Proceedings of a Synthesis Meeting:

The St. George Basin Environment and Possible Consequences of Planned Offshore Oil and Gas Development

Anchorage, Alaska — April 28-30, 1981

M. J. Hameedi (Editor)
Outer Continental Shelf Environmental Assessment Program
Juneau, Alaska

March 1982

United States
Department of Commerce
Malcolm Baldridge, Secretary

National Oceanic and
Atmospheric Administration
John V. Byrne, Administrator

Office of Marine Pollution Assessment
R. Lawrence Swanson, Director

United States
Department of the Interior
James E. Watt, Secretary

Bureau of Land Management
Robert F. Burford, Director

NOTICES

This report has been reviewed by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration's Outer Continental Shelf Environmental Assessment Program Office, and approved for publication. The interpretation of data and opinions expressed in this document are those of the authors and synthesis meeting participants. Approval does not necessarily signify that the contents reflect the views and policies of the Department of Commerce or those of the Department of the Interior.

The National Oceanic and Atmospheric Administration (NOAA) does not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to NOAA or to this publication in any advertising or sales promotion which would indicate or imply that NOAA approves, recommends, or endorses any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this publication.

PREFACE

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) was established by a basic agreement between the National Oceanic and Atmospheric Administration (NOAA) and the Bureau of Land Management (BLM) to conduct environmental research on Alaskan continental shelf areas identified by BLM for potential oil and gas development. OCSEAP's activities include review of existing data, planning and management of original research on all aspects of marine science, and transfer of information to BLM and other users. Scientific information is gathered and disseminated in journal articles, monographs, and books; digital data products; progress reports and final reports from individual research projects; and proceedings of disciplinary program reviews and synthesis meetings.

OCSEAP synthesis meetings are interdisciplinary and address environmental issues and resource use conflicts which have arisen in a proposed oil and gas lease area. OCSEAP investigators, other scientists, OCSEAP management, BLM personnel, and representatives from the State of Alaska, petroleum industry, local residents, and other interest groups attend these meetings.

Synthesis reports are based on the proceedings of the meeting and include interpretation of data by scientists and others knowledgeable about the lease area or the environmental problems of offshore oil and gas development. Within OCSEAP, synthesis reports are the most direct avenue from scientists to decisionmakers. Interpreting a variety of scientific data so as to predict the effects of oil and gas development is complex. It requires a comprehensive scientific and objective understanding of the environment that may be more difficult and time-consuming than the tasks some scientists have undertaken in the past. Nonetheless, active participation of scientists in this process is crucial and within OCSEAP it will continue.

This report evaluates available environmental data in light of proposed oil and gas development in the St. George Basin. Many issues and topics have been addressed and resolved; a number of questions remain unanswered due either to a paucity of data or to lack of specificity in the questions or problems to be addressed. Future synthesis meetings will be held as necessary and as more refined and analytical interpretation of environmental data are available.

Esther C. Wunnicke
Manager, Alaska Outer Continental Shelf Office
Bureau of Land Management

Herbert E. Bruce
Director, Alaska Office, Office of Marine Pollution Assessment
National Oceanic and Atmospheric Administration

ACKNOWLEDGMENTS

This report was prepared with contributions and assistance from scientists within and outside the Outer Continental Shelf Environmental Assessment Program (OCSEAP), representatives of several federal agencies, the State of Alaska, the petroleum industry, interest groups, and the public at large. Special thanks are due the Workshop Chairpersons and meeting participants who submitted text and graphic material for the report.

This report is published as part of OCSEAP, a program of marine environmental research established through Basic Agreement between the Bureau of Land Management, U.S. Department of the Interior, and the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

EXECUTIVE SUMMARY

1. The continental shelf southeast of the Pribilof Islands has been proposed for oil and gas lease sale (OCS Sale 70). The proposed sale area, which includes the St. George Basin, would consist of 479 blocks covering over 1 million hectares at water depths of 98-154 m. This sale is scheduled for February 1983.

2. The proposed lease sale area is located on a flat and relatively featureless part of the continental shelf. Two prominent submarine canyons, Pribilof Canyon and Bering Canyon, cut into the outer shelf and slope and appear to have been dominant factors in the distribution of sediment. Circulation over the shelf is bound to the west by a northwesterly boundary current with mean speeds of 5-10 cm/s over the continental slope. Although this current, per se, does not flow onto the shelf, exchange of mass or momentum does occur between the oceanic and shelf regimes and cross-shelf current pulses have been observed.

3. Shelf circulation is dominated by tidal currents and, particularly over the middle shelf, is responsive to episodic meteorologic conditions, i.e., those associated with migrating storms or outbreaks of cold and dry continental air over water. Mean currents averaged over many tidal cycles and wind events are usually 1-5 cm/s.

4. Vector mean wind speeds observed on St. Paul Island are about 1 m/s in summer and 2.5 m/s in winter. These winds would transport surface oil at about 3-8 cm/s. Much stronger winds, 10-30 m/s, can be expected during the frequent storms. Such winds would move oil on the sea surface at 30-90 cm/s or about 35-100 km/d.

5. Surface trajectories have been calculated for oil released from a point source located at 55°30'N and 166'W and at other locations for summer and winter conditions. In summer (June-August), spilled oil would have moved 85 km to the east and spread over about 250 km^2 after 10 days. Oil released from sites in the southern lease sale blocks could reach the coastline along the Alaska Peninsula within 30 days. In winter (December-May), oil spill trajectories would reflect a more energetic flow. After 10 days, oil would have moved 150 km west-southwest and spread over about 225 km^2. Spilled oil is not likely to reach the shoreline in a winter spill. The calculated greater area covered by spilled oil in summer is due to temperature considerations alone.

6. If 50,000 bbl of crude oil were spilled, dissolved oil in concentrations shown to be toxic to various fish and shellfish larvae would probably persist for about 10 days in the upper mixed layer and subsurface water over the shelf. The oil would cover 100-300 km^2.

7. Crude oil from a 50,000 bbl spill could be delivered to the botton in concentrations on the order of g/m^2 over about 100 km^2; lesser concentrations could occur over a much larger area. These estimates do not take into account the effects of weathering and advective processes.

8. The physical factors which influence oil transport vary little spatially over the shelf; concentrations of dissolved oil, area of impact, and trajectories that spilled oil might follow would be similar, whatever the location of the spill. On the other hand, physical factors in summer and winter differ markedly.

9. The low topographic gradient, age of sediment, lack of modern sediment input, sediment texture, and little reworking of sediment by bottom currents strongly suggest that sediment is probably normally consolidated and stable as a foundation material. There is substantial evidence for potential sediment instability along the continental slope from the Pribilof Canyon to Bering Canyon and for possible gas charging in deep subsurface sediment (300 m or more below the surface sediment) of the St. George Basin.

10. The St. George Basin is a graben bounded by growth faults. Seismic events probably occur along these boundary faults. The probability that a randomly selected site within the Basin will experience ground motion in excess of 0.2 g acceleration within 40 years is 11 percent;

for 0.5 g acceleration it is about 3 percent. Great earthquakes and ground motion of 1 g acceleration are likely in locations south of the Alaska Peninsula, such as the Shumagin region, between 159° and 162°W. There is also a potential for the generation of local tsunami heights of about 30m in the region. Such events could endanger human life as well as structures and facilities associated with oil and gas development.

11. The probability of volcanic activity in the Pribilof Islands is very low. On the other hand, several volcanoes on the Alaska Peninsula and the Aleutian Islands are highly likely to erupt and could damage life and property.

12. Sea ice will probably at least partially cover northern lease sale blocks between December and April, the southern lease sale blocks only in March. Lateral forces and localized pressure from sea ice could damage ships and structures; storm waves could drive large ice floes into structures, causing suspension of operations or damage to equipment and facilities.

13. Twenty-four species of marine mammals, including eight species of endangered cetaceans, are believed to occur in the St. George Basin. Some very important breeding and feeding grounds of a number of species are located within the lease area. Unimak Pass is the major corridor for marine mammals migrating into and out of the Bering Sea.

14. The endangered whales (gray, fin, sei, humpback, bowhead, right, blue, and sperm whale), fur seal, Steller sea lion, harbor seal, and sea otter are most likely to be affected by offshore oil and gas development. The bowhead, right, sei, and sperm whales only occasionally use the area. Humpback, fin, and gray whales regularly visit this part of the southeastern Bering Sea. Pinnipeds use the shelf heavily. About 75 percent of the world population of fur seal breeds on the Pribilofs. A large portion of the sea otter population in the southern Bering Sea is concentrated in waters between Cape Leontovich and Port Moller on the Alaska Peninsula.

15. Four food webs are utilized by marine mammals: benthic, coastal, deepwater, and pelagic. Most marine mammals are pelagic feeders; they feed primarily on euphausiids and pelagic and semidemersal fishes, especially pollock, herring, and capelin. Several species of toothed whales, in particular sperm and beaked whales and Dall's propoise, feed on cephalopods, bathypelagic and meso-pelagic fishes, and crustaceans in deep water off the Bering Sea shelf. The gray whale, walrus, and bearded seal feed heavily upon benthic organisms in other parts of their range, and it is expected that they do so in the proposed lease sale area as well. The coastal food web is dominated by the sea otter but is otherwise poorly understood.

16. Sea otter, fur seal, gray whale, and right whale are the species most sensitive and vulnerable to a major oil spill. The sea otter and fur seal are sensitive to oiling due to their reliance upon their fur for thermal protection. The gray whale is highly vulnerable because of its near-exclusive use of Unimak Pass to enter and exit the Bering Sea. The right whale is considered vulnerable because its population has been so depleted.

17. The high productivity of the southeastern Bering Sea supports major segments of world, North American, and Pacific Flyway marine bird and waterfowl populations. These birds feed primarily on fish, euphausiids, amphipods, benthic invertebrates, and eelgrass.

18. Four regions in or near the St. George Basin are especially important for seabirds and waterfowl: the Pribilof Islands (2.75 million breeding seabirds); the Fox Islands (1.8 million breeding seabirds); the coast of the Alaska Peninsula (1.2 million migrant and wintering waterfowl); and the pelagic waters of the St. George Basin and adjacent areas, notably Unimak Pass (over 20 million seabirds). At the Pribilofs, 88 percent of the world population of Red-legged Kittiwakes nests, whereas 45 percent of the Alaska population of the Tufted Puffin and about 50 percent of the world population of the Whiskered Auklet breed in the Fox Islands. Between 75 and 100 percent of the Pacific Flyway populations of the Black Brant, Lesser Canada Goose, and Black Scoter, and 75-100 percent of the North American

populations of the Emperor Goose, Steller's Eider, and King Eider use the lagoons on the north shore of the Alaska Peninsula as a migratory rest stop, a molting area, or an overwintering area. In the pelagic zone, most of the world population of the Short-tailed Shearwater spends the austral winter in the Bering Sea, migrating through the Aleutian passes, in particular Unimak Pass.

19. Breeding seabirds are at their colonies on the Pribilof and Fox Islands from May to October. Eggs and chicks are present from June to September. This period is believed to be critical as the presence of eggs and young forces adult birds to forage close to their nests. Around the Pribilofs birds forage within 60 km of the colonies, whereas near the Fox Islands they forage in the passes.

20. In August and September, large numbers of flightless adult and young murres and murrelets are concentrated in the waters immediately surrounding their colonies before post-breeding dispersal.

21. Seabirds have low reproductive rates and long adult life spans. Pribilof populations of some species may raise fewer young per pair than populations elsewhere in the world. Species other than Black-legged Kittiwakes and Red-faced Cormorants lay only one egg. Because the birds of the Pribilofs and St. George Island particularly appear to be already under stress (due to competition for food), any factor that decreases the availability of food or increases stress is likely to have a long-term influence on young of the populations. Modeling studies suggest that a long-term 15-20 percent drop in the fecundity of murres causes their populations to decline irreversibly.

22. Oiling of birds almost always kills them. Computer simulations indicate that the death of adults affects the time of population recovery more than the death of any other age class. Mortality of up to 100 percent of the subadults has only about one-third the effect of mortality of the adults.

23. A bird energetics model incorporating information on foraging behavior, annual survivorship, and fecundity has been used to predict the long-term effects of a catastrophic spill on Pribilof Islands' Thick-billed Murre and Black-legged Kittiwake populations. Simulations predict that murre populations would take about 20 years to recover from an oil spill that killed 50 percent of the breeding adults and young of the year. Since murres gather in immense rafts on the water near the islands, a single spill might easily kill this many birds. The Black-legged Kittiwake population would take about 10 years to recover from an oil spill that killed 50 percent of the breeding adults and young of the year.

24. Offshore oil and gas development activities may endanger bird populations, especially at or near colonies. Effects of these activities include disturbances by aircraft, boats, or shooting; reduction of food supplies; and physiological damage from oil contamination that would further reduce the already low reproductive rates of seabirds.

25. The commercial groundfish of the region are extensively harvested by Japan, South Korea, Taiwan, and, until 1980, the U.S.S.R. Major U.S. fisheries include salmon, halibut, and developing groundfisheries.

26. The most important commercial finfish species are Pacific salmon, Pacific halibut, walleye pollock, and yellowfin sole. Of lesser importance are Pacific herring, Pacific cod, sablefish, Greenland turbot, and rock and flathead sole. Except for sablefish and halibut, these stocks are considered to be healthy.

27. Major finfish users are man — for commercial and subsistence purposes — and marine mammals and birds. Apex consumers (birds and mammals) remove about 3 million metric tons of finfish annually, roughly twice the entire commercial catch from the eastern Bering Sea.

28. At-sea conflicts between the fishery and petroleum industries that do not affect the resource itself are pre-emption of fishery grounds, damage to gear, contamination of catch, and competition for port facilities.

29. The species of finfish in the St. George differ in spawning season, preferred depth, and migration pattern. Eggs, larvae, juveniles, or adults of one species or another are present year round. The eggs and larvae are the most sensitive life stages. Pelagic fish (salmon and herring) are the most sensitive to spilled oil, although demersal (flatfish) fish are known to accumulate hydrocarbons and convert them to potentially harmful metabolites.

30. The biological consequences of an offshore crude oil spill of 50,000 bbl may include the following:

    a. **Summer Surface Spill.** A complete kill of organisms unable to avoid oil in the small area at the spill (including eggs, larvae, or juveniles of Pacific cod, sablefish, pollock, rock sole, and flathead sole) would occur. Mortality and sublethal effects would decline gradually from the origin to the outer edge of the spill. Pollock would be the species most affected.
    b. **Winter Surface Spill.** This spill would be more destructive than the summer spill. Since most species considered are winter spawners, more eggs and larvae would be present. In addition, the oil-water mix would be somewhat deeper. At the origin, all eggs, larvae, or juveniles of Pacific cod, pollock, rock and flathead sole, Greenland turbot, and halibut would be killed.
    c. **Well Blowouts.** In both the summer and winter cases, expected results would be similar to those for the surface spills. There would be a larger kill at the origin due to oil and water mixing from the bottom to the surface there.
    d. **Slicks** produced by either winter or summer spills would attain their full areal extent after the second day of the spill, with toxic fractions of the seawater-soluble fraction greatest in the upper 0.5 m of the water column.

31. Because the various life stages of the St. George Basin finfish populations are widely distributed throughout the lease area, an offshore spill would not cause a devastating loss to a particular year class or stock. Commercial or subsistence fisheries would be affected only temporarily.

32. The southeastern Bering Sea supports lucrative fisheries for king crab, Tanner crab, Korean hair crab, shrimp, and snails. Annual shellfish catches are worth more than $150 million, not including millions of crabs harvested as a by-catch by foreign trawlers.

33. The waters around the Pribilof Islands are the center of abundance of blue king crabs in the Bering Sea. Blue king crabs migrate from shallow inshore waters, where they spawn from April to August, to greater depths, where they feed. Young of this species remain in nearshore waters for several years.

34. Red king crab are found throughout the southeastern Bering Sea but are most abundant in the St. George Basin between September and March. Red king crab migrate from deep overwintering and feeding grounds in the St. George Basin to coastal waters north of the Alaska Peninsula where adult crabs spawn and juveniles are reared.

35. Two species of Tanner crabs, *Chionoecetes opilio* and *Chionoecetes bairdi*, are found in the St. George Basin; *C. opilio* is the more abundant. Like king crabs, Tanner crabs migrate in spring to spawn but remain at greater depths during the summer in the waters north of the Alaska Peninsula. Juveniles remain along the coast for several years before joining the adults in their annual migration.

36. Spilled oil in the region could damage the valuable shellfish resources of the region as follows: (a) by direct kill of organisms, especially larval and juvenile forms; (b) by incorporation of sublethal amounts of petroleum hydrocarbons into organisms, resulting in reduced

resistance to disease and other stresses, failure to reproduce, and abnormal growth and development; (c) by chronic exposure to poisons resulting in tumors and morphological abnormalities affecting survival and commercial value; (d) by sublethal exposure to contaminants resulting in interference with feeding, migration, or other activities necessary for the survival of the species; and (e) by contamination of shellfish, making them unfit for human consumption.

37. Spilled oil can be transported to the benthos in zooplankton fecal pellets and by storm-induced suspension of bottom sediments. The potential rate of transfer of spilled oil from the water column to the benthos by copepods for the southern Bering Sea is estimated to be 20 mg of oil/m^3/d. If 50,000 bbl of oil were spilled on the sea surface, sediment in an area of about 100 to 300 km^2 would be contaminated at a concentration of about 7 parts per thousand. Storm-induced vertical mixing in shallow water, less than 60 m deep, could deliver oil to the bottom sediments in concentrations on the order of parts per thousand over 100 km^2. Such concentrations could cause major ecological changes due to mortality of biota as well as from biological dysfunctions resulting from sublethal effects.

38. "Tainting" of shellfish (i.e., the perception of an objectionable taste or odor in seafood) as the result of petroleum contamination is of great concern to fishermen because they fear that tainted catches will be unsaleable. However, recent evidence indicates that acutely contaminated organisms can usually depurate within two weeks when placed in clean water.

39. The southernmost and northernmost portions of the St. George Basin lease area are locations where spilled oil could be most detrimental to red and blue king crab populations, respectively.

40. There is now a substantial data base to address the numerous concerns about probable environmental and resource damage from offshore oil and gas development in this region and to make prudent and informed decisions. The data base is, however, far from being comprehensive and complete. Further information needed to adequately deal with major environmental issues and to minimize resource use conflicts is described below.

Pollutant Transport

i) Continued research to refine models of oil spill trajectories and weathering.

ii) Description of mechanisms of spilled oil delivery, residence time, and fate in the benthic environment.

Fisheries

i) Avoidance studies of major commercial species; studies evaluating the sensitivity of invertebrate prey species (mysids, copeponds amphipods, and euphausiids).

ii) In the case of a spill in Alaskan waters, a rapid on-scene response to obtain information on oil concentrations and short-term biological effects.

iii) The effects of chronic exposure to petroleum hydrocarbons on eggs of red king crab.

iv) Larval distributions of king crab in the southeastern Bering Sea.

v) Nearshore biology and ecology of larval and juvenile king crabs.

vi) Effects of chronic exposure to petroleum hydrocarbons on king crab reproductive activities.

vii) The biology of Korean hair crab.

viii) A compilation of pertinent oil and gas literature which would be easily accessible.

Marine Birds

- i) Physiologic and demographic data on reproductive potential, mortality and age structure.
- ii) Information on winter numbers and distribution between November and March.
- iii) Food habits of birds at sea.
- iv) The development of an objective method for assessing risk and establishing protection priorities.
- v) Ecosystem and oil vulnerability studies of lagoon systems.

Marine Mammals

- i) Site-specific ecological studies, especially at Unimak Pass.
- ii) Population estimates and natural history information for many species of cetaceans and other marine mammals.
- iii) Understanding the effects of noise, vessel traffic, and other development activities on marine mammals.
- iv) The effects of oiling on cetaceans and the ability of marine mammals to detect and avoid oil spills.
- v) The development and use of an oil spill response team and a long-term monitoring strategy.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Chapter 7. Shellfish Resources 141

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

CHAPTER 1

INTRODUCTION

M. J. Hameedi

1.1 PROPOSED ACTION

The present national need for energy resources, coupled with recent advances in the technology of offshore petroleum extraction, has accelerated exploration of offshore petroleum resources. Many potential oil and gas production areas over the continental shelf of the United States under federal jurisdiction (beyond the three-mile limit of state sovereignty) are being leased for development. Continental seabed between the state limit and 200-m water depth located around Alaska covers about 1.45 million km², or 68 percent of total U.S. submerged lands extending to the water depth of 200 m. In the southeastern Bering Sea, the continental shelf is broad, extending east and west as far as 950 km. The Alaskan continental shelf in general and that of the Bering Sea in particular constitutes the nation's largest unexplored petroleum area. Consequently, Alaska has received special recognition in the planning schedule for Outer Continental Shelf (OCS) oil and gas development.

An OCS oil and gas lease sale for the St. George Basin (OCS Sale 45) was first scheduled for March 1977. This sale was later postponed and then cancelled. A new lease sale (OCS Sale 70) was proposed for this region in 1979. According to the current OCS planning schedule, revised in July 1981, this sale is scheduled for February 1983.

The proposed Sale 70 includes 479 blocks covering over 1 million hectares (ha) southeast of the Pribilof Islands (Fig. 1.1). These blocks are

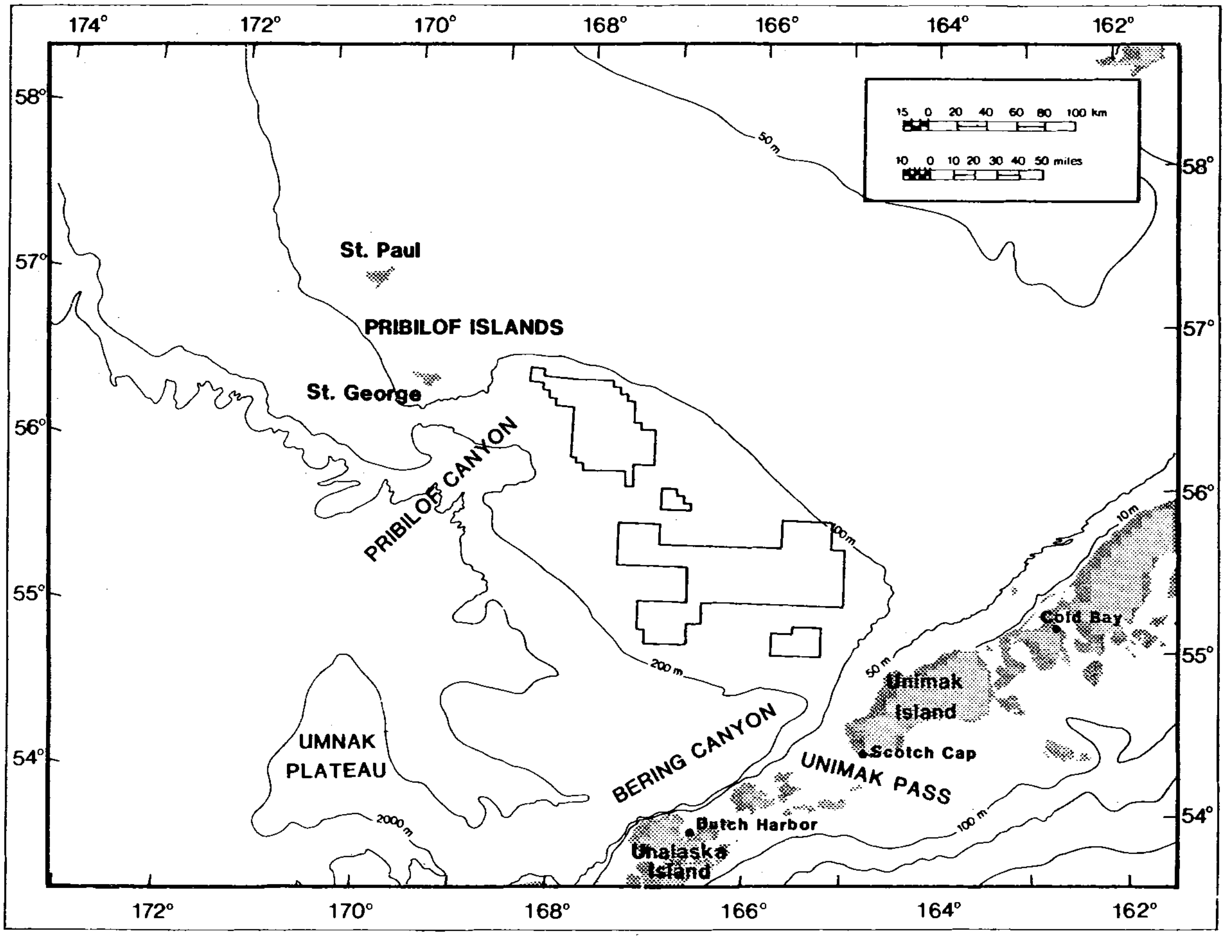

Figure 1.1. Index map for proposed OCS Lease Sale #70, St. George Basin.

located 61-178 km offshore in water depths of 98-154 m. The average water depth in the proposed lease area is estimated at 125 m.

As in the case of other OCS frontier regions, estimates of recoverable petroleum resources for the St. George Basin are speculative. In October 1980, the U.S. Geological Survey estimated the five percent (maximum), the mean, and 95 percent (minimum) levels of recoverable resources as follows:

	Maximum (5%)	Mean	Minimum (95%)
Oil, billion barrels	3.04	1.12	0.24
Gas, trillion cubic feet	8.80	3.66	1.48

These figures show that, for example, if petroleum hydrocarbons are found within the sale area, there is a 95 percent chance that they will amount to 0.24 billion barrels (1 barrel = 0.159 m^3) of oil and 1.48 trillion ft^3 (1 ft^3 = 0.0283 m^3) of natural gas. For a mean case, 1.12 billion barrels of oil and 3.66 trillion cubic feet of gas could be expected.

The decision to offer a lease sale is preceded by the preparation of a Draft Environmental Impact Statement (DEIS) at least nine months before the scheduled sale, a public hearing two months after the publication of the DEIS, and notice of sale a month before the sale. In all, there are 10 pre-sale decision steps or milestones in the leasing process.

Post-sale petroleum operations include four phases: exploration, development, production, and shutdown. Since tracts within a lease area vary in potential, these phases vary in duration and often overlap. The timing and extent of activities are influenced by market conditions, proximity of logistical support and shore facilities, environmental conditions, federal, state, and local governmental policies, and the availability of suitable land for the construction of onshore service and supply bases. If exploration efforts are successful, follow-up sales in the vicinity may result in a consolidation of these activities and/or overlap of phases.

It is too early to predict the level of industrial activity in the area. If the planned lease sale is successful, the exploratory phase will probably begin in 1983 and end by 1987. According to projections made by the Bureau of Land Management (BLM) Alaska OCS Office, exploratory drilling is expected to peak in 1985; five drilling rigs are expected to complete 15 exploratory and delineation wells in that year. Exploratory support activities could be staged from Cold Bay, St. Paul Island, or Dutch Harbor/Unalaska. Because of its superior airport facilities and proximity to the proposed lease area, Cold Bay will probably serve as the primary site of aircraft support operations. Personnel and perishable items would arrive in Cold Bay via jet aircraft and then be transported to drill sites by long-range helicopter.

Marine support operations could be conducted almost entirely from Dutch Harbor. Dutch Harbor's location near Unimak Pass, its good natural anchorage and existing infrastructure make it the best choice as the marine port facility. Its supply yard could be as large as 4 ha.

Exploratory drilling would probably be carried out from either drill ships or semisubmersibles. Depending on the extent and distribution of seasonal sea ice, drilling could continue throughout the year or stop in the fall until the ice breaks up in the spring.

Data on types, number, and location of production platforms, length and route of pipelines, potential sites for processing and storage facilities, and expected means of petroleum transportation, are not included in this report. These aspects of development and production are far in the future and even more speculative than details of the exploration phase. (The reader is referred to the BLM Alaska OCS Office for development scenarios and statistics for OCS Sale 70.)

1.2 ENVIRONMENTAL IMPLICATIONS OF THE PROPOSED ACTION

Widespread and severe environmental pollution, loss or impairment of natural habitats, and changes in socioeconomic organization are possible consequences of OCS oil and gas development, particularly in a previously unexplored region. Because current petroleum development scenarios for OCS Sale 70 are tentative and general, site-specific effects cannot be predicted. The following paragraphs consider in general terms some of the implications of the proposed offshore oil and gas development on the environment of the St. George Basin.

1.2.1 Loss of Habitat

Space — water, land, and air — will be needed to explore, develop, produce, and transport petroleum resources. Coastal and marine habitats will be lost or altered by leveling of land for the construction of shore facilities, dredging to maintain navigational channels, construction of breakwaters to provide sheltered harbors, placement of pipelines and platforms, and the settlement of dredged sediment, drilling muds, and cuttings. Critical or protected habitats located in the vicinity of the proposed lease area (for example, the Pribilof Islands, Izembek Lagoon, and Unimak Pass) could be endangered by offshore oil and gas development activities.

Development sites and transportation routes will ultimately be determined by the needs of industry, the policies and control of local, state, and federal governments, and by evaluation of predicted environmental effects. Resource requirements, conflicts of interest, probable effects on socioeconomic structure of the region, and environmental hazards are factors which must be considered in selecting sites and routes. According to its resource management policies, the State of Alaska, in selecting or approving sites for development, must also protect "ecologically sensitive areas including but not limited to: estuaries, wetlands, river deltas, fish spawning grounds, intensive-use habitats, bird nesting areas, migration routes, wildlife wintering habitat and sea mammal rookeries and hauling-out grounds" by requiring environmentally acceptable technology or, if necessary, by recommending alternate sites (Kramer et al., 1978).

1.2.2 Preemption of Fishing Areas

The southeastern Bering Sea is fished extensively by U.S. and foreign fishermen. Commercial fisheries and seafood processing are important elements of the local economy, particularly in coastal villages. Damage to the commercial fisheries of the region would result in economic hardship in the fishing industry regionally, nationally, and internationally. Commercial fisheries could be hurt by preemption of fishing areas by offshore structures (a semisubmersible rig, with its anchor system of 450 m radius, would occupy 130 ha), increased marine traffic, and easements. Gear and buoys could be lost through entanglement with structures, vessels, and debris, fish or their prey could become contaminated, or fishermen could lose out in competition for limited harbor facilities.

1.2.3 Effluents and Emissions

Potential sources of low-level, chronic pollution include support and supply bases, platforms, petroleum transportation systems, and increased traffic. Operational discharges are regulated by various governmental agencies.

The following types of discharge usually accompany exploratory drilling:

1. Effluents from the sewage treatment system.
2. Brine from the domestic freshwater distillation unit.
3. Seawater from the ballast system.
4. Treated effluent from the petroleum/seawater separator.
5. Freshwater, water-soluble fractions of oil and antifreeze from the blowout preventer.

Because of the small quantities and short duration of discharges, some of these effluents may have little effect on the environment.

In addition, formation waters (waters occurring naturally in sedimentary strata), drilling muds, and other pollutants may be discharged into the marine environment.

Increased municipal sewage may result in the introduction of synthetic organics, changes in the populations of microorganisms, and an increase in the incidence of disease. Increased use of ground and surface fresh water, and emission into the air of pollutants from storage and loading terminals, pump stations, and increased residential and commercial fuel consumption also may lower water and air quality.

1.2.4 Drilling Muds and Fluids

Special drilling muds are used to lubricate the drill bit, control pressure in the well, seal the strata until casings are in place, support the bore hole walls, and carry drill cuttings up to the surface. Typically, about a dozen of the over 500 different formulations of drilling muds are used at a given well. The formulations used depend on the characteristics of the individual site and are usually proprietary. Barite, caustic soda, bentonite clays, and lignosulfonates are the most commonly used components of water-based drilling muds. Caustic soda, lignosulfonates, and some bactericides are considered the main toxic components of muds.

After use, drilling muds and fluids are separated but substantial amounts of muds are usually discharged because of incomplete separation. Other discharges occur if the mud formulation is changed or when drilling is finished. Although the amount of mud discharged in the environment is highly variable and regulated, typically 60 m^3 of drilling muds can be expected to be discharged during drilling of a well 2,000 m deep (USDI, 1980).

1.2.5 Drill Cuttings

Drill cuttings, consisting of chipped and pulverized sediment and rock, are usually dumped directly into the seawater near rigs and platforms. Drill cuttings are heavier and coarser than drilling muds and thus settle out faster. In the water column and on the seabed, these cuttings are sorted out, dispersed, and carried away. Local accumulation of large particles is usually not a problem, but if several wells were drilled from a single platform, large accumulations could result. It is estimated that drilling of a well to a depth of 2,000 m would produce 130 m^3 of cuttings.

1.2.6 Accidental Oil Spills

There is a definite probability of large accidental oil spills during petroleum development and transportation. In calculating the probabilities of accidental well blowouts, other operational mishaps, and tanker accidents, it is assumed that realistic estimates of future accidents can be predicted from previous data, that accidents (and spills) occur independently of one another, and that the accident rate depends on the volume of oil produced and transported. Such statistics, largely based on data from the Gulf of Mexico, indicate that about eight oil spills larger than 1,000 barrels (bbl), and about four larger than 10,000 bbl, can be expected from production and transportation of 1 billion bbl of oil. In the St. George region, as in other OCS frontier areas, where no previous drilling has occurred, subsurface pressures are unknown, and the physical environment poses hazards to equipment; probabilities of well blowouts and other accidents may be higher than in an established field elsewhere in the world.

The probability of an oil spill in the OCS Sale 70 area has not been calculated. For Norton Sound (OCS Sale 57), the probable number of oil spills greater than 1,000 bbl during the development and transportation of petroleum resources (mean estimate: 480 million bbl of oil) is 2.8. The estimated number of spills greater than 10,000 bbl for that region is 1.5 (USDI, 1981). The number of oil spills expected in the St. George Basin is probably greater, in proportion to the large quantities of recoverable resources.

1.2.7 Increased Human Activities, and Vessel and Air Traffic

Petroleum development in the St. George Basin will cause an increase in air and sea traffic, construction of buildings and yards, and human activities. These may be detrimental, beneficial, or have no effect on the biota of the region.

Birds could be disturbed by increased traffic or by construction of facilities near their breeding habitats or foraging or migration areas. Petroleum development activities and noise from increased sea traffic can cause marine mammals to abandon or curtail the use of hauling grounds, breeding rookeries and foraging areas, or to alter their migratory routes. Low-frequency sound from large vessels is thought to interfere with communication of some of the baleen whales.

1.2.8 Aesthetic Considerations

The coast and islands in the vicinity of the proposed lease sale area, including the Alaska Peninsula, Pribilof Islands, and eastern Aleutian Islands, are nearly or totally undeveloped, and in some places uninhabited by humans. The whole area supports vast populations of fish and wildlife. Coastal lagoons are highly productive and support migratory birds and waterfowl; sea cliffs and islands abound with nesting birds and hauled-out marine mammals; ice floes are used as platforms by seals and walruses; and Unimak Pass is the main thoroughfare for whales migrating in and out of the Bering Sea. There are regions with unique biological communities, and some of the bays are pastoral and severe. The presence of platforms and shore facilities, with attendant human activities, could detract from the aesthetic value of the region.

Unlike some other Alaskan regions, the coastal marine environment of the southeastern Bering Sea receives large amounts of fish processing waste from shore-based and floating processors. Small bays with low to moderate flushing rates may already have exceeded their natural capacity to accommodate such discharges. Any addition of highly organic municipal or industrial waste may cause serious degradation of water quality, loss of benthic populations and habitat, and reduced utilization by pelagic species. These discharges could eventually destroy sport and subsistence fisheries in the area.

1.3 THE MEETING

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) investigators, other scientists conducting research in the southeastern Bering Sea, and managers of resources of the region met in Anchorage, Alaska, 28-30 April 1981. OCSEAP's and other data were used to: (1) describe the marine and coastal environments of the St. George Basin Lease Area; and (2) discuss and record environmental issues of concern and environmental consequences of the proposed oil and gas development, including effects of hypothetical cases of oil spills and other pollution incidents. These topics were also presented to help BLM in the preparation of the Draft Environmental Impact Statement for OCS Sale-70.

The following topics were discussed in workshops and plenary sessions at the St. George Synthesis Meeting:

1. Pollutant transport mechanisms and the fate of spilled oil.

2. Environmental hazards and restrictions to petroleum development technology and facilities.
3. Potential effects of oil and gas development on marine mammals, especially endangered species, with emphasis on key habitats such as Unimak Pass and the Pribilof Islands.
4. Potential effects of development on the finfish resources and pelagic ecosystems, with emphasis on salmon, halibut, pollock, and yellowfin sole fisheries.
5. Potential effects of development on marine and coastal birds, with emphasis on major colonies and foraging areas such as the Pribilof Islands region.
6. Potential effects of development on the shellfish resources and benthic ecosystem, with emphasis on king and Tanner crab fisheries.

1.4 REFERENCES

Kramer, L. S., V. C. Clark, and G. J. Cannelos. 1978. Planning for offshore oil development: Gulf of Alaska OCS handbook. Alaska Dep. of Community and Regional Affairs, Juneau.

USDI. 1980. Final environmental impact statement: Proposed 5-year OCS oil and gas lease sale schedule — March 1980-February 1985.

USDI. 1981. Draft environmental impact statement proposed OCS oil and gas Lease Sale 57 Norton Sound. BLM.

CHAPTER 2

TRANSPORT AND FATE OF SPILLED OIL

J. D. Schumacher

With contributions from E. Baker, J. Cline, R. Emerson, B. Griffiths, J. Karinen, B. Kirstein, J. Leendertse, D. Liu, S. Martin, J. Overland, J. Payne, M. Pelto, and J. Ray.

2.1 INTRODUCTION

The Bureau of Land Management has proposed the sale of 479 blocks on the outer continental shelf of the southeastern Bering Sea in February 1983 (see Fig. 1.1). The St. George Basin lease area, or Sale 70 area, is 1.1 million ha. The proposed lease area encompasses about 25 percent of the region known as the outer shelf hydrographic domain or current regime (Kinder and Schumacher, 1981, a. b). The blocks which comprise the proposed sale are located approximately 100-275 km offshore in water depths of 98154 m. Hydrocarbon resource estimates for the proposed sale are set at 1.12 billion barrels of oil and 3.66 trillion ft^3 of natural gas. Based on this resource estimate, the expected number of oil spills greater than 10,000 bbl is 2.8 over the 27-yr expected life of the field (U.S. Geological Survey, October 17, 1980, memo).

This chapter addresses the transport and fate of spilled oil and materials released during drilling operations. Circulation, property distributions, meteorology, and ice processes over the outer shelf are reviewed in the next section. Several references are made in this chapter to the IXTOC-I blowout. That blowout resulted in an initial rate of oil release of 30,000 bbl/d, later diminishing to 3,000 bbl/d. Between 3 June 1979 and 24 March 1980 an estimated 3.3 million bbl of oil were added to the Bay of Campeche, Mexico. This is the largest spill ever documented. In comparison, the *Amoco Cadiz* spill, which caused significant environmental and economic damage along the French coast in 1978, released approximately 1.5 million bbl of oil (Wood and Hannah, 1981). The fate of pollutant oil and possible adverse environmental effects of drilling fluids are treated in general in Section 2.3; more specific treatment requires a knowledge of the composition of St. George Basin oil and specific drilling fluids used. In section 2.4, case studies of spilled oil are presented using various models to interpret field observations and to provide trajectories and estimates of areal extent of spilled oil. Interactions of oil with ice over the lease area are also discussed.

2.2 THE PHYSICAL ENVIRONMENT OF THE ST. GEORGE BASIN

The eastern half of the Bering Sea is underlain by a vast, relatively flat, shallow continental shelf. This includes the outer shelf domain which has been defined (Kinder and Schumacher, 1981a) as that portion of the southeastern Bering Sea between Unimak Pass and St. George Island and from the shelf break (~ 170 m) Landward to the 100-m isobath. The area is about 5×10^4 km^2 with a water volume of 6×10^3 km^3. This shelf supports one of the world's richest fisheries as well as potentially large quantities of petroleum.

2.2.1 Circulation

Forcing mechanisms for shelf flow include interactions with oceanic currents, mass distribution generated by freshwater flux (baroclinicity), winds, and tides. The area is bounded on the west by the Bering Slope Current which flows parallel to the shelf break from near Unimak Pass to near Cape Navarin. The current is broad (~ 200 km) with speeds of 5-15 cm/s and transports ~ 5×10^6 m^3/s (Kinder et al., 1975). During the summer of 1977, six satellite-tracked drifters (drogued at 17 m) were deployed over the shelf/slope region north of Unimak Pass. Their trajectories (Fig. 2.1) indicated that over the basin mesoscale (10-100 km radius) eddies were present. Maximum speeds were ~ 50 cm/s, however, vector mean speeds were 5-15 cm/s towards the northwest with even lower (1-3 cm/s) vector movement over the shelf (Kinder et al., 1980). There is no evidence that the Bering Slope Current flows over the shelf proper; however, interactions between eddies and bathymetry can result in alongshelf pressure gradients which would drive cross-shelf barotropic flow (Csanady, 1978; Beardsley and Winant, 1979).

Kinder and Schumacher (1981b) summarized current data (Fig. 2.2) and noted that tides dominate horizontal kinetic energy (HKE), accounting for 60-80 percent of the total kinetic energy. Over the outer shelf domain, low frequency flow accounted for 20-40 percent of the energy (fre-

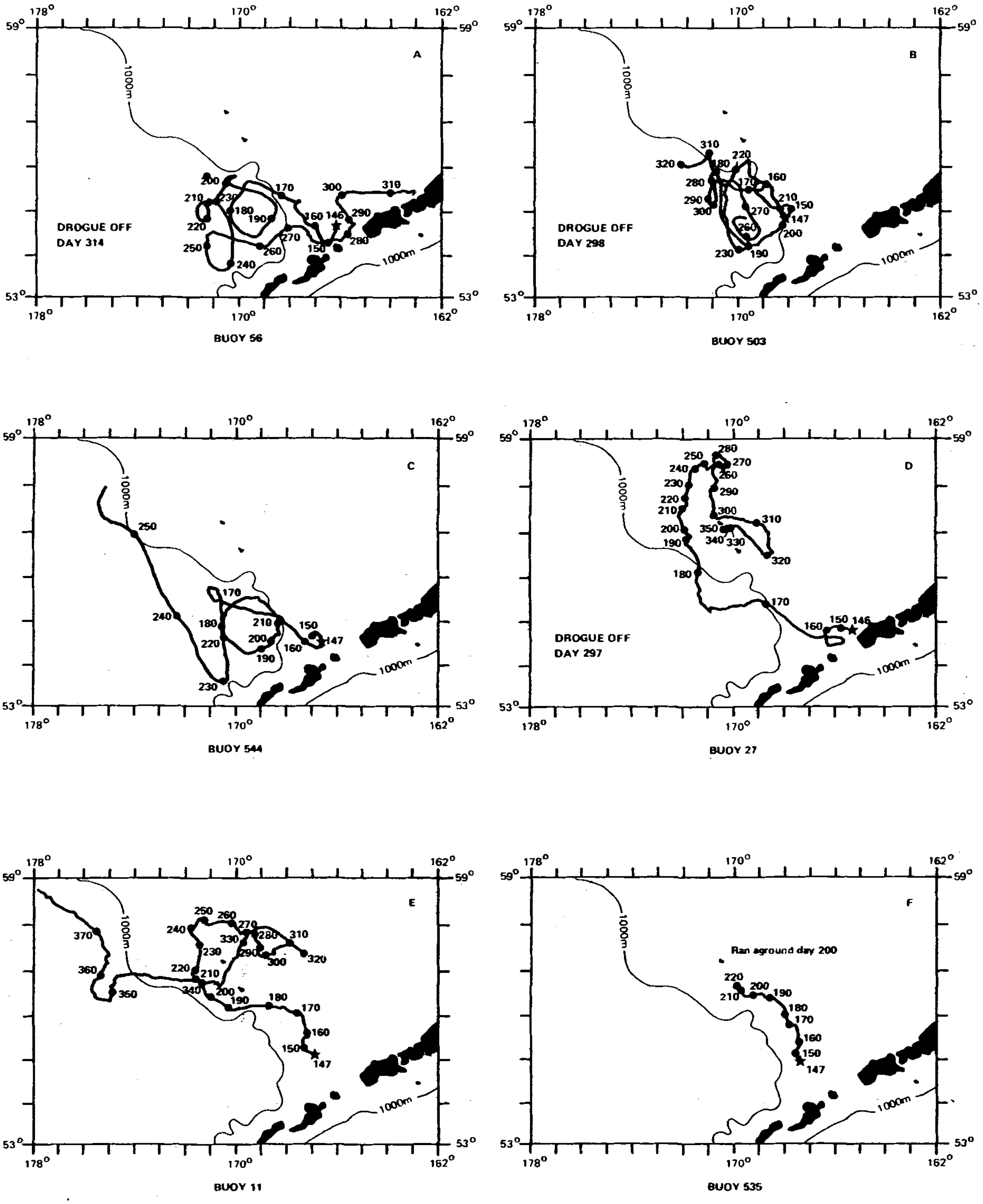

Figure 2.1. Satellite-tracked drogue buoy trajectories over the St. George Basin (from Kinder et al., 1980).

quencies in these bands match those of weather phenomena [2-10 d] and of longer period variability of the Bering Slope Current). As shown in Fig. 2.2, vector mean flow generally had a larger component parallel to the bathymetry and a lesser cross-shelf flow component (see Table 2.1, adapted from Kinder and Schumacher, 1981b). These authors noted that the current records contain little or no seasonal signal at any frequency. The increase in kinetic energy of the wind was not reflected in current spectra. Although there were year-to-year changes in low frequency kinetic energy, these occurred at periods longer than 10 days and hence were probably associated with changes in oceanic forcing. Further, there was little spatial or vertical coherence except at tidal frequencies.

Current records in the spring of 1980 from either side of the middle front (Coachman, 1980) showed that over a period of one month there was a 3 cm/s convergence at the middle front. This helps to maintain the characteristic isopleth dis-

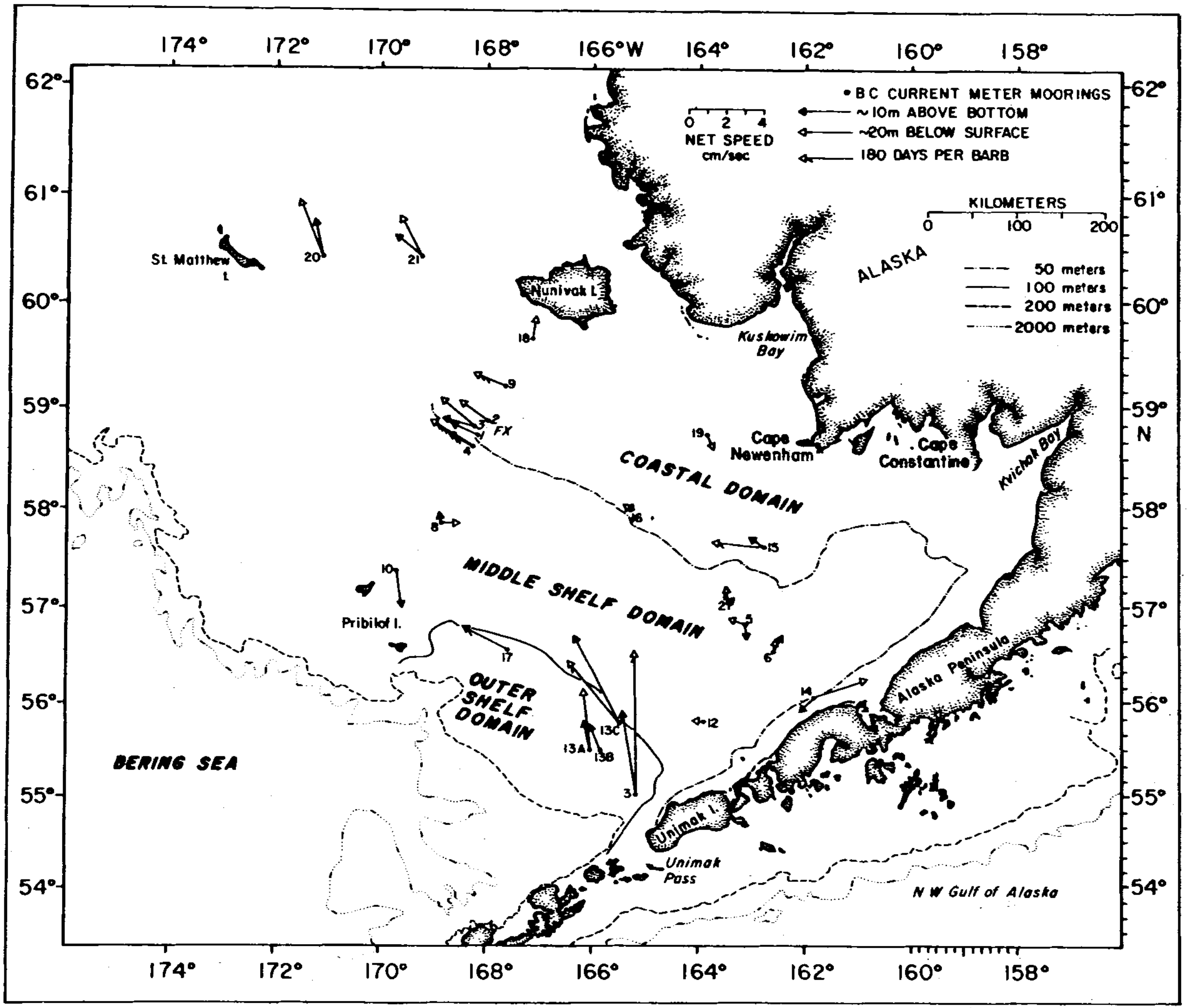

Figure 2.2 Observed vector mean currents (from Kinder and Schumacher, 1981a).

tributions marking the front and requires an upward velocity at the middle front to preserve continuity. But the convergence was not steady over a period greater than a few days; there was a one 2-d period when the current records indicated divergent flow. An example of time-dependent currents which imply convergence is shown in Fig. 2.3. The record in panel (A), which was obtained from the outer shelf domain, had a vector mean cross-shelf flow of 2 cm/s. The record from the middle shelf domain (B) had a vector mean current less than 1.0 cm/s.

Table 2.1. Summary of current records.

Mooring	Water depth (m)	Water depth (m)	Scalar speed (cm/s)	Mean speed[1] (cm/s) along	Mean speed[1] (cm/s) cross	Record length (d)	Period
BC-3A	115	20	29.0	1.8	2.7	130	11/07/75-03/16/76
BC-3B	116	25	27.8	2.7	0.9	9	03/17/76-03/25/76
		105	17.4	1.1	0.5	73	05/29/76-05/28/86
BC-3C	114	20	31.8	9.4	14.2	123	05/29/76-09/28/76
		100	20.5	4.7	4.7	123	05/29/76-09/28/76
BC-13A	122	20	20.6	2.6	2.0	69	03/22/76-05/29/76
		100	11.9	1.3	0.9	87	03/22/76-06/16/76
BC-13B	115	100	17.3	1.5	0.5	36	06/06/76-07/12/76
BC-13C	108	22	25.2	5.0	1.6	202	09/29/76-04/19/77
		96	16.1	4.4	0.4	83	09/29/76-12/21/76
BC-17A	104	96	18.1	3.0	− 1.0	142	09/22/76-03/11/77

---

[1] This is the vector mean resolved into along-shelf (315°T) and cross-shelf (45°T) components.

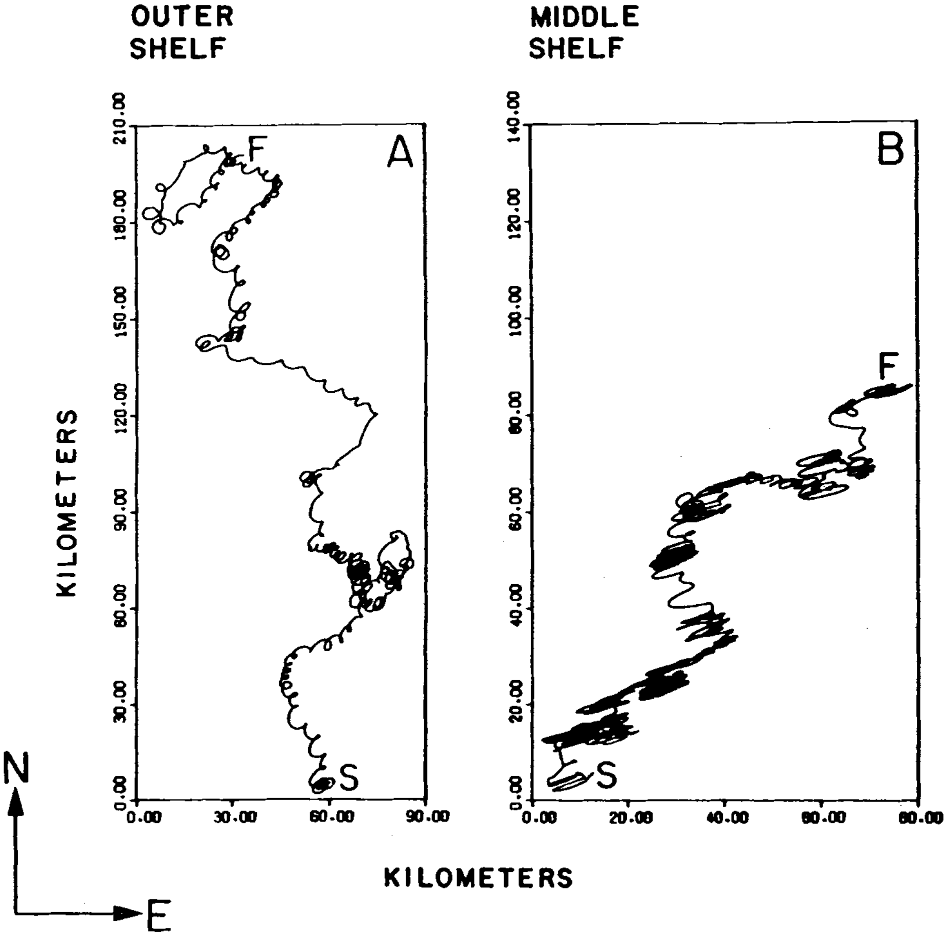

Figure 2.3. Progressive vector diagrams from current records over the A) outer shelf and B) middle shelf of the southeastern Bering Sea (from Kinder and Schumacher, 1981a). The middle front is oriented along the dashed line (45°F). Cross front flow was 2.7 and 1.0 cm/s in the outer and middle shelf, respectively.

Tidal frequencies contained most of the energy over the outer shelf, and roughly 80 percent of this energy was semidiurnal and 20 percent diurnal. Tidal ellipses major axes were directed cross-shelf (cf. Fig. 2.4 and Table 2.2). The observed tidal speeds (10-30 cm/s) resulted in tidal excursions of about 5-7 km. Tides are considered to be in part responsible for the cross-shelf flux of salt required to maintain the observed mean salt balance; over much of this shelf, tidal diffusion appears to be a dominant transport mechanism (Coachman et al., 1980).

Three current meters, deployed in March 1980 and recovered in August 1980, provide the only direct observations of currents from Unimak Pass (Fig. 2.5). Preliminary results (Schumacher et al., 1981) indicate that unlike currents on the outer shelf, there was a strong seasonal signal: vector mean flow was ~ 20 cm/s into the Bering Sea between March and May and ~ 5 cm/s for the remainder of the observation period (Fig. 2.6). A forcing mechanism for net inflow appeared to be baroclinic flow along the Pacific side of the Alaska Peninsula. This feature may be similar to the Kenai Current (Schumacher and Reed, 1980). The fluctuations were coherent with estimated atmospheric pressure gradient fluctuations normal to the peninsula. Changes in magnitude and direction of the atmospheric pressure gradient (hence winds) apparently drove flow reversals (up to 2.5–d duration) which occurred in 18 percent of the winter and 31 percent of the summer 35–h filtered current observations. The authors noted that largescale winds may be from a different direction than those through the pass, since the latter winds are directly down the local pressure gradient.

2.2.2 Property Distributions

The outer shelf was defined in terms of vertical structure (Fig. 2.7), where the energy balances generating such structure appear tied to local bathymetry and, hence, the domains are nearly fixed in space (Kinder and Schumacher, 1981a). Since the water depth over the outer shelf typically exceeds the sum of the depth of wind and tidally stirred layers, there is a layer at mid-depths where energy for vertical mixing is low. Further, while waters over the middle shelf exhibit different temperatures and salinities (Fig. 2.8,

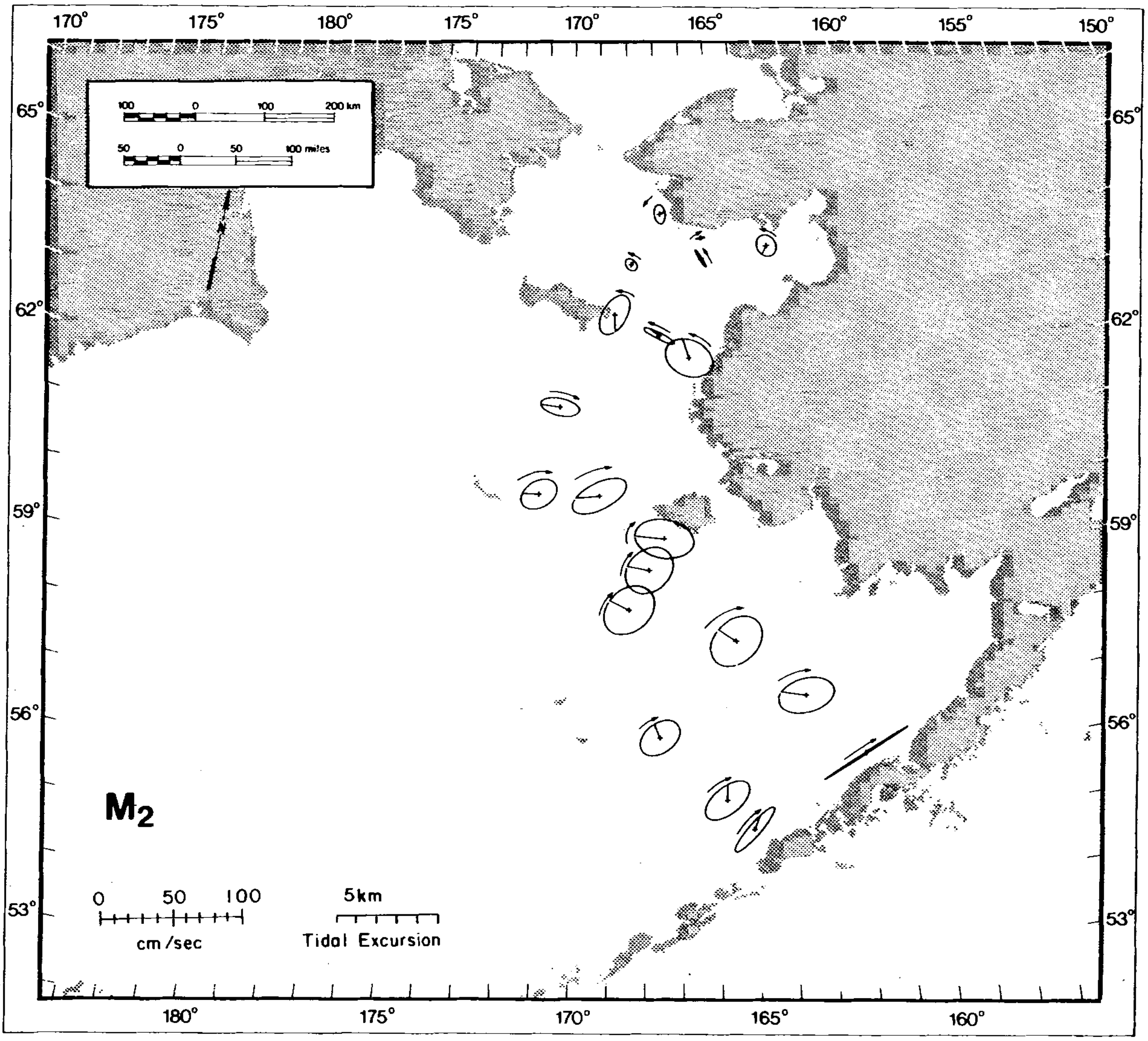

Figure 2.4. Tidal current ellipses for the M_2 and K_1 constituents (from Pearson et al., 1980).

Table 2.3), they are approximately the same density. As noted by Coachman and Charnell (1977, 1979), this juxtaposition of water types, under the influence of a pressure gradient, will result in interleaving of waters: the large-scale exchange is in the form of an intrusion of slope waters cross-shelf in a bottom layer and a seaward movement of middle shelf water at mid-depths. The seaward midlayer movement is in the form of interleaving sheets and layers at fine-structure scales (1-10 m thick).

The estimated fluxes (Fig. 2.9) required to maintain a nearly steady-state salinity distribution (given the extant freshwater flux) and recent current data (Coachman, 1980) imply convergent transport at the middle front between middle and outer shelf domains. The result is that over the region (50-75 km wide) of a little steeper bottom slope, centered near the 100-m isobath, enhanced horizontal gradients (the middle front) are generated by convergence. The salt flux model assumed no horizontal flux in the upper layer over the outer shelf and, considering the observed weak vector current motion, was consistent with numerous observations indicating a region of less saline (≥ 32.0 g/kg) water in the vicinity of the middle front. Over the middle front and across the middle shelf domain, fluxes into the surface layer are reduced during stratification. Hence, the surface layer here is last to regain salt to raise the salinities reduced by ice melt.

At the southeastern portion of the outer shelf domain, in the vicinity of Unimak Pass, both horizontal and vertical salinity gradients (Fig. 2.10) are stronger than those observed elsewhere. It is likely that this resulted from the flow of less saline (< 31.5 g/kg) water from the Gulf of Alaska into this region.

St. George Island lies at the northwestern corner of the outer shelf domain. The seafloor topography shoals less than 50 m rather abruptly around this island. Hydrographic data and satellite infrared imagery indicate transitions occurred

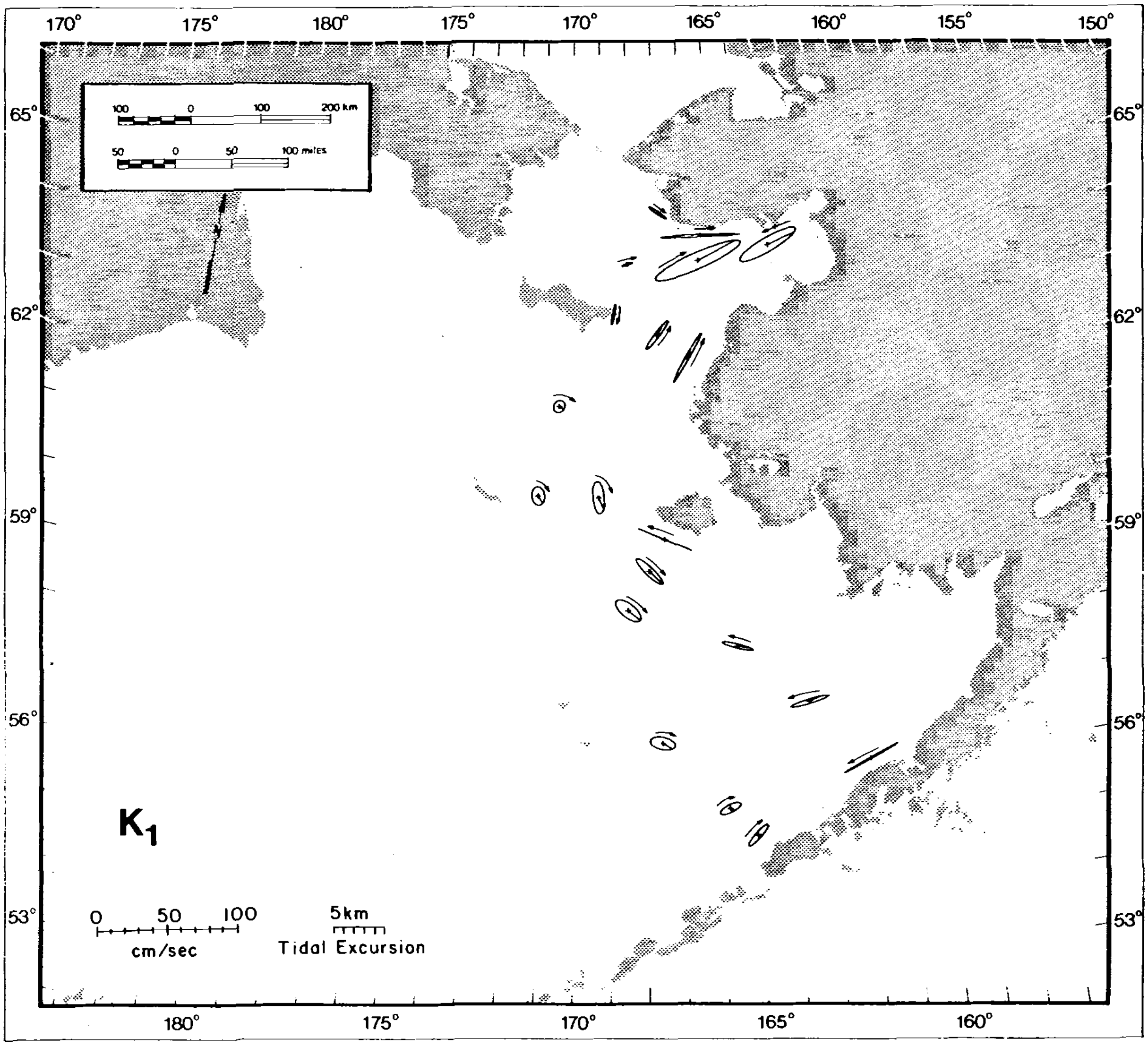

Figure 2.4. continued.

between two-layered and well-mixed water separated by a structural or inner front (Schumacher et al., 1979). However, stratified water was found within 10 km of St. George; the inner front appears more diffuse and ill-defined here when compared to St. Paul or the vicinity of Nunivak Island. Satellite images show that the inner front does not always encompass the island.

Methane is another constituent of St. George Basin waters which was measured and used to elucidate transport processes (Cline, 1981). The concentration of methane in the bottom mixed layer was elevated with respect to background levels (Fig. 2.11). The highest concentration observed was 2,500 n ℓ/ℓ. Plume configuration shows a northwest-southeast orientation, which may be the result of anisotropic mixing or an elongated methane source. Although it is difficult to be precise, the plume structure appears to originate from a localized source in the seafloor. If it is a gas seep, the methane appears to be of biological origin because of its compositional characteristics, that is, near absence of C_2+ hydrocarbons. Later in this chapter, we will describe the methane plume in terms of a two-dimensional diffusion/advection model.

Observations were also conducted in February 1981, and the near-bottom methane plume (Fig. 2.12) was quite similar to the distribution observed in August 1980. Again it appears that methane arises from a point source or possibly a short-line source and disperses along an axis parallel to the isobaths. Maximum concentrations of methane observed were near 1,500 n ℓ/ℓ, or aproximately half the value observed in August.

2.2.3 Marine Climatology

The Bering Sea is affected by arctic, continental, and maritime air masses. In summer the entire region is normally under the influence of maritime air from the Pacific. The southern portion of the Bering Sea is most frequently under the influence of maritime air, except during

Table 2.2 Tidal current statistics.

									O^1					K^1					N^2					M^2				
									major			min		major			min		major			min		major			min	
							Yr	JD	H	G	D	H	R	H	G	D	H	R	H	G	D	H	R	H	G	D	H	R
BC3	114	20	55	02	165	10	76	150	7.9	245	52	1.7	C	9.8	279	57	1.0	C	6.5	26	37	1.8	C	26.4	71	38	7.6	C
BC3	114	100	55	02	165	10	76	150	7.8	265	52	1.2	C	10.4	281	48	2.1	C	4.9	11	50	0.6	C	21.0	61	47	4.4	C
BC13B	115	100	55	30	165	49	76	158	5.6	272	71	2.2	C	8.0	289	68	2.8	C	5.3	3	50	2.2	C	18.9	67	54	9.6	C
BC17	104	96	56	34	167	34	76	266	6.5	312	109	1.8	C	9.1	326	105	4.3	C	6.4	27	61	4.0	C	15.9	81	53	10.5	C
BC4	51	30	58	37	168	14	75	251	7.4	330	140	3.1	C	11.7	350	133	6.2	C	9.6	45	49	7.2	C	27.3	118	50	22.2	C
BC4	51	47	58	37	168	14	75	251	7.3	331	128	2.6	C	10.9	0	131	4.8	C	4.9	28	46	3.3	C	20.2	107	51	15.1	C
BC9	41	33	59	12	167	43	77	133	8.5	332	130	0.9	C	13.0	359	134	2.8	C	7.0	60	47	5.1	C	18.7	120	51	14.6	C
BC18	31	20	59	40	167	07	77	132	12.7	333	113	0.6	A	20.5	356	116	0.1	A	6.3	130	109	4.8	C	21.2	186	103	13.8	C
BC16	50	37	57	59	165	16	77	123	7.7	308	102	1.3	A	11.4	328	108	1.5	A	6.8	69	69	5.8	C	20.8	101	52	15.1	C
BC2	65	50	57	04	163	22	75	310	8.6	292	77	1.1	A	14.1	309	81	1.6	A	5.9	76	81	2.9	C	20.4	145	80	12.1	C

[1] Amplitudes H are cm/s, phases G are referred to Greenwich, and direction D of major axis is compass degrees. C refers to clockwise rotation, A to anticlockwise. To obtain phase and direction of minor axis, add 90° to major axis direction; then add 90° to major axis phase if rotation is clockwise, or subtract 90° if anticlockwise.

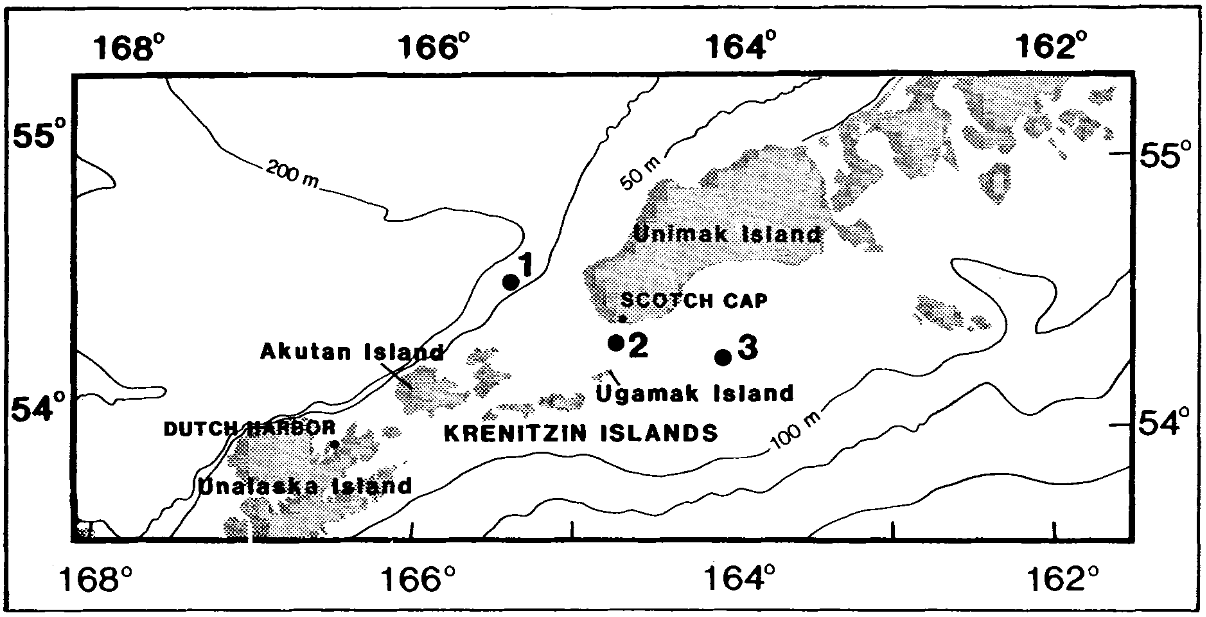

Figure 2.5. Location of current and pressure gauge moorings 1, 2, and 3 in Unimak Pass.

January and February (Grubbs and McCollum, 1968), when normally a strong flow of air from the north and east brings in continental and arctic air. For the remainder of the year, the movement of low-pressure centers and associated winds dominate the atmospheric circulation.

A major influence of the general atmospheric circulation in the area is the region of low pressure normally located in the vicinity of the Aleutian chain, referred to as the Aleutian Low. On monthly mean-pressure charts, this appears as a low-pressure cell normally oriented with the major axis in an east-west direction. This is a statistical low, indicating only that pressures are generally lower along the major axis as a result of the passage of low-pressure centers or storms. Storms are most frequent in this area and are more intense there than in adjacent regions. The most frequent track or trajectory of movement of these storms is along the Aleutian Islands and into the Gulf of Alaska in winter, and along the same general path in the west but curving northward into the Bering Sea in summer (Overland, 1981). The monthly frequency of low-pressure centers in the southern Bering Sea is slightly higher in winter (generally four to five) than in summer (three to four). However, winter storms are much more intense.

In winter, the most frequent airflow is northeasterly around the northern side of the low-pressure cell present at some location along the Aleutian chain. In summer, with the movement of lows into the Bering Sea, a more southwesterly mean flow develops over the lower two-thirds of the region. Climatology of the southern Bering Sea is characterized by a progression of storms rather than fixed weather types (Overland, 1981). These storms produce increased cloudiness, reduced diurnal temperature range, and winds that rotate through the compass. During the summer in the southern Bering Sea, frontal activity can be severe as very cold arctic or continental air comes in contact with the warm air from the Pacific Ocean, forming a sharp discontinuity and localized winds.

