach analysis in March-April 1987-89. This included 155 (144 males and 11 females) from mined areas and 123 (120 males and 3 females) from unmined areas. The number examined annually from 1987 through 1989 at mined and unmined areas were 58 and 33, 56 and 54, and 41 and 36, respectively (Table 14).

Crab sizes (both sexes) from mined and unmined areas in 1987-89 were not significantly different ($p = 0.06$; power = 0.34; t-test); those from the mined area averaged 101 (± 1.2) mm CL and those from the unmined area averaged 105 (± 1.2) mm CL. All males were assumed to be adults based on their size ($\bar{x} = 104 \pm 0.8$ mm CL) (Powell *et al.*, 1983). The condition of the exoskeleton of the males was mostly new shell. The females consisted of nine adults ($\bar{x} = 77 \pm 2.4$ mm CL) and five juveniles ($\bar{x} = 71 \pm 1.8$ mm CL). Of the adults, four were carrying uneyed, purple eggs (indicative of recent spawning), four were carrying eyed, orange-brown eggs (indicative of eggs near hatching), and one adult had no eggs. All juveniles had dark purple internal ova.

Approximately 89% of all crabs examined contained food: 84.6% from unmined

Table 13. Two-way ANOVA test results on abundance of pot-caught king crabs from mined and unmined areas in the offshore Nome vicinity, 1987-90.

Source of Variation	d.f.	MS effect	F-statistic	p-value	Power
Year	3	53.61	2.14	0.096	0.295
Treatment	1	87.59	3.49	0.062	0.332
Interaction	3	20.20	0.81	0.492	0.050
Error	220	25.07	-	-	-

Table 14. Total number of king crabs examined for stomach analyses according to mined and unmined stations and year. Number of empty stomachs are in parenthesis.

	MINED STATIONS			UNMINED STATIONS			
Year	R6	R7	ALL	C3	C4	R7[1]	ALL
1987	58 (4)	-	58 (4)	10 (0)	16 (2)	7 (1)	33 (3)
1988	28 (3)	28 (2)	56 (5)	28 (13)	26 (2)	-	54 (15)
1989	21 (2)	20 (1)	41 (3)	19 (0)	17 (1)	-	36 (1)
1987-89	107 (9)	48 (3)	155 (12)	57 (13)	59 (5)	7 (1)	123 (19)

[1] Before R7 was mined.

areas were feeding and 92.3% from mined areas were feeding (Table 14). The biomass of the stomach contents was compared between mined and unmined stations to test the hypothesis that there is no difference in prey quantity. No differences were observed in the prey biomass from the mined and unmined areas in any of the years (1987: $p = 0.695$; 1988: $p = 0.448$; 1989: $p = 0.372$; Mann-Whitney U Test) or when all years were pooled (1987-89: $p = 0.269$; Mann-Whitney U Test). Thus, the null hypothesis was accepted.

Thirty-three crab prey taxa were identified in 1987-89 (Table 15). The most important food groups, in terms of the Food Index (FI), in crabs from mined and unmined areas were teleost fishes and sea urchins (Strongylocentrotidae); sand dollars (Echinarachniidae), sea stars (Asteroidea), bivalves, hydroids and plants were of lesser importance (Table 16). Comparison of the composition of these seven dominant food groups was made with FI and biomass values. The distribution of the FI values of these food groups were simulated using the bootstrap method. Comparisons between mined and unmined groups revealed no significant differences ($p \leq 0.05$) (overlapping 95% confidence intervals) in FI values for most of these prey groups between mined and unmined areas (Table 17). The only instances in which significant differences were apparent were with plants and hydroids. Plants, which consisted of mainly eelgrass *Zostera marina*, had greater FI values at mined stations in 1988 and in all years combined (1987-89). Hydroids had greater FI values at mined stations in 1987. The overlap of confidence intervals was marginal for the comparison of hydroids in 1988. The Kruskal-Wallis ANOVA test on the biomass of the seven dominant prey groups was significant at $\alpha/n = 0.05/22 = 0.0023$. The biomass of all major groups, except plants and hydroids, were not significantly different between mined and unmined stations in each year and in all years combined (Table 18). The biomass for plants and hydroids were greater at mined areas in 1988 and all years combined. Therefore, the null hypothesis that there is no difference in prey composition (using FI and biomass values) between mined and unmined

Table 15. List and quantity of prey taxa in king crab stomachs from mined and unmined areas in the offshore Nome vicinity, 1987-89.

	Mined		Unmined	
Prey Taxa	% Wt.	% Freq.	% Wt.	% Freq.
Hydrozoa	0.38	31.06	0.14	14.66
Polychaeta	0.01	3.11	<0.01	<0.01
Polynoidae	0.01	3.11	<0.01	<0.01
Pectinariidae	0.13	4.97	0.04	1.72
Mollusca	<0.01	0.62	<0.01	0.86
Bivalvia	0.15	6.21	0.03	1.72
Nuculanidae	0.05	0.62	<0.01	<0.01
Yoldia sp.	0.05	0.62	<0.01	<0.01
Cardiidae	0.36	2.48	0.57	5.17
Serripes groenlandicus	<0.01	0.62	<0.01	<0.01
Gastropoda	0.04	3.11	<0.01	0.86
Trochiidae	<0.01	0.62	<0.01	0.86
Cylichna alba	<0.01	0.62	<0.01	<0.01
Crustacea	1.36	7.45	1.36	2.59
Balanus sp.	0.01	1.86	<0.01	<0.01
Amphipoda	0.15	8.07	0.45	1.72
Protomedeia sp.	<0.01	0.62	<0.01	<0.01
Anonyx sp.	0.01	0.62	<0.01	<0.01
Caprellidae	<0.01	0.62	<0.01	<0.01
Decapoda	0.08	1.24	0.12	1.72
Paguridae	0.56	0.62	<0.01	<0.01
Echiura	<0.01	0.62	<0.01	<0.01
Bryozoa	0.10	3.73	0.02	1.72
Echinodermata	0.29	1.24	<0.01	<0.01
Strongylocentrotus droebachiensis	13.83	13.04	10.39	16.38
Echinarachnius parma	0.44	6.21	10.28	10.34
Ophiuroidea	<0.01	0.62	<0.01	<0.01
Diamphiodia craterodmeta	0.04	1.24	<0.01	<0.01
Asteroidea	5.43	3.11	6.28	4.31
Urochordata	0.46	0.62	<0.01	<0.01
Teleostei [1]	28.31	33.54	33.49	38.79
Unidentified animal tissue	1.20	6.21	<0.01	<0.01
Phaeophyta	<0.01	0.62	<0.01	<0.01
Zostera marina	1.14	26.71	0.09	5.17
Unidentified tissue	44.39	78.26	35.76	59.48
Sediment	0.90	13.66	0.72	6.03

[1] Includes fish eggs.

Table 16. Comparison of food indices (FI = % frequency of occurrence x % weight x 100) of prey groups in king crab stomachs from mined and unmined areas in the offshore Nome vicinity.

	1987		1988		1989	
Prey Group	Mined	Unmined	Mined	Unmined	Mined	Unmined
Hydrozoa	0.08	<0.01	0.21	0.03	0.12	0.04
Polychaeta	0.08		<0.01	<0.01	<0.01	
Bivalvia	0.08	<0.01	0.08	0.15	0.04	
Gastropoda	0.01			<0.01		
Crustacea (unid.)	<0.01	<0.01	0.12	<0.01	0.48	0.49
Cirripedia		<0.01	<0.01			
Amphipoda	<0.01	<0.01	<0.01	<0.01	0.08	0.05
Decapoda					0.06	
Bryozoa			0.02	<0.01	<0.01	
Echinodermata (unid.)	0.01				<0.01	
Strongylocentrodidae	1.01	5.78	0.36	2.08	3.64	0.78
Echinarachniidae	0.20	6.30		0.16		
Ophiuroidea	0.01					
Asteroidea	0.03	0.50		0.39	1.91	
Urochordata					0.05	
Teleostei	8.49	2.90	20.05	21.24	2.54	13.30
Plant	0.01	0.01	1.61	0.01	0.01	
Sediment	0.25	0.11	0.14	0.03	0.01	0.03

Table 17. Bootstrapped 95% confidence intervals of food index (FI) values for predominant king crab prey groups. The central FI values are from the original data.

Year	Treatment	Prey Groups	Lower Bound	FI Value	Upper Bound
1987	Mined	Fishes	2.730	8.490	16.740
		Sea Urchins	<0.010	1.010	3.920
		Sand Dollars	0.010	0.200	0.760
		Bivalves	<0.010	0.080	0.310
		Hydroids	0.020	0.080*	0.210
		Sea Stars	0.000	0.030	0.330
		Plants	0.001	0.009	0.025
1987	Unmined	Sand Dollars	0.170	6.300	17.100
		Sea Urchins	0.190	5.780	19.580
		Fishes	0.200	2.900	9.980
		Sea Stars	0.000	0.500	3.140
		Bivalves	0.000	<0.010	0.020
		Hydroids	0.000	<0.010*	0.006
		Plants	0.000	0.008	0.039
1988	Mined	Fishes	9.660	20.050	32.110
		Plants	0.777	1.612*	2.804
		Sea Urchins	0.000	0.360	1.930
		Hydroids	0.075	0.210	0.390
		Bivalves	0.010	0.080	0.280
		Sea Stars		NA	
		Sand Dollars		NA	
1988	Unmined	Fishes	9.380	21.240	34.470
		Sea Urchins	0.030	2.080	6.180
		Sea Stars	0.000	0.390	2.190
		Sand Dollars	<0.010	0.160	0.770
		Bivalves	0.010	0.150	0.470
		Plants	<0.010	0.012*	0.07
		Hydroids	<0.010	0.030	0.077
1989	Mined	Sea Urchins	0.290	3.640	10.210
		Fishes	0.300	2.540	7.950
		Sea Stars	<0.010	1.910	6.960
		Hydroids	0.010	0.120	0.390
		Bivalves	<0.010	0.040	0.200
		Sand Dollars		NA	
		Plants	<0.010	0.006	0.020
1989	Unmined	Fishes	3.750	13.300	27.600
		Sea Urchins	<0.010	0.780	3.000
		Hydroids	<0.010	0.040	0.130
		Bivalves		NA	
		Sand Dollars		NA	
		Sea Stars		NA	
		Plants		NA	
1987-89	Mined	Fishes	5.540	9.930	15.330
		Sea Urchins	0.170	1.240	3.010
		Plants	0.142	0.321*	0.593
		Sea Stars	<0.010	0.190	0.780
		Hydroids	0.060	0.130	0.230
		Bivalves	0.020	0.070	0.180
		Sand Dollars	<0.010	0.030	0.100
1987-89	Unmined	Fishes	6.620	12.340	19.620
		Sea Urchins	0.650	2.640	5.850
		Sand Dollars	0.070	0.930	2.860
		Sea Stars	<0.010	0.240	1.070
		Bivalves	<0.010	0.040	0.120
		Hydroids	<0.010	0.020	0.040
		Plants	<0.010	0.006*	0.02

NA = Not Applicable since the prey group was not present in stomachs for that treatment.

* = Comparison is significantly different at $\alpha = 0.05$

Table 18. Kruskal-Wallis ANOVA test results (p-value) of biomass comparison of king crab prey groups from mined and unmined areas. The significance level of these tests were corrected by the Bonferroni method, therefore, test results are significant at $\alpha = 0.0023$.

	DOMINANT PREY GROUPS						
Years	Plants	Hydroids	Bivalves	Sea Urchins	Sand Dollars	Sea Stars	Fishes
1987	0.6333	0.0344	0.2110	0.0090	0.3363	0.2681	0.6018
1988	< 0.0001*	0.0013*	0.9013	0.1698	NA	NA	1.0000
1989	NA	0.4093	NA	0.2175	NA	NA	0.0380
1987-89	< 0.0001*	0.0004*	0.2101	0.1553	0.2839	0.7042	0.3427

NA = Not applicable since the prey group was not present in crab stomachs for each treatment group.

* = Mined > Unmined

areas was accepted for all dominant prey groups, except plants and hydroids.

Fishes were the predominant prey group throughout the study period (Tables 15 and 16). Their remains were typically bone fragments, tissue and eyed eggs. The identity of fish prey was not determined due to the poor condition of the digested fish remains and absence of scales or otoliths. Size of eggs in stomachs were 1.6-2.0 mm diameter. Examination of bone fragments suggested that a wide range of fish sizes were taken. Detailed examination of fish remains in 1988 revealed that fishes were taken in nearly equal amounts from mined and unmined areas, i.e., 50 and 46% frequency of occurrence, respectively, and 40 and 46% of prey weight, respectively. Among the remains, bones with tissue were most frequently found, with 79% from mined areas and 76% from unmined areas. Stomachs containing only eyed fish eggs, and no other fish remains, were in 39 and 48% of the fish-eating crabs from mined and unmined areas, respectively. Eighteen and 24% of the respective mined and unmined fish-eating crabs contained bones, tissue and eggs.

Sea urchin and sand dollar skeletal remains were *Strongylocentrotus droebachiensis* and *Echinarachnius parma*, respectively. No whole specimens were found. Crabs containing sand dollars often had a green tint on their mouthparts and the crushing margin of the chela, an indication of a recently eaten food item (pulverized sand dollars are green, pers. observ.). Sea stars in crab stomachs were not identifiable to species.

Plant material (mainly eelgrass) and hydroids were taken by crabs in greater quantities in mined areas, although their biomass was always low. Of the bivalve mollusks in stomachs, only *Yoldia* sp. and *Serripes groenlandicus* were identified. Crustacean remains included barnacles (Cirripedia), amphipods (Amphipoda), and hermit crabs (Paguridae). Sediment was common in stomachs; however, it is not known if it was a food component or if it was taken incidentally with prey items. Nevertheless, it is presented in Tables 15 and 16 to show its relative value.

DISCUSSION

The effects of mining activity on red king crabs are discussed here as related to dredge-related substrate alterations depicted through multi-year bathymetric, side-scan sonar surveys (Chapter 1) and natural environmental disturbances. Side-scan sonar surveys (1987-91) of the mined areas encompassing R6 and R7 and unmined areas encompassing S3 and C3 demonstrated significantly finer material (seen as a Smooth substrate = fine sand/mud) in mined areas than unmined areas. Conversely, significantly more gravel (Very Coarse substrate) was in unmined areas. Little change in proportions of surficial substrate types were apparent at unmined areas over the five-year period. However, much variation in substrates was evident at mined areas over the same period. The proportion of the surveyed mined areas that was gravel ranged from 12% in 1987 to 50% in 1988; gravel in unmined areas ranged from 47-55% over the five years. Great differences in relief were also apparent at unmined and mined areas. Relief at unmined areas was low and did not change throughout all years. Initial relief at mined R6 had depressions to depths to 17 m and mounds to < 6 m. Multiyear bathymetric and side-scan sonar surveys in the vicinity of R6 from 1987 through 1991 showed continued smoothing of ocean bottom relief in the mined area (i.e., erosion of tailings piles and shoaling of depressions left by the mining operation) (Chapter 1). Dredging destabilized the sediments so that fines were redistributed by local currents and sea conditions. In general, the turbidity plume derived from mining activities indicated that solids suspended from dredging were transported downcurrent and mainly settled out within 0.5 km (pers. observ.). Although physical disturbance of the mined seabed at R6 was only about 0.09 km^2, substantial alteration was still apparent five years after the 1986 mining event. A small (0.13 km^2) experimental gravel dredging study in the North Sea revealed considerable sediment transport during the first two years following dredging (Kenny &

Rees, 1996). Although the dredging scars in the latter study had virtually disappeared after two years, benthic biomass was still substantially reduced due to a local increase in sediment disturbance caused by tide and wave action.

Natural disturbances on the bottom are a common phenomenon in the lease area. Gross littoral drift (mainly sand) in the nearshore Nome vicinity was calculated to be approximately $5 \times 10^5\ m^3\ y^{-1}$ (Tetra Tech, 1980). Side-scan images corroborate that fine sand/mud (Smooth substrate) is continuously redistributed in the study area by storms, ice, and currents, resulting in modification of the surficial substrate (Chapter 1). Strong winds and storms in Norton Sound vary annually in intensity and frequency, and the project area is commonly affected by these conditions. For example, exceptionally high storm-force winds occurred in Norton Sound between July 1, 1990 and June 30, 1991. The peak surface winds at Nome exceeded $13\ m\ s^{-1}$ for 79 days from July 1990 through June 1991. During October and November 1990, there were 24 days that had peak easterly winds over $13\ m\ s^{-1}$ (NOAA Local Climatological Data Monthly Summaries). These winds battered the northern coastline (Pers. Observ.) and presumably disrupted the nearshore subtidal habitat. ROV observations in March 1986-88 revealed grounded and gouging ice to be pervasive throughout the study area, but most common at depths < 7 m. As a consequence of this ice activity, sessile organisms such as sponges, hydroids, and bryozoans at shallower depths were less common than in deeper waters. There was generally a lush growth of these organisms at depths > 7 m.

Habitat utilization

Crabs move up to $4\ km\ d^{-1}$ under ice nearshore (Rusanowski *et al.*, 1990). Crab movements at C3 and R7 were related to seafloor substrate type by comparing side-scan sonar records with tracking data of ultrasonic-tagged crabs over 10 days (Rusanowski *et* *al.*, 1988). Superimposition of crabs at 141 contact points on side-scan images revealed that 62% of the crabs occurred on cobble and 38% on fine sediment. The proportions of substrates utilized were similar at mined and unmined stations. ROV and SCUBA observations in the present study supported these findings, with 76% of the crabs present on cobble and 24% on fine sediment in the study areas.

The pot surveys in March and April did not demonstrate a significant avoidance response to mining-related activities. The ROV data revealed that crab density was nearly twice as great from unmined areas (0.0038 crab m^{-2}) as mined areas (0.0019 crab m^{-2}). However, the data were inadequate for a statistical comparison since only 19 crabs were observed in the three years of ROV filming. The apparent contradiction in pot and ROV findings is likely a function of the attractive capability of baited pots. Even if crabs were less abundant in the disturbed mined zone, pots set here likely lured crabs from adjacent undisturbed areas. The distance across any segment mined in a given year was always less than a kilometer. Since crabs seem to prefer a cobble substrate, as demonstrated in the ROV surveys, and mined areas generally had less cobble than unmined areas, they may have avoided these locations to some extent. Reduction of crabs at mined locations may reflect a reduced food benthos here. An assessment of benthic infauna and small epifauna in the study area revealed that numerically predominant families, many of which were king crab prey, were reduced at mined relative to unmined areas (Chapter 1). Regardless of the seemingly contrary findings between CPUE and ROV data, the weight of evidence is with the CPUE data because its larger data base was conducive to statistical treatment.

Crab mortality associated with entrainment or burial was probably of minor importance in the present study, unlike the major dredging impacts to Dungeness crabs (*Cancer magister*) and associated biota elsewhere (Stevens, 1981; McGraw *et al.*, 1988). It is assumed that entrainment and burial were negligible since most crabs had moved offshore by the time mining commenced in June. Upon ice breakup, typically in May, crabs begin their migration offshore to deeper waters. Crabs tagged with sonic tags in early June, after the ice receded, migrated offshore 2-4 km within 1-2 d of their release, demonstrating their offshore movement (Rusanowski *et al.*, 1990). This exodus to offshore waters is reflected in the paucity of crabs found in the June ROV and SCUBA surveys (2 crabs) in comparison to the March ROV surveys (19 crabs) (Table 11).

Small crabs (< 67 mm CL) were absent in the study area, in contrast to southern populations in the southeast Bering Sea and Gulf of Alaska where young crabs commonly occur inshore (Jewett & Onuf, 1988). Presumably the summertime low bottom-water salinities (as low as 16 ‰ in 1988) in the study area preclude their year-round presence.

The failure of any of the 768 marked crabs to be recaptured could be due to 1) loss of marks (rubber bands or colored wires) on the crabs so that the crabs subsequently reentered pots undetected, 2) marked crabs learned to not reenter pots, and 3) the population was mobile and large enough so that the probability of catching a marked crab was small. The latter is the likely explanation as to why no marked crabs were recaptured.

The paucity of females (25 males to 1 female) in pot collections is presumably due to their behavior during the reproductive period of March-April. Feeding by molting females is curtailed during the molting/mating period (Powell & Nickerson, 1965), consequently few females entered the baited pots. The male to female ratio of red king crabs on the mating grounds in the Gulf of Alaska approximates 1:2 to 1:4 (data via trawling: Gray & Powell, 1966).

Prey composition

King crab feeding data corroborated the CPUE data, in that, significant differences between mined and unmined stations were not apparent. Either crabs were able to find similar quantities and composition of food in both areas or they mainly fed from unmined area before entering pots in the mined area. Crabs were observed via ROV feeding in mined areas. However, the latter scenario is more plausible. As stated previously, benthic sampling showed that many of the prey taxa typically taken by king crabs were reduced at mined relative to unmined areas (Chapter 1). Since crabs can move up to 4 km d^{-1} under ice nearshore (Rusanowski *et al.*, 1990) and the longest distance across mined areas was < 1 km, it is probable that crabs captured in one area could have been attracted from another area where they recently foraged.

King crabs are opportunistic omnivores with a preference for animal food. They take a wide variety of prey with mollusks (mainly bivalves), crustaceans (mainly barnacles, amphipods, and assorted crabs), and echinoderms (mainly brittle stars, sand dollars, and sea urchins) the most important items (see Jewett & Onuf, 1988 for review). Their opportunistic feeding strategy presumably enables them to switch between prey when a particular food resource becomes depleted. As examples of their prey diversity, adult and subadult king crabs examined from shallow (5-15 m) waters near Kodiak Island, Alaska had 53 different prey taxa in their stomachs (Feder & Jewett, 1981b; Jewett & Feder, 1982). These crabs were feeding on a variety of substrates including mud, sand, and coarse bottoms with and without attached epifauna. In the Nome study area, foods identified in crabs on coarse substrates included sessile organisms such as hydroids, bryozoans, and urochordates, while foods from crabs on soft substrates included polychaetes, bivalves, amphipods, and sand dollars. Prey in common from both substrates included gastropods, crustaceans other than amphipods, sea urchins, sea stars, fishes and fish eggs.

Fishes and fish eggs were the dominant component of the diet in mined and unmined areas in all years (33.5 and 38.8% frequency of occurrence, respectively). There are numerous accounts of king crabs feeding on fishes (see Jewett & Feder, 1982, for review), but none listed fishes as an important component of the diet. The frequency of occurrence of fishes within king crabs elsewhere ranged from 4 - 13% (Cunningham, 1969; Pearson *et al.*, 1984) in the southeastern Bering Sea, 5% on the west Kamchatka shelf (Feniuk, 1945) and 8% on the west coast of South Sakhalin Island (Kulichkova, 1955). The most likely candidates of fish prey in the study area, based upon their abundance, ubiquity and lifestyle in Norton Sound, are saffron cod (*Eleginus gracilis*), sculpins (Cottidae), and Pacific sand lance (*Ammodytes hexapterus*) (Wolotira *et al.*, 1977; Barton, 1978).