2.2.4 Ice

The climate of the Bering Sea is strongly related to the presence and movement of marginal sea ice (Overland, 1981). In October and November, ice forms in situ along the coasts in the northern part of the Bering Sea. Under the influence of predominantly northeasterly winds, this ice is driven toward the southwest creating polynyas along the southern side of Seward Peninsula and St. Lawrence Island. These coastal polynyas act as production sites for new ice during most of the winter (Muench and Ahlnäs, 1976; McNutt, 1981). The leading floes along the edge of the pack ice are advected into water that is warmer than the freezing point, and the floes melt. This melt water combines with the large, sensible heat flux from the ocean caused by the cold off-ice winds to cool the ocean so that the pack may advance. Thus, as noted by Pease (1980), in midwinter movement characteristics of the ice can be described as a kind of conveyor belt: ice grows primarily in the north, is advected by wind stress generally southward, and decays at the southern thermodynamic limit. The ice may replace itself two to five times during a winter season by this mechanism, which represents a substantial latitudinal heat flux. Advection of sea ice by currents is of secondary importance, as tidal currents dominate the horizontal kinetic energy on the continental shelf and vector mean

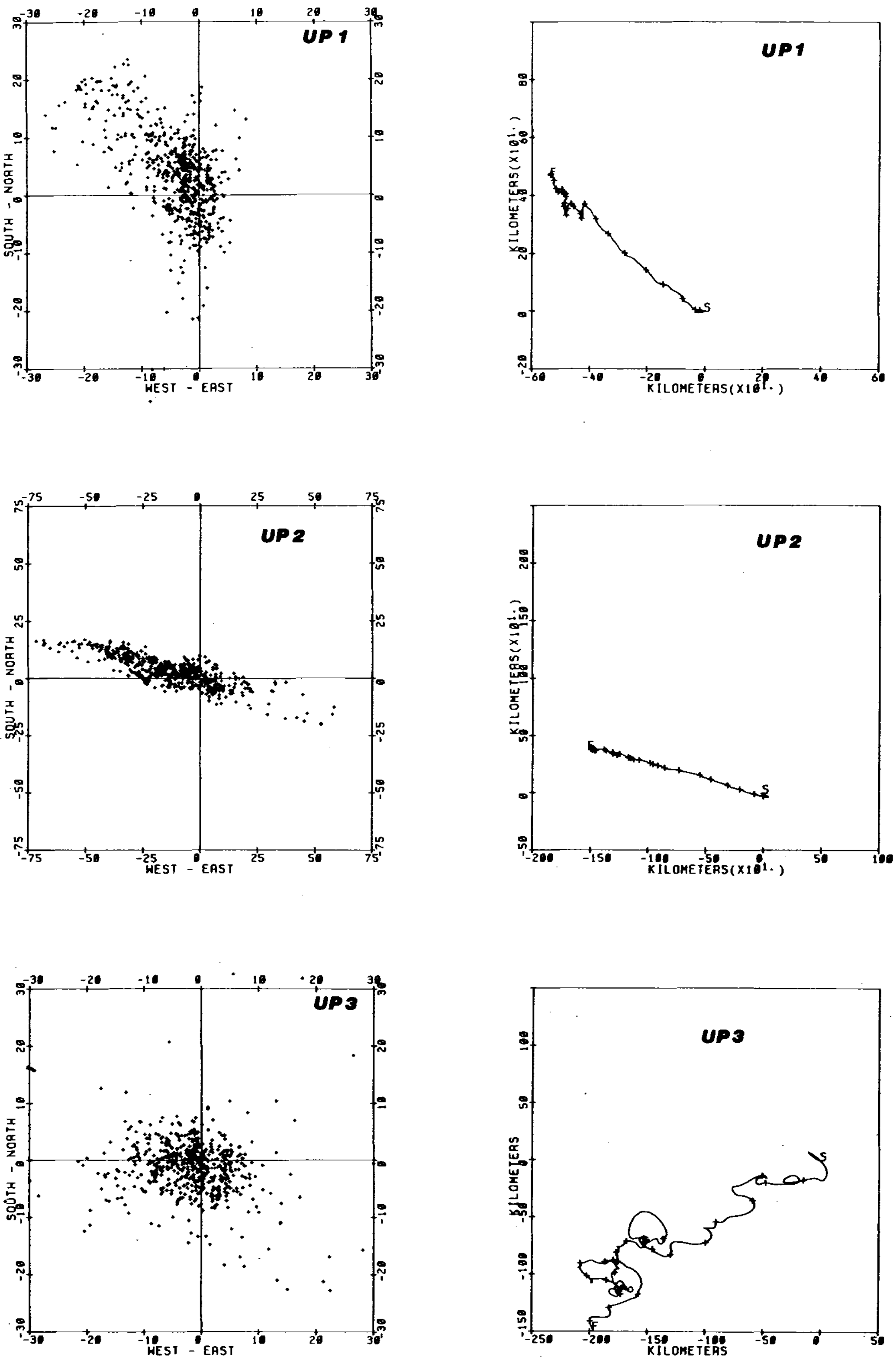

Figure 2.6. Current records from the Unimak Pass study shown as scatter diagrams (crosses represent the end of a current vector) and progressive vector diagrams (crosses at 5-d intervals). Note: tidal currents were removed by filtering.

flow is 1-5 cm/s toward the north or northwest. In a year of heavy ice, the pack will reach St. Paul Island and beyond, whereas in a light ice year, the pack may reach only beyond St. Matthew and Nunivak Islands (Webster, 1979). Maximum extent occurs between mid-February and late March (Dunbar, 1967). At approximately the time of the vernal equinox, the radiation balance at the surface of the ice changes so that the ice melts over most of the basin even under continued northeasterly winds. Increased southerly to southeasterly winds also contribute to spring decay. Sea ice is absent by the end of June.

Although many of the individual features of the dynamics and thermodynamics of Bering Sea ice have been explored, the relation between in-

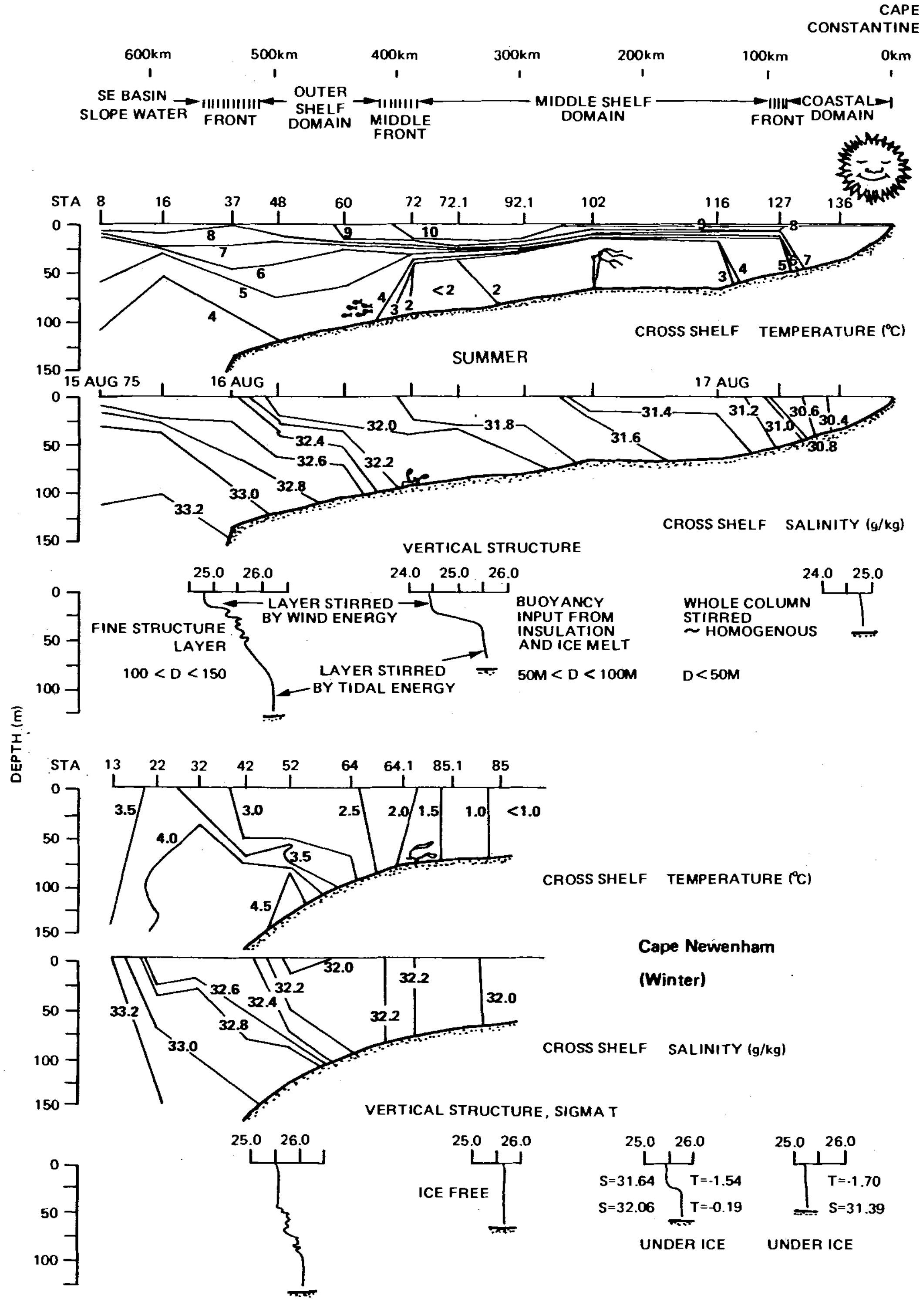

Figure 2.7. Hydrographic characteristics of southeast Bering Sea shelf waters.

terannual variations in sea ice extent and atmospheric forcing has only recently been discussed in detail (Overland and Pease, 1981). Rapid ice advance with northeasterly winds generally occurs during episodes when arctic high pressure dominates the northern Bering Sea. The ice advance is interrupted by penetration of cyclone activity into the Bering Sea bringing warm, moist, oceanic air masses with southerly winds. Overland and Pease noted that the frequency of cyclones and of westerly tracks of cyclones reduced the total duration of northeasterly winds during an ice growth season and determined the overall ice maximum extent in any given year. Using 25 years of observations, these authors presented the range of the five heaviest and five lightest ice

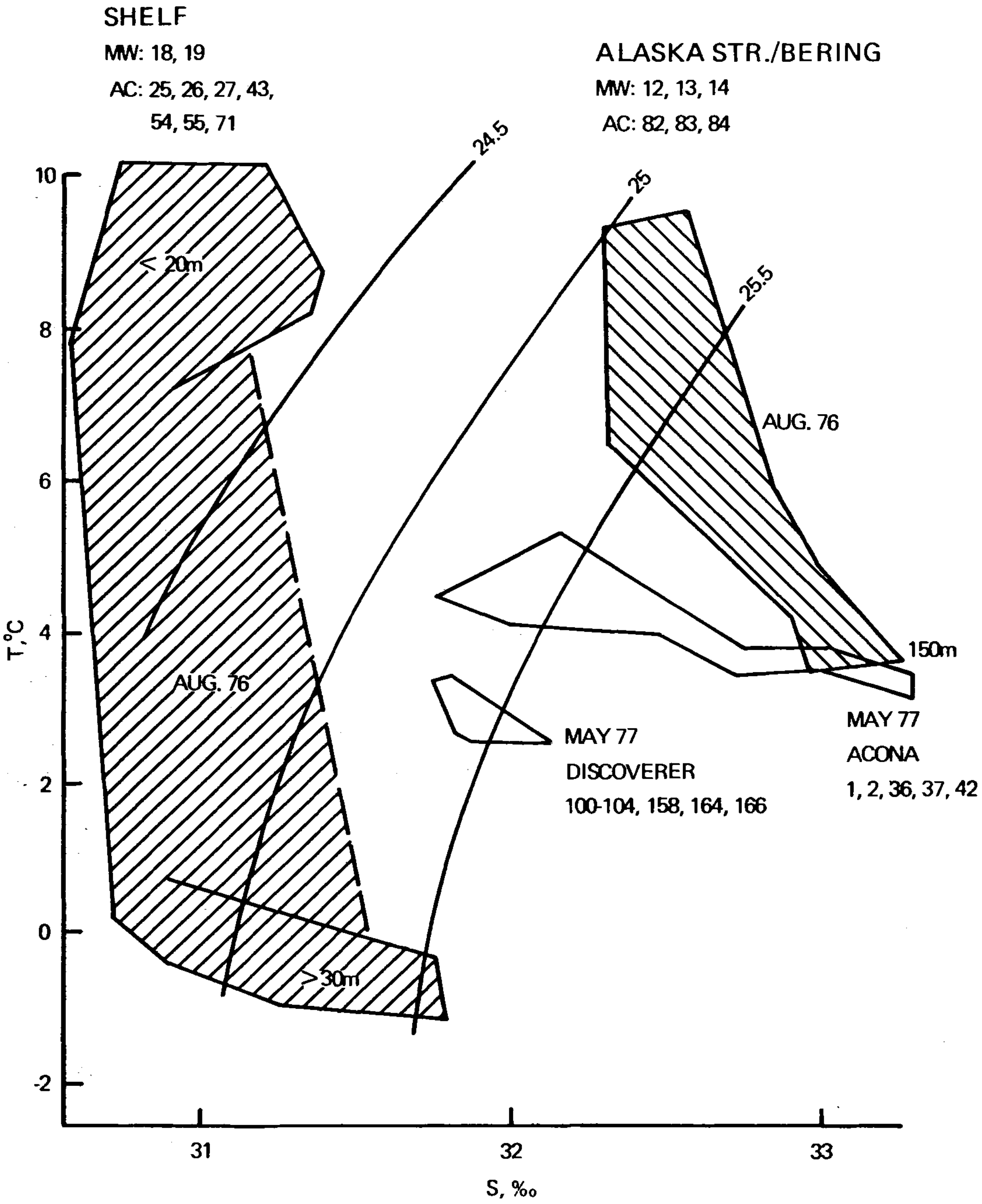

Figure 2.8. Temperature-salinity correlations, middle domain (SHELF) and oceanic domain (ALASKA STR./BERING). Envelopes drawn from data gathered in August 1976 and May 1977 illustrate the warmer and saltier oceanic water at the same density as the cooler and fresher shelf water, and interleaving occurs across the outer domain (From Coachman and Charnell, 1979).

years (Fig. 2.13). The interannual variation in the extent of sea ice is very large. During heavy ice years, the St. George Basin will be partially (50-80 percent) covered with ice; however, since 1975 there has been only one heavy ice year.

2.3 FATE OF OIL AND DRILLING MUDS

2.3.1 Weathering of Oil

Compositions of crude oils vary extensively and depend upon the original organic material from which the petroleum was derived and the diagenetic conditions under which it has matured. All crude oils have certain common chemical components, however; these have been classified in detail by Clark and Brown (1977). The hydrocarbons are classified as paraffinic and naphthenic for the saturated straight-chain and cyclic compounds, respectively. Aromatic hydrocarbons are also prominent and extremely varied, although they generally constitute lesser overall compound composition percentages when compared to the aliphatic compounds. In general, alkyl-substituted aromatic compounds predominate over the parent nonsubstituted aromatic structures. A wide variety of nitrogen-, sulfur-, and oxygen-substituted (NSO) com-

Table 2.3. Hydrographic characteristics of middle and outer shelf water.

	Middle	Outer
Vertical structure	**summer:** usually two-layered with the upper layer 10 to 30 m thick, but can be stirred to the bottom by storms **winter:** well mixed when ice is not present but two-layered under ice cover	surface mixed layer (40-50 m in winter, 10-30 m in summer); stratified interior; bottom mixed layer (10-30 m thick)
Depth	50 ≤ depth ≤ 100 m thickness of surface + bottom mixed layers	≥ 100 m, greater than surface + bottom mixed layers. Interior region contains finestructure.
Temperature[1]	**summer:**	
	upper layer: 8 to 11°C	7 to 10°C
	lower layer: −1 to 4°C	3 to 5°C
	winter: −1.5 to 3°	upper layer: 1 to 3°C lower layer: 3 to 5°C
Salinity	upper layer: 31.9-32.2 ‰	31.8-32.8 ‰
	lower layer: 32.0-32.4 ‰	32.5-33.5 ‰

---

[1] Note: The values presented represent maxima and minima, since winter 1975/76 was one of extreme ice cover while 1979/80 was a winter of minimal ice cover.

pounds occur in petroleum to lesser extents, and there also may be significant differences in trace metal content and subtle differences in specific aliphatic and aromatic compound content.

The following parameters of a given oil will affect its fate in the environment: (1) flash point, (2) vapor pressure (volatility), (3) component solubility, (4) specific gravity, and (5) viscosity (as it relates to pour point).

The flash point and volatility of petroleum and refined products are closely related. Table 2.3 shows the flash points for various pure components present to varying degrees in crude petroleum and refined products. The concentrations of these materials and the rates of their concomitant evaporation and dissolution from spilled oil will affect their ability to sustain a flame over water when spilled at sea. Generally, spilled oil itself will not sustain a flame for extended periods (Mackay, 1981), due to rapid dissipation of heat and the relatively rapid loss of the more flammable lower molecular weight components by evaporation and dissolution. In the IXTOC-I spill in the Gulf of Mexico the fire was confined primarily to the methane gas plume released from the subsurface blowout. During the *Burmah Agate* incident, the flames were generally restricted to the immediate vicinity of the broken vessel (Kana et al., 1981); however, some drifting patches of burning oil were observed. The duration of the burn on drifting oil patches was short when compared to the two months that the vessel and cargo continued to burn out of control (Kana et al., 1981). In both cases, the sustained burn

Table 2.4 Flash points[1] and physical properties of pure components common to Prudhoe Bay and Cook Inlet crude oils.

Compound	Molecular weight	Boiling point (°C)	Specific gravity	Flash point (°C)
Propane	44	− 42	0.53	−104
Butane	58	0	0.60	− 60
Cyclopentane	70	49	0.74	− 37
Methylbutane	72	28	0.62	− 57
Pentane	72	3	0.63	− 49
Cyclohexane	84	81	0.78	− 19
2-Methylpentane	86	60	0.66	− 23
Benzene	78	80	0.88	− 11
Hexane	86	69	0.66	− 23
Methylcyclohexane	98	101	0.77	− 4
Toluene	92	111	0.87	4
Heptane	100	98	0.68	− 4
Isooctane	114	99	0.69	− 12
Xylene	116	139	0.86	32
Nonane	128	151	0.72	30

---

[1] Temperature at which a liquid gives off a vapor sufficient to form an ignitable mixture with air near the surface of the liquid.

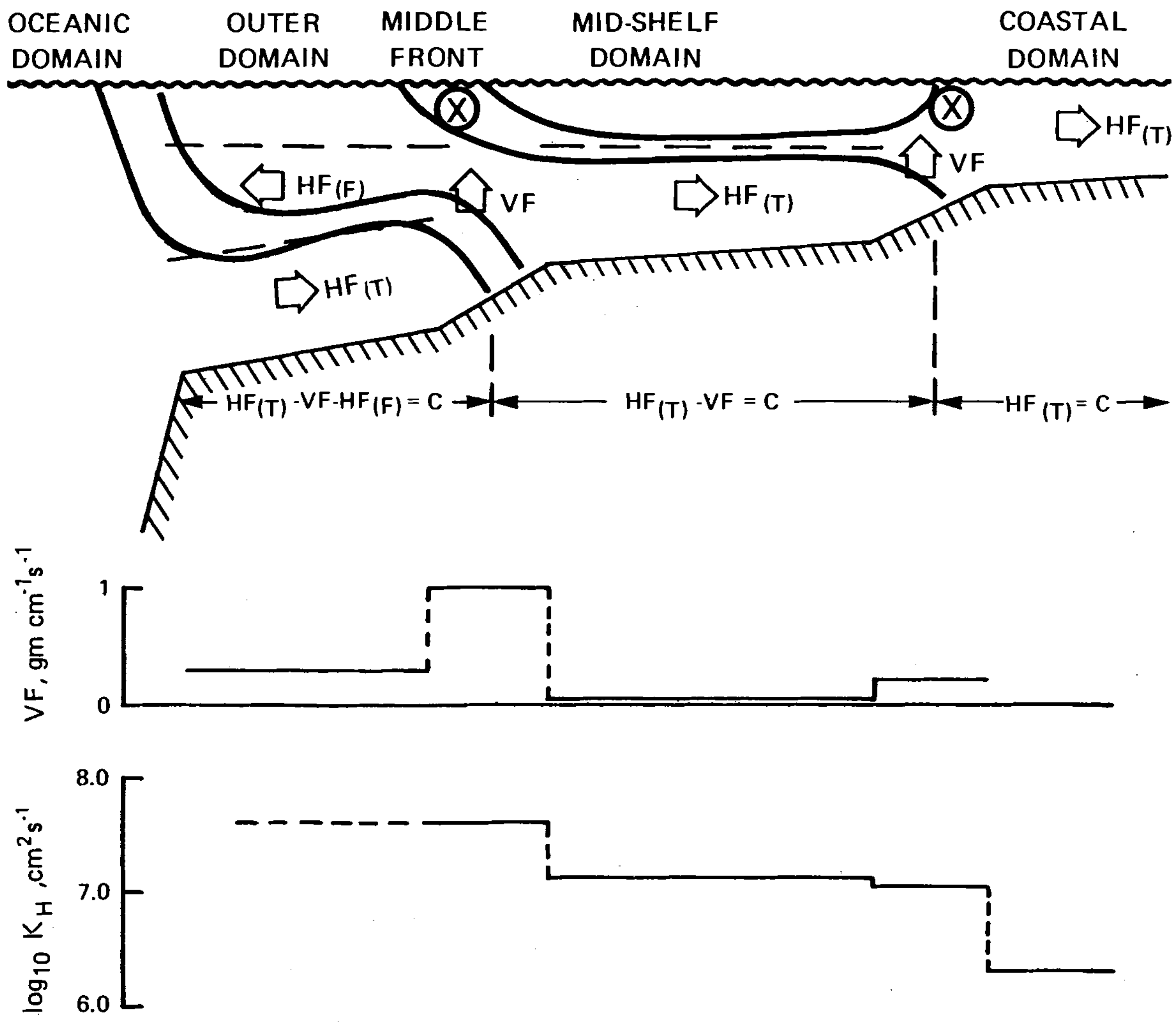

Figure 2.9. Schematic diagram of the salt balance hypothesis. Values of vertical flux and horizontal eddy coefficient for the tidal-diffusive layer for a constant salt flux of 1 g/cm/s are shown beneath in relation to their cross-shelf position (from Coachman et al., 1980). Crosses represent baroclinic flow into the page.

from the wellhead or the oil spilling from the tanker was maintained by the presence of high concentrations of volatile components and sufficient oxygen to sustain a flame.

Several investigators have indicated that evaporation will quickly remove most of the volatile components from oil spilled on the sea surface (McAuliffe, 1977), and Mackay (1981) has suggested that as much as 25 percent of a spill may be removed by evaporation in the first two to five days. This loss is generally believed to be restricted to compounds with boiling points below 200°C. Clearly, a wide variety of components ranging from propane to nonane are rapidly lost; Fig. 2.14 shows the time-dependent 14-h decreases in some components in the air above a test spill in an evaporation/dissolution chamber, as measured by gas chromatographic analyses of the heat desorbed components trapped on Tenax columns.

Removal of lower molecular weight materials from the slick is not limited to evaporation. Dissolution occurs simultaneously, and Fig. 2.15 shows the increase in concentration of several volatile components in the water column under the slick as a function of time. Generally there is a rapid buildup to an equilibrium concentration limited by the mixed-phase component solubilities and the mole fraction of components initially in the oil. After this equilibrium condition is reached, an exponential decrease in water column concentration due to evaporative loss through the air/sea interface is observed. Components with higher molecular weights, such as naphthalene and 1- and 2-methylnaphthalene, are not lost as rapidly from the water column, which reflects their moderate solubilities and lower vapor pressures. These compounds have relatively long residence times (on the order of days) in the water beneath the slick.

While the measured airborne and water column concentrations of lower-molecular-weight aliphatic and aromatic compounds suggest their rapid removal from the slick, concomitant meas-

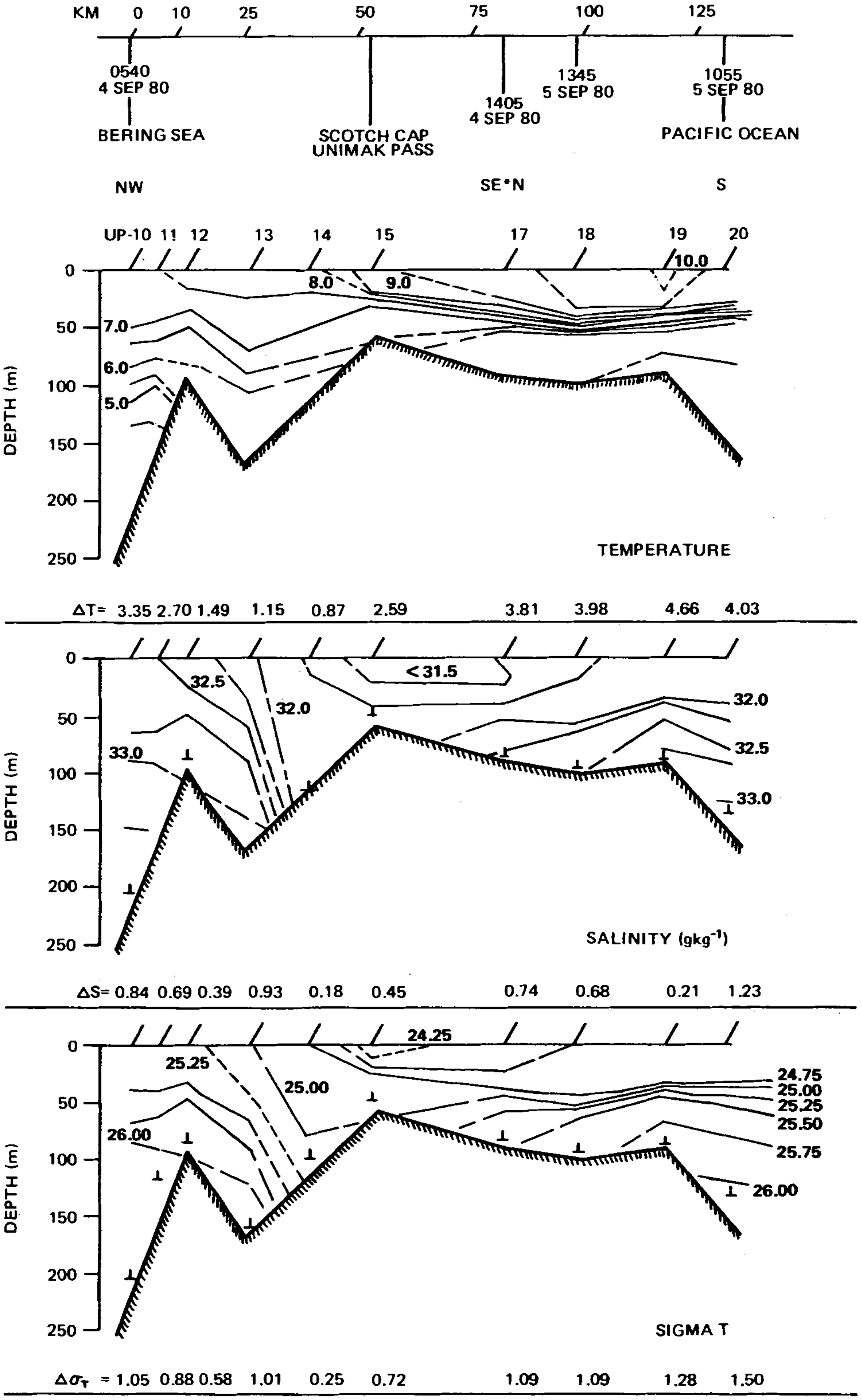

Figure 2.10. Temperature, salinity, and sigma-t sections through Unimak Pass, September 1980.

urements of many of these components in the oil itself showed significantly longer residence times. Presumably, this reflects diffusion of these compounds out of the bulk oil after initial weathering has caused skin formation. Increased viscosities and densities limit mass transport through the oil itself (Kirstein, 1981). Recent laboratory studies by Payne (1981) elucidate losses of aromatics of intermediate molecular weight ranging from trimethylbenzene to 2-methylpenanthrene (KOVAT index 990 to KOVAT index 1887) from the oil slick itself as a function of time. His data showed a rapid loss of the lower-molecular-weight alkyl-substituted ben-

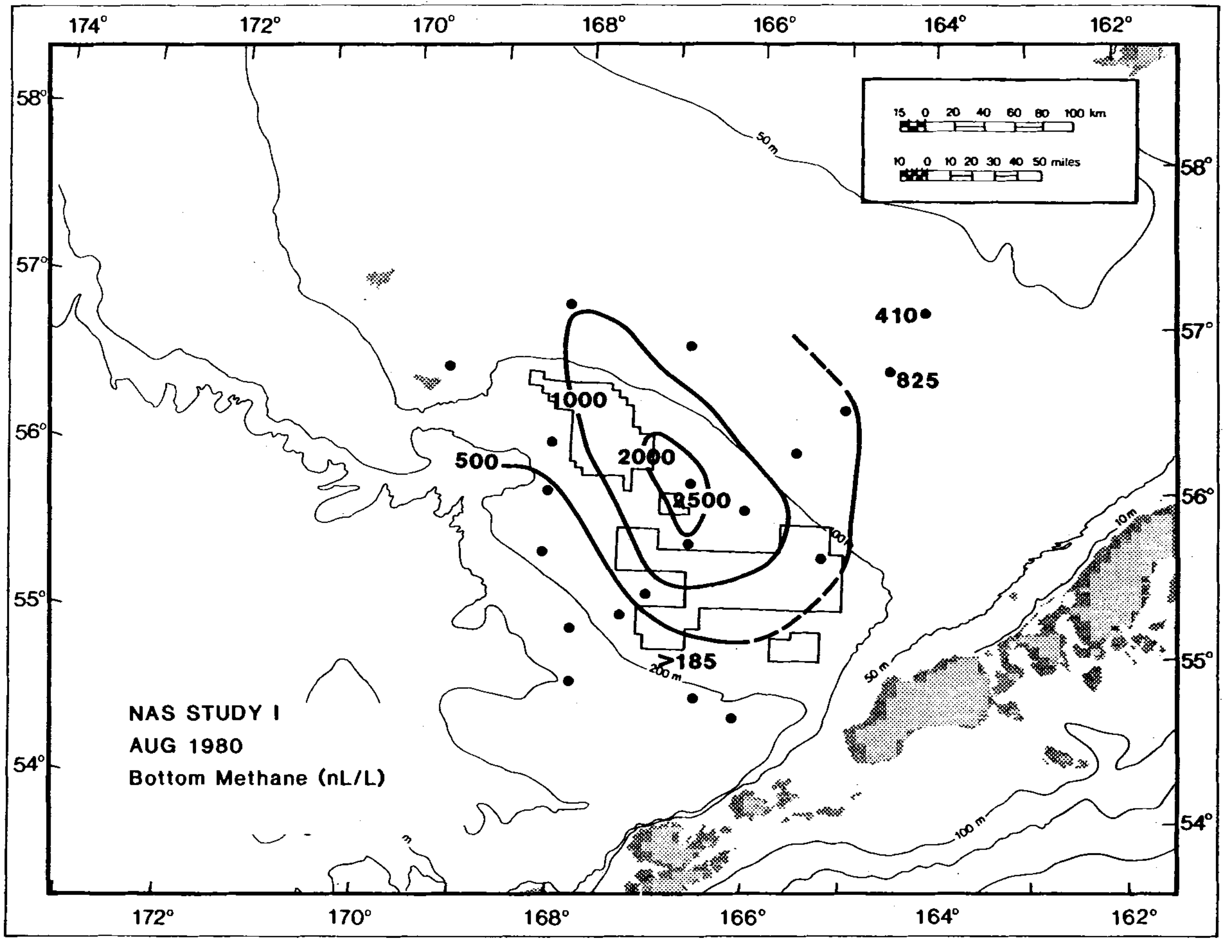

Figure 2.11. Near-bottom (bottom-5 m) distribution of methane in St. George Basin, August 1980.

zenes, with nondetectable levels of trimethylbenzene being reached after 30 h. Naphthalene showed an exponential decrease from 600 μg/ℓ initially in the oil to nondetectable levels after 70 h. Interestingly, 2-methylnaphthalene was detected in the surface oil at significant concentrations up to 220 h as were 1-methylnaphthalene and 2-methylnaphthalene. This latter compound was detected for up to 320 h. These longer-lived concentrations of semivolatile materials may reflect the diffusion-controlled loss of these components from the slick. Compounds with higher molecular weights (such as 1,1-methyl-bis-benzene, 4-methyl-dibenzothiophene, dibenzothiophene, phenanthrene, and 2-methylphenanthrene) were not significantly lost from the slick due to either dissolution or evaporation. In fact, the relative oil-phase concentrations of dibenzothiophene, phenanthrene and 2-methylphenanthrene appear to increase about 300-450 h following the spill due to the removal of the more volatile and water-soluble lower-molecular-weight components. Since these materials are retained in spilled oil undergoing weathering at 19°C, their continued presence in oil undergoing weathering in subarctic conditions can also be expected. In this case, lower temperatures would lead to increased viscosities resulting in extensive diffusion control limiting the loss of these compounds. Experiments are under way at this time to determine rates of loss due to evaporation and dissolution of these components from Prudhoe Bay crude oil at 3° and 13°C.

While evaporation has been reported to predominate over dissolution in surface spills (McAuliffe, 1977; Mackay, 1981), the relative importance of evaporation and dissolution depends on the position of oil release (Payne et al., 1980a). When subsurface blowouts occur in the open ocean, dissolution competes very effectively with evaporation for the more water-soluble aromatic components (Payne et al., 1980a). Fig. 2.16 shows the relative concentrations of aliphatic and aromatic hydrocarbons in the water column and the air immediately above the slick measured in a 38-km down-plume (downwind) transect from the IXTOC-I blowout in the Bay of Campeche. Elevated (up to 100 μg/ℓ) levels of benzene, toluene, and xylene occurred in the water column for a considerable distance. While aliphatic compounds with similar vapor pressures but lower water solubilities predominate in the air

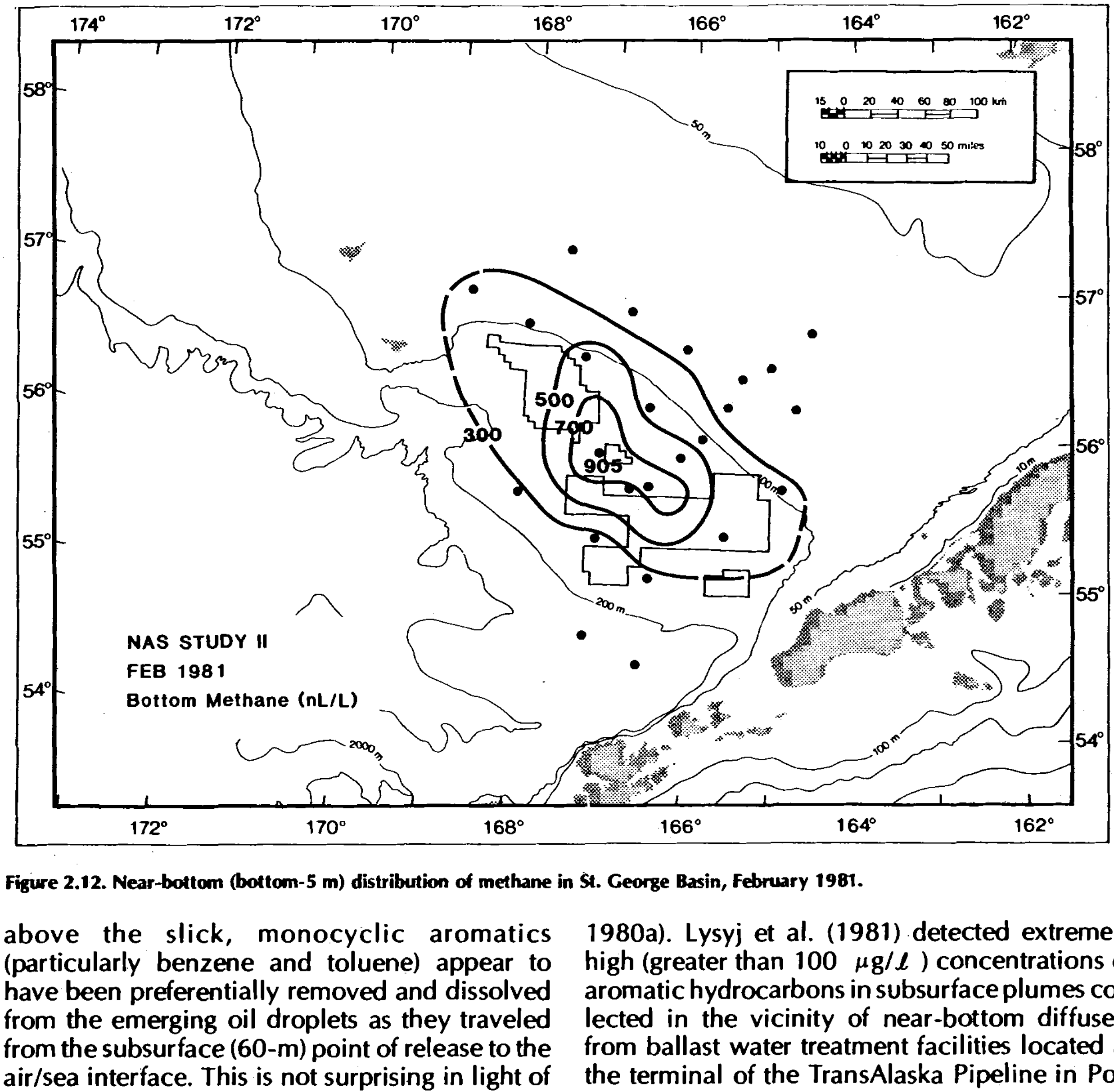

Figure 2.12. Near-bottom (bottom-5 m) distribution of methane in St. George Basin, February 1981.

above the slick, monocyclic aromatics (particularly benzene and toluene) appear to have been preferentially removed and dissolved from the emerging oil droplets as they traveled from the subsurface (60-m) point of release to the air/sea interface. This is not surprising in light of their solubilities in water which are several orders of magnitude higher than those of straight-chain and cyclic aliphatic hydrocarbons with similar molecular weights and vapor pressures (Sutton and Calder, 1975; Clark and MacLeod, 1977; and Wheeler, 1978).

Thus, while laboratory test-tank data showed a loss of aromatics from the water column after reaching maximum concentration values, subsurface advection of water containing dissolved aromatics could prevent their loss due to evaporation for considerable periods. If subsurface advection of aromatic enriched waters occurs under stratified water-column conditions, removal of the more toxic aromatic components from the water column would be limited to mixing and diffusion. High levels of aromatic hydrocarbons, presumably from the IXTOC-I blowout, were found in subsurface Gulf of Mexico water at 25-28°C where evaporative loss would be expected to be high (Payne et al., 1980a). Lysyj et al. (1981) detected extremely high (greater than 100 $\mu g/\ell$) concentrations of aromatic hydrocarbons in subsurface plumes collected in the vicinity of near-bottom diffusers from ballast water treatment facilities located at the terminal of the TransAlaska Pipeline in Port Valdez, Alaska.

The specific gravity or density of spilled oil will directly affect its buoyancy and ability to form oil-in-water dispersions. As a result of time-dependent density increases from differential weathering, causing removal of the more volatile and water-soluble components, surface spilled oil can form significant oil-in-water dispersions in surface released oil (Raj, 1977; Stoltzenback et al., 1977). Oil-in-water dispersions can also occur readily in subsurface oil blowouts. In this instance, vigorous mixing due to the release of gas bubbles, often exceeding 100 times the oil volume (Mackay, 1981), can result in the formation of very fine oil droplet. Boehm and Fiest (1980) reported subsurface plumes of dissolved and particulate oil up to 25 km from the IXTOC-I wellhead.

The viscosity and pour points of released oil are also affected by oil composition and weathering. Viscosity has been demonstrated to be signif-

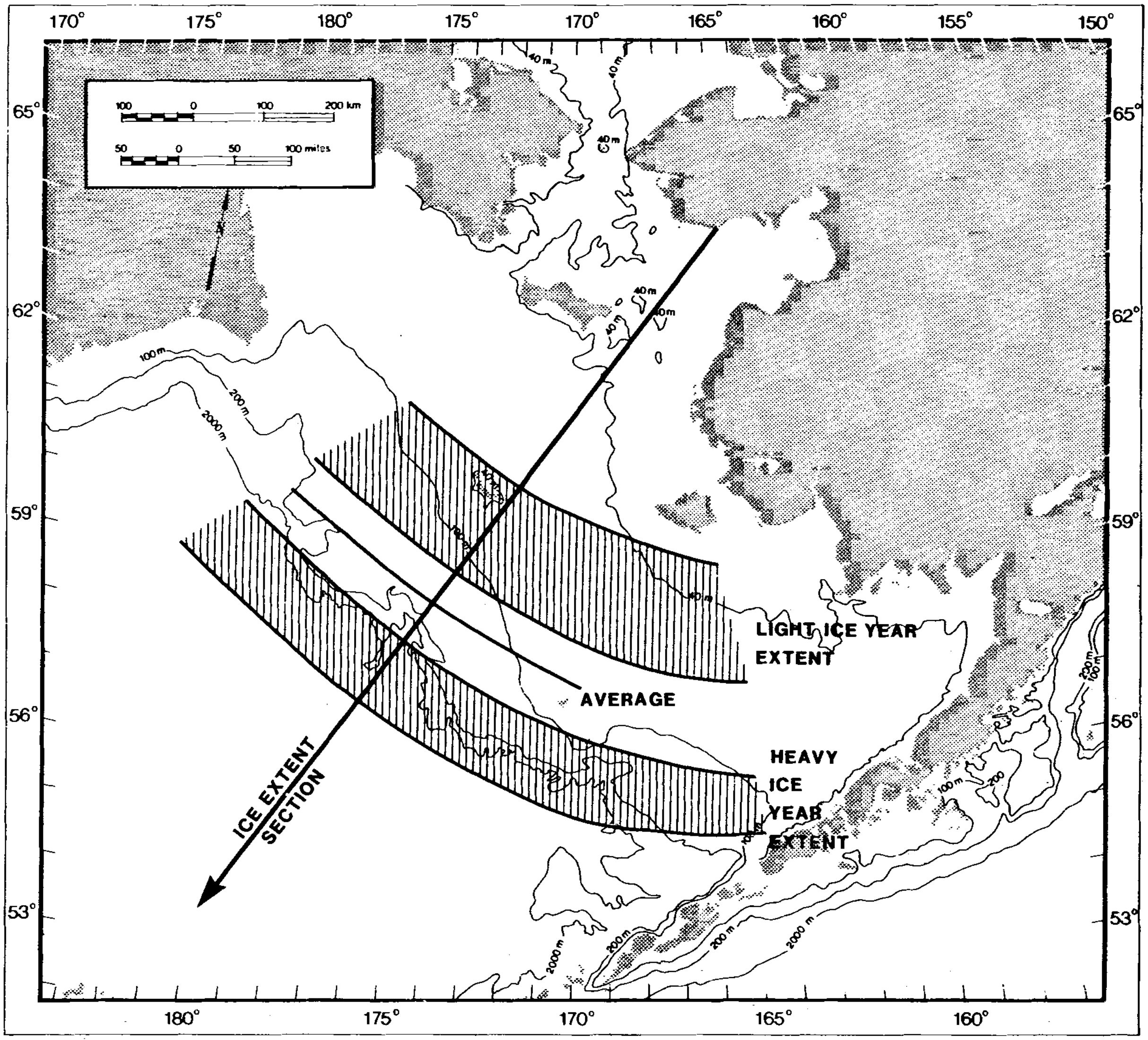

Figure 2.13. Section along which maximum ice extent was computed, and extrapolated zones of minimum and maximum ice extent for this quarter century relative to the section.

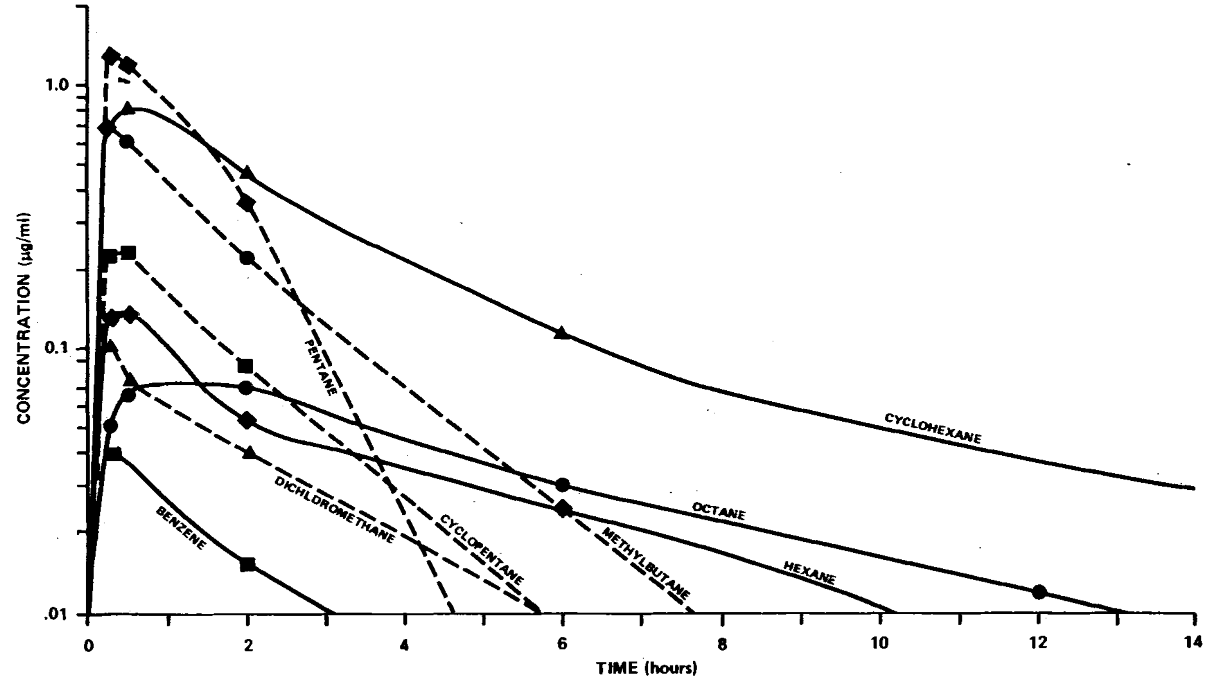

Figure 2.14. Atmosphere concentrations of Prudhoe Bay crude oil at 19°C under the influence of a 7-kn wind (from Payne, 1981).

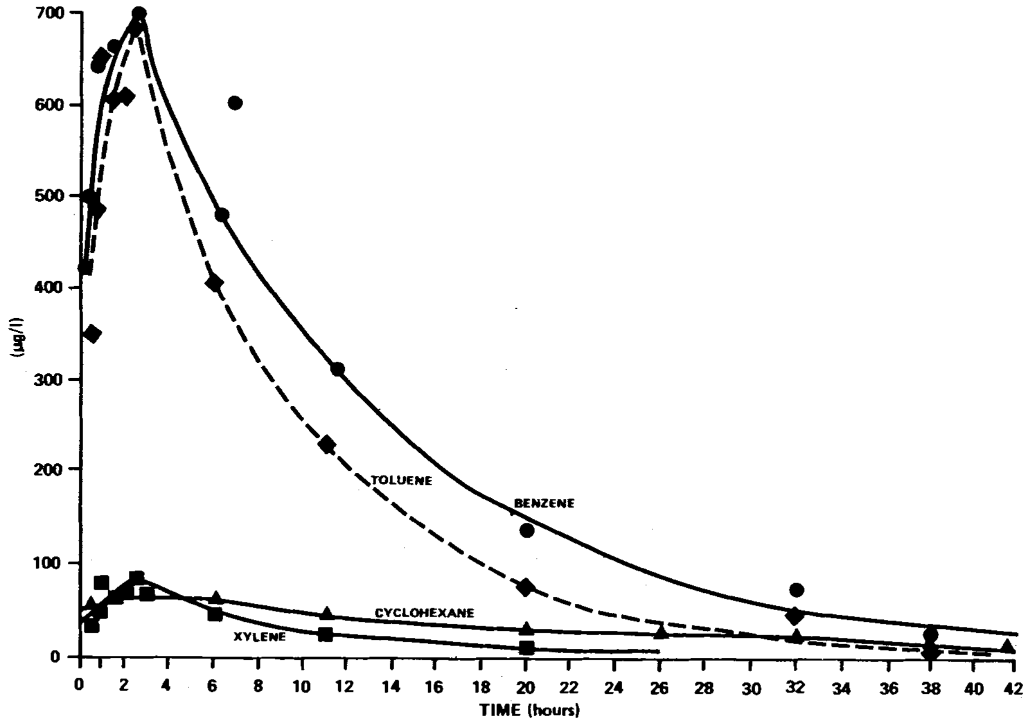

Figure 2.15. Time-dependent concentrations of volatile hydrocarbons in seawater after equilibration with Prudhoe Bay crude oil at 19°C (under a 7-kn wind). Volatiles measured by purge and trap FID gas chromatography (from Payne, 1981).

icantly higher in cold environments resulting in limited spreading and smaller slick areas. Allen and Nelson (1981), Rosenegger (1975), and Belicek and Overall (1976) noted that oil spills yield thicker slicks (on the order of several millimeters versus hundredths of millimeters) in arctic versus temperate environments. Viscosity alterations also occur as a result of water-in-oil emulsion (mousse) formation, and it has been demonstrated that mousse does not spread as effectively or flow beneath ice. In fact, oil viscosities generally go up by several orders of magnitude due to the formation of water-in-oil emulsions, and this significantly limits spreading even in warm environments (Payne et al., 1980b). In the IXTOC-I spill, large (20 m × 2-3 m) mousse logs occurred in windrows and along the edges of oceanic fronts. Similar oceanographic conditions may occur during the summer in the St. George Basin, and similar mousse formation might be expected. Once mousse logs are formed, further weathering is extremely limited. That is, oxidation products and water-soluble components are not lost due to extremely slow diffusion within the mousse itself. The data suggest that after mousse formation only limited further chemical alterations of the agglomerated oil occurs (Payne et al., 1980b; Atlas et al., 1980; Boehm and Fiest, 1980). In the IXTOC-I spill, the absence of significant microbial degradation was believed to be due to extremely limited nutrient concentrations and possibly due to elevated levels of dissolved and toxic aromatic hydrocarbons in the water column. In the subarctic environment of the St. George Basin, nutrient concentrations may be expected to vary seasonally; in general, microbial degradation has been shown to be slower in subarctic environments (Atlas, 1975; ZoBell, 1973).

Several other findings from the IXTOC-I blowout, as reported by Mackay et al. (1981) and Payne et al. (1980b), are important for predicting the effect of oil on the St. George Basin:

(1) Oil injected into the water column from the seabed blowout remained in the water column for long periods, the period presumably depending upon droplet size, buoyancy, and water-column hydrography. Subsurface plumes of oil extended up to 20 km from the wellhead.

(2) Filtered seawater collected from several depths in the water column (to 20 m) had a composition similar to the "water-soluble fractions" used by many researchers in evaluating acute and sublethal toxicities. This water was enriched in alkyl benzenes and naphthalenes. Concentrations of total aromatics in water from two m beneath the slick to 10 km from the wellhead in the Gulf of Mexico was 2.8 ppm, well into the toxic range for most sensitive species.

(3) Suspended particulate material samples were examined for adsorbed hydrocarbons, and it was found that the majority of higher-molecular-weight aliphatic fraction components were associated with the particulate load up to several kilometers

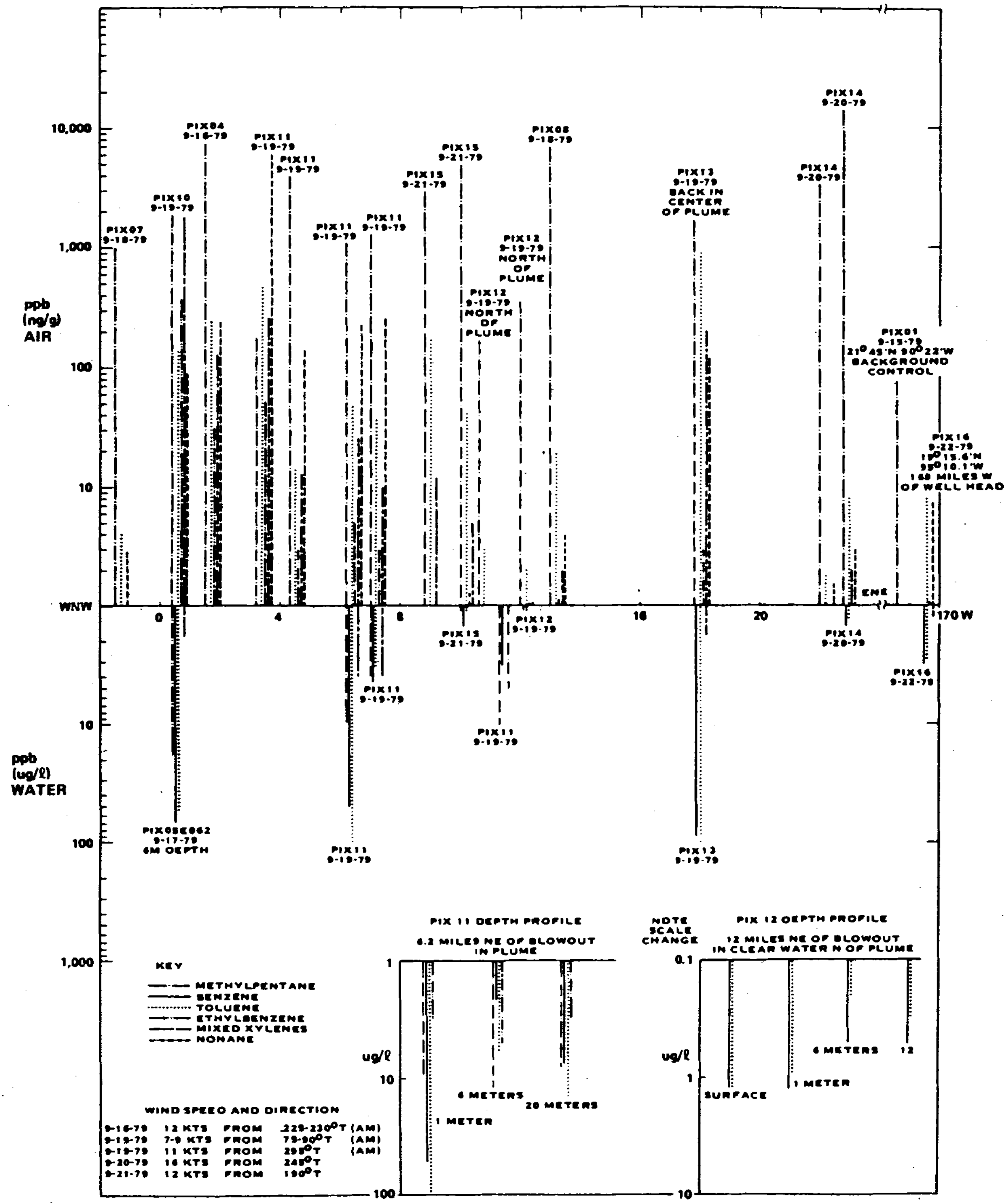

Figure 2.16. Display of the differential partitioning between evaporation and dissolution for selected volatile components along the G. W. Pierce down-plume transect. The horizontal axis represents distance from the wellhead in nautical miles (from Payne et al., 1980a).

from the slick. In general, the particulate-bound oil concentrations were one to two orders of magnitude higher than the dissolved-phase levels.

Observations on the extent of subsurface plumes and the concentration gradient of the water-soluble component at the IXTOC-I spill suggest that a continuous subsurface spill of about 30,000 bbl/d would affect about 100 km². (Note that the concentrations shown in Fig. 2.16 were observed about 100 d after the blowout began and, thus, represent a spill of about 30 million bbl.)

2.3.2 Drilling Muds and Cuttings

Two types of discharges occur: cuttings with mud which are discharged only during drilling and bulk discharges from storage tanks at the end of the exploratory drilling. During drilling, the mud discharge with cuttings usually ranges from

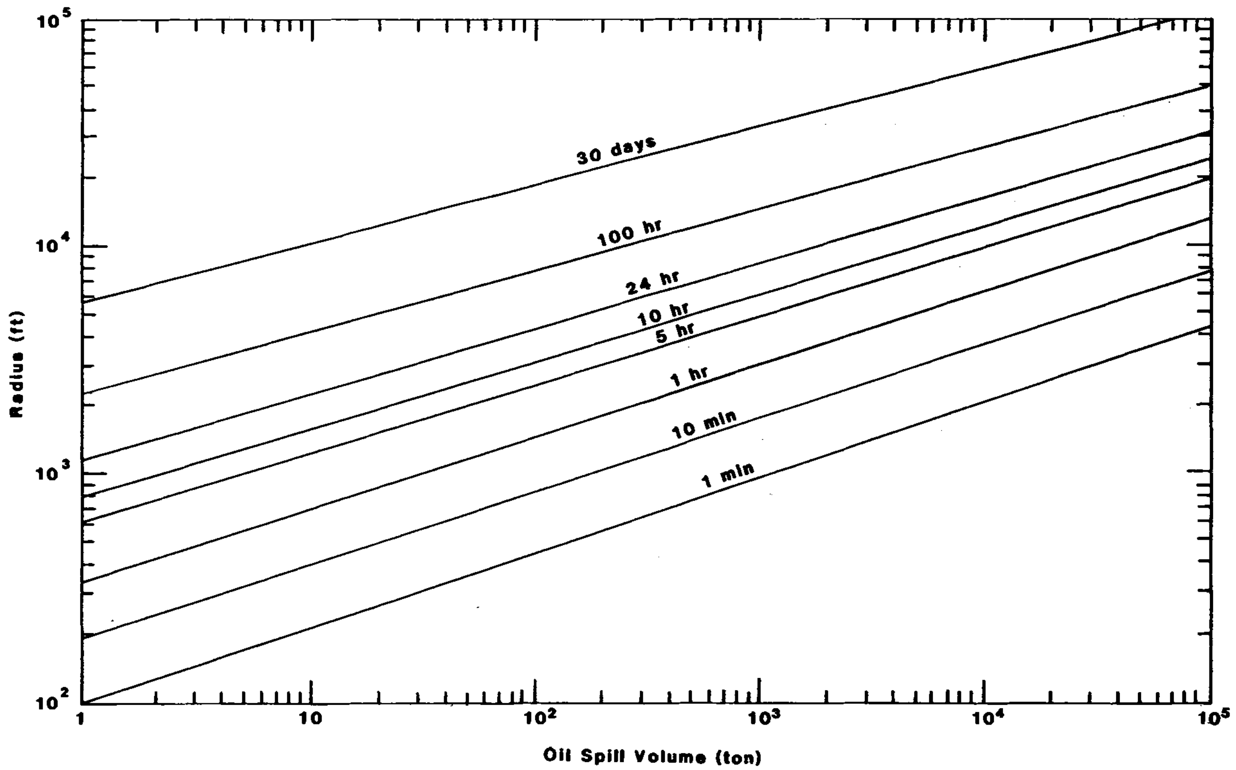

Figure 2.17. Estimated radius of oil spreading under calm summer conditions for various volumes and times after release (from Liu and Leendertse, 1981).

at 55.5°N, 166° Was either 50,000 bbl at once or as 5,000 bbl/d for 10 d.

2.4.1 Surface Oil Trajectories

The Rand Trajectory Model (RTM) comprises several sub-models including (1) a three-dimensional model of tides and circulation which incorporates field observations of bottom pressure, mass distribution, ice coverage and currents (Liu and Leendertse, 1979); (2) gravity-wave or Stokes' drift component which results in a surface drift speed of about 1.6 percent of the wind speed in the direction of wave propagation; (3) a model to predict dimensions of the spilled oil; and (4) a two-dimensional stochastic weather (wind) model to simulate the evolutary behavior of wind field changes according to Monte Carlo procedure using transitional matrix derived from nineteen year's weather data (from Putnins, 1966). For oil spill risk analyses, a stochastic weather model (as opposed to a deterministic one) was necessary. It provides the essential statistical parameters in the subsequent computation of the conditional probabilities of spill-risk. The reliability of the stochastic weather model has been tested. A comparison of simulated winds with long-term wind data from a land-based weather station at Nome, Alaska showed that simulated wind came within e percent of the observed average wind speed and direction (given in 22.5° segments) during summer and winter months (Liu and Leendertse, 1981).

Trajectories under 20 summer weather scenarios originated from one launch point are shown in Fig. 2.18. Trajectories are computed every half-hour. The dots on each trajectory represent the location at the end of the day, and each 30-day trajectory was computed according to the evolution of weather type as well as dynamic effects such as tidal circulation, vertical density structure and shore's effects. These effects can be seen in Fig. 2.19 in which even under identical weather scenarios the trajectories bear different orientation depending on the local hydrodynamics mentioned earlier. From 20 samples drawn out of more than 1200 trajectories, Fig. 2.18 does illustrate a general tendency of probable oil transport direction and the probability density distribution associated with the stochastic process. As shown in Fig. 2.18, after 10 days, the mean drift was 85 km toward the east over about 250 km². During summer, trajectories approach the Alaska Peninsula from Unimak Island eastward for about 200 km. Trajectories from release sites south of 55.5°N, 166°W (Fig. 2.19) indicate that an oil spill in summer could reach this shoreline. Using weather types representative of fall (September through November), the RTM predicts that a spill would probably reach the Alaska Peninsula.

Under winter conditions, trajectories from the hypothetical release site (Fig. 2.20) indicated more energetic flow; after 10 d, the mean trajectory indicated that surface oil would be transported about 150 km towards the northwest and would cover about 225 km². The spill has a lower probability to reach land, except that oil spilled over the northern lease sites could reach the Pribilof Islands (Fig. 2.21). Since the lease area is located near ice's edge, oil spilled under the ice would travel beneath the ice or with the ice at the beginning. It travels at a different drift angle until it reaches the shelf break where most of the ice would melt. Under winter conditions, the smaller areal extent is due mainly to the combined effects of oil properties, water temperature and more persistent northerly wind direction.

Oil trajectories presented in these figures are only a few samples of the simulation. They indicate a general tendency and the outmost trajectories in each figure do not indicate the limits of the areal risk due to the asymtotic nature of the probability distribution. They do reflect, however, based on the nineteen-years' data, certain predominant movements of storms through the region for each particular time period. Areas covered by the low probability of risk may still be hit by a particular combination of storm track, intensity of wind and time of spill. Since the probability of the occurrence of major storms is low, such trajectories have a low probability of realization. They would have negligible effect on subsequent oil spill risk analysis carried out by the USGS.

2.4.2 Discharge of Oil from the Seabed

Hydrographic characteristics (Fig. 2.7) of the St. George Basin lease area show that this domain is always stratified, having a wind-mixed upper layer, a layer of minimal vertical turbulence which contains fine-structure, and a tidally mixed bottom layer. Waters shoreward of the lease area (in the Middle Shelf domain) are either two-layered (summer) or well mixed. The mean velocity field (Fig. 2.2) indicates an along-shelf current of 2-5 cm/s and a cross-shelf component of 1-3 cm/s. In contrast to meteorological conditions and surface oil trajectories, analysis of subsurface current data indicated little or no seasonal signal. Thus, dissolved oil transport models apply in any season. Two models were employed one based on studies of Brooks (1960) and the other on work by Csanady (1973). In the first model, oil was added at 5,000 bbl/d for 10 d and, in the second model, 50,000 bbl of oil were added instantaneously. In both models, it was assumed that: (1) approximately 10 percent by weight of the released oil dissolved; (2) dissolved oil in a subsurface release was confined by the density structure to the bottom 30 m of the water column; and (3) vertical diffusion and biological oxidation were taken to be zero. The last assumption, even though unrealistic, was made to max-

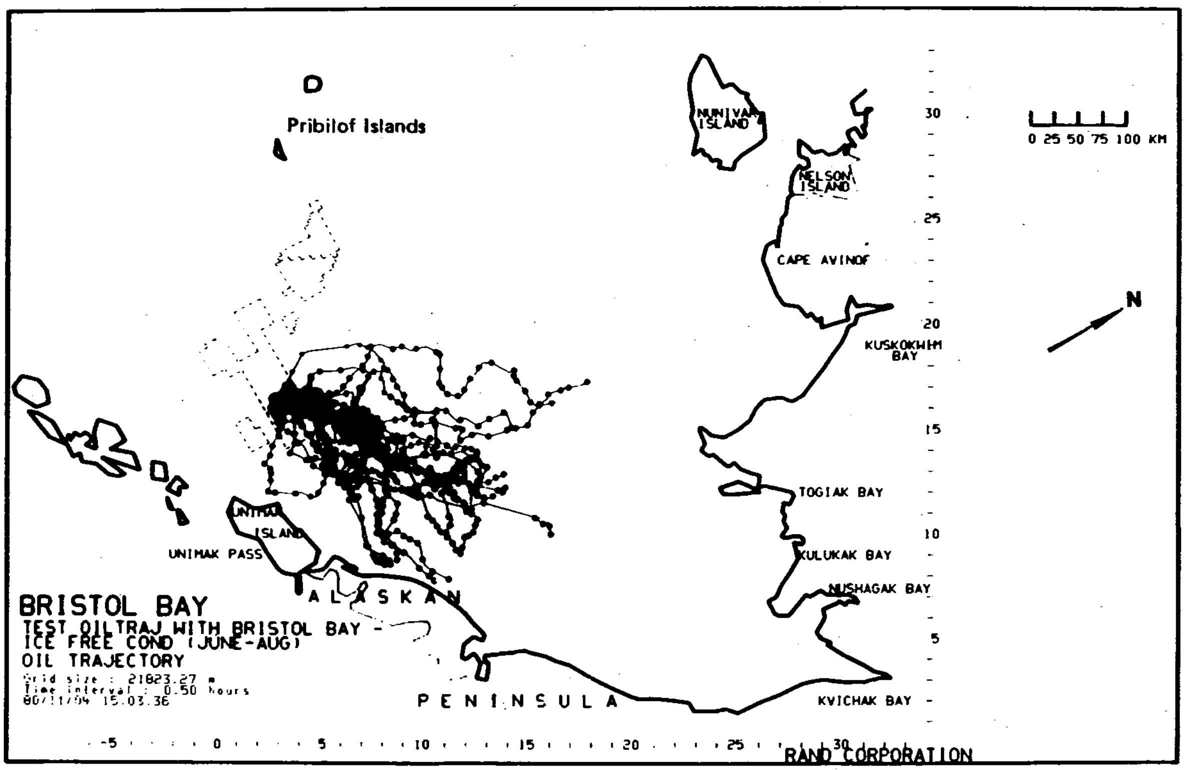

Figure 2.18. Oil trajectories from case study release site under various wind scenarios for summer conditions. Dots represent 1-d intervals (from Liu and Leendertse, 1981).

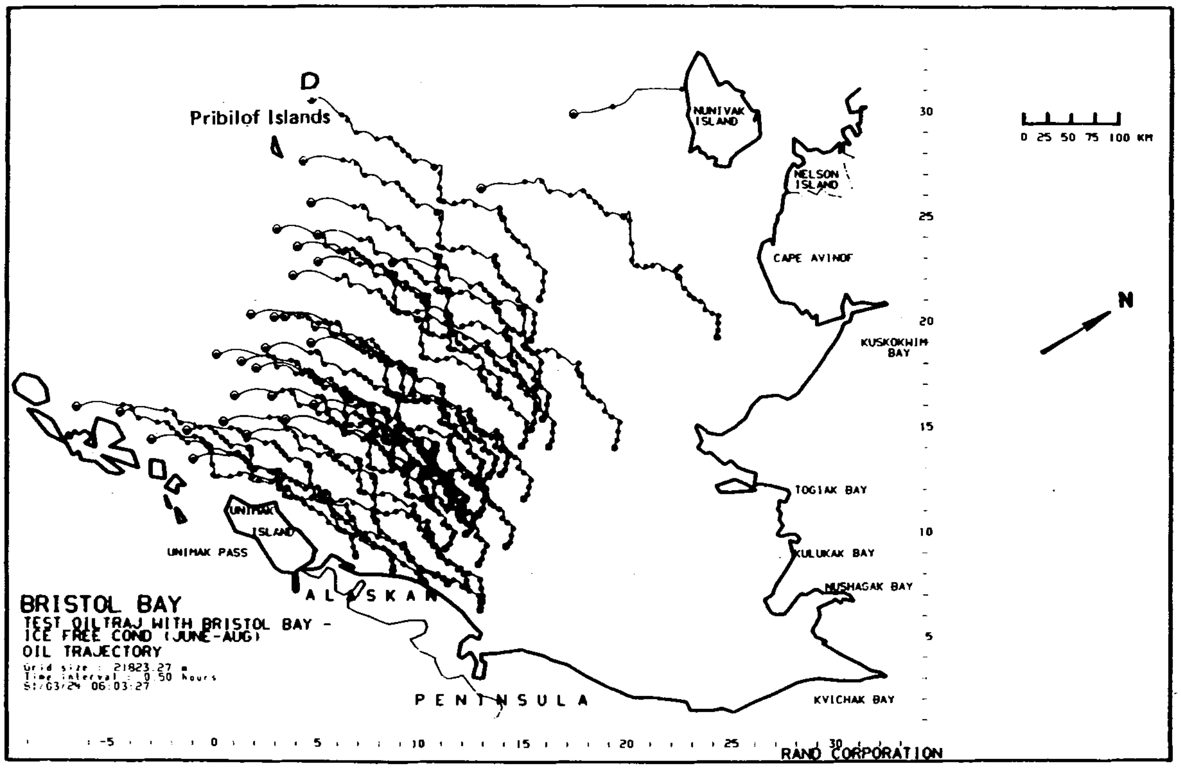

Figure 2.19. Oil trajectories from various release sites in the St. George Basin for summer winds (from Liu and Leendertse, 1981).

imize possible impact. The course of the spilled oil is discussed below.

Model I. In the vicinity of oil release, concentrations are 10 ppm with all nondissolved fractions floating to the surface, thus following surface trajectories. Using observed tidal current speeds (about 20 cm/s), it is estimated that at 5 km from the release site, the concentration of oil has been reduced to 1 ppm. Concentrations along the centerline of the plume decrease by an order of magnitude every 3-5 km downstream. The area encompassed by concentrations greater than 20 ppb extends about 20 km from the source and is 510 km wide on either side of the centerline. Thus, an area of 100-200 km^2 has dissolved oil concentrations of 20 ppb or more.

Model II. The distributions of naturally occurring methane about 5 m above the seabed are shown in Figs. 2.11 and 2.12. They show a plume whose alongshore length is about twice its cross-shelf width and which appears to be nearly aligned with the bathymetry. Table 2.5 shows changes in plume length and concentration when 50,000 bbl is spilled instantaneously at a point source and advected along isobaths by a mean current of 2.5, 5.0, and 10 cm/s, while being diffused across the shelf. (See also Fig. 2.22.)

For an oil concentration of 0.1 ppm with a vector mean current of 5 cm/s, the oil spill would move a maximum of 30 km. The nominal plume width (taken to be four standard deviations) would be 3 km, the area covered by the spill 90 km^2. If the spill site were in the Middle Shelf domain (in nonstratified water during winter), all concentrations would be reduced, since the depth over which oil would be mixed would increase. Further, this model predicts an even smaller area affected by the dissolved oil under a surface spill, since volatile compounds would eventually be lost through evaporation.

Both models predict that dissolved oil in bottom water would affect an area covering

Table 2.5. Results from dissolved oil transport Model II.

Vector mean current (cm/s)	Plume length (km)	Concentration of oil	Time after injection (d)
2.5	6.5	1 ppm	3
	22.0	70 ppb	10
5.0	13.0	1 ppm	3
	43.0	70 ppb	10
10.0	39.0	1 ppm	3
	86.0	70 ppb	10

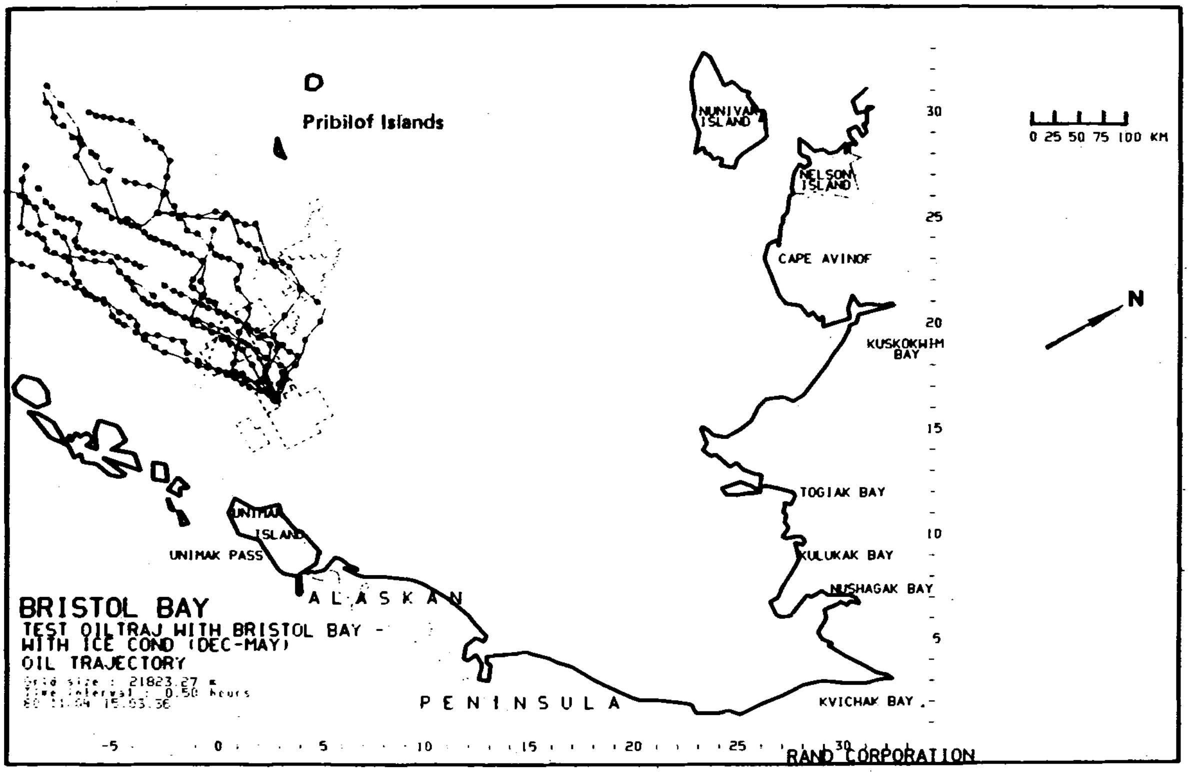

Figure 2.20. Same as Fig. 2.18 but for winter winds with ice cover (from Liu and Leendertse, 1981).

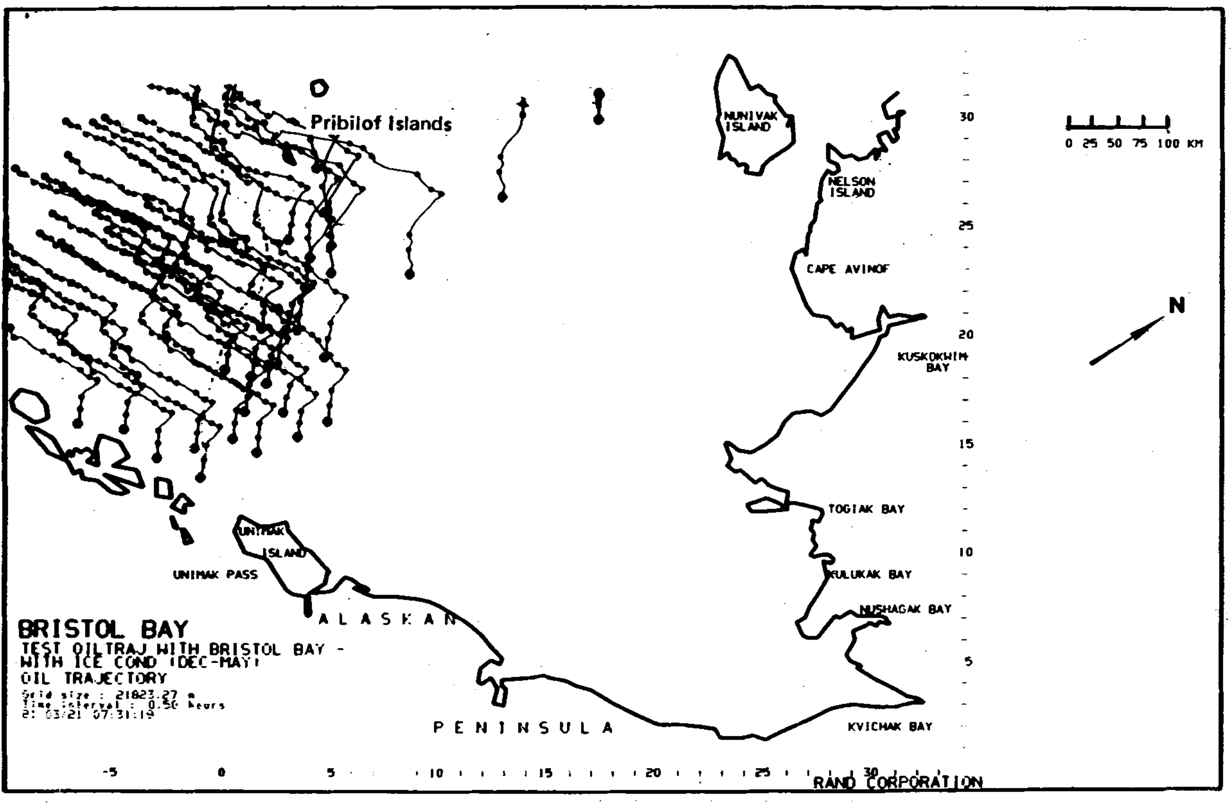

Figure 2.21. Same as Fig. 2.19 but for winter winds with ice (from Liu and Leendertse, 1981).

hundreds of square kilometers the same as that predicted for a surface spill. This is less than one percent of the basin area, however.

2.4.3 Oil in the Upper Part of the Water Column (Mixed Layer)

Oil dissolved in the mixed layer, the depth of which is dependent on wind-mixing energy and is generally 20-40 m thick, will behave similarly to dissolved oil in the bottom layer. Then the length scales and concentrations predicted by Model II will occur.

The concentrations of dissolved hydrocarbons under the surface oil can also be estimated by

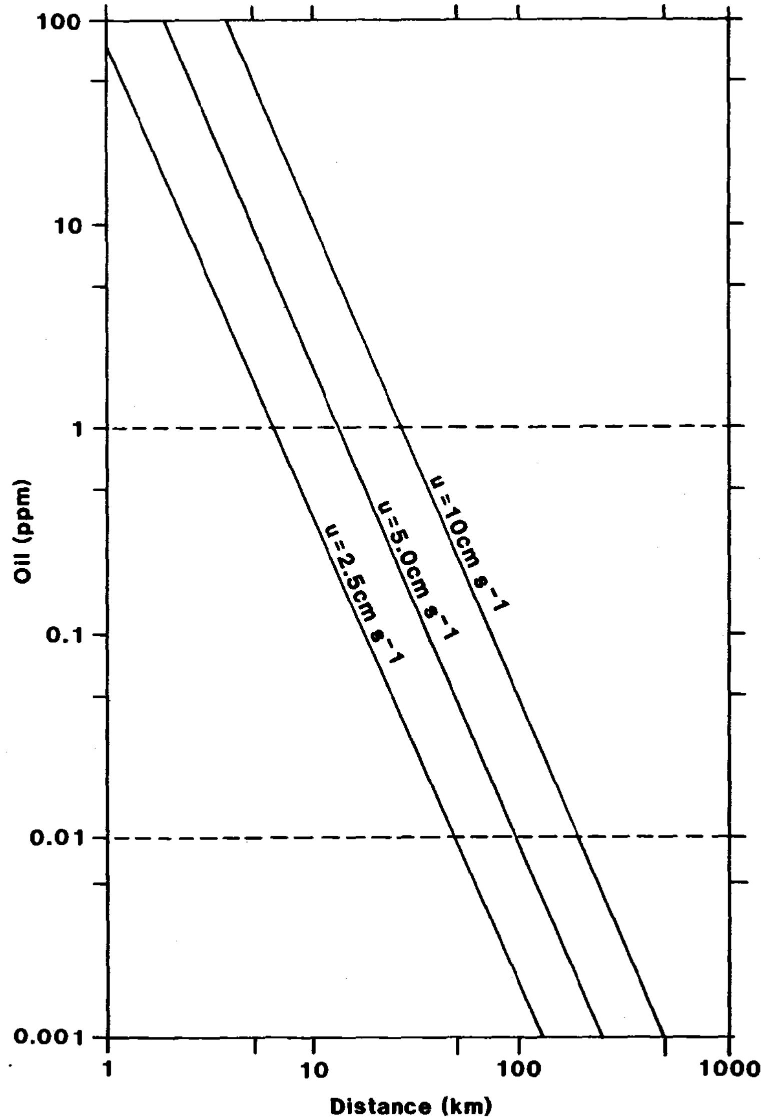

Figure 2.22. Model II predictions of the maximum concentration of dissolved and emulsified oil in the lower boundary layer of St. George Basin for assumed values of mean flow. Oil was introduced as a point source (6.72 × 10^8 g) instantaneously and allowed to advect and disperse according to the mean velocities assumed. Vertical exchange across the pycnocline and biological oxidation were ignored.

using a diffusive two-layered model. The oil layer is estimated to be 0.25 cm thick and to have a molecular diffusion coefficient of about 1 × 10^{-7} cm²/s. The thickness of the water-column layer is taken to be 30 m, with a vertical eddy diffusion coefficient of 0.01 cm²/s. During storms and/or periods of surface cooling, the upper mixed layer can extend to about 75 m, resulting in decreased oil concentrations. The time for the integrated concentration of either layer to change by 50 percent is about 2 d. If 75 percent of the oil is stable, 25 percent will dissolve (the polar fraction) or evaporate. This model predicts that the integrated water-column concentration is 1 ppm 2 d after the initial spill and 2 ppm in 10 d. Thus far, the volume of oil has not been specified, only its thickness, 0.2 cm. If 50,000 bbl had been added instantaneously, then the area covered would be about 3.2 km². If spreading were ideal, as shown in Fig. 2.17, after 2 d the projected area would be about 117 km². Conservation of mass of the oil spilled implies that, if the area were 117 km², then the concentration would decrease to about 28 ppb, a value which is consistent with other estimates. This estimate is high, since spreading of dissolved compounds under the slick and velocity shear between slick and water have been neglected.

2.4.4 Transport of Oil to the Seabed

In a recent review of petroleum in the deep sea environment, Karinen (1980) noted several mechanisms for transport of oil to the sediments. Those mechanisms which are most important for the St. George Basin include:

(1) interaction of particulate matter with oil,
(2) transport by fecal pellets and crustacean exoskeletons, and
(3) transport by vertical water movement.

Adsorption and absorption play major roles in the flux of natural organic matter (Riley, 1970) as well as petroleum hydrocarbons (Karrick, 1977; Clark and MacLeod, 1977; Cauwet, 1978; Lal, 1977; Harris, 1977; Spencer et al., 1978). Sorption is involved in three predicted sinking mechanisms for transport of petroleum to the sediment (Clark and MacLeod, 1977): (1) formation of solid or liquid particles of hydrocarbons and/or degradation products of hydrocarbons with specific gravities which cause them to sink; (2) sorption of hydrocarbons and/or degradation products on or within suspended particulate matter, increasing the specific gravity of the particle; and (3) flocculation of suspended, colloidal, or dissolved hydrocarbons and degradation products, producing a heavy sinking particle.

Formation of solid or liquid particles of hydrocarbons depends primarily on evaporation and dissolution, leaving behind the high-molecular-weight components which in some cases, such as tar, may float. Sorption and coalescence of small particles into larger particles, along with the incorporation of water, may produce particles that sink. Particles formed in this manner may serve as adsorption sites for other dissolved compounds. Oil may also be dispersed into the water column as globules (not dissolved) by wind and gravity wave energy (Belen et al., 1981). Leinonen and Mackay (1977) found a correlation between wind velocity and percent of oil dispersed per day. Their step-function relation can be approximated by the linear relation,

$$y = x + 15\%,$$

(where y is the percent of surface oil dispersed per day and x is the wind speed in m/s). It indicates that, given wind speeds of 15-25 m/s, about 35 percent of the surface oil would be dispersed per day. This mechanism transfers oil from the surface into the wind-mixed layer where it may become associated with suspended particulate matter and sink. Thus, effects due to oil on the surface decrease while those on the benthic environment increase.

Hydrocarbons from crude oil and refined products are rapidly and tightly adsorbed by minerals and sediments in saline solutions. Minerals vary in their ability to adsorb No. 2 fuel oil and crude oil (Meyers and Quinn, 1973). These authors found, pertinent to the Bering Sea Shelf, that almost three times as much anthracene was adsorbed on bentonite at 10°C than at 25°C (60 vs 22 percent). If other aromatic compounds behave similarly, the potential for movement of petroleum to sediments in the St. George Basin may be much greater than in warmer waters.

Ho and Karim (1978) reported on a laboratory study of the adsorption of crude oil by minerals and sediments. The chemical nature of the adsorbent surface on particles was of greater influence on crude oil retention than surface area. Iron and aluminum content of the particles seemed to facilitate the adsorption of crude oil. An iron oxide coating on quartz sand (a poor adsorbent surface in itself) attracted a thick layer of oil around the grains. The iron content of geothite, illite, and iron-coated quartz sand was thought to account for their high adsorption of oil. Although association of hydrocarbons with fine particulate matter is important in almost all instances of sinking oil, two large particle types, fecal pellets and crustacean exoskeletons, may accelerate transport of oil to the benthos. Biological ingestion and excretion of fecal pellets is important in the rapid settling of organic matter to the sediments (Riley, 1970). Spencer et al. (1978) found that of the total flux of particulate matter to 5,400 m in the Sargasso Sea, only five percent of the clay, most of the calcium carbonate, and 90 percent of the organic matter were contributed by rapidly settling large particles (fecal pellets) recently derived from the ocean surface. Fecal pellets may thus transport petroleum to the benthos. Direct evidence for sinking of oil by copepod feces was provided by Conover (1971). Clark and MacLeod (1977) reported that a population of 2,000 individuals/m^3 of seawater, covering an area of 1 km^2 to a depth of 10 m, could remove as much as 3 t of oil daily if the oil concentration were 1.5 p/b or greater.

The molted exoskeletons of pelagic crustaceans could also carry petroleum to the bottom. There are exuvia in the water column throughout the year, with largest quantities during the spring and summer periods of maximum growth. Although most exuvia are probably eaten before they reach the bottom, they may transport oil to intermediate depths both above and below the thermocline. Hydrocarbons and hydrocarbon metabolites would probably readily be absorbed on exuvia, as they are with other particulates (Meyers and Quinn, 1973).

Vertical transport of dissolved oil and globules can occur with water mass movement. Over the Outer Shelf, vertical structure of density is characteristic and thus transport from the upper to the lower water column is not expected. In water depths less than about 100 m, i.e., over the Middle Shelf, vertical mixing can occur to the bottom either during strong storms or periods of surface cooling. If oil were transported from the lease area to the coastal domain (either around the Pribilof Islands or along the Alaska Peninsula), wind-driven coastal convergence could carry oil to the sediments. Finally, if oil is in the surf zone, breaking-wave energy and high concentrations of suspended matter will result in oiled sediments.

Four models permit us to estimate the amount of oil (in g/m^2) transported to the bottom:

1) The vertical flux of oil due to detrital rain has been estimated by Clark and MacLeod (1977) as 3 t/d of oil over an area of 1 km^2. This is equivalent to 3 g/m^2 per day of oil on the bottom. If the required concentration of detritus were not the limiting factor, then the availability of a sufficient concentration of oil would dictate the areal extent. Our oil transport models and observations at IXTOC-I predict that the areal extent of oil in sufficient amounts is on the order of hundreds of square kilometers.
2) To provide a high estimate of oil transport to the bottom where available oil is the limiting factor, we assume that 50,000 bbl of oil are spilled instantaneously and allowed to spread only by the nature of the oil itself (see Fig. 2.17). In this way, we minimize the extent but maximize the possible concentration of oil on the bottom. After a day, the areal extent of the oil would be about 66 km^2. Under conditions of intense turbulent mixing and neglecting advective transport, then, following Leinonen and Mackay (1977), as much as 45 percent of the spilled oil could be dispersed into the water column and available for removal by interactions with suspended particulate matter (SPM). If removal were complete, 3.2×10^9 g of oil would cover 66 km^2 of the bottom, or about 48 g/m^2. Because of the nature of assumptions made in calculations, this concentration of oil on the bottom is exceedingly high and would not be realized in nature.
3) We now consider a model in which oil is available, but concentrations of SPM are limited. We assume that particulate matter is resuspended during a storm according to the equation

$$y = ae^{bx}$$

   where y is height above the bottom and x is the concentration of SPM in g/m^3. The constants a and b are determined for a given set of parameters, and b will be negative, so that as distance above the bottom increases, concentrations of suspended sediment decrease. In this example, the concentration of SPM is 1 g/m^3 at the surface and 5 g/m^3 about 5 m above the bottom. We note that near-bottom values observed over the Outer Shelf domain are generally 1-2 g/m^3 (E. Baker, pers. comm.). Using the former concentrations, the amount of SPM is given by the expression

$$\int_1^5 211e^{-0.75x}\,dx = 125 \text{ g/m}^2$$

   Assuming that the near-bottom SPM concentration in the Coastal Domain is much greater, i.e. 20 g/m^2, then the total SPM in the water column would be 593 g/m^2. If the amount of oil adsorbed onto SPM is about 10 percent of the SPM weight, the amount of oil delivered to the bottom in these examples will be about 13 and 59 g/m^2. Again, because of the assumptions, such values are not expected to be realized in nature. The processes of weathering and advection, for example, will most likely reduce the concentration and increase the areal extent of the spilled oil available for transport by SPM.
4) Shaw (in press) has performed experiments to develop a predictive model of the amount of oil likely to be transferred from the water column to the benthos by sorption and sedimentation. All experiments were performed with naturally occurring, glacially derived sediments, which are low in organic carbon. All experiments used dissolved hydrocarbons; no attempt was made to model a situation where the oil was present as particles. The model predicts that a maximum of three percent of the dissolved oil will be associated with SPM. Thus, if 50,000 bbl were added instantaneously and 10 percent were dissolved, three percent would be about 2.1×10^7 g. If this amount were delivered to the bottom in one day, the oil concentration would be 0.3 g/m^2 over 67 km^2. These estimates are probably low, as only low-molecular-weight dissolved oil components (not particulate-bound or dispersed components) are considered.

2.4.5 Interactions of Oil with Ice

Oil and sea ice interaction processes in the Bering Sea may be divided into those which incorporate oil and those which transport it (Martin, 1981). The processes of incorporation include the interaction of oil with smooth, unbroken first-year ice, the entrainment of oil by rafted or ridged first-year ice and by grease and pancake ice, and the interaction of ocean swell, oil, and the ice floes at the ice edge. The transport processes include the interaction of oil with a Langmuir circulation in the leeshore polynyas where grease ice occurs, the general advection of oil by large-scale ice movement, and the specific advection of oil by the ice bands which form at the ice edge. In the St. George Basin, there is little or no grease ice, so processes involving grease ice are not important. From historical records of ice extent and recent studies (Overland and Pease, 1981), we expect ice in the lease area to occur from about mid-March through April about 1 year in 5.

The most important capture process for the St. George Basin is the interaction of ocean swell, oil, and ice floes at the ice edge. In the field, there are two situations in which oil may be associated with ice floes oscillating in a wave field: it may be released under the ice, or it may be released at the ice edge in the 10-20 km zone of floes agitated by ocean swell. It is important in both situations that (1) the floes and cakes exist as separate units with either open water or water and grease ice around them and, (2) the incident swell or wind waves cause the floes to oscillate so that crude oil can be pumped onto their surfaces. For example, Martin and Bauer (1981) show that ice floes which have been broken by the incident swell oscillate in this swell and have wetted edges caused by the pumping of seawater onto the floe surfaces. In a laboratory study (Martin, 1981) about 25 percent of the oil spilled was found on the ice surface; however, during years when ice is present in the lease area there are fewer storms, and winds from the north tend to dominate. Thus, both swell and wave action at the ice edge will be minimal. Even though most floes are 1-5 in thick, their relatively low free-board will allow oil to pool on the surface. Thus, oil will accumulate at the edge, within the cracks between the floes, and on their surfaces.

Advection of oil by the ice bands will be the dominant transport process. As the ice floes are advected southwestward, they approach the ice edge, and propagation of ocean swell into the pack breaks them into smaller floes. As they continue to approach the edge, wind and swell cause rafting and ridging, forming sails as high as 1 m and keels as deep as 5 m. This increase in aerodynamic roughness causes the wind to move these floes to the southwest faster than those of the unroughened pack. At the ice edge these floes are organized into the bands observed on satellite photographs (Martin and Bauer, 1981); these bands move southwest at velocities of about four percent of the wind speed at 25° to the right of the wind. As they move into warmer water, the bands disintegrate by melting and by wave erosion of the leading edge. This limits the bands to a zone extending about 60 km from the ice edge where they occupy no more than 10-20 percent of the area and have a lifetime of 1-2 d.

Oil initially within the bands will be transported with them and released as they disintegrate. Because the bands are advected more rapidly than the water, an oil slick ahead of a band will be overrun, transported generally westward, and released upon melting. The general ice transport process would tend to move oil away from land.

2.5 SUMMARY

Workshop participants presented descriptions of the St. George Basin physical environment, studies on the weathering of oil, information from actual oil spills, and various models to predict the effects of petroleum development in the lease area. While there must be numerous assumptions and the specific nature of petroleum in the lease area is unknown, we believe that the following conclusions are realistic for a 50,000-bbl release of oil:

1) Concentrations of dissolved oil known to kill or injure larvae of fish and shellfish (> 20 ppb) would exist in an area between 100 and 300 km² in the bottom and upper mixed layers after about 10 d.
2) Oil on the surface would have a similar areal extent, and trajectories show that it could reach the shoreline of the Pribilof Islands and locations along the Alaska Peninsula from Unimak Pass eastward to the vicinity of Port Moller. Spilled oil may also be influenced by subsurface currents, but the present models do not incorporate this mode of oil transport.
3) Oil could be delivered to the benthos in concentrations from about 13-60 g/m² over an area of about 100 km²; lesser but unquantifiable concentrations could occur over an area on the order of hundreds of square kilometers.
4) Unlike areas in the southern Bering Sea such as Norton Sound, sea ice in the St. George Basin will be neither an important hazard nor an important transport mechanism; however, oil could be associated with hundreds of kilometers of the "shoreline" of the ice bands.
5) The extent and effect of cuttings and mud discharged during drilling would be limited to about 1 km² around a given platform.

2.6 REFERENCES

Allen, A. A., and W. G. Nelson. 1981. Oil spill counter-measures in land fast sea ice, pp. 297-304. *In:* Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Clean-up). March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG (API Pub. 4334).

Atlas, R. M. 1975. Effects of temperature and crude oil composition on petroleum biodegradation. Appl. Microbiol. 30:296-403.

Atlas, R. M., G. Roubal, A. Bonner, and J. Haines. 1980. Microbial degradation of hydrocarbons in mousse from IXTOC-I, pp. 411-435. *In:* Proc. Symposium on Preliminary Results from the September 1979 *Researcher/Pierce* IXTOC-I Cruise, Key Biscayne, Florida, June 9-10, 1980. NOAA/OMPA, Boulder, Colo.

Ayers, R. C., Jr., T. C. Sauer, Jr., R. P. Meek, and G. Bowers. 1980. An environmental study to access the impact of drilling discharges in the mid-Atlantic. I. Quantity and fate of discharges, 1:382-418. *In:* Proc. Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings. Lake Buena Vista, Florida. January 21-24, 1980.

Beardsley, R. C., and C. D. Winant. 1979. On the mean circulation in the mid-Atlantic bight. J. Phys. Oceanogr. 9:612-619.

Belen, M. S., W. J. Lehr, and H. M. Cekirge, 1981. Spreading, dispersion, and evaporation of oil slicks in the Arabian Gulf, pp. 161-164. *In:* Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup). March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG. API Pub. 4334).

Belicek, J., and J. Overall. 1976. Some aspects of weathering and burning of crude oil in a water-and-ice environment. NORCOR Rep. 107-1.

Boehm, P. D., and D. L. Fiest. 1980. Subsurface water column transport and weathering of petroleum hydrocarbons during the IXTOC-I blowout in the Bay of Campeche and their relation to surface oil and microlayer compositions, pp. 169-185. *In:* Proc. Symposium on Preliminary Results from the September 1979 *Researcher/Pierce* IXTOC-I cruise, Key Biscayne, Florida, June 9-10, 1980. NOAA/OMPA, Boulder, Colo.

Brooks, N. H. 1960. Diffusion of sewage effluent in an ocean current. *In:* Proc. First Inter. Conf. on Waste Disposal in the Marine Environment, Pergamon Press, New York.

Cauwet, G. 1978. Organic chemistry of sea water particulates: Concepts and developments. Oceanologica Acta 1:99-105.

Clark, R. C., Jr., and D. W. Brown. 1977. Petroleum: Properties and analyses in biotic and abiotic systems, 1:1-89. *In:* D. C. Malins (ed.), Effects of petroleum on arctic and subarctic marine environments and organisms. Academic Press, New York.

Clark, R. C., Jr., and W. D. MacLeod. 1977. Inputs, transport mechanisms, and observed concentrations of petroleum in the marine environment, 1:91-223. *In:* D. C. Malins (ed.), Effects of petroleum on arctic and subarctic marine environments and organisms. Academic Press, New York.

Cline, J. D. 1981. Distributions of dissolved LMW hydrocarbons in Bristol Bay, Alaska. Implications for future oil and gas development. 1:425-444. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash.

Coachman, L. K. 1980. PROBES Progress Report: Water circulation and mixing. Unpub. MS.

Coachman, L. K., and R. L. Charnell. 1977. Finestructure in outer Bristol Bay, Alaska. Deep-Sea Res. 24:809-889.

Coachman, L. K., and R. L. Charnell. 1979. Lateral water mass interactions — a case study, Bristol Bay, Alaska. J. Phys. Oceanogr. 9:278-287.

Coachman, L. K., T. H. Kinder, J. D. Schumacher, and R. B. Tripp. 1980. Frontal systems of the southeastern Bering Sea shelf, pp. 917-933. *In:* T. Carstens and T. McClimans, (eds.), *Stratified Flows,* 2nd Inter. Assoc. Hydraulic Res. Symposium, Trondheim, June 1980. TAPIR, Norway.

Conover, R. J. 1971. Some relations between zooplankton and Bunker C oil in Chedabucto Bay following the wreck of the tanker *Arrow.* J. Fish. Res. Bd. Can. 28:1327-1330.

Csanady, G. T. 1973. Turbulent diffusion in the environment. D. Ridel, Boston.

Csanady, G. T. 1978. The arrested topographic wave. J. Phys. Oceanogr. 8:47-62.

Dunbar, R. G. 1967. The monthly and extreme limits of ice in the Bering Sea, 1:687-703. *In: Physics of Snow and Ice.* Inst. Low Temp. Sci., Univ. Hokkaido, Hokkaido, Japan.

Fay, J. A. 1969. The spread of oil slicks on a calm sea, pp. 53-63. *In:* D. P. Hoult (ed.), *Oil on the Sea.* Plenum Press, New York.

Grubbs, B. E., and R. D. McCollum, Jr. 1968. A climatological guide to Alaska weather. Scientific Services Section, 11th Weather Squadron, Elmendorf AFB, Alaska.

Harris, J. E. 1977. Characterization of suspended matter in the Gulf of Mexico. II. Particle size analysis of suspended matter from deep water. Deep-Sea Res. 24:1055-1061.

Ho, C. L., and H. Karim. 1978. Impact of adsorbed petroleum hydrocarbons on marine organisms. Mar. Poll. Bull. 9:156-162.

Kana, T. W., and E. P. Thompson, and R. Pavio. 1981. *Burmah Agate* — Chronology and containment operations, pp. 131-138. *In: Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup).* March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG (API Pub. 4334).

Karinen, J. F. 1980. Petroleum in the deep sea environment: Potential for damage to biota. Environ. Inter. 3:135-144.

Karrick, N. L. 1977. Alterations in petroleum resulting from physio-chemical and micro-biological factors, 1:225-299. *In:* D. C. Malins (ed.), *Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms.* Academic Press, New York.

Kinder, T. H., L. K. Coachman, and J. A. Galt. 1975. The Bering Slope current system. J. Phys. Oceanogr. 5:231-244.

Kinder, T. H., J. D. Schumacher, and D. V. Hansen. 1980. Observation of a baroclinic eddy: An example of mesoscale variability in the Bering Sea. J. Phys. Oceanogr. 10:1228-1245.

Kinder, T. H., and J. D. Schumacher. 1981a. Hydrographic structure over the continental shelf of the southeastern Bering Sea, 1:31-52. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash.

Kinder, T. H., and J. D. Schumacher. 1981b. Circulation over the continental shelf of the southeastern Bering Sea, 1:53-75. *In:* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: Oceanography and resources. NOAA/OMPA, Seattle, Wash.

Kirstein, B. E. 1981. Mass transfer and spreading of oil slicks. Unpub. MS.

Lal, D. 1977. The oceanic microcosm of particles. Science 198:997-1009.

Leinonen, P. J., and D. Mackay. 1977. Mathematical model of the behavior of oil spills on water with natural and chemical dispersion. Econ. Tech. Rev. Rep. EPS-3-EC-77-19, prepared for Fisheries and Environment Canada.

Liu, S.-K., and J. J. Leendertse. 1979. A three-dimensional model for estuaries and coastal seas: Vol. VI, Bristol Bay simulations. Prepared for NOAA, U. S. Dep. Commerce, R-2405-NOAA.

Liu, S.-K., and J. J. Leendertse. 1981. Oil-spill analysis and simulation for the proposed oil-lease area in the St. George Basin, Alaska. The Rand Corp., WD-1026-NOAA.

Lysyj, I., G. Perkins, J. S. Farlow, and R. W. Morris. 1981. Distribution of aromatic hydrocarbons in Pt. Valdez, Alaska, pp. 47-53. *In:* Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup). March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG (API Pub. 4334).

Kinder, T. H., and J. D. Schumacher. 1981b. Circulation over the continental shelf of the southeastern Bering Sea, 1:53-75. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Kirstein, B. E. 1981. Mass transfer and spreading of oil slicks. Unpub. MS.

Lal, D. 1977. The oceanic microcosm of particles. Science 198:997-1009.

Leinonen, P. J., and D. Mackay. 1977. Mathematical model of the behavior of oil spills on water with natural and chemical dispersion. Econ. Tech. Rev. Rep. EPS-3-EC-77-19, prepared for Fisheries and Environment Canada.

Liu, S.-K., and J. J. Leendertse. 1979. A three-dimensional model for estuaries and coastal seas: Vol. VI, Bristol Bay simulations. Prepared for NOAA, U. S. Dep. Commerce, R-2405-NOAA.

Liu, S.-K., and J. J. Leendertse. 1981. Oil-spill analysis and simulation for the proposed oil-lease area in the St. George Basin, Alaska. The Rand Corp., WD-1026-NOAA.

Lysyj, I., G. Perkins, J. S. Farlow, and R. W. Morris. 1981. Distribution of aromatic hydrocarbons in Pt. Valdez, Alaska, pp. 47-53. *In: Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup)*. March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG (API Pub. 4334).

Mackay, D. 1981. Fate and behavior of oil spills, pp. 7-27. *In:* J. B. Sprague, J. H. Vandermeulen, and P. G. Wells (eds.), Oil and dispersants in Canadian seas — Research appraisals and recommendations. Res. Dev. Div., Environ. Emerg. Br., Environ. Prot. Serv. Ottawa, Ont.

Mackay, D., S. Paterson, P. Boehm, and D. L. Fiest. 1981. Physical-chemical weathering of petroleum hydrocarbons from the IXTOC-I blowout — Chemical measurements and a weathering model, pp. 453-460. *In: Proc. 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup)*. March 2-5, 1981, Atlanta, Georgia. API, EPA, USCG (API Pub. 4334).

Martin, S. 1981. Anticipated oil-ice interactions in the Bering Sea, 1:223-243. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Martin, S., and J. Bauer. 1981. Bering Sea ice-edge phenomena, 1:189-211. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

McAuliffe, C. D. 1977. Evaporation and solution of C_2 to C_{10} hydrocarbons from crude oils on the sea surface, pp. 363-372. *In:* D. A. Wolfe (ed.), *Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms*. Pergamon Press, Oxford.

McNutt, S. L. 1981. Remote sensing analysis of ice growth and distribution in the eastern Bering Sea, 1:141-165. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Meek, R. P., and J. P. Ray. 1980. Induced sedimentation accumulation and transport resulting from exploratory drilling discharges of drilling fluids and cuttings on the southern California outer continental shelf, 1:259-284. *In: Proc. Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings*. Lake Buena Vista, Florida, January 21-24, 1980.

Meyers, P. A., and J. G. Quinn. 1973. Association of hydrocarbons and mineral particles in saline solution. Nature 244:23-24.

Muench, R. D., and K. Ahlnäs, 1976. Ice movement and distribution in the Bering Sea from March to June 1974. J. Geophys. Res. 81:4467-4468.

Overland, J. E. 1981. Marine climatology of the Bering Sea, 1:15-22. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf, Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Overland, J. E., and C. H. Pease. 1981. Cyclone climatology of the Bering Sea and its relation to sea ice extent. Unpub. MS.

Payne, J. R. 1981. Chemical properties of crude oils and petroleum products as they relate to trajectory, dispersion and weathering of oils spilled in the marine environment. Background paper for St. George synthesis meeting. Unpub. MS.

Payne, J. R., N. W. Flynn, P. J. Mankiewicz, and G. S. Smith. 1980a. Surface evaporation/dissolution partitioning of lower molecular weight aromatic hydrocarbons in a down-plume transect from the IXTOC-I wellhead, pp. 2349-263. *In:* Proc. Symposium on Preliminary Results from the September 1979 *Researcher/Pierce* IXTOC-I Cruise, Key Biscayne, Florida, June 9-10, 1980. NOAA/OMPA, Boulder, Colo.

Payne, J. R., G. S. Smith, P. J. Mankiewicz, R. S. Shokes, N. W. Flynn, V. Morena, and J. Altamirano. 1980b. Horizontal and vertical transport of dissolved and particulate-bound higher-molecular-weight hydrocarbons from the IXTOC-I blowout, pp. 119-166. *In:* Proc. Symposium on Preliminary Results from the September 1979 *Researcher/Pierce* IXTOC-I Cruise, Key Biscayne, Florida, June 9-10, 1980. MOAA/OMPA, Boulder, Colo.

Pearson, C. A., H. Mofjeld, and R. B. Tripp. 1980. Tides of the Eastern Bering Sea Shelf, 1:111-130. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Pease, C. H. 1980. Eastern Bering Sea ice processes. Monthly Weather Rev. 108:2015-2023.

Putnins, P. 1966. The sequence of baric pressure patterns over Alaska, Studies on the meteorology of Alaska. First Interim Rep., Environ. Data Serv., ESSA, Washington, D.C. (NTIS-AD-042679).

Raj, P. P. K. 1977. Theoretical study to determine the sea state limit for the survival of oil slicks on the ocean. Arthur D. Little, Cambridge, Mass. AD-A049 794/ISL.

Ray, J. P., and R. P. Meek. 1980. Water column characterization of drilling fluids dispersion from an offshore exploratory well on Tanner Bank, 1:223-258. *In: Proc. Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings*. Lake Buena Vista, Florida. January 21-24, 1980.

Riley, G. A. 1970. Particulate and organic matter in sea water. Adv. Mar. Biol. 8:1-118.

Rosenegger, L. W. 1975. The movement of oil under sea ice. Beaufort Sea Project, Dep. Environ., Victoria, B. C., Beaufort Sea Tech. Rep. 28.

Schumacher, J. D., T. H. Kinder, D. J. Pashinski, and R. L. Charnell. 1979. A structural front over the continental shelf of the eastern Bering Sea. J. Phys. Oceanogr. 9:79-87.

Schumacher, J. D., C. A. Pearson, and J. E. Overland. 1981. Preliminary results from current, hydrographic and meteorological observations: Unimak Pass, Alaska. Environmental Assessment of the Alaskan Continental Shelf, NOAA/OCSEAP, Ann. Rep. (in press).

Schumacher, J. D., and R. K. Reed. 1980. Coastal flow in the northwest Gulf of Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 6:118-149.

Shaw, D. G. in press. Hydrocarbons: Natural distribution and dynamics on the Alaskan outer continental shelf. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Phys.

Spencer, D. W., P. G. Brewer, A. Fleer, S. Honjo, S. Krishnaswami, and Y. Nozaki. 1978. Chemical fluxes from a sediment trap experiment in the deep Sargasso Sea. J. Mar. Res. 36:493-523.

Stoltzenback, K. S., O. S. Madsen, E. E. Adams, A. M. Pollack, and C. K. Copper. 1977. A review and evaluation of basic techniques for predicting the behavior of surface oil slicks. MIT Dep. Civ. Engng. Rep. 222.

Sutton, C., and J. A. Calder. 1975. Solubility of alkyl benzene in distilled water and seawater at 25°C. J. Chem. Engng. Data 20:320-322.

Webster, B. D. 1979. Ice edge probabilities for the eastern Bering Sea. NOAA Tech. Memo, NWS AR-26.

Wheeler, R. B. 1978. The fate of petroleum in the marine environment. Exxon Production Research Co. Spec. Rep.

Wood, E. G., and R. P. Hannah. 1981. IXTOC-I oil spill — the damage assessment program and ecological impact, pp. 439-444. *In: 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup.* 2-5 March, 1981, Atlanta, Georgia: API, EPA, USCG. (API Pub. 4334).

ZoBell, C. E. 1973. Microbial degradation of oil, present status, problems and perspectives, pp. 3-16. *In:* D. G. Ahearn and S. P. Meyers (eds.), Microbial degradation of oil pollutants. Louisiana State Univ. Center for Wet Land Resources, Pub. LSU-SG-73-01.

CHAPTER 3

ENVIRONMENTAL HAZARDS TO PETROLEUM INDUSTRY DEVELOPMENT

W. M. Sackinger and R. A. Combellick

With contributions from D. Comer, J. Davies, J. Gardner, R. Herrera, G. Martin, R. E. Peterson, J. Prince, G. Springer, W. Stringer, and F. R. Wright.

3.1 INTRODUCTION

The environmental hazards to petroleum operations in the St. George Basin have been divided into two categories: those due to local geology or geological processes, and those due to sea ice. Seafloor features that may be hazardous in the region include sediment instability, gas-charged sediment, and active seafloor faults. The risk posed by earthquake activity must also be considered. Volcanoes in the Aleutian Islands represent a possible hazard to the siting of pipeline terminals and tanker facilities.

Exploration drilling in the St. George Basin will probably proceed throughout the year as long as the drilling fleet can handle ice conditions. Ice-strengthened drillships or semisubmersibles can probably work safely year round in the generally light ice conditions in the St. George Basin region in the years that have ice. Moreover, with icebreaker support, year-round drilling seems very feasible in all years (J. Prince, pers. comm.).

Storm conditions could produce waves of sufficient height to require use of semisubmersible drilling platforms. For production, year-round operations from a fixed, bottom-founded structure are envisioned in the scenarios. The structure may be either of the gravity type or pile-founded, but in either case it will be designed to withstand the additional vertical loads due to spray ice accretion. Because of the deep water, the overturning moment due to sea ice loading is larger than in Cook Inlet, for example, and special designs (such as inclined structure surfaces at the waterline) may be considered to reduce the lateral forces. A statistical distribution of ice thickness in the St. George Basin region would be useful in optimizing structure design. Such data have yet to be obtained.

Scenarios for transportation of petroleum include either a seafloor pipeline to a port in the Aleutians, or an offshore tanker loading facility at the production location. Hazards due to unstable seafloor sediment, earthquakes, and active surface faults which threaten a pipeline are discussed below. The year-round offshore tanker loading would require ice-breaking tankers of a class which has been used in Finland and Russia for many years. The technological details of offshore loading in ice-infested waters remain to be refined, however.

No particular mitigating measures or lease stipulations were proposed by the group to reduce the exposure to environmental hazards. It was felt that industry designers should take into account the hazards mentioned, and that considerably more statistical information about the hazards should be obtained in order to optimize designs.

3.2 POTENTIAL SEAFLOOR HAZARDS

3.2.1 Introduction

This section summarizes the results of discussions on seafloor hazards which took place as part of the Environmental Hazards Workshop at the St. George Synthesis Meeting (April 28, 1981). These discussions dealt primarily with data collected by the USGS Pacific-Arctic Branch of Marine Geology and data collected under contract for the USGS Conservation Division.

The USGS Pacific-Arctic Branch collected geophysical profiles, sediment samples, and oceanographic data in 1976 and 1977 aboard the R/V *Sea Sounder* and R/V *S. P. Lee*, from an area roughly 400 km wide between Unimak Pass and St. Paul Island. Geophysical data included both shallow penetration, high-resolution seismic profiles and deep penetration, low-resolution profiles with trackline spacings varying between approximately 10 km and 50 km. Approximately 170 sediment samples were collected and included cores, surface grab samples, and dredge hauls. The samples were analyzed for grain-size distribution, mineralogy, total carbon, and inorganic geochemistry. Some samples were tested for hydrocarbon gas content and composition.

High-resolution seismic profile records have also been collected in the St. George Basin area under contract for the USGS Conservation Division. Coverage by these data is much more detailed (3- to 5-km trackline spacing), but is restricted to the areas of lease tracts selected by the Department of Interior for further consideration in proposed OCS Lease Sale 70.

Seafloor features and hazards discussed at the synthesis meeting are largely summarized in the final report for OCSEAP Research Units 206 and 556 (Gardner et al., 1979). Detailed bathymetric, structure, isopach, and seafloor hazard maps are now in preparation by the Conservation Division of the USGS, based on the contracted geophysical surveys. Some preliminary results of these data were presented by D. Comer of the Conservation Division. In addition to these nonproprietary sources of data, several proprietary surveys have been conducted by the oil industry.

3.2.2 Seafloor Characteristics

The Outer Continental Shelf area encompassed by proposed Lease Sale 70 ranges in depth from 98 to 154 m (see Fig. 1.1) and is very flat, with an average slope of about 0.03°. The shelf break is at about 170 m, beyond which the slope increases to between 1.4° south of the lease area and 3° to the west. Two prominent submarine canyons, Pribilof and Bering Canyons, dissect the outer shelf and slope and appear to have been dominant factors in the distribution of sediment in the region. Bering Canyon is probably a barrier to northward transport of bottom sediment from the Aleutian arc to the southern Bering Shelf. Pipelines either to the Aleutians or to the Pribilof Islands will have to be routed around these features to avoid steep slopes and irregular topography.

Surface sediments in the St. George Basin area are generally silt and silty sand (Fig. 3.1). The finest sediment is silt (0.004- to 0.0625-mm grain diameter) which appears near the center of the lease area. The sediment becomes more coarse to the northwest and southeast, and is predominantly fine sand at these extremities of the lease area. Clay content is generally less than 15 percent. For the most part, the sediment is poorly sorted, which suggests that bottom current activity is not strong enough to produce significant winnowing. Oceanographic data indicate very sluggish bottom currents that are too weak to move even the finest bottom sediment encountered in the area. Tidal currents and storm waves may periodically resuspend fine silt and clay, but there appears to be little or no net transport across the shelf. Thus, the observed sediment texture and distribution cannot be the result of present-day oceanographic processes and are probably relict.

Mineralogy of the surface sediment provides additional clues as to the influence of present-day versus past oceanographic processes on the distribution and movement of bottom sediment. Volcanic components dominate the heavy mineral fraction and show a gradient northwestward from the Aleutian arc onto the southern Bering shelf. Combined concentrations of the clay minerals smectite plus vermiculite show a similar gradient starting in the vicinity of Unimak Pass and Unimak Island. Eleven major, minor, and trace elements also show a trend of higher concentrations near Unimak Pass, decreasing to the northwest. Other components show contributions from the Yukon-Kuskokwim Delta region, but this is minor compared to the volcanic sediment contribution from the Aleutian arc. Although several rivers deliver large volumes of sediment to the Inner Shelf of the southern Bering Sea, oceanographic conditions and low topographic gradient do not permit significant transport of the sediment to the Outer Shelf, which is over 500 km away. Moreover, the dominance of Aleutian arc volcanic material in the sediments on the Outer Shelf must reflect transport processes which are no longer operative, because the Bering Canyon provides an effective barrier to northward movement of sediments under the present-day regime of weak bottom circulation. The mineralogy and texture of surface sediments, when considered in relation to the regional geography and oceanography, suggest that significant quantities of sediment are not being transported to the St. George Basin area today from any source, and the observed surface distribution must be essentially relict from a previous depositional environment, probably at least as old as the last low sea level stand (15,000-20,000 years before present) when the area was closer to terrestrial sediment sources.

3.2.3 Sediment Instability

High-resolution seismic profiles show no evidence of significant sediment instability in the outer shelf region encompassed by the proposed St. George lease area. Although there is very little public data on the engineering properties of sediment in this area, it is reasonable to conclude from the above arguments that as a result of the low topographic gradient, age of the sediment, lack of modern sediment input, sediment texture (dominantly silt and fine sand), and lack of significant reworking by bottom currents, the sediment is probably normally consolidated and stable as a foundation material.

Substantial evidence of sediment instability is present along the entire continental slope from Pribilof Canyon to Bering Canyon (Fig. 3.2), beginning at the shelf break at about 170 m. Nearly all high-resolution seismic profiles across the slope and rise show one or more of the following features indicative of gravity slides, slumps, or

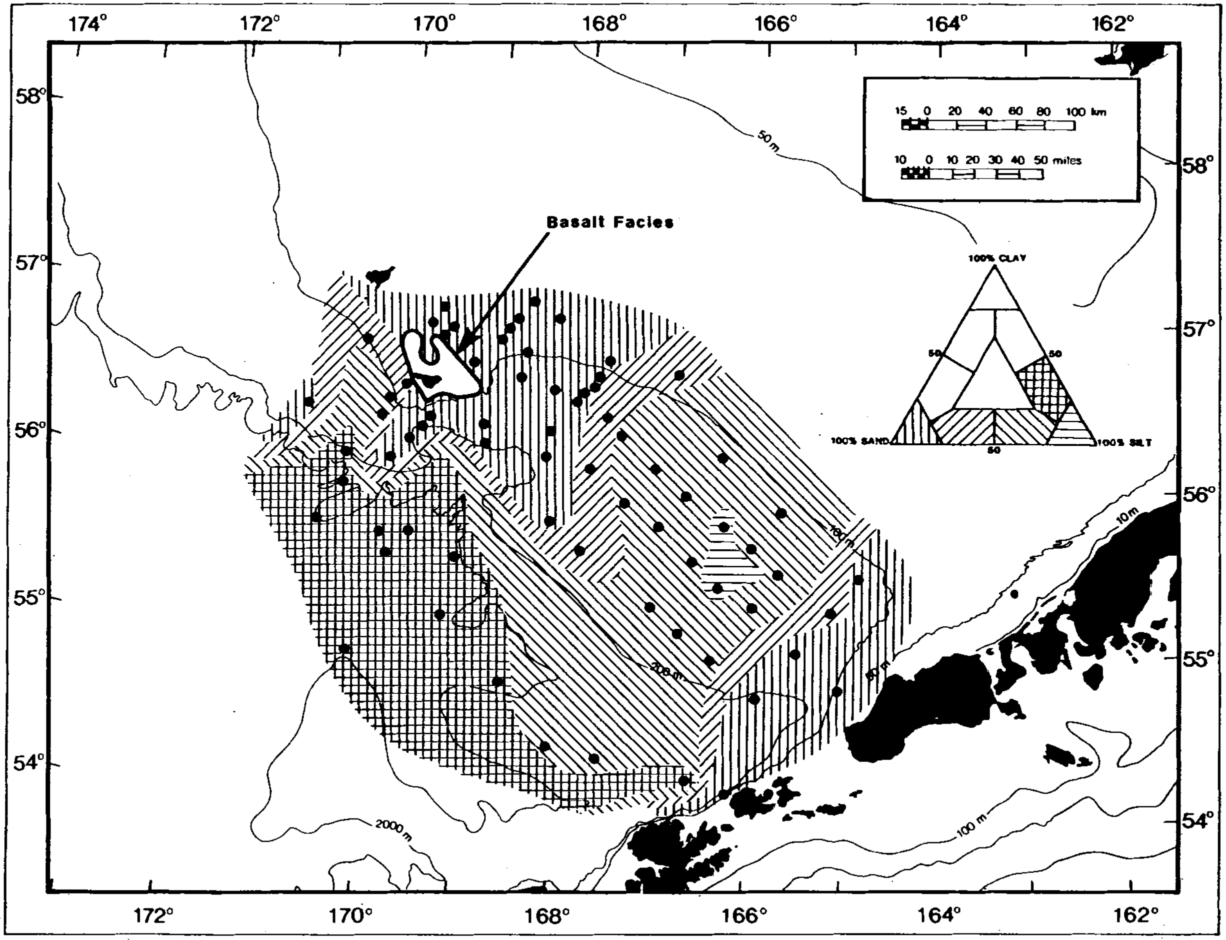

Figure 3.1. Surface sediments in the St. George Basin area. Dots indicate station locations. A ternary diagram of grain size in percentage of sand, silt, and clay provides a legend for the patterned areas (adapted from Gardner et al., 1979).

creep: (1) surface faults with steep scarps and rotated surfaces, (2) deformed bedding and/or discontinuous acoustic reflections, (3) hummocky topography, (4) anomalously thick sediment accumulation, and (5) acoustically transparent sediment masses. Although instability on the slope will not be a hazard to structures within the lease area, it will be a hazard to pipelines if they are not routed so as to avoid the submarine canyons, continental slope, and shelf break areas.

3.2.4 Gas-Charged Sediment

Seismic reflection data collected by the USGS Pacific-Arctic Branch show extensive evidence of possible gas charging in deep subsurface sediment of the St. George Basin at a depth of 300 m or deeper below the sediment surface. Gas-charged sediment would be a potential blowout hazard if penetrated during drilling. Evidence for gas charging appears as acoustic anomalies, where subsurface reflectors terminate on the profiles leaving zones of acoustic turbidity. Acoustic turbidity results from absorption or erratic reflection of seismic energy, which in turn is often caused by gas incorporated in the sediment. Additional high-resolution data collected under contract to the Conservation Division show similar evidence of possible gas charging not only in the deep subsurface but in near-surface sediments (less than 100 m below the surface). The latter could be a potential foundation hazard to structures built in the area. However, gascharged sediment is not unique to the St. George Basin area; its presence has been a design consideration for foundations in many areas throughout the world (J. Prince, pers. comm.).

Sediment samples collected in 1976 and 1977 were analyzed for the presence and composition of gases in the sediment to determine their distributions and possible sources. Small quantities of hydrocarbon gases were found in all samples analyzed, with methane the most abundant. There was no observed correlation between gas concentrations and acoustic anomalies, and no evidence of concentrations in the surface sediments that would suggest a possible hazard due to gas charging. However, it may be possible that subsurface gas accumulations are present but are effectively capped by impenetrable overlying sediment, preventing seepage to the surface. In the absence of positive information on the cause of the acoustic anomalies, gas charging should be regarded as a potentially serious hazard.

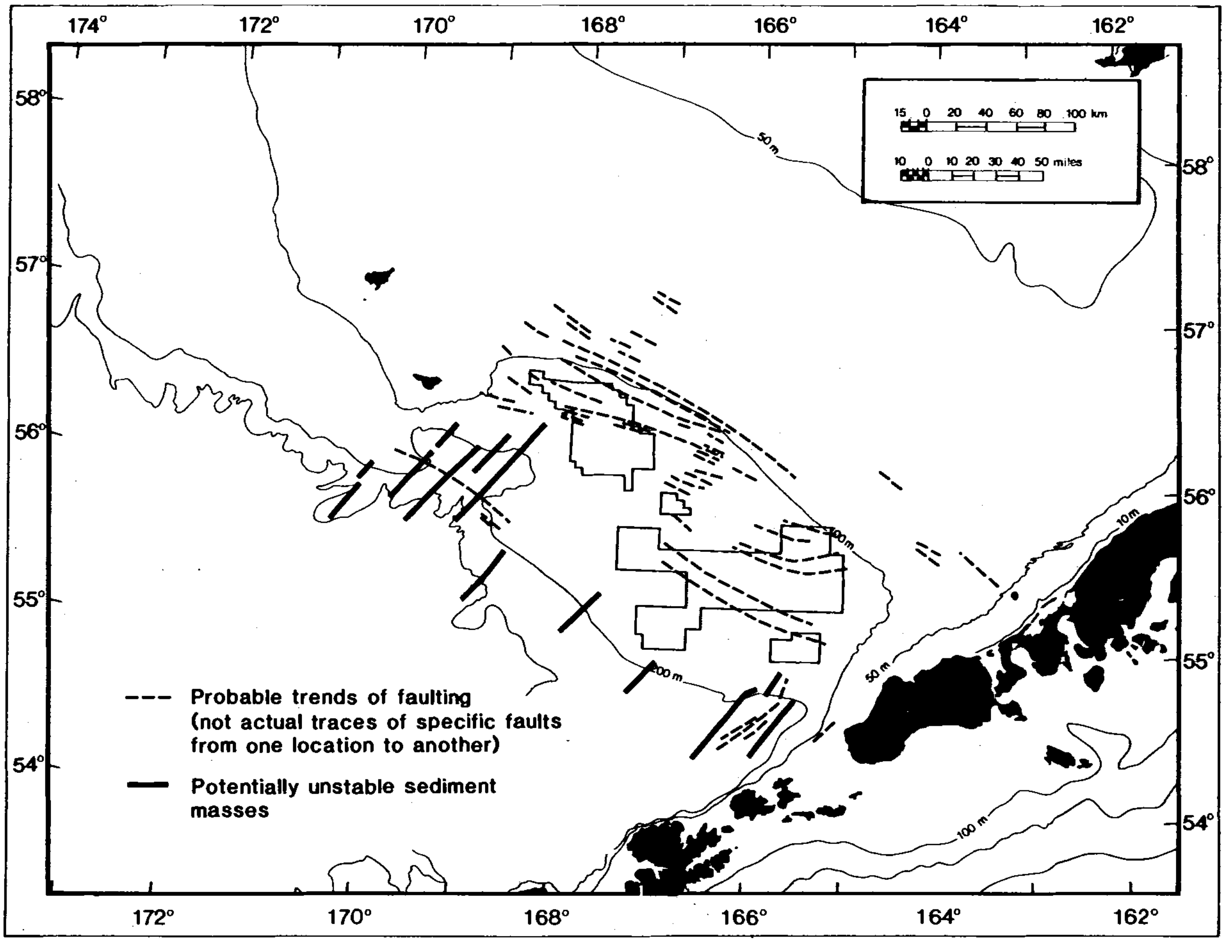

Figure 3.2. Inferred fault trends and areas of potential slope instability, as deduced from seismic reflection surveys (adapted from Gardner et al., 1979).

3.2.5 Faulting

Figure 3.2 shows the general distribution and inferred trends of faults in the St. George Basin area. Most faults parallel the axis of the basin and are probably associated with its formation as a graben. Many of the faults, including the major boundary faults along the margins of the Basin, intersect the sediment surface or can be traced to within a few meters of the surface. Surface fault scarps up to a few meters high can be observed in the northern part of the area. Since the surface sediments which these faults displace are relict from late Pleistocene or early Holocene, it is only possible to conclude on the basis of geologic evidence that active faulting has occurred some time within the last several tens of thousands of years.

Numerous earthquakes have occurred in the region over the past several decades which would suggest that the faulting may still be active. A single seismograph on St. Paul Island has recorded substantial low magnitude earthquake activity since 1976, but it has not been possible to locate these events with just the one station. Arrival time differences between S and P waves often indicate epicentral distances from St. Paul which would be consistent with locations in the St. George Basin area. As with gas charging, there is not enough evidence to confirm active surface faulting in the area, but there is sufficient evidence to conclude that faulting has occurred in the recent geologic past and may still be active. In addition to the potential hazard from active faulting within the lease area, there would be a hazard to pipelines transiting the shelf to the Alaska Peninsula. Surface faults are present along the margins of Amak Basin, trending east-west, and along the margins of Bering Canyon in the vicinity of Unimak Pass.

3.3 SEISMIC ACTIVITY

3.3.1 Historic Record

The earthquake record prior to the development of sensitive seismographs in the late 1890's and early 1900's relies on observations of the effects of earthquakes on people and objects. For southern Alaska, the Aleutians in particular, these observations are most complete during the period of the Russian occupancy, generally from about 1740 to 1870. Earthquakes for this period have been cataloged by Davis and Echols (1962), Coffman and von Hake (1973), and Kisslinger et al. (in prep.).

The historic record of earthquakes (i.e., those not recorded by seismographs) in the Pribilof Islands region is summarized in Table 3.1. The epicenters and maximum intensities of these events are poorly known, and it is not possible to compare the occurrence rate for this period, 1815-61, to that computed from the instrumentally recorded events for the period 1957-78. The observation that the 1836 earthquake caused damage rated at Modified Mercalli (M.M.) intensity X on the Pribilof Islands is significant. This event, along with those of 1847 and 1954 which were felt with M.M. intensity V-VI, and instrumentally recorded events of 1925 (magnitude 7.2), 1942 (6.75), 1958 (6.38), and 1959 (6.50), demonstrate that large earthquakes have occurred in the St. George region, and the Pribilof Islands in particular, and must be expected in the future.

3.3.2 Record of Instrumentally Recorded Earthquakes

Earthquakes recorded by a network of seismographs and located within the St. George Basin area are shown in Fig. 3.3. The data for this map are derived from four sources: (1) International Seismological Center, (2) Preliminary Determination of Epicenters, published by the USGS and archived by NOAA, (3) relocations by Tobin and Sykes (1966), and (4) relocations by Sykes (1971).

Deep events (depths greater than 112 km, shown by squares in Fig. 3.3) are associated with the northernmost limb of the Pacific lithospheric plate, which is being subducted along the Aleutian arc. Interspersed with the epicenters of deep events are about 30 events whose epicenter depths are unknown, but are probably shallow (depths less than 75 km). To the northwest of this band of interspersed epicenters of deep and shallow events; there are 19 additional events with unknown depths. We assume from their locations that these are probably shallow. Epicenters appear to be concentrated in the immediate region of the St. George Basin. A second concentration is centered in the southwest corner of the research area; these events are in the vicinity of the Umnak Plateau and the Bering Canyon. Lastly, a few outliers occur in the northeast part of the area.

The frequency of earthquake occurrence in the St. George Basin area is shown by a histogram of all instrumentally recorded events (Fig. 3.4). The increase in the number of events per year starting about 1957 is due to improved detection capabilities by seismograph networks, and is not due to a natural increase in activity.

In addition to seismograph records from the worldwide network, a single seismograph has been installed on St. Paul Island to monitor the frequency of occurrence of activity in the area. Since it takes a minimum of two stations to locate an earthquake, this station can only be used to detect events and provide an estimate of their distance from the station. The seismometer was installed in the Seismic Cottage (near the National Weather Service Observatory) on St. Paul Island during October 1975. The sensitivity of this seismograph is limited by surf noise propagated by alluvium on which the Seismic Cottage is located.

Table 3.2 gives arrival times, distances, and magnitudes for events detected at St. Paul which might have occurred in the St. George Basin; without azimuths, only the distance can be determined. A plot of magnitude vs. distance shows that the detection threshold at about 450 km is approximately magnitude 4. In other words, an earthquake in the southern St. George Basin must

Table 3.1. Earthquakes in the Pribilof Islands region located without seismographic records.

Year	Date	Location	Comments	References*
1815	-----	NE of St. George	With eruption?	3
1826	April 2	Pribilof Islands	"Violent," identical with 1836?	2, 3
1835	April 14	Pribilof Islands	"Severe," probably identical with 1836	2, 3
1836	April 2	Pribilof Islands	Milne III, Rossi-Forel intensity X	1, 2, 3
1836	August	Pribilof Islands	Weaker than April 2	2, 3
1847	-----	St. Paul	Rossi-Forel intensity VI	3
1861	April 28	St. George	"Light earthquake"	1, 2, 3
-----	-----	-----	-----	-----
1954	May 16	St. George	Modified Mercalli intensity V	2

*References
1. Davis and Echols (1962)
2. Coffman and von Hake (1973)
3. Kisslinger et al. (in prep.)

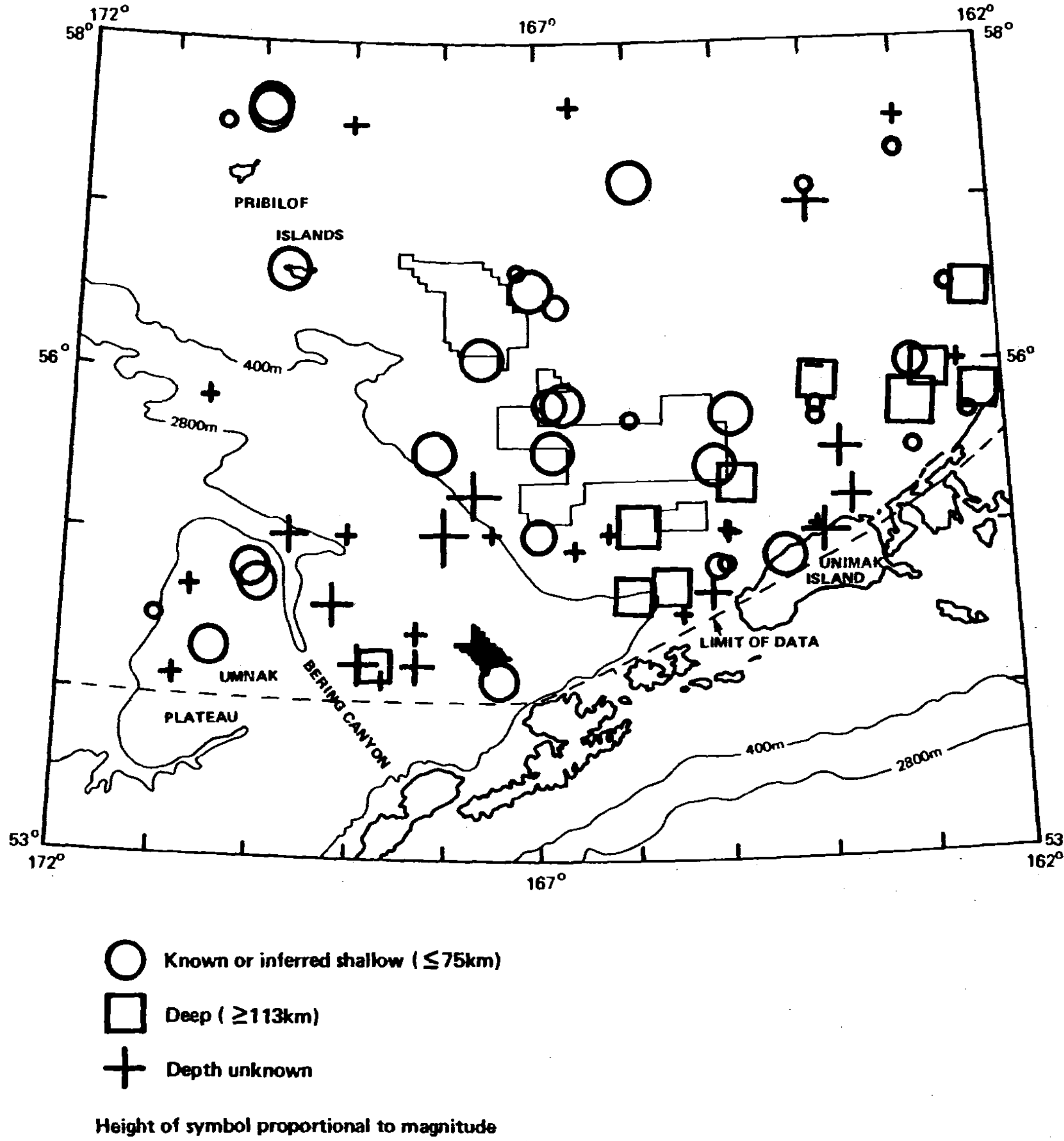

Figure 3.3. Locations of earthquakes in the St. George Basin area recorded by seimographs between 1925 and 1978 (see text for data souces). Magnitudes for these events range from 3.3 to 7.2, and most are between 4 and 5.

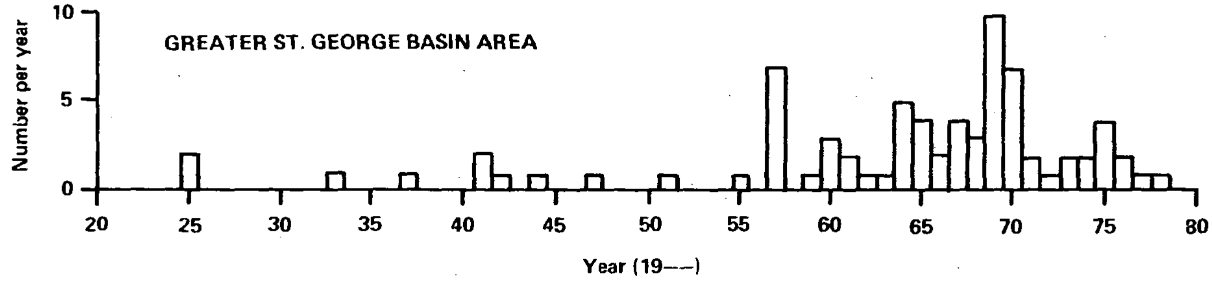

Figure 3.4. Histogram of earthquake occurrence in the St. George Basin area.

have a magnitude of 4 or greater to be detected at St. Paul.

In an attempt to determine the azimuth of the events recorded by this station, two remote stations were installed on St. Paul Island in July 1980. Unfortunately, none of the local events recorded since then have been impulsive enough so that arrival times could be read with any confidence, and therefore locations could not be calculated.

The occurrence rate of earthquakes of various magnitudes can be estimated from statistical analysis of the historical record. In doing this, it is necessary to have recorded all events occurring within a particular time interval and magnitude range. Certain assumptions are also made regard-

Table 3.2. Events detected at St. Paul Island in a distance range such that origin in St. George Basin is possible (May 1977 - July 1980).

Date (year month day)	Time	Distance from station (km)	Magnitude (local)
77 05 20	12:50	64	2.2
77 07 20	21:19	149	2.7
77 07 21	12:56	240	3.8
77 08 11	01:54	272	3.8
77 09 25	17:21	85	2.1
77 11 30	00:15	102	2.0
78 03 07	02:56	85	4.1
78 07 13	13:26	241	4.5
78 07 24	14:52	68	3.0
78 08 09	01:51	431	4.0
78 08 24	09:01	252	3.6
78 09 24	16:43	88	3.0
78 11 28	17:42	112	2.5
79 04 29	14:16	42	1.8
80 02 08	13:38	77	2.5
80 03 22	10:31	231	3.5
80 07 23	17:13	51	1.6

ing the natural frequency of occurrence when probabilities of future events, based on the occurrence rate calculated from historical records, are estimated. Using data for the St. George Basin area, estimates of the occurrence rate and probability of future events have been calculated (J. Davies, pers. comm.). The data available for this type of statistical analysis are very limited, and conclusions drawn from the analysis must be used carefully. The preliminary nature of this analysis and limited data make further discussion inappropriate for a report of this nature.

3.3.3 Estimation of Ground Acceleration

The limited region is that shown in Figure 3.3 excluding the Umnak Plateau and the northeast corner of the figure: an elongate region immediately surrounding the Basin and about 81,000 km² in area. Within the region, between 1957 and 1978 there were about 24 shallow events with magnitude larger than 4.2. If one assumes that the slope of the frequency-magnitude relation (the b-value) is about 1.0 we can use this number of previous earthquakes to infer how many earthquakes are to be expected in each of the magnitude ranges 4-5, 5-6, 6-7 and 7-8 during the next 40 years. Alternatively one can express this as a probability for the occurrence of an event in one of these ranges. Then using the radius inside of which accelerations would be expected to exceed 0.2, for example, for an event in a given range of magnitude, one can use the ratio of the area of this circle to that of the whole region (81,000 km²) to form the probability that an event of a certain size is close enough to cause accelerations exceeding the specified value, in this case, 0.2 g. Finally, the probabilities computed in this manner are summed for the four ranges indicated above to arrive at an estimate for the probability that a given site will experience an acceleration exceeding the specified value from all sources. When this is done for the levels 0.2 and 0.5 g, the probabilities 0.11 and 0.03, respectively are obtained for a 40 year time span.

There are two fundamental weaknesses in the above calculation, apart from the simple method itself. First, the data set is limited, but more data does not exist. The second is the lack of knowledge of the relationship of the size and distance of an earthquake to the accelerations it will cause. In the above calculation, data from the western United States were used along with limited data from the eastern Aleutians. In the OASES study (Woodward-Clyde, 1978) data from Japan were assumed to apply to the Aleutians. Neither of these data sets may be accurate for the Bering Shelf. Given these fundamental limitations in the data, it does not appear that a more sophisticated methodology would yield more satisfactory estimates of the probabilities for ground acceleration than those given above. Measurements of ground acceleration at offshore seafloor locations on the Bering Shelf are needed to resolve this difficulty.

Earthquake activity in the St. George Basin will be a consideration in the design of offshore structures, particularly those which have foundations on the seafloor, such as drilling platforms and submerged pipelines. The frequency of occurrence and ground motions to be expected will be extremely important in designing shore-based facilities on the Aleutian arc as well.

3.4 VOLCANIC ACTIVITY

3.4.1 Pribilofs

Mushketov and Orlov (1893, p. 198) report "a submarine earthquake and eruption" northeast of St. George in 1815. Barth (1956) cites Landgrebe (1855) for the statement that "flames have been seen to rise from the sea northeast of the Pribilof Islands." It is likely that both of these reports are based on a report from Kotzebue around 1821 to 1828 which we have not been able to find. Barth (1956, p. 154) concludes, "However, in spite of these assertions any present volcanic activity must be regarded as doubtful." Hopkins (1976) similarly concludes, "The volcanic hazard is small on and near St. Paul Island and negligible elsewhere." He also states, "The numerous isolated shocks in the vicinity of the Pribilof Islands *are probably* (emphasis ours) mostly ancient, eroded, volcanic centers . . . appropriate paleontological or radiometric methods (should be) used to establish their age." We conclude that volcanic activity is unlikely but suggest that Hopkins' advice be followed if any structures are to be built on or near St. Paul and St. George.

3.4.2 Makushin Bay

In 1878 the village of Makushin was destroyed by an earthquake (Mushketov and Orlov, 1893). The earthquake and associated tsunami have been reported as part of a crater-forming event at Okmok Volcano (Hantke 1951). Apparently the village was destroyed by the tsunami that swept along the north shore of Unalaska Island. Note that Makushin Bay is also exposed to Bogoslof Volcano at a distance roughly equal to that of Okmok.

3.4.3 Scotch Cap

The 1978 eruption of Westdahl deposited 1 m of ash on the U.S. Coast Guard light station at Scotch Cap. The ash damaged the light and forced the evacuation of the site; meltwater floods washed out the road to Cape Sarichef.

3.4.4 Other Volcanic Activity

Table 3.3 is a summary of reports of volcanic activity (Hickman, unpublished files) in the eastern Aleutian arc from Okmok Volcano on Umnak Island to Pavlof Volcano on the Alaska Peninsula. Of the 16 volcanoes listed, eight are rated as having high potential for eruption (4.5 on a scale of 0-5; see footnote 1,): Okmok, Bogoslof, Makushin, Akutan, Pogromni, Westdahl, Shishaldin, and Pavlof. Isanotski is given a moderate potential (3) and the remaining seven are rated at a low to negligible potential (2-0).

For the purpose of siting a pipeline terminal or tanker facility, those volcanoes with a high potential for eruption should be regarded as likely to produce the following hazards:

(1) Lavaflows, mudslides, floods, incandescent bombs, and nuees ardentes on the flanks and in valleys around the volcano.

(2) Ash and sand clouds capable of depositing up to a meter of material several tens of kilometers downwind from the volcano and a few centimeters of material at 100-150 km. The fine particles will produce a plume 100-200 km wide and 200-500 km long in which planes should not fly. This phase may persist from hours to days.

(3) Local tsunamis to distances of 100-150 km.

(4) Several hours to tens of hours of radio interference during the eruption.

3.5 SEISMIC AND VOLCANIC RISK

3.5.1 Pribilof Islands and St. George Basin

This region has produced earthquakes of magnitude 7.2 (1925) and intensity up to X (1836). The St. George Basin is a graben structure bounded by growth faults, one of which shows a scarp of about one meter. It is likely that the larger events occur along these boundary faults. A preliminary estimate suggests the probability that a randomly selected site within the St. George Basin region will experience accelerations due to strong ground shaking in excess of 0.2 g (g = gravity) within 40 years is about 11 percent; for 0.5 g it is about three percent. These values are based on 22 years of the teleseismic record of earthquakes in the St. George region, excluding Benioff zone events of the Aleutian arc. Existing data indicate activity of the same order as calculated from the teleseismic record. The probability of volcanic activity in the Pribilofs is very low. However, the possibility of recent submarine eruptions exists.

3.5.2 Aleutian Arc: Umnak to Pavlof Bay

The seismic potential of this region has been described by Sykes et al. (1980), Davies et al. (1981), and House et al. (1981). Of principal concern are the Shumagin Gap (162°-159°W) and the possible Unalaska Gap (167°-164°W). Both of these regions have a relatively high potential to produce a very great earthquake ($M_W > 8.7$) or a series of very large earthquakes ($M_W > 7.8$). The risk is greatest on the south side of the arc where there is the possibility of strong ground motion (~ 1 g) and local tsunami heights of ~ 30 m. The seismic risk of the southeasternmost St. George Basin is higher than estimated above for the whole Basin as a result of the potential for these very large or great earthquakes.

Within the Aleutian arc from Okmok to Pavlof are eight volcanoes that have a high potential for eruption with localized effects described in the last section. These effects along with the seismic risk are discussed for specific sites below:

(1) Bering Canyon. There is a suggestion in the epicenter map shown in Fig. 3.3 of a tendency for earthquakes to occur beneath the Bering Canyon. It is possible that the canyon may be an active structure, although it is not

Table 3.3 Reports of volcanic activity in the eastern Aleutian arc from Okmok Volcano, Umnak Island, to Pavlof Volcano, Alaska Peninsula.

Volcano	Report of activity Earliest		Latest	Eruption[1] Potential	Remarks
Okmok	1805	-	1958	5	1878, Makushin Village destroyed
Bogoslof	1796	-	1926	5	1796, 1883, 1926: island-forming events
Makushin	1768	-	1980	5	Two volcanoes active in 1768, Bishop Pt. mudflow 30 m high at shore
Akutan	1790	-	1980	5	Mud flow 1929, 1 km lava flow 1978
Akun	1828	-	1880	1	No historic eruptions, deeply dissected
Pogromni	1795	-	1965	4	
Westdahl	1826	-	1979	4	1 m of ash fell on Scotch Cap forcing evacuation, damaging light, floods washed out road, 1978
Fisher	1826	-	1826	1	Questionable report of eruption, 1826
Shishaldin	1775	-	1979	5	1978 Sept. 28, caused radio interference
Isanotski	1690	-	1845	3	1825: mudslides, ask to Pavlov Bay
Roundtop	none			0	No reports
Frosty	1768	-	1951	1	Reports for Walrus & Morshova assigned to Frosty[2]
Amak	1700	-	1715	1	No activity since 1804 at latest
Emmons	1768	-	1953	1	Reports for Medviednikof assigned to Emmons[3]
Pavlof	1790	-	1980	5	1914 eruption: 5 cm of sand on Unga
Pavlof's Sister	1762	-	1786	2	Not active since major eruption in 1786

---

[1] Eruption potential: scale 0-5. 0 = no historic activity, 1 = no historic eruptions, but smoke or steam reported, 2 = last eruption in 1700's, 3 = last eruption in 1800's, 4 = last eruption in 1900's, and 5 = last eruption in 1900's and I > 25.

[2] Morzhovoi = Walrus (Orth, 1967) but Walrus Peak is nonvolcanic. Waldron (1961) thinks Morshova and Frosty are the same. We tentatively agree.

[3] Medvied = Bear; Medvednikova Zaliv = Bear Bay on Alaska Peninsula at 162°W (Orth, 1967). Since Emmons Volcano is at 162°W, it seems possible that the old ($\leq$ 1850) reports for Medviednikof refer to Emmons. Note that Emmons received its present name about 1940.

possible to conclude this on the basis of the poorly located events mapped in Fig. 3.3. The Umnak Plateau region is seismically active, thus increasing the probability for slumps along the walls of the Bering Canyon and edge of the Bering Shelf.

(2) Makushin Bay. An eruption of Makushin Volcano could produce a significant ash fall in Makushin Bay. Also, the Bay opens toward both Okmok and Bogoslof Volcanoes, thus exposing it to the risk of a local tsunami. If the Unalaska seismic gap ruptures, strong ground motion will occur here.

(3) Dutch Harbor. Makushin Volcano or one of the volcanoes north of Wide Bay could deposit a significant amount of ash at Dutch Harbor; small amounts might also originate from Akutan. A local tsunami from Akutan is possible. If the Unalaska Gap ruptures, strong ground motion and a weak tsunami (1-3 m) will occur here.

(4) Ikatan or Morzhovoi Bay. Moderate ash fall from Shishaldin is possible. If either the Unalaska Gap or the Shumagin Gap ruptures, strong ground motion and a large tsunami (~ 10-30 m) will occur here. Ikatan Bay would be less exposed to an Unalaska event and more exposed to a Shumagin event, and vice versa for Morzhovoi Bay.

(5) Cold Bay. Small amounts of ash are possible from Shishaldin or Pavlof Volcanoes. Strong ground motion will occur if the Shumagin Gap ruptures. Depending on the exact rupture area, this bay may be somewhat sheltered from the tsunami.

(6) Pavlof Bay. Heavy ash fall is possible from Pavlof Volcano, as is a local tsunami. Strong ground motion and a large tsunami are possible if the Shumagin Gap ruptures. The Pavlof Islands may moderate the tsunami height within the bay.

3.6 SEA ICE: FREQUENCY AND OCCURRENCE

3.6.1 Introduction

The St. George Basin lies between the Pribilof Islands and the Alaska Peninsula and is generally the region of the southern limit of yearly oceanic ice in the eastern Bering Sea. With the advent of offshore petroleum leasing in these waters, questions have been raised concerning the extent and coverage of annual sea ice.

At the pack ice edge, storm conditions occur during which wave heights are substantial enough to drive ice floes against offshore platforms with destructive force. Observations and calculations related to this environmental hazard are not as yet available. However, the localized impact of such ice floes upon structures would be similar to the impact of ice floes upon the sides of icebreaking vessels when they are underway in areas of less than 100 percent ice cover. Such localized ice impact forces must be anticipated during the structure design process.

If seawater temperatures are near the freezing point, superstructure icing also becomes a potential hazard. This phenomenon can result in the rapid accumulation of large masses of ice on exposed surfaces. Its formation requires low air and sea surface temperatures, along with maximum surface winds to generate waves and spray. Spray icing should be considered an important factor in the design of offshore platforms for the St. George Basin.