Demersal trawl surveys in Norton Sound determined that saffron cod was the most abundant fish present in the late 1970's (Wolotira *et al.*, 1977; Sample & Wolotira, 1985). Adult saffron cod generally move inshore in winter when king crabs are present. Demersal spawning by the fish occurs under coastal sea ice in 2-10 m of water (Wolotira, 1985). Their eggs (1.5-2.0 mm diameter) are demersal and slightly adhesive to coarse substrates. Their size matches the size of eggs randomly mearsured within crab stomachs. Saffron cod in western Alaska waters have a high rate of natural mortality. Approximately 60-80% of the population dies annually and less than 1% of the stock survives past the age of 5 years (Wolotira, 1985). Therefore, deposition of eggs on the bottom, combined with a high natural mortality rate, makes saffron cod a likely food source for crabs in winter.

Although sculpins are among the most abundant fishes in Norton Sound (Wolotira *et al.*, 1977), nothing is known about their natural mortality. Sculpins inhabit coastal waters near Nome where they spawn under the ice during winter attaching large (2-3 mm) eggs in clusters among rocks (Hart, 1973; Eschmeyer *et al.*, 1983). It is probable that some fish eggs taken by crabs in the study area are those of sculpins.

Sand lance spawn in shallow subtidal regions along Alaskan coasts, inclusive of Norton Sound, burrowing into coarse sand substrates or fine gravel (Dick & Warner, 1982; pers. observ.). Sand lance are abundant in the vicinity of Nome (Barton, 1978), and they were occasionally found while sampling the benthos (Chapter 1). On several occasions I observed them emerging from the substrate while diving in the study area (pers. observ.). The abundance and burrowing habits of sand lance makes it vulnerable to capture by Dungeness crabs along the Washington coast (Stevens *et al.*, 1982) and, presumably also by king crabs. It is doubtful that sand lance eggs were taken by crabs since the eggs of this fish range from 0.9 - 1.2 mm in diameter (Healey, 1984), smaller than the eggs found in king crab stomachs.

Prey of secondary importance to crabs were the echinoids *Strongylocentrotus droebachiensis* and *Echinarachnius parma* and sea stars. Both echinoids were frequently observed throughout the study area. Benthic sampling revealed significantly more *E. parma* on unmined sand substrates (Chapter 1), while *S. droebachiensis* had significantly greater abundance, albeit low (4 urchins m^{-2}), on unmined cobble substrates (unpubl.). Urchins typically had a rock on their aboral surface, which appeared to prevent their tumbling over the substrate under prevailing strong currents. Sand dollars were visible at the sediment surface and slightly buried (<1 cm). Their trails were often visible in the fine sand/silt at depths exceeding 10 m. Although both species are taken by king crabs (i.e., Feniuk, 1945; Kun & Mikulich, 1954; Cunningham, 1969), *S. droebachiensis* is typically the more common echinoid eaten (Kulichkova, 1955; Tarverdieva, 1976; Pearson *et al.*, 1984). Instances where *S. droebachiensis* was consumed in appreciable amounts mainly occurred when crabs were feeding nearshore (e.g., Tarverdieva, 1979 - Bering Sea; Feder & Jewett, 1981b - Kodiak Island; current study). Crabs taken from the deeper waters of Norton Sound in 1976 and 1985 did not contain *S. droebachiensis* (Jewett *et al.*, 1990b), even though it was one of the predominant members of the epifaunal community (Hood *et al.*, 1974; Feder & Jewett, 1978a). Other prey such as bivalves and brittlestars were more common in crabs in the latter study (Jewett *et al.*, 1990b). Also, *E. parma* was rarely taken by crabs in deeper waters of Norton Sound outside the lease area (Jewett *et al.*, 1990b).

Sea stars (Asteroidea) in crab stomachs in mined and unmined areas were not identifiable to species. However, eleven species of sea stars were identified in Norton Sound by Feder & Jewett (1978a), and most of these were observed by divers in the study area (pers. observ.). Sea stars are reported as king crab food elsewhere, but never in appreciable quantities (e.g., McLaughlin & Heberd, 1961; Tarverdieva, 1976: Feder & Paul, 1980; Feder & Jewett, 1981a; Jewett & Powell, 1981; Jewett & Feder, 1982).

Hydroids were ubiquitous throughout the study area on coarse substrates in mined and unmined areas. However, their presence in crab stomachs was significantly more common in mined areas. These sessile organisms are reported in stomachs of king crabs elsewhere (e.g., Tsalkina, 1969; Tarverdieva, 1976; Feder & Paul 1980; Pearson *et al.* 1984). Eelgrass was the plant material most often consumed by crabs in mined areas. No eelgrass exists within the study area, although stands of eelgrass are known to occur upstream from the study area (Barton, 1978). The significance of plant material as a king crab food item is variable. For example, plant remains, mainly *Laminaria* and *Phyllospadix*, amounted to more than 80% of the weight of 101 king crabs (*Paralithodes brevipes*) stomach contents off the West Kamchatka Shelf (Kun & Mikulich, 1954). Conversely, plant material only accounted for about 3% of the food weight in 713 crabs near Kodiak Island (Feder & Jewett, 1981b; Jewett & Feder, 1982) and about 1% of the food weight in the current study. Observations with the ROV at the mined areas during March 1988 revealed unusual accumulations of assorted debris, including hydroids and eelgrass, within depressions in dredged areas. These depressions acted as catch basins for material loosened by mining or natural disturbances, thereby providing a readily available food source for crabs.

It is not known if the high incidence of sediment in crab stomachs represents deliberate ingestion for the attached and associated bacteria, diatoms, foraminiferans, and meiofauna (Rice, 1980) or accidental ingestion while taking larger organisms. Most king crab researchers (e.g., Feniuk, 1945; Cunningham, 1969; Tarverdieva, 1976; Pearson *et al.*, 1984) tend to adhere to the latter notion.

CONCLUSIONS

The assessment of mining effects on king crabs was judged to be negligible. This is based upon finding no differences between mined and unmined areas regarding crab catches, crab sex and size composition, prey quantity, and few differences in crab stomach contents (prey composition). The only negative effect is from an apparent reduction in crab density at mined locations based on a few ROV observations. The absence of any demonstrable effects of mining on the crab is due to the high natural dynamics (i.e., current scour, storms, ice gouging, bioturbation) of the region, the relatively small area affected by mining (about 1.5 km^2 or < 2% of the lease area), and the high mobility (up to 4 km d^{-1} under ice nearshore) and opportunistic feeding habits (at least 33 prey taxa) of this crab.

CHAPTER 3: ASSESSMENT OF THE BENTHIC ENVIRONMENT FOLLOWING OFFSHORE PLACER GOLD MINING IN NORTON SOUND, NORTHEASTERN BERING SEA - III. HEAVY METALS IN THE RED KING CRAB *PARALITHODES CAMTSCHATICUS* [1]

Abstract: Heavy metal concentrations in red king crabs, *Paralithodes camtschaticus*, were monitored during 1987-90 to assess the impact of offshore placer gold mining in Norton Sound, northeastern Bering Sea, Alaska. Crabs were only present in the study area during ice-covered months when mining was suspended. Arsenic, Cd, Cr, Cu, Pb, Ni, Zn and Hg concentrations in muscle and hepatopancreas tissues were generally not different between mined and unmined areas. Furthermore, concentrations of these metals were not different in surficial sediments upcurrent and downcurrent of mining. The levels of most metals in both tissues fluctuated over the study period, with no apparent temporal trend. Also, most metal concentrations differed between the tissues; Cr, Pb and Zn were greater in muscles, whereas Cd, Cu and Ni were greater in hepatopancreas. Arsenic and Hg had similar contents in both tissues. All elemental concentrations in the crab muscle tissues from Norton Sound were below or within the range of concentrations observed in red king crabs from five other locations in the North Pacific, including a mined area. In Norton Sound, of the metals in red king crabs regulated by the U.S. Food & Drug Administration (i.e., As, Cd, Cr, Pb, Ni and Hg) all, except Cd, were at least an order of magnitude below the federal guidance levels for contamination or human consumption. This investigation showed that mining activities did not affect the concentrations of the measured heavy metals in red king crabs.

[1]Jewett, S.C. Submitted. Assessment of the benthic environment following offshore placer gold mining in Norton Sound, northeastern Bering Sea - III. Heavy metals in the red king crab *Paralithodes camtschaticus*. Mar. Environ. Res. **00:** 00-00.

INTRODUCTION

The Bering Sea is one of the most productive marine ecosystems of the world, with high benthic biomass and large populations of demersal and pelagic fishes, seabirds, and marine mammals (Hood & Calder, 1981). Today, approximately 25 species of mollusks, crustaceans and fishes of the Bering Sea are important commercially (NRC, 1996). Foremost in economic importance among the crustaceans is the red king crab (*Paralithodes camtschaticus* [Tilesius, 1815]).

Considerable attention has recently been given to assessing the state of the Bering Sea, especially in relation to the concentration, transport and biological effects of anthropogenic contaminants (NRC, 1996). The attention was generated from the finding of significant concentrations of heavy (trace) metals in some Alaskan arctic marine biota which are either directly consumed by the indigenous people or are the food of animals harvested for subsistence use (e.g., Hansen, 1986; Taylor *et al.*, 1989; Langston, 1990; Asmund, 1992).

An offshore placer gold mining operation between 1985 and 1990 in the shallow waters of Norton Sound in the northeastern Bering Sea represented a potential risk of heavy metal contamination of marine waters. Consequently, a long-term environmental program, initiated in 1986, was developed to assess the physical and biological characteristics of the mined area. One of the major concerns with the mining operation was that dredging would result in resuspension or discharge of a variety of pollutants (e.g., heavy metals) which might then enter the food web. Red king crab, a high-profile, commercial/subsistence organism within Norton Sound, was the center of this concern. The potential effects of mining on this crab are addressed in Chapter 1, which examines the benthos that serves as food for the crab, and in Chapter 2, which compares crab relative abundance, distribution and prey between mined and unmined areas.

This chapter 1) examines the concentration of eight heavy metals (As. Cd. Cr. Cu.

Pb, Ni, Zn, and Hg) in red king crabs and surficial sediments relative to the mining activity, 2) compares the heavy metal concentrations in crabs from Norton Sound with those in red king crabs elsewhere, and 3) discusses the human health concerns of consuming crabs from the mined area.

Mining overview

The Offshore Placer Project was conducted near the City of Nome, Alaska in ice-free months (June - November) by Western Gold Exploration & Mining Company (WestGold) using the world's largest operable bucket-line offshore dredge, the BIMA. The BIMA's dimensions were approximately 110 m long, 43 m wide, and 45 m high with a 88 m long bucket ladder that contained 134 buckets, each of which had a 0.85 m^3 capacity. Variable substrate types were mined, materials processed onboard, and tailings returned to the excavation site. Mining occurred in 9-20 m water depths. The approximate locations and extent mined from 1986 through 1990 are shown in Figure 9. The area and volume mined within the 88 km^2 (21,750 acres) lease area was approximately 1.5 km^2 (371 acres) and 5.5 x 10^6 m^3, respectively (Howkins, 1992). The area and volume mined annually was 0.093 km^2 and 3.1 x 10^5 m^3 in 1986, 0.218 km^2 and 1.2 x 10^6 m^3 in 1987, 0.583 km^2 and 2.0 x 10^6 m^3 in 1988, 0.320 km^2 and 1.1 x 10^6 m^3 in 1989, and 0.287 km^2 and 9 x 10^5 m^3 in 1990 (Howkins, 1992). The Nome Offshore Placer Project ceased operation on September 20, 1990.