Preliminary field sampling of ice floe size, shape, and thickness was carried out by S. Martin and is published elsewhere (Martin and Bauer, 1979). The average velocity of ice movement in the St. George Basin region has been obtained from sequential satellite images. However, very little information is published on the mechanical properties of warm (-2°C) sea ice as is frequently found in the Bering Sea. Effects of crystal orientation, grain size, and salinity upon strength have not been measured on that type of sea ice. It is important to recognize that the strength of sea ice depends upon strain rate, which in turn depends upon the instantaneous velocity of the ice adjacent to offshore structures and platforms at the location of ice failure. The local strain rate, corresponding to typical drift velocities of 30-50 cm/s, will cause brittle failure as the maximum value of its compressive strength is approached (Sackinger, 1981; Schwarz, 1971).

3.6.2 Monthly Sea Ice Distribution Maps

The U.S. Navy Fleet Weather Facility, Suitland, Maryland, compiles and publishes weekly sea ice charts of worldwide sea ice conditions. These charts are produced largely by means of satellite imagery, but direct aircraft observations are also utilized for verification purposes. In particular, aircraft with highly accurate positioning equipment are used to monitor the ice edge. We have utilized these charts to compile the maps presented here.

Because sea ice statistics tend to be more sensitive to latitude than longitude, the region of interest was divided into cells of 1° latitude by 5° of longitude. The Naval sea ice charts from 1972 to present were scaled for presence of ice in each cell and the average concentration reported for the cell. These numbers were then averaged on a monthly basis.

The monthly maps attached as part of this report show both these parameters for each cell. From left to right within each cell the first number gives the frequency with which ice was found within that cell during a particular calendar month and the second number gives an average of concentration over those occasions when ice had been present. Hence, for the cell containing the lower half of Nunivak Island, whose upper left-hand corner is located at 60° latitude and 165° longitude, there was ice present during 67 percent of the Novembers between 1972 and 1980 and the average of the concentrations on those occasions was six-tenths.

3.6.3 Results

Figure 3.5 gives the results of this analysis during the eight months starting in November when oceanic ice is found in this region. The cells containing the St. George Basin Lease Area have been indicated by an asterisk. The following observtions were made from these charts:

November By this month ice appears as far south as 57°N with a frequency of 33 percent. It is interesting to note that for a given latitude the frequency and coverage appear to be greater in cells adjacent to land than in cells removed from land. No ice appears yet in St. George Basin.

December Now ice appears as far south as 56°N about 22 percent of the time. However, the average coverage is only 20 percent. Again there is a tendency for frequency and coverage to be greater in cells adjacent to shore. Another interesting feature on this map is the appearance of cells which have had a 100 percent frequency of the occurrence of ice, two of which have had an average of 90 percent coverage. The northern cell containing the St. George Basin now has an ice frequency of 14 percent with an average coverage of 20 percent.

January Ice appears no farther south than in December. However, the frequency of occurrence in each cell tends to be greater. Of the five cells which have 100 percent frequency, three also have 100 percent coverage. The tendency for cells adjacent to land to contain ice more frequently and with greater coverage continues. Again only the northern cell containing the St. George Basin Lease Area has a nonzero probability of containing ice.

February Ice still appears no farther south than 56°N. However, the frequency and coverage are generally greater than in January. The tendency for cells adjacent to land to contain more ice than cells not adjacent to land appears to break down and reverse in some cases. The northern cell containing the St. George Lease Area now has a 56 percent frequency of containing ice with an average coverage of 30 percent.

March This is the month of greatest ice extent. Ice now appears as far south as 55°N. It is interesting that while in previous months many cells contained ice on 100 percent of all observed occasions, these cells now have contained ice between 60 and 90 percent of the years of observation. Furthermore, the earlier tendency for cells adjacent to shore to contain ice more frequently than cells removed from shore has completely disappeared. This is the only month during which both cells containing the St. George Basin have a nonzero history of containing ice. Although the frequency is 20 percent in both cells, the average coverage on those occasions is 90 percent in the northern cell and 30 percent in the southern cell.

April The average extent of ice begins to receed during this month. The maximum ice edge has retreated to 56°N. In addition, the frequency and coverage in all cells are reduced from the previous month. Only the northern cell containing the St. George Basin has ice during this month (20 percent of all Aprils) and the average coverage on those occasions is 40 percent.

May The maximum edge of ice remains at 56°N during this month. However, the frequency of ice and average coverage tend to decrease generally in the area. (No cell contains ice during more than 40 percent of all Mays.) The cell containing the northern portion of the St. George Lease Area still contains ice 20 percent of the time with an average concentration of 20 percent. At this time there is a general tendency for cells not adjacent to land to contain ice approximately twice as frequently as those adjacent to land.

June Ice is absent from nearly the entire study area. The small amount of ice remaining could well be fast ice grounded on shoals in nearshore waters.

There are two main blocks of leased being considered in the St. George Basin. One of these lies roughly in the northern cell discussed above and the other in the southern cell. Although both cells statistically contain ice during the winter, the frequency and coverage are much greater in the northern cell. The southern cell lies in the statistical southern limit of Bering Sea ice. The results for these two lease blocks are summarized below:

Month	Lease block	Frequency (%)	Average Coverage (%)
December	north	14	20
	south	0	0
January	north	11	20
	south	0	0
February	north	56	30
	south	0	0
March	north	20	90
	south	20	30
April	north	20	40
	south	0	0

Thus, between December and April, the northern lease tract has a finite chance of ice each month between December and April while the southern lease block only has had ice during March. During that month, the probability of ice in the northern block is nearly 60 percent.

Pease (1981) has shown that in late winter the Bering Sea may at times act as a "conveyor belt," transporting thick ice grown in the northern Bering Sea, or possibly even the Chukchi Sea, to the region of the ice edge. These results show that the entire St. George lease area lies within the extreme ice edge. The "conveyor belt" concept suggests that fairly thick floes (~ 1 m) may be transported to this ice edge. Certainly the design of structures and operating procedures related to offshore petroleum exploration and development in the St. George Basin should take this possibility in consideration.

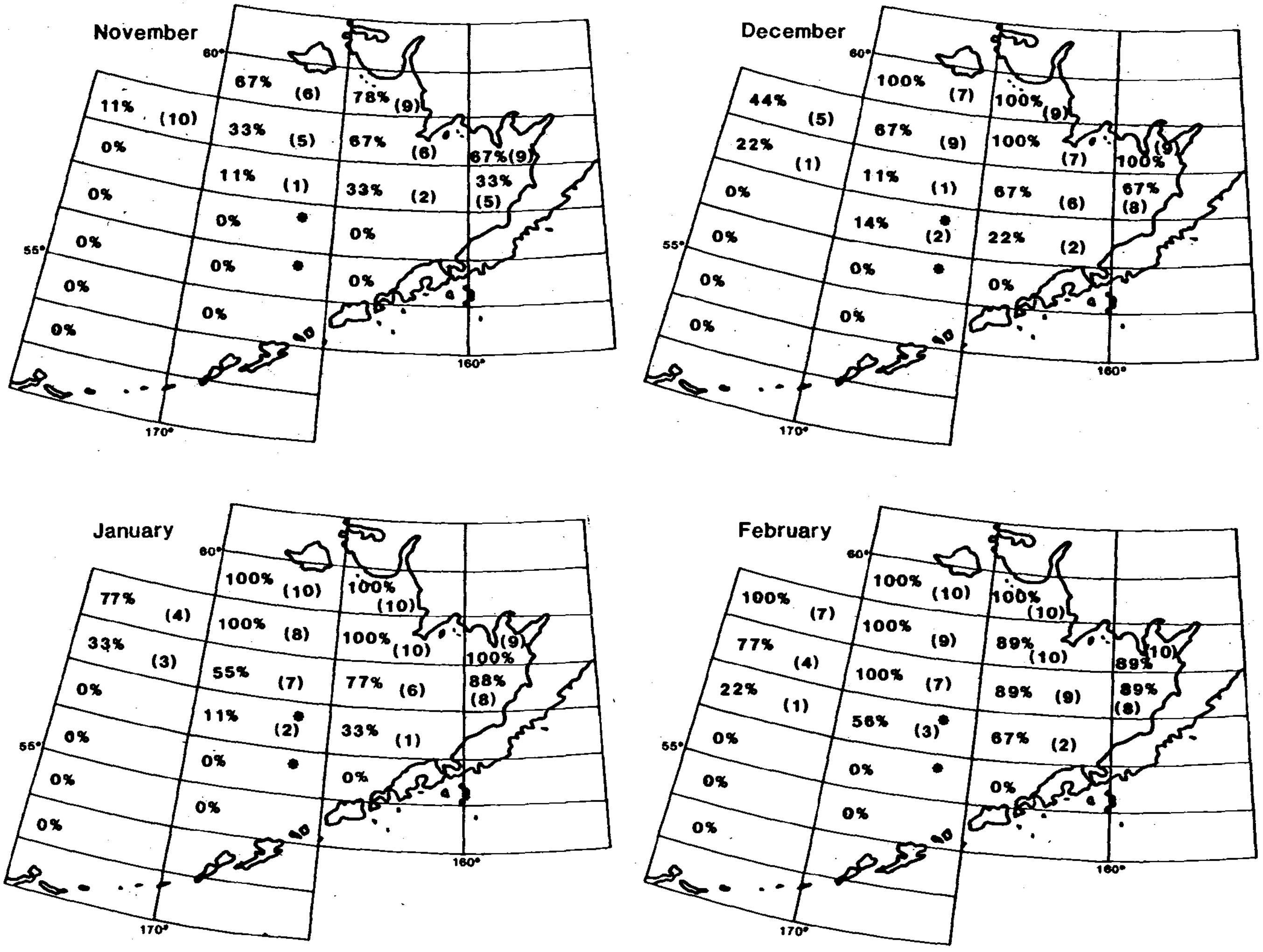

Figure 3.5. Frequency of occurrence and extent of ice coverage when ice is present in southeastern Bering Sea. The St. George Basin lease area occurs within cells indicated by an asterisk. See text for further description of values in cells.

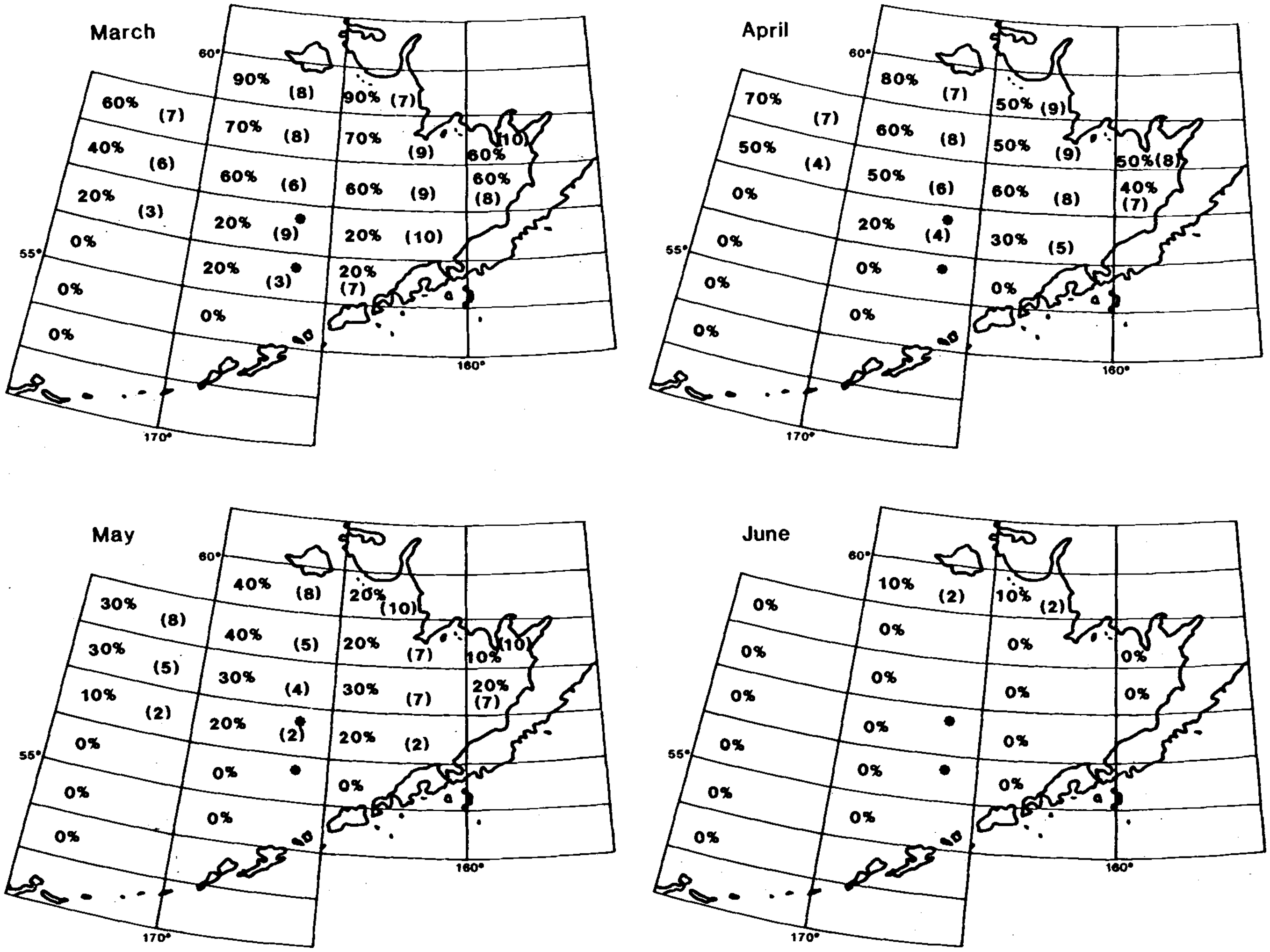

Figure 3.5. continued.

3.7 COASTAL GEOLOGIC PROCESSES

3.7.1 Status of Knowledge

The information available on coastal geomorphology and processes in the region of the southern Bering Sea, western Alaska Peninsula, and eastern Aleutian Islands is presently limited to the results of aerial and ground reconnaissance surveys. Berryhill (1963) described beach sediments in Bristol Bay with an emphasis on possible placer deposits. In an atlas format, Sears and Zimmerman (1977) depicted gross beach sediment texture, beach profile, and biological cover from aerial surveys at a scale of approximately 1:100,000. Sallenger et al. (1977) described beach sediment characteristics and coastal morphology for the Alaska Peninsula from Cape Mordvinof (Unimak Island) to Kvichak Bay, and interpreted littoral drift directions from the morphology. A similar reconnaissance study was also performed for the shorelines of Pavlof and Cold Bays on the Gulf of Alaska side of the peninsula (Sallenger et al., 1978). Very little published information is available on coastal morphology, sediments, and processes for the islands west of Unimak Pass, except for brief statements on beach materials contained with the series of U.S. Geological Survey bulletins on the geology of the Aleutian Islands (e.g., Drewes et al., 1962). One of these islands, Unalaska, is likely to be considered for OCS-related onshore facilities, either at Unalaska Bay or Makushin Bay.

The Bristol Bay shoreline of the Alaska Peninsula is comparatively straight, but is segmented by a number of shallow embayments. Although these embayments (e.g., Port Moller, Bechevin Bay) are too shallow for port facilities, several on the opposite side of the peninsula (e.g., Morshovoi Bay, Pavlof Bay) may be considered, possibly involving a pipeline crossing from the Bristol Bay side. Approximately 96 percent of the coast from Cape Mordvinof to Kvichak Bay is lined with beaches, the only exceptions being short segments associated with the relatively few headlands along this coastline. Most embayments are separated from open ocean by barrier islands or spits. Between embayments the shoreline is backed by vegetated erosional bluffs. These features seem to indicate that the long-term trend is generally that the embayments and their mouths have been sites of deposition at the expense of erosion of the exposed segments of coastline between them (Sallenger et al., 1977). Erosional features can be identified along approximately 26 percent of the coastline. In contrast to the northern Bering Sea coast where beach processes are dominated by relatively rare major storms, beaches of the southern Bering Sea are exposed to more frequent storm wave energy and undergo more constant modification.

Net longshore sediment transport, as interpreted from beach morphology, is generally to the northeast along the Bering Sea side of the Alaska Peninsula with local reversals near the embayments (Sallenger et al., 1977). Divergence is 10 to several tens of kilometers northeast of the embayments, and convergence is at the bay mouths creating sites of deposition there. Rates and volumes of sediment transport and rates of erosion have not been determined.

Coastal morphology and beach composition along the Gulf of Alaska side of the peninsula reflect the relatively high wave energy, low sediment supply, and predominance of volcanic bedrock. Bare rock cliffs, platforms, and steep beaches composed of boulders and gravel comprise much of the exposed coastline of the peninsula and offshore islands (Sears and Zimmerman, 1977). Sand and mud beaches are restricted primarily to the inner, protected areas of embayments, the west side of Pavlof Bay, and the south coast of Unimak Island. With the exception of these and other depositional areas within embayments, most of the coastline is erosional.

Sallenger et al. (1978) determined longshore sediment transport directions for Pavlof and Cold Bays. As expected, sediment is transported inward along the sides of the bays and deposited in the bay heads. Drift directions have not been determined for the remainder of the coastline. As with the Bristol Bay coastline, rates and volumes of longshore sediment transport and rates of erosion have not been determined.

3.7.2 Possible Geologic Hazards in Relation to Coastal Development

Sufficient information is not available to support specific conclusions about coastal geologic hazards or impacts that will be associated with development along the western Alaska Peninsula or eastern Aleutian Islands, except possibly those associated with the major events described elsewhere in this report, namely volcanic eruptions, earthquakes, tsunamis, and seiches. Sites have not yet been designated or proposed by the industry for shore facilities in support of oil-related activities in the St. George Basin (Sale 70) and North Aleutian Shelf (Sale 75) lease areas. Dutch Harbor and Cold Bay are likely support base locations for exploration, and Makushin Bay on Unalaska Island has been suggested as a possible pipeline terminus and site for production facilities (see section on seismic and volcanic hazards for a discussion of related hazards in Makushin Bay). Although it has been possible to generalize on areas of erosion and deposition, wave energy, coastal morphology, and longshore sediment transport, the evaluation of hazards and impacts associated with these processes will be largely site-specific due to their variability. Clearly there will be problems with coastal erosion in some areas, but the magnitude is unknown until more detailed studies of processes and rates can be made on a site-specific basis.

Depending on wave energy and rates of longshore sediment transport, coastal facilities such as jetties, breakwaters, and unburied pipelines may accelerate erosion or deposition, change a segment of coastline from one of deposition to one of erosion, or alter the coastal habitat. Some nearshore dredging may be required in bays developed for port facilities, such as Morzhovoi, Pavlof, and Cold Bays on the south side of the Alaska Peninsula, and the rates of sediment refilling and fate of dredged materials will also depend on these processes. These concerns are common to most coastal areas and require site-specific studies. Timing of the studies will be dictated by the results of exploration and the proposed types and locations of shore facilities appropriate to develop recoverable oil and gas resources, if any are discovered. When the proposed shore sites are known, area- and site-specific studies will be needed to determine long-term rates of erosion and longshore sediment transport.

For facilities on the Gulf of Alaska side of the peninsula, the hazard from a tsunami may be high. As discussed in the section on seismic hazards, there is a high probability of a great earthquake (magnitude 8.5 or greater) in the vicinity of the Shumagin Islands within the next 20 years. Depending on the depth of focus and nature of submarine ground rupture associated with such an event, a tsunami up to 30 m high may be generated. The effect at locations within embayments on the southeast side of the peninsula is difficult to predict because it will depend on the location of the offshore source and on complex interaction of the tsunami waves with offshore bathymetry and islands. Some areas, such as Cold and Pavlof Bays, appear to be protected in the sense that the shallow bathymetry and islands directly offshore of the bay mouths will probably diffuse tsunami energy before the wave hits the peninsula. Even so, a major effect may be the substantial withdrawal of water which always precedes arrival of a tsunami wave. Morzhovoi Bay would be particularly vulnerable to a tsunami, especially if its source is directly offshore near Sanak Island, because there are no bay-mouth islands nor shallow bathymetry to offer protection as for Cold and Pavlof Bays.

Coastal facilities within bays on both sides of the peninsula and Aleutian Islands may face serious damage from seiches generated by volcanic eruptions and associated mudflows, landslides, and earthquakes. This hazard is potentially more serious than the tsunami hazard described above because of the amplification effect of wave resonance within the bay. Again, the specific nature of these hazards can only be determined by site-specific studies for the locations proposed for shore facilities.

3.8 SUMMARY

In the St. George Basin, seafloor sediments are generally silt and silty sand, and bottom currents are very weak. The sediment is normally consolidated and stable as a foundation material. However, a subsea pipeline from the St. George Basin to a shipment point in the Aleutians should be routed around the Bering Canyon, where there is evidence of sediment instability, presumably triggered by seismic events or extreme storm activity. Similar sediment instability areas occur on the continental slope and shelf break, and pipeline routes should be chosen taking this into account. At depths of the order of 300 meters in the sediment of the St. George Basin, seismic reflection data have suggested that gas-charged sediment exists. During exploration drilling, rapid downhole pressure changes should be anticipated as these layers are penetrated. In some parts of the Basin, these gas-charged sediments are less than 100 meters below the surface and should be a consideration in foundation design for offshore structures. Seafloor surface fault scarps several meters high are found in the northern part of the Basin; active faulting has occurred in recent geologic time and these faults may still be active, but the existing seismic data base does not permit a definitive statement as to which faults are active. Analysis of existing earthquake records shows that between 1957 and 1978 there were 24 shallow events in the region with magnitude larger than 4.2, and that the seafloor accelerations of 0.2 g and 0.5 g have probabilities of 0.11 and 0.03, respectively, over a 40-year time span. (It is important to recognize that the relationship between earthquake magnitude and seafloor acceleration used in this calculation was obtained in the western United States, and its appropriateness in the Bering shelf remains to be checked.) The occurrence of a tsunami of appreciable height in the St. George Basin is not likely, but there is a very high probability of a 30-meter high tsunami on the south side of the Aleutians in the Shumagin region in the next 40 years. Any site for an oil terminal in the Aleutians should be sheltered from that tsunami. Furthermore, any terminal should be at least 100 km from the eight active volcanoes having a high potential for eruption: Okmok, Bogoslof, Makushin, Akutan, Pogromni, Westdahl, Shishaldin and Pavlof.

There is an appreciable probability of annual sea ice in the St. George Basin from December through May. As the pack ice edge is in this area, there are storm conditions in which wave action may drive ice floes against offshore platforms with localized high impact force; such forces should be anticipated during the structure design process. It is also likely that substantial superstructure ice accumulation will take place, when the wind velocity is high and the sea and air temperatures are low. This is an important consideration in the design of offshore platforms for the St. George Basin. When the annual pack ice has reached an offshore structure, substantial lateral forces due to ice may be expected, as found in Cook Inlet, but because of the greater water depth, the overturn movement is larger, and appropriate modifications in structure design will be necessary.

3.9 REFERENCES

Barth, T. F. 1956. Geology and petrology of the Pribilof Islands, Alaska. U. S. Geol. Surv. Bull. 1028-F, pp. 101-160.

Berryhill, R. V. 1963. Reconnaissance of beach sands, Bristol Bay, Alaska. U. S. Bur. Mines, Rep. Inv. 6214.

Coffman, J. L., and C. A. von Hake (eds.). 1973. Earthquake history of the United States. U. S. Dep. Commerce/NOAA, U. S. Govt. Printing Off., Washington, D.C. Pub. 41-1

Davies, J. N., L. R. Sykes, L. House, and K. H. Jacob. 1981. Shumagin seismic gap, Alaska Peninsula: History of great earthquakes, tectonic setting, and evidence for a high seismic potential. J. Geophys. Res. 86:3821-3855.

Davis, T. N., and C. Echols. 1962. A table of Alaskan earthquakes 1788-1961. Geophys. Inst., Univ. Alaska, Fairbanks. Geophys. Rep. 8.

Drewes, H., G. D. Fraser, G. C. Snyder, and H. F. Barnett, Jr. 1962. *In:* Geology of Unalaska Island and adjacent insular shelf, Aleutian Islands, Alaska. U. S. Geol. Surv. Bull. 1028-S, pp. 583-676.

Gardner, J. V., T. L. Vallier, and W. E. Dean. 1979. Sedimentology and geochemistry of surface sediments and the distribution of faults and potentially unstable sediments, St. George Basin region of the outer continental shelf, southern Bering Sea. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Phys. 2:181-271.

Hantke, G. 1951. Review of volcanic activity 1941-47. Bull. Volcan. 11:161 (in German).

Hopkins, D. M., 1976. Fault history of the Pribilof Islands and its relevance to bottom stability in the St. George Basin. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 13:41-68.

House, L., L. R. Sykes, J. N. Davies, and K. H. Jacob, 1981. Identification of a possible seismic gap near Unalaska Island, eastern Aleutians, Alaska, pp. 81-92. *In:* P. G. Richards and D. W. Simpson, (eds.), *Earthquake Prediction – an International Review.* Maurice Ewing series 4, Amer. Geophys. Union, Washington, D.C.

Kisslinger, J. B., J. N. Davies, L. R. Sykes, K. H. Jacob, and L. House (in preparation). Historical earthquakes in Alaska during the period of Russian ownership.

Landgrebe, G. 1855. Naturgeschichte der Vulkane, Gotha.

Martin, S., and J. Bauer. 1979. Properties of the Bering Sea ice edge during March 1979. Monthly Westher Rev. 108:2045-2056.

Mushketov, I., and A. Orlov. 1893. Catalog of earthquakes of the Russian Empire. Contr. Russian Geog. Soc., General Geography, 26.

Orth, D. J. 1967. *Dictionary of Alaska Place Names.* U. S. Geol. Surv. Prof. Paper 567.

Page, R. A., D. M. Boore, W. B. Joyner, and H. W. Coultner. 1972. Ground motion values for use in the seismic design of the Trans-Alaska Pipeline System. U. S. Geol. Surv. Circ. 672.

Pease, C. H. 1981. Eastern Bering Sea ice dynamics and thermodynamics, *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 1:213-243

Sackinger, W. M. 1981. A review of technology for Alaskan offshore petroleum recovery, pp. 735-754. *In:* Proc. Sixth Inter. Conf. Port and Ocean Engineering Under Arctic Conditions (POAC-81), Quebec, Canada.

Sallenger, A. H., Jr., R. Hunter, and J. R. Dingler. 1977. Coastal processes and morphology of the Bering Sea Coast of Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 18:159-225.

Sallenger, A. H., Jr., J. R. Dingler, and R. Hunter. 1978. Coastal processes and morphology of the Bering Sea Coast of Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 12:451-503.

Schwarz, J. 1971. The pressure of floating ice-fields on piles, pp. 373-385. *In:* Proc. 1AHR Symposium on Ice Problems, Hanover, N.H.

Sears, H. S. and S. T. Zimmerman. 1977. *Alaska Intertidal Survey Atlas.* U.S. Dep. Comm., NOAA/NMFS, Auke Bay, Alaska.

Sykes, L. R. 1971. Aftershock zones of great earthquakes, seismicity gaps, earthquake prediction for Alaska and the Aleutians. J. Geophys. Res. 76:8021-8041.

Sykes, L. R., J. B. Kisslinger, L. House, J. N. Davies, and K. H. Jacob. 1980. Rupture zones of great earthquakes, Alaska-Aleutian arc, 1784-1980. Science 210:1343-1345.

Tobin, D. G., and L. R. Sykes, 1966. Relationship of hypocenters of earthquakes to the geology of Alaska. J. Geophys. Res. 71:1659-1667.

Waldron, H., 1961. Geologic reconnaissance of Frosty Peak Volcano and vicinity, Alaska. U.S. Geol. Surv. Bull. 1038-T.

Woodward-Clyde Consultants, 1978. Offshore Alaska seismic exposure study (OASES). Prepared for the Alaska Subarctic Offshore Committee, March 1978.

CHAPTER 4

MARINE MAMMALS

H. W. Braham, G. W. Oliver, C. Fowler, K. Frost, F. Fay, C. Cowles, D. Costa, K. Schneider and D. Calkins.

4.1 INTRODUCTION

The St. George Basin holds some of the most important fish and wildlife resources in Alaska. Located in the southeastern Bering Sea between the eastern Aleutian and Pribilof Islands, the Basin is the gateway for virtually every marine mammal, fish, and bird species moving between the North Pacific and the Bering Sea; it includes or adjoins wintering grounds for most of the species that move between the Arctic Ocean and the Bering Sea and North Pacific. The diversity and seasonal abundance of these animals in and adjacent to Unimak Pass and along the continental slope can be found in no other part of Alaska and perhaps the world. The ecological significance of this region to marine mammals (as well as other wildlife and fishes) is not yet fully understood, but in sheer numbers and multitude of species it is a region of primary importance. Of about 35 marine mammal species in the northern North Pacific and Bering Sea, 89 percent of the baleen whales, 57 percent of the toothed whales, and 73 percent of the pinnipeds and carnivores regularly frequent the Basin. There are two reasons for this diversity in the Basin: (1) it contains important breeding and feeding habitats, and (2) it is a transition zone for migrating animals (Table 4.1).

About 75 percent of the world population of northern fur seals *(Callorhinus ursinus)* breed and feed in the Basin and adjacent Pribilof Islands. For the eastern North Pacific gray whale *(Eschrichtius robustus)*, the Basin and immediate adjacent waters are also vital during migration. Large numbers of Steller (northern) sea lions *(Eumetopias jubatus)*, harbor seals *(Phoca vitulina)*, spotted seals *(P. largha)*, ribbons seals *(P. hispida)*, bearded seals *(Erignathus barbatus)*, walruses *(Odobenus rosmarus)*, fin whales *(Balaenoptera physalis)*, and sea otters *(Enhydra lutris)* feed in and near the Basin and, in several cases, mate, pup, and rear their young there as well.

4.2 THE ENVIRONMENT

About half of the St. George Basin lease area is comprised of shallow continental shelf waters from 40 to 200 m deep; depths in the southern half range mainly from 200 to 3,500 m. The proposed OCS lease area is located on the shelf, within the Basin proper, in waters 100-200 m deep, about midway between the Pribilofs and Unimak Island (see Fig. 1.1). The importance of the lease area as a migratory corridor for many species of marine mammals as well as fish and birds entering and leaving the Bering Sea is well documented. The Basin and Unimak Pass also are on the main shipping lane between the Bering Sea and North Pacific Ocean, and will be on the route for tankers carrying oil from more northern fields after production begins. Support facilities for OCS development activities are likely to be situated near the Basin (e.g., at Makushin Bay, Cold Bay, Dutch Harbor, or St. Paul).

4.3 DATA SOURCES

Sighting information used for this report is from NOAA's Platforms of Opportunity Program, (POP) data base (c.f. Fiscus et al., 1976; Consiglieri and Braham, in prep.), several OCSEAP studies between 1975 and 1978 (c.f. Braham et al., 1977), unpublished National Marine Fisheries Service and Alaska Department of Fish and Game data collected in the 1950's, 1960's, and 1970's, unpublished OCSEAP data collected in the late 1970's, and published reports. We also depended heavily on Severinghaus (1979) and Braham and Rugh (in prep.).

Information concerning fur seals is summarized in the Environmental Impact Statement on the Interim Convention on Conservation of North Pacific Fur seals (U.S. Dep. Comm., 1980), which also lists other important sources of information not covered in the EIS itself. Further information is given by Kajimura et al. (1979, 1980), Kozloff (1981), and McAlister (in prep.).

4.4 THE MAMMALS

At least 24 species of marine mammals regularly frequent the St. George Basin lease area (Table 4.1). Those marked with an asterisk are designated as endangered species, pursuant to the Endangered Species Act of 1973. Plots of cetacean sightings are shown in Figs. 4.1 and

Table 4.1. Marine mammals of the St. George Basin.

Species	Population size	Current population status	Seasonal usage	Migrating	Feeding	Breeding
*Gray whale	13,000- 17,000 (NP)	increasing	Sp, F	X	?	
*Fin whale	17,000 (NP)	unknown	Sp, S, F	X	X	
*Humpback whale	850 (NP)	unknown	Sp, S, F	X	X	
*Bowhead whale	2,300 (BS)	unknown	Sp, W			
*Right whale	150-200 (NP)	unknown	S, F	?	X	
*Blue whale	1,500 (NP)	unknown	S		X	
*Sperm whale	780,000 (NP)	presumably stable	S		X	
Minke whale	unknown	probably healthy	Sp, S, F, W	X	X	?
Killer whale	unknown	probably healthy	Sp, S, F, W	X	X	X
Bottlenose whale	unknown	unknown	unknown	?	X	?
Goosebeaked whale	unknown	unknown	unknown	?	X	?
Sabertoothed whale	unknown	unknown	unknown	?	X	?
Belukha whale	9,000- 16,000 (NP)	probably healthy	Sp, S, F, W		X	X
Dall's porpoise	80,000- 1,300,000 (NP)	unknown	Sp, S, F, W	?	X	X
Harbor porpoise	unknown	unknown	unknown	?	X	?
Northern fur seal	1,250,000 (SGB)	decreasing	Sp, S, F	X	X	X
Steller sea lion	33,000 (SGB)	unknown	Sp, S, F, W	X	X	X
Harbor seal	30,000- 35,000 (SGB)	healthy	Sp, S, F, W		X	X
Ribbon seal	100,000 (BS)	healthy	Sp, W		X	X
Ringed seal	1,000,000 (BCB)	healthy	Sp, W		X	
Spotted seal	200,000- 250,000 (BS)	healthy	Sp, W		X	
Bearded seal	300,000 (BCB)	healthy	Sp, W		X	X
Walrus	23,000- 30,000 (SGB)	increasing	Sp, W		X	X
Sea otter	17,000 (SGB)	increasing	Sp, S, F, W		X	X

NP = North Pacific Ocean and Bering Sea
BS = Bering Sea
SGB = St. George Basin
BCB = Bering, Chukchi, and Beaufort seas
* = Designated as endangered species under the Endangered Species Act of 1973

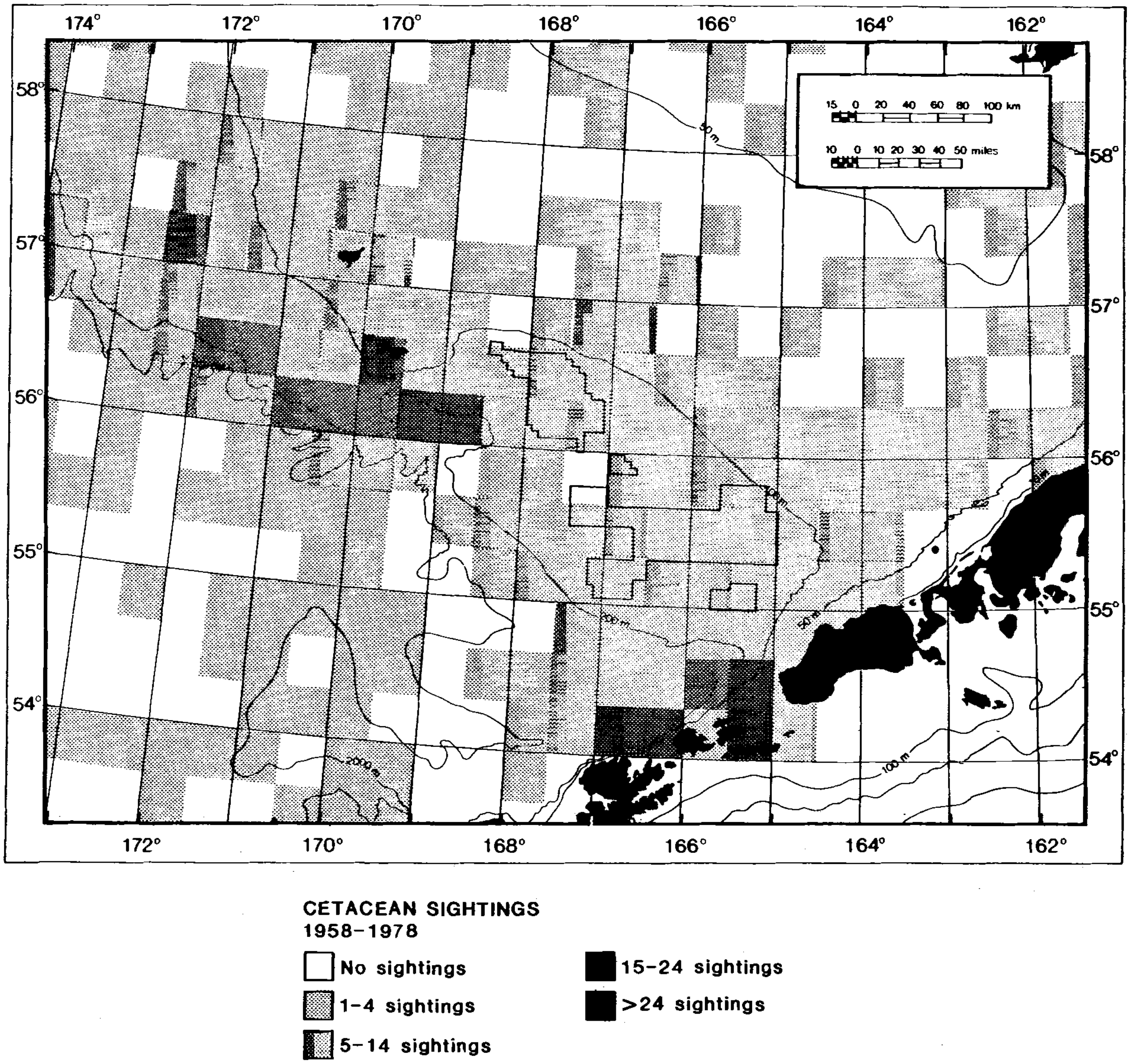

Figure 4.1. Distribution of sightings of cetaceans. Data from NMFS Platforms of Opportunity Program 1966-80 (compiled from Braham et al., 1977; Braham and Rugh, in prep.).

4.2, and pinniped distribution in Figs. 4.3, 4.4, and 4.5.

4.4.1 Cetaceans

Gray Whale *(Eschrichtius robustus)*

The gray whale is endemic to the North Pacific. The current Eastern North Pacific stock is estimated at 15,000-17,000 individuals (Reilly et al., 1980; Reilly, 1981), 13,000-15,000 of which occur in the Bering Sea from April to December (Rugh and Braham, 1979). The Korean stock is nearly extinct (Brownell, 1977). Gray whales migrate annually in autumn from their northern feeding grounds in the Chukchi and Bering seas to their southern calving areas along Baja California, Mexico, then back to the Bering-Chukchi seas in spring. Both northerly and southerly migrations are coastal (Pike, 1962; Rice and Wolman, 1971; Braham et al., 1977). The whales apparently feed in Alaskan waters during their northward migration (Braham, in prep.). All pass through Unimak Pass in spring and summer (Braham, 1977; Hall et al., 1977) and in fall (Rugh and Braham, 1979) and hug the west coast of Unimak Island, thus skirting the eastern edge of the lease area (Fig. 4.2). In spring, a few may migrate directly northwestward to the Pribilof and St. Matthew Islands. Several dozen are seen there annually; however, most remain near shore throughout Bristol Bay (Braham et al., 1977; Braham, in prep.). During the southbound migration from mid-October to late December in the southeastern Bering Sea, an unknown fraction of the population migrates directly through the northeastern part of the St. George Basin toward Unimak Pass, whereas the remainder follow the coastal route.

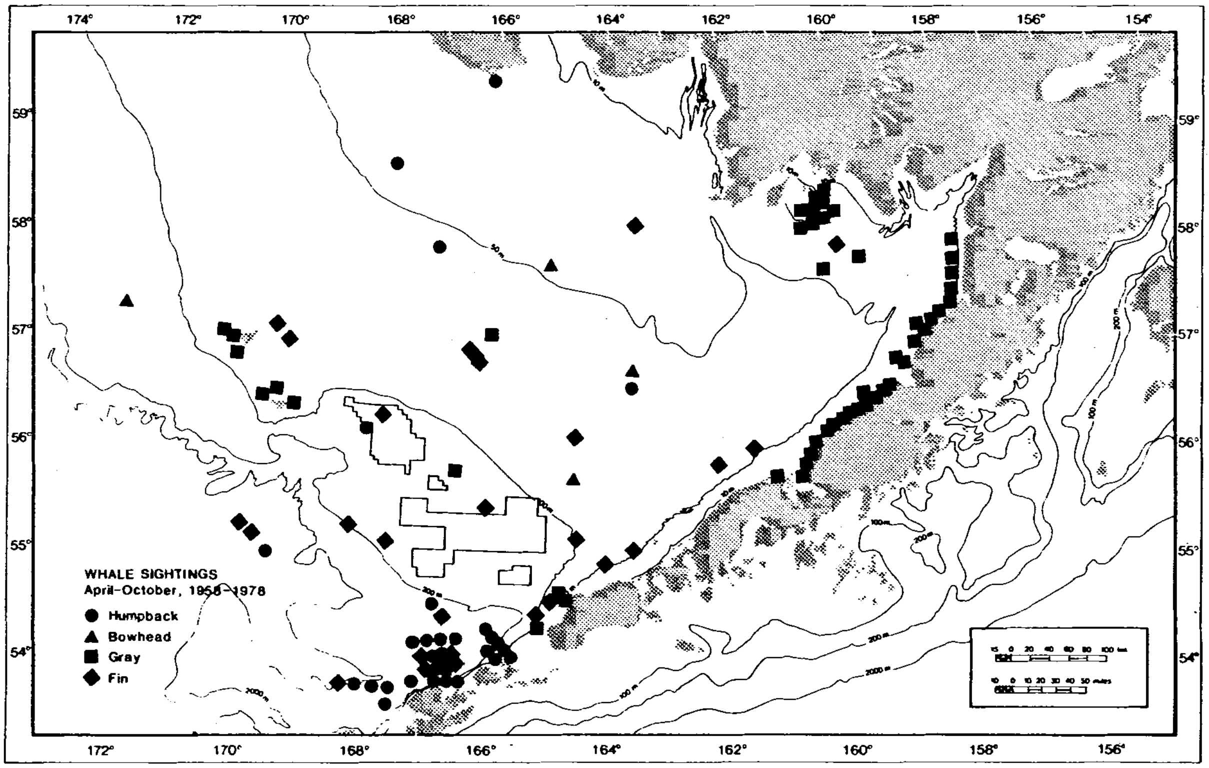

Figure 4.2. Distribution of sightings of baleen whales. Data from NMFS Platforms of Opportunity Program 1966-80 (Braham and Rugh, in prep.).

Fin Whale *(Balaenoptera physalus)*

The North Pacific population of the fin whale has been estimated at 17,000 (Tillman, 1975), but it is not known what percentage of these whales enters the Bering Sea. Each spring, fin whales migrate north from their southern calving grounds in the warm waters of the Pacific to feeding grounds in the North Pacific and Bering Sea and remain there until late autumn (Nemoto, 1959; Tomilin, 1957). The northern limit of their range is the Chukchi Sea (Berzin and Rovnin, 1966). One migratory route appears to parallel the continental slope in the Bering Sea from the southeast to the northwest. They appear to enter the Bering Sea via Unimak Pass, and perhaps to a lesser extent through passes west of the Basin. Fin whales spend six to eight months in the St. George Basin and feed over the continental slope and shelf (Fig. 4.2) (Nemoto, 1959).

Humpback Whale *(Megaptera novaeangliae)*

The North Pacific population of the humpback whale is estimated to be 850 (Rice, 1978a). It is not known how many occur in the Bering Sea. Humpback whales begin to arrive on the northern feeding grounds of the southern Bering Sea and the North Pacific in early summer (Nishiwaki, 1967). They are found in the St. George Basin from May through October. Photo-identification of these whales indicates migratory routes between Hawaii and southeastern Alaska, and between Mexico and southeastern Alaska, but we do not know which animals summer in the Bering Sea. Formerly, large numbers of humpback whales were regularly sighted in the southern portion of the Basin. Heavy commercial exploitation from 1912 to 1965 in the eastern Aleutian Islands apparently devastated the population frequenting the Basin. There have been few sightings since 1966. Soviet and Japanese tagging and whaling records (Ivashin and Rovnin, 1967; Ohsumi and Masaki, 1975) indicate that humpbacks heading for the Basin migrate between Japan and the southeastern Bering Sea. Data from southeastern Alaska indicate site fidelity and some overwintering; however, this behavior is unknown for humpbacks in the Bering Sea.

Bowhead Whale *(Balaena mysticetus)*

The Bering Sea population of the bowhead whale is estimated at 1,800 to 2,900, with a best estimate of 2,300 to 2,900 (Braham et al., 1979; Krogman et al., 1981; Krogman, pers. comm. to Braham). Bowheads migrate from their wintering grounds in the west-central Bering Sea to summer and fall feeding areas of the Chukchi and Beaufort seas (Braham, et al., 1980b,c). They are rarely seen in the Basin; only three individual sightings (Fig. 4.1) have been made near the Basin, all in early spring (Braham et al., 1977). Another sighting was made just west of St. Paul Island in April 1976 (Braham et al., in press, a). During unusual ice conditions, some bowheads are likely to be found in or near the northwest section of the Basin.

Right Whale *(Balaena glacialis)*

The Pacific right whale population is near extinction because of overexploitation during this century. The current estimate is 150 to 200 animals (Wada, 1975). Only two sightings of four individuals have been made in recent years, both in the Gulf of Alaska. The literature and past sighting data suggest that right whales previously and regularly occurred in the Basin during the summer (Omura, 1958).

Minke Whale *(Balaenoptera acutorostrata)*

The minke whale is the smallest of the rorquals and apparently the most abundant; no current population estimates are available, however. Their migration in the North Pacific is poorly understood but apparently is northward in the spring and southward in the fall (Tomilin, 1957), They arrive in the Basin earlier than other rorquals. Individuals of this species have been sighted in the Bering Sea pack ice in April. They may occupy the St. George Basin year round, with greatest concentrations in summer near the eastern Aleutian Islands.

Blue Whale *(Balaenoptera musculus)*

About 1,500 blue whales inhabit the North Pacific (Tillman, 1975). They rarely enter the Bering Sea. Berzin and Rovnin (1966) found seven just south of the Pribilof Islands during summer. There have been no recent sightings.

Sperm Whale *(Physeter macrocephalus)*

Sperm whales are the most abundant large cetacean in the North Pacific, with approximately 725,000 individuals (Rice 1978c). They occur offshore in all oceans. Adult females and immatures are found primarily in waters warmer than 10°C, and thus south of the Basin. Adult males regularly occur from 40°N to polar seas, although they are more common in antarctic than arctic waters. Occasionally, bulls have been observed feeding in the deep waters off the continental shelf north of the Aleutian Islands during the summer months (Ohsumi, 1966; Ohsumi and Masaki, 1977).

Dall's Porpoise *(Phocoenoides dalli)*

The North pacific population of *P. dalli* has been estimated at 800,000-1,350,000 (Bouchet, 1981), but the size of the southeastern Bering Sea population is unknown. These porpoises range from Baja California, along the west coast of North America, across the North Pacific Ocean to the coastal waters of Japan; their northern limit is about 66°N (U. S. Dep. Comm., 1981). Dall's porpoises inhabit the Basin the entire year but are most abundant near the continental slope in summer. Migratory movements are not well understood; however, sightings from the POP suggest seasonal onshore-offshore movements through the Basin. Porpoises are believed to calve and feed in and near the lease sites (U.S. Dep. Comm., 1981).

Killer Whale *(Orcinus orca)*

The population size and status of killer whales are unknown. They are cosmopolitan. Their migration is poorly understood, but cumulative data suggest that killer whales migrate in response to the distribution of their prey, especially fish. Resident groups are known to occur in Puget Sound and southwest British Columbia but are unknown for the southeastern Bering Sea. Killer whales range throughout the Basin at all seasons but are most abundant during summer just south of the Pribilof Islands on the continental shelf and slope, and along the north side of the eastern Aleutian Islands (Kawamura, 1975; Braham and Dahlheim, in press). All life cycle activities are believed to take place in the Basin. Though a definite calving period has not yet been determined, preliminary data for the Puget Sound area suggest fall births (M. E. Dahlheim, pers. comm. to Braham).

Giant Bottlenose or Baird's Beaked Whale *(Berardius bairdii)*

Little information is available on this medium-sized cetacean. It is endemic to the North Pacific, ranging from the Chukchi Sea southward (Sleptsov, 1961a), especially from St. Matthew Island, in the Bering Sea, through the Gulf of Alaska and south to southern California (Rice, 1978b). Seasonal movements are poorly understood; however, their presence in the Basin is expected.

Belukha or White Whale *(Delphinapterus leucas)*

The belukha is the most numerous and widely distributed cetacean in the Arctic. The Alaska population is composed of a Cook Inlet stock and one or, more likely, several stocks in Bristol Bay and throughout the Bering Sea (Braham, in press, a). The Cook Inlet stock is estimated at 300-400 animals. (Klinkhart, 1966) The Bristol Bay-Bering Sea stock is estimated at 9,000-16,000 (Interagency Task Group, 1978). About 1,500 of the latter are concentrated in Bristol Bay (Sergeant and Brodie, 1975; Interagency Task Group, 1978). Belukhas may occur in the Basin in the winter and spring when the seasonal pack ice is present, as evidenced from April 1976 sightings (Braham et al., 1977), but they are probably absent in ice-free months (Braham et al., in press, a). They apparently inhabit coastal waters of Bristol Bay year round, particularly in summer when calving occurs.

Harbor Porpoise *(Phocoena phocoena)*

The harbor porpoise is a boreal-temperate zone species found along much of the North Pacific coast between Point Barrow and central California. No estimates of their numbers are available. They inhabit the Basin but are elusive, and they have probably been overlooked during surveys. Their abundance apparently increases south and east of the St. George Basin in coastal waters, although this has not been quantitatively verified.

Goose-beaked or Cuvier's Beaked Whale *(Ziphius cavirostris)*

Ziphius is found in all oceans, except for arctic and antarctic waters. There are no population estimates, and migration patterns are unknown. This species is believed to frequent deeper, pelagic waters; however, they have been reported from coastal areas of the Aleutian Islands west of the Basin (Kenyon, 1961). At least one was sighted north of Unimak Island (Braham et al., 1977), and a skull was found on Akun Island (Fiscus et al., 1969).

Bering Sea Sabertooth, or Stejneger's Beaked Whale *(Mesoplodon stejnegeri)*

Only one of the three North Pacific species of *Mesoplodon* is believed to frequent subarctic waters of the Bering Sea (Moore, 1966). *M. stejnegeri* is reported for the Aleutian Islands and the southern Bering Sea near the Pribilof Islands (presumably *stejnegeri)* up to approximately 60°N (Jellison, 1953; Sleptsov, 1961b; Moore, 1966; Loughlin et al., in prep.). There are no population size estimates and no understanding of temporal habits such as migration. They are believed to feed in deep waters, presumably on the continental slope or farther out to sea. Recent sightings of up to 52 *Mesoplodon* sp. individuals were made in summer 1979 by Loughlin et al. (in prep.) near the central Aleutian Islands west of the St. George lease area.

4.4.2 Pinnipeds

Northern Fur Seal *(Callorhinus ursinus)*

The most abundant pinniped in the St. George Basin is the northern fur seal. Fur seals occur in large concentrations in the Pribilof Islands area from May to November. The Pribilof population of fur seals is estimated to be about 1.25 million animals, 80 percent of which are found on St. Paul Island (Lander, 1980). This is about 74 percent of the world population. Over 200,000 pups are born on the Pribilofs each year.

Pupping and breeding peaks in the first week of July. After giving birth, the females spend about two-thirds of their time at sea near the edge of the continental shelf and slope where prey populations are concentrated (Fig. 4.3). Presumably, the young of both sexes (one-and two-year-olds) are also found in these or similar feeding areas farther from the islands.

There is a marked age and sex segregation in the arrival and departure of the fur seals at the Pribilof Islands. Adult males appear in late May and June and establish their breeding territories. Active breeding males do not feed again until mid-August or later. Females begin to arrive in June, the pregnant individuals appearing first. Numbers increase through the summer as progressively younger animals return; few of the one- to two-year age classes are seen on the Pribilof Islands until late August and September. Adult males leave the islands first (August and September); females leave by late October; and the pups, which first enter the water at a few weeks of age and spend increasingly longer periods of time there, leave in October-November.

Areas where fur seals migrate and feed are of particular concern in predicting the effects of the exploration and development of petroleum resources in the St. George Basin. As they migrate to and from the Pribilofs, fur seals pass through the Aleutian Island chain, primarily through Unimak Pass (Fig. 4.3). During the breeding season, the seals are concentrated near the islands. Females and subadults tend to travel to the southwest near the edge of the continental shelf for feeding. Nursing females may not range as far as others, since they repeatedly return to feed their pups.

Steller (Northern) Sea Lion *(Eumetopias jubatus)*

Sea lions are common on haul-out and breeding rookeries year round on eastern Aleutian Islands and, to a lesser extent, on Amak Island, Sea Lion Rock, and Round Island to the east of the Basin (Braham et al., 1980a). Six important pupping areas are Adugak and Ogchul Islands off the west end of Umnak Island; Bogoslof Island, north of Umnak Island; the southwest end of Unalaska Island at Cape Izigan; Cape Morgan, on Akutan Island; and Ugamak Island in Unimak Pass. Breeding rookeries also are present on Sea Lion Rock near Amak Island, northeast of Unimak Island, and on Walrus Island in the Pribilofs. Cape Morgan and Ugamak Island are the largest, accounting for over 55 percent of the total animals (15,000-35,000) seen on breeding islands or sites (Braham et al., 1980a). The total estimated population for the eastern Aleutian Islands, Amak Island, and Sea Lion Rock is about 30,000. An additional 2,000-3,000 animals occur on St. George, St. Paul, Otter, and Walrus Islands (C. Fiscus, pers. comm. to Braham). The Alaska population is estimated to be greater than 250,000 (Fiscus et al., in press; D. Calkins, pers. comm.).

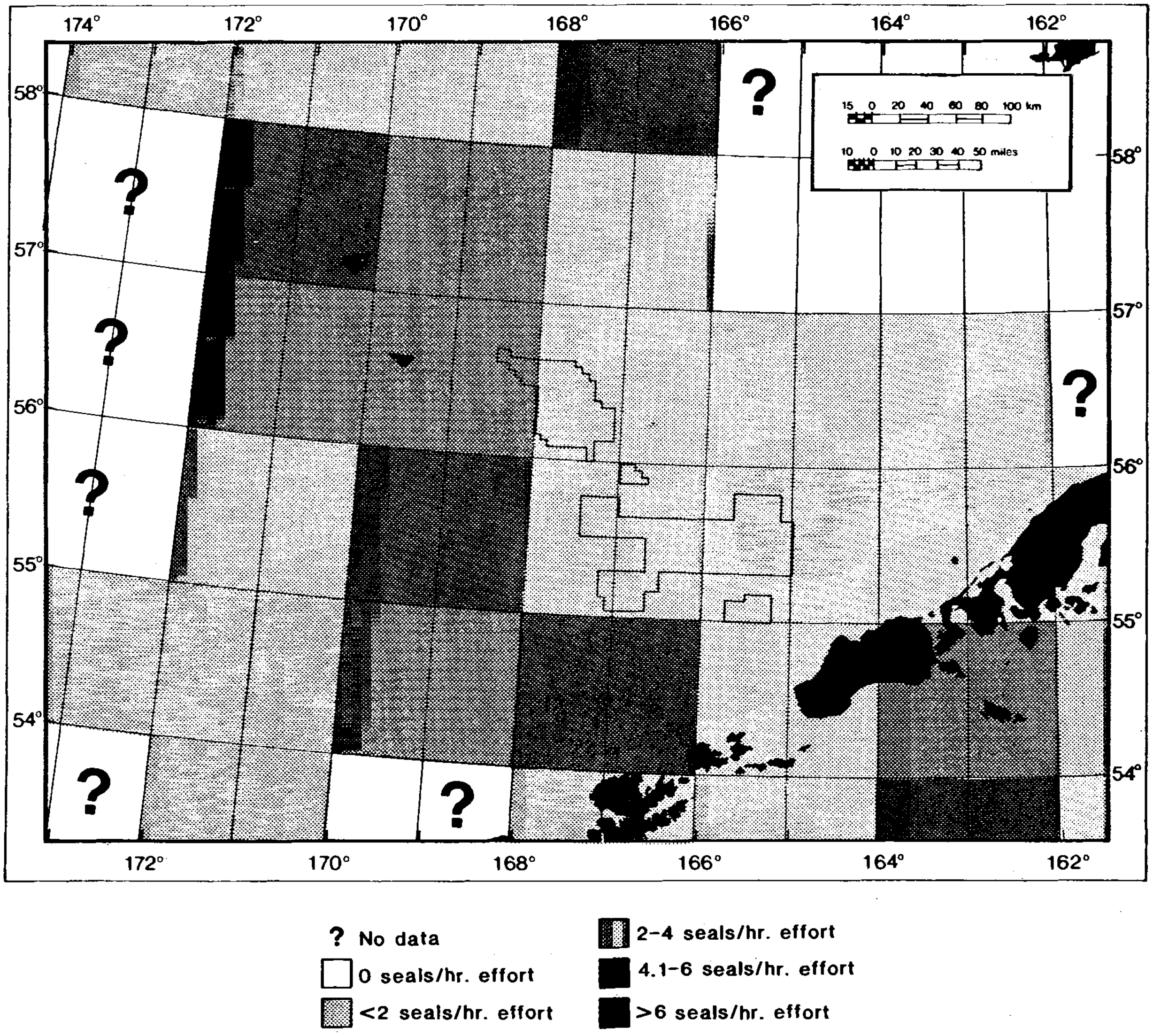

Figure 4.3 Sightings of northern fur seals in the St. George lease area, 1958-74 (Marine Mammal Division, 1978).

When pack ice enters the Basin, as in March and April 1976 and 1977, sea lions frequently haul out on the ice near the ice edge. It is unknown whether these animals come from the Pribilofs, the Aleutian Islands, or both.

Sea lions are common visitors to the Basin and the lease sites (Fig. 4.4). Although some are certainly migrating, most are probably at sea to forage. The Basin is an important commercial fishing area to which sea lions are frequently attracted; if the reported sightings are a fair indication of the number of animals present, the Basin includes important feeding habitat for northern sea lions.

Harbor Seal *(Phoca vitulina)*

The land-breeding harbor seal is abundant on islands in coastal waters of the eastern Aleutian Islands on the north side of the Alaska Peninsula, on the Pribilof Islands, and in Bristol and Kuskokwim Bays. At least 30,000-35,000 inhabit the southeastern Bering Sea (Everitt and Braham, 1980). Only about 20 percent of these occur on the eastern Aleutian Islands (Braham et al., 1977) with about another 1,500 on the Pribilof Islands (C. Fiscus, pers. comm. to Braham). These represent several small, local populations which appear to be resident, breeding on the islands and feeding year-round in the adjacent waters. Few harbor seals have been sighted offshore in the Basin, because of their scarcity in open water and the difficulty of seeing them at sea.

Ice-associated Pinnipeds

As the pack ice advances southward in the Bering Sea during winter and spring, ribbon *(Phoca fasciata)*, spotted *(P. largha)*, ringed *(P. hispida)*, and bearded *(Erignathus barbatus)* seals move with it, often into the St. George Basin Lease Area. Pupping and mating take place on the ice during spring, mainly April (Burns, 1970; Fay 1974), usually at the time of maximal extent of the ice (Burns et al., 1977). Although all species generally occur throughout the ice-covered Bering

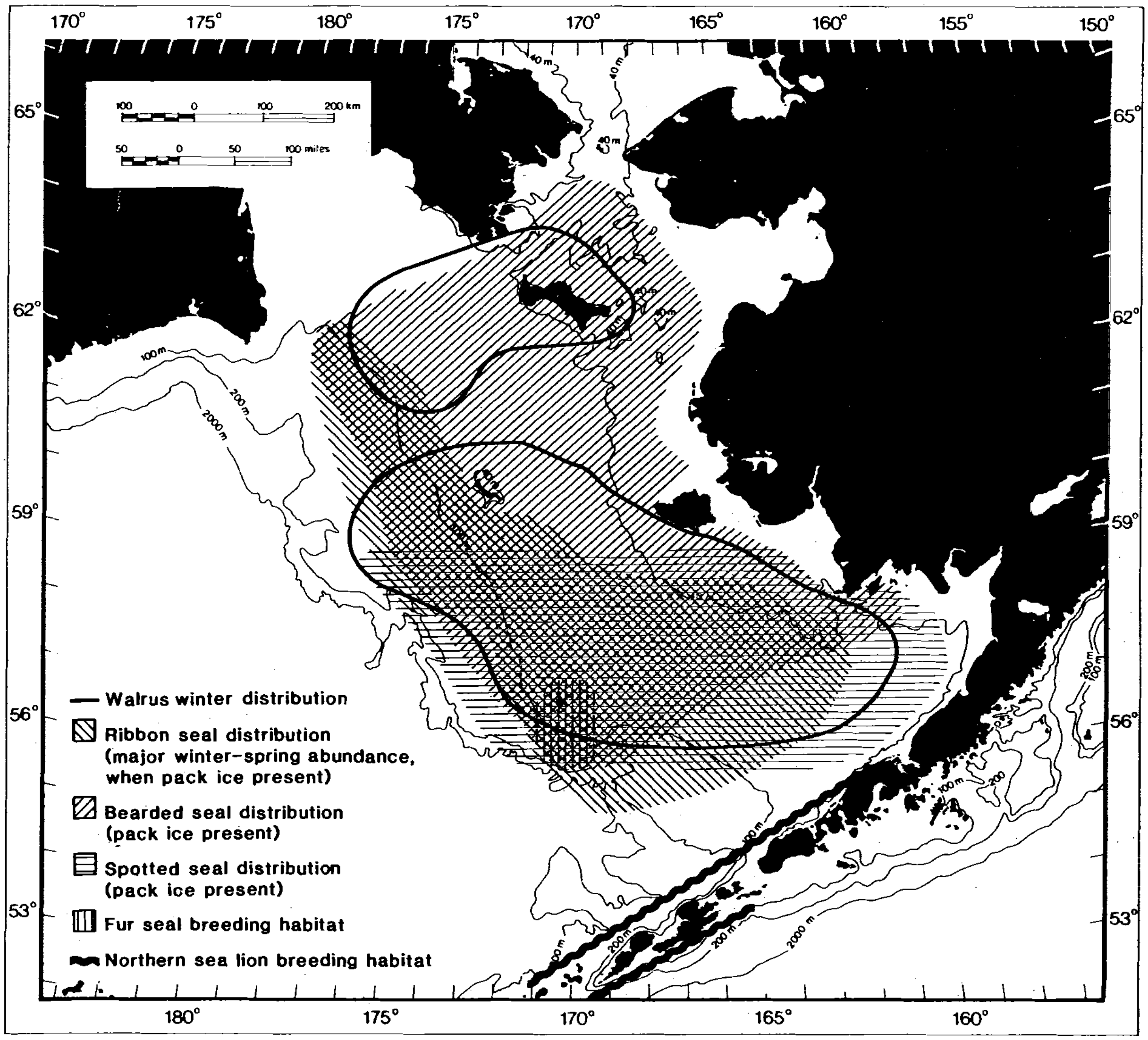

Figure 4.4. Distribution of ice-associated pinnipeds in late winter and spring, and breeding habitat for northern fur seals and Steller sea lions in and near the St. George Basin (see text for references).

Sea, habitat partitioning on the ice occurs (Burns, 1970).

When the pack ice is near its maximum in the Basin, spotted and ribbon seals occur more frequently and in greater numbers than the other ice seals (Fig. 4.4). Ribbon seals are found near the western edge of the Basin and spotted seals in the eastern portion when ice is present. The centers of abundance for these species are west and north of the Basin, respectively. Bearded seals most often occur deeper in the pack, rather than near the southern edge, whereas ringed seals are most abundant in the nearshore fast ice (Braham et al., 1977, in press, b; Burns and Frost, 1980). Ringed seals have been reported in the Basin near the Pribilof Islands (Kenyon, 1960; Burns and Harbo, 1977; Braham et al., in press, b). Most of the ice-associated pinnipeds move north with the receding pack ice in late spring and leave the Basin usually by late April or early May, migrating to the northern Bering Sea and Arctic Ocean to feed. A few ribbon and spotted seals may remain in the area during summer, though sighting data are lacking.

Pacific Walrus *(Odobenus rosmarus)*

The Bering/Chukchi population now exceeds the 1975 estimate of 165,000-205,000 (Estes and Gilbert, 1978; USFWS, unpub.). In winter, 23,000-60,000 (Kenyon, 1972; Krogman et al., 1979) walruses, or 12 to 36 percent of this population, reside on the pack ice of the southeastern Bering Sea, mainly in the vicinity of Kuskokwim and Bristol Bays and in the northern part of the St. George Basin lease area (Fig. 4.4). Mating takes place there from January to March. The animals also feed there (at depths to 80 m) until mid- to late April, when the females and young males begin to migrate northward to summering areas in the Chukchi Sea. Remaining in the southeastern Bering Sea throughout the summer are about 15,000 adult males (Fay et al., 1977); they move between hauling grounds in Bristol Bay (Round Island and occasionally Amak Island) to their feeding areas, some of which may be within the St. George lease area. Another group of males formerly summered in the Pribilof Islands area; this area eventually may be recolonized as the population continues to grow (F. Fay, pers. comm.).

4.4.3 Sea Otter

Sea Otter *(Enhydra lutris)*

About 17,000-18,000 sea otters inhabit the Bering Sea waters surrounding the eastern Aleutian Islands, the Alaska Peninsula, and the Pribilof Islands (Schneider, 1981) (Fig. 4.5). As year-round residents, sea otters complete their life cycle within the Basin.

The former range of the sea otter included most nearshore waters of the eastern Bering Sea south of the limit of sea ice (Kenyon, 1969). These included southern Bristol Bay, the eastern Aleutian Islands, and the Pribilof Islands. Fur hunting reduced the population to a small colony near Unimak Island and perhaps a few individuals in the Fox Islands. During the past 70 years, the numbers of otters have increased remarkably, but large areas of uninhabited or only partially repopulated habitat remain (Schneider, 1981).

Four separate colonies became established in the Fox and Krenitzen Islands during the 1960's. All are growing rapidly, but they amount to only a few hundred animals, and most of the reproductively active animals remain concentrated in small areas (Schneider, 1981).

The remnant colony north of Unimak Island grew steadily and expanded northeastward along the Alaska Peninsula (Kenyon, 1969). Extreme sea ice conditions in the early 1970's reduced the range and the size of this population (Schneider and Faro, 1975). Most of the sea otters in this population now are found between Cape Mordvinof and Cape Leontovich. They appear to be much more pelagic than other Alaskan sea otters. Pods of up to 1,000 otters have been observed as far as 50 km offshore; these are believed to be composed almost exclusively of adult males (Schneider, 1981).

Small numbers of sea otters have been transplanted to the Pribilof Islands, and a few may have immigrated there, probably from Bristol Bay (Schneider, 1981). Kenyon (1969) speculated that sea otters may be carried to the Pribilof Islands from Bristol Bay on floating ice. Reproduction has not been sufficient to assure the stability of the Pribilof population, however (D. Costa, pers. obs.).

Sea otters have occasionally been sighted in the northern Bering Sea. These certainly represent stray animals, since the regular formation of sea ice in the north appears to preclude the establishment of permanent sea otter populations there (Schneider, 1981).

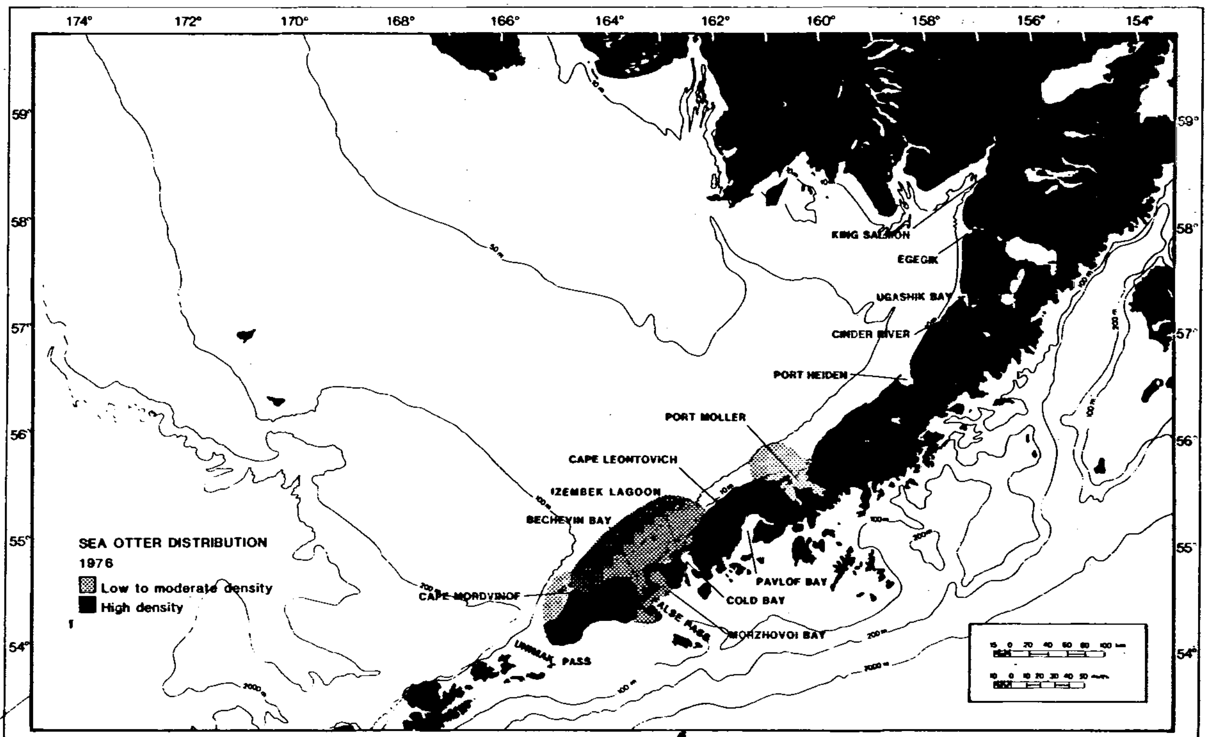

Figure 4.5. Distribution of sea otters north of the Alaska Peninsula and Unimak Island, 1976 (Schneider, 1976, 1981).

4.5 TROPHICS

Marine mammals individually consume copious amounts of food and collectively are major structuring agents of the Bering Sea ecosystem. Three recent papers review their food habits: Frost and Lowry (1981), Lowry and Frost (1981), and McAlister (in prep.).

The diet of most marine mammals is rarely consistent. Geographical, seasonal, and annual variations of food habits within a single species are frequently numerous (Nemoto, 1959). These probably reflect changes in the distribution and relative abundance of prey. Feeding habits also vary by age and sex within a species. These sources of variation tend to hinder our understanding of trophic interactions. The data presented here are drawn from many sources and represent animals collected in different locations, seasons, and years. Numbers represent relative rather than absolute importance of particular prey items. Undoubtedly, further field work will refine these preliminary estimates.

The trophic interactions occurring within the St. George Basin are complex and imperfectly understood. Four food webs are utilized by the marine mammals: benthic, coastal, deepwater, and pelagic. The major prey types and their relative importance to the individual marine mammal species are presented in Table 4.2

Within the pelagic zone two food webs were identified: one relying upon prey found over the shelf (the pelagic web), and a second characterized by deepwater prey found at and beyond the shelf break (the deepwater web). These food webs of course are interdependent.

4.5.1 Deepwater Web

Dall's porpoise, sperm whales, and beaked whales feed heavily upon the deepwater food web. Cephalopods and meso- and bathypelagic fishes are the primary prey types (Table 4.3). Squid, especially those of the family Gonatidae, are heavily utilized by Dall's porpoise and sperm whales. Beaked whales also are known to eat squid, although little else is known of their food habits. Fish are less important than squid in the diet of sperm whales and Dall's porpoise. There are few records of sperm whale stomachs with high bony fish contents, suggesting that fish are rarely the primary prey (W. McAlister, pers. comm. to Fowler). Tomilin (1957) found sharks and skates to be more important for sperm whales than bony fish, although they do eat such bony fish as salmon, Pacific saury, pollock, grenadiers, lancet fish, Pacific cod, Atka mackerel, rockfish, sculpins, and lamprey, as well as some crabs. Myctophids constitute over 90 percent of all the fish consumed by Dall's porpoise (Crawford, 1981), with capelin, herring, hake, sand lance, cod, and deepsea smelts also constituents of their diet (Kajimura et al., 1980).

Many of these prey species undergo a diel vertical migration toward the surface at night. Preliminary data suggest sperm whales and Dall's porpoise take advantage of this movement by feeding primarily at night. The most common myctophid, *Protomyctophum thompsoni*, found in Dall's porpoise stomachs comes to within 90 m of the surface at night (Crawford, 1981). Radio-tagged sperm whales dove for shorter periods and shallower at night than during the day (Lockyer, 1977). In the Antarctic, sperm whales collected at night and in the early morning had fuller stomachs than those taken at midday (Nemoto, 1957).

Although there is considerable overlap in the types of cephalopods eaten within the deepwater food web, the competition is minimized by selection by Dall's porpoise of smaller and younger squid than those taken by sperm whales (Crawford, 1981; Tomilin, 1957).

4.5.2 Pelagic Food Web

Most marine mammals feed within the pelagic zone on euphausiids, cephalopods, and semidemersal fishes (Tables 4.2 and 4.4). Large swarms of euphausiids are consumed directly by baleen whales, squid, pelagic birds, and many of the forage fishes in turn consumed by cetaceans and pinnipeds. Foremost of these fishes are the pollock, whose stocks are estimated to represent over 60 percent of the total fish biomass of the eastern Bering Sea (see chapter 6). In addition to supporting large marine mammal populations, pollock are the prey of millions of seabirds and the target of the largest single-species fishery in the Northern Hemisphere (Fig. 4.6). Thus it is essential to understand the ecology of euphausiids and pollock in order to understand the pelagic food web.

Capelin, herring, and cephalopods, especially squid, are surpassed only by euphausiids and pollock in their importance as prey within the pelagic food web. Yet of all of these only pollock and to a lesser extent herring, the two commercially exploited species, have been adequately studied. Data on the distribution and abundance of the euphausiid, capelin, and squid stocks are especially necessary to understand the pelagic and deepwater food webs.

Although many marine mammals feed on the same prey, differences in size of prey and geographical and seasonal selectivity may reduce competition among them. Within the pelagic system, fin whales eat only pollock shorter than 30 cm, whereas humpbacks take pollock 40-50 cm

Table 4.2. Relative importance of major prey types in diet of marine mammals in eastern Bering Sea (Adapted from Lowry et al. 1980a; Frost and Lowry, 1981; Lowry and Frost, 1981).

	Pelagic						Benthic			Deepwater		Coastal
Predator	Pelagic and semi-demersal fish	Fish	Cephalopods	Copepods	Euphausiids	Marine mammals	Nektobenthic invertebrates	Epifaunal invertebrates	Infaunal invertebrates	Deepwater fish	Cephalopods	Epifaunal macro-invertebrates
Baleen Whales												
Fin whales	Major		Minor	Major	Major							
Humpback whales	Major	Minor	Minor	Minor	Major	Minor						
Minke whale	Major		Minor	Minor	Major							
Bowhead whale				Major	Major		Minor					
Gray whale	Minor								Major			
Toothed Whales												
Sperm whale	Minor	Minor						Minor		Major	Major	
Killer whale	Major	Minor	Minor			Major						
Beaked whale	Minor						Minor			Major/Minor	Major	
Belukha whale	Major	Minor	Minor				Minor					
Harbor porpoise	Major						Minor					
Dall's porpoise	Minor				Minor		Minor			Major/Minor	Major	
Pinnipeds												
Harbor seal	Major	Minor					Minor					
			Major (J)				Minor (A)					
Spotted seal	Major	Minor					Major (J)					
Ribbon seal	Major	Major					Minor					
Ringed seal	Major	Minor	Major				Major					
Bearded seal		Minor					Major	Major	Major			
Walrus							Minor	Minor	Major			
Fur seal	Major		Major									
Steller sea lion	Major	Minor	Minor			Minor	Minor					
Sea Otter												Major

J = Juvenile
A = Adult

Table 4.3. Food consumed by marine mammals in the deepwater food web (Adapted from McAlister, in prep.).

Species	Cephalopods	Euphausiids	Fish	Annual food consumption in 10^3 t
Dall's porpoise[1]	90	1	9	87
Sperm whale[2]	89	1	10	795

[1] Data from Crawford, 1981.
[2] Data from Betesheva, 1961.

long as well (Nemoto, 1959). Near the Aleutians, humpbacks eat Atka mackerel, but fin whales in the same area do not (Nemoto, 1957). Harbor seals and Steller sea lions feed on many of the same species, especially pollock, capelin, and herring, but the sea lions take significantly larger individuals (Pitcher, 1979). Different seasonal distributions also reduce the competition; for example, spotted seals are major consumers of herring and capelin in the Basin during the winter, whereas the baleen whales feed on these fishes during the summer.

4.5.3 Benthic Food Web

Gray whales, bearded seals, and walruses feed almost exclusively on nektobenthic, epifaunal, and infaunal invertebrates (Table 4.5). Energy pathways within this system are short, frequently involving only two transfer steps from producer to consumer: phytoplankton and detritus → clam → walrus. Feeding low on the food chain reduces competition. Benthic foraging by these marine mammals disturbs the benthos and significantly affects the community composition (Nerini, in press).

Gray whales feed predominantly on the dense gammarid amphipod communities of the northern Bering and Chukchi seas but also consume polychaetes, small bivalves, gastropods, mysids, and herring (Zimushko and Lenskaya, 1970; Frost and Lowry, 1981; Nerini, in press). Gray whales were formerly assumed to feed only on these

Table 4.4. Preliminary estimates of food consumption by marine mammals in the eastern Bering Sea. (Adapted from McAlister, in prep.).

	Percent of each species in diet				
Prey Species	Fur seal[1]	Northern sea lion[2]	Harbor seal[3]	Ribbon seal[4]	Spotted seal[4]
Herring	5	8	5	–	19
Capelin	39	18	12	13	21
Other smelts	–	–	9	–	10
Salmonids	–	1	4	–	–
Pollock	32	60	25	24	5
Pacific cod	–	4	–	–	–
Saffron cod	–	1	–	–	4
Other gadids	–	–	3	–	–
Eelpout	–	–	–	18	–
Flatfish	–	1	3	5	–
Rockfish	–	1	1	–	–
Sculpin	–	1	2	3	24
Sand lance	–	–	1	–	8
Skates	–	2	1	–	–
Prickleback	–	–	–	7	–
Poacher	–	–	–	3	–
Snailfish	–	–	–	5	–
Other fish	7	1	4	–	–
Total fish (percent)	84	97	70	78	90
Mammals		< 1			
Squid	16	1	14	–	–
Octopus	–	–	–	8	–
Shrimp, crab	–	2	16	8	9
Gastropod, snail	–	–	–	3	–
Clams	–	–	–	3	–
Other invertebrates	–	–	–	–	1
Euphausiids and copepods					
Total invertebrates (percent)	16	< 4	30	22	10
Total consumption (10^3 t)	493	133	71	131	288

Table 4.2. Relative importance of major prey types in diet of marine mammals in eastern Bering Sea (Adapted from Lowry et al. 1980a; Frost and Lowry, 1981; Lowry and Frost, 1981).

	Pelagic						Benthic			Deepwater		Coastal
Predator	Pelagic and semi-demersal fish	Fish	Cephalopods	Copepods	Euphausiids	Marine mammals	Nektobenthic invertebrates	Epifaunal invertebrates	Infaunal invertebrates	Deepwater fish	Cephalopods	Epifaunal macro-invertebrates
Baleen Whales												
Fin whales	Major		Minor	Major	Major							
Humpback whales	Major	Minor	Minor	Minor	Major	Minor						
Minke whale	Major		Minor	Minor	Major							
Bowhead whale				Major	Major		Minor					
Gray whale	Minor								Major			
Toothed Whales												
Sperm whale	Minor	Minor						Minor		Major	Major	
Killer whale	Major	Minor	Minor			Major						
Beaked whale	Minor						Minor			Major/Minor	Major	
Belukha whale	Major	Minor	Minor				Minor					
Harbor porpoise	Major						Minor					
Dall's porpoise	Minor				Minor		Minor			Major/Minor	Major	
Pinnipeds												
Harbor seal	Major	Minor					Minor					
			Major (J)				Minor (A)					
Spotted seal	Major	Minor					Major (J)					
Ribbon seal	Major	Major					Minor					
Ringed seal	Major	Minor	Major				Major					
Bearded seal		Minor					Major	Major	Major			
Walrus							Minor	Minor	Major			
Fur seal	Major		Major									
Steller sea lion	Major	Minor	Minor			Minor	Minor					
Sea Otter												Major

J = Juvenile
A = Adult

Table 4.3. Food consumed by marine mammals in the deepwater food web (Adapted from McAlister, in prep.).

Species	Cephalopods	Euphausiids	Fish	Annual food consumption in 10^3 t
Dall's porpoise[1]	90	1	9	87
Sperm whale[2]	89	1	10	795

[1] Data from Crawford, 1981.
[2] Data from Betesheva, 1961.

long as well (Nemoto, 1959). Near the Aleutians, humpbacks eat Atka mackerel, but fin whales in the same area do not (Nemoto, 1957). Harbor seals and Steller sea lions feed on many of the same species, especially pollock, capelin, and herring, but the sea lions take significantly larger individuals (Pitcher, 1979). Different seasonal distributions also reduce the competition; for example, spotted seals are major consumers of herring and capelin in the Basin during the winter, whereas the baleen whales feed on these fishes during the summer.

4.5.3 Benthic Food Web

Gray whales, bearded seals, and walruses feed almost exclusively on nektobenthic, epifaunal, and infaunal invertebrates (Table 4.5). Energy pathways within this system are short, frequently involving only two transfer steps from producer to consumer: phytoplankton and detritus → clam → walrus. Feeding low on the food chain reduces competition. Benthic foraging by these marine mammals disturbs the benthos and significantly affects the community composition (Nerini, in press).

Gray whales feed predominantly on the dense gammarid amphipod communities of the northern Bering and Chukchi seas but also consume polychaetes, small bivalves, gastropods, mysids, and herring (Zimushko and Lenskaya, 1970; Frost and Lowry, 1981; Nerini, in press). Gray whales were formerly assumed to feed only on these

Table 4.4. Preliminary estimates of food consumption by marine mammals in the eastern Bering Sea. (Adapted from McAlister, in prep.).

	Percent of each species in diet				
Prey Species	Fur seal[1]	Northern sea lion[2]	Harbor seal[3]	Ribbon seal[4]	Spotted seal[4]
Herring	5	8	5	–	19
Capelin	39	18	12	13	21
Other smelts	–	–	9	–	10
Salmonids	–	1	4	–	–
Pollock	32	60	25	24	5
Pacific cod	–	4	–	–	–
Saffron cod	–	1	–	–	4
Other gadids	–	–	3	–	–
Eelpout	–	–	–	18	–
Flatfish	–	1	3	5	–
Rockfish	–	1	1	–	–
Sculpin	–	1	2	3	24
Sand lance	–	–	1	–	8
Skates	–	2	1	–	–
Prickleback	–	–	–	7	–
Poacher	–	–	–	3	–
Snailfish	–	–	–	5	–
Other fish	7	1	4	–	–
Total fish (percent)	84	97	70	78	90
Mammals		< 1			
Squid	16	1	14	–	–
Octopus	–	–	–	8	–
Shrimp, crab	–	2	16	8	9
Gastropod, snail	–	–	–	3	–
Clams	–	–	–	3	–
Other invertebrates	–	–	–	–	1
Euphausiids and copepods					
Total invertebrates (percent)	16	< 4	30	22	10
Total consumption (10^3 t)	493	133	71	131	288

Table 4.4 (continued)

Prey species	Minke whale*[5]	Fin whale*[6]	Humpback whale*[7]	Bowhead whale*[8]	Killer whale*[9]	Harbor porpoise*[10]	Belukha whale*[11]
Herring	√√	√√	√√	–	√√	√√	√√
Capelin	√√	√√	√√	–	√√	√√	√√
Other smelts	–	–	√	–	√√	–	–
Salmonids	–	√	√	–	√	–	√√
Pollock	√√	–	√√	–	–	–	–
Pacific cod	√√	√√	√	–	√√	–	√√
Saffron cod	√√	√	√	–	–	√√	√√
Other gadids	–	√	√	–	√	√	√√
Eelpout	–	–	–	–	–	–	–
Flatfish	–	–	–	–	–	–	√√
Rockfish	–	–	√	–	–	–	–
Sculpin	–	–	–	–	–	–	–
Sand lance	√√	–	√√	–	–	–	–
Skates	–	–	–	–	√	–	–
Prickleback	–	–	–	–	–	–	–
Poacher	–	–	–	–	–	–	–
Snailfish	–	–	–	–	–	–	–
Other fish	–	–	√	–	–	–	√
Total fish (percent)	68	10	22	< 1	41	99	63
Mammals	–	–	–	–	27	–	–
Squid	< 1	1	< 1	< 1	30	< 1	–
Octopus	–	–	–	–	–	–	–
Shrimp, crab	–	–	–	–	–	–	–
Gastropod, snail	–	–	–	√	–	–	–
Clams	–	–	–	√	–	–	–
Other invertebrates	–	–	√	√	–	–	–
Euphausiids and copepods	32	89	78	98	3	< 1	37
Total invertebrates	32	90	78	99	33	1	37
Total consumption (10^3 t)	58	83	12	53	21	2	150

*Percent of each prey species in diet not known.

√√ Common component of diet.

√ Occasional component of diet.

[1] Perez and Bigg, (1981).

[2] Calkins and Pitcher, (1979); 193 samples collected from Kodiak Island, Kenai Coast, and Prince William Sound.

[3] Pitcher (1977), and Pitcher and Calkins (1978); samples collected along Kodiak Island, northeast Gulf of Alaska, and Prince William Sound.

[4] Lowry and Burns (1976), and Lowry, Frost, and Burns (1977, 1978); 28 samples during March-April in the southeast Bering Sea.

[5] Mitchell (1974) found a 98 percent fish diet in North Atlantic minke whales; Jonsgaord (1951) found a 48 percent fish diet in whales off Norway and a 20 percent fish diet in offshore whales. Omura and Sakimura (1956) found a 37 percent fish diet in minke whales off Japan. The value used here is a composite.

[6] Nemoto (1959). The diet of 7,000 fin whales from the North Pacific was about 92 percent euphausiids and copepods, 1 percent squid and 7 percent fish. The diet of 2,000 whales from the Bering Sea and Aleutians comprised over 98 percent euphausiids and copepods and less than 1 percent fish. The diet of 156 fin whales taken on the Alaskan shelf consisted of 97 percent fish (mostly pollock), and only 3 percent copepods. This suggests the extreme variability of the fin whale diet. Values are based on the observed distribution of fin whales, mostly in the central Aleutian area, with a maximum of 10 percent predicted to be in shallower waters.

[7] Nemoto (1959).

[8] Lowry and Burns (1980); Marquette et al. (In press). Data are for bowhead whales in the Beaufort Sea.

[9] Nishiwaki and Handa (1958). About 370 stomachs from killer whales taken off Japan were analyzed.

[10] Prescott and Fiorelli (1979).

[11] Kleinenberg et al. (1969). Data used as most representative were those of Arsenev from belukha near western Sakhalin.

Table 4.4 (continued)

northern grounds, but recent evidence indicates that they also feed during migration and on the southern wintering grounds (Braham, in prep.; Norris, 1979; Swartz and Jones, 1981). Nerini (in press) found that feeding gray whales leave depressions in the benthic sediments while removing the amphipods. Highly mobile scavenging amphipods and mysids are attracted to these disturbances. They move in and appear to maintain an environment suitable for the rapid recol-

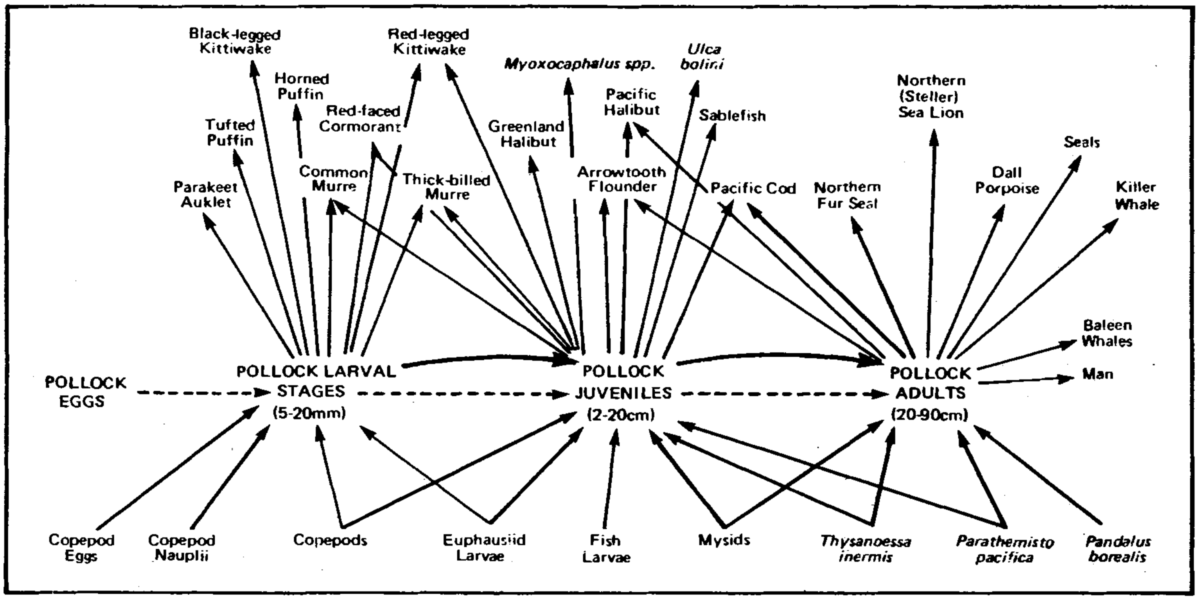

Figure 4.6. Postulated food web of walleye pollock in the Bering Sea (Smith, 1981).

onization of the area by *Ampelisca* and other gammarid amphipods upon which the gray whales feed (Nerini, in press).

The walrus's diet in the southeastern Bering Sea is dominated by such infaunal clams as *Tellina, Spisula, Serripes,* and *Siliqua*; Tanner crabs, polychaetes, echiurids, and snails are of secondary importance (Fay et al., in prep.; Lowry and Frost, 1981). Fay et al. (1977) expressed concern that walrus may be depleting their food resources, especially in the northern Bering Sea. Competition for these resources is partially decreased by differential selectivity in prey size by males and females. Males feed primarily on large clams of large species, particularly *Mya* and *Spisula,* whereas females eat the smaller species and smaller individuals of the larger species.

Bearded seals in the Basin eat mostly Tanner crabs, shrimps, and clams. Geographical and seasonal variations in the relative importance of prey species are evident in the northern Bering and southern Chukchi seas (Lowry and Frost, 1981). Shrimps are important prey throughout the year. The highest proportion of shrimps and crabs in the diet occur in the fall and winter; clams are eaten in significant quantities only during spring and summer. The importance of clams in the diet increases with age, and the importance of shrimp decreases. Fish appear to be of greater importance in the northern portion of the bearded seal's range. Bearded seals and walruses compete for *Serripes* and snails, and the combined predation on these molluscs may be depleting some of these stocks (Lowry et al., 1980b).

4.5.4 Coastal Food Web

The coastal food web is poorly understood. It is dominated by sea otters, which are far more pelagic than otter populations elsewhere; no information on their food habits is available. In other areas of Alaska otters feed on herbivorous epibenthic macroinvertebrates such as sea urchins, limpets, chitons (Simenstad et al., 1978), clams, crabs, and sea stars (Calkins, 1978). In other areas, sea otters have been identified as keystone predators which shape the nearshore community structure (Estes and Palmisano, 1974).

Simenstad et al. (1978) argue that sea otter usage of an area results in decreased macroalgal predation, increased nearshore fish populations, and suitable food resources for harbor seals. Too little is known about this food web in the southeastern Bering Sea to speculate further.

4.5.5 Problems and Interactions

Trophic interactions are difficult to assess because of the lack of synoptic sampling. Feeding data collected during different years for different species in the same food web may give a false impression. Seasonal, geographical, age, and sex differences in diet have been reported. The geographical and seasonal differences suggest considerable plasticity within the prey types consumed by marine mammals. Longer-term shifts in selection of major prey species may be occurring. For example, within the pelagic food chain, pollock currently is the most common finfish consumed. Herring and capelin are next in importance. Whether this reflects only the current abundance of these three species, the seasonality of the samples, or selective predation by the mammals is unclear. Will overfishing of pollock or partial destruction of the stock during oil and gas development cause the seals and whales to exploit herring and capelin to a greater extent? If

Table 4.5. Food consumption by marine mammals within the benthic food web (Adapted from McAlister, in prep.).

	Diet composition in percent						
Species	**Cephalopods**	**Amphipods**	**Fish**	**Crab, shrimp**	**Clams**	**Other invertebrates**	**Annual total consumption in 10^3 t**
Gray whale[1]	1	85	1	--	--	14	315
Bearded seal[2]	-	--	17	64	--	19	666
Walrus[3]	-	--	--	--	93	7	1,500

[1] Zimushko and Lenskaya (1970).

[2] Burns and Frost (1980).

[3] Fay et al. (1977).

the biomass of these three fish species stays constant, how will the various mammal species be affected? Behavioral differences in the three fish species are poorly understood, and it is probable that these are factors which would determine the ability of the mammals to exploit changes in the relative proportions of these populations. Caloric values are similar, but the energy expended by the mammals to capture these three fishes may differ.

Consumption of and competition for the food of the Bering Sea is high. Hunt (in Frost and Lowry, 1981) estimates that 1.97 million tons (t) of food are annually consumed by a minimum of 30 million seabirds. Marine mammals consume at least 2.29 million t of finfish annually (McAlister, in prep.). Walruses consume 1.5 million t of bivalves in the southeastern Bering Sea (Fay et al., 1977). Landings from the pollock fishery averaged 1.3 t/yr from 1968 to 1977 (North Pacific Fisheries Management Council, 1978, cited in Lowry and Frost, 1981). The commercial fisheries compete for crab, herring, and salmon, and the capelin fishery is expected to be developed in the 1980's. If the system can be considered in equilibrium, a tenuous assumption at best, any stresses added to the system by oil and gas development could have system-wide ramifications.

4.6 SENSITIVITY AND VULNERABILITY

Although many of the marine mammals inhabit the St. George Basin part of the year, their entire life cycle is frequently carried out within existing or proposed OCS lease areas. They simply move from one lease area to another (e.g., belukhas: St. George and Bristol Bay → Norton Sound → Hope and Chukchi → Beaufort → McKenzie Delta; gray whales: through the California lease areas → St. George and Bristol Bay → Norton Sound and Hope Basin; walrus: St. George and Bristol Bay → Norton Sound → Hope Basin and Chukchi). Thus, these species are likely to be exposed to disturbance over their entire range.

In considering the effects of OCS development we examined the sensitivity and vulnerability of species likely to be affected by changes in the environment, at both the individual and population level, using Geraci and St. Aubin's (1980) review as a framework. Potential hazards of the

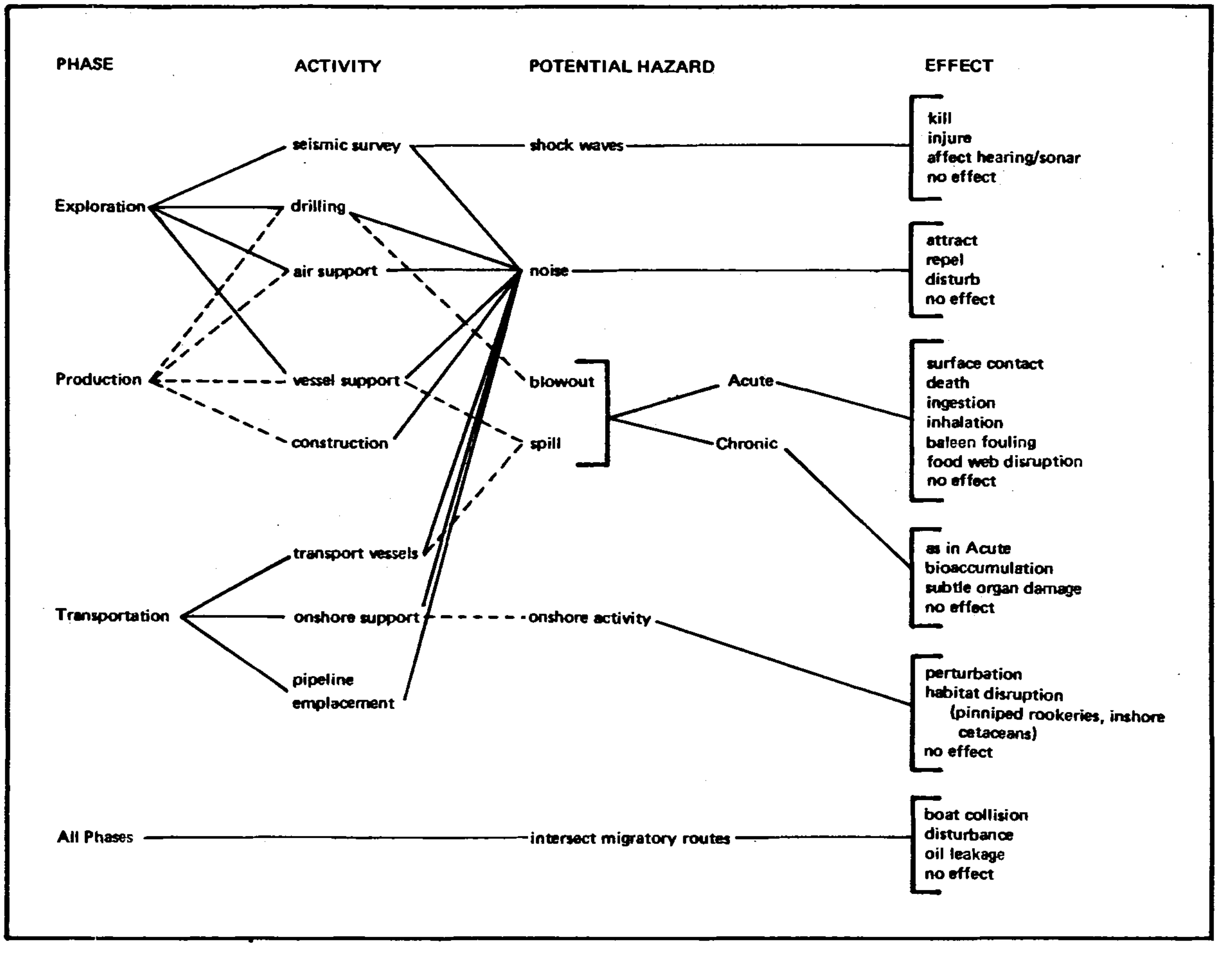

Figure 4.7. Proximate factors associated with offshore oil exploration and their effects on marine mammals (Geraci and St. Aubin, 1980).

various stages of development and their effects upon marine mammals are shown in Fig. 4.7.

Vulnerability refers to an individual's or population's geographical and temporal distribution, whereas sensitivity measures an individual's behavioral and/or physiological response to a particular condition. For example, sea otters have been shown to be highly sensitive to oiling, but they would not be highly vulnerable to a spill occurring near the Pribilof Islands because few are there.

Sensitivities to disturbance are likely to vary with age, sex, and season. When metabolic requirements are most demanding, as in pregnant and lactating females, the sensitivity will be highest. Lockyer (1976) calculated that for newly mature and older adult sperm whales, food needs increased 10 percent and 5 percent respectively, during pregnancy and 67 percent and 32 percent, respectively, during lactation. Thus, the most sensitive segments of a population are expected to be pups, lactating females and, for pinnipeds, molting individuals.

4.6.1 Oil Spills

Inhaled and ingested oil is toxic and potentially harmful. Ringed seals rapidly absorb crude-oil hydrocarbons into body tissues and fluids and ultimately excrete them in their bile and urine (Engelhardt et al., 1977). However, harp seals force-fed up to 75 mℓ of crude oil showed neither clinical, biochemical, nor morphological evidence of tissue damage (Geraci and Smith, 1976).

Long-term hydrocarbon accumulation is expected to be greatest in benthic foragers such as walrus, bearded seals, sea otters, and gray whales. Generally, deposit feeders accumulate hydrocarbons to a greater extent than suspension feeders, and representatives of this group form a significant portion of the diet of gray whales and walrus (Nerini, in press; Vibe, 1950; and Fay et al., 1977).

4.6.2 Noxious Effects

Ringed seals experimentally immersed in oil-covered seawater developed irritated and inflamed eyes, skin, and mucous membranes (Geraci and Smith, 1976). Oil-fouled cetaceans have not been observed, but because cetacean epidermis is not keratinized, it is likely to be particularly sensitive to oiling (Geraci and St. Aubin, 1980).

Sea otters have been shown to be highly sensitive to direct contact with oil (Costa and Kooyman, 1981). The oil mats the fur and decreases thermoregulatory efficiency. Studies of captive sea otters demonstrate that when less than 30 percent of the body surface is oiled, the metabolic rate increases up to 41 percent. Since sea otters consume about 25 percent of their body weight/day and lack the blubber which might serve as a food reservoir, undernourishment and starvation rapidly may result.

Sea otters are vulnerable to oiling due to their habit of spending much of their time on the surface — eating, resting, grooming. The ability of sea otters and other marine mammals to detect and avoid oil spills at the surface is unknown. If they are near shore, they may not be able to escape around the edges of a spill. If otters are oiled over more than half their bodies, they will die (D. Costa, pers. comm.). The dose tolerated in summer may be higher than that in winter, as the need to retain body heat is somewhat less in summer; annual fluctuations in tolerance could also be expected. During years of heavy ice, sea otters will be especially sensitive (Schneider, 1981).

Age and sex differences in sea otter sensitivity and vulnerability are expected. Oiling is expected to be most stressful to pups and lactating females. The woolly pelage of pups is more easily wetted than is the adult fur. Also, because of the pups' higher surface-to-volume ratio, any decrease in the thermal insulation of their coat would be greater than that of the adults, given equal percentage of oiled surface. Lactating females also are expected to be highly sensitive because of the increased energy requirements of nursing. Adult males are the segment of the population most vulnerable to a spill because they use both the nearshore and pelagic habitats.

The sea otter population of the St. George Basin and Aleutian Chain is not highly vulnerable to destruction by a single oil spill. Oil spills, although they may spread over a large area, tend to be localized. The natural history of the sea otter, its tendency to establish concentrated populations and then when the density reaches a certain point to expand into available habitat, would be highly advantageous in the event of a large spill. Even if many animals were killed directly by a spill, recolonization would probably occur, although the time required would depend on the location and distance to the nearest unaffected population center. If the spill did not kill all otters in an area, the number of adult females remaining would be the most important factor in determining how quickly the population recovered. As sea otters may be a keystone species in some areas (Estes and Palmisano, 1975), reductions in their density may profoundly affect the structure of the nearshore communities (Schneider, 1981).

Pinnipeds

Due to the concentrating effects of the breeding islands, feeding areas, and migration (primarily through Unimak Pass), there are three areas in the St. George Basin where fur seals are vulnerable to activities and accidents associated with development. Most of the population is found near the Pribilof Islands from June through August. Large numbers also occur there in May, September, and October, but they are more dispersed. Thus, in spite of their large population, fur seals are highly vulnerable because they are concentrated in a small area.

The fur seals at the Pribilof Islands are vulnerable to direct and indirect effects of oiling. Nursing females, the most productive segment of the population (and the segment on which the population depends for recruitment), must travel back and forth between the islands and the feeding areas. An oil spill in the feeding areas or between them and the islands would be especially destructive. Fur seals are highly sensitive to direct contact with oil. In addition to skin irritation, oiling can cause severe thermal stress by destroying the insulative properties of their thick fur. When the blubber layer is thin, oiling of the fur will result in excessive heat loss (Kooyman et al., 1976). Pups, breeding males just returning to the sea, and lactating females have less fat than other segments of the population and thus will be most affected. Indirect affects could result through oiling of food resources. Oiling of food organisms could (1) reduce numbers of prey, (2) contaminate them with toxic substances, or (3) redistribute them so that they are less available to fur seals.

Much of the fur seal population migrates through Unimak Pass in April-June and September-November. A spill in this area during these months is likely to affect fur seals. Spills west of Unimak Pass would likely affect fewer seals, although the movement of oil requires modelling.

Pups begin to enter the water in July and leave the islands in October-November. An oil spill in this area could devastate this age class because of (1) their high surface-to-volume ratio, (2) their loss of weight following weaning, and (3) their concentration near the islands. Although the population probably would recover eventually, harvesting would be severely restricted for several years.

The maintenance of the mother-pup bond probably depends on olfactory cues (C. Fowler, pers. comm.). If oil contamination (either external or internal) altered or overrode the odors used in this process, it would very likely disturb the bond, resulting in mother-pup separation, and death of the pup.

Adults of bearded, spotted, ribbon, ringed, and harbor seals; sea lions; and walruses are insulated by blubber, and some oiling is not expected to place a thermal stress on them. Pups, however, will be highly sensitive to such stress until they build up a blubber layer. These species also would be subject to indirect effects on the food chain and on olfactory cues, as previously noted for fur seals.

The ice-inhabiting seals and walruses in St. George Basin would be vulnerable largely in winter and spring during years of extensive ice cover. However, feeding, mating, pupping, nursing, and molting all take place at this time. Harbor seals and sea lions are year-round residents of the Basin and would thus be vulnerable in all seasons.

Cetaceans

The effects of oil spills on cetaceans are largely unknown. Migrating gray whales were observed near Santa Barbara, California, during January 1981, as they passed through oil slicks caused by natural seepages. The whales did not appear to detect the slicks, but when the whales surfaced in a slick, at least two-thirds of the animals changed their behavior. They increased their dive time, erratically deviated from their previously preferred depth contour, and, occasionally, groups changed from synchronous to asynchronous breathing patterns. When the whales emerged from the spill, they returned to the behavior patterns observed before they entered the slick (S. Leatherwood, pers. comm. to Oliver). During the 1979 *Regal Sword* spill, fin and humpback whales were observed feeding near the oil slick and Atlantic white-sided dolphins *(Lagenorhynchus acutus)* were observed in the slick.' According to aerial observers of the University of Rhode Island, the animals all appeared to behave normally (Goodale et al. 1981)

Experimental, laboratory studies of fouling of baleen plates of the bowhead whale by Prudhoe crude show a decrease of 2.4-14.8 percent in filtering efficiency (Braithwaite, 1980). The effect of this reduction in efficiency could be devastating, especially for pregnant and lactating females. Estimates of the energy costs of pregnancy and lactation in baleen whales are not available, but for now, we presume they are similar to those of the sperm whale. Stored nutrients in the form of blubber could delay the effects of lack of food, possibly for months.

The effects on cetaceans of oil ingestion and external contact are unknown. However, exposure of the eyes to oil probably would likely lead to conjunctivitis as in seals (Geraci .and Smith, 1976).

Vulnerability of cetaceans to spills in the Basin will, of course, depend on their presence there. Gray whales, harbor porpoises, and belukhas could be exposed to spills occuring in or carried to nearshore waters, and all other cetaceans could encounter spills in the pelagic region (Table 4.6).

4.6.3 Spills in Particular Areas

Oil spills that reach either Unimak Pass or the Pribilof Islands are of major concern. Spill trajectory models (Chapter 2) indicate that a spill within the Basin could reach the Pribilof Islands during winter conditions. As previously noted, a fall spill could have serious consequences for fur seal pups which spend increasing amounts of time in the water at weaning, and for adult fur seals preparing to leave the islands. Spills occurring in or reaching Unimak Pass would soon be washed away by the strong local currents. This prediction is largely based on knowledge of the deepwater flow through the pass and not upon the more relevant but lesser-known surface currents. The effect of a spill in Unimak Pass will depend upon its size, residence time, and time of year. Marine mammals are most abundant from late spring to autumn during the migration of fur seals and gray whales, and during feeding periods for other large whales.

4.6.4 Disturbance and Noise

During the exploratory phase of oil and gas development, there will be increased geophysical activity, resulting in increases in ambient noise levels and vessel and aircraft traffic. If commercially exploitable reserves are discovered, construction of platforms, pipelines, and shore sites will follow. Vessel and aircraft traffic will peak during the construction phase. Direct disturbance by increased contact with humans and indirect disturbance due to increased noise levels from these activities may result. Quantitative information is limited; thus a review of existing data is proposed. Preliminary data from OCSEAP, BLM, and NMFS field studies and anecdotal information allow some insights, although they are occasionally conflicting and by no means comprehensive.

Human Presence

A fur seal rookery on St. Paul Island has recently been vacated because of human disturbance (C. Fowler, pers. comm.). In Santa Barbara, California, however, a breeding colony of harbor seals adjacent to a fuel pier has remained viable, and the seals have apparently accommodated to the vessel and truck traffic as well as to observers on the pier; but if a person moves off the pier and onto the beach, the seals immediately move from the rookery into the sea (D. Costa, pers. comm.).

Noise

Oil and gas development within the Basin will result in an increase in such noise as that of aircraft and vessel traffic, seismic operations, and construction and production activities. Increases in ambient noise levels may interfere with active and passive acoustic means of prey detection, and with communication by masking (Payne and Webb, 1971). Marine mammals may become habituated to constant noise sources but not to periodic noises such as those generated during seismic operations. Noise may also result in attraction of animals.

Aircraft

Johnson (1977) studied the effects of aircraft disturbance during the breeding season on a harbor seal rookery in the Gulf of Alaska. Frequent disturbances increased the wariness and disturbability of the seals. Helicopters and large planes were more disturbing than small planes, and the lower the altitude the greater the reaction of the seals. Aircraft flying at 120 m or less caused mass movement of animals from the rookery. The seals rarely returned to the rookery within 2 h of the overflight. Pups born 2 hours before or up to half an hour after an overflight were frequently abandoned by their mothers and died. Evidently, the mother-pup bond is not firmly established until several hours after birth. Over 10 percent of pup mortality was ascribed to overflights.

Bowhead whale groups in autumn responded to a twin-engine, fixed-wing aircraft flying overhead at altitudes of up to 305 m by spending less time at the surface and by scattering (LGL, 1981). In another study, in early spring, only 11 percent of 160 bowheads observed responded in an evasive manner to overflights of helicopters between 152 and 229 m. (Braham et al., 1980c). Dolphins (*Stenella* sp. and *Tursiops* sp.) have reacted similarly (Reeves, 1977).

Table 4.6. Cetaceans most likely to be affected directly or indirectly by oil spills using the criteria of habitat usage, abundance and/or general population status within the St. George Basin.

Surface oil spill in productive feeding waters	Mid-water spill in fish runs or zooplankton bloom	Spill in coastal or inshore waters and benthic contamination
Right whale	Humpback whale	Gray whale
Humpback whale	Fin whale	Harbor porpoise
Fin whale	Dall's porpoise	Minke whale
	Minke whale	Belukha whale

Responses to Vessels

Changes in haulout patterns of harbor seals in response to increased vessel traffic near rookeries in San Francisco Bay and Puget Sound have been documented (Paulbitski, 1975; Calambokidis et al., 1978, respectively). Seals hauled out for shorter periods during the day (when vessel traffic was highest) but hauled out longer periods at night (when traffic was lowest).

Increased vessel traffic has been implicated in the abandonment of embayments by gray and humpback whales. Before salt mining was begun in Guerrero Negro Lagoon, Mexico, gray whales bred and calved there. While the salt mine was in operation, ship and barge traffic was heavy, and whales used the lagoon less. After salt mining ceases, the whales returned to the lagoon (Gard, 1974). The decline in the number of humpback whales in Glacier Bay, Alaska, has been correlated with increased vessel traffic (Jurasz and Jurasz, 1979), although changes in food resources have also been implicated (Bryant et al., 1981). These studies are controversial, however; further work is being managed by the National Marine Mammal Laboratory under contract to the National Park Service.

Bowhead whales respond to the presence of vessels closer than 3.7 km by changing their respiratory patterns, orienting and moving away from the vessel (LGL, 1981). Respiration and swimming movements returned to normal more quickly than did social regrouping.

Spotted porpoises, *Stenella attenuata*, respond to tuna boats as far away as 7.4 km. In the tropical Pacific, a propoise herd which had been dispersed while the animals were apparently feeding coalesced and moved away when a fishing vessel increased its power to begin an approach (Acoustical Society of America, 1981).

Seismic Exploration

Current exploratory work relies upon the use of sound waves to map the sediments and underlying geophysical structure. Intense, highly impulsive sound sources are necessary for adequate penetration and definition; explosives have traditionally been the preferred sound source, but recently air guns and sparkers have predominated use offshore. All of these are used in arrays to allow overlapping mapping. As a result, seismic exploration is characterized by a series of closely linked, broad-banded signals of short duration and high intensity.

Since cetaceans and pinnipeds have excellent hearing, they may be highly sensitive to such disturbance (Fig. 4.8). If the sound source and intensity are close enough, baleen whales and pinnipeds could suffer ruptured eardrums; and, toothed whales could suffer hearing loss from sublethal shock waves because sound is conducted to the inner ear via blubber and fat (Hill, 1978). Most of these species would be most vulnerable to sounds of seismic exploration from spring through fall. If all seismic operations in St. George Basin were conducted during the winter, they would affect few animals.

4.6.5 Recovery Rates and Disturbance

Marine mammals are poorly adapted to respond to sudden decreases in their population size. They are long-lived, have low rates of fecundity and parental care may last up to two years, eg. walruses and sperm whales. Density-dependent changes probably occur at high population levels (Fowler, 1981).

Hunting by humans has severely depleted most large baleen whale populations, and previously, sea otters, and walrus. Of these, only the walrus and the gray whale have apparently fully recovered. Although sea otters have been completely protected since 1911, they have yet to recolonize all of their former range. Right whales have been protected for 45 years, but their population has shown no signs of increase, and they may be nearing extinction. The factors influencing recovery are poorly understood. Recovery rates are in most cases very slow, and any further disturbance may cause some populations to suffer further decline.

4.7 INFORMATION NEEDS

The following section draws heavily on general recommendations of Geraci and St. Aubin (1980). Those recommendations have been related to the species of major concern in the St. George Basin; priorities are shown in Table 4.7.

4.7.1 Oil Effects

Much information is needed on the effects of oil on marine mammals. Direct contact with spilled oil may result in thermal stress, irritation of the skin, ingestion, accumulation, or changes in behavior. Indirect effects through changes in trophic relationships may occur, particularly for those species which feed on sedentary organisms.

Thermal Effects

Although it is possible to predict which species will show significant metabolic heat loss if oiled (e.g., in or near St. George Basin, the fur seal and sea otter), information comes largely from laboratory experiments. Verification of these effects through controlled field experiments would be useful. However, such studies are low in priority, since some information is available.

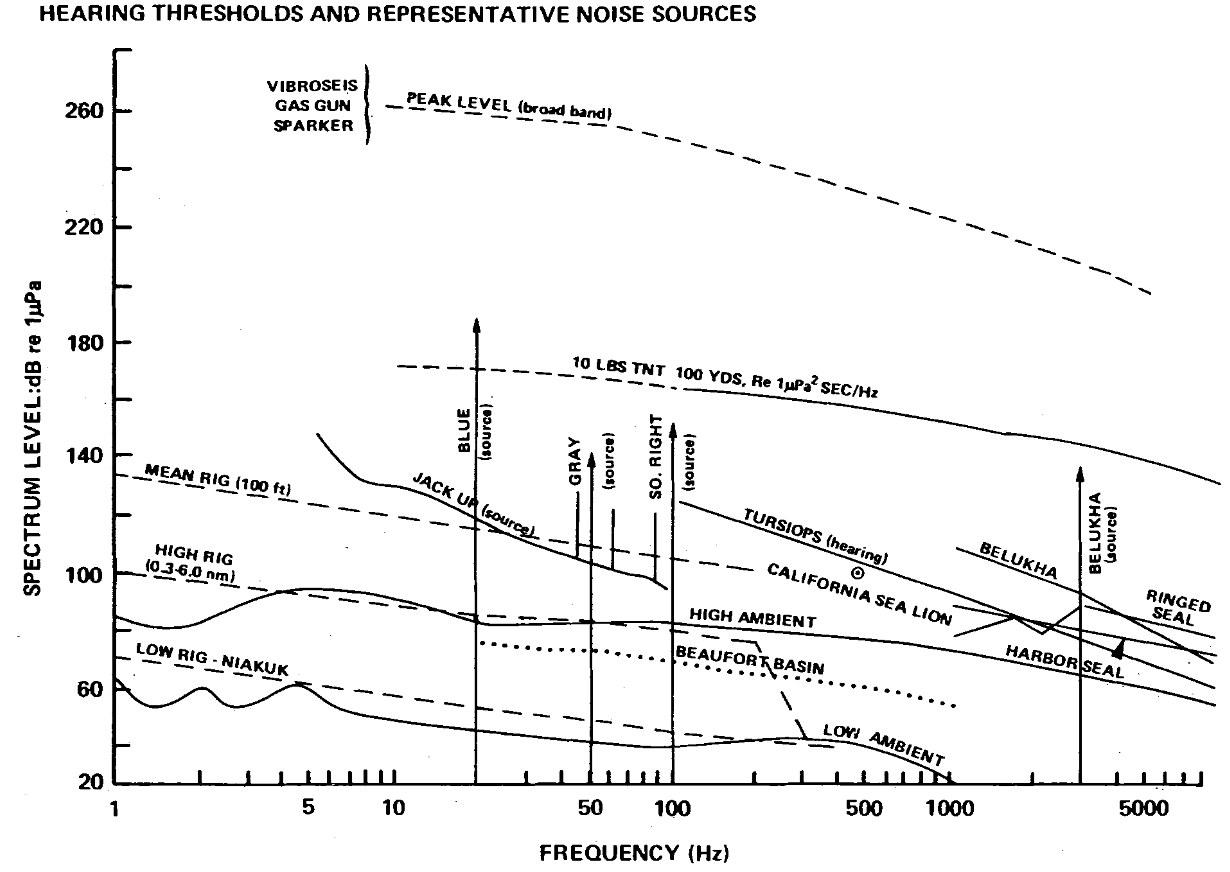

Figure 4.8. Marine mammal hearing thresholds and representative noise sources (American Acoustical Society, 1981).

Noxious Effects

Little is known of the effect of oil on cetacean epidermis or other potentially sensitive tissues. Similarly, dispersants may affect marine mammals. Some laboratory experimentation may be feasible. For example, it may be possible to study sea lions, pagophilic seals, or even selected small cetaceans under controlled conditions. *In situ* controlled oil spills may also prove instructive if done in the presence of or at a place where a particular whale species (e.g., gray whale) may occur.

Ingestion and Accumulation

Phocid seals may be capable of detoxifying or excreting ingested oil and may suffer few, if any, immediate pathological effects. The long-term effects of chronic hydrocarbon contact and/or ingestion of foods containing hydrocarbons remain unknown. Benthic feeders, such as walruses and gray whales, use areas in and near the St. George Basin and ingest sediments with their food. Sea otters are also likely to ingest and accumulate oil. Monitoring programs (see below) and/or continued surveillance of free-ranging or stranded animals are probably the most useful approaches to these problems.

Behavioral Responses

Little is known of the ability of marine mammals to avoid spilled oil. In the St. George Basin, little is known about mother-pup recognition, feeding, diving, herd organization, grooming, and hauling out. Hypotheses may be tested using captive fur seals or sea lions, or using hauled-out wild animals in the field. Such research could aid in predicting reproductive success of fur seals and sea lions in the event of a spill near rookeries. However, these kinds of studies are generally objectionable. Opportunities for field experiments in pelagic environments are limited. Probably the greatest priority in this area is to study avoidance behavior, if possible. Again, common species or species which do well in captivity such as certain toothed whales, sea otters, fur seals, and sea lions may serve as potential subjects.

4.7.2 Effects of Noise and Disturbance

Noise may have physiological or psychological consequences. Research must be directed to most likely causative agents and the most sensitive species. Stress on a population due to noise will be difficult to quantify due to complex interactions of the habitat, social factors, climate, food quality and quantity, and interspecific com-

Table 4.7. Research priorities for marine mammals in the St. George Basin.

High:	
	Ecological study of Unimak Pass.
	Ability to detect animal behavior within an oil spill.
	Responses to seismic and industrial noise.
	Distribution and abundance of cetaceans, especially those listed in the Endangered Species Act, 1973.
	Trophic interrelationships of ribbon seals, spotted seals, sea lions, sea otters, and fur seals.
	Field response research team to spills.
	Development and implementation of long-term monitoring strategy.
Medium:	
	Modelling trophic relations.
	Effects of oil spills on sensitive species.
	Distribution and life history studies of capelin and euphausiids and their importance to marine mammals.
	Noxious effects of oil and dispersants on cetacean skin.
Low:	
	Field studies in thermoregulatory effects of oiling on seals.

petition. However, studies of the effects of noise levels and characteristics or behavior at rookeries may be of value. Such studies can help to determine options for mitigation. The effects of noise on fur seals, sea lions, and walruses could be studied at concentration sites or during important life stages.

The potential effects of seismic exploration on the behavior of cetaceans and other marine mammals need to be studied. Ongoing studies on ringed seals and bowhead whales may provide guidelines for future efforts. The effects of other industrial noise, such as chronic drilling noise, on gray and bowhead whales should be studied.

4.7.3 Distribution and Abundance

Cetaceans

Indices of relative abundance and seasonal occurrence of endangered and non-endangered cetaceans within the southern Bering Sea are needed. Systematic surveys of potential lease areas and adjacent regions are also needed. Those which are repeated at intervals would be beneficial. Few statistically reliable population estimates are available for the region.

Pinnipeds and Sea Otters

Although some data exist on pinniped distribution and abundance, updating is necessary. Summer distribution of ribbon seals is the least understood; this may be because few animals occur here, however. Updates on sea lion and sea otter abundance along the Aleutian Chain and Alaska Peninsula are needed on a periodic basis. Systematic surveys of the sale areas that are reported at intervals would be beneficial.

4.7.4 Synthesis Efforts

Trophic Analyses

Trophic interactions between marine mammals and finfish (especially pollock) in the St. George Basin are key links to an understanding of this ecosystem. Preliminary modeling has been done, but should be continued and refined to increase predictive power. Additional fieldwork on food habits of ribbon seals, spotted seals, sea lions, and sea otters of the southern Bering Sea would support these studies. A study of pollock is essential.

The Effects of Oil Spills on Sensitive Species

Dynamic models of oil spill risk to sensitive species such as fur seals or sea otters would provide useful information to decisionmakers. Since oil spill trajectory prediction is well developed, relating those models to those of well-studied populations may be fruitful. It would be best to study species for which effects of contact are likely to be most extreme, such as the fur seal or sea otter.

4.7.5 Assessment of the Effects of Individual Spills and Long-term Monitoring

Field Response Team

Because certain types of field experiments are not now feasible and because existing predictive techniques need to be validated, regional response teams with expertise in marine mammal behavior, ecology, and pathology should be organized. These teams would arrive at the scene of an oil spill soon after it occurred; they would be able to gather information that is currently unavailable. Observations of the behavior of animals affected by spills are generally lacking.

Development-Stage Monitoring

In the event of OCS development, monitoring programs to document pathological or toxicological findings, or to measure changes in animal abundance or distribution will be necessary. This may be the only approach which will provide data on the long-term effects of offshore oil and gas development, especially low-level, chronic factors. The success of such monitoring depends largely on predevelopment studies of distribution, abundance, and physiology of marine mammals of the Bering Sea and adjacent waters of the North Pacific Ocean.

4.8 SUMMARY

The marine mammal fauna of the St. George Basin is richer and more diverse than anywhere else in Alaska or perhaps the world; 24 species, including eight of endangered whales, occur in the Basin. Critical breeding and feeding grounds are found there, and Unimak Pass is the major corridor for marine mammals migrating into and out of the Bering Sea.

Marine mammal species most likely to be affected by oil and gas development within the Basin are northern fur seal, Steller (northern) sea lion, harbor seal, sea otter, and the endangered species of whales. The bowhead, right, sei, and sperm whales use the area only occasionally. Bowhead and sei whales are normally found north and south of the Basin, respectively. Male sperm whales are occasionally seen feeding along the shelf break during summer. Right whales were once regularly seen in the Basin, but the population is near extinction, and there have been no recent sightings. Although sightings of whales have been infrequent, all of these species are endangered and thus have special status and protection. Section 7 of the Endangered Species Act of 1973 requires that any environmental assessment must include a determination of jeopardy to endangered populations from development.

Humpback, fin, and gray whales regularly use the area. Virtually the entire eastern Pacific population of gray whales travels through Unimak Pass on its northerly and southerly migration. Most gray whales travel close to the coast, but a few move directly from Unimak Pass to the Pribilof Islands. Gray whales formerly were thought to feed only in the northern Bering and Chukchi seas, but recent evidence indicates they feed along the migratory route as well. Fin and humpback whales pass through Unimak and other Aleutian passes on their way into and out of the Bering Sea. They are found for six to eight months in the St. George Basin, where they feed.

Pinnipeds use the Basin heavily. Northern fur seals migrate through Unimak Pass on their way to the Pribilof Islands, where 75 percent of the world population annually gathers to mate and pup. Fur seals feed along the edge of the continental shelf, and there is a constant stream of animals moving between the feeding grounds and the rookeries. Although most of the fur seals use the Basin between May and November, some of the adult males remain in the southeastern Bering Sea year round. Steller sea lions, harbor seals, and sea otters are year-round residents of the Basin. The sea lions range widely within the area and complete their life cycle within the Basin. The current status of the sea lion population is unknown. A 50 percent decline occurred between 1971 and 1975 in the eastern Aleutian Islands, but its cause has not been determined.

During years of extensive ice cover, large numbers of ice-associated seals may be found in the Basin. The spotted and ribbon seals, which occupy the fringe and frontal zones of the seasonal pack ice, would be expected to be more numerous than the bearded and ringed seals. During the winter and spring, these animals feed, breed, pup, and molt on the ice. Walruses also are associated with the sea ice; they may recolonize the Pribilofs as the pressures from the Bristol Bay and northern Bering Sea population centers increase.

The sea otter population is centered in the eastern Aleutian Islands and between Cape Mordvinof and Port Moller on the Alaska Peninsula. This population is growing and continues to recolonize its previous range. The otters are usually found close to shore, but many (mostly adult males) range out to the 80-m contour.

The trophic interactions within the St. George Basin are complex. Four food webs are utilized by marine mammals here: benthic, coastal, deep water, and pelagic. Most marine mammals feed on the pelagic food chain. Major prey species are euphausiids and pelagic and semidemersal fishes, especially pollock, capelin, and herring. Pollock are eaten by fin, humpback, and minke whales and are a major prey item of fur seals, harbor seals, ribbon seals, spotted seals, and sea lions. In addition, they are eaten by large numbers of seabirds and support the largest single-species commercial fishery in the Northern Hemisphere. Several species of toothed whales — in particular, sperm and beaked whales and some Dall's porpoise — feed in the very deep water off the shelf. The major prey in the deepwater food chain are cephalopods, bathypelagic and mesopelagic fishes, and some crustaceans. Gray whales, walruses, and bearded seals feed heavily on benthic organisms in other parts of their range over the shallower continental shelf. Although information on their food habits within the St. George Basin is scanty, they probably rely heavily upon the benthos there. Gray whales may also feed on small fish and nekton. The coastal food web is poorly understood. It is dominated by sea otters, which are unlike any other species of marine mammal found in the Basin. These otters are far more pelagic than other otter populations, and no information on their food habits in the area is available. Outside the St. George Basin, they feed on herbivorous epibenthic macroinvertebrates such as sea urchins, limpets, and chitons.

Sea otters, fur seals, gray whales, and right whales are probably the species most sensitive and vulnerable to a major oil spill within the Basin. Sea otters and fur seals rely on their fur for thermal protection. Oiling mats it and thereby reduces its thermal efficiency. Gray whales are vulnerable because of their near-exclusive use of Unimak Pass to enter and exit the Bering Sea. Right whales are particularly vulnerable because of the extreme depletion of their numbers. The ability of marine mammals to detect and avoid oil spills, however, is unknown.

Information was not available to assess the consequences of oil and gas development upon the endangered species of whales, but they probably will not be favorable. Although little is known of the effect of oil in the water on the distribution of schooling pelagic fishes or zooplankton, concern was expressed that if it alters either the distribution or the degree of patchiness in prey species, the consequences for marine mammals might be severe.

To have a comprehensive management plan, the following topics should be addressed: site-specific ecological studies, especially at Unimak Pass; population estimates and natural history of many species of cetaceans; food habits and trophic interactions; the effects of noise and vessel traffic on marine mammals; the effects of oiling upon cetaceans; ability to detect and avoid oil on the surface; and development and implementation of an oil spill response team and a long-term monitoring strategy.

4.9 REFERENCES

Acoustical Society of America. 1981. San Diego workshop on the interaction between man-made noise and vibration and Arctic Marine Wildlife, 25-29 February 1981, San Diego, Calif. Alaskan Eskimo Whaling Commission, Barrow, Alaska. 84p.

Berzin, A. A., and A. A. Rovnin. 1966. Distribution and migration of whales in the northeastern part of the Pacific Ocean, Bering and Chukchi Seas, pp. 103-136. *In:* K. I. Panin (ed.), *Soviet Research on Marine Mammals of the Far East.* (Transl. U.S. Dep. Int., Bur. Comm. Fish.)

Betesheva, E. I. 1961. Pitanie promyslovykh kitov Prikuril'skogo raiona (Food of the commercial whales in the Kurile region). Tr. Inst. Morfol. Zhivotnykh Akad. Nauk SSSR. 34:7-32. (In Russian.)

Bouchet, G. C. 1981. Estimation of the abundance of Dall's porpoise *(Phocoenoides dalli)* in the North Pacific Ocean and Bering Sea. Northw. Alaska Fish. Cent., Seattle, Wash. Proc. Re. 81-1.

Braham, H. W. 1977. California gray whale. *(Eschrichtius robustus)* spring migration in Alaska. *In,* Proc. Second Conf. Biol. Marine Mammals, San Diego, Calif., 12-15 December 1977. p. 59.

Braham, H. W. in press (a). Reproduction in white whales *(Delphinapterus Leucas)* and narwhals *Monodon monoceros)*: A review, with comments on stock assessment. Rep. Int. Whal. Comm. (Special Issue No. 4).

Braham, H. W. In press (b). Gray Whale: A historical biological account. *In,* J. Vargas (ed.) *Survival of the Gray Whale.* Mexico City, D.F. (In Spanish).

Braham, H. W. In prep. Migration and feeding of gray whales *(Eschrichtius robustus)* in Alaska. 25p.

Braham, H. W., J. Burns, G. Fedoseev, and B. Krogman. In press (b). Distribution and density of ice-associated pinnipeds in the Bering Sea. *In:* F. Fay (ed.), *USSR-U.S. Marine Mammal Cooperative Research* I: Pinnipeds.

Braham, H. W. and M. E. Dahlheim. In press. Killer whales in Alaska documented in the Platforms of Opportunity Program. Rep. Int. Whal. Comm.

Braham, H. W., R. D. Everitt, B. D. Krogman, D. J. Rugh, and D. E. Withrow. 1977. Marine mammals of the Bering Sea: A preliminary report on distribution and abundance, 1975-76. Northwest and Alaska Fish. Cent. Proc. Rep. 90p.

Braham, H. W., R. D. Everitt, and D. J. Rugh. 1980a. Northern sea lion population decline on eastern Aleutian Islands, Alaska. J. Wildl. Manage. 44:25-33.

Braham, H. W., M. Fraker, and B. Krogman. 1980b. Spring migration of the western Arctic population of bowhead whales. Mar. Fish. Rev. 42(9-10):36-46.

Braham, H. W., B. D. Krogman, and G. Carroll. In press (a). Population biology of the bowhead whale *(Balaena mysticetus)* II: Migration, distribution and abundance in the Bering, Chukchi, and Beaufort Seas, with notes on the distribution and life history of white whales *(Delphinapterus leucas).* NOAA Tech. Memo.

Braham, H. W., B. Krogman, J. Johnson, W. Marquette, D. Rugh, R. Sonntag, T. Bray, J. Brueggeman, M. Dahlheim, M. Nerini, and S. Savage. 1980c. Population studies of the bowhead whale *(Balaena mysticetus)*: Preliminary results of the 1979 spring research season. Rep. Inter. Whal. Comm. 30:391-404.

Braham, H. W., B. Krogman, S. Leatherwood, W. Marquette, D. Rugh, M. Tillman, J. Johnson, and G. Carroll. 1979. Preliminary report of the 1978 spring bowhead whale research program results. Rep. Inter. Whal. Comm. 29:291-306.

Braham, H. W. and D. J. Rugh. In prep. Occurrence of marine mammals in the eastern Bering and southern Chukchi Seas, with special reference to Alaskan Outer Continental Shelf oil and gas lease area. NOAA Tech. Memo.

Braithwaite, L. F. 1980. Studies on effects of baleen fouling by oil, pp. 92-96. *In:* Draft proceedings of the interagency meeting to review, coordinate, and plan bowhead whale research, other cetacean research, and related research bearing upon the conservation and protection of endangered marine species in Alaska and elsewhere, November 1980. U.S. Dep. Int., BLM, Washington, D.C.

Brownell, R. L. 1977. Current status of the gray whale. Rep. Inter. Whaling Comm. 27:209-211.

Burns, J. J. 1970. Remarks on the distribution and natural history of pagophilic pinnipeds in the Bering and Chukchi Seas. J. Mammal. 51:445-454.

Burns, J. J., and K. J. Frost. 1980. The natural history and ecology of the bearded seal, *Erignathus barbatus.* Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol.

Burns, J. J., and S. J. Harbo. 1977. An aerial census of spotted seal, *Phoco vitulina largha,* and walruses, in the ice front of the Bering

Sea. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep. (Quart, Rep., April-June) 1:58-132.

Burns, J. J., L. H. Shapiro, and F. H. Fay. 1977. The relationships of marine mammal distributions, densities, and activities to sea ice conditions. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:503-554.

Bryant, P. J., G. Nichols, T. B. Bryant, and K. Miller. 1981. Krill availability and the distribution of humpback whales in southeastern Alaska. J. Mammal. 62(12):427-430.

Calambokidis, J., K. Bowman, S. Carter, J. Cubbage, P. Dawson, T. Fleishner, J. Schuett-Hames, J. Skidmore, and B. Taylor. 1978. Chlorinated hydrocarbons: Concentrations and the ecology and behavior of harbor seals in Washington State waters. Evergreen St. Coll., Olympia, Wash. 121p. (Unpubl. Ms.)

Calkins, D. G. 1978. Feeding behavior and major prey species of the sea otter, *Enhydra lutris*, in Montague Strait, Prince William Sound, Alaska. Fish. Bull. 76:125-131.

Calkins, D. G., and K. Pitcher. 1979. Population assessment, ecology and trophic relationships of Steller sea lions in the Gulf of Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:144-208.

Consiglieri, L. and H. Braham. In prep. Distribution of marine mammals in the Gulf of Alaska, 1958-1980. Environmental assessment of the Alaskan continental shelf. NOAA Tech. Memo.

Costa, D. P., and G. L. Kooyman. 1981. Effects of oil contamination in the sea otter, *Enhydra lutris*. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol. 10:65-107.

Crawford, T. 1981. Food habits of Dall's porpoise. Master's Thesis, Univ. Washington, Seattle.

Engelhardt, F. R., J. R. Geraci, and T. G. Smith. 1977. Uptake and clearance of petroleum hydrocarbons in the ringed seal, *Phoca hispida*. J. Fish. Res. Bd. Can. 34:1143-1147.

Estes, J. A., and J. R. Gilbert. 1978. Evaluation of an aerial survey of Pacific walruses *(Odobenus rosmarus divergens)*. J. Fish. Res. Bd. Can. 35:1130-1140.

Estes, J. A., and J. F. Palmisano. 1974. Sea otters: Their role in structuring nearshore communities. Science 185:1058-1060.

Everitt, R., and H. Braham. 1980. Aerial survey of Pacific harbor seals in the southeastern Bering Sea. Northw. Sci., 54(4):281-283.

Fay, F. H. 1974. The role of ice in the ecology of marine mammals of the Bering Sea, pp. 383-399. *In:* D. W. Hood and E. J. Kelley (eds.), Oceanography of the Bering Sea. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Occ. Pub. 2.

Fay, F. H., Y. A. Bukhtiyarov, S. W. Stoker, and L. M. Shults. In prep. Food of the Pacific walrus in the winter-spring period in the Bering Sea.

Fay, F. H., H. M. Feder, and S. W. Stoker. 1977. An estimation of the impact of the Pacific walrus population on its food resources in the Bering Sea. Mar. Mamm. Comm. Rep. MMC-75/06, 74/03.

Fiscus, C. H., D. W. Rice, and A. M. Johnson. 1969. New records of *Mesoplodon stejnegeri* and *Ziphius cavirostris* from Alaska. J. Mammal. 50:127.

Fiscus, C. H., H. W. Braham, R. W. Mercer, R. D. Everitt, B. D. Krogman, P. D. McGuire, C. E. Peterson, R. M. Sonntag, and D. E. Withrow. 1976. Seasonal distribution and relative abundance of marine mammals in the Gulf of Alaska. Northwest and Alaska Fisheries Center Proc. Rep., NOAA/NMFS, Seattle, Wash. 238p.

Fiscus, C. H., D. J. Rush, and T. R. Loughlin. In press. Census of northern sea lions *(Eumetopic jubatus)* in the central Aleutian Islands, Alaska, June 17 - July 15, 1979, with notes on other marine mammals. NOAA Tech. Memo.

Fowler, C. 1981. Density dependences as related to life history strategy. Ecology, 62(3):602-610.

Frost, K. J., and L. F. Lowry. 1981. Foods and trophic relationships of cetaceans in the Bering Sea, 2:825-836. *In* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash. Vol. :p

Gard, R. 1974. Aerial surveys of gray whales. Calif. Fish. Game. 60:132-144.

Geraci, J. R., and D. J. St. Aubin. 1980. Offshore petroleum resource development and marine mammals: A review and research recommendations. Mar. Fish. Rev. 42(11):1-12.

Geraci, J. R., and T. G. Smith. 1976. Direct and indirect effects of oil on ringed seals *(Phoco hispida)* of the Beaufort Sea. J. Fish Res. Bd. Can. 33:1976-1984.

Goodale, D. R., M. A. Hyman, and H. E. Winn, 1981, cetacean responses in association with the *Regal Sword* Oil Spill in "A Characterization of Mature Mammals and Turtles in the Mid- and North-Atlantic areas of the U.S. Outer Continental Shelf, Annual Report for 1979." University of Rhode Island. U.S. Dept. of Interior, BLM, Wash, D.C.

Hall, J. D., C. S. Harrison, J. Nelson, and A. Taber. 1977. The migration of California gray whales into the Bering Sea. *In:* Proc. Second Conf. Biol. Marine Mammals, San Diego, Calif., 12-15 December 1977. p. 8.

Hill, S. H. 1978. A guide to the effects of underwater shock waves on arctic marine mammals and fish. Inst. Ocean. Sci., Patricia Bay, Sidney, B.C., Pac. Mar. Sci. Rep. 78-26 (unpub.).

Interagency Task Group (ITG). 1978. Final environmental impact statement: Consideration of a waiver of the moratorium and return of management of certain marine mammals to the State of Alaska. 1. Summary and text. U.S. Dep. Comm., U.S. Dep. Int., Washington, D.C.

Ivashin, M. V., and A. A. Rovnin. 1967. Some results of the Soviet whale marking in the waters of the North Pacific. Norsk Hvalfangst-tid. 56-123-135.

Jellison, W. L. 1953. A beaked whale, *Mesoplodon sp.*, from the Pribilofs. J. Mamm. 34(2):249-251.

Johnson, B. W. 1977. Disturbance of harbor seals by aircraft. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:422-432.

Jonsgard, A.a. 1951. Studies on the little piked whale or minke whale *(Balaenoptera acutorostrata)*. Norsk Hvalfangst-tid. 40:209-232.

Jurasz, C., and V. Jurasz. 1979. Ecology of the humpback whale in Glacier Bay, Alaska. U.S. Nat. Park Serv., Juneau.

Kajimura, H., R. H. Lander, M. A. Perez, A. E. York, and M. A. Bigg. 1979. Preliminary analysis of the pelagic fur seal data collected by the United States and Canada during 1958-1974. 22nd Ann. Meet., Standing Sci. Comm. North Pac. Fur Seal Commission, NMML, Seattle, Wash.

Kajimura, H., R. H. Lander, M. A. Perez, A. E. York, and M. A. Bigg. 1980. Further analysis of pelagic fur seal data collected by the United States and Canada during 1958-74. 23rd Ann. Meet. Standing Sci. Comm. North Pac. Fur Seal Commission, NNML, Seattle, Washington.

Kawamura, A. 1975. Whale distribution in the Bering Sea and southern North Pacific in summer, 1974. Bull. Japan. Soc. Fish. Oceanogr. 25:119-128.

Kenyon, K. W. 1960. A ringed seal from the Pribilof Islands, Alaska. J. Mammal. 41:520-521.

Kenyon, K. W. 1961. Cuvier beaked whales stranded in the Aleutian Islands. J. Mammal. 42:71-76.

Kenyon, K. W. 1969. The sea otter in the eastern Pacific Ocean. U.S. Fish Wildl. Serv., N. Amer. Fauna 68.

Kenyon, K. W. 1972. Aerial surveys of marine mammals in the Bering Sea, April 6-16, 1972. U.S. Fish Wildl. Serv., Bur. Sport Fish. Wildl., Seattle, Wash. 79 p. (Unpubl.)

Kleinenberg, S., A. Yablokov, B. Belkovich, and M. Tarasevich. 1969. Beluga *(Delphinapterus leucas)*. Investigation of the species. (Transl. from Russian by Israel Prog. Sci. Transl. NTIS TT 67-51345. 376p.)

Klinkhart, E. 1966. The beluga whale in Alaska. Alaska Dep. Fish Game, Fed. Aid Wildl. Restoration Proj. Rep. 7:1-11.

Kooyman, G., R. Gentry, and W. B. McAlister. 1976. Physiological impact of oil on pinnipeds. Northw. Alaska Fish. Cent. Proc. Rep., NOAA/NMFS, Seattle, Wash. 23p.

Kozloff, P. 1981. Fur seal investigations, 1980. Northw. Alaska Fish. Cent., Seattle, Wash. Proc. Rep. 81-2.

Krogman, B., H. Braham, R. Sonntag, and R. Punsly. 1979. Early spring distribution, density, and abundance of the Pacific walrus *(Odobenus rosmarus)*. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep. 47p.

Krogman, B., R. Sonntag, D. Rugh, R. Gradefendt, and G. Priebe. 1981. Population estimation of the western arctic stock of the bowhead whale. Rep. Int. Whal. Comm. SC/33/p. 54.

Lander, R. 1980. A life table and biomass estimate for Alaskan fur seals, pp. 44-57. *In:* H. Kajimura et al., Further analysis of pelagic fur seal data collected by the United States and Canada during 1958-1974, Northw. Alaska Fish Cent., NMFS, NOAA, Seattle, Wash.

Lockyer, C. 1976. Estimates of growth and energy budget for the sperm whale, *Physeter catodon*. FAO, Sci. Consult. Mar. Mamm., ACMRR/MM/SC/38.

Lockyer, C. 1977. Observations on diving behavior of the sperm whale, *Physeter catodon. In:* M. Angel (ed.)., *A Voyage of Discovery.* Pergamon Press, New York. pp.591-609.

Loughlin, T. R., C. H. Fiscus, A. M. Johnson, and D. J. Rugh. In prep. Observations of Stejneger's beaked whale *(Mesoplodon stejnegeri)* in the Central Aleutian Islands, Alaska. (In review, J. Mammal.)

Lowry, L. F., and J. Burns. 1980. Foods utilized by bowhead whales near Barter Island, Alaska, Autumn 1979. Mar. Fish. Rev. 42(9-19):88-91.

Lowry, L. F., and J. J. Burns. 1976. Trophic relationships among ice inhabiting phocid seals. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:303-332.

Lowry, L. F., and K. J. Frost. 1981. Feeding and trophic relationships of phocid seals and walruses in the eastern Bering Sea, *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 2:813-824.

Lowry, L. F., K. I. Frost, and J. J. Burns. 1977. Trophic relationships among ice inhabiting phocid seals. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:303-390.

Lowry, L. F., K. I. Frost, and J. J. Burns. 1978. Trophic relationships among ice inhabiting phocid seals. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:161-372.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1980a. Variability in the diet of ringed seals *Phoca hispida*, in Alaska. Can. J. Fish. Aquat. Sci. 37:2254-61.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1980b. Feeding of bearded seals in the Bering and Chukchi Seas and trophic interaction with Pacific walruses. Arctic 33:330-42.

LGL. 1981. The effects of noise and disturbance on bowhead whales. BLM, Anchorage, Ann. Rep.

Marine Mammal Division. 1978. Fur seal investigations, 1977. Northwest and Alaska Fisheries Center Proc. Rep., NOAA/NMFS, Seattle, Wash. 94p.

Marquette, W., H. Braham, M. Nerini, and R. Miller. In press. Bowhead research results, Autumn 1980 - Spring 1981: Harvest, biology and distribution. Rep. Inter. Whal. Comm.

McAlister, W. B. In prep. Estimates of fish consumption by marine mammals in the eastern Bering Sea and Aleutian Island area. U.S. Dep. Comm., NMFS, NMML, Seattle, Wash.

Mitchell, E. 1974. Preliminary report on Newfoundland fishery for minke whales *(Balaenoptera acutorostrate)*. Rep. Int. Whal. Comm. 24:159-176.

Moore, J. C. 1966. Diagnoses and distributions of beaked whales of the genus *Mesoplodon* known from North American waters. *In:* K. S. Norris (ed.), *Whales, Dolphins and Porpoises.* Univ. Calif. Press, Berkeley, Calif. p. 32-61

Nemoto, T. 1957. Foods of baleen whales in the northern Pacific. Sci. Rep. Whales Res. Inst. 12:33-89.

Nemoto, T. 1959. Food of baleen whales with reference to whale movements. Sci. Rep. Whales Res. Inst. 144:149-290.

Nerini, M. In press. Feeding ecology of gray whales. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol.

Nishiwaki, M. T. 1967. Distribution and migration of marine mammals in the North Pacific area. Bull. Univ. Tokyo, Ocean Res. Inst. 1:1-64.

Nishiwaki, M., and C. Handa. 1958. Killer whales caught in the coastal waters off Japan for recent 10 years. Sci. Rep. Whales Res. Inst. 13:85-96.

Norris, K. W. 1979. Gray whale lagoon entrance aggregations. *In*, Third Biennial Conf. Biology of Marine Mammals, October 7-11, 1979, Seattle, Wash. (Abst.)

Ohsumi, S. 1966. Sexual segregation of the sperm whale in the North Pacific. Sci. Rep. Whales Res. Inst. 20:1-16.

Ohsumi, S., and Y. Masaki. 1975. Japanese whale markings in the North Pacific, 1963-1972. Bull. Far Seas Fish. Res. Lab. 12:171-219.

Ohsumi, S., and Y. Masaki. 1977. Stocks and trends of abundance of the sperm whale in the North Pacific. Rep. Inter. Whaling Comm. 27:167-175.

Omura, H. 1958. North Pacific right whale. Sci. Rep. Whales Res. Inst. 13:1-52.

Omura, H., and H. Sakimura. 1956. Studies on the little piked whales from the coast of Japan Sci. Rep. Whales Res. Inst. 11:1-38.

Paulbitski, W. 1975. The seals of Strawberry Spit, Pacif. Discovery 18:12-16.

Payne, R. S., and D. Webb. 1971. Orientation by means of long-range acoustic signaling in baleen whales. Ann. N.Y. Acad. Sci. 188:11-141.

Perez, M., and M. Bigg. 1981. An assessment of the feeding habits of the northern fur seal in the eastern North Pacific Ocean and eastern Bering Sea. Northw. Alaska Fish. Cent., Seattle, Wash. Unpub. rep.

Pike, G. C. 1962. Migration and feeding of the gray whale *(Eschrichtius robustus)*. J. Fish. Res. Bd. Can. 19:815-835.

Pitcher, W. 1977. Population productivity and food habits of harbor seals in the Prince William Sound — Copper River Delta area, Alaska. Final Rep. to Mar. Mamm. Comm. (Avail. NTIS, Springfield, Va). 36p.

Pitcher, K. 1979. Prey of the Steller sea lion, *Eumetopias jubatus* in the Gulf of Alaska. Unpub. MS.

Pitcher, K., and D. Calkins. 1978. Biology of the harbor seal, *Phoca vitulina richardi*, in the Gulf of Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:80-98.

Prescott, J., and P. Fiorelli. 1979. Review of the harbor porpoise *(Phocoena phocoena)* in the U.S. Northwest Atlantic. U.S. Mar. Mamm. Comm. Contract MM8AC016. Unpub. MS.

Reeves, R. R. 1977. On the question of harassment. Mar. Mamm. Comm. Final Rep.

Reilly, S. 1981. Population assessment and population dynamics of the California gray whale (*Eschrichtius robustus*). Ph.D. Dissertation, Univ. of Washington, Seattle, Wash. 265p.

Reilly, S., D. Rice, and A. Wolman. 1980. A preliminary population estimate for the California gray whale based upon Monterey shore censuses. Rep. Inter. Whaling Comm. 30:359-368.

Rice, D. W. 1978a. The humpback whale in the North Pacific: Distribution, exploitation, and numbers, pp. 29-44. *In:* K. S. Norris and R. R. Reeves (eds.), Report of a workshop on problems related to humpback whales *(Megaptera novaeangliae)* in Hawaii, U.S. Mar. Mamm. Comm., Rep. NMC-77/03.

Rice, D. W. 1978b. Beaked whales, pp. 88-95. *In:* D. Haley (ed.), *Marine Mammals of Eastern North Pacific and Arctic Waters*, Pacific Search Press, Seattle, Wash.

Rice, D. W. 1978c. Sperm whales, pp. 82-87. *In:* D. Haley (ed.), *Marine Mammals of Eastern North Pacific and Arctic Waters*, Pacific Search Press, Seattle.

Rice, D. W., and A. A. Wolman. 1971. Life history and ecology of the gray whale, *Eschrichtius robustus*. Amer. Soc. Mamm. Spec. Pub. 3.