Study area

This study was conducted within State of Alaska offshore mining leases adjacent to Nome in northwestern Norton Sound (Fig. 9). The westward, counter-clockwise flow of

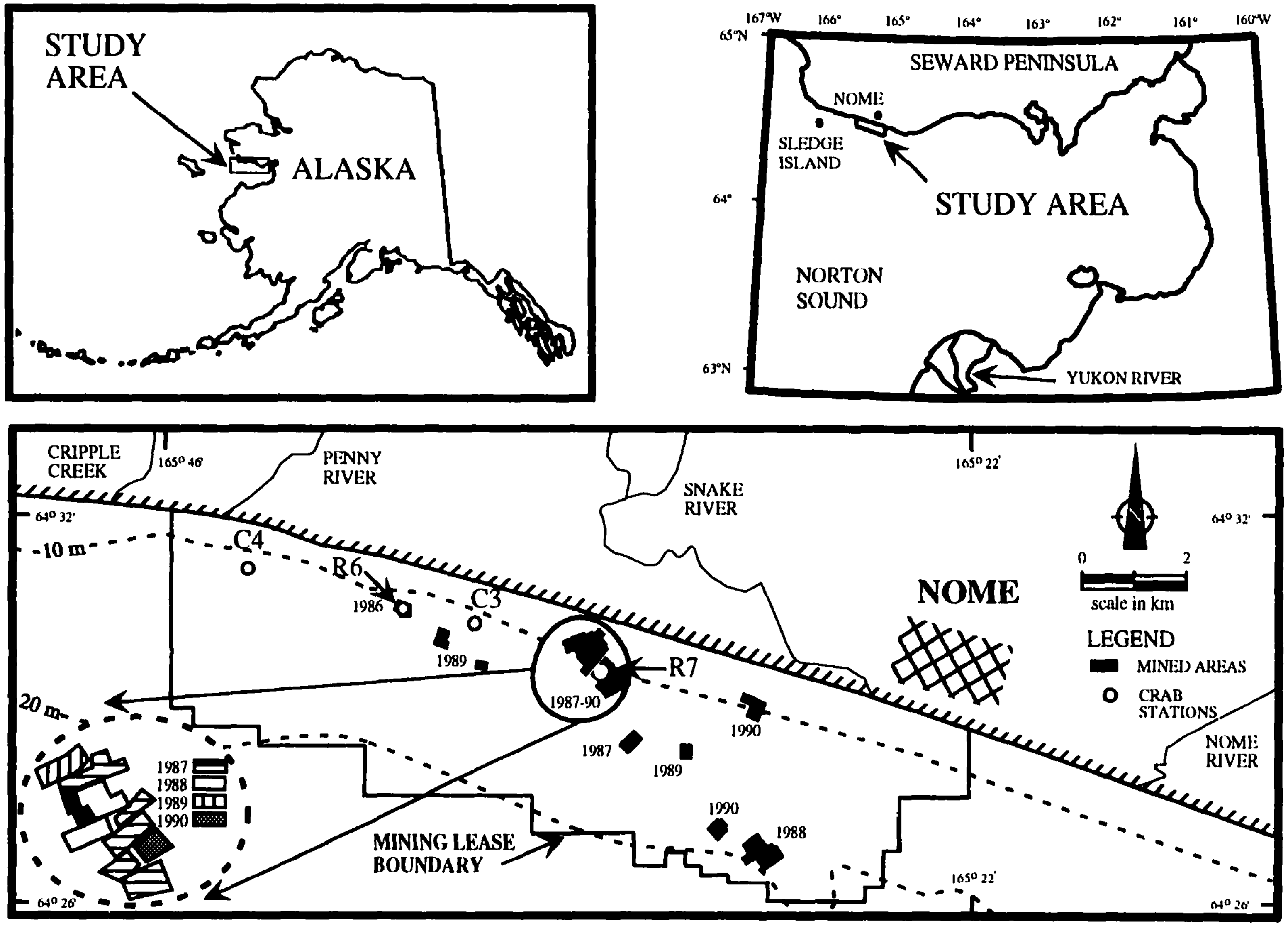

Figure 9. Map of the Nome Offshore Placer Project showing mining lease boundary, areas mined by year, and four stations surveyed for heavy metals in red king crabs.

water offshore along the south coast of the Seward Peninsula (Hood *et al.*, 1974), results in a predominant current off Nome directed to the west (Tetra Tech, 1980; Muench *et al.*, 1981). The speed of surface currents in the western portion of Norton Sound ranges from 5 to 20 cm s^{-1} with a maximum value of 50 cm s^{-1}. Strong coastal currents reaching speeds up to 100 cm s^{-1} are reported in the vicinity of Nome (Nelson & Hopkins, 1972). Bottom-current speeds are typically 10 to 20 cm s^{-1} in the western part of the Sound (Muench *et al.*, 1981). Tides in Norton Sound are primarily diurnal, have a tidal range of about 0.5 m (Pearson *et al.*, 1981), and are frequently amplified by occasional storms.

Surface sediments within the study area consist of a mosaic of sediment types, consisting of relict gravel and sand intercalated with modern very fine sand and mud derived from the Yukon River (Drake *et al.*, 1980; Hess & Nelson, 1982, Naidu & Mowatt, 1983). Fine sand/silt, overlying the more permanent cobble substrate, is transient in nature and subject to redistribution by storms, littoral currents and ice gouging. The littoral currents at Nome move the fines alternately in easterly and westerly directions. The net nearshore sand transport which is in a westerly direction (Drake *et al.*, 1980), is approximately 5 x 10^5 m^3 y^{-1} (Tetra Tech, 1980).

In ice-free months of June through November bottom temperatures and salinities in the study area typically range from near 0 to 12 °C and 21 to 34 ‰, respectively. During ice-covered months from December through May bottom temperatures and salinities range from -1.8 to 1.5 °C and 32-34 ‰, respectively (Hood *et al.*, 1974; Muench *et al.*, 1981; Jewett, unpubl.).

Norton Sound is usually covered by ice six to seven months per year. Shorefast ice develops in November - December (Muench *et al.*, 1981). Thickness of sea ice is variable, but often approaches 1.2 m. The seaward edge of the ice generally extends to the 20-m isobath and may be anchored by ice keels in the 10-20 m region (Stringer, 1981). Ice gouges generally occur inside the 20-m isobath and the gouge-incision depth ranges from 0.25 to 1 m deep (Larsen *et al.*, 1981). Ice-gouge widths range from 5 to 60 m, but 15-25 m are most common.

Norton Sound supports the northern-most commercial and subsistence fisheries for the red king crab (Powell *et al.*, 1983; Lean & Brennan, 1995). The commercial summer/fall fishery is traditionally centered in the northwestern Sound, south and east of Sledge Island (Wolotira *et al.*, 1977; Powell *et al.*, 1983). In winter, small commercial and large subsistence fisheries exist through the ice adjacent to coastal villages, particularly at Nome (Powell *et al.*, 1983; Lean & Brennan, 1995). A northeasterly migration of adult and subadult crabs into coastal waters of Norton Sound occurs in late fall/winter (Powell *et al.*, 1983). Reproductive activities (i.e., egg-hatching, female-molting, grasping, mating, and egg extrusion) are intense while nearshore, particularly from March through May when some ice is still prevalent (Powell *et al.*, 1983; Otto *et al.*, 1990). The crabs migrate offshore during nearshore ice breakup (usually May) when temperatures increase and salinities decrease (Muench *et al.*, 1981; Powell *et al.*, 1983). Therefore, crabs were generally in deeper water offshore when mining occurred.

METHODS

Field

King crabs were collected for heavy metal analyses through the ice with baited pots in 10-12 m depth at mined and unmined reference (control) stations March and April 1988-90. Additional crabs were collected from a mined station in 1987. Although numerous areas were mined over the five-year period (Fig. 9), a post-hoc decision was made to only monitor stations R6 and R7 because they were the first ones mined and represented the longest temporal data sets. Station R6 was only mined in 1986 and R7 in 1987-90. Tissue samples were collected from muscle of the merus segment of a walking leg and hepatopancreas (large lobate digestive gland that occupies most of the space under the carapace) for determination of heavy metals in crabs. To minimize metal contamination, pre-cleaned, stainless steel scissors and forceps were used in dissections. Carapace length (CL), exoskeleton condition and sex were recorded for each crab. Samples of at least 20 g of each tissue in each crab were collected.

Sediments were periodically collected at 50-100 m downcurrent and 500-2,000 m upcurrent of the BIMA's 100-m mixing zone in 1987-89. The positions of the upcurrent, reference samples were always at unmined sites. Sediments were collected once weekly with a Ponar grab (0.06 m^2). A sand/mud subsample was removed from the top 2-3 cm of the grab sediment with a teflon spoon.

Tissue and sediment samples were placed in plastic bags and pre-cleaned glass containers, respectively, frozen and air-shipped to the analytical laboratory. A total of 271 tissue samples and 74 sediment samples were analyzed.

Laboratory

Tissue and sediment samples were analyzed for heavy metals by AmTest, Inc. in Redmond, Washington in 1987-89, and Columbia Analytical Services, Inc., Kelso, Washington in 1990, using the USEPA digestion methods 3020 (1987 samples) and 3050 (1988-1990 samples). Each of the samples was first thawed and homogenized. Briefly, the digestion methods consisted of the following. A 1-g wet sample was taken into a conical glass beaker and digested on a hot plate first with 10 ml of 1:1 HNO_3 followed by additional digestions in 5 ml hot concentrated HNO_3 acid and a mixture of 2 ml of water and 3 ml of 30% H_2O_2, respectively. The digest was then refluxed with either 10% HNO_3 or HCL, made up to 100 ml with distilled water and centrifuged to remove undigested solids. The acid solution was analyzed for Cr, Cu, Ni, and Zn using either PE 2380 inductively coupled plasma (ICP) or ICP 61 unit. Arsenic, Cd, and Pb were analyzed using either PE 603 Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS) or Spectra 300 GFAAS unit. Mercury was analyzed by Cold Vapor AAS on a PE 50, PE 603, or Spectra 20 unit, following the EPA method 7471/245.1.

Portions of the wet tissue and sediment sample were weighed and the loss in weight upon drying at 100 °C was determined. The elemental concentrations (μg g^{-1}) are reported in terms of dry weights. The ranges of the method detection limits, MDL (μg g^{-1} wet wt), for each element over the four-year sampling period were: As 0.05-0.1, Cd 0.02-0.025, Cr 0.25-0.3, Cu 0.1-1.5, Pb 0.05-0.15, Ni 0.4-2.5, Zn 0.1-0.5, and Hg 0.01. When the concentration of a metal for any individual tissue sample was under the MDL, the MDL value was used as the concentration of that metal for the tissue. The analytical accuracy and precision for the tissues were checked via analysis of National Bureau of Standards (NBS) certified reference materials (CRM): bovine liver NBS 1577a, oyster NBS 1566, lobster hepatopancreas NBS TORT-1, dogfish muscle NBS DORM-1, whereas for sediments they were clarified via NBS 1645, 1646, 2704, and MESS-1. The heavy metal measurements on the CRMs for all elements were either close to or within the ranges (average ± 95% confidence interval) of the elemental estimates published by NBS. The precision was generally < 12% (coefficient of variation).