Rugh, D., and H. Braham. 1979. California gray whale *(Eschrichtius robustus)* fall migration through Unimak Pass, Alaska, 1977: A preliminary report. Rep. Inter. Whaling Comm. 29:315-320.

Schneider, K. B. 1976. Distribution and abundance of sea otters in southwestern Bristol Bay. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep. (Quart. Rep., Oct.-Dec.) 1:469-526.

Schneider, K. B. 1981. Distribution and abundance of the sea otters in the eastern Bering Sea, 2:837-845. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash.

Schneider, K. B., and J. Faro. 1975. Effects of sea ice on sea otters. J. Mammal. 56:91-101.

Sergeant, D. E., and P. F. Bradie. 1975. Identity, abundance, and present status of populations of white whales, *Delphinapterus leucas*, in North America. J. Fish. Res. Bd. Can. 32:1047-1054.

Severinghaus, N. 1979. Selected annotated references on marine mammals of Alaska. Northw. Alaska Fish. Cent. Seattle, Wash. Proc. Rep. 79-15. 178p.

Simenstad, C. A., J. A. Estes, and K. W. Kenyon. 1978. Aleuts, sea otters, and alternate stable state communities. Science 200:403-411.

Sleptsov, M. M. 1961a. Fluctuation in the numbers of whales in the Chukchi Sea in various years, (Transl. by U.S. Nav. Oceanogr. Off., Washington, D.C., Transl. 478).

Sleptsov, M. M. 1961b. Feeding regions of whales in the Bering Sea. Akad. Nauk SSSR, Tr. Inst. Morfol. Zhivotnykh 34:65-78. (In Russian)

Smith, G. B. 1981. The biology of walleye pollock. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash. Vol. 2:527-551

Swartz, S. and M. L. Jones. 1981. Demographic studies and habitat assessment of gray whales, *Eschrichtius robustus*, in Laguna San Ignacio, Baja California Sur, Mexico. Rep. Int. Whal. Comm. SC/33/p.512.

Tillman, M. 1975. Assessment of North Pacific stocks of whales. Mar. Fish. Rev. 37(10):1-4.

Tomilin, A. G. 1957. Cetacea, 9:1-756. *In:* V. G. Heptner (ed.), Mammals of the USSR and adjacent countries. (Transl. from Russian by Israel Prog. Sci. Transl.)

U.S. Dep. Comm. 1980. Final environmental impact statement on the Interim Convention on Conservation of the North Pacific Fur Seals. U.S. Dep. Commer., NOAA, NMFS, Wash., D.C. 116p.

U.S. Dep. Comm. 1981. Report on studies of the incidental take of marine mammals particularly Dall's porpoise, *Phocoenoides dalli*, in the Japanese salmon fishery. NOAA, NMFS, NMML, Seattle, Wash. Unpub. MS.

Vibe, C. 1950. The marine mammals and the marine fauna in the Thule District (northwest Greenland) with observations on ice conditions in 1939-41. C. A. Reitzels, Copenhagan.

Wada, S. 1975. Indices of abundance of large-sized whales in the North Pacific in 1973 whaling season. Rep. Inter. Whaling Comm. 25:129-165.

Zimushko, V. V., and S. A. Lenskaya. 1970. Feeding of the gray whale (*Eschrichtius robustus*) at foraging grounds. Ekolog. Akad. Nauk SSSR 1(3):26-35. (Transl. by Consultants Bur., Div. of Plenum Pub. Corp., 227 west 17th St., N.Y., NY.)

CHAPTER 5

MARINE BIRDS

J. G. Strauch, Jr. and G. L. Hunt, Jr.

With contributions from P. A. Baird, R. G. Ford, D. J. Forsell, P. J. Gould, R. E. Gill, Jr., W. N. Holmes, J. Hubbard, L. E. Jarvela, J. L. Kaiwi, D. N. Nettleship, D. Nyswander, G. A. Sanger, and D. Schneider.

5.1 INTRODUCTION

Marine birds are long-lived organisms with low reproductive rates. They are adapated to life in a variable environment in which natural conditions may prevent successful breeding in any one year, or possibly for several years during the adult life span. Their populations persist because low adult mortality rates permit a long adult life span and because reproductive success can be high in "good" years.

Thus, any factor increasing adult mortality is likely to have severe consequences for seabird populations. On the other hand, the loss of a year or two of reproductive success is likely to have less serious consequences, unless the lost years coincide with years that would have otherwise been good for reproduction, an unpredictable stochastic event. Long-term chronic depression of reproductive success clearly will be disastrous.

Given these features, we must be particularly concerned with pelagic and coastal distributions, adult mortality, and long-term reproductive success. We therefore first present data on the distribution and abundance of birds and then describe their reproductive biology and ecology.

5.2 DISTRIBUTION

5.2.1 Breeding Colonies

Two major complexes of seabird breeding colonies are found near the St. George lease area (Hunt et al., 1981c): the Pribilof Islands (59 km to the northwest) (Hickey and Craighead, 1977), and the Fox Islands (78 km to the south) (see Fig. 1.1). Almost five million birds (about 2.8 million on the Pribilofs and about 1.8 million on the Fox Islands, Table 5.1), or about 20 percent of the known Alaska seabird breeding population, nest in these areas (Sowls et al., 1978; U.S. Fish and Wildlife Service, unpub.). The Pribilof colonies include about 88 percent of the world's population of Red-legged Kittiwakes *(Rissa brevirostris)* and about 97 percent of the known Alaska population of this species. The world's largest colony of Thick-billed Murres *(Uria lomvia)* is also present there. The Fox Islands support about 50 percent of the Alaska popuation of Whiskered Auklet *(Aethia pygmaea)* and about 45 percent of the Alaska population of Tufted Puffin *(Lunda cirrhata)*.

5.2.2 Pelagic Distribution

High densities of seabirds at sea occur over most of the St. George Lease Area and adjacent waters. The distribution and abundance of seabirds in the St. George lease area depend on the availability of food and the location of nesting sites. Food availability in turn is controlled by oceanographic conditions (Iverson et al., 1979). The pelagic distribution of seabirds in the St. George Basin differs considerably from species to species and from season to season. An area of lower density between isobaths of 50 and 100 m is evident (Fig. 5.1; Hunt, et al., 1981d).

The highest densities of pelagic birds occur in summer and fall (Fig. 5.1). They result mainly from increases in the numbers of shearwaters. For species other than shearwaters, overall density has a tendency to peak in the spring (Fig. 5.1a). This spring peak, however, reflects the concentrating effect that ice cover has rather than indicating a larger total population. From June through September, the Short-tailed Shearwater *(Puffinus tenuirostris)* is the most abundant species in the Bering Sea. Shearwaters are typically found over the continental shelf, with only moderate numbers occurring over the shelf break. In the Bering Sea, they are concentrated near and within the 50-m isobath. Flocks of at least 100,000 are common, and flocks of over 1,000,000 have been recorded. Few data are available on winter distributions of any species in the Bering Sea.

Murres are abundant and widespread in the southeastern Bering sea (Shuntov, 1972). Both Common *(U. aalge)* and Thick-billed Murres are present, but since they are difficult to distinguish in the field, observations of these species are

Table 5.1 Estimated breeding populations of St. George Basin lease area colonies (U.S. Fish and Wildlife Service, unpub.).

Species	Fox Islands	Pribilof Islands	Total
Northern Fulmar	4	70,700	70,704
Fork-tailed Storm-Petrel	250,000+	0	250,000+
Leach's Storm-Petrel	138,000+	0	138,000+
Cormorants	11,800	7,700	19,500
Glaucous-winged Gull	24,000	+	24,000+
Black-legged Kittiwake	2,000	108,000	110,000+
Red-legged Kittiwake	2,300	222,200	224,500
All murres	107,400	1,849,300	1,956,700
Pigeon Guillemot	11,800	0	11,800
Ancient Murrelet	27,500	0	27,500
Cassin's Auklet	8,600	0	8,600
Parakeet Auklet	600	184,000	184,600
Crested Auklet	0	34,000	34,000
Least Auklet	0	273,000	273,000
Whiskered Auklet	14,000	0	14,000
Horned Puffin	12,000	32,400	44,400
Tufted Puffin	1,227,000+	7,000	1,234,000
Total	1,837,004	2,788,300	4,625,304

usually combined. Murres are most commonly found over the continental shelf (Table 5.2). In the spring they occur throughout areas of open water. In the summer they are concentrated around the major breeding colonies. In the fall they again disperse over the continental shelf. They are the most abundant seabird wintering in the Bering Sea and because they stay on or below the surface they are among the most vulnerable to spilled oil.

Statistical analysis of the numbers of birds across the shelf shows higher densities of non-diving species (fulmars, storm-petrels, and kittiwakes) over the slope and outer continental shelf waters and higher densities of divers and pursuit plungers (shearwaters and alcids) over the central shelf (Fig. 5.2).

Seabirds typically occur in groups which vary greatly in size. This tendency for seabirds to be found in clumps is conveniently illustrated by the coefficient of variation (cf. Odum, 1971, pp. 205-207), which gives the ratio of the standard deviation to the mean for equal size areas of ocean. Figure 5.3 shows how this statistic varies with location and season. The greatest number of different values occurs in the summer. If only birds found on the water are considered, large coefficients are most common for the areas around the Pribilof Islands and near Unimak Pass (Fig. 5.4).

The waters around the eastern Aleutian Islands and the Pribilof Islands are especially important for birds. In both areas seabirds have short flying time to a variety of marine environments, including a broad continental shelf, a precipitous shelf break, and deep oceanic expanses. In addition, the eastern Aleutians have many deep and protected bays and inlets, and a tidal flow which creates rip tides within an abundance of straits and passes.

High densities and large aggregations of birds are frequently found in and near Unimak Pass (Table 5.3). In the summer, large numbers of

Table 5.2. Density (birds/km^2) for seasons and habitats in the eastern Bering Sea. Data are derived from combined ship and air surveys. Habitats include continental shelf (CS), shelf break (SB), and oceanic (OC) waters (Hunt, et al., 1981d).

Species/	Winter[a]			Spring			Summer			Fall		
species group	CS	SB	OC	CS	SB	OC	CS	SB	OC	CS	SB	OC
Fulmar	1	3	2	3	11	2	3	16	3	12	35[b]	9
Shearwaters	0	0	0	3	3	+	81[b]	13	3	35	104	2
Storm-petrels	0	3	1	1	2	2	2	7	2	1	6	3
Larus gulls	+[c]	1	+	1	2	1	1	1	+	1	2	+
Kittiwakes	+	+	1	1	2	1	2	2	1	3	5	1
Alcids	16	2	2	34	20	5	15	17	2	9	3	2
Murres	14	0	0	19	2	1	9	1	+	4	1	+
Tufted Puffins	0	0	0	1	1	1	1	2	1	2	1	+
Total birds minus Shearwaters & fulmars	24	6	5	50	27	10	25	29	5	18	18	4
Total birds	25	9	7	56	41	12	109[b]	58	11	65	157[b]	16

---

a Based on a single aerial survey and no shipboard surveys.

b These indices are highly biased from sightings of large flocks.

c All indices have been rounded to nearest whole number. A "+" indicates fewer than 0.5 birds/km^2.

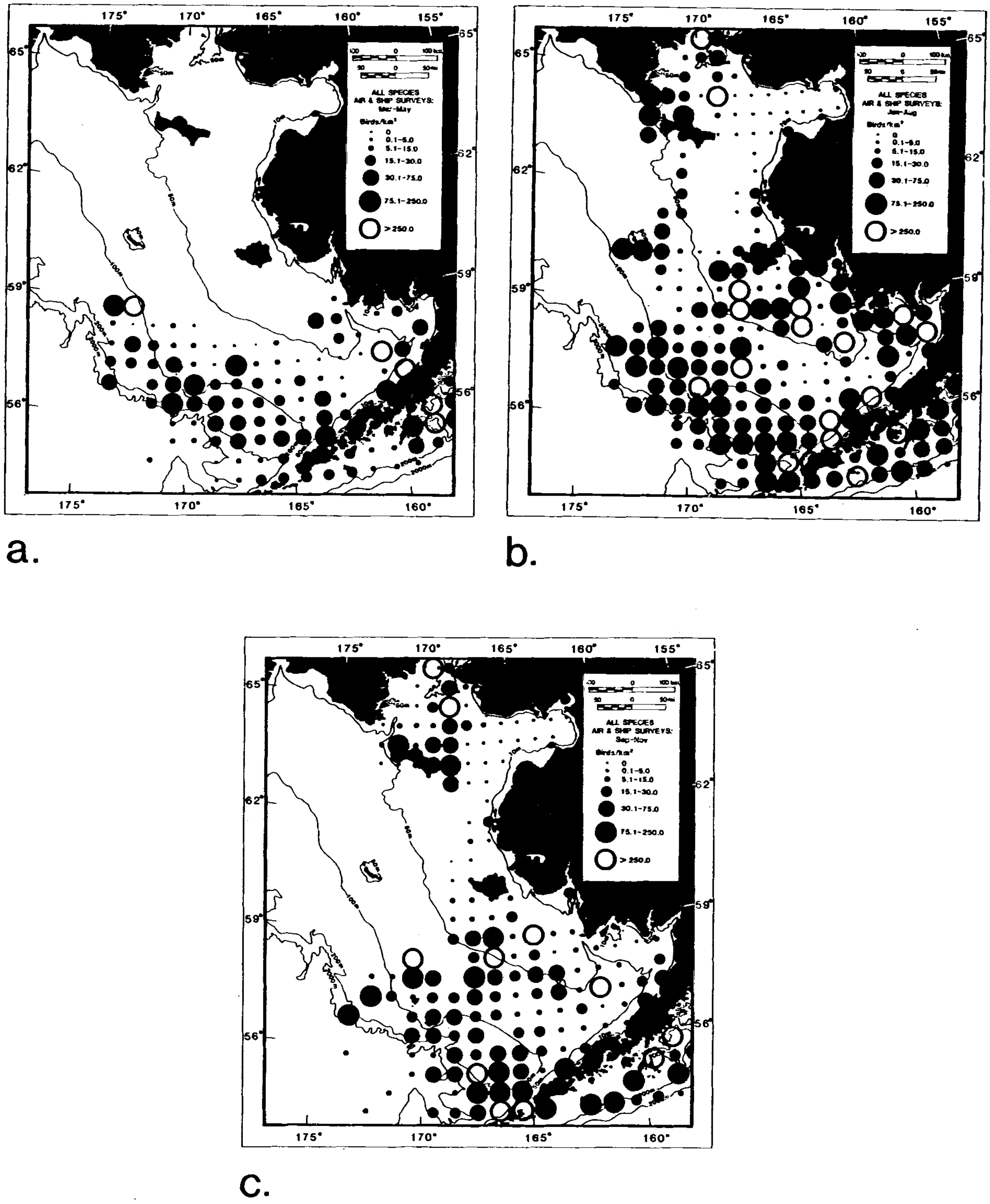

Figure 5.1. Pelagic distribution of all birds: a. spring, b. summer, c. fall (Hunt et al., 1981d).

Sooty and Short-tailed Shearwaters are found moving back and forth between the north Pacific and Bering seas (Fig. 5.5). A mean population estimate of 1.1 million shearwaters has been recorded for Unimak Pass at one time in the fall (U.S. Fish and Wildlife Service, unpub.). The mean density of all marine birds in Unimak Pass in the summer is 224/km² (Table 5.3), giving a population estimate of 720,000 birds.

Highest densities of all birds occur within 10 nmi (18.5 km) of St. George Island and within 10 nmi (18.5 km) on the shelfward side of St. Paul Island (Fig. 5.6) (Hunt et al., 1981b). Significantly higher densities of Red-legged Kittiwakes are found within 30 nmi (55.6 km) of the shelfward side of St. George Island (Fig. 5.6b), whereas the highest densities of murres are found within 10 nmi (18.5 km) of St. George (Fig. 5.6c).

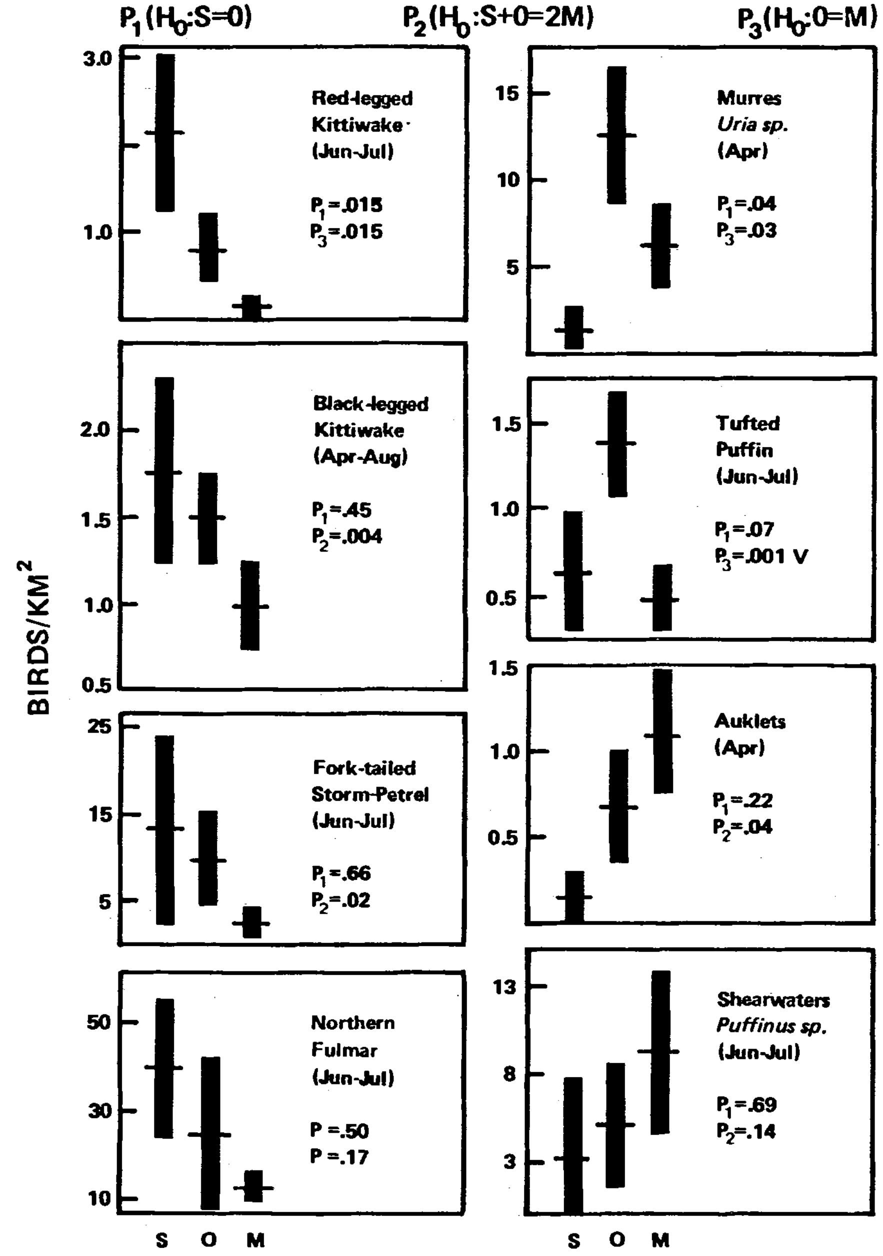

Figure 5.2. Density of seabirds in middle shelf (M), outer shelf (O), and slope (S) waters of the St. George Basin lease area, 1975-1979. Bars show two standard errors on either side of the mean (D. Schneider and G. Hunt, unpub.).

5.2.3 Coastal Habitats

Many species of Alaska marine birds migrate into and through the eastern Bering Sea (Gill et al., 1979). Most species migrate within broad corridors (Fig. 5.7), the locations of which are believed to be determined by the locations of suitable resting and feeding areas, by weather patterns, landmarks, and tradition. For most species, spring migration is more direct and occurs within a shorter period than fall migration. In the fall, many species make short flights to staging areas, where they molt and/or build up fat reserves for extended migration. Some species, especially alcids, congregate at breeding colonies in the summer and disperse over wide areas in the winter, but do not exhibit the well-defined migratory patterns of other species.

Knowledge of the migratory habits of Alaskan birds has been derived from bird-banding recovery data, shipboard and aerial surveys, site-specific studies, and anecdotal accounts in the literature, rather than from specific studies of migration. Migratory pathways have thus been inferred from observations made at a few locations. Most of the information on migration and staging in the eastern Bering Sea comes from Unimak Pass, Nelson Lagoon, and Cape Pierce.

Aerial surveys (Arneson, in press) of the coastal areas along the north shore of the Alaska Peninsula and around the Fox Islands were made in

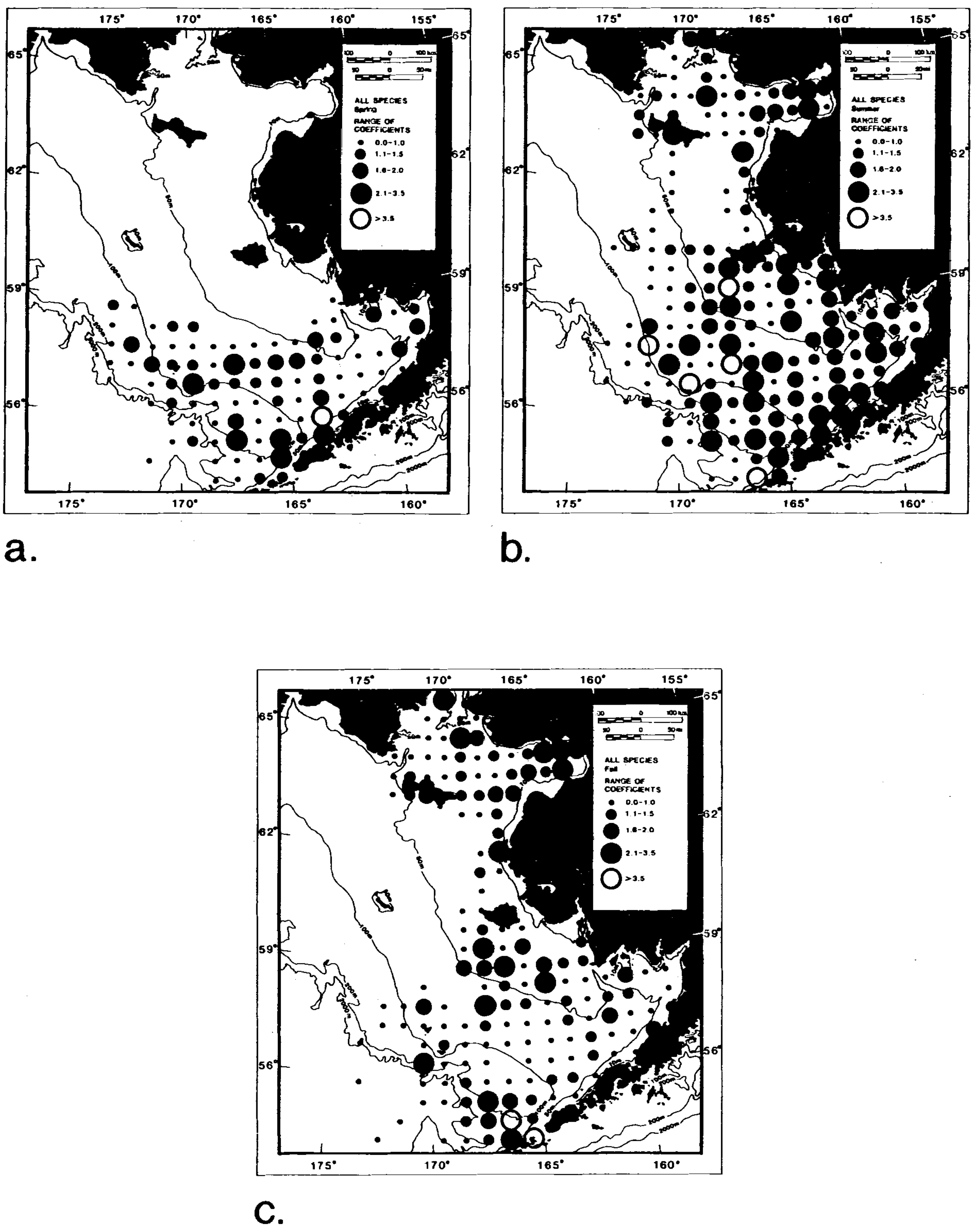

Figure 5.3. Coefficients of variation: a. spring., b. summer, c. fall (G. Hunt, J. Kaiwi, and D. Schneider, unpub.).

1975 through 1977 (Figs. 5.8-5.13). There were two spring, two fall, and three partial winter surveys along the Alaska Peninsula and one winter survey around the Fox Islands (Tables 5.4 and 5.5).

The north side of the Alaska Peninsula supports in various seasons the major portion of either the North American or Pacific Flyway populations of several species of waterfowl (Table 5.6), (King and Dau, 1981). In spring about 200,000 birds (including 55,000 Black Brant [*Branta bernicla*], 31,000 Emperor Goose [*Philacte canagica*], 15,500 dabbling ducks, 23,000 Steller's Eider [*Polysticta stelleri*], and 44,000 gulls) were recorded along the north shore of the Alaska Peninsula. A mean density of 141 birds/km^2 was found. The highest densities were found in Nelson Lagoon (849 birds/km^2) and Applegate Cove in

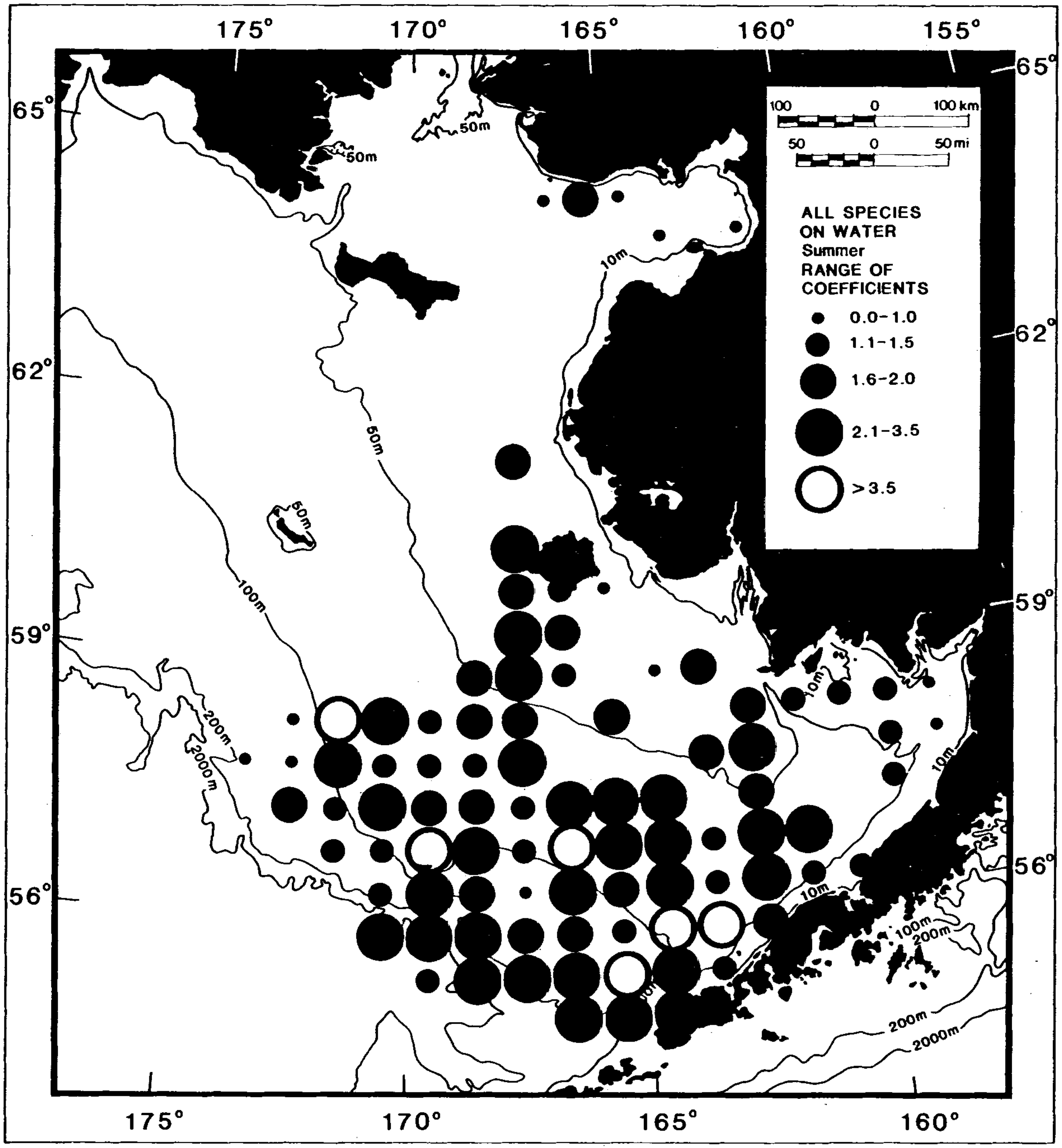

Figure 5.4. Coefficients of variation for all species observed on the water in the summer (G. Hunt, J. Kaiwi, and D. Schneider, unpub.).

Izembek Lagoon (358 birds/km^2) (Fig. 5.8), and Port Moller (618 birds/km^2). In Applegate Cove, the most abundant birds were geese (932 birds/km^2) and Steller's Eider. In Nelson Lagoon, the most abundant birds were Emperor Goose (388 birds/km^2), sea ducks (88 percent Steller's Eider. 233 birds/km^2), and gulls (208 birds/km^2). The most abundant species in Applegate Cove were Brant (319 birds/km^2). Overall, 28 percent of all birds were found in lagoons (mostly geese and sea ducks); 12 percent on lagoon mudflats (geese, dabbling ducks, sea ducks, shorebirds, and gulls), and 10 percent on protected delta mudflats (geese, dabbling ducks, and gulls).

In fall, over a million birds (including 144,000 Canada Goose *Branta canadensis)*, 368,000 Brant, 106,000 Emperor Goose, 54,500 dabbling ducks, 85,000 Steller's Eider, 51,000 scoters *(Melanitta sp.)*, 96,000 shorebirds, and 31,000 Glaucous-winged Gull *(Larus glaucescens)* were recorded along the north shore of the Alaska Peninsula. A mean density of 453 birds/km^2 was found (Fig. 5.9). The highest densities were found in Applegate Cove (1,044 birds/km^2), Nelson Lagoon (746 birds/km^3), and Port Moller (618 birds/km^2). In Applegate Cove, the most abundant birds were geese (932 birds/km^2) and Steller's Eider (66 birds/km^2). In Nelson Lagoon,

Table 5.3. Density (birds/km²) of selected species and species groups of marine birds in Unimak Pass[a] (U.S. Fish and Wildlife Service, unpub.).

	Shipboard surveys			Aerial surveys		
Species-species group	Spring	Summer	Fall	Spring	Summer	Fall
Northern Fulmar	+[b]	8[b]	17	+	+	4
Shearwaters	+	164	351	0	1	3
Storm-petrels	0	12	1	0	5	+
Glaucous-winged Gull	1	1	1	6	7	2
Kittiwakes	1	2	4	1	+	5
Murres	28	7	9	10	1	2
Tufted Puffin	1	22	5	+	11	0
(Total alcids)	(43)	(34)	(36)	(11)	(12)	(4)
Total birds	47	224	400	20	26	17
Total transects	24	39	29	15	6	12

---

[a] Unimak Pass for this purpose is defined as 54°00'N-54°40'N by 164°30'W-165°30'W.
[b] Birds per square kilometer, + = less than 0.5.

the most abundant birds were Emperor Goose (168 birds/km²), sea ducks (Steller's Eider and Black Scoter [*M.. nigra*]: 420 birds/km²), and shorebirds (100 birds/km²). At Port Moller, the most abundant birds were geese (mostly Steller's Eider: 156 birds/km²) and sea ducks (360 birds/km²). Overall, 70 percent of all birds (mostly geese) were found on lagoons and 21 percent were found on protected deltas.

In winter, about 34,000 birds (including 2,000 Emperor Goose, 4,000 Steller's Eider, and 4,500 Glaucous-winged Gull) were recorded along the north shore of the Alaska Peninsula and about 40,000 birds (including 7,000 Emperor Goose, 4,000 King Eider *(Somateria spectabilis)*, 5,500 shorebirds, and 2,500 Glaucous-winged Gull) around the Fox Islands. A mean density of 53 birds/km² (mostly sea ducks and gulls) was found along the north shore of the Alaska Peninsula (Fig. 5.10), and a mean density of 94 birds/km² (mostly sea ducks) was found around the Fox Islands (Fig. 5.10). Along the Peninsula, the highest density of birds (197 birds/km²), mostly sea ducks, was found between Port Heiden and the Seal Islands. The highest density of birds (3,240 birds/km²), mostly sea ducks, was found around Samalga Island. The most abundant species around Samalga Island were Emperor Goose (1,435 birds/km²), sea ducks (416 birds/km²), and shorebirds (1,240 birds/km²). In both areas, most birds were found in exposed habitats.

The coastal areas of the north shore of the Alaska Peninsula are especially important as wintering and staging areas of waterfowl and shorebirds (Gill et al., 1977; 1978). The Yukon-Kuskokwim Delta, one of the most productive and largest (almost 70,000 km²) waterfowl breeding areas in western Alaska, lies just north of Bristol

Table 5.4. Densities of birds in coastal areas by season as determined from aerial surveys, 1975-1977 (Arneson, in Press).

	Mean densities (birds/km²) North Shore Alaska Peninsula			Fox Islands
Species groups	Spring	Fall	Winter	Winter
Loons	T	T	T	T
Grebes	T	T	T	T
Tubenoses	0	T	0	T
Cormorants	T	1	T	4
Swans and geese	60	268	3	17
Dabbling ducks	11	23	T	1
Diving ducks	2	1	T	1
Sea ducks	26	97	33	43
Mergansers	1	T	T	T
Raptors	T	T	T	T
Cranes	T	0	0	0
Shorebirds	9	41	T	13
Jaegers and gulls	31	19	13	11
Terns	1	T	0	0
Alcids	T	T	2	5
Corvids	T	T	T	T
Other passerines	T	1	T	T
Other birds	T	1	0	T
Totals	141	453	53	94

T = Trace

Table 5.5. Number of birds in each species group within regions of south-central Alaska by season as determined from aerial, coastal bird surveys in 1975-1978 (Arneson, in press).

	North shore, Alaska Peninsula			Al. Sh.
Species groups	Spring	Fall	Winter	Winter
Loons	135	138	35	28
Grebes	38	37	17	34
Tubenoses	0	82	0	39
Cormorants	57	1,293	292	1,503
Swans and geese	87,253	623,965	2,154	7,236
Dabbling ducks	15,597	54,605	5	238
Diving ducks	2,507	1,899	108	278
Sea ducks	37,832	226,465	21,181	18,233
Mergansers	1,031	109	15	73
Raptors	58	62	41	69
Cranes	173	0	0	0
Shorebirds	13,184	95,864	15	5,659
Jaegers and gulls	44,335	45,220	8,628	4,681
Terns	1,359	1	0	0
Alcids	43	246	1,146	1,938
Corvids	40	63	73	78
Other passerines	143	1,461	150	67
Other birds	273	3,353	0	125
Totals	204,058	1,054,861	33,860	40,279
No. of surveys	2	2	3	1
Total area (km²)	1451	2328	642	427

Bay. In the spring, birds headed for the Yukon-Kuskokwin Delta and beyond gather in the lagoons and estuaries of the Alaska Peninsula as they wait for northern areas to thaw. Similarly, in the fall, as freezeup forces them off their breeding grounds, waterfowl and shorebirds again use the lagoons for several weeks before they move on to their wintering grounds. These lagoons are critical habitat for species such as the Black Brant, which in the fall migrate directly from Izembek Lagoon to northern California. Most waterfowl have been found to use the same areas year after

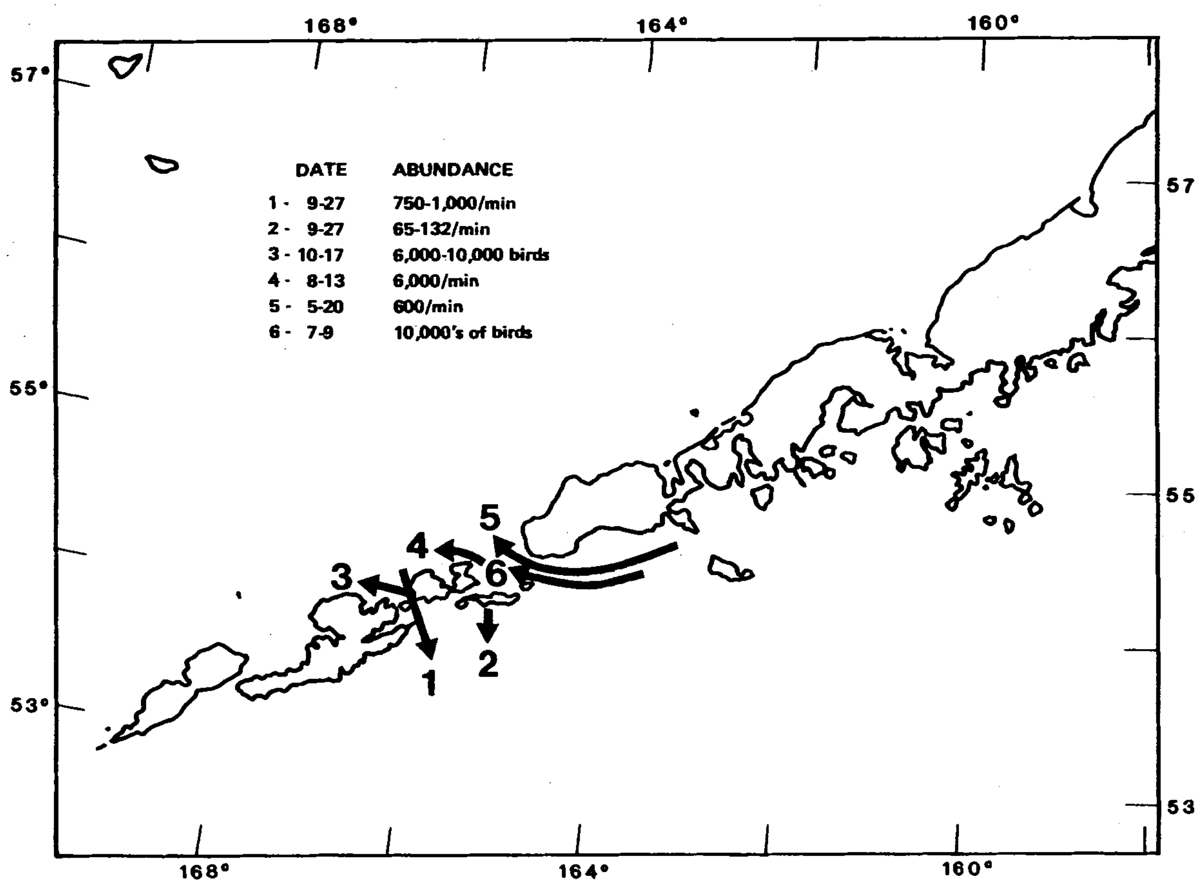

Figure 5.5. Distribution of flying flocks of 10,000 or more shearwaters in the eastern Aleutian Islands (U.S. Fish and Wildlife Service, unpub.).

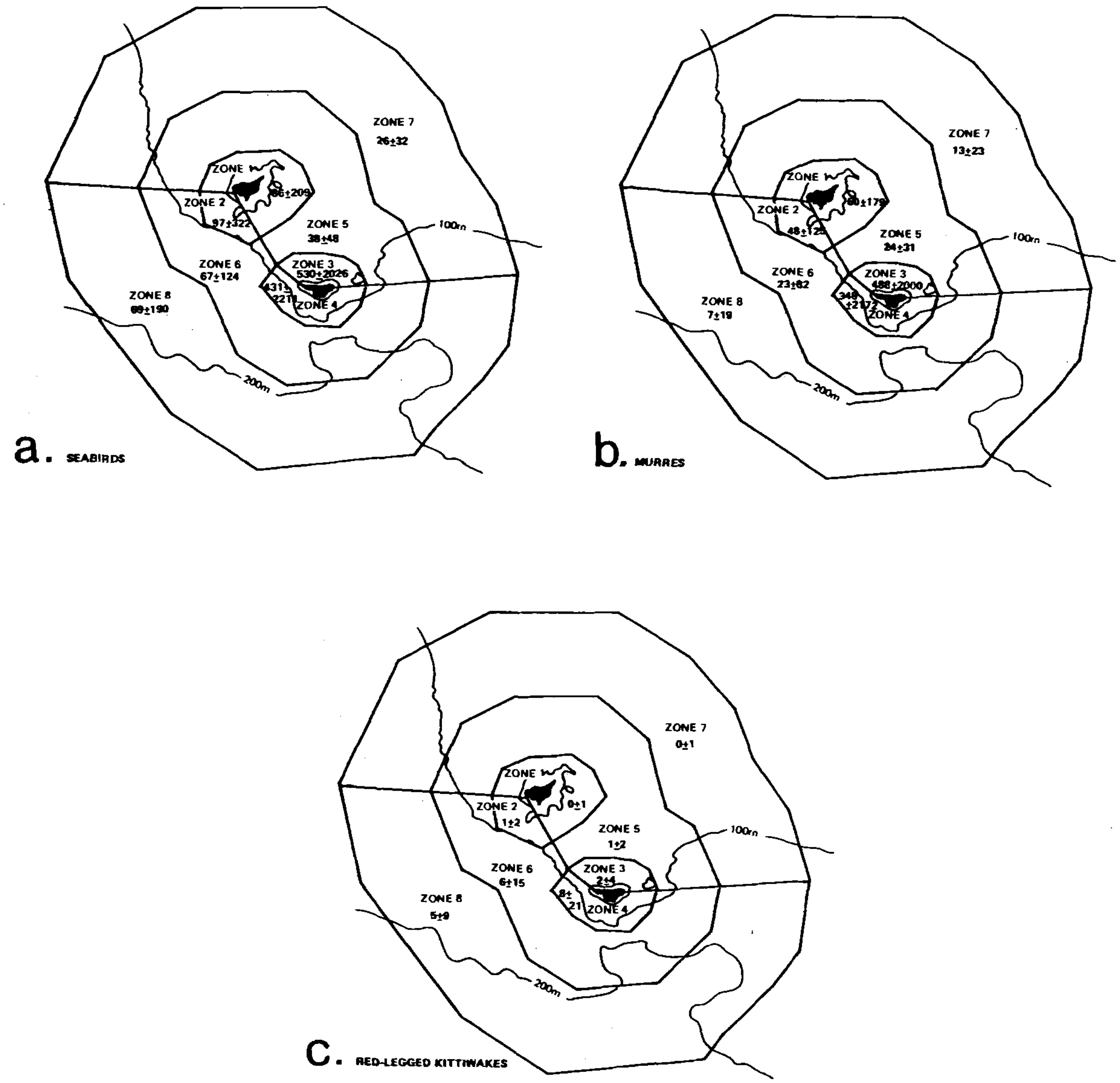

Figure 5.6. Distribution of seabirds near the Pribilof Islands, 1975-1979. Values are mean number of birds/km² ± one standard deviation. Concentric rings at 10, 30, and 60 nautical miles from the island: a. all birds, b. Red-legged Kittiwakes, c. murres (Hunt et al., 1981b).

year for molt and staging and the same migratory routes. Thus, if their food supply were seriously damaged, it is unlikely that Black Brant would be able to seek out and use resources in other areas, and many would attempt their long migration with inadequate fat reserves.

5.3 ECOLOGY

5.3.1 Food

An understanding of the feeding and diet of marine and coastal birds gives insight into the roles that various species play in the local ecosystems (Ainley and Sanger, 1979). Also, knowledge of important foods may indicate potential vulnerability to secondary effects of oil contamination of food chains. To identify their role in food webs and nutrient and energy cycles, however, specific dietary information is needed. Specializations in prey and habitat requirements are often identified from trophic data. Currently, little information is available on the ability of birds to alter their diet or on the kind of habitat in which they feed when the availability of food changes suddenly. Many species have been observed to change their diet according to seasonal changes in prey availability, to have different food preferences in different geographic regions, and to exploit feeding habitats during migration which differ from those used on the breeding or wintering grounds. These differences, however, occur gradually in time and space and are highly predictable. If the change is sudden and unpredictable, as when the food supply is suddenly reduced during the occurrence of El Niño along the Peruvian coast (Ashmole, 1971), vast numbers of marine birds may die.

The feeding ecology of marine birds in the eastern Bering Sea has been summarized by Hunt

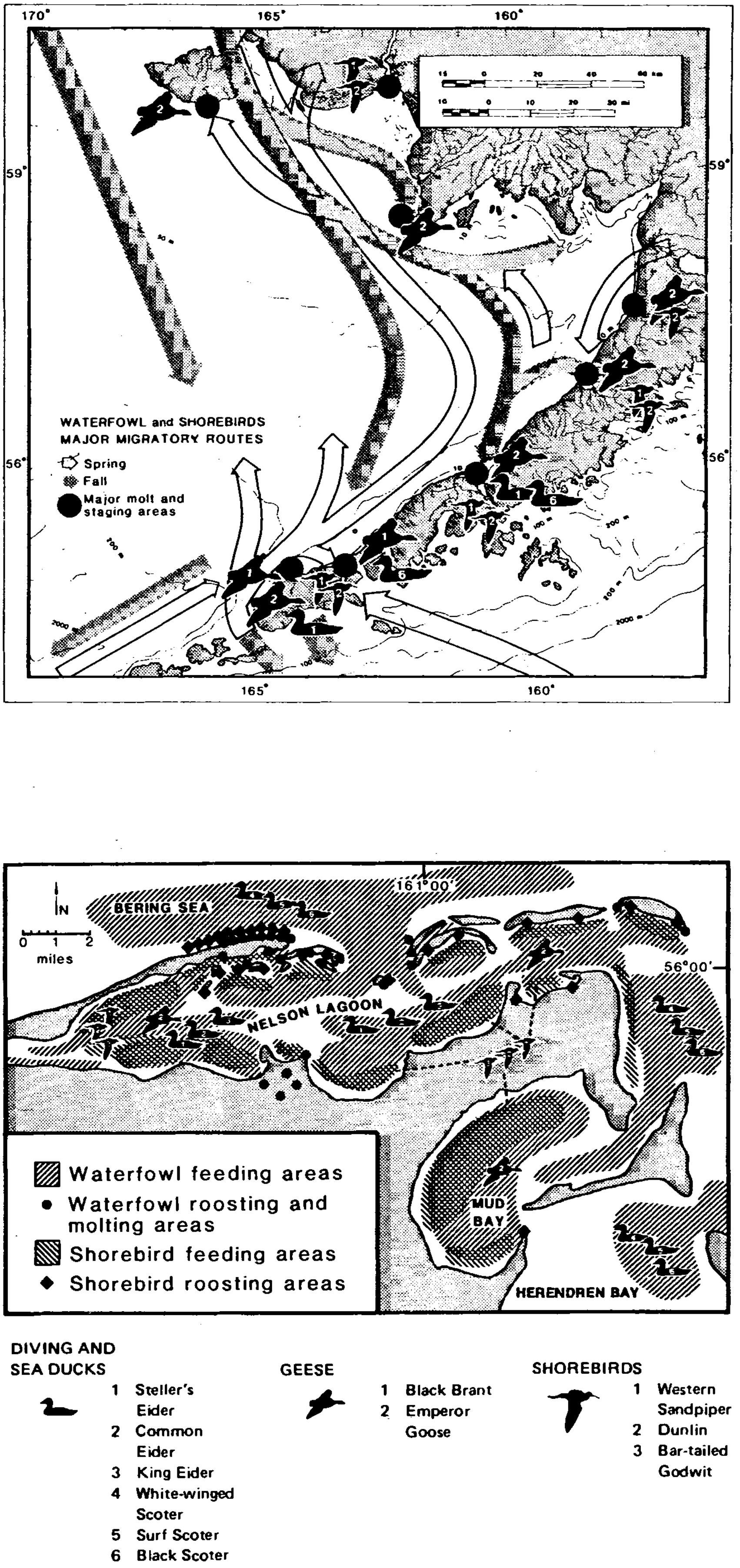

Figure 5.7. Major migratory routes and feeding areas of waterfowl and shorebirds in the southeastern Bering Sea (Gill et al., 1979).

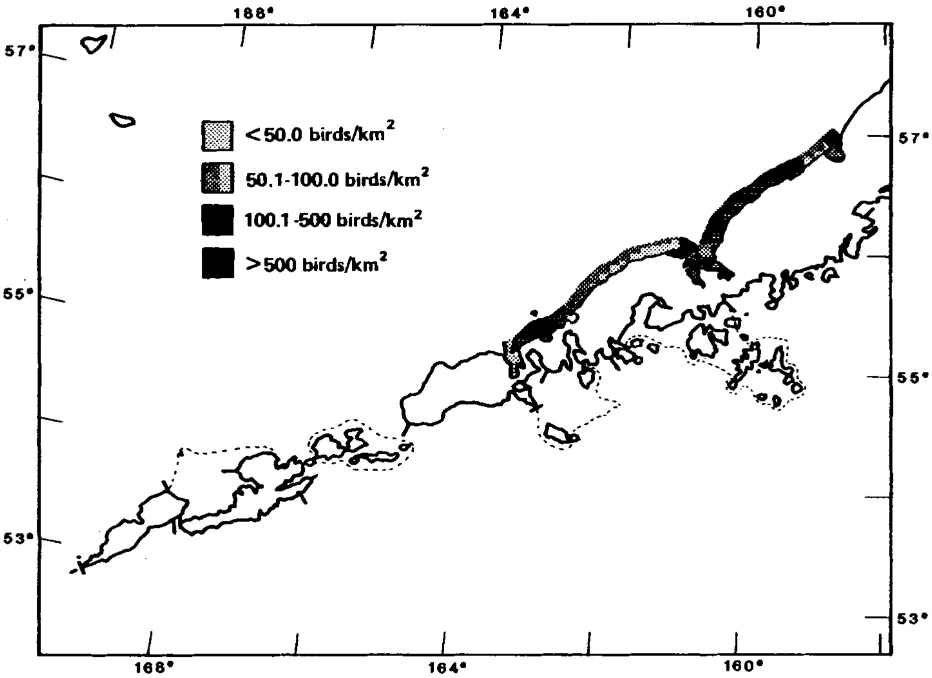

Figure 5.8. Spring densities of coastal birds (Arneson, in press).

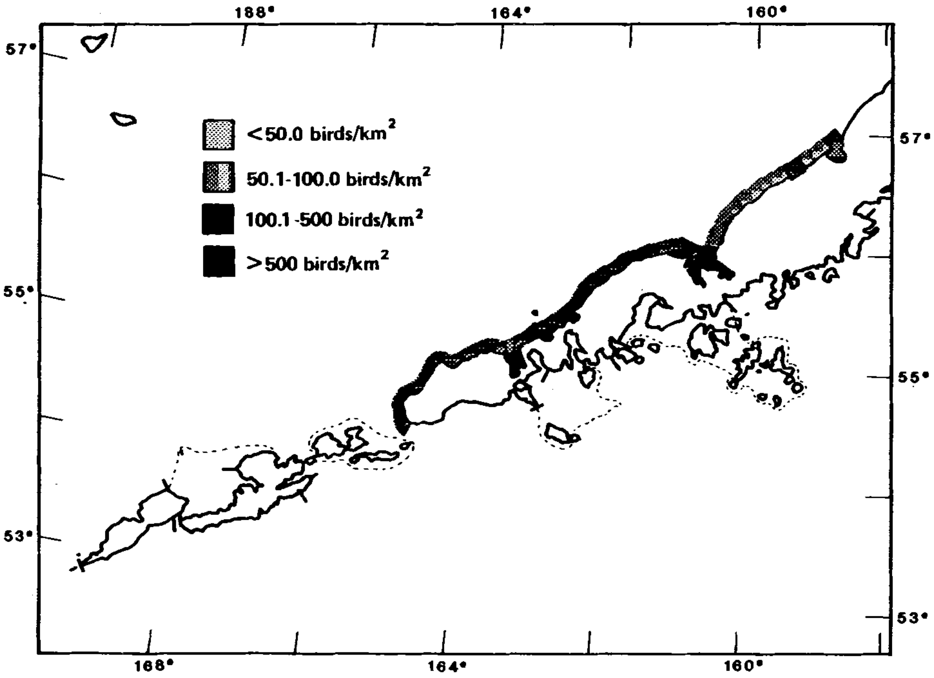

Figure 5.9. Fall densities of coastal birds (Arneson, in press).

et al. (1981a). A summary of seabird diets at the Pribilof Islands is given in Fig. 5.14. Fish are the major food of cormorants, gulls, murres, and puffins breeding on the Pribilofs, whereas the auklets specialize on invertebrates. Of the kinds of fish consumed, walleye pollock was by far the most important for all fish-eating species, with the exception of the Red-legged Kittiwake and the inshore-feeding Red-faced Cormorant *Phalacrocorax urile*). Euphausiids, amphipods, and copepods are the most important invertebrates. Estimates of the average annual food consumption of adult birds breeding on the Pribilofs are given in Table 5.7.

In Izembek Lagoon, Black Brant and Emperor Geese feed almost exclusively on eelgrass. The major food items of the staging and wintering sea ducks are bottom-dwelling molluscs and crustaceans (Cottam and Knappen, 1939; Sanger et al., 1979), but detailed information on the foods of these populations is lacking. Thus, the health of these birds can be affected not only directly by oil

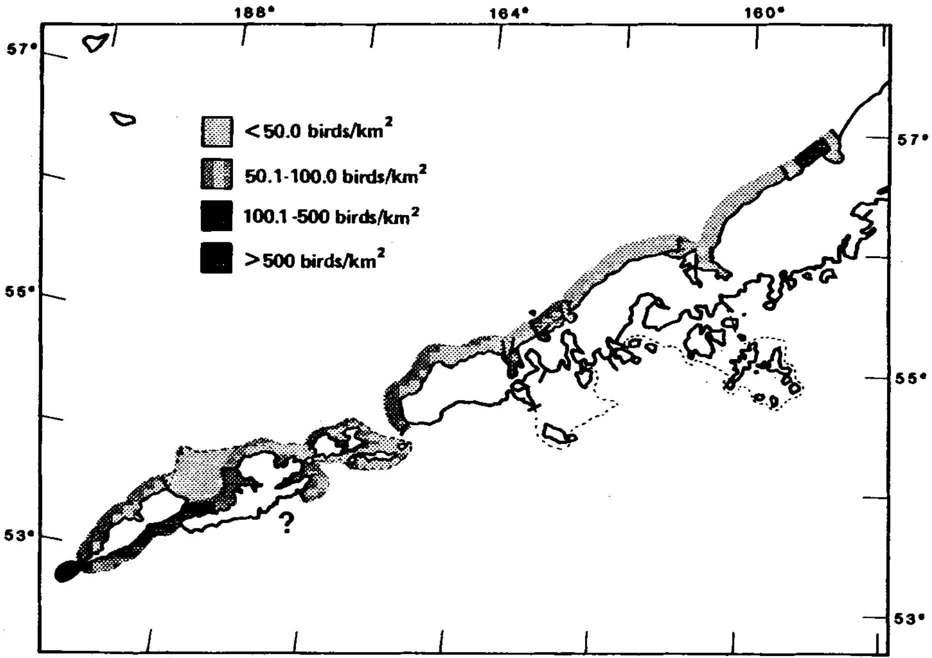

Figure 5.10. Winter densities of coastal birds (Arneson, in press).

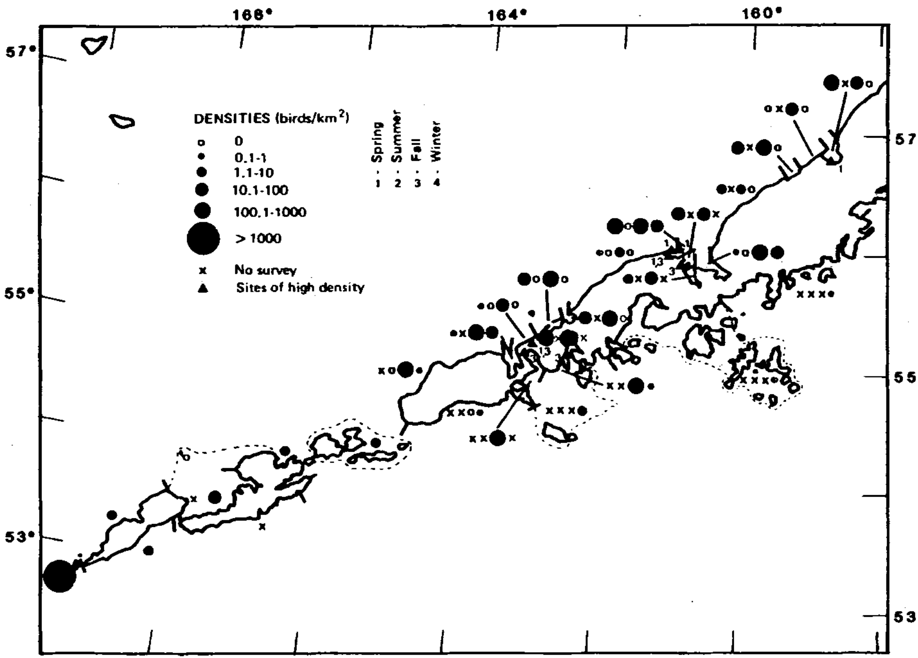

Figure 5.11. Goose and swan density by section along North and South Alaska Peninsula during four seasons as determined by aerial surveys. Densities read from left to right: spring, summer, fall, winter. Spring, fall, and winter were coastal surveys; summer surveys were pelagic (Arneson, in press).

spills when they are present, but also indirectly at any time of the year by a spill that kills or contaminates their food.

5.3.2 Reproduction

Two features of reproductive biology are particularly relevant to OCS development. First, the timing of breeding (phenology) determines when birds will be concentrated near their colonies. In this period, spills and disturbances may not only decrease reproductive success, but may destroy large numbers of adults in a very short time. Second, measures of reproductive success show how well the colony is doing and provide, if life-table data are available, a means of estimating whether the reproductive output of a particular colony balances the adult mortality. For a given colony, the number of offspring produced may be too many, too few, or sufficient to balance mortality. Colonies with excessive pro-

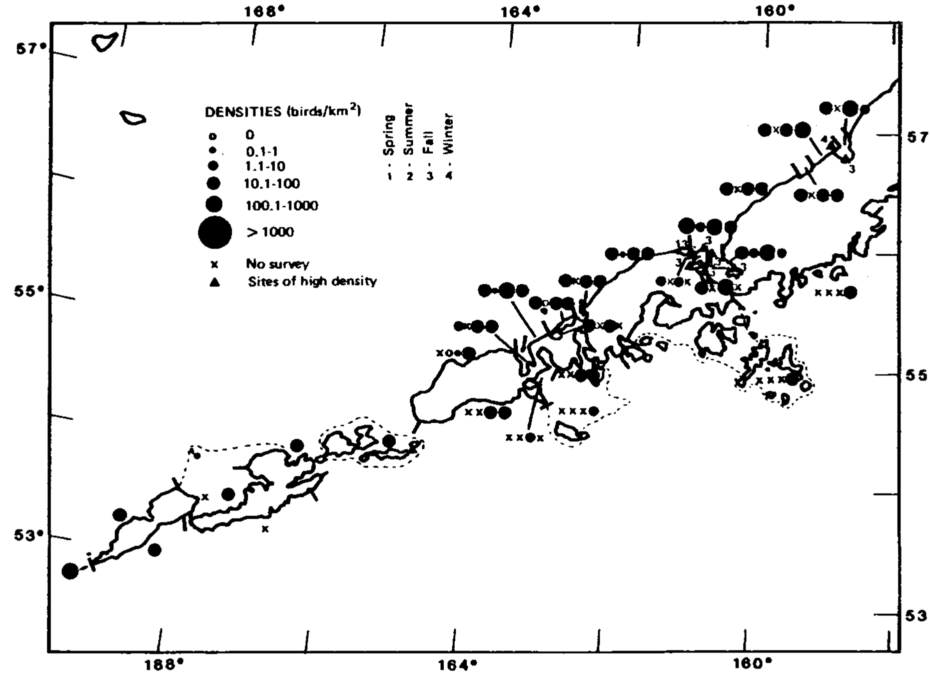

Figure 5.12. Sea duck density by section along North and South Alaska Peninsula during four seasons as determined by aerial surveys. Densities read from left to right: spring, summer, fall, winter. Spring, fall, and winter were coastal surveys; summer surveys were pelagic (Arneson, in press).

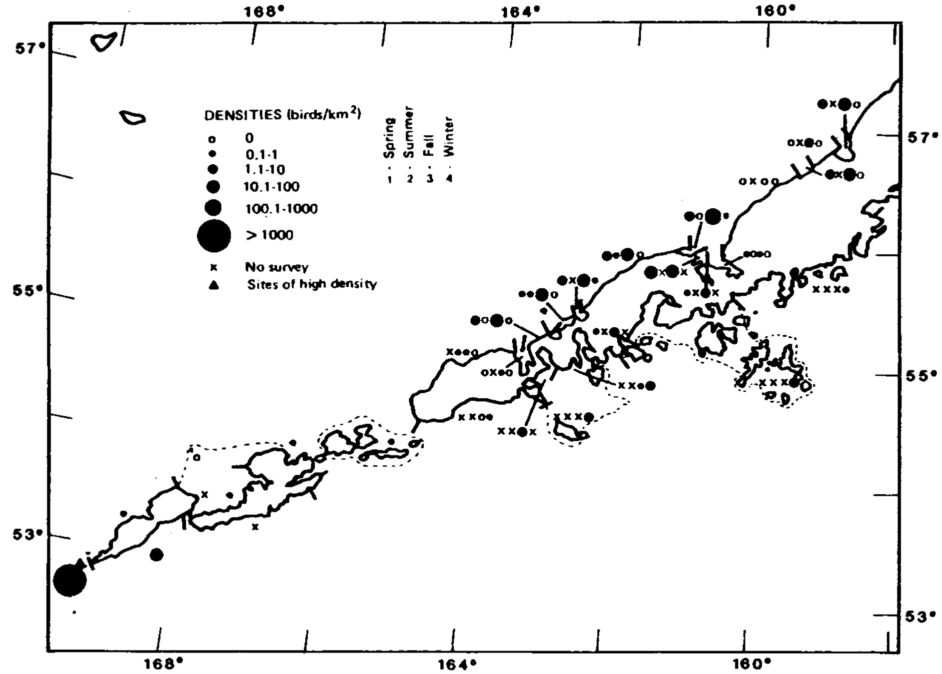

Figure 5.13. Shorebird density by section along North and South Alaska Peninsula during four seasons as determined by aerial surveys. Densities read from left to right: spring, summer, fall, winter. Spring, fall, and winter were coastal surveys; summer surveys were pelagic (Arneson, in press).

ductivity may be critical for maintaining regional populations.

5.3.3 Phenology

Figure 5.15 summarizes the timing of major breeding events on the Pribilof Islands. Red-faced Cormorants are some of the earliest birds to begin nesting, with clutch initiation beginning in late May and early June. Peak egg-laying for most species occurs in late June and early July, and most hatch chicks about 30 days later. Cormorant and murre chicks have left their nests by late August, and most other species fledge by late September. Tufted and Horned Puffins and possibly fulmars may have chicks as late as October. Thus, the critical period during which

Table 5.6. Species with major segments of their population dependent on areas within and adjacent to the St. George Basin lease area (U.S. Fish and Wildlife Service, unpub.).

Species	Estimated population (1000's)	% respective population N. Amer.	Pacific Flyway	Alaska	Period of use	Preferred habitat(s)
Black Brant	150		100		Fall-Spring	intertidal
Emperor Goose	90	90[a]			Fall-Spring	intertidal
Lesser Canada Goose	90		60-75		Sep-Nov	intertidal
Steller's Eider	250	100[b]			Jul-May	inter. & nearshore
King Eider	375-650	75[a]			Winter	nearshore, inshore & offshore
Black Scoter	70		60-80		Fall-Spring	nearshore & inshore
White-winged Scoter	38			50	Fall-Spring	nearshore & inshore

---

[a] Use of areas depends on the severity of the winter in Bristol Bay, with more birds moving to the western Alaska Peninsula and eastern Aleutians during severe winters.

[b] Use of areas is specific to age-class and sex; e.g., 100 percent of subadults use Nelson Lagoon, whereas most adult females use Izembek Lagoon.

birds are concentrated and tied to islands is June-September.

5.3.4 Productivity

Productivity of Pribilof Islands seabirds is usually moderate to low, and Pribilof populations of some species may have lower reproductive output than populations elsewhere in the world. Most species lay but a single egg; the Black-legged Kittiwake and the Red-faced Cormorant, with up to two and up to three/four eggs, respectively, are the only exceptions. The clutch size of Black-legged Kittiwakes in the Pribilofs may be smaller than that of other populations of the same species, possibly due to competition.

Productivity of some Pribilof seabirds is summarized in Table 5.8. The low rate of fledging, coupled with an expected (but undocumented) high post-fledging mortality, suggests that recruitment into the breeding population from locally raised young will be slow.

Although reproductive output was the same on St. Paul and St. George Islands for all species studied except the Red-faced Cormorant (higher on St. Paul), growth rates and fledging weights were often lower for St. George Island birds. It is possible that either scramble or interference competition on the waters near the large St. George colony depresses the rate at which food can be obtained and brought to chicks. Thus, any activity that depresses food availability is likely to be quickly reflected in chick fledging weights or reproductive success. The birds of the Pribilofs and of St. George Island in particular appear to be already under energetic stress; any factor decreasing the availability of food or increasing stress is likely to have a long-term influence on recruitment of young to the population. Thus, we may expect that these and possibly other very large colonies will be more sensitive to energetic stress than smaller colonies that are not already pushing at the limits of their energy resource.

Two of the unknowns for Pribilof Islands seabirds are the rates of adult mortality and the percentage of the population that is nonbreeding. We have no information on local mortality rates of Bering Sea marine birds, although information is available for some North Atlantic populations. Between 47 and 72 percent of the birds collected at the Pribilof colonies were breeding. While this may not be an unbiased sample, it does show that many birds are not now breeding. We do not know whether this is because of shortages of space or food or because of other factors.

With the disappearance of introduced Arctic fox, large numbers of seabirds are again breeding on the Fox Islands. Details of their breeding biology are not yet known. Seabirds are probably present on the colonies from at least April through November (Fig. 5.16). Eggs are present beginning in May, and chicks appear near the end of June. Leach's Storm-Petrel *(Oceanodroma leucorhoa)* and Tufted Puffin chicks may fledge as late as October or November.

5.3.5 The Growth Potential of Populations

Bird populations appear to maintain themselves near an equilibrium size (Ricklefs, 1973). The growth potential of a population determines how rapidly it can return to this equilibrium after a reduction in size or at what rate it can be exploited without change.

The theory of population growth and regulation was developed from observations and experiments on many species (Lack, 1954; Hutchinson, 1978). The relative importance, however, of the many factors which regulate

SUMMARY OF SEABIRD DIETS AT THE PRIBILOF ISLANDS, 1975-1978

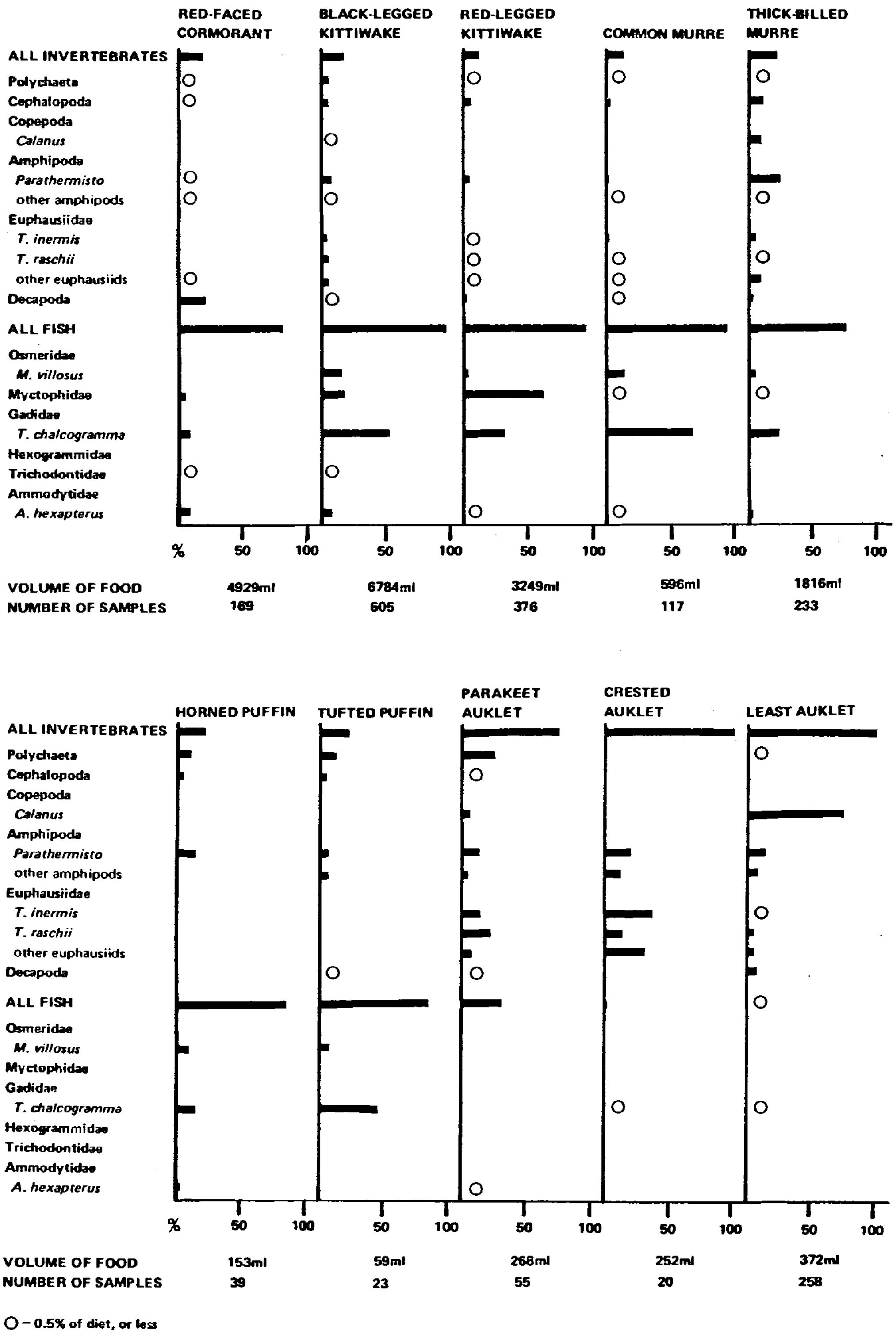

Figure 5.14. Summary of seabird diets at the Pribilof Islands, 1975-1979 (Hunt et al., 1981b).

populations is still hotly debated. Small populations with unlimited resources have been found to grow exponentially. Most of the evidence concerning such populations comes from experiments, since natural populations in this stage are rarely available for study. The classic field exemple for birds is Einarsen's (1945) study of a Ring-necked Pheasant *(Phasianus colchicus)* population introduced on Protection Island, Washington. In five years the population grew from 8 to 1,325. As a population grows, it eventually strains its resources and becomes more vulnerable to predation and disease. The result is that reproduction and survival fall until recruitment

Table 5.7. Estimates of average annual food consumption (in metric tons) by adult seabirds at the Pribilofs. Assumed is a consumption of 20 percent of the bird's body weight per day (Hunt et al., 1981a).

	NF	RFC	BLK	RLK	CM	TBM	TP	HP	PA	CA	LA
All invertebrates	1.6	0.8	0.8	0.6	1.7	62.6	0.6	0.2	4.7	11.1	3.2
Polychaetes			0.1	0.3			0.1	0.1	1.5		
Cephalopods	1.4		0.1		0.3	13.0	*	*	2.6		
Copepods:											
Calanus						10.4					2.4
Amphipods:											
Parathemisto			0.2	0.1	0.3	26.1	0.4	*	0.6	0.2	0.3
Other								*	0.1	0.1	0.2
Euphausiids	0.2		0.4		0.3	15.6			2.1	0.8	0.1
Decapods		0.8		0.1		2.6					0.1
All fish	4.8	4.4	6.5	11.9	32.0	198.2	2.7	0.8	1.7		
Mallotus			0.7	0.1	3.0	5.2	0.2	0.1			
Myctophids			*	0.8	7.1						
Gadid	4.0	*	3.7	3.4	20.6	106.9	0.3	0.4			
Hexagrammos							0.8				
Trichodon							0.8				
Ammodytes		*	0.2			2.6	0.3				
Days in area	150	360	150	150	150	180	180	120	120	120	120
Total food consumed by adults (10^2 mt)	6.6	5.3	7.3	12.5	33.7	260.8	3.3	0.98	6.4	1.1	3.3
Percent of food taken	2	2	2	4	10	76	1	*	2	*	1

NF = Northern Fulmar
RFC = Red-faced Cormorant
BLK = Black-legged Kittiwake
RLK = Red-legged Kittiwake
CM = Common Murre
TBM = Thick-Billed Murre
TP = Tufted Puffin
HP = Horned Puffin
PA = Parakeet Auklet
CA = Crested Auklet
LA = Least Auklet

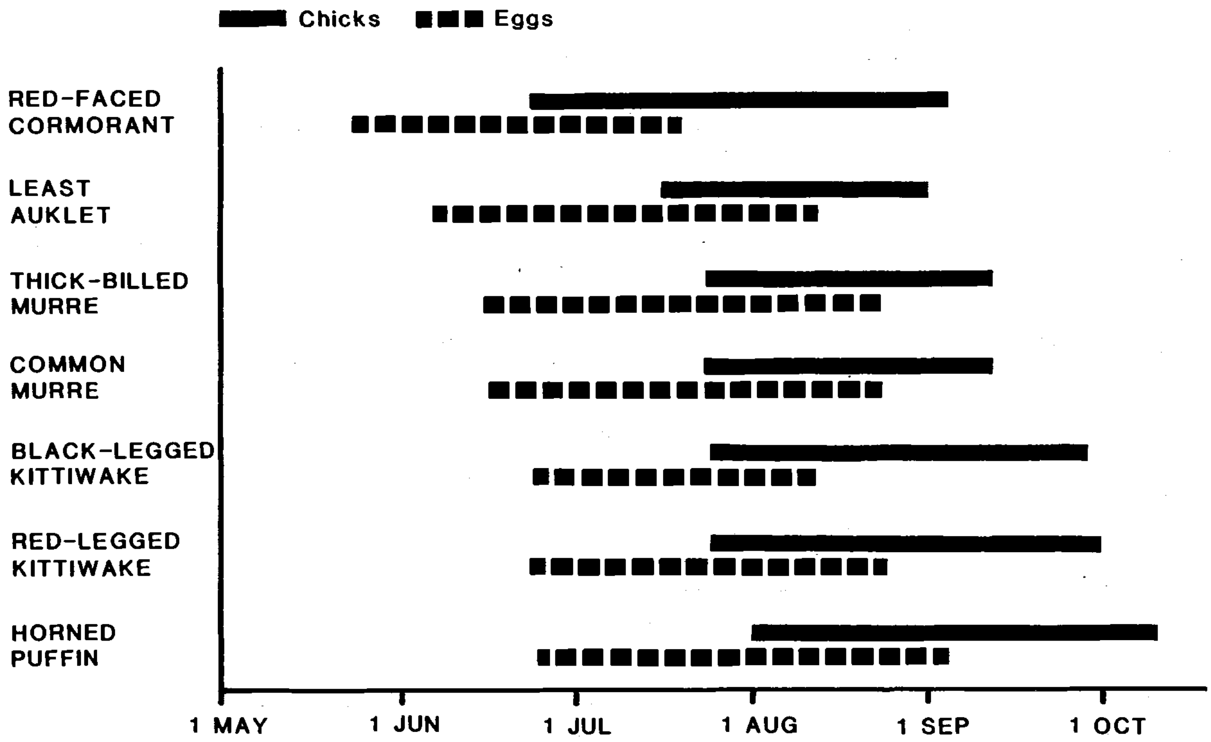

Figure 5.15. Presence of eggs and chicks in nests of seven species of seabirds, Pribilof Islands, 1975-1979 (Hunt et al., 1981b).

balances mortality. The regulation of most bird populations appears to depend on density, but density-independent sources of mortality, such as storms or landslides, are sometimes important, at least locally.

Because density-dependent factors act most strongly on dense populations, the growth potential of a population is least restricted when its numbers are least. This, however, is also the condition in which it faces the greatest probability of extinction by random accident. The balance between the capacity for population increase and population density, which ordinarily can carry a population through most of its difficulties, may be inadequate in the presence of a new source of mortality. If a population is to maintain its numbers, mortality must not remove more than the reproductive surplus produced each year. The surplus is the difference between the mortality of adults and the recruitment of new birds into the breeding population.

Recruitment depends on survival of the young until they breed for the first time. Although OCSEAP workers have gathered information on mortality up to the time the young fledge, no information has been gathered on post-fledging mortality. Recruitment to individual colonies also depends on the emigration and immigration rates of the young. There is considerable evidence that some seabird colonies do not produce enough young to maintain their numbers, whereas others produce a surplus. The maintenance of a population of a species over a large area thus may depend on the productivity of only a few key colonies.

Using computer simulations, Wiens et al. (1979) examined the responses of Black-legged Kittiwake and Common and Thick-billed Murre populations to the death of a given fraction of their numbers by a hypothetical one-time event, and to changes in the rate of annual adult survival. They used Birkhead's (1977b)

Table 5.8. Reproductive success of Pribilof Islands seabirds (Hunt et al., 1981b).

Species	No. young fledged/nest
Northern Fulmar	0.27[a]
Red-faced Cormorant	1.25
Black-legged Kittiwake	0.43
Red-legged Kittiwake	0.38
Common Murre	0.62[b]
Thick-billed Murre	0.49-0.62[b]

[a] Chicks fledged/mean no. adults in the study area

[b] Chicks fledged/egg laid

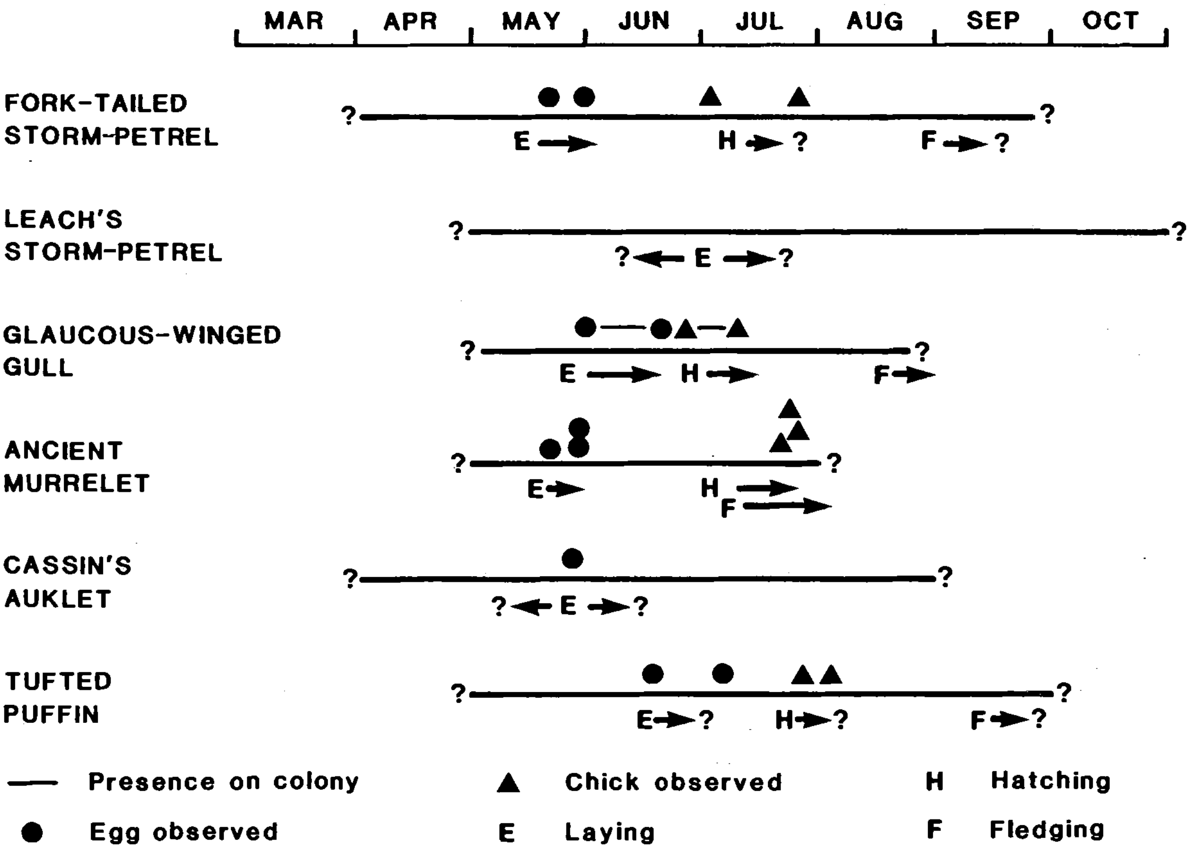

Figure 5.16. Estimated phenologies of seabirds on the Fox Islands (U.S. Fish and Wildlife Service, unpub.).

survivorship data for North Atlantic populations of the murres, Coulson and his associates' (Coulson and White, 1959; Coulson and Wooller, 1976; and Wooller and Coulson, 1977) survivorship data for British populations of Black-legged Kittiwake, and estimates of fecundity for these species from the Pribilof Islands. The trends that they found in the recovery of populations from loss are expected to hold for the St. George area, though the details may be different.

In their simulations, Wiens et al. used the following scenarios of imposed mortality:

1. mortality on first-year age-class only,
2. equal mortality on all subadult age-classes,
3. mortality on adults only,
4. equal mortality on adults and chicks,
5. equal mortality on all age-classes.

The first two scenarios were used to compare the relative importance of breeding and nonbreeding birds to the maintenance of the population. There may not be an actual situation in which only these age-classes would be killed. Scenario three could represent the effect of an oil spill early in the breeding season when only the adults were present at a colony. Scenario four could represent the effect of an oil spill during the period when adults accompany chicks at sea. Scenario five could represent the effect of an oil spill during the winter, when all age groups may occur together.

The time to recover (defined as the time for a population to attain its original size) from a one-time imposed mortality for the five scenarios is shown in Fig. 5.17. These results indicate, first, that the time for recovery is an exponential function of the one-time mortality rate. The recovery time from an event that causes the death of 50 percent of the population is more than twice that from an event that causes the death of 25 percent of the population. Second, the death of adults affects the time of recovery more than the death of any other age-class. Mortality of up to 100 percent of the subadults has only about one-third the effect of mortality of the adults.

It is predicted that a Thick-billed Murre population would take about 20 years and a Black-legged Kittiwake population about 10 years to recover from a catastrophe. These differences are due to differences in estimates of the fecundity or survival of the species. Black-legged Kittiwake had a higher rate of adult survival than murres.

Changes in the annual survival of adults were found to have drastic effects on recovery time (Wiens et al., 1979). For Thick-billed Murres, a one-percent decrease in annual adult survival is predicted to cause a fourfold increase in recovery

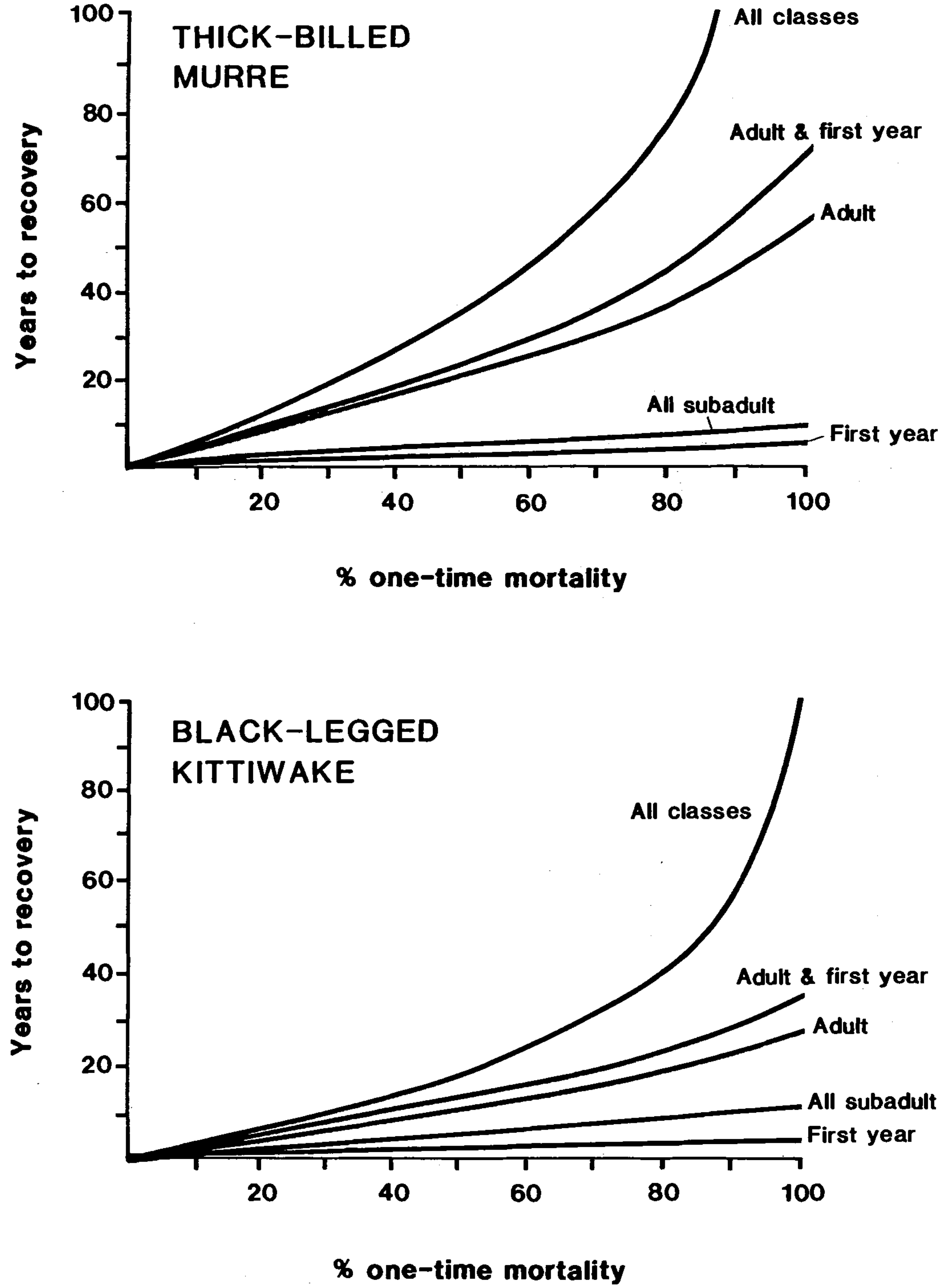

Figure 5.17. Time to recover as a function of one-time mortality of various age-class combinations of the Thick-billed Murre and Black-legged Kittiwake (Wiens et al., 1979).

time, whereas a one-percent increase would cause only a 1.7-fold decrease in recovery time. This outcome suggests that the population could not recover if annual adult survival decreased more than 1.3 percent. The time for recovery as a function of a change in mean fecundity rate, at 50 percent one-time adult and chick mortality, is shown in Figure 5.18 for kittiwakes and murres. Populations of kittiwakes could not recover if there were a persistent reduction in fecundity of more than about 35 percent. Murres were found to be even more sensitive to reductions in fecundity, recovery being impossible for Thick-billed Murres if fecundity fell by about 15 percent.

The model predicts that the effects of long-term sources of mortality could damage a population more severely than a short-term catastrophe. Although Wiens et al. (1979) were concerned mainly with the effects of oil development on bird populations, disturbances caused by the fishing industry, such as the death of birds in fishing

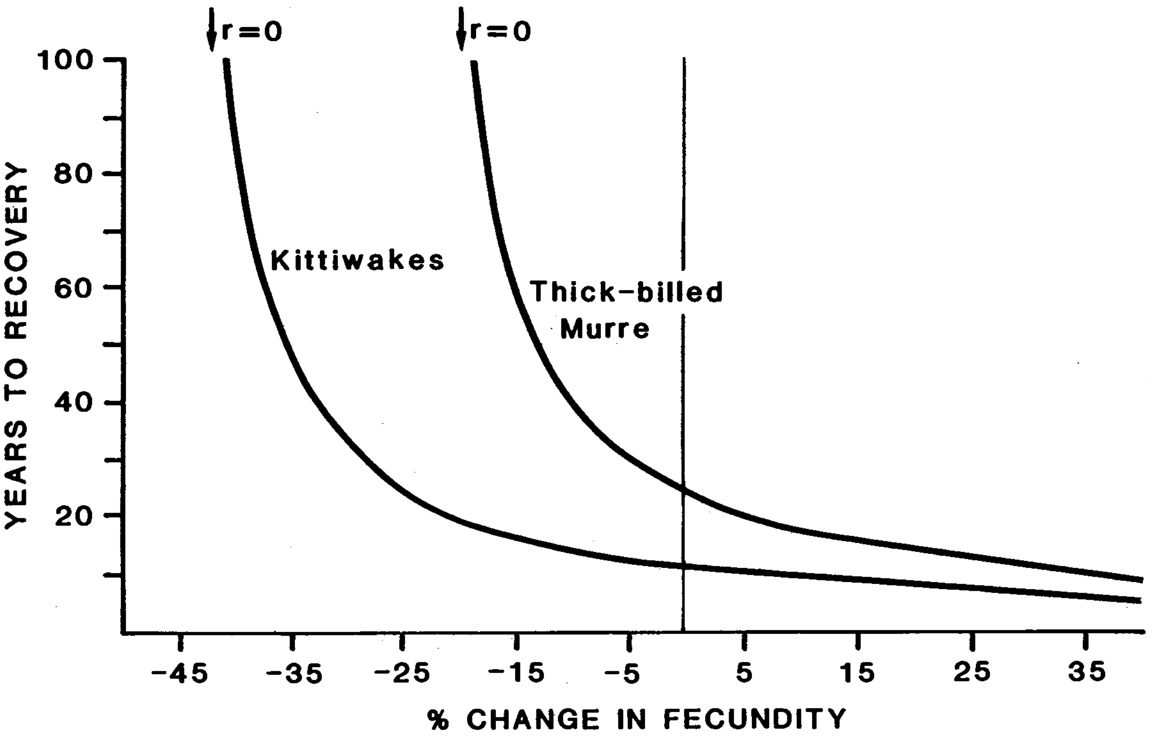

Figure 5.18. Time to recover as a function of change in mean fecundity rate, at 50 percent one-time adult and chick mortality for Thick-billed Murre and Kittiwake (Wiens et al., 1979).

gear or reduction of the food supply, could also be important.

The results presented here vary with changes in the values of survivorship and fecundity used in the simulations (Wiens et al., 1979). The environmental causes of the variability in these and other population parameters are not well understood. In a 28-year study of breeding Northern Fulmar in Orkney, Dunnet et al. (1979) found a year-to-year variation in the number of breeding birds of -37 to +50 percent while the colony was in a long-term growth, and of -34 to +26 percent while the colony was in a long-term decline. The causes of this variability were not identified but were thought not to be the consequence of human activities. Growth and decline in seabird populations are highly unpredictable and will remain so as long as we are ignorant of the environmental causes of the variation in annual survival and fecundity.

The first major oil pollution incident involving birds occurred in 1907. The schooner *Thomas W. Ralston,* the supertanker of its day, went aground on the Scilly Isles in the western English Channel, spilling 1,500 tons of oil — the seabird colonies there have never fully recovered (Nettleship, 1977). They and other Channel-associated colonies were dealt a further blow 60 years later with the wreck of the *Torrey Canyon,* when 81 percent of the Common Murres, 89 percent of the Razorbills and 84 percent of the Atlantic Puffins on Sept Isles,Brittany, died; and again in 1978 with the wreck of the *Amoco Cadiz;* followed more recently by two other oil incidents. These events have reduced regional murre and puffin numbers to virtually zero. The British and French English Channel experience is a portent of what we may expect in Alaska and other areas in the United States and Canada with the opening up of northern waters to offshore oil drilling and shipping.

5.4 POTENTIAL EFFECTS OF OCS DEVELOPMENT

Two kinds of hazards to bird populations in the St. George area can result from petroleum development: contamination of the environment by oil and disturbance by humans. Most dramatic and visible are the oiling and death of large numbers of birds and the littering of beaches with their bodies after a catastrophic spill or blowout. An estimated 100,000 birds, mostly alcids and waterfowl, died near Kodiak during the winter of 1970 as the result of petroleum contamination, thought to be ballast dumped by tankers entering Cook Inlet (Bartonek et al., 1971, cited in McKnight and Knoder, 1979).

Less spectacular but more likely is chronic spillage from platforms, pipelines, terminal and storage facilities, and tankers. Indeed, chronic pollution in "areas where oil development and transport activities are taking place probably kills more birds every year than die after a single catastrophic spill" (McKnight and Knoder, 1979). Most oil-caused mortality of seabirds in Danish waters was found to result from generally unnoticed pollution (Joensen, 1972).

Pelagic census data can be used to estimate the relative risk that a random oil spill in the eastern Bering Sea would encounter a large number of birds. Risk is predicted to be higher with high densities of birds and persistence of high density through time and space. The seasonal distribution of relative risk for areas in the eastern Bering Sea is shown in Fig. 5.19. Areas of high risk are found near the Pribilofs in the spring, throughout the St. George Lease Area but especially near the Pribilofs and in and near Unimak Pass in the summer, and near the Pribilofs and in and near Unimak Pass in the fall. Areas with variable high risk are those with high average densities of birds but with highly variable densities. Thus, given two areas, both containing large numbers of birds, there is a great likelihood that an oil spill will encounter many birds if the mean density is consistently high; there is a great, but lesser likelihood that a spill will encounter many birds if the mean density is high but variable. Since different species have different flocking patterns, they are likely to be affected differently by spills. Numerous species which do not flock will thus probably suffer some mortality, no matter where a spill occurs. They will thus be vulnerable to

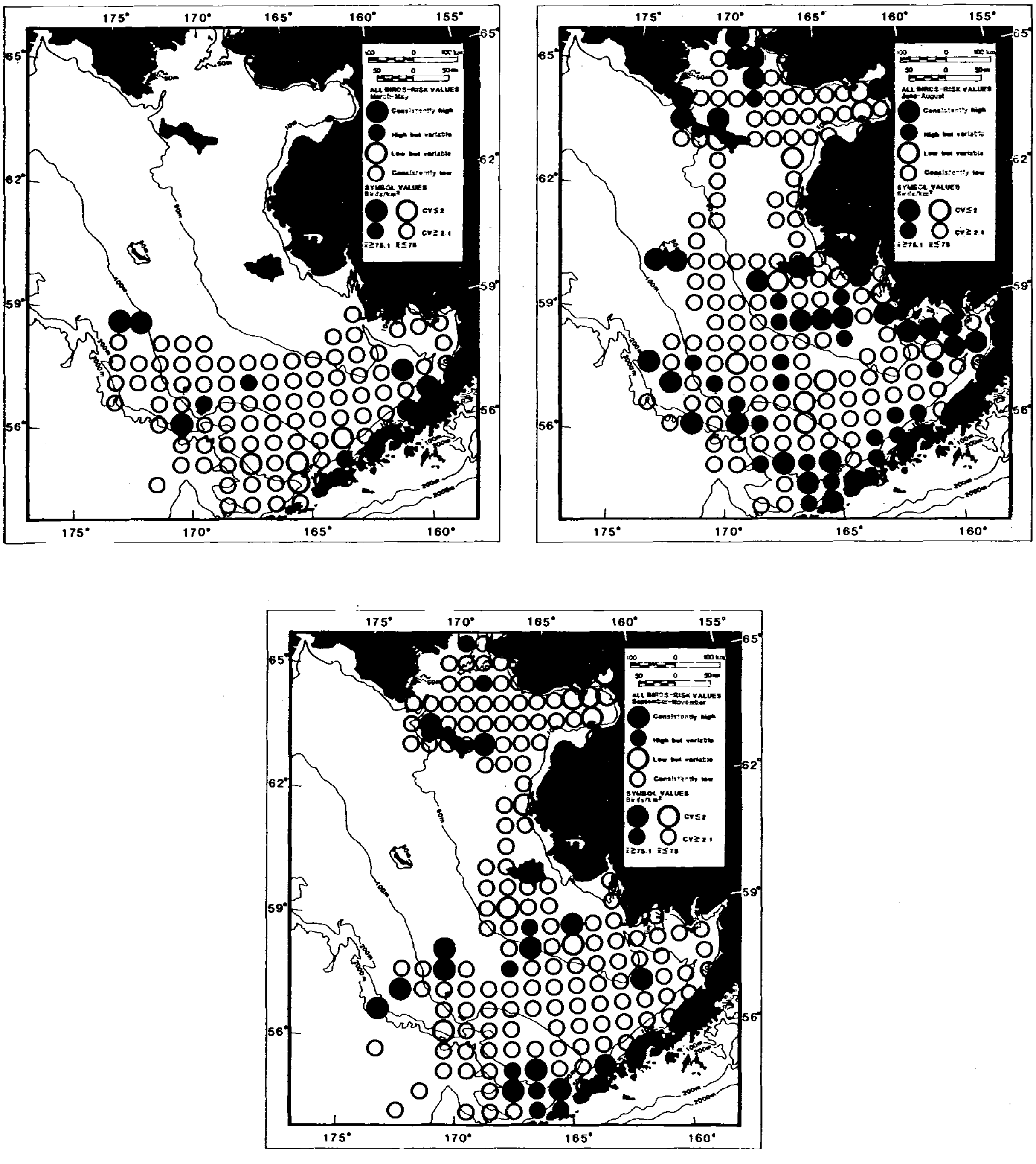

Figure 5.19. Seasonal estimates of risk of encounter for all birds.

chronic effects. Species which form dense flocks will be less likely to encounter a spill, but when they do, mortality will be catastrophic.

The known distribution of birds around St. George was used to model adult murre mortality from a 1,000-km^2-offshore oil spill (Wiens et al., 1979). The authors assumed that birds do not learn to avoid an oil spill. Their results indicate that a spill which persisted for 30 days would kill about 40,000 kittiwakes and 100,000 murres (Fig. 5.20), if the probability of death following contact with the spill was 0.5 for kittiwakes and 1.0 for murres. They also considered the effect of the environmental tracking rate (essentially the rate at which new birds would enter the area of the spill) on mortality (Fig. 5.21). Their model was more sensitive to the rate at which birds entered the spill area than it was to the probability that death followed spill contact.

The effects of oil pollution on birds may be direct or indirect. Most obvious is the direct fouling of the plumage by floating oil. Even small amounts of oil on the plumage can destroy buoyancy, waterproofing, and insulation. Affected birds may drown, starve, or die from exposure. Clark (1970) has pointed out that "by mischance, the species most vulnerable to oil slicks have an exceptionally low reproductive rate."

Oil may be ingested during feeding or preening. The effects of ingested oil on birds are under investigation. Miller et al. (1978) reported that young gulls ceased to grow when fed crude oil, due to alteration in the intestinal transport of nutrients. However, Gorman and Simms (1978) asserted that the ingestion of crude oil had no effect on the growth of young chickens, ducks, and gulls. They suggest that Miller et al. used experimental animals which had completed their natural growth before the experiment began. Szaro (1977) suggested that oil ingestion, while perhaps not a major cause of seabird mortality, could affect the birds' physiology and reproduction.

Holmes and Cronshaw (1977) found that ducks maintained under laboratory conditions tolerated the chronic administration of oil-contaminated food. Those subjected to cold stress, however, showed increased mortality.

In addition to indirect effects on reproduction through ingestion of oil, breeding seabirds can transmit oil from their plumage to their eggs. Experiments have shown that "minute quantities" of No. 2 fuel oil applied to eggs caused significant embryo mortality and reduced hatchability in the eggs of aquatic birds (White et al., 1979). Albers (1978) showed that oiling of eggs was most lethal when adult birds were in the early stages of incubation. Grau et al. (1978) studied effects of oil on eggs of Cassin's Auklets *(Ptychoramphus aleuticus)* on the Farallon Islands in California. They found a reduction in the reproductive success of auklets which ingested Bunker C oil, as well as in auklets whose brood patches had been smeared with oil. Egg production of smeared birds was even lower than that of birds that had been fed oil. This suggests that eggs are indirectly vulnerable to oil even before they are laid, as well as being harmed directly by oil after laying (Albers, 1978; White et al., 1979).

Another important indirect effect of oil pollution on birds is contamination of their prey and of the food source of their prey. Prey not killed outright could be ingested. If prey organisms were killed by oil before they could be eaten, a food source for the birds would have been lost. This

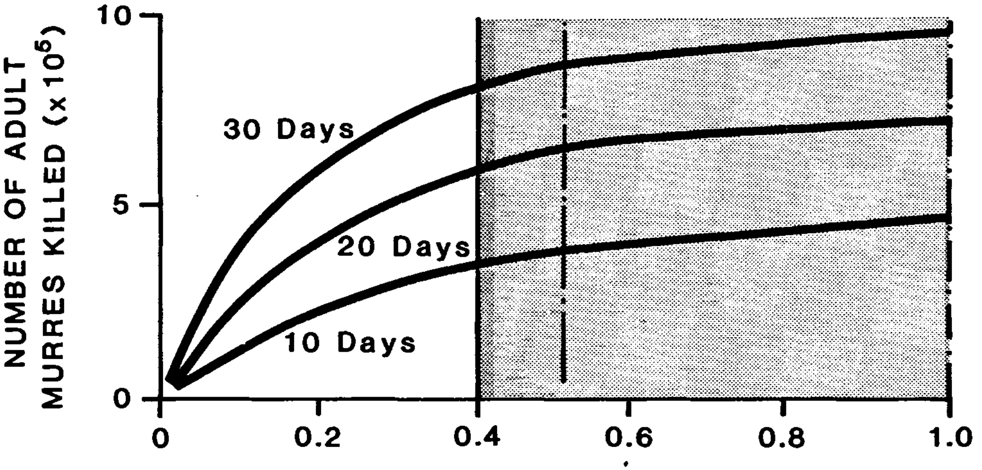

Figure 5.20. The number of adult murres killed by a 1,000-km^2 offshore oil spill simulated with persistence times fo 10, 20, and 30 days. The impact of the spill is plotted as a function of P, the probability of death following spill encounter. Dashed lines indicate values used in model runs; 0.5 for kittiwakes and 1.0 for murres. The stippled region corresponds to what is considered a reasonable range of values of P. (Wiens et al., 1979).

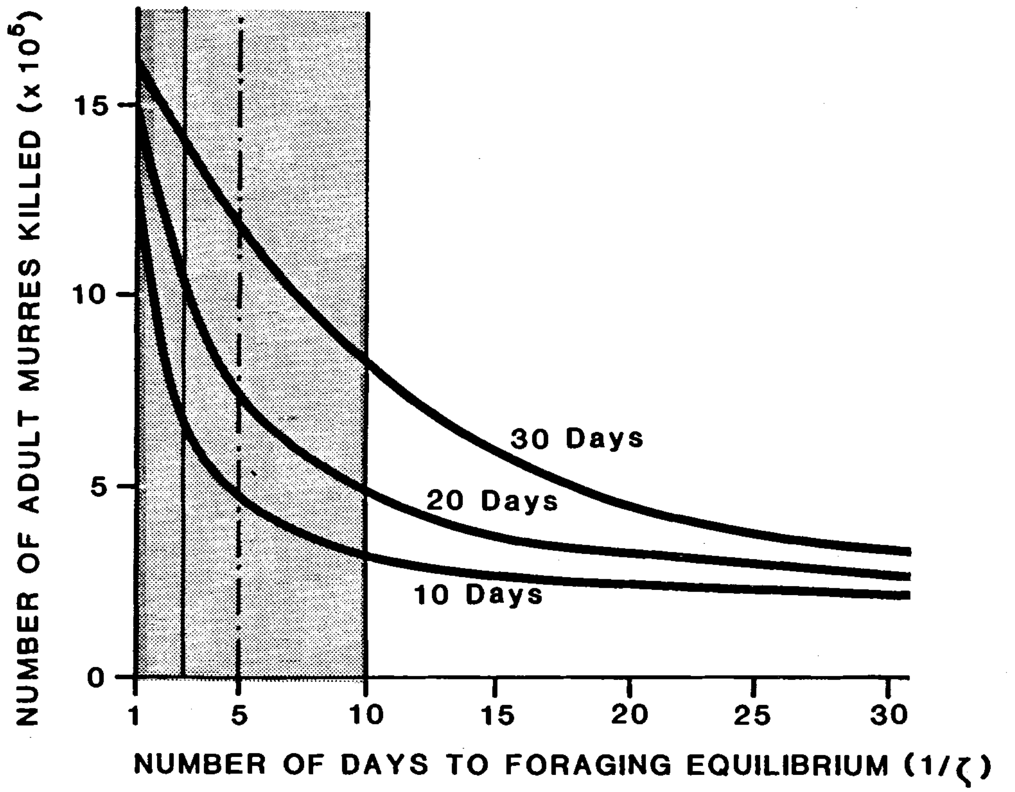

Figure 5.21. The number of adult murres killed by a 1,000-km² offshore oil spill simulated with persistence times of 10, 20, and 30 days. The impact of the spill is plotted as a function of 1/ , the number of days required for the population to reach a new equilibrium foraging distribution following perturbation. Stippled region and dashed lines as in Fig. 5.20 (Wiens et al., 1979).

could have serious consequences if it happened when the birds were staging for migration or during the breeding season.

The second kind of hazard to bird populations from oil development is human interference. These disturbances may include drilling rigs in foraging areas or major migratory pathways, aircraft and vessel traffic, or construction activities near coastal nesting and foraging habitat. When adult birds are frightened from their nests, whether by vessel noises, aircraft noises, or by foot traffic, they leave their young vulnerable to exposure and predation.

The amount of disturbance which will damage a colony varies from species to species. Murres, which are cliff-nesters jump off their ledges in panic-flights when even approached by humans, kicking eggs and chicks down to the beach or ocean. Tufted and Horned Puffins likewise stream off colonies if approached within 100 m by boat or within about 25 m overland (Baird et al., 1981). In their panic-flights out of their burrows or crevices, they may also kick eggs into the ocean (in the case of Horned Puffins), but more likely they will just move the egg close to the nest entrance, where it may either roll out or be consumed by gulls. On the Farallon Islands, Robert and Ralph (1975) found that loss of eggs and very small young was directly proportional to the frequency of disturbance. In the western Aleutian Islands, Trapp (1978) found that the nesting success of Red-faced Cormorants in a disturbed colony was only 6 percent, compared to 81 percent at a nearby undisturbed colony. Repeated disturbance of a Common Murre colony can cause long-term reduction in productivity (Birkhead, 1977a).

At St. George Island, murres fled from the nesting cliffs when a helicopter approached within 180-250 m (Hunt, 1978). The murres also fled when the aircraft was flown perpendicular or parallel to the cliffs. Helicopters scared most of the birds off King and Little Diomede Islands (Biderman and Drury, 1978). Repeated helicopter flights to Little Diomede during the summer of 1976 may have partly caused the scarcity of Crested Auklets observed on the island in 1977. Biderman and Drury (1978) found rotten eggs in several burrows that appeared to have been abandoned the year before. Helicopters have been reported to disturb seabirds at greater distances than fixed-wing aircraft (Biderman and Drury, 1978; Jones and Peterson, 1979). Some studies (Dunnet, 1977; Kushlan, 1979) indicate that birds may become habituated to the close approach of aircraft. Such studies, however, lack information on the size and productivity of the colonies before exposure to aircraft and follow-up studies of breeding success after the reported slight response to aircraft. Other phases of the life cycle which can be upset by human interference are molting and staging before migration. When aircraft traffic disrupts molting, which usually takes place where the birds are safest from predation, increased predation on the flightless birds may ensue (McKnight and Knoder, 1979). Staging geese were found to be disturbed by the noise of gas compressors (McKnight and Knoder, 1979). This might have the same effect as reducing the food supply directly, for geese which do not feed adequately before migration are less likely to survive their flight south (Wiseley, 1974).

Bird populations in the St. George area are at greater risk from oil contamination than those at lower latitudes. More northerly populations are "characterized by numerical dominance of a few species, relatively simple food chains, and an inherent instability or fragility" (Dunbar, 1968, in McKnight and Knoder, 1979). They must endure extremes of weather conditions, uncertain food supply, and the need to reproduce in a brief period. Already under stress from the harsh environment, they are thus particularly vulnerable to the man-caused stress of oil developments (Dunbar, 1968, in McKnight and Knoder, 1979). The ingestion of spilled oil by birds under the stressful natural conditions of the St. George marine environment might be expected to result in increased mortality, as in the experimental results cited by Holmes and Cronshaw (1977).

Contamination of the food supply would be especially serious because of the short food chains and lack of alternative food sources. An expected result would be a decrease in the carrying capacity of the habitat for marine birds (McKnight and Knoder, 1979). Other elements of the food chain would then be affected as well. The bird groups most likely to be affected by oil development are alcids, which constitute the majority of birds inhabiting coastal areas in winter, and the sea ducks, because of their diving and flocking habits and their flightless molt period (McKnight and Knoder, 1979).

King and Sanger (1979) have devised an Oil Vulnerability Index (OVI) for marine birds of the northeast Pacific. It is based on such characteristics of the species as range, population, habits, mortality, and exposure to oil development. Birds with high indices are more vulnerable to oil development than those with lower indices. King and Sanger (1979) confirm that alcids and sea ducks are the most vulnerable groups. Table 5.9 shows OVI's for marine birds of the southeast Bering Sea. They are arranged according to ranges of OVI. According to King and Sanger (1979), an OVI of 1-20 indicates species with low vulnerability; damage or future costs would not be expected. An OVI of 21-40 indicates species for which there is slight concern. An OVI of 41-60 indicates species for which it would not be catastrophic if some birds were adversely affected. An OVI of 61-80 or 81-100 indicates species for which concern is high.

If these indices are compared with those for other regions, it is seen that the number of species with OVI greater than 61 is similar to that for the Aleutian Islands and much higher than that for southeast Alaska or the northeast Pacific region.

5.5 DEVELOPMENT CONCERNS

The Pribilof Islands, Unimak Pass, and the lagoons on the north shore of the Alaska Peninsula were identified as the areas of highest concern with respect to birds. As it was the consensus of the Bird Workshop members that highest priority should be given to protection of the Pribilofs, we therefore recommend Alternative C, deletion of the extreme northwestern tracts. It was felt that any risk of disturbance or oil contamination to the bird fauna of the Pribilofs was unacceptable because of its importance to Alaska and world populations and because it would be almost impossible to reduce the catastrophic effects a spill would have there. One spill during the breeding season could kill more than half of the breeding populations, leading to an irreversible decline.

Oil spills in Unimak Pass or in the lagoons would also be major disasters. During molt, many waterfowl could not escape an oil slick. Destruction of the benthic food supply would have long-lasting effects. Those areas, however, are and will increasingly be threatened by traffic from other lease areas, regardless of the outcome of development in the St. George Basin lease area. To ensure the health and longevity of the areas' bird populations in the event of development, steps must be taken to (1) minimize adult mortality, (2) minimize reduction of the long-term reproductive rates, and (3) minimize reduction in the lagoon food supplies.

It is suggested that the utmost efforts be made to mitigate disturbance to those areas. The establishment and rigorous enforcement of ship traffic plans for Unimak Pass, along with installation and use of modern navigational aids and the permanent stationing of tugs able to rescue and control fully laden tankers, are minimum requirements. The most efficient containment and cleanup devices available should be stationed at Izembek and Nelson lagoons. Contingency plans for rescuing flightless waterfowl from the area should be developed.

5.6 RESEARCH NEEDS

The members of the Bird Workshop noted several important areas in which current knowledge is too meager to allow firm decisions on management and conservation of the southeastern Bering Sea bird fauna. There is little information

Table 5.9. OVI's for pelagic seabirds in the St. George Basin area, summarized by 20-unit increments. No birds have OVI's in the 81-100 increment, and 13 species of trace occurrence during one season had only one OVI point each (U.S. Fish and Wildlife Service, unpub.).

OVI 21-40		OVI 41-60		OVI 61-80	
Pomarine Jaeger	34	Laysan Albatross	48	Northern Fulmar	63
Parasitic Jaeger	36	Sooty Shearwater	49	Short-tailed Shearwater	63
Long-tailed Jaeger	32	Leach's Storm-Petrel	45	Fork-tailed Storm-Petrel	67
Glaucous Gull	35	Red-faced Cormorant	49	Spectacled Eider	61
Sabine's Gull	37	Oldsquaw	49	Common Murre	63
Arctic Tern	31	Black Scoter	53	Thick-billed Murre	67
		Red Phalarope	50	Ancient Murrelet	71
		Northern Phalarope	53	Parakeet Auklet	74
		Glaucous-winged Gull	48	Crested Auklet	69
		Black-legged Kittiwake	46	Least Auklet	78
		Red-legged Kittiwake	54	Whiskered Auklet	70
				Horned Puffin	65
				Tufted Puffin	73
Totals	205		544		884

on the wintering grounds of most of the breeding species. It is thus impossible to predict what effect hazards such as the Japanese gillnet fisheries pose to the population or whether winter development activity is of serious concern. Basic demographic data such as age structure of the breeders and mortality tables are unknown. Only with such information can the current health and vigor of these populations and their ability to recover from perturbation be assessed. Long-range population trends remain unknown as does the magnitude of yearly variation in breeding populations. Without such information there will be no way to distinguish man-induced perturbations from natural ones, and thus little possibility of detecting and mitigating damage before its effects become irreversible. These data gaps can be closed only with long-term, intensive banding studies. To be fruitful, such studies will probably require a decade of work. Because of the effort required, such studies will need to be conducted on a few carefully chosen species and sites.

More information is needed on the tophics of nonbreeding pelagic birds. Although shearwaters are the most abundant species in the southeastern Bering Sea in the summer, their diet and methods of finding prey are poorly known. Such knowledge is essential to understanding the role seabirds play in the dynamics of the Bering Sea ecosystem.

Only pilot studies have been made of the lagoon ecosystems. Sound decisions on the use of the lagoons for shore facilities and for protecting their avifauna require further knowledge.

Finally, there remains the problem of how to rank alternatives which involve environmental risk. However complete the description of an ecosystem, if choices are to be made which will likely lead to different effects on the system, then the scientific basis of the priorities which determine such choices should be made as explicit as possible.

5.7 SUMMARY

The southeastern Bering Sea supports an extraordinary, if not unique, marine bird resource; the Bird Workshop identified four areas in which spilled oil could cause major damage to North American bird populations: The Pribilof Islands, the Fox Islands, Unimak Pass, and the lagoons on the north side of the Alaska Peninsula.

The seabird resource is concentrated in four well-defined areas near, but outside, the St. George lease area. The Pribilof Islands support 2.75 million and the Fox Islands 1.8 million breeding birds, whereas the inshore area of the Alaska Peninsula supports over 1.2 million migrant and wintering waterfowl and the pelagic area over 20 million seabirds. These populations contain major segments of world, North American, or Pacific Flyway populations. At the Pribilofs, 88 percent of the world population of Red-legged Kittiwakes and 33 percent of the Bering Sea populations of Thick-billed Murres nest, whereas 45 percent of the Alaska population of Tufted Puffins and about 50 percent of the world population of Whiskered Auklets breed in the Fox Islands. For waterfowl, 75-100 percent of the Pacific Flyway populations of four species and 75-100 percent of the North American populations of three species use the lagoons on the north shore of the Alaska Peninsula as a migratory rest stop, a molting area, or an overwintering area. In the pelagic zone, a major portion of the world's population of Short-tailed Shearwaters spends the austral winter in the Bering Sea, migrating through the passes, in particular Unimak Pass, where on occasions up to 1.1 million birds may be found. Of the seabirds present, the alcids are probably the most vulnerable to spilled oil because they spend most of their time on or under water. Species that sleep on the water at night or concentrate in large flocks are also especially vulnerable.

The food base to support such a concentration of birds must be large, stable, and dependent on an unusually high level of productivity. Such areas are rare in the world and are patchily distributed. The food base for marine birds is primarily fish, in particular, walleye pollock and myctophids (for Red-legged Kittiwakes), whereas euphausiids and amphipods are the most important invertebrates. The food base for waterfowl is a combination of benthic invertebrates and eelgrass. The loss of any of these foods, especially pollock, eelgrass, and inshore benthic invertebrates, would have disastrous consequences for the bird populations.

The breeding birds are present in their colonies from May to October, with the most critical period being from June to September, when eggs and chicks on the islands force adult birds to limit the area of foraging to the vicinity of the colonies. Most foraging is concentrated within 60 km of the Pribilofs or in the passes near the Fox Islands. Additionally, in August-September, flightless adults and young of murres and murrelets are present in large numbers on the water near colonies as they leave for postbreeding molt and dispersal.

The fecundity of most marine birds is extremely low. Most marine species have a clutch of one and produce 0.4-0.6 young per year. Indications are that Pribilof populations of seabirds may already have lower reproductive output than populations of the same species elsewhere in the world. Thus, further depression of reproduction over a long period (15-20 yr) might result in the destruction of these colonies.

Because the life history of seabirds is characterized by low reproductive rates and long adult life span, loss of adult birds will have the greatest long-term effect on populations. Since oiling of birds almost always leads to death, spilled oil in the four areas identified as having high bird numbers would be of great concern. For murres, a one-time mortality of 50 percent of the Pribilof colony would require more than 20 years for the population to recover. Since these birds occur in immense rafts on the water near the islands, a single small spill could easily destroy 50 percent or more of the birds.

Spills reaching the lagoons would be of concern at any season, even if waterfowl were not present. Contamination by oil or destruction of food supplies could jeopardize the availability of energy resources critical for successful overwintering or migration and affect future reproduction.

At colonies, disturbance by aircraft, boats, or shooting; reduction of food supplies; and physiological damage related to oil contamination that would further reduce the already low reproductive rates of seabirds all could have serious consequences. Modeling studies suggest that a long-term 15-20 percent drop in the fecundity of murres would lead to an irreversible decline of their populations to extinction. Any drop would greatly increase the time needed to recover from adult mortality.

The consensus of the workshop was that special measures be taken during the OCS development to 1) minimize any developments in the Pribilof Islands that would increase colony disturbance, 2) protect foraging alcids on the water near the Pribilof and Fox Islands from spilled oil, particularly from May through September, 3) protect Unimak Pass from spills, and 4) protect the lagoons on the north side of the Alaska Peninsula.

Still needed are 1) demographic data on mortality and age structure; 2) information on winter population numbers and distribution between November and March, and on 3) food use by birds at sea; 4) the development of an objective method for assessing risk and establishing protection priorities; and 5) ecosystem and oil vulnerability studies of the lagoon systems.

5.8 REFERENCES

Ainley, D. G., and G. A. Sanger. 1979. Trophic relations of seabirds in the Northeastern Pacific Ocean and Bering Sea, pp. 95-122. *In:* J. C. Bartonek and D. N. Nettleship (eds.), Conservation of marine birds of northern North America. U.S. Dep. Int., Fish. Wildl. Serv., Washington, D.C. Wildl. Res. Rep. II.

Albers, P. H. 1978. The effects of petroleum on different stages of incubation in bird eggs. Bull. Environ. Contam. Toxicol. 19:624-630.

Arneson, P. D. In press. Identification, documentation and delineation of coastal migratory bird habitat in Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol.

Ashmole, N. P. 1971. Sea bird ecology and the marine environment. *In:* D. S. Farner and J. R. King (eds.), Avian biology. Academic Press, New York. 1:223-286.

Baird, P. A. In prep. Breeding biology and feeding ecology of marine birds in the Gulf of Alaska.

Biderman, J. O., and W. H. Drury. 1978. Ecological studies in the northern Bering Sea: Studies of seabirds in the Bering Strait. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 2:751-838.

Birkhead, T. R. 1977a. The effect of habitat and density on breeding success in the Common Guillemot *(Uria aalge)*. J. Anim. Ecol. 46:751-764.

Birkhead, T. R. 1977b. Population parameters for the Common Guillemot *Uria aalge*. Ornis Scand. 8:145-154.

Clark, R. B. 1970. Oiled seabird research unit. Mar. Poll. Bull. 1(NS)(2):22-24.

Cottam, C. and P. Knappen. 1939. Food of some uncommon North American birds. Auk 56:138-169.

Coulson, J. C., and E. White. 1959. The post fledging mortality of the Kittiwake. Bird Study 6:97-102.

Coulson, J. C., and R. D. Wooller. 1976. Differential survival rates among breeding Kittiwake Gulls *Rissa tridactyla* (L.). J. Anim. Ecol. 45:203-213.

Dunnet, G. M. 1977. Observations on the effects of low-flying aircraft at seabird colonies on the coast of Aberdeenshire, Scotland. Biol. Conserv. 12:55-63.

Dunnet, G. M., J. C. Ollason, and A. Anderson. 1979. A 28-year study of breeding Fulmars *Fulmarus glacialis* in Orkney. Ibis 121:293-300.

Einarsen, A. S. 1945. Some factors affecting Ring-necked Pheasant population density. Murrelet 26:39-44.

Gill, R., P. D. Jorgensen, A. R. DeGange, and P. Kust, Sr. 1977. Avifaunal assessment of Nelson Lagoon, Port Moller and Herendeen Bay, Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 4:594-616.

Gill, R. M. Petersen, C. Handel, J. Nelson, A. DeGange, A. Fukuyama, and G. Sanger. 1978. Avifaunal assessment of Nelson Lagoon, Port Moller, and Herendeen Bay, Alaska — 1977. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 3:69-131.

Gill, R. E., Jr., and C. M. Handel, and M. Petersen. 1979. Migration of birds in Alaska marine habitats. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol. 5:245-288.

Gorman, L. M., and C. E. Simms. 1978. Lack of effect of ingested Forties Field crude oil on avian growth. Mar. Poll. Bull. 9:273-276.

Grau, C. R., D. G. Ainley, T. Roudybush, and S. Morrell. 1978. Influence of petroleum on egg formation and embryonic development in seabirds. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Quart. Rep., Oct.-Dec., 1:467-475.

Hickey, J. J., and F. L. Craighead. 1977. A census of seabirds on the Pribilof Islands. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 2:96-195.

Holmes, W. N., and J. Cronshaw. 1977. Biological effects of petroleum on marine birds, 2:359-398. *In:* D. C. Malins (ed.), Effects of petroleum on arctic and subarctic marine environments and organisms. Academic Press, New York.

Hunt, G., Jr. 1978. Reproductive ecology, foods, and foraging areas of seabirds nesting on the Pribilof Islands. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:570-775.

Hunt, G. L., Jr., B. Burgeson, and G. A. Sanger. 1981a. Feeding ecology of seabirds of the eastern Bering Sea. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 2:629-647.

Hunt, G. L., Jr., Z. Eppley, B. Burgeson, and R. Squibb. 1981b. Reproductive ecology, foods and foraging areas of seabirds nesting on the Pribilof Islands, 1975 - 1979. *In:* Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP. Final Rep., Biol. 12:1-257.

Hunt, G. L., Jr., Z. Eppley, and W. H. Drury. 1981c. Breeding distribution and reproductive biology of marine birds in the eastern Bering Sea. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 2:649-687.

Hunt, G. L., Jr., P. J. Gould, D. J. Forsell, and H. Peterson, Jr. 1981d. Pelagic distribution of marine birds in the eastern Bering Sea. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 1:689-718.

Hutchinson, G. D. 1978. An introduction to population ecology. Yale Univ. Press, New Haven.

Iverson, R. L., L. K. Coachman, R. T. Cooney, T. S. English, J. J. Georing, G. L. Hunt, Jr., M. C. Macauley, C. P. McRoy, W. S. Reeburg, and T. E. Whitledge. 1979. Ecological significance of fronts in the southeastern Bering Sea. *In:* R. J. Livingston (ed.), *Ecological Processes in Coastal and Marine Systems.* Plenum Press, New York. pp. 437-466.

Joensen, A. H. 1972. Studies on oil pollution and seabirds in Denmark 1968-1971. Danish Rev. Game Biol. 6(9):1-32.

Jones, R. D., Jr., and M. R. Petersen. 1979. The pelagic birds of Tuxedni Wilderness, Alaska. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 2:187-232.

King, J. G., and C. P. Dau. 1981. Waterfowl and their habitats in the eastern Bering Sea. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources.* NOAA/OMPA, Seattle, Wash. Vol. 2:739-753.

King, J. G., and G. A. Sanger. 1979. Oil Vulnerability Index for marine oriented birds, pp. 227-239. *In* J. C. Bartonek and D. N. Nettleship (eds.), Conservation of marine birds of northern North America. U. S. Dep. Int. Fish Wildl. Serv. Washington, D.C. Wild. Res. Rep. 11.

Kushlan, J. A. 1979. Effects of helicopter censuses on wading bird colonies. J. Wildl. Manage. 43:756-760.

Lack, D. 1954. The natural regulation of animal numbers. Oxford Univ. Press, Oxford.

McKnight, D. E., and C. E. Knoder. 1979. Resource Development along coasts and on the ocean floor: Potential conflicts with marine bird conservation. U.S. F & W., Wild. Res. Rep. 11: 183-194.

Miller, D. S., D. B. Peakall, and W. B. Kinter. 1978. Ingestion of crude oil: sublethal effects in herring gull chicks. Science 199:315-317.

Nettleship, D. N. 1977. Seabird resources of eastern Canada: status, problems, and prospects, pp. 96-198. *In:* T. Mosquine, and C. Suchal (eds.). Proc. Symposium on Canada's Threatened Species and Habitats. Can. Nat. Fed., Ottawa.

Odum, E. P. 1971. *Fundamentals of Ecology.* 3rd ed. Saunders, Philadelphia.

Ricklefs, R. E. 1973. Fecundity, mortality, and avian demography. *In:* D. S. Farner (ed.), *Breeding Biology of Birds.* Nat. Acad. Sci. Washington. pp. 366-447.

Robert, H. C., and C. J. Ralph. 1975. Effects of human disturbance on the breeding success of gulls. Condor 77:495-499.

Sanger, G. A., R. D. Jones, and D. W. Wiswar. 1979. The winter feeding habits of selected species of marine birds in Kachemak Bay, Alaska. pp. 309-347. *In:* Env. Ass. of the Ak CS, Annual Report Vol. 2.

Shuntov, V. P. 1972. Marine birds and the biological structure of the oceans. (Transl. from Russian.) Bur. Sport Fish. Wildl./Nat. Sci. Found., Washington, D.C. NTIS TT 74-53032.

Sowls, A. L., S. A. Hatch, and C. J. Lensink. 1978. Catalog of Alaskan seabird colonies. U.S. Dep. Int., Fish Wildl. Serv., Biol. Serv. Prog. FWS/OBS 78/78.

Szaro, R. C. 1977. Effects of petroleum on birds. Trans. 42nd N. Amer. Wildl. Nat. Res. Conf., pp. 374-381.

Trapp, J. L. 1978. Effects of human disturbance on a Red-faced Cormorant nesting colony (Abstract only). Pacif. Seabird Gp. Bull. 5(2):88.

White, D. H., K. A. King, and N. C. Coon. 1979. Effects of No. 2 fuel oil on hatchability of marine and estuarine bird eggs. Bull. Environ. Contam. Toxicol. 21:7-10.

Wiens, J. A., G. Ford, D. Heinemann, and C. Fieber. 1979. Simulation modeling of marine bird population energetics, food consumption, and sensitivity to perturbation. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. 1:217-270.

Wisley, A. N. 1974. Disturbance of Snow Geese and other large waterfowl species by gas-compressor sound simulation, Komakuk, Yukon Territory, August-September, 1973. *In:* Gunn, W. W. H., W. J. Richardson, R. E. Schweinsburg, and T. D. Wright (eds.), Studies on Snow Geese and waterfowl in the Northwestern Territories, Yukon Territory and Alaska, 1973. Arctic Gas Rep. Ser. 27(3):1-35.

Wooller, R. D., and J. C. Coulson. 1977. Factors affecting the age of first breeding of the Kittiwake *Rissa tridactyla.* Ibis 119:339-349.

CHAPTER 6

FINFISH RESOURCES

F. V. Thorsteinson and L. K. Thorsteinson

With contributions from R. Bakkala, E. Best, C. Bowden, J. Hawkes, J. Houghton, W. Jensen, S. Korn, B. Morris, L. Moulton, M. Pelto, R. Straty, R. Wienhold, and R. Wolotira.

6.1 INTRODUCTION

The southeastern Bering Sea is one of the world's major fishing grounds. These waters have been fished mainly by fleets from Japan, South Korea, Taiwan, and, until 1980, the U.S.S.R. A single West German vessel began fishing in the area in late 1980. United States trawlers are now fishing there in a joint venture with the U.S.S.R. The productivity of the area and the potential for domestic fleets are well demonstrated by total foreign fleet catches in the Bering Sea-Aleutian area for 1977-79 (Table 6.1). In 1977, foreign fleets paid the United States $7.77 million in vessel tonnage fees and allocated catch fees. The St. George Basin is a major part of the Bering Sea fishing grounds and contributes about one-third of the total area catch. In 1977, of 1.15 million t taken in the southeastern Bering Sea, 453,000 t were caught in the St. George Basin. The ex-vessel value of the St. George Basin catch was about $59 million.

Except for Pacific ocean perch, sablefish, and halibut, groundfish stocks of the southeast Bering Sea are considered to be capable of producing maximum sustainable yields. Pacific ocean perch and sablefish stocks are depleted (i.e., the current equilibrium yield is less than one-half of the maximum sustainable yield). There have been no signs of improvement in stocks of Pacific ocean perch, but the relatively strong year class of sablefish which will be recruited in 1981 or 1982 may improve the condition of this stock. Pacific halibut stocks are depressed (i.e., current equilibrium yield is below the maximum sustainable yield) but may be improving.

6.2 SELECTED FISHES OF THE ST. GEORGE BASIN

The Bering Sea is inhabited by over 300 species of finfish of at least 43 families. Eight families are of commercial significance. Fishes of the St. George Basin are listed in Table 6.2.

6.2.1 Abundance

OCSEAP-sponsored surveys of demersal fish resources of the eastern Bering Sea carried out by the National Marine Fisheries Service during August-October 1975 and April-June 1976 encompassed the area of call of the St. George Basin Lease Area (Figs. 6.1, 6.2). The biomass has been estimated for the total survey area and for the St. George call area (Table 6.3) (NMFS, 1979). Some species were inadequately sampled, however. The biomass of walleye pollock and Pacific cod was underestimated because some fish were above the trawling gear or outside the survey area. This condition prevailed during the 1976 survey of pollock. In addition, the overall distribution of Greenland turbot, halibut, arrowtooth flounder, rockfish, and sablefish was

Table 6.1. Foreign fleet catch in the Bering Sea-Aleutian area, 1977-79 (in metric tons, t)

Species	1977	1978	1979
Pollock	886,686	973,604	923,385
Yellowfin sole	58,373	138,433	99,017
Other flounders	62,252	95,276	91,365
Pacific cod	36,582	45,803	38,572
Atka mackerel	20,975	24,250	23,264
Salmon	0	34,006	30,984
Herring	21,287	16,288	19,055
Other rockfish	7,727	20,892	24,640
Sablefish	3,826	1,960	2,170
Halibut	3	4	0
Other finfish	64,072	81,841	58,883
Total	1,161,783	1,432,357	1,311,335

Table 6.2. Fishes of the St. George Basin

- Family Rajidae — skates and rays
  - _Raja_ spp. — skates
- Family Clupeidae — herring
  - *_Clupea harengus pallasi_ — Pacific herring
- Family Salmonidae — salmon
  - **_Oncorhynchus nerka_ — sockeye
  - **_O. tshawytscha_ — chinook
  - **_O. gorbuscha_ — pink
  - **_O. kisutch_ — coho
  - **_O. keta_ — chum
- Family Gadidae — cods and hakes
  - *_Gadus macrocephalus_ — Pacific cod
  - _Eleginus gracilis_ — saffron cod
  - **_Theragra chalcogramma_ — walleye or Alaska pollock
  - _Boreogadus saida_ — Arctic cod
- Family Macrouridae — grenadiers
  - _Albatrossia_ spp. — pectoral rattail
  - _Coryphanoides_ spp. — rattails
- Family Scorpaenidae — rockfish
  - _Sebastes alutus_ — Pacific ocean perch
  - _Sebastes_ spp. — other rockfish
- Family Anoplopomatidae — sablefish
  - *_Anoplopoma fimbria_ — sablefish
- Family Hexagrammidae — greenling
  - _Pleurogrammus monopterygius_ — Atka mackerel
- Family Pleuronectidae — righteye flounders
  - _Isopsetta isolepis_ — butter sole
  - *_Reinhardtius hippoglossoides_ — Greenland turbot
  - _Platichthys stellatus_ — starry flounder
  - *_Lepidopsetta bilineata_ — rock sole
  - **_Hippoglossus stenolepis_ — Pacific halibut
  - *_Hippoglossoides elassodon_ — flathead sole
  - _Pleuronectes quadrituberculatus_ — Alaska plaice
  - _Glyptocephalus zachirus_ — rex sole
  - _Atheresthes stomias_ — arrowtooth flounder
  - **_Limanda aspera_ — yellowfin sole
  - _L. proboscidea_ — longhead dab
  - _Microstomus pacificus_ — Dover sole

**denotes primary importance, and *secondary importance

poorly sampled because the depths where they occur on the continental slope were not surveyed.

Seasonal offshore and inshore migrations are reflected by the biomass estimates of the proportion of fish in the St. George Basin call area compared to that in the overall survey area: about 39 percent in summer 1975, and about 52 percent in the spring of 1976.

Within the call area, most of the biomass of commercially important species is concentrated in block Nos. 2-8, 3-7, NN3-1, and NN3-3.

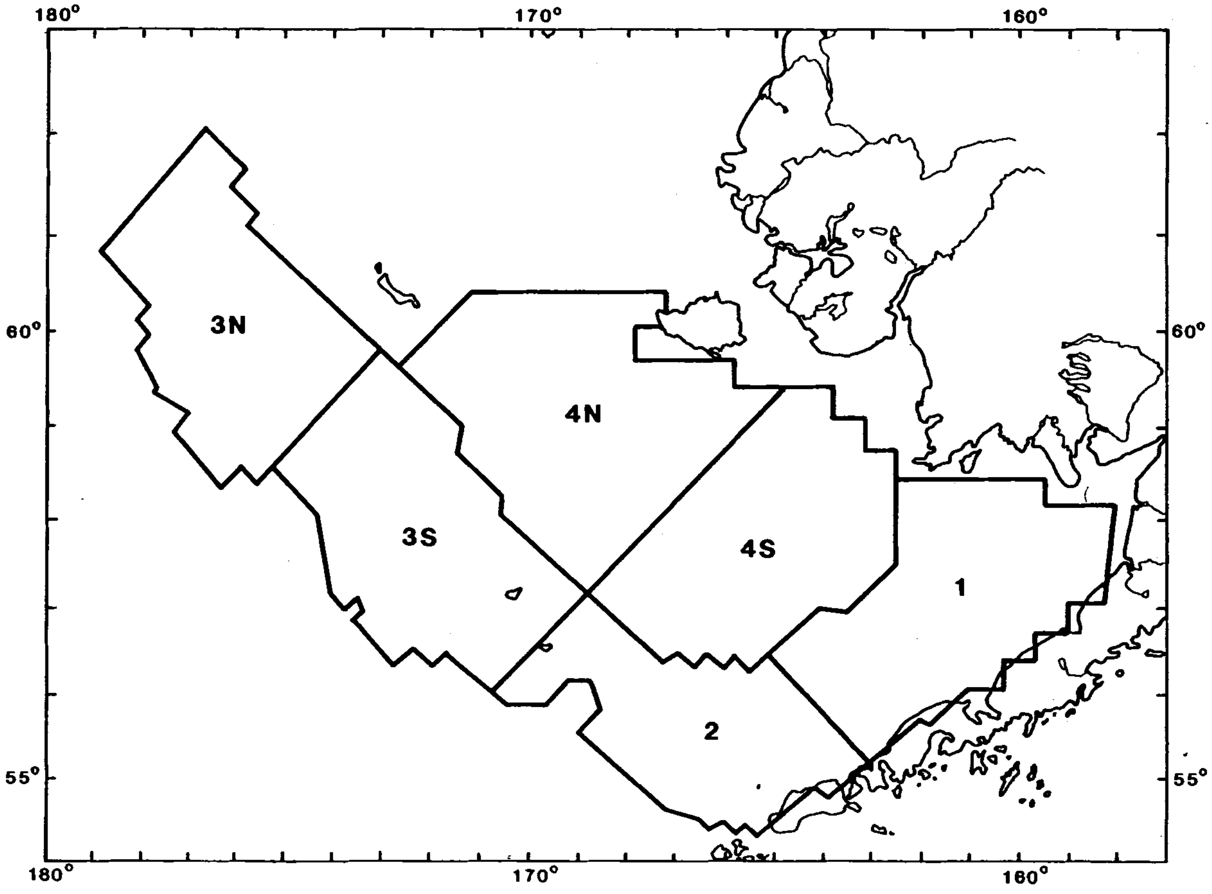

Figure 6.1. Statistical subdivisions of the study area used for the 1975 eastern Bering Sea baseline survey (Pereyra et al., 1976).

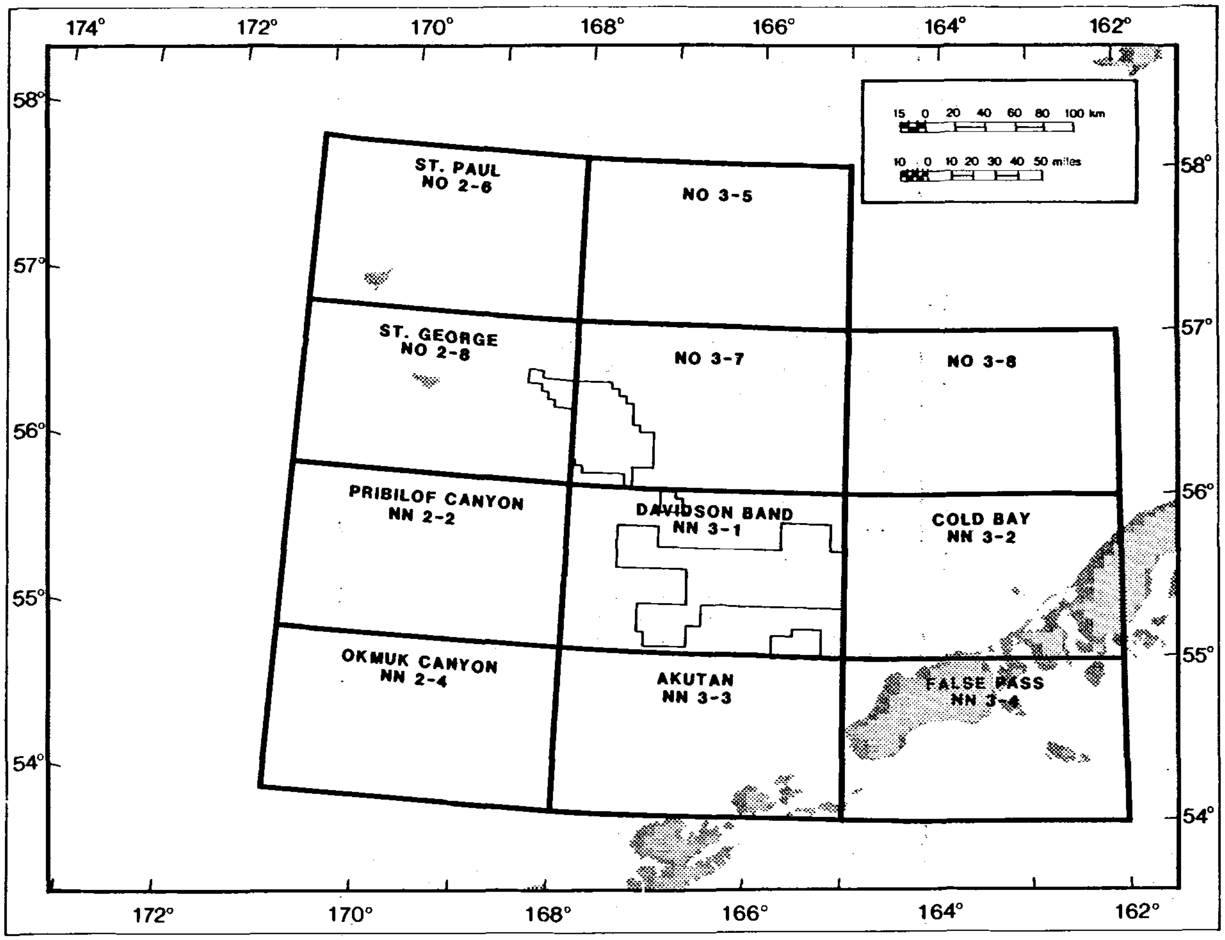

Figure 6.2. Proposed St. George Basin lease area, catch subareas, and tracts selected for further study.

These blocks generally correspond to OCSEAP survey subarea 2, which covers the Outer Shelf region between the Pribilof Islands and Unimak Island. Biomass estimates of demersal fish for subarea 2 are 1.28 million t in 1975 and 1.25 million t in 1976; these estimates are 80 percent and 92 percent, respectively, of the estimated call area biomass for those years. Catch data for 1977 (Table 6.4) confirm the biomass estimate and emphasize the importance of block Nos. 2-8, 3-7, NN3-1, and NN3-3; 77 percent of the total catch in the St. George Basin call area was taken in these four blocks. The majority of tracts selected for further study lie within blocks No. 3-7 and NN3-1. The 1977 catch in these two blocks of 181,136 t amounts to 40 percent of the St. George Basin call area catch. Thus, the area of tracts selected for further study and areas of greatest catches coincide.

6.2.2 Life Histories and Distribution

Although some information on the distribution of finfish in the St. George Basin can be obtained from catch data, more detailed information on distribution by life history stages is required to predict the effects of oil and gas development there. Life history characteristics of major finfish species of the St. George Basin are summarized in Table 6.5.

Pollock

Walleye pollock is one of the most important species in the eastern Bering Sea. They represent a large fraction of the total standing stock of demersal fishes of the region; they support the largest single-species commercial fishery in the Northern Hemisphere, and they are a significant component of the Bering Sea food web, as both prey and predator.

In the eastern Bering Sea, pollock are widely distributed over the continental shelf but are most abundant along the shelf edge. The overall distribution pattern varies with life stage, season, and year. The timing and extent of seasonal movements are highly influenced by environmental conditions (e.g., water temperature).

Walleye pollock are thought to spawn during a single period each year. In the eastern Bering Sea, the spawning period runs from the end of February through June, with a peak generally in May. It is not clear whether mature females release their eggs in one short pulse or in multiple releases over several weeks.

Walleye pollock probably spawn along the entire eastern Bering Sea shelf edge; the outer shelf

Table 6.3. Estimated biomass of commercially important species of demersal fish within the OCSEAP survey area and the St. George call area, August-October 1975, and April-June 1976.[1]

	Estimated biomass (t) Aug-Oct 1975			Estimated biomass (t) Apr-Jun 1976		
Species	**OCSEAP survey area**	**St. George call area**	**Percent in call area**	**OCSEAP survey area**	**St. George call area**	**Percent in call area**
Pollock	2,426,400	1,075,100	44.3	679,500	453,400	66.7
Pacific cod	64,500	32,200	49.9	102,400	94,000	91.8
Yellowfin sole	1,033,600	255,400	24.7	1,192,600	195,100	16.4
Rock sole	170,300	64,200	37.7	236,000	302,900	128.3[2]
Flathead sole	113,000	62,800	55.6	99,400	85,300	85.8
Alaska plaice	127,100	62,400	49.1	169,900	135,300	79.6
Greenland turbot	126,700	21,000	16.6	51,000	22,000	43.1
Arrowtooth flounder	28,000	16,100	57.5	40,300	39,900	99.0
Pacific halibut	30,600	13,100	42.8	30,900	30,400	98.4
Sablefish	—	100	—	500	500	100.0
Total	4,120,200	1,602,400	38.9	2,602,500	1,358,800	52.2

---

[1] From NMFS, October 1979

[2] The larger biomass derived for the lease area probably results from high variability in catch rates for rock sole encountered in the survey.

Table 6.4. Fish catch, in metric tons, of all species by all nations during 1977 according to subarea (see Fig. 6-2) and months in the St. George Basin (data from NMFS 1979).

Month	Area 1 (NN 2-8)	Area 2 (NN 2-6)	Area 3 (NN 2-4)	Area 4 (NN 2-2)	Area 5 (NO 2-8(	Area 6 (NO 2-6)	Area 7 (NO 2-4)	Area 8 (NN 3-5)	Area 9 (NN 3-3)	Area 10 (NN 3-1)	Area 11 (NO 3-7)	Area 12 (NO 3-5)	Area 13 (NO 3-3)	All Areas
1	129	0	0	495	2,279	0	0	0	0	8	6,504	0	0	9,415
2	4	12	0	356	764	0	0	0	0	30	3,210	7	0	4,303
3	100	0	0	102	357	0	0	6	0	0	7	0	0	572
4	69	3	0	643	271	5	0	14	0	0	71	25	0	1,101
5	578	104	0	323	127	17	177	67	0	0	5	3	0	1,401
6	1,003	415	6	7,613	17,219	108	0	46	5,542	3,279	7,991	0	0	43,222
7	841	135	4	7,641	9,938	0	0	34	23,078	32,294	5,464	6	0	79,435
8	815	237	20	8,277	3,840	0	0	1,127	34,153	14,302	8,146	160	0	71,077
9	626	56	0	904	1,622	8	9	10,144	29,670	45,400	5,772	860	7,510	102,661
10	242	18	0	5,211	2,532	24	18	9,134	23,275	31,100	3,838	7,962	2,634	85,988
11	63	289	313	4,015	1,021	25	22	5,582	9,114	6,233	198	8,968	0	35,943
12	151	63	0	1,609	2,287	0	0	4,294	339	64	7,140	2,058	0	18,005
Annual	4,621	1,332	343	37,189	42,257	187	226	30,448	125,171	132,790	40,346	20,049	10,144	453,103

Table 6.5. Summary of life history characteristics of major finfish species inhabiting the St. George Basin.

Species	Spawning period	Spawning location	Eggs	Larvae	Juvenile	Migration	Maximum Age	Average age of maturity in females and mean fecundity in the Bering Sea
Pacific cod	January-May	Slope in 100-200 m can occur in 20-70 m	Demersal 150-200 m, January-May	Pelagic, 25-150 m most abundant 75-100 m, February-August	Pelagic	Winter over shelf break at depths > 200 m, move E to shelf in summer	12	4 1.2×10^6
Sablefish	December-April	Eastern slope in 250-700 m	Pelagic, December-April	Pelagic, February-September	Pelagic in surface waters near shore to 150 m	Tend to remain year around at depths > 200 m	20	7 4×10^5
Greenland turbot	October-December	Slope, 100 m	Demersal, October-December	Pelagic, October-April	Pelagic, move south and down slope tending to cooler water pockets	Winter on slope and shelf, shelf edge from 30-900 m. Moves to shallower waters in summer	25	13-14 2.5×10^4
Rock sole	March-June	Shelf and slope, 70-140 m	Demersal, March-June	Pelagic, March-September	Demersal, nearshore	Winter on outer shelf, move to inner shelf, and near-shore in summer	16	5-7 2×10^5
Flathead sole	March-June	Shelf and slope, 160-200 m	Demersal, March-June	Pelagic, near surface March-June	Pelagic, March-September	Winter at depth of 70-400 m. Summer at 20-180 m. Perhaps diel movement to surface at night	21	6 5×10^4
Pacific herring	Late April-June	Intertidal zone in coastal lagoons, bays, and rocky headlands	Adhere to intertidal vegetation April-June	Pelagic, June-August	Pelagic, move offshore in late summer	Adults move seaward from July to October. Migrate back to coastal waters in March	15	2-6 $26\text{-}70 \times 10^3$
Pollock	February-June	Shelf edge. Major location west and northwest of Unimak Island	Pelagic, near surface February-June	Pelagic, near surface 2 to 3 months, March-September	Pelagic, over shelf. Diel movement to surface at night	From deep water in winter to shelf in summer	17	3 1×10^5
Yellowfin sole	June-September	Southeast and northwest of Nunivak Island	Pelagic, July-September	Pelagic, July-January	Demersal, coastal waters of Alaska Peninsula	Winter in deep water. Move to shallow waters of Bristol Bay flats in summer	17	9 8×10^5
Halibut	November-February	200-500 m	Bathypelagic, 84-425 m November-February	Pelagic, rise to shallow water along north shore of Alaska Peninsula December-April	Demersal. Along north shore of Alaska Peninsula	Winter along shelf edge. Move to shallow waters of Bristol Bay in summer	42	12 $1\text{-}2 \times 10^6$
Salmon	Summer-fall	Coastal rivers and streams	Coastal rivers and streams	Coastal rivers and streams	Pelagic, upper 5 m June-October	Juveniles sea-ward in spring and summer. Adults to coastal rivers mid-May to September through upper 30 m of ocean water column	7	2-7 $2\text{-}4 \times 10^3$

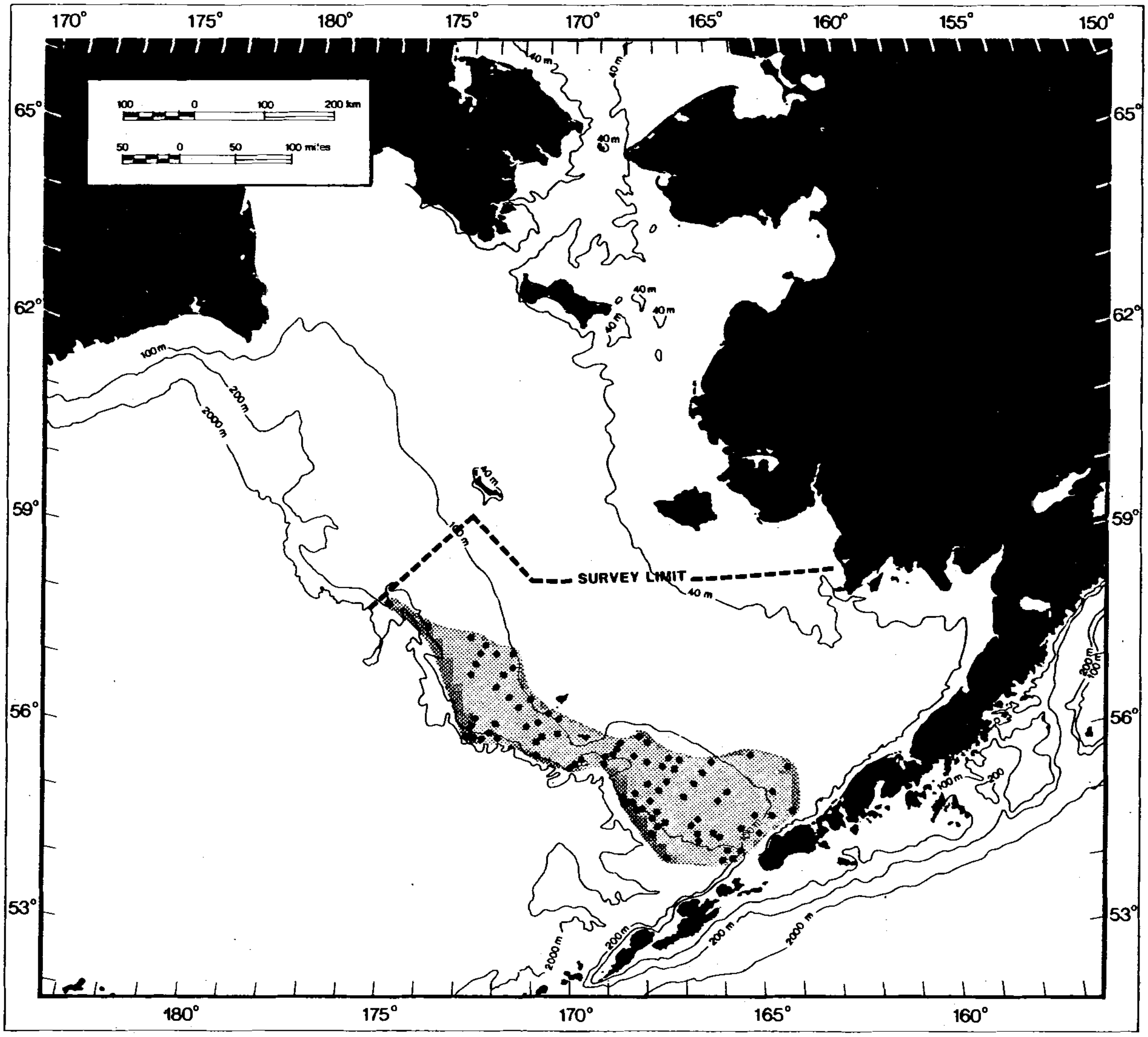

Figure 6.3. Locations of individuals observed in spawning condition during NMFS surveys, April-June 1976. Dots show exact positions, shading indicates inferred range of spawning activities (from Smith, 1981).

region just west and northwest of Unimak Island is a major spawning area. Highest concentrations of pollock eggs and larvae have been reported along the Outer Continental Shelf between the Pribilof Islands and the Alaska Peninsula. An example of this distribution is shown in Fig. 6.3. Schools of spawning (and prespawning) fish move high into the water column and form dense midwater layers. Eggs are broadcast into the water and fertilized externally. The fertilized eggs (and, later, larvae) are pelagic. The length of incubation varies with water temperature (10 days at 10°C). Larvae may take two or three months to develop into juveniles.