Statistical analyses

Possible effects of dredging activities were examined by testing the following null hypotheses:

- heavy metal concentrations in king crabs at mined sites are not significantly different from concentrations in the crabs at adjacent unmined (reference) sites: and
- heavy metal concentrations in surfical sediments downcurrent are not significantly

different from concentrations in sediments upcurrent of the mined sites. Heavy metal data on male and female crabs were combined because few females were collected and analyzed. The metal data were *ln*-transformed prior to statistical analyses to reduce heterogeneity of variances. The data were compared between mined and unmined areas, crab tissues, upcurrent and downcurrent, and years using Student's t and ANOVA tests with STATISTICA software (StatSoft, 1994). Averages in the text are presented with ± one standard error. Statistical significance was determined at $p \leq 0.05$, however, the Bonferroni correction, $\alpha* = \alpha/n$ (Rice, 1995), was used to correct the significance level to ensure all tests simultaneously had a confidence interval of 95% ($\alpha = 0.05$). The power of the t-test is also presented (Peterman, 1990).

RESULTS

King crab

The sex composition of king crabs from 1987-89 was 116 males and 10 females. Nearly 85% of all males had new exoskeletons, indicative of molting within the past year. Of the females, four had old exoskeletons and eyed eggs (near hatching), three had new exoskeletons with uneyed eggs (recently extruded), and three juveniles had new exoskeletons with developing internal ova. The crab composition from 1988 and 1989, the years in which data were available from mined and unmined stations, was 39 males and 5 females at mined stations and 56 males and 1 female at unmined stations. The size of males at mined and unmined stations were not significantly different ($p = 0.342$: t-test). The average size of 95 males and 6 females was 105 ± 1.4 mm CL and 77 ± 2.8 mm CL, respectively.

A total of 271 crab tissue samples were analyzed for heavy metal concentrations; 79 muscle and 68 hepatopancreas from the mined area, and 67 muscle and 57 hepatopancreas from the unmined area (Table 19). A series of 39 t-tests were conducted to compare metal

Table 19. Mean and 95% confidence interval of heavy metal concentrations ($\mu g\ g^{-1}$ dry wt) in red king crab tissues from mined and unmined stations in Norton Sound.

Year	Mined/ Unmined	Tissue	N	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc	Mercury
1987	Mined	Muscle	25	8.34 ± 1.86	0.25 ± 0.09	2.11 ± 0.59	64.82 ± 12.59	0.23 ± 0.01	0.79 ± 0.31	176.66 ± 6.96	0.029 ± 0.001
1987	Mined	Hepatopancreas	24	1.97 ± 0.58	14.14 ± 3.26	0.83 ± 0.33	174.28 ± 53.75	0.12 ± 0.01	3.65 ± 1.04	94.60 ± 10.79	0.057 ± 0.036
1988	Mined	Muscle	24	10.93 ± 2.00	0.24 ± 0.12	0.59 ± 0.10	56.76 ± 5.63	0.71 ± 0.05	1.08 ± 0.38	191.38 ± 10.25	0.046 ± 0.008
1988	Unmined	Muscle	37	7.85 ± 1.47	0.25 ± 0.17	0.75 ± 0.12	56.93 ± 5.63	0.70 ± 0.04	0.85 ± 0.16	189.01 ± 8.16	0.033 ± 0.006
1988	Mined	Hepatopancreas	24	15.01 ± 2.76	8.92 ± 1.84	0.47 ± 0.07	138.68 ± 54.14	0.45 ± 0.11	2.29 ± 0.73	133.42 ± 13.76	0.044 ± 0.011
1988	Unmined	Hepatopancreas	37	14.03 ± 2.23	7.79 ± 1.47	0.61 ± 0.08	133.16 ± 34.87	0.42 ± 0.05	2.42 ± 0.66	124.33 ± 11.24	0.037 ± 0.007
1989	Mined	Muscle	20	31.40 ± 3.01	0.29 ± 0.06	1.67 ± 0.11	82.03 ± 10.67	0.81 ± 0.07	2.81 ± 0.20	174.79 ± 8.94	0.056 ± 0.004
1989	Unmined	Muscle	20	25.53 ± 3.32	0.20 ± 0.04	1.63 ± 0.13	90.95 ± 9.24	0.82 ± 0.06	4.90 ± 0.72	168.10 ± 18.89	0.060 ± 0.005
1989	Mined	Hepatopancreas	20	29.82 ± 3.49	11.75 ± 2.38	0.99 ± 0.12	75.15 ± 40.02	0.49 ± 0.08	3.48 ± 0.96	131.21 ± 11.17	0.075 ± 0.019
1989	Unmined	Hepatopancreas	20	36.13 ± 4.72	13.52 ± 3.48	0.91 ± 0.11	127.48 ± 48.60	0.45 ± 0.06	2.55 ± 0.60	147.10 ± 17.43	0.070 ± 0.013
1990	Mined	Muscle	10	15.16 ± 1.77	0.15 ± 0.07	No Data	77.85 ± 12.36	0.23 ± 0.04	1.84 ± 0.30	147.10 ± 15.27	0.105 ± 0.027
1990	Unmined	Muscle	10	16.31 ± 2.63	0.19 ± 0.06	No Data	74.45 ± 14.21	0.26 ± 0.04	2.07 ± 0.33	159.55 ± 31.88	0.139 ± 0.051

concentrations in samples of muscle from 1988, 1989 and 1990, and hepatopancreas from 1988 and 1989 between mined and unmined stations. It can be generally inferred from these analyses that no significant difference (significant at $\alpha* = 0.0063$) existed in metal concentrations in either tissue between treatment locations in any year (Table 20). The only exception was with Ni which had a significantly ($p < 0.0001$) higher concentration in muscle tissues from unmined stations in 1989. Power of the individual t-tests not significant was generally low, < 0.7. Thus, with this one exception, the null hypothesis of no difference in heavy metal concentrations in crabs from mined and unmined stations was accepted.

For yearly comparisons (mined and unmined data pooled) of elemental concentrations in the two crab tissues, most of the eight metals differed significantly over the years (Figs. 10 and 11). Exceptions were for Cd in muscle tissue and Ni in hepatopancreas tissue. No apparent temporal trend was generally evident with most metals in both tissues. Exceptions were for Hg in muscle tissue and As in hepatopancreas tissue which showed progressive significant increases each year (Figs. 10 and 11).

For comparisons of metal contents in the two tissues over the 1987-89 period, significant differences existed in partitioning of most metals between tissues (Fig. 12). Muscles had higher concentrations of Cr, Pb and Zn, whereas hepatopancreas had higher concentrations of Cd, Cu and Ni. There were no differences in As or Hg content in the two tissues.

Sediment

A total of 74 sediment samples were analyzed for heavy metal concentrations; 37 samples upcurrent and downcurrent from the mined area (Table 21). Two-way ANOVA comparisons, using location and year as factors, were made to test the null hypothesis that there was no difference in sediment heavy metal concentrations downcurrent and upcurrent

Table 20. Comparisons of mean heavy metal concentrations (*ln* μg g⁻¹ dry wt) in red king crab muscle (A) and hepatopancreas (B) tissues from mined and unmined stations in Norton Sound. Test results are significant at $\alpha = 0.0063$*.

A. MUSCLE

1988

Metal	Mined	Unmined	d.f.	t-statistic	p-value	Power
Arsenic	2.22	1.79	59	-2.00	0.0500	0.383
Cadmium	-1.80	-1.92	59	-0.64	0.5200	0.050
Chromium	-0.64	-0.37	59	2.88	0.0264	0.512
Copper	4.00	3.98	59	-0.21	0.8350	0.050
Lead	-0.35	-0.38	59	-0.53	0.5950	0.050
Nickel	-0.12	-0.25	59	-1.14	0.2600	0.078
Zinc	5.25	5.23	59	-0.34	0.7350	0.050
Mercury	-3.18	-3.52	59	-2.81	0.0067	0.741

1989

Metal	Mined	Unmined	d.f.	t-statistic	p-value	Power
Arsenic	3.42	3.20	38	-2.62	0.0126	0.657
Cadmium	-1.34	-1.70	38	-2.68	0.0109	0.681
Chromium	0.50	0.47	38	-0.51	0.6088	0.050
Copper	4.36	4.48	38	1.31	0.1980	0.122
Lead	-0.22	-0.22	38	<-0.01	0.9969	0.050
Nickel	1.02	4.54	38	6.34	<0.0001*	1.000
Zinc	5.16	5.09	38	-1.00	0.3230	0.050
Mercury	-2.90	-2.84	38	1.16	0.2551	0.082

1990

Metal	Mined	Unmined	d.f.	t-statistic	p-value	Power
Arsenic	2.70	2.76	18	0.63	0.5343	0.050
Cadmium	-2.12	-1.83	18	1.07	0.2967	0.063
Chromium	NO DATA					
Copper	4.33	4.27	18	-0.46	0.5530	0.050
Lead	-1.51	-1.38	18	0.99	0.3343	0.050
Nickel	0.57	0.70	18	0.99	0.3343	0.050
Zinc	4.98	5.02	18	0.37	0.7168	0.050
Mercury	-2.33	-2.17	18	0.60	0.5556	0.050

B. HEPATOPANCREAS

1988

Metal	Mined	Unmined	d.f.	t-statistic	p-value	Power
Arsenic	2.61	2.53	59	-0.69	0.4933	0.050
Cadmium	2.06	1.93	59	-0.95	0.3478	0.050
Chromium	-0.83	-0.60	59	1.89	0.0641	0.334
Copper	4.57	4.58	59	0.04	0.9679	0.050
Lead	-0.89	-0.93	59	-0.33	0.7430	0.050
Nickel	0.50	0.59	59	0.38	0.7083	0.050
Zinc	4.86	4.79	59	-1.06	0.2914	0.061
Mercury	-3.26	-3.40	59	-1.18	0.2441	0.088

1989

Metal	Mined	Unmined	d.f.	t-statistic	p-value	Power
Arsenic	3.36	3.55	38	2.18	0.0352	0.462
Cadmium	2.35	2.48	38	0.79	0.4326	0.050
Chromium	-0.04	-0.13	38	-1.16	0.2530	0.083
Copper	3.94	4.43	38	1.69	0.0995	0.249
Lead	-0.75	-0.82	38	-0.86	0.3945	0.050
Nickel	1.07	0.80	38	-1.44	0.1576	0.162
Zinc	4.86	4.96	38	1.35	0.1866	0.132
Mercury	-2.72	-2.74	38	-0.11	0.9173	0.050

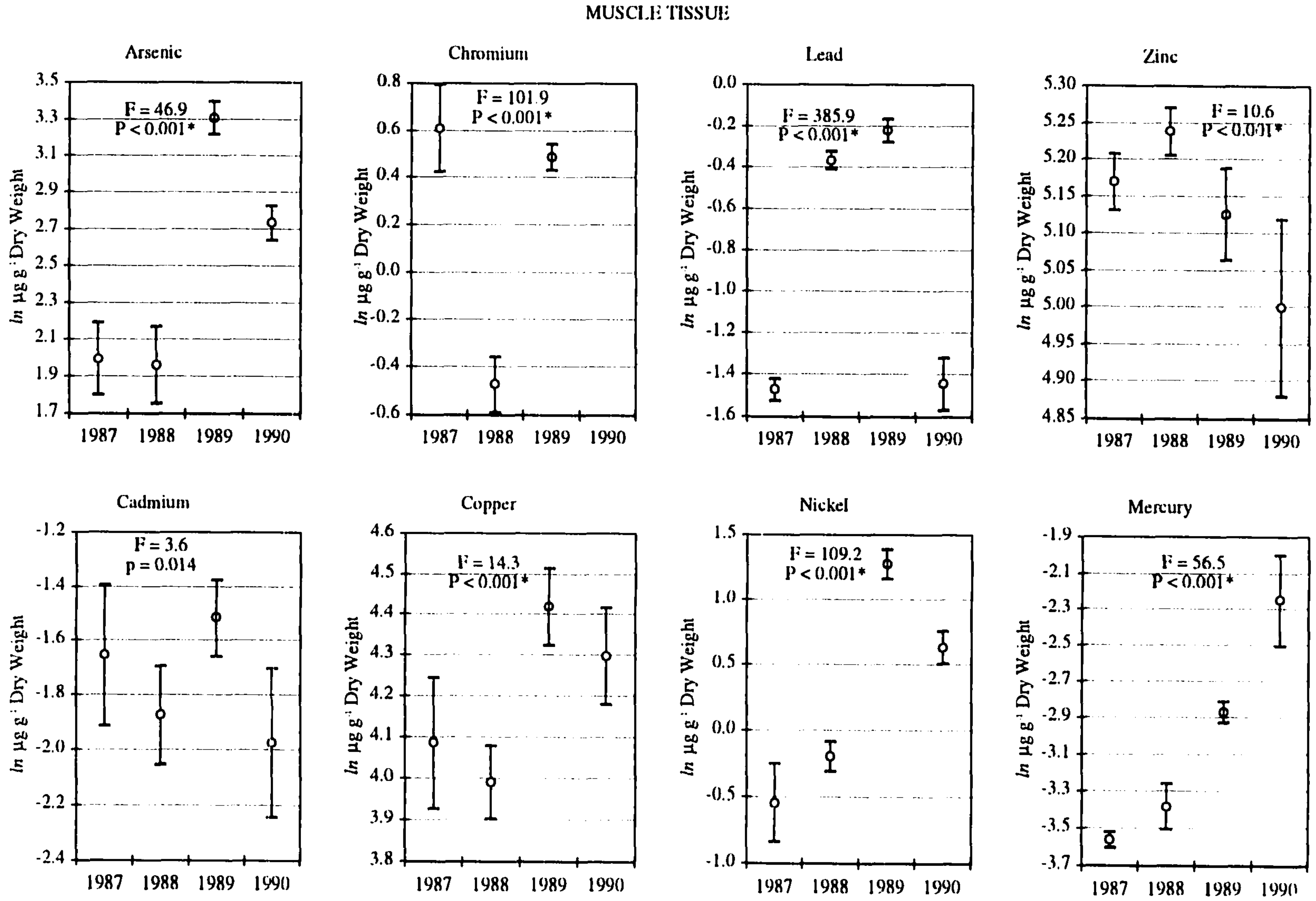

Figure 10. Comparison (mean ± 95% CI) of heavy metal concentrations in red king crab muscle tissue from Norton Sound. Test results are significant at $\alpha = 0.0063$*.

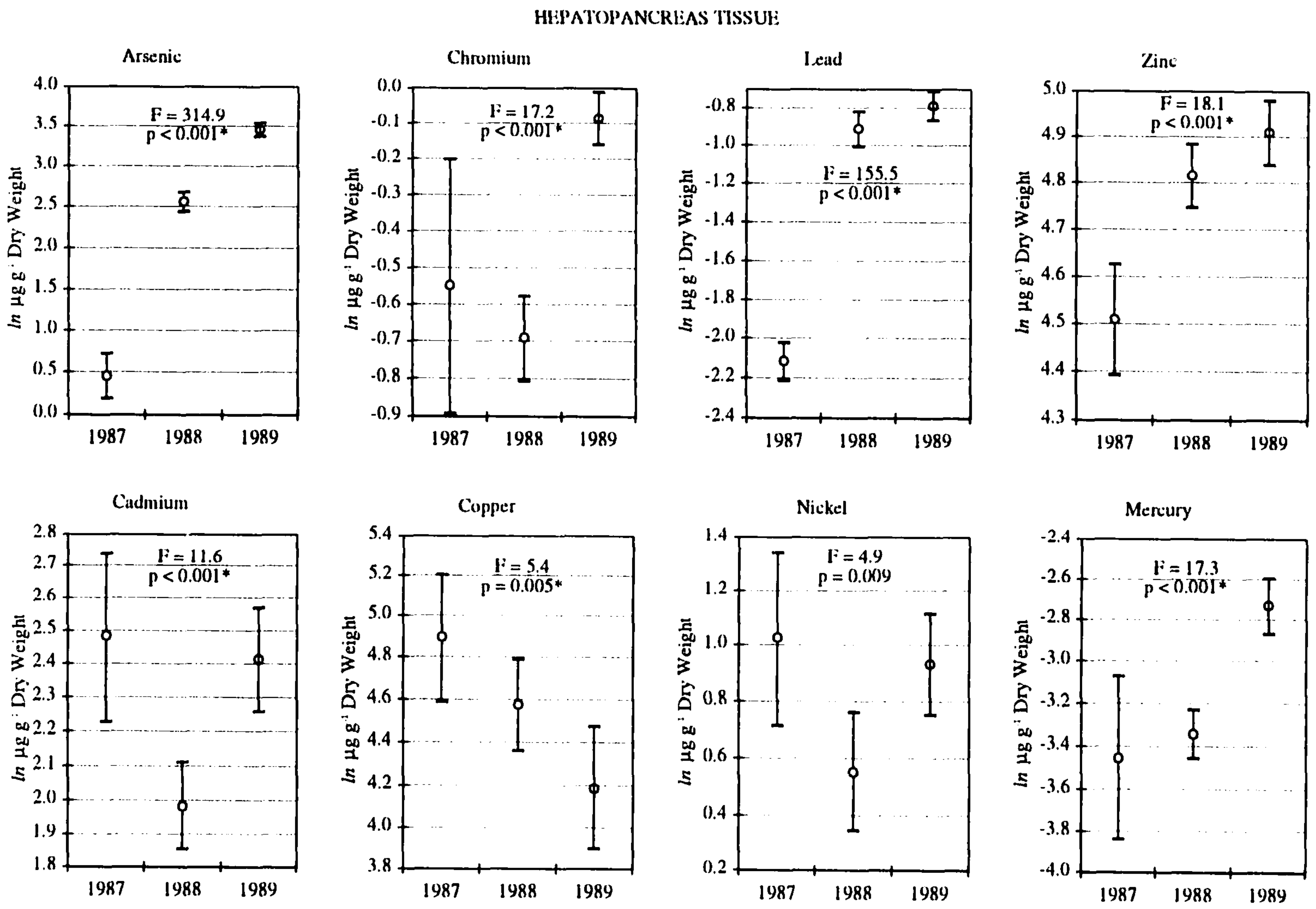

Figure 11. Comparison (mean ± 95% CI) of heavy metal concentrations in red king crab hepatopancreas tissue from Norton Sound. Test results are significant at $\alpha = 0.0063$*.

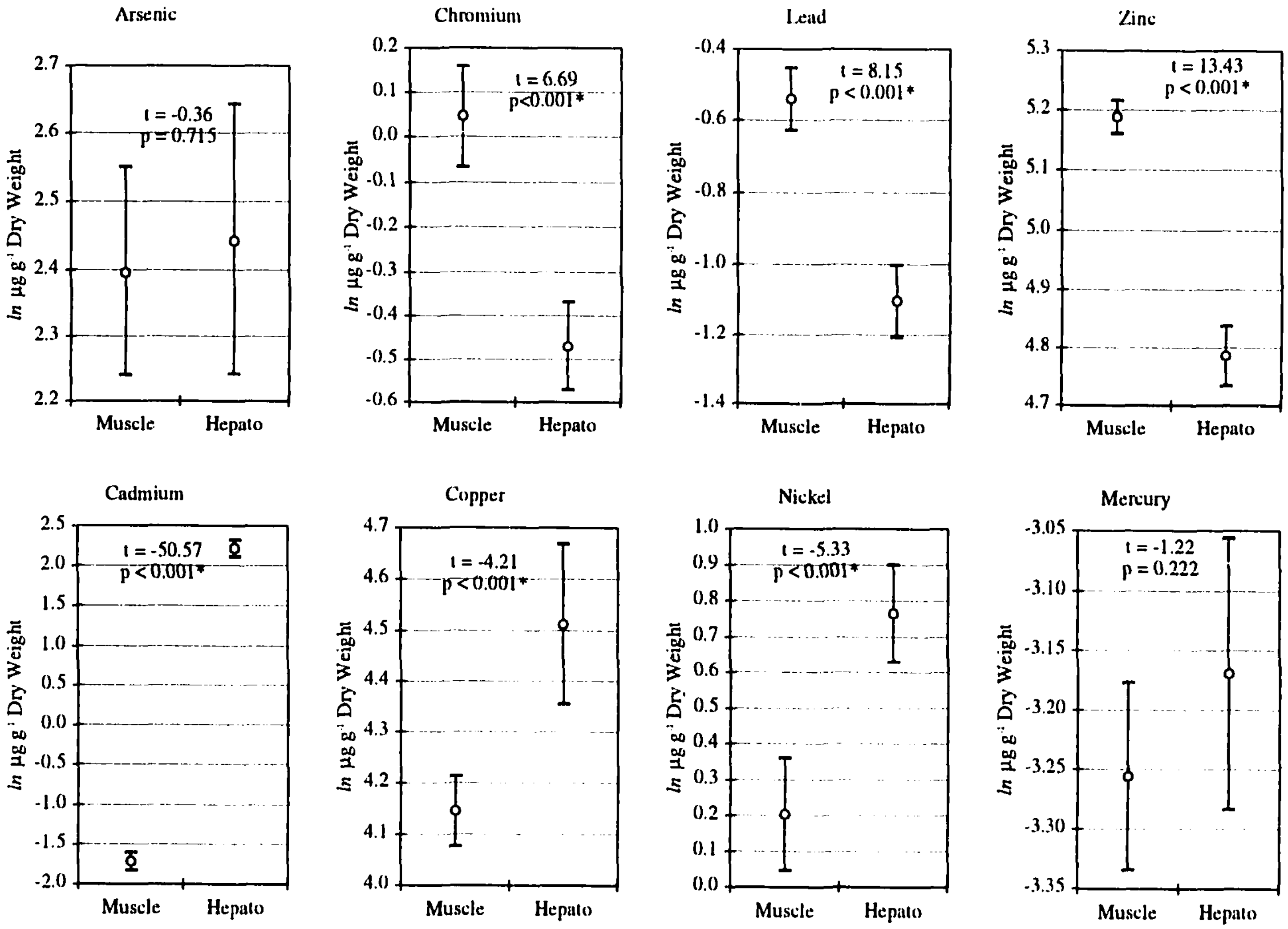

Figure 12. Comparison (mean ± 95% CI) of heavy metal concentrations in red king crab muscle and hepatopancreas tissues from Norton Sound, 1987-89. Test results are significant at $\alpha = 0.0063$*.

Table 21. Mean and 95% confidence interval of heavy metal concentrations ($\mu g\ g^{-1}$ dry wt) in surficial sediments upcurrent and downcurrent of mining in Norton Sound.

Year	Sample Location	N	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc	Mercury
1987	500 m Upcurrent	15	62.6 ± 23.9	4.23 ± 4.73	21.7 ± 4.5	28.3 ± 5.2	18.3 ± 10.6	42.9 ± 9.9	71.9 ± 9.2	0.027 ± 0.018
1987	100 m Downcurrent	15	59.8 ± 23.2	1.02 ± 0.20	20.6 ± 4.3	23.2 ± 5.9	12.8 ± 6.3	39.1 ± 6.3	70.9 ± 10.5	0.070 ± 0.068
1988	500 m Upcurrent	13	57.0 ± 16.7	1.90 ± 1.89	22.5 ± 6.2	23.4 ± 6.5	9.3 ± 3.2	30.7 ± 8.8	64.5 ± 7.6	0.032 ± 0.013
1988	50 m Downcurrent	13	67.4 ± 11.5	0.22 ± 0.08	20.3 ± 1.8	18.9 ± 4.5	7.7 ± 3.5	30.6 ± 4.0	64.2 ± 8.6	0.018 ± 0.007
1989	2000 m Upcurrent	9	53.4 ± 17.3	0.27 ± 0.05	23.3 ± 4.7	19.8 ± 6.4	18.0 ± 18.2	27.1 ± 6.9	61.7 ± 12.9	0.050 ± 0.059
1989	100 m Downcurrent	9	61.7 ± 8.2	0.24 ± 0.02	21.3 ± 4.7	19.1 ± 6.1	6.9 ± 2.2	29.1 ± 4.7	59.2 ± 12.7	0.017 ± 0.010

of the mined stations in 1987-89. Generally, no significant effects regarding location (mining), year, and interaction (effects between mining and year) occurred among the eight metals (Table 22). The null hypothesis was accepted for seven metals. The only year effect was with cadmium in which 1987 values were higher than 1988 and 1989.

DISCUSSION

Mining effects

No significant differences in heavy metal concentrations were generally found in either of the two crab tissues in mined and unmined locations. The rationale for establishing the null hypotheses was based on the factors of the spatially-restricted area mined, the high mobility and opportunistic feeding behavior of red king crabs, and the natural hydrodynamics and associated sediment processes of the Norton Sound region. During each of the 6-month mining seasons, when the crabs were generally well offshore of the mining vicinity, less than 0.58 km^2 was mined (Howkins, 1992). During non-mining, ice-covered months when crabs were in the study area they moved up to 4 km d^{-1} (Rusanowski *et al.*, 1990) and foraged on a variety of benthic organisms from mined as well as unmined areas (Chapter 2). Crabs captured within an unmined area could have foraged previously within an adjacent mined area, since the greatest distance across any mined area was < 1 km. Additionally, the region is subject to constant natural disturbances from episodic storms, ice gouging, and bioturbation (Chapter 1). These events tend to resuspend sediment particles and redisperse them, which would diminish or mask mining effects. Nearly 5×10^5 m^3 y^{-1} of gross littoral drift (mainly sand) occurs in the nearshore Nome vicinity (Tetra Tech, 1980). Cadmium, Cu and Zn may have been originally diagenically mobilized into porewater in the subsurface anoxic sediment and subsequently co-precipitated in Fe/Mn oxides and/or oxyhydroxides as primary precipitates (Naidu *et al.*,

Table 22. Two-way ANOVA test results on *ln* -transformed heavy metal concentrations in sediments upcurrent and downcurrent of mined stations in the offshore Nome vicinity, 1987-89. Test results are significant at $\alpha = 0.00625$ (*).

Metal	Source of Variation	d.f.	MS effect	F-statistic	p-value	Power
Arsenic	Year	2	1.682	2.098	0.130	0.226
	Location	1	0.716	0.893	0.347	0.050
	Interaction	2	0.108	0.135	0.873	0.050
Cadmium	Year	2	22.328	31.230	<0.001*	1.000
	Location	1	5.154	7.208	0.009	0.696
	Interaction	2	0.889	1.244	0.294	0.084
Chromium	Year	2	0.149	0.671	0.513	0.050
	Location	1	0.001	0.008	0.928	0.050
	Interaction	2	0.030	0.139	0.870	0.050
Copper	Year	2	0.282	0.909	0.407	0.050
	Location	1	0.193	0.623	0.432	0.050
	Interaction	2	0.029	0.937	0.910	0.050
Lead	Year	2	1.260	2.049	0.136	0.217
	Location	1	1.603	2.607	0.110	0.224
	Interaction	2	0.286	0.465	0.629	0.050
Nickel	Year	2	0.472	1.571	0.215	0.136
	Location	1	0.305	1.014	0.317	0.050
	Interaction	2	0.003	0.013	0.987	0.050
Zinc	Year	2	0.031	0.117	0.889	0.050
	Location	1	0.117	0.437	0.510	0.050
	Interaction	2	0.069	0.259	0.772	0.050
Mercury	Year	2	1.363	0.994	0.375	0.050
	Location	1	1.424	1.038	0.311	0.051
	Interaction	2	1.622	1.182	0.312	0.075

1989). Significant amounts of these elements and perhaps others may have been introduced into overlying waters, in solution, following dredging activities. However, any heavy metals that might have been discharged in the overlying waters consequent to dredging would likely have been dissipated and diluted because of the prevailing natural turbulence. Hence, no metal enrichment was observed in sediments downstream of the BIMA's active digging activities relative to upstream locations. The only instance of difference between mined and unmined locations was actually for less metal (Ni) from mined stations, a result which cannot be readily explained.

The near absence of female crabs (n = 10) in this investigation was not related to mining activities. Instead, it was an artifact of their reproductive condition at the time of attempted capture. Females were hatching eggs, molting, mating, and extruding eggs in March and April, a time when female feeding is known to be curtailed (Powell & Nickerson, 1965). Hence, females were not attracted to the baited sampling pots.

Comparison with other studies

A comparison of the heavy metal concentrations in crabs from Norton Sound with red king crabs from other regions is warranted. Data from this investigation were compared with data from five other locations: two from the southeast Bering Sea (Hall *et al.*, 1978; Robertson & Abel, 1979), one from the Kodiak Island vicinity (Hall *et al.*, 1978), one from southeast Alaska (Hall *et al.*, 1978) and one from coastal British Columbia, Canada (Farrell & Nassichuk, 1984) (Table 23). The latter study is the only other assessment of heavy metals in king crabs from a mined area. Information in Hall *et al.* (1978) and Robertson and Abel (1979) were provided as baseline data for assessing potential environmental impacts from future natural or anthropogenic disturbances. Concentrations of all heavy metals in crab muscle tissues of Norton Sound were below or

Table 23. Comparison of heavy metal concentrations ($\mu g\ g^{-1}$ dry wt) in red king crab muscle tissues from various locations. ND = no data.

	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg
Norton Sound: Present Study 1987-90								
N	146	146	126	146	146	146	146	146
Mean	15.166	0.235	1.275	68.983	0.589	1.852	177.585	0.053
Std. Dev.	10.202	0.313	0.931	25.174	0.265	1.638	31.312	0.040
SE Bering Sea 1: Robertson & Abel (1979)								
N	11	ND	12	ND	ND	ND	12	12
Mean	41		<0.45				117	0.33
Std. Dev.	10						18	0.14
SE Bering Sea 2: *Hall et al.* (1978) [1]								
N	10	10	10	9	10	10	10	10
Mean	26.008	0.902	1.539	40.138	3.366	1.648	319.586	0.620
Std. Dev.	8.403	0.373	0.839	15.032	1.200	0.632	145.893	0.103
Kodiak Is.: *Hall et al.* (1978) [1]								
N	10	10	10	10	10	10	10	6 [2]
Mean	24.871	1.298	1.608	82.539	4.739	2.343	329.983	0.218
Std. Dev.	5.370	0.391	0.706	42.338	1.976	0.913	182.769	0.069
SE Alaska: *Hall et al.* (1978) [1]								
N	9	9	8 [3]	9	8	9	9	9
Mean	33.148	1.390	0.655	35.129	2.648	1.775	378.576	0.735
Std. Dev.	15.686	0.258	0.264	10.724	0.718	0.391	158.932	0.402
Alice Arm, BC: Farrell & Nassichuk (1984)								
N	6	6	6	6	6	6	6	6
Mean	43.7	0.23	0.6	84.1	0.18	<2.0	196.3	0.15
Std. Dev.	14.31	0.083	0.15	22.12	0.130		22.38	0.080

[1] = Dry weights converted from wet weights: ww/0.1741 (mean % solids). Mean % solid value obtained from 20 random red king crab muscle samples in Norton Sound, 1988.

[2] = Three values were below detection limit; they were not included in calculations.

[3] = One value was below detection limit; it was not included in calculations.

within the range of concentrations (average ± 95% confidence interval) observed in crabs from other locations (Table 23; Fig. 13). The interpretation of these comparisons is necessarily somewhat subjective because of the inherent differences in the analytical approaches used by all investigators. While Robertson and Abel (1979) used the neutron activation analysis on all metals, the other investigations generally used a combination of atomic absorption spectrometry (As, Cd, Pb), inductively coupled plasma spectrometry (Cr, Cu, Ni, Zn), and cold vapor atomic absorption spectrometry (Hg). Method detection limits (MDLs) also varied. MDLs were not presented in Hall *et al.* (1978) and Robertson and Abel (1979), however, MDLs were in Farrell and Nassichuk (1984) and they were comparable to values used in the present investigation. All elemental concentrations below MDLs were considered as the MDL values in calculations from Farrell and Nassichuk (1984) as well as the present study. Regardless of these analytical constraints, mining activities in Norton Sound did not elevate muscle tissue metal concentrations above the range of concentrations in crabs elsewhere from unmined waters in Alaska or from mined waters in British Columbia.

The lack of temporal trends in muscle metal concentrations (except Hg) over the life of the Norton Sound mining activities is generally consistent with the findings of the British Columbia operation. There was no significant elevation in heavy metal (As, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Zn, and Hg) concentrations in crab muscle tissues in two years of monitoring the impact of a British Columbia molybdenum mine tailing discharge on red king crabs and two other crab species (Farrell & Nassichuk, 1984). The temporal enrichment of Hg in crab tissues off Nome is apparently not due to mining since there was no concomitant increase of Hg in sediments. Nelson *et al.* (1975) reported that Hg values in the vicinity of the study area were highest in modern beaches where onshore gold mining once occurred ($\bar{x} = 0.22\ \mu g\ g^{-1}$ dry wt: metallic Hg was used for amalgamating the gold)

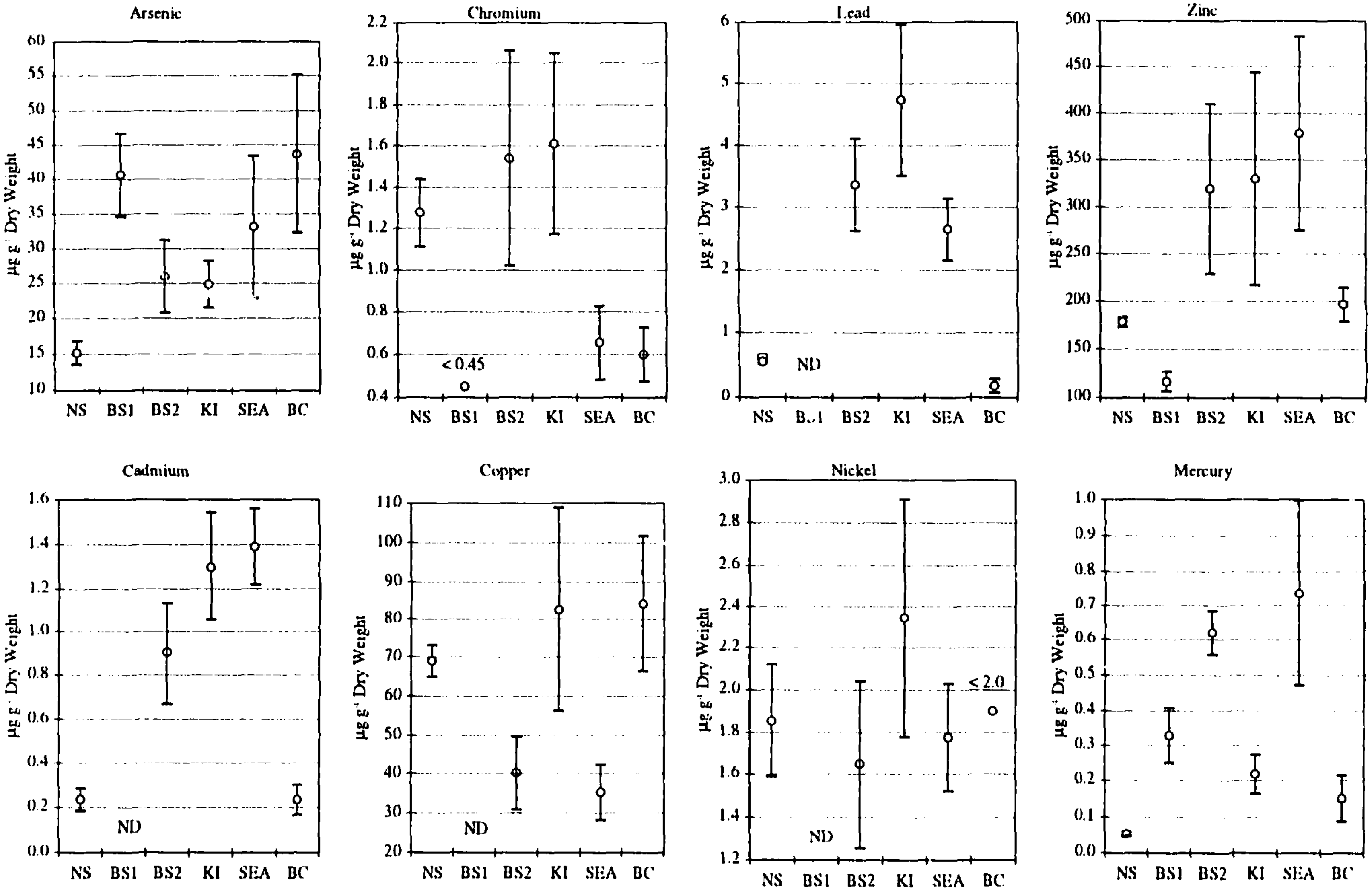

Figure 13. Comparison (mean ± 95% CI) of heavy metal concentrations in red king crab muscle tissues from various locations. NS = Norton Sound, BS1 = southeast Bering Sea 1, BS2 = southeast Bering Sea 2, KI = Kodiak Island, SEA = southeast Alaska, BC = British Columbia. ND = no data. See Table 23 for data sources.

and in nearshore subsurface gravels ($\bar{x}$ = 0.06 $\mu g\ g^{-1}$ dry wt). Perhaps the numerous storms that disturbed subtidal as well as beach sediments made more Hg available for crab uptake.

Mercury is one of the non-essential metals to decapod crustaceans, i.e., metals for which no metabolic role has been established; other non-essential metals include Cd and Pb; essential metals include As, Cr, Cu, Ni, and Zn (Rainbow, 1988). Body regulation of non-essential metals does not seem to occur in decapods, since the higher the concentration of these metals to which decapods are exposed, the more it accumulates (Rainbow, 1988). Both essential and non-essential heavy metals can be toxic to organisms at elevated concentrations by acting as enzyme inhibitors (Viarengo, 1989). However, the toxic effects are typically manifested in aberrant physiology, pathology, reproduction, feeding, and development (Engel & Brouwer, 1984). No such aberrations were noted among king crabs in Norton Sound since the mining operation was initiated.

Health concerns

The concern over the potential for heavy metal accumulation in marine organisms harvested for human consumption targeted red king crabs because of its preeminent use over other local marine organisms. During this investigation, from 1986 through 1990, the open-water commercial harvest of this crab in Norton Sound averaged 96,000 ± 18,036 males (no fishing occurred in 1991; Lean & Brennan, 1995). The average winter commercial (males only) and subsistence (both sexes) harvests (mainly in the Nome vicinity) from 1986 through 1991 averaged 1,910 ± 627 and 6,865 ± 1,253 crabs, respectively. The average subsistence harvest per family that fished during this six-year period was 78 ± 9 crabs (Lean & Brennan, 1995). Edible portions of king crabs that are traditionally used from the commercial and subsistence harvests are predominantly leg muscles and occasionally the hepatopancreas (C. Lean, Alaska Department of Fish & Game, Nome, AK; pers. comm.). The U.S. Food & Drug Administration (USFDA) established guidelines on the acceptable optimum levels of specific heavy metals in shellfish for human consumption. The USFDA "Level of Concern" for As, Cd, Cr, Pb and Ni, either relative to contamination or consumption, was established for human intake of crustaceans (based mainly on body, claw, and tail tissues of blue and Dungeness crabs, American lobster, Atlantic spiny and Pacific spiny lobsters, and ocean and pink shrimps; USFDA, 1993a,b,c,d,e). The total "Level of Concern", calculated as the tolerable daily intake of a metal / daily intake of crustaceans, was attained for individuals consuming crustaceans on a chronic basis, at the 90^{th} percentile level. Additionally, USFDA established a limit of 1 $\mu g\ g^{-1}$ (wet wt) for methyl mercury in "fish", which also included crustacean shellfish (Foulke, 1994). Based on all years of data compiled in this study all of the elemental concentrations ($\bar{x} \pm 95\%$ CI) in red king crab muscle and all but one metal (Cd) in hepatopancreas were at least an order of magnitude below USFDA's guidance levels (Table 24). Even the highest yearly elemental concentrations were well below the limit guidelines. Only Cd in hepatopancreas tissue ($\bar{x} = 3.2 \pm 0.16\ \mu g\ g^{-1}$ wet wt) approached the "Level of Concern", 3 $\mu g\ g^{-1}$ (wet wt). Highest Cd concentrations in crustaceans have been invariably recorded in the hepatopancreas, and lowest in edible muscle (Eisler, 1981). The reason for relatively high Cd values in the hepatopancreas is presumably because much of the accumulated Cd is bound in a detoxified form by metallotheineins, particularly in the hepatopancreas (Rainbow, 1988).

Table 24. Comparison of heavy metal concentrations in Norton Sound red king crabs with the USFDA guidelines for crustacean contamination or human intake. All concentrations are in $\mu g\ g^{-1}$ wet weight. ND = no data.

		Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc	Mercury
Red King Crab	N	146	146	126	146	146	146	146	146
Muscles	Average	2.61	0.04	0.214	12.19	0.099	0.31	30.98	0.010
(1987-90)	Std. Dev.	1.66	0.06	0.151	5.24	0.039	0.25	5.44	0.008
Red King Crab	N	125	125	125	125	125	125	125	125
Hepatopancreas	Average	5.33	3.20	0.219	39.00	0.115	0.83	37.30	0.016
(1987-89)	Std. Dev.	3.85	1.79	0.142	33.42	0.063	0.59	8.27	0.013
USFDA Level of Concern for Crustaceans		76	3	12	ND	1.5	70	ND	1*

* = USFDA limit in "fish" which includes crustacean shellfish.

CONCLUSIONS

Mining activities did not result in elevated concentrations of any of the eight heavy metals measured in crab tissues or sediments. Furthermore, the metal values observed in Norton Sound crabs were below or within the range of values for king crabs from other mined and unmined locations. Crabs from the mining area of Norton Sound were safe for human consumption based on comparisons with USFDA guidelines for most metals.

SYNOPSIS

Over the past decade considerable attention has been given to assessing the state of the Bering Sea, especially relative to declining stocks of some marine mammals and commercially-important species, and the concentration, transport and biological effects of anthropogenic contaminants (NRC, 1996). Consequently, much concern was generated in the mid 1980's over a plan by WestGold mining company to conduct offshore placer gold mining in the shallow waters of the northeastern Bering Sea off Nome, Alaska. Ultimately, a NPDES permit was granted to the company, which stipulated that environmental monitoring was to occur annually while in operation and one year after ceasing operation. A long-term environmental monitoring program was implemented in 1986 and concluded in 1991 which included research on physical and biological characteristics of the mining locations and the Nome vicinity (Rusanowski *et al.*, 1987, 1988; Jewett *et al.*, 1989, 1990a, 1991, 1992). The main environmental concern with this mining endeavor was the potential impact to the red king crab (*Paralithodes camtschaticus*), a species with commercial and subsistence importance in Norton Sound. This crab only occurred nearshore in the vicinity of mining activity during the ice-covered period, a time when dredging operations were suspended. This monitoring program addressed four areas of concern: 1) changes to the seafloor; 2) biological characteristics of sea floor habitats; 3) king crab distribution and feeding; and 4) potential for heavy metal accumulation in the marine food chain.

Mining and environmental monitoring were conducted within 88 km^2 (21,750 acres) of State of Alaska offshore mining leases adjacent to Nome. Mining occurred on variable substrates in 9-20 m water depths between 1986 and 1990 with the world's largest operable bucket-line offshore dredge, the BIMA. The area and volume mined was approximately 1.5 km^2 (371 acres) and 5.5 x 10^6 m^3, respectively (Howkins, 1992).

I hypothesized that offshore mining operations had no effect on selected segments of the benthic community in the Nome vicinity. My research focused primarily on the benthic macroinvertebrates, as potential prey for red king crabs, and crab relative abundance, food, and heavy metal concentrations.

The research revealed extensive, short-term, local, mining effects on the substratum and associated benthos, as measured approximately eight months after mining. Mining produced more fines at the surface of the "sand" substrates and more coarse material at the surface of the "cobble" substrates. Most macrofaunal community parameters (i.e., total abundance, biomass, number of taxa, richness, and diversity) and the abundance of dominant taxa were reduced in both substrates at the mined area. Furthermore, it appears that mining affected the size structure of benthic organisms, since smaller representatives of the community dominants were present at mined locations. Mining/dredging operations elsewhere resulted in variable alterations in surficial granulometry, but typically, as with this study, yielded a decreased benthos shortly after the disturbance (McCauley *et al.*, 1977; Swartz *et al.*, 1980; Jones & Candy, 1981; Poiner & Kennedy, 1984; López-Jamar & Mejuto, 1988; Kenny & Rees, 1994).

Multi-year bathymetric and side-scan sonar surveys of the physical changes of an area mined once (Station R6) in 1986 showed a progressive restoration of the seafloor. However, moderate evidence of disturbance was still visible after five years, indicating that the mined area had not yet stabilized physically. As for the biota, recovery was well underway in both substrates after four years, but this process was interrupted in the fall of the fourth year (1990) by several severe storms. Norton Sound is subject to a suite of natural disturbances (e.g., strong currents, frequent intense storms, grounded and gouging ice, and bioturbation) that keep the benthic community, especially at shallow depths in the mining area, from attaining stability. The dominance of opportunistic taxa, characteristic of disturbed environments, was a feature common to mined and unmined areas. Therefore, although local mining activites affected the benthos, the effects were relatively inconsequential spatially and temporally in comparison to the natural disturbances there.

Since extensive local mining effects were demonstrated for benthic organisms, many of which serve as food for king crabs, a short-term localized effect of mining activity on crab food availability seemed possible. The expectation of mining effects on crabs from a reduced food benthos was not borne out in this study. Through-the-ice sampling of crabs, when mining was suspended, revealed no differences between mined and unmined areas regarding crab catches, crab sex and size composition, prey quantity, most prey taxa, and concentrations of the eight heavy metals measured in crab tissues. Plants (mainly eelgrass) and hydroids, which accumulated in mining depressions, were more common in crab stomachs from mined areas. Crabs from the mining vicinity of Norton Sound did not have higher concentrations of heavy metals than red king crab from other mined and unmined locations. Furthermore, Norton Sound crabs were safe for human consumption, based on USFDA guidelines for most metals. The absence of any demonstrable effects of mining on this crab is due to the high natural dynamics (i.e., current scour, storms, ice gouging, bioturbation) of the region, the relatively small area impacted by mining (about 1.5 km^2 or < 2% of the lease area), and the high mobility (up to 4 km d^{-1} under ice nearshore) and opportunistic feeding habits (at least 33 prey taxa) of this crab.

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