Pollock eggs and larvae inhabit near-surface waters. Soviet investigators have found eggs and larvae over much of the Outer Continental Shelf northward to St. Matthew Island, but principally in St. George Basin (Fig. 6.4).

Unlike eggs and larvae, pollock juveniles rise to the surface at night to feed and descend to bottom or midwater depths during the day. Areal distribution of young of the year is centered west and northwest of the Pribilof Islands (Smith, 1981). One-year-olds are distributed over nearly the entire eastern Bering Sea continental shelf in summer.

Over the continental shelf, adults are semidemersal, forming schools near the bottom during the day and dispersing up into the water column at night. Along the Outer Continental Shelf and slope, pollock form schools that may exceed 50 km in length and have a mean density of up to 9 t/ha.

In general, eastern Bering Sea pollock adults migrate to deep water during winter, to Outer Shelf spawning sites in spring, and then to extensive areas of the outer and central continental shelf to feed during summer. Two migratory routes from wintering and spawning sites to summer feeding grounds have been postulated. One is based on the premise that one stock of

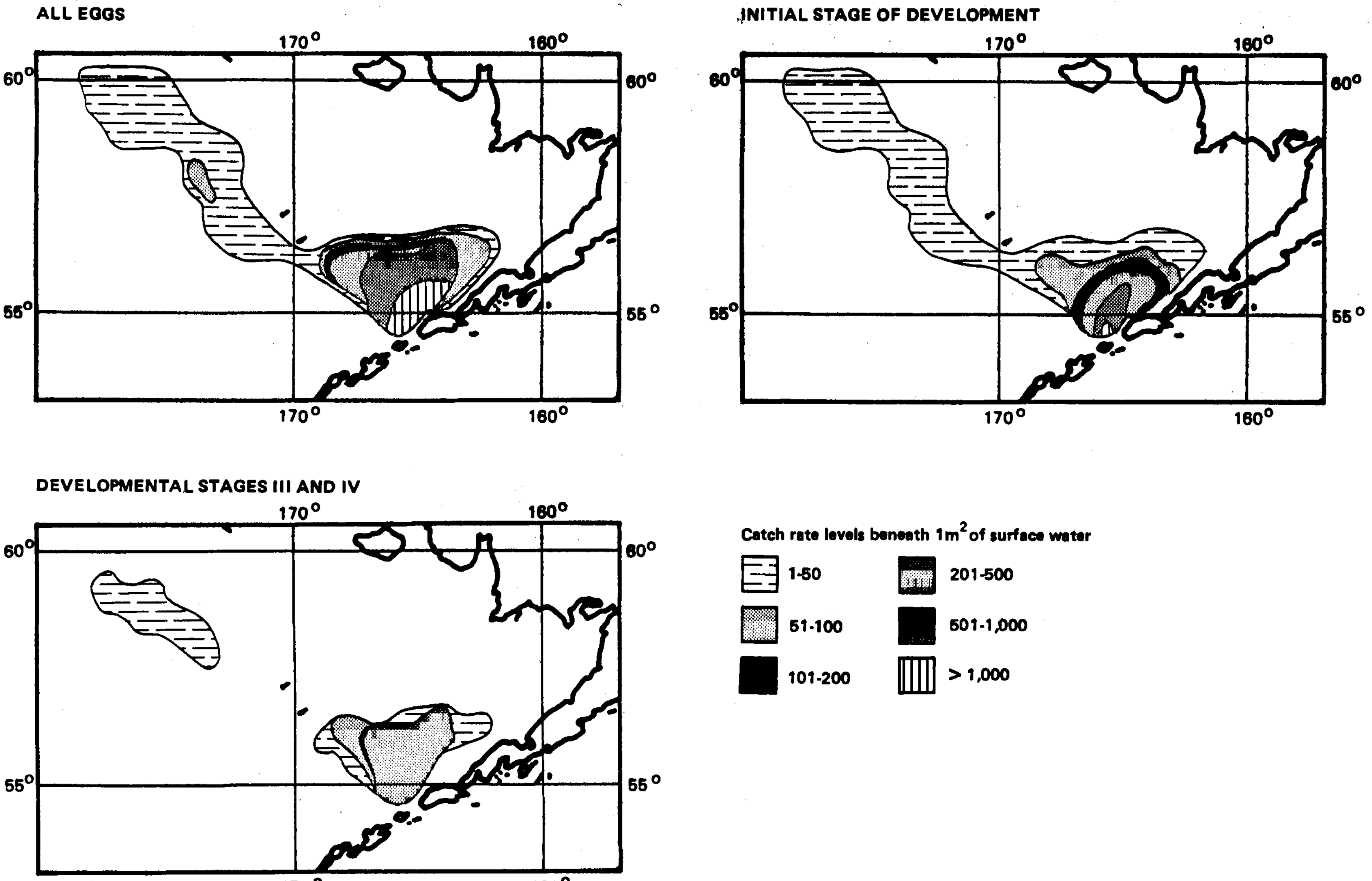

Figure 6.4. Distribution of pollock eggs in the eastern Bering Sea in March-May 1965 (from Serobaba, 1967)

pollock exists in the eastern Bering Sea, and the other is based on the assumption that two stocks exist.

According to the single-stock assumption, the major spawning area lies in St. George Basin; fish from this area move both northwestward and northeastward in the spring. The greatest movement of fish is northwestward, and by summer and early fall a major concentration of foraging fish is found north of the Pribilof Islands and west and northwest of St. Matthew Island. Those fish that move northeast to the central shelf feed in this region during the summer, whereas others continue their migrations as far as St. Matthew Island. When shelf waters cool in the fall, pollock return to the wintering sites south of the Pribilof Islands.

According to the two-stock theory, separate stocks north and south of the Pribilof Islands have their own wintering, spawning, and foraging areas. A comparison of age structures of commercial catches from several years, however, indicates that pollock harvested from northwest and southeast of the Pribilof Islands (and the remainder of the eastern Bering Sea) are from a single stock.

NMFS research vessel surveys of the eastern Bering Sea continental shelf have also found differences in the distribution of pollock of different ages. During summer, one-year-old fish are widely dispersed, overlapping most of the adult range and also extending far inshore into shallow Inner Shelf areas from Bristol Bay northward (at least in some years) into the southeastern Chukchi Sea. Pollock two years old and older are found mainly in deeper waters of the Central and Outer Shelf. This age (and size) distribution, however, varies substantially from year to year.

Yellowfin Sole

Yellowfin sole is a major component of the ichthyofauna in the eastern Bering Sea. In a major survey of the eastern Bering Sea continental shelf in 1975, yellowfin sole represented 64 percent of the total flounder biomass and 23 percent of the total fish biomass. Data from a more comprehensive survey in 1979 confirmed these proportions: yellowfin sole represented 63 percent of the total flounder biomass and 22 percent of the total fish biomass.

Yellowfin sole stocks declined substantially in the early years of the foreign fishery when this species was the primary target species of Japanese and U.S.S.R. distant-water fisheries. This decline is believed to have been caused by overfishing between 1959 and 1962, when catches averaged 400,000 t annually. Abundance continued to decline through the 1960's, but since 1972 they have shown a remarkable recovery. Yellowfin sole today are thought to be as numerous as the population was before the fishing began.

Information on location and timing of spawning yellowfin sole comes primarily from eggs and larvae caught during U.S.S.R. plankton surveys (Fig. 6.5); spawning adults have rarely been observed. Spawning begins in early July and probably ends in September. Eggs have been observed over a broad area of the eastern Bering Sea shelf from off Bristol Bay to St. Lawrence Island. Egg densities indicate that spawning is heaviest southeast and northwest of Nunivak Island in nearshore waters. The overall distribution of eggs, however, suggests that yellowfin sole may spawn in water from 15 to 75 m deep.

Yellowfin sole eggs are pelagic. They hatch in about four days at 13°C, but it is not known when metamorphosis to the juvenile stage takes place. Partially metamorphosed young, about 1.7 cm long, have been found in plankton hauls; since larger juveniles have not been found during plankton surveys, it is assumed that they have descended to the bottom to live.

The locations of yellowfin sole larvae, taken from plankton surveys, are illustrated in Fig. 6.6. These catches were made during summer and fall and usually consisted of fewer than 20 larvae per station. The data indicate that larvae were distributed in the inshore shallow part of the continental shelf at depths of less than 50 m.

The young juvenile fish are thought to occupy coastal waters. They are first observed in demersal trawl surveys in nearshore waters when they are 5-10 cm long and two to three years old. These age groups have been observed in small numbers off Kuskokwim Bay, in Bristol Bay, and along the Alaska Peninsula. The juveniles gradually disperse to more offshore waters; by the time they are 16-20 cm long and five to eight years old, they occupy much the same waters as the larger fish.

Yellowfin sole form dense concentrations on the Outer Continental Shelf of the eastern Bering Sea in winter. The largest of these concentrations is found near Unimak Island. Although the area was sampled in April, it is believed that this distribution is like that in winter because the spring of 1976 was unusually cold. The second largest wintering concentration is located west of the Probilof Islands. A third, smaller concentration may be located either south or east of St. George Island.

Extensive tagging of yellowfin sole by Japanese scientists illustrates that these concentrations move inshore during spring and that the Unimak and St. George Island concentrations remain relatively separate throughout the year. The Unimak Island concentration is found off Bristol Bay

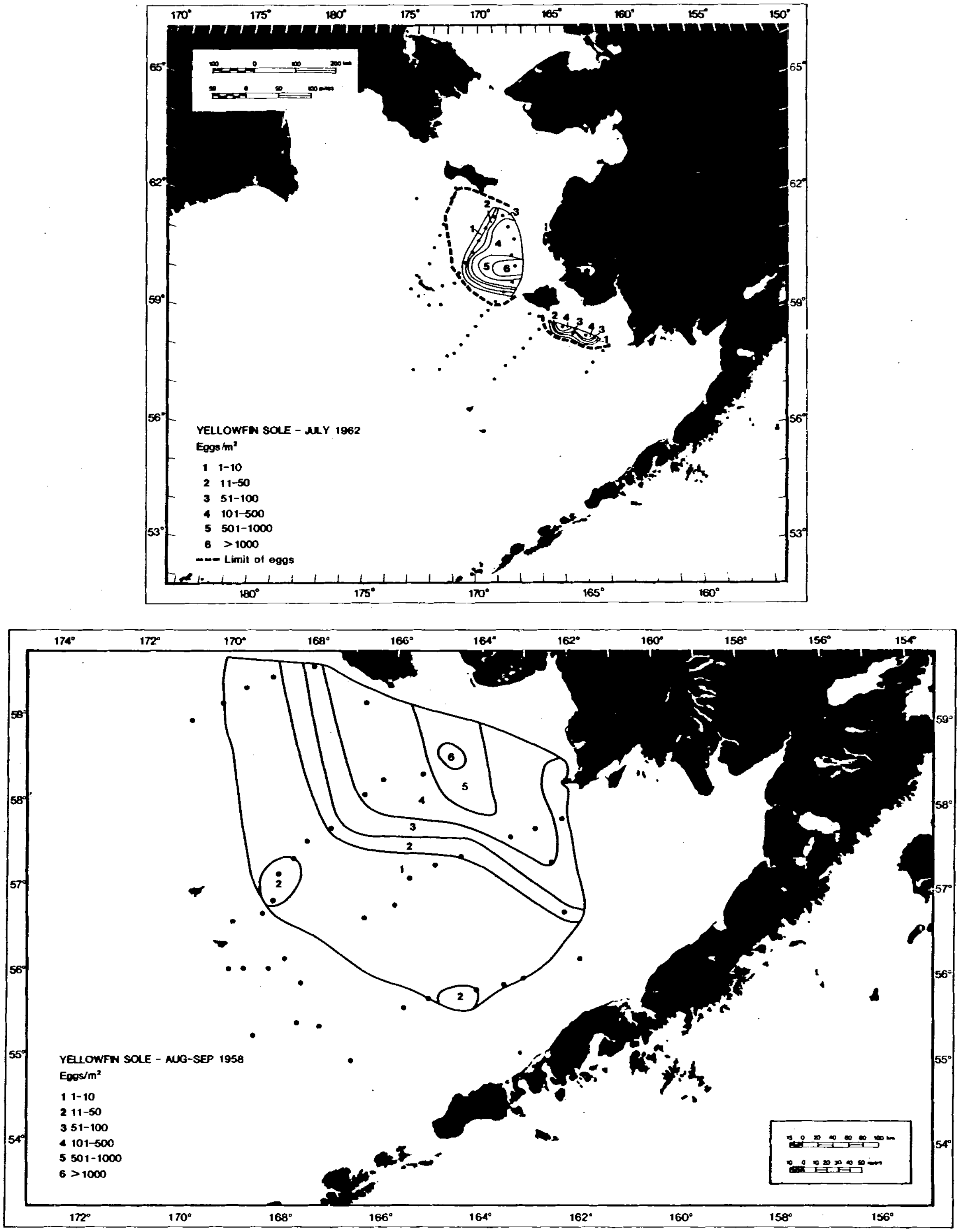

Figure 6.5. Distribution of yellowfin sole eggs as shown by plankton surveys in July 1962 and in August — early September 1958 (from Bakkala, 1981).

northwestward to off Kuskokwim Bay. The St. George group is found near Nunivak Island.

The 1976 spring OCSEAP survey data, when examined by month, demonstrate routes of inshore migrations. By May, the large concentration located north of Unimak Island in April had moved eastward toward Bristol Bay. By June this concentration had moved farther inshore and was apparently also dispersing northward to waters usually occupied in summer.

Yellowfin sole would be most vulnerable to oil and gas contamination from the St. George Basin during winter and spring, when they are concentrated on the Outer Shelf. These concentrations, particularly the concentrations that form south or east of St. George Island and north of Unimak

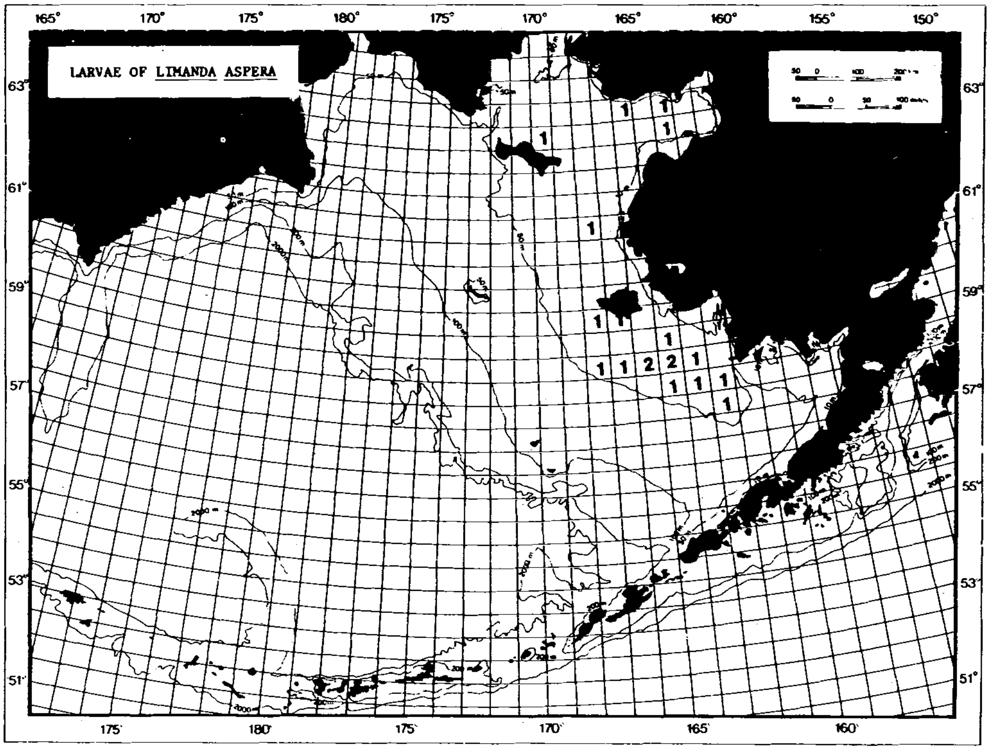

Figure 6.6. Locations of catches of larvae of yellowfin sole during plankton surveys, as summarized by Waldron (1981).

Island, may be located in or adjacent to some lease sites. They are at times extremely dense. During an April 1976 survey of the large concentration north of Unimak Island, the NWAFC caught an estimated 23,000-32,000 kg of yellowfin sole per 30-minute tow. Concentrations of this magnitude and density probably represent substantial portions of the total population. Oil spills in areas of heavy concentrations could seriously harm the yellowfin sole population.

Pacific Salmon

The marine life of Pacific salmon may be divided into three phases: seaward migration, ocean life, and spawning migration. Seasonal timing and length of each phase is species- and race-specific and also fluctuates because of environmental variations. Salmon in each of these three phases occupy waters of the St. George Basin.

The seaward migrations of Pacific salmon begin in the spring when juveniles leave their rivers of origin to enter the Bering Sea. An estimated 85.7 percent of the total salmon produced in the rivers and streams of land masses bordering the Bering Sea shelf are from Bristol Bay and the north side of the Alaska Peninsula. Juveniles, fish with less than one year of ocean life, leaving these areas typically move along the southeast side of Bristol Bay and the north side of the Alaska Peninsula in a belt up to 110 km offshore; within this belt they are most abundant from 18 km to 55 km offshore. They occupy the upper 5 m of the water column, with sockeye congregating in small schools in the upper 2 m, chinook somewhat deeper. Between early summer and late fall, the fish grow rapidly and ultimately leave nearshore waters for more pelagic regions. Timing of this offshore movement is species-specific and varies according to annual differences of time of entry into the Bering Sea. In years when ice breaks up and the water warms early, salmon move earlier in the season than when these conditions occur later. Further, the more rapidly juveniles grow, the sooner they move offshore.

Juveniles are present in the St. George Basin from mid-June at least through September. Surveys have not been made there after late September, but juveniles probably are most abundant during September and October. Chinook enter the area first in mid- to late June, followed by sockeye (July), chum (August), and pinks and coho (September and October).

While salmon are dispersed throughout the Bering Sea and North Pacific Ocean they grow rapidly and attain sexual maturity. This period of ocean life may last from one to six years, depending upon species and growing conditions. More than one generation of sockeye, chinook, chum, and coho are present in the Bering Sea during ocean life. Immature and maturing salmon of different races and ocean ages and from different geographic areas may, depending upon the season, become segregated from or intermixed with one another.

Immature salmon, those one year or more younger than those of spawning age, have been taken incidentally by Japanese trawlers in the eastern Bering Sea. The catch data have been summarized for the area 165°W and 169°W and between 55°N and 57°N which encompasses the St. George Basin. Although no exceptionally large numbers of salmon were taken (1977: 14,777, 1978: 3,852, and 1979: 25,889) the data indicate their year-round presence. Most of the catch was taken along the 200-m isobath, with the greatest numbers taken in the fall and winter of 1977 and 1979 and spring and early summer of 1978.

Salmonids en route from offshore grounds to natal streams segregate into units called races, bound for particular locations and regimes of timing. An oil spill, although affecting only a small portion of the population, could devastate one or more of these races. Despite environmental fluctuations, such as annual variation in sea temperatures, individual races arrive on the spawning grounds at about the same time every year. Adults tend to remain offshore, in the upper 30 m of the water column, until they approach their home streams.

Migrating adults are present in the St. George Basin from mid-May to mid-September. Maturing chinook enter this region earliest, followed, in order, by sockeye, summer chum, pink, fall chum, and coho.

Sockeye. Sockeyes are the most abundant salmon species during the spawning migrations in the southeastern Bering Sea shelf area. They are concentrated in two bands offshore, north and south of the Pribilof Islands. They are most numerous in the southern band, which traverses much of the St. George Basin. These fish are bound primarily for rivers that empty into Bristol Bay and those on the north side of the Alaska Peninsula. Sockeye salmon bound for rivers on the north side of Bristol Bay (i.e., those rivers entering Nushagak and Togiak and Kuskokwim Bays) are apparently more numerous in the northern band.

Chum. Chum salmon are more widely dispersed throughout the Bering Sea shelf during the spawning migration than sockeye salmon, probably because chum salmon spawn in many more streams from Bristol Bay north to Kotzebue Sound and along the north side of the Alaska Peninsula. Like sockeye, chum salmon are heavily concentrated in two bands, one north and the other south of the Pribilof Islands. The southern band traverses the St. George Basin and includes fish bound primarily for the rivers of Bristol and Kuskokwim Bays and the north side of the Alaska Peninsula.

Pink. Pink salmon have been caught throughout the offshore areas of the Bering Sea shelf during the spawning migration. Like sockeye and chum, pink salmon traversing the Bering Sea shelf during spawning migration are concentrated in two bands north and south of the Pribilof Islands. This distribution is apparently related to the size of pink salmon populations migrating to specific streams or river systems and the geographic location of these systems. Pink salmon migrating south of the Pribilof Islands through the St. George Basin are bound primarily for rivers entering Kuskokwim and Bristol Bays and streams along the north side of the Alaska Peninsula.

Chinook. Maturing chinook salmon have been caught throughout the Bering Sea shelf during spawning migrations, but the direction in which they are traveling has not been ascertained. If chinook salmon respond similarly to the same environmental cues as other salmon during spawning migration, they probably follow similar routes.

Coho. Coho salmon have been caught at only a few locations on the Bering Sea shelf, primarily because there has been no exploratory fishing from late July to late August, when they probably are most abundant. They have been caught most frequently on the southeastern Bering Sea shelf where research fishing has concentrated on the sockeye salmon bound for the rivers and streams tributary to the Alaska Peninsula and Bristol Bay. Although coho salmon have not been caught within the St. George Basin, they probably migrate through this region if they respond to the same environmental cues as other salmon.

Halibut

The Pacific halibut is an important fish species of St. George Basin and the Bering Sea. This stock supported an intensive fishery for a few years but this exploitation coupled with large incidental catches by foreign trawl fleets caused a decline in abundance. The fishery originated on the shelf edge between Unimak and Pribilof Islands, adjacent to but in slightly deeper water than the tracts now considered for further study. The stock is considered depleted, and a nursery area, closed to commercial fishing, has been established. It is bounded by a line from Cape Sarichef to 57°15′N, 170°W, and thence to Cape Newenham. The nursery area encompasses most of the tracts being considered for further study. Currently, fishing for halibut takes place primarily along the Aleutian Islands as far west as Adak. A small day-boat long-line fishery is now being established by local residents in waters adjacent to the Pribilof Islands.

The water temperature near the bottom influences the distribution of halibut within the Bering Sea. Halibut are usually found in waters of 2-8°C, although they can tolerate colder temperatures for short periods. This temperature preference forces halibut to vacate the shallow flat area of Bristol Bay during the winter when water temperatures drop to near 0°C. At this time, the fish concentrate in deeper water just beyond the continental shelf near the lease sites. With the return of warmer weather, the fish move back to the flats to feed. The rate and extent of this movement is governed by the rate of warming. The larger fish may travel great distances; adults have been reported as far north as the Bering Strait in September. Halibut migrate annually across the St. George Basin.

Halibut in the Bering Sea are believed to spawn between December and February during their migration to deeper, warmer water beyond the shelf break. Spawning takes place at water depths of 200-500 m. Eggs are bathypelagic; in the Gulf of Alaska, eggs and early larval stages were found at depths from 85 m to 425 m. Older larvae rise to the surface and move into shallow water; by June most larvae were taken in waters averaging 12 m in depth. The same sequence probably occurs in the Bering Sea. One-year-old fish have been regularly taken in surveys along the north shore of the Alaska Peninsula.

Tag returns from halibut released in the Bering Sea indicate that juveniles remain within the area. Adults, particularly larger fish, appear to migrate into the Pacific Ocean and probably remain there.

Other Commercial Species

Other important commercial fish species in the St. George Basin are Pacific cod, sablefish, Greenland turbot, rock sole, flathead sole, and Pacific herring. Their life history and behavior are briefly described below.

Pacific Cod. The distribution of this fish along the margin of the continental shelf is similar to that of the pollock. It occupies shallower water than pollock, however, and major concentrations occur in the eastern and central region of the Bering Sea at depths of from less than 80 m to 550 m. Migratory habits are unclear. It is believed that cod winter in deep water over the shelf break and shallower regions of depths greater than 200 m, then migrate east in summer to the continental shelf, where they form local populations.

Spawning probably occurs from January to May. Eggs are demersal and have been found at depths of 150-200 m. The pelagic larvae have been found at depths from 25-150 m and appear to be most abundant between 75 and 100 m. Juveniles, age one to three years, appear to occupy shallow waters of the shelf. Pacific cod reach a maximum age of 12 years. Average age of females at maturity is four years.

Sablefish. The sablefish lives mainly on the continental slope. Although schools of sablefish are geographically widely distributed, the exploitable biomass largely occurs at depths of 150-1,200 m and in the central part of its range in the Gulf of Alaska. About 13 percent of the estimated exploitable biomass is located in the Bering Sea region.

Tagging studies indicate that some sablefish migrate extensively. Interchange of fish probably takes place between the Bering Sea, the Gulf of Alaska, and the Pacific Northwest. Sablefish also occupy a wide range of depths: the pelagic eggs and larvae in surface waters, juveniles in surface and inshore waters down about 150 m, and adults from about 150 to 1,200 m.

Daily vertical movements of sablefish in the eastern Bering Sea have been observed. During the day, sablefish are in the upper water layers feeding on pelagic and off-bottom prey; at night, they lie near the sea bottom and prey on bottom-dwelling fish and invertebrates. These diurnal movements are opposite to those of most other demersal species which descend to the bottom during the day.

Sablefish are believed to spawn between December and April at depths of 250-700 m on the continental slope west of St. George Basin. The mechanisms controlling the distribution of these eggs and subsequent larval forms are not known, but one-year-old sablefish appear annually in shallow coastal waters. As they approach maturity, young sablefish move seaward and become demersal. By the fifth year about half the males are mature, but females require an average of seven years to reach maturity. Fish up to 12 years old are common, and an occasional fish may reach 20 years.

Greenland Turbot. This species is widely distributed over the continental shelf and slope of the eastern Bering Sea; juveniles are found mainly in shelf waters (< 200 m) and adults in slope waters (> 200 m). Spawning takes place from October to December on the continental shelf and slope at depths greater than 100 m. Eggs are bathypelagic and develop in deeper waters; larvae rise to shallower waters of 30-130 m. Greenland turbot live as long as 25 years; females mature at an average age of 13-14 years.

Rock Sole. Rock sole are found mainly on the eastern Bering Sea shelf, often in association with Greenland turbot, flathead sole, pollock, cod, and Tanner crab. During spring, summer, and fall they occur on the shelf, usually at depths shallower than 100 m, in four main areas: (1) directly east of the Pribilof Islands, (2) at various locations in Bristol Bay, (3) north of Unimak Island, and (4) south of Nunivak Island. Wintering grounds are east of the shelf break. Rock sole spawn from March to June at depths of 70-140 m on the shelf and slope. Eggs are demersal and adhesive; larvae are pelagic. Young rock sole (ages two and three years) were found almost exclusively in outer Bristol Bay and near the Pribilof Islands during August-October 1975. These may be important rearing areas. Rock sole may live to be 16 years old; the average age of females at maturity is five to seven years.

Flathead Sole. Flathead sole are found mainly on the eastern Bering Sea shelf in somewhat deeper water than yellowfin and rock sole. Adults spend the fall and winter in deep water of the outer shelf and upper slope at depths of 70-400 m. In the spring, they migrate eastward to shallower waters of the shelf (40-180 m), and during the summer they are widely dispersed over the outer shelf area from Unimak Island northwest to the central Bering Sea. In addition to geographic and bathymetric seasonal migrations, flathead sole may migrate vertically between dusk and dawn.

Flathead sole spawn at depths of 100-200 m from March to June. Eggs are demersal and may be transported from the spawning grounds to nearshore waters (30 m or less) or to deeper offshore waters. Larvae are pelagic and float near the surface until they metamorphose to the adult form and descend to the seabed. This species lives to a maximum age of 21 years; the average age of females at maturity is six years.

Pacific Herring. The Pacific herring is a widely distributed species that exhibits strong schooling and migratory behavior. Herring spend about eight months in the open sea; in spring, adults migrate across the St. George Basin to the coast to spawn, and in fall, juveniles and adults migrate seaward to wintering grounds northwest of the Probilof Islands.

Pacific herring spawn from late April to June in intertidal zones of bays, lagoons, and rocky headlands along the north shore of the Alaska Peninsula, Bristol Bay, and farther north. The adhesive eggs are deposited on eelgrass and seaweeds. Larvae drift pelagically for six to eight weeks and then metamorphose to juveniles. Juveniles form small schools and gradually move offshore. By early fall, they have formed dense schools, and by late fall, most of these schools move into deeper offshore waters to the wintering grounds. Herring reach a maximum age of 15 years; females reach maturity at two to six years.

6.3 RESOURCE USERS

Aside from the commercial fisheries, and, of course, predation among finfish themselves, the major consumers of finfish are (1) villagers along the Aleutian Islands, the north shore of the Alaska Peninsula and, in the case of salmon, Bristol Bay and farther north to the Yukon River and Norton and Kotzebue sounds, (2) marine mammals, and (3) marine birds.

6.3.1. Subsistence Fisheries

Residents of villages adjacent to the Bering sea and its drainages and St. George Basin all rely to some degree on subsistence fishing to supplement their relatively new cash economy. The outlying villages of Atka and Nikolski depend more on subsistence fishing than other villages. Both have few outside visitors or opportunities to make money, and they are far from St. George Basin. The communities of Akutan, Unalaska, False Pass, Nelson Lagoon, Port Moller, and those in the Pribilof Islands depend heavily on marine industries and a cash economy. Although subsistence use permits are required, except by residents of Atka and Nikolski, they often are not returned, so the amount of fish taken by subsistence users is not known.

The most important subsistence fishes are salmon and halibut. Other species currently taken are Pacific cod, Atka mackeral, Arctic char, and rock greenling. Species taken in the past (and perhaps currently when available) include herring, capelin, and sand lance. Most salmon migrating through the St. George Basin are bound for Bristol Bay, where they are heavily fished by local residents. People living along the coast and streams of the eastern Bering Sea take more salmon in subsistence fisheries than those living elsewhere in Alaska; these salmon may also pass through the St. George Basin. Similarly, herring that pass through or near the proposed lease area during spring and fall migrations are an important subsistence resource for coastal villages from Bristol Bay to Norton Sound.

6.3.2 Marine Mammals and Birds

During the summer, the Bering Sea contains more marine mammals per unit area than any other ocean area and more marine birds than the rest of the Northern Hemisphere. Marine mammals and birds are apex predators, and they consume about 3 million t of finfish a year from the Bering Sea, about twice the total catch by the fisheries of all nations (Laevastu and Favorite, 1981). Marine mammals consume about 2.3 million t of finfish per year (Workshop III), mainly pollock, capelin, and herring. Marine birds consume 500,000-750,000 t of finfish per year; again, pollock, herring, and capelin are the principal species taken (Workshop V).

6.4 AT-SEA CONFLICTS BETWEEN THE FISHING AND PETROLEUM INDUSTRIES

At present, the major activity in St. George Basin is commercial fishing. With oil and gas development in this area, conflict between the commercial fishing and petroleum industries is likely. Oil and gas development could affect commercial fishing without affecting the resource itself by (1) preemption of fishing grounds, (2) loss of or damage to gear, (3) contamination of gear or catch, or (4) competition for port facilities.

6.4.1. Preemption of Fishing Grounds

Fishing grounds could be lost by siting of offshore drilling rigs and platforms, offshore loading facilities, pipelines; by prohibiting fishing in safety zones around these structures; and, at least temporarily, by an oil spill. The extent of loss would depend on the number and locations of structures and the size of the safety zones required; these would persist through the life of the field. Fishermen would probably be unwilling to enter an oil spill area for fear of fouling gear or contaminating their catch.

6.4.2 Loss of or Damage to Gear

Trawl gear could be fouled on seafloor completions, unburied pipelines, exposed wellheads, mooring chains and anchors, or large debris left on the seabed. Vessels could overrun set gear, especially at night or during periods of low visibility. Oil from a spill could coat gear with oil, necessitating expensive cleaning, at the very least.

6.4.3. Contamination of Catch

Oil-coated fishing gear would foul the catch, which might have to be abandoned. At-sea processors or crabbers who require circulating seawater intake and circulation might take on oil-polluted waters that could render the catch unsalable for human consumption.

6.4.4 Competition for Port Facilities

Unalaska will probably be a major support base for petroleum industry operation in the St. George Basin. This port currently leads the nation in value of fish landings. Dock space, warehouse and supply yards, and living accommodations and services could become less available and more expensive.

6.5 EFFECTS OF OIL ON FISH

Offshore oil and gas development in the St. George Basin will inevitably result in the escape of petroleum hydrocarbons into this productive environment. Spilled hydrocarbons, at some level, can seriously damage the finfish resources of this area. Many factors determine the degree and duration of damage from a spill. These include (1) the chemical composition and physical properties of the petroleum (crude oils from different origins vary widely), (2) size and duration of the spill, (3) prevailing environmental conditions, (4) species and developmental stages of fish exposed, and (5) time and geographic location of the spill.

The acute toxicity of the various fractions of crude oil has been attributed primarily to the low-molecular-weight aromatic hydrocarbons such as benzene, alkylated benzenes, and xylenes, some of the medium- and high-molecular-weight aromatics, and certain phenolic components such as the naphthenic acids (Clark and Finley, 1977). Refined oils (i.e., gas, diesels) are considered to be more toxic than crudes because they contain larger aromatic fractions and are less viscous and thus have a greater potential for rapid spreading and more complete mixing. Acute or chronic discharges of refined products may therefore be more harmful to marine organisms than those of crude oils. When oil is spilled at sea, it immediately weathers; aromatic fractions are removed rapidly through evaporation and dissolution. Although temperature can affect the persistence of toxicity, the aromatic fractions of fresh crude spilled in subarctic waters of the southeastern Bering Sea would probably be weathered out within 10-12 days.

High mortality of fishes may occur almost immediately or within a short time after a spill. Fish may die by coating and asphyxiation, contact poisoning, or exposure to water-soluble toxic components of oil at some distance in time and space from the accident (Malins et al., 1981). Soluble aromatic hydrocarbons can be lethal to adults at concentrations of 1-100 ppm, and to the more sensitive larval stages at 0.1-1 ppm. Experimental results of static and continuous-flow bioassays using the seawater-soluble fraction of Cook Inlet crude oil suggest that pelagic fish such as the salmonids and pollock are more sensitive than benthic species such as the flounders and sculpins (Rice et al., 1979) Median tolerance limits (96-h TLM's) or the concentration that kills 50 percent for total aromatics, were 1-3 ppm for herring, sockeye and pink salmons, and pollock. The 96-h TLM's of total aromatics for starry flounders and great sculpins were > 5.34 and 3.96 ppm, respectively. Fish respond quickly to oil exposure. The 96-h TLM's of fish exposed to seawater-soluble fractions show little difference by species after two to four days; therefore additional deaths several days after a spill are unlikely. The long-term effects of chronic exposures, however, are largely unknown.

Much research has been done on the effects of oil in seawater on fish. Acute toxicity bioassays have provided information on the ranges of the seawater-soluble fractions (SWSF) of several oils (e.g., Prudhoe Bay crude, Cook Inlet crude, and others) needed to kill test fishes. Experimental

Table 6.6. Effects studies performed on flatfish, semidemersal, and pelagic fishes occurring in the St. George Basin or on similar species.

		Life stages at which effects studies have been performed for St. George similar fishes			
Species group	**Species in St. George Basin**	**Eggs**	**Larvae**	**Juveniles**	**Adults**
Flatfish	Rock, flathead and yellowfin sole; halibut, greenland turbot	English sole Sand sole Plaice[1] Flounder[2]	English sole Sand sole Black sea flounder	English sole	Starry flounder Rock sole Winter flounder
Semidemersal	Pacific cod Sablefish Pollock	Atlantic cod	Atlantic cod		Pollock Saffron cod[3] Arctic cod
Pelagic	Pink salmon Chum Coho Sockeye Chinook Pacific herring	Pinks Coho Pacific herring Surf smelt[4]	Pinks Coho Pacific herring	Pinks Chum Coho Sockeye Chinook Dolly Varden[5] Arctic char[6]	Coho Chinook Capelin Pacific herring Pacific sand lance[7]

[1] *Pleuronectes* sp.

[2] *Platichthys* sp.

[3] Acute toxicity measuring total paraffins

[4] *Hypomesus pretiosus*

[5] *Salvelinus malma*

[6] *Salvelinus alpinus*

[7] *Ammodytes hexapterus*

results suggest that the possibility of reaching and sustaining lethal concentrations of oil in the open ocean after a spill is remote. Mixing and dilution of oil and seawater would rapidly reduce hydrocarbon concentrations from levels that are most acutely toxic. Fish unable to avoid the oil may suffer from numerous sublethal and delayed effects. Laboratory and field studies have shown that such low-level exposures cause changes in the behavior, physiology, chemistry, and pathology of test animals.

Acute toxicity and sublethal effects studies have not been undertaken for many of the major finfish species of the St. George Basin and southeast Bering Sea; thus results of effects studies on similar species have been used to predict the probable effects of a spill in this region, (Table 6.6). The results of experimental effects of oil on fish have been summarized for flatfish (flounders), semidemersals (cods and sablefish), and pelagic (salmon and herring) species. Except for tests on pink salmon, Arctic cod, and sculpin, acute toxicity bioassays have been conducted under static conditions. The results are therefore more applicable to spills in protected bays and lagoons than to those occurring in open ocean areas like the St. George Basin. Unless noted otherwise, these bioassays have measured the lethal response to the soluble aromatic component of various crudes.

Most flatfish have early life stages that are pelagic. By the time these fish take up a demersal existence they appear to be more tolerant than the more pelagic species to oil in seawater (the 96-h TLM for starry flounder = > 5.34 ppm total aromatics). Laboratory studies have shown the eggs and larvae of flatfish to be sensitive to the SWSF of various oils, with larvae tending to be more sensitive than eggs. The structure of the cell membranes of eggs has been shown to vary among flatfish species and may be the reason for differences in sensitivity to oils. Abnormal growth and development of embryos and larvae have been reported in sand and English soles exposed to the SWSF's of Prudhoe Bay crude as low as 27 ppb (Malins, 1980). Most larvae exhibited morphological abnormalities, the most common being scoliosis (deformed notochord), and some histological changes such as disruptions of olfactory cilia and abnormal mitochondria in skin cells. Similar results have been reported for embryos and larvae of plaice *(Pleuronectes platessa)* and flounder *(Platichthys flexus)* exposed to Ekofisk crude for short periods (1-15 h) (Malins et al., 1981).

Eggs and larvae of many flatfish may be particularly vulnerable to floating oil and to the seawater-soluble fraction since they are incubated or grow at or near the surface of the water column and have no way of avoiding toxic components. English and sand soles do not avoid oiled sediments and have been shown to incorporate hydrocarbons into liver, skin, and muscle when exposed through the diet, water column, or sediment (Malins, 1980). Recent research (Malins et al., 1981) has demonstrated the bioconversion of these accumulated parent hydrocarbons into metabolites such as phenols and dihydrodiols, some of which are known to be mutagenic and carcinogenic in mammals. The uptake and metabolism of hydrocarbons in flatfish and consequent storage of potentially toxic metabolites in tissues at concentrations many times higher than the parent hydrocarbons have resulted in pathological changes, such as liver tumors and fin erosion; they may alter feeding, schooling and reproductive behavior or cause physiological dysfunctions leading to reduced survivorship or resistance to disease (Malins, 1980). Low-level aromatics remain largely unconverted in sediments (microbes prefer alkanes) and can be continuously available for uptake in flatfish. Oiled sediments did not affect the juvenile English soles' ability to resist bacterial disease under laboratory conditions. However, if other environmental stresses are present, flatfish may be more susceptible to bacterial infection (Malins et al., 1981). Feeding rates of winter sole *(pseudopleuronectes americanus)* declined considerably when they were exposed to sediments freshly oiled with Venezuela crude. The result was a decline in growth rate and fitness needed to survive the winter, during which they do not feed (Fletcher et al., 1981).

Of the semidemersal species found in Alaskan waters, toxicity studies have been performed on adult pollock and Arctic cod *(Boreogadus saida)* (Rice et al., 1979). Ninety-six-hour TLM values for total aromatics for these species are 1.73 and 1.71 ppm, respectively, using the seawater-soluble fraction of Cook Inlet crude oil. Because of the paucity of studies on the semidemersal species of the North Pacific, much information has been drawn from observations on the effects of the SWSF's of crude oils on Atlantic cod *(Gadus morhau)* larvae. Eggs and larvae of fish from the semidemersal group would not be able to avoid the slick from a spill or its toxic seawater-soluble fractions. Juveniles and adults would probably move away from contaminated waters with total hydrocarbon levels greater than 1.5 ppm. Eggs of Atlantic cod exposed to Ekofisk crude oil for 1-15 h developed deformed notochords and abnormalities of the head region (Malins et al., 1981). Larvae exposed to this crude had changes in pigment cell distribution. These morphological changes could affect the animal's survival by increasing its chances of being preyed upon (position and coloration) and could affect its ability to locate and capture food. Adults and juvenile fish that do not avoid sublethal concentrations are likely to accumulate hydrocarbons, convert them to metabolites, and store them in tissues, with unknown behavioral or pathological effects.

Like the semidemersals, the pelagic fishes are quite sensitive to the SWSF's of crude oil, showing 96-h TLM for total aromatics of 1-3 ppm. Many members of this group have been tested, especially the juvenile and adult salmonids. Laboratory and field studies (Patten, 1977) have shown that juvenile and adult salmon avoid SWSF concentrations less than 1.6 ppm, but do not move from exposures less than 0.75 ppm. Eggs and alevins of salmon have shown delayed hatching and abnormal growth in the presence of the soluble aromatic fraction of Prudhoe Bay crude oil. Pink salmon fry migrating seaward in nearshore waters could be severely harmed by spilled oil. At sublethal concentrations juvenile salmon have shown signs of narcosis, unresponsiveness to fright stimuli, altered schooling (swimming to the surface), and "coughing." Chum smolts were preyed upon more heavily by coho predators during the first three days of exposure to the SWSF of Cook Inlet crude oil. After 96 h, cohos fed less on oiled prey. Oiled coho preyed less heavily on non-oiled chum than did control groups. The coho predators began to quit feeding at SWSF's approaching 320 ppb. Juvenile and adult salmon are known to accumulate hydrocarbons through their diet in liver and muscle (Malins, 1980). Metabolites may be formed (and are thought to be the cause of altered feeding behavior), but the pathological consequences of such bioconversions are not yet known.

Spilled oil may also alter the timing of migration in salmon. Adult salmon arrive on their spawning grounds in the southeast Bering Sea at about the same time every year, presumably when spawning conditions are best. Survival of outmigrating salmon is thought to depend on movements through waters rich in such foods as amphipods and copepods that may be available only for short periods each year. Any change in the timing of arrival of juveniles to feeding grounds or adults to spawning habitats may result in migrations away from optimal conditions and greatest chances for survival.

Pacific herring, like salmon, are quite sensitive to the seawater-soluble fraction of oil. The eggs of herring occur in the intertidal zone, and larvae develop near shore. Neither eggs nor larvae could avoid exposure of spilled oil in the nearshore environment, and mortalities from concentrations greater than 0.75 ppm would be high. SWSF's greater than 1 ppm approach reported lethal concentrations and would probably be avoided by juveniles and adults. Studies determining the sublethal effects of oil on herring (and other forage species with similar life histories) have shown that fewer eggs hatch and these grow and develop abnormally at concentrations as low as 25 ppb (Malins, 1980). Surf smelt embryos exposed to the hydrocarbons in 54 or 113 ppb Cook Inlet crude oil showed severe changes in the neurons of the forebrain and retina, leading to extensive necrosis (Hawkes and Stehr, 1981). Swimming and feeding behavior of larval herring were reduced by low SWSF concentrations, and it is probable that schooling would also be affected. Abnormal heart rates and fin development as well as morphological changes in the head region of larvae have been reported (Malins, 1980). As in salmon, it is likely that the swimming behavior of juvenile and adult herring would be altered in exposures nearing 1 ppm. Altered swimming could affect their availability as prey or ability to locate food. Growth in juveniles was hindered at concentrations as low as 400 ppb. It is speculated that herring may ingest oil globules or oiled foods and accumulate hydrocarbons in tissues, with unknown pathological effects.

A summary of the lethal and sublethal effects of the soluble aromatic components (~ total hydrocarbons at various concentrations on fishes is shown in Table 6.7.

Oil in the marine environment may make fish unfit for human consumption. Tainting (i.e., the presence of an objectionable oily taste or odor in commercial preparations of fish) by petroleum hydrocarbons has been frequently recorded, but the petroleum fractions have not been identified. A "kerosene-like" mixture of alkanes, methylated benzenes, and naphthalenes has been implicated. Tainting in salmon has been demonstrated when fish were exposed to 40-50 ppm oil in seawater for four days. Most fish discharge hydrocarbons from all tissues when placed in clear water for 7-14 days. The patterns for the uptake, retention, and release of petroleum hydrocarbons in fish are extremely difficult to correlate with tainting; all information suggests that a minor component of the oil may be the major taint-producer. Possible contributing factors are differences in the physical and chemical characteristics of the target organisms (i.e., where hydrocarbon is accumulated), processing, and even the perception of the consumer. Effects on the economy of the fishery are unknown. Because depuration is rapid, tainting would probably not be a problem in the case of a spill in the St. George region. However, in shallower areas, where the toxic components of oil are likely to be transported to and retained in sediments, the accumulation of carcinogens either directly from petroleum or from the formation of metabo-

Table 6.7. Concentrations of seawater-soluble fractions of total hydrocarbons causing lethal or expected sublethal effects on flatfish, semidemersal, and pelagic fishes.

		Lethal effects	Sublethal effects	
Species group	Life stage	Seawater-soluble fraction concentration of total hydrocarbons	Seawater-soluble fraction concentration of total hydrocarbons	
Flatfish				
	Eggs	0.1 - 1 ppm	> 25 ppb	Abnormal growth and development
	Larvae	0.1 - 1 ppm	> 25 ppb	Abnormal growth and development, behavioral changes
	Juveniles	> 5.34 ppm	< 5 ppm	Accumulation and bioconversion of hydrocarbons in tissues, behavioral and pathological changes
	Adults	> 5.34 ppm	< 5 ppm	Accumulation and bioconversion of hydrocarbons in tissues, pathological changes
Semidemersal				
	Eggs	0.1 - 1 ppm	> 25 ppb	Abnormal growth and development
	Larvae	0.1 - 1 ppm	> 25 ppb	Abnormal growth and development, behavioral changes
	Juveniles	1 - 3 ppm	< 1.5 ppm	Accumulation of hydrocarbons in tissues, behavioral changes, unknown pathological effects
	Adults	1 - 3 ppm	< 1.5 ppm	Accumulation of hydrocarbons in tissues, behavioral changes, unknown pathological effects
Pelagic (Salmon)				
	Eggs	NA	NA	Abnormal growth and development
	Larvae	NA	NA	Abnormal growth and development
	Juveniles	1 - 3 ppm	< 1.6 ppm	Accumulation of hydrocarbons, behavioral changes, unknown pathological effects, possible delayed effect on survival
	Eggs	NA	NA	Abnormal growth and development
	Adults	1 - 3 ppm	< 1.6 ppm	Accumulation of hydrocarbons, behavioral changes, unknown pathological effects, possible delayed effect on spawning
(Pacific herring)				
	Eggs	0.1 - 1 ppm	> 25 ppb	Reduced hatching success, abnormal growth and development
	Larvae	> 0.75 ppm	> 25 ppb	Abnormal growth and development, behavioral changes
	Juvenile	1 - 3 ppm	< 1 ppm	Probable accumulation of hydrocarbons, unknown pathological effects, behavioral changes
	Adults	1 - 3 ppm	< 1 ppm	Probable accumulation of hydrocarbons, unknown pathological effects, behavioral changes

lites in commercial species may pose a serious health hazard.

The prospect of exploratory drilling for petroleum hydrocarbons in the resource-rich waters of the Bering Sea has generated concern from the fishing industry and others regarding the potential biological effects of discharges of drilling fluids and formation rock cuttings from drilling vessels (Houghton, 1981). Drilling fluids and cuttings discharged in the water column offshore have been shown to separate into an upper plume containing liquids, finer silts, and clays; and a lower plume containing the bulk of discharged solids, cuttings, and caked or flocculated muds.

The upper or near surface plume may affect the organisms drifting or swimming in the pelagic portion of the water column. High rates of dilution along the narrow surface plume have been reported within 100 m of the discharge. Within the zone a few meters downcurrent of the downpipe where fluids and cuttings are discharged, toxic whole mud concentrations exceeding measured 96-h LC_{50} (concentration that kills 50 percent of test animals) values for many fish species (on the order of parts per hundreds) infrequently could be experienced for 15 minutes to three hours by organisms actively swimming to stay in the plume. The likelihood that significant numbers of juvenile or adult fish will remain in this area long enough to be killed or suffer sublethal stress is remote because the near-field discharge area is small and the high-volume discharges are infrequent.

In the zone from a few meters to 100 m from the discharge, toxic concentrations (in parts per thousand) might infrequently affect active swimmers that remain in the plume. Beyond 100 m, the plume concentrations (in ppm) would be further diluted and dispersed by currents to sublethal levels. Although fish exposed to those concentrations might experience sublethal stresses, only a negligible fraction of the population of any given species would be vulnerable. Pelagic eggs and larvae of fish could receive maximum exposure to drilling effluents if entrained in the plume for several hundred meters downstream. However, the width and depth of the plume and the brief duration and low frequency of discharges reduce the chances of significantly affecting any population in offshore regions like the St. George Basin. It is possible that fish remaining around the drilling rig could incorporate some heavy metals into tissues, but this has not been verified.

The effects of drilling fluids and cuttings from the lower plume on demersal species is highly dependent on depth, current, wave regimes, and substrate type; and on the nature and volume of the discharges, cutting sizes, and the depth of the downpipe. Effects may be of short duration: mud toxicity and burial by mud and/or cuttings, or more permanent: chemical and physical alteration of the sediments. Accumulations of cuttings and muds could bury benthic infauna within 150 m of wells at depths of 75-100 m or greater. Demersal fish are unlikely to be killed directly and may be attracted to the rig by the disturbance and increased availability of food. Discharges may locally reduce the productivity of infaunal prey organisms, however, so that fish will not be able to feed there. Changes in the substrate may alter patterns of reproduction of fish. Former conditions would probably be restored within one or two years as organisms recolonize the area and as bottom currents and biological activity disperse the discharged materials.

6.6 HYPOTHETICAL OIL SPILLS

6.6.1 Description

To gain some insight into the biological consequences of a possible oil spill in the St. George Basin lease area, two offshore spill cases were postulated to occur at 55°30′N, 166°W. The spills were to persist for 10 days and could occur in either winter or summer. The first case is an instantaneous release of 50,000 bbl at the surface; the second, a well blowout at the bottom (~ 100 m) releasing 5,000 bbl/d. Summer months are June through August and winter months are December through May.

Characteristics of the spills, the plumes containing mixed soluble seawater fractions of total hydrocarbons and emulsified oil (Table 6.8), and the surface slicks, are assumed to present worst cases in terms of ichthyofauna vulnerability. However, an actual spill in the St. George Basin would undoubtedly be less severe: weathering would result in lower concentrations and net circulation would result in less coverage by the slick. The plumes from both the surface instantaneous release and the well blowout would be driven to the northwest in both summer and winter by prevailing currents. Hydrocarbons mix deeper in winter than in the summer because of disintegration of the seasonal thermocline.

Dispersion of the wind and tide-driven slicks produced by the two postulated spills would diffuse from that of the plumes; slicks would mainly affect the upper surface meter of water. Based on material from Workshop I (Pollutant Transport), Table 6.9 shows the characteristics of the surface spill slicks during summer and winter.

During the summer the slick trajectory moves to the east and southest, in the winter, to the west and southwest. Expected hydrocarbon concentrations under the slicks are values that have been measured beneath weathered Prudhoe Bay crude oil (Payne, 1981).

Table 6.8. Characteristics of the plumes of hypothetical oil spills in the St. George Basin lease area.

		Origin		Origin to 5 km		5 to 20 km	
Spill case		**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Surface plume	Total hydrocarbons	5 ppm	5 ppm	5 ppm decreasing to 1 ppm	5 ppm decreasing to 1 ppm	1 ppm decreasing to 80 ppb	1 ppm decreasing to 80 ppb
	Areal coverage	7800 m²	7800 m²	25 km²	25 km²	75 km²	75 km²
	Depth of mixing	20-30 m	75-100 m	20-30 m	75-100 m	20-30 m	75-100 m
Well blowout plume	In the case of the well blowout, all features are the same as above except that hydrocarbon mixing would occur from the bottom (100 m) to the surface at the spill site during summer and winter.						

Table 6.9 Characteristics of summer and winter surface spill slicks.

		Areal coverage of trajectory (km²)		Expected seawater-soluble fraction of total hydrocarbons under the trajectory	
Spill case	**Time after release**	**Summer**	**Winter**	**Surface - 0.5 m**	**0.5 - 1 m**
Surface spill slick	Day 1	200	200	100 ppm	10 ppb
	Day 2	250	225	100 → 25 ppm	10 → > 0.1 ppb
	Day 3-5	250	225	25 → 5 ppm	0.1 → 0.01 ppb
	Day 6-10	250	225	5 ppm →∼ 50 ppb	> 0.01 ppb

Table 6.10. Increase in area covered by well blowout slick with decrease in SWSF of total hydrocarbons in first surface meter.

		(km²		
Spill case	**Time after release**	**Summer**	**Winter**	**Expected seawater-soluble fraction of total hydrocarbons in first surface meter**
Well blowout slick	Day 1	8.5	15	5 ppm → 1 ppm
	Day 2	17.0	30	5 ppm → 1 ppm → 200 ppb
	Day 3	25.5	45	5 ppm → 1 ppm → 200 ppb → 100 ppb
	Day 4-10	34-85	60-150	5 ppm → 1 ppm → 200 ppb → 100 ppb → 50 ppb

Table 6.11. Species presence in impacted zones and expected lethal and/or sublethal consequences.

			Species				
			Yellowfin sole	Rock sole	Flathead sole	Greenland turbot	Halibut
Spill case	Spill zone	Expected situation	E[1] L J A	E L J A	E L J A	E L J A	E L J A
Plume resulting from summer surface spill	**Site**						
	SWSF = 5 ppm[2]	Present	− − − −[3]	− + − −	− + + −	− − − −	− − − −
	Mix = 20-30 m	Lethal	− − − −	− + − −	− + + −	− − − −	− − − −
	Area = 7800 m^2	Sublethal	− − − −	− − − −	− − − −	− − − −	− − − −
	Site → 5 km						
	SWSF = 5 → 1 ppm	Present	− − − −	− + − −	− + + −	− − − −	− − − −
	Mix = 20-30 m	Lethal	− − − −	− + − −	− + − −	− − − −	− − − −
	Area = 25 km^2	Sublethal	− − − −	− − − −	− − + −	− − − −	− − − −
	5 km → 20 km						
	SWSF = 1 ppm-80 ppb	Present	− − − −	− + − −	− + + −	− − − −	− − − −
	Mix = 20-30 m	Lethal	− − − −	− + − −	− + − −	− − − −	− − − −
	Area = 75 km^2	Sublethal	− − − −	− + − −	− − + −	− − − −	− − − −
Plume resulting from winter surface spill	**Site**						
	SWSF = 5 ppm	Present	− − − +	+ + − +	− + + +	+ + + +	+ + − +
	Mix = 75-100 m	Lethal	− − − +	+ + − +	− + + +	+ + + +	+ + − +
	Area = 7800 m^2	Sublethal	− − − −	− − − −	− − − −	− − − −	− − − −
	Site → 5 km						
	SWSF = 5 ppm-1 ppm	Present	− − − +	+ + − +	− + + +	+ + + +	+ + − +
	Mix = 75-100 m	Lethal	− − − −	+ + − −	− + − −	+ + − −	+ + − −
	Area = 75 km^2	Sublethal	− − − +	− − − +	− − + +	− − + +	− − − +
	5 km → 20 km						
	SWSF = 1 ppm-80 ppm	Present	− − − +	+ + − +	− + + +	+ + + +	+ + − +
	Mix = 75-100 m	Lethal	− − − −	+ + − −	− + − −	+ + − −	+ + − −
	Area = 75 km^2	Sublethal	− − − +	+ + − +	− + + +	+ + + +	+ + − +

Table 6.11 (continued)

			Species																			
			Pacific cod				**Sablefish**				**Pollock**				**Salmon**				**Pacific herring**			
Spill case	**Spill zone**	**Expected situation**	E[1]	L	J	A	E	L	J	A	E	L	J	A	E	L	J	A	E	L	J	A
Plume resulting from summer surface spill	**Site**																					
	SWSF = 5 ppm[2]	Present	−	+	+	−	−	−	+	−	+	+	+	−			+	+	−	−	+	+
	Mix = 20-30 m	Lethal	−	+	+	−	−	−	+	−	+	+	+	−			+	+	−	−	+	+
	Area = 7800 m^2	Sublethal	−	−	−	−	−	−	−	−	−	−	−	−			−	−	−	−	−	−
	Site → 5 km																					
	SWSF = 5 → 1 ppm	Present	−	+	+	−	−	−	+	−	+	+	+	−			+	+	−	−	+	+
	Mix = 20-30 m	Lethal	−	+	+	−	−	−	+	−	+	+	+	−			+	+	−	−	+	+
	Area = 25 km^2	Sublethal	−	−	−	−	−	−	−	−	−	−	−	−			−	−	−	−	−	−
	5 km → 20 km																					
	SWSF = 1 ppm-80 ppb	Present	−	+	+	−	−	−	+	−	+	+	+	−			−	−	−	−	+	+
	Mix = 20-30 m	Lethal	−	+	−	−	−	−	+	−	+	+	−	−			−	−	−	−	+	+
	Area = 75 km^2	Sublethal	−	+	+	−	−	−	+	−	+	+	+	−			−	−	−	−	+	+
Plume resulting from winter surface spill	**Site**																					
	SWSF = 5 ppm	Present	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+
	Mix = 75-100 m	Lethal	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+
	Area = 7800 m^2	Sublethal	−	−	−	−	−	−	−	−	−	−	−	−			−	−	−	−	−	−
	Site → 5 km																					
	SWSF = 5 ppm-1 ppm	Present	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+
	Mix = 75-100 m	Lethal	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+
	Area = 75 km^2	Sublethal	−	−	−	−	−	−	−	−	−	−	−	−			−	−	−	−	−	−
	5 km → 20 km																					
	SWSF = 1 ppm-80 ppm	Present	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+
	Mix = 75-100 m	Lethal	+	+	−	−	−	−	+	−	+	+	−	−			−	−	−	−	+	+
	Area = 75 km^2	Sublethal	+	+	+	+	−	−	+	−	+	+	+	+			+	−	−	−	+	+

Table 6.11 (continued)

			Species				
			Yellowfin sole	**Rock sole**	**Flathead sole**	**Greenland turbot**	**Halibut**
Spill case	**Spill zone**	**Expected situation**	E[1] L J A	E L J A	E L J A	E L J A	E L J A
Plume resulting from summer well blowout	**Site**						
	SWSF = 5 ppm[2]	Present	– – – –	+ + – +	+ + + +	– – + +	– – – +
	Mix = 20-30 m	Lethal	– – – –	+ + – +	+ + + +	– – + +	– – – +
	Area = 7800 m^2	Sublethal	– – – –	– – – –	– – – –	– – – –	– – – –
	Site → 5 km						
	SWSF = 5 → 1 ppm	Present					
	Mix = 20-30 m	Lethal					
	Area = 25 km^2	Sublethal		Effects same as in summer surface inatantaneous spill			
	5 km → 20 km						
	SWSF = 1 ppm-80 ppb	Present					
	Mix = 20-30 m	Lethal					
	Area = 75 km^2	Sublethal					
Plume resulting from winter well blowout	**Site**			Blowout in winter will have same effects as winter surface spill			
	SWSF = 5 ppm	Present					
	Mix = 75-100 m	Lethal					
	Area = 7800 m^2	Sublethal					
	Site → 5 km						
	SWSF = 5 ppm-1 ppm	Present					
	Mix = 75-100 m	Lethal					
	Area = 75 km^2	Sublethal					
	5 km → 20 km						
	SWSF = 1 ppm-80 ppm	Present					
	Mix = 75-100 m	Lethal					
	Area = 75 km^2	Sublethal					

Table 6.11 (continued)

			Species																			
			Pacific cod				Sablefish				Pollock				Salmon				Pacific herring			
Spill case	**Spill zone**	**Expected situation**	E[1]	L	J	A	E	L	J	A	E	L	J	A	E	L	J	A	E	L	J	A
Plume resulting from summer well blowout	**Site**																					
	SWSF = 5 ppm[2]	Present	+	+	+	+	−	−	+	+	+	+	+	+			+	+	−	−	+	+
	Mix = 20-30 m	Lethal	+	+	+	+	−	−	+	+	+	+	+	+			+	+	−	−	+	+
	Area = 7800 m^2	Sublethal	−	−	−	−	−	−	−	−	−	−	−	−			−	−	−	−	−	−
	Site → 5 km																					
	SWSF = 5 → 1 ppm	Present	Effects same as in summer surface instantaneous spill																			
	Mix = 20-30 m	Lethal																				
	Area = 25 km^2	Sublethal																				
	5 km → 20 km																					
	SWSF = 1 ppm-80 ppb	Present	Blowout in winter will have same effects as winter surface spill																			
	Mix = 20-30 m	Lethal																				
	Area = 75 km^2	Sublethal																				
Plume resulting from winter well blowout	**Site**																					
	SWSF = 5 ppm	Present																				
	Mix = 75-100 m	Lethal																				
	Area = 7800 m^2	Sublethal																				
	Site → 5 km																					
	SWSF = 5 ppm-1 ppm	Present																				
	Mix = 75-100 m	Lethal																				
	Area = 75 km^2	Sublethal																				
	5 km → 20 km																					
	SWSF = 1 ppm-80 ppm	Present																				
	Mix = 75-100 m	Lethal																				
	Area = 75 km^2	Sublethal																				

[1] E = eggs; L = larvae; J = juvenile; A = adults.

[2] SSWF = Seawater-soluble fractions of total hydrocarbons mixed in plume to depth.

[3] + = Presence in affected zones and lethal or sublethal effects expected.
− = Absence from impacted zones and no expected effects.

[4] S B = surface-to-bottom mixing.

The daily incremental expanse of slicks resulting from the well blowout was derived by assuming the seasonal rates of movement and distances covered as described in Workshop I (Pollutant Transport) (Table 6.10).

Slick trajectories for both summer and winter move in the same directions as the surface spill slicks but cover a smaller area. The slicks produced by the blowout would appear as separate streamers emanating from the origin; each streamer would be more susceptible to destruction by wave motion than the slick produced by the surface spill. The sum of streamer width, indicating the total affected area, would probably not exceed 1 km. Expected hydrocarbon concentrations are again derived from studies of Prudhoe Bay crude oil and are similar to those found at the IXTOC-I spill.

6.6.2 Biological Consequences of Hypothetical Spills

Few oil toxicity studies have been performed on finfish species that inhabit the St. George Basin. Because of this, lethal and sublethal concentrations of seawater-soluble fractions of total hydrocarbons were drawn from studies on similar species as mentioned earlier (Table 6.6). These values and the expected concentrations given in the description of the postulated spills have been used to assess probable effects of the hypothetical oil spills.

Life histories of the finfish species inhabiting St. George Basin differ in season of spawning, depth of occurrence, and migration patterns. Eggs, larvae, juveniles, or adults of one species or another are present year round. Thus, biological effects of the hypothetical spills must be considered separately for each species according to the presence or absence of life stages in the contaminated zones. While effects cannot be quantified, expected consequences can be described in terms of mortality or sublethal effects for each spill zone. This information is summarized in Table 6.11 for selected species.

The instantaneous spill of 50,000 bbl at the surface is characterized by: (1) a 50-m band at the origin of the spill containing 5 ppm of seawater-soluble fractions of total hydrocarbons, mixed to a depth of 20-30 m in the summer (75-100 m in winter); (2) from the origin out to about 5 km oil concentrations gradually decline from 5 ppm to 1 ppm at the 5-km edge, mixed to a depth of 20-30 m in the summer (75-100 m in winter); and (3) from the 5-km edge to the outer edge of the spill at 20 km, oil would be reduced from 1 ppm to 80 ppb with similar mixing.

Because of spawning time or location and distribution of life stages, halibut, yellowfin sole, and Greenland turbot would not be in the spill area and thus would not be affected by the summer surface spill. At the origin of the spill, a complete kill of eggs, larvae or juvenile Pacific cod, sablefish, pollock, rock sole, and flathead sole would occur due to direct oiling, asphyxiation, and acute toxicity. Juvenile and adult herring passing through the area of spill origin during earlier stages of their seaward migrations would probably be trapped and killed on Day 1 of the sudden release of 50,000 bbl, but others would likely avoid this zone thereafter. A similar situation is expected for migrating juvenile and adult salmon. Consequences would be less severe in the origin-to-5-km zone and from 5 km to the spill edge, but a mix of lethal and sublethal effects would be expected. Pollock would be the species most affected.

The surface spill in winter would be more destructive than one occurring in summer because most of the fish present in the area are winter spawners, and more of the early life stages as well as adults would be present; also, the depth of oil mixing would be much greater. Further, oil toxicity would persist longer because of the colder temperatures. Juveniles and adults present at the site and time of instantaneous release of oil would be killed, but others would be apt to avoid the area after the first few hours. All eggs and larvae occurring in the 50-m band at the origin of the spill would be killed. These affected species would include Pacific cod, pollock, rock sole, flathead sole, Greenland turbot, and halibut. As in the summer case, biological effects of the spill would be less acute in the zones from the origin out to 5 km and from 5 km to the edge. More lethal and sublethal effects would result from the winter spill than from the summer spill. Flatfish, with the exception of yellowfin sole, and pollock would suffer the most damage.

Except for oil toxicity at the spill origin, biological effects of the hypothetical well blowout will be the same as those of the summer and winter surface spills in an area from the origin to the spill edge at 20 km. In the 50-m band, more early life stages would be affected because the seawater-soluble fractions of total hydrocarbons would be mixed in the water column from the bottom to the surface. Juveniles and adults of all species in the origin area would be trapped and killed in the first release; others would avoid this area thereafter. All eggs or larvae of rock sole, flathead sole Pacific cod, pollock, Greenland turbot, and pollock would be killed. Again, pollock would be the species most seriously affected.

Slicks produced by the surface spill would contain the same concentrations of the seawater-soluble fraction of total hydrocarbons in both summer and winter, but toxicity is likely to persist longer in winter because of colder water temperatures. Lethal or sublethal concentrations would occur in the upper meter, with highest concentrations in the upper one-half meter. The slick would reach the full extent of surface areal coverage by Day 2. Oil concentrations would diminish through evaporation and dissolution from 100 ppm on Day 1 to 5 ppm by Day 5, and to 50 ppb by Day 10 in the upper one-half meter; in the lower one-half meter oil concentrations would decrease from 10 ppb on Day 1 to 1 ppb by Day 5, and to less than 0.01 ppb by Day 10. Eggs, larvae, and juveniles of rock sole, flathead sole, Greenland turbot, halibut, sablefish, pollock, herring, and juvenile and adult salmon would be present in the first meter of water beneath the slick (Table 6.12). Eggs and larvae in the upper one-half meter would all be killed through Day 6; from Days 7 through 10 they would be likely to experience sublethal effects. Juveniles and adults exposed to oil on Day 1 of the slick would be killed; others would likely avoid the area after Day 2. Toxic fractions are low in the lower one-half meter, and sublethal effects would be expected by exposure through Day 2.

The slick trajectory resulting from a surface spill in winter is to the west and southwest. During severe winters, northern reaches of the St. George lease area would be under ice. Ice is expected one year out of five and would be present for about 45 days between March and April. Large ice bands broken off the pack would be constantly moving to the west-southwest. These ice bands move faster than the pack and would likely overrun an oil slick, transport oil to the west, and release it upon melting. Oil would thus be distributed away from nearshore waters just as in a winter without ice.

During the winter, the slicks formed by surface or subsurface spills would move west-southwest over the continental slope and break to deep waters (> 200 m). The areas affected by the slicks and soluble hydrocarbons beneath them in the upper meters would be small, especially in the well-blowout scenario; only the pelagic eggs and larvae of winter spawners would be affected, as the juveniles and adults of all species are found at much greater depths. The mortality of fish of any species under the slicks would have a negligible effect on their total population. However, the eggs and larvae of rock and flathead sole, sablefish, and pollock would be present in the greatest abundance in surface layers during winter. The larvae of Greenland turbot and Pacific halibut would also be found near the surface, and some would be killed through acute exposure during the first 10 days after the spill.

Model trajectories calculated for summer months in the St. George Basin show slick movement to the east and southeast. Slicks would be transported over the upper continental slope and over shelf waters. As in the winter case, the slick resulting from a 50,000-bbl spill would cover a small fraction of the St. George Basin and would not seriously harm commercial species. All species considered would be abundant over the upper slope and shelf during summer, with adult halibut and sablefish more likely to be found in deeper waters. Only those species that occur in the upper meter are likely to be affected by a summer slick. Adult salmon and herring migrate through surface layers but would avoid lethal concentrations or move rapidly through sublethal concentrations to clean waters and would suffer no deleterious effects. Eggs and larvae of pollock, flathead sole, rock sole, and sablefish would be present in surface layers. Lethal and sublethal exposures would be experienced by these species, but damage to the resource as a whole would be negligible.

Table 6.12. Species occurrence in upper meter of water beneath oil slick.

	Summer				Winter			
	E	L	J	A	E	L	J	A
Yellowfin sole	-	-	-	-	-	-	-	-
Rock sole	-	+	-	-	-	-	-	-
Flathead sole	+	+	-	-	+	+	-	-
Greenland turbot	-	-	-	-	-	+	-	-
Halibut	-	-	-	-	-	+		-
Pacific cod	-	-	-	-	-	-	-	-
Sablefish	-	+	+	-	+	+	+	-
Pollock	+	+	+	-	+	+	+	-
Salmon	-	-	+	+	-	-	+	-
Pacific herring	-	-	+	+	-	-	+	-

E = Eggs
L = Larvae
J = Juveniles
A = Adults

\+ = Present
\- = Absent

Trajectory modeling indicates the possible movement of a summer slick originating in the St. George Basin to nearshore waters along the northern coast of the Alaska Peninsula. Many flatfish species, outmigrating salmon, and spawning herring grow and develop here; the area also contains the migrational corridors of adult salmon heading for spawning habitats (and commercial fisheries) in Bristol Bay.

Toxic fractions of oil mixed to depth and under the slicks resulting from the hypothetical oil spills would cause mortalities and sublethal effects, but the overall impacts on finfish populations of St. George Basin would be negligible. The area contaminated by the spill comprises less than .002 percent of the total St. George Basin area. Fish populations and their various life stages are widely distributed and fractions of these populations exposed to contaminated waters would be very small. Additionally, most fish are long-lived (Table 6.5) and have high fecundities, and even though larval survival is low under normal conditions, a spill would not impact a significant portion of all eggs released or developing larvae over their range. There would be no devastating loss of a particular year class or stock.

The effects of a spill on commercial fisheries would be transitory without harm to the resource itself. Problems encountered include: (1) oiling of gear, (2) temporary loss of catch, and (3) contamination of catches of at-sea processors or crabbers in the spill area that require seawater intake. The hypothetical offshore spills would have little effect on subsistence fisheries, unless oil reached shore or nearshore areas and fouls gear. This is not to say that oil spills in this region would not be harmful to finfish. Larger spills would have similar characteristics as those of the hypothetical spills (i.e., total hydrocarbon concentrations would be similar) but would affect larger areas. Spills in which oil was transported to the productive nurseries along the north shore of the Alaska Peninsula would be more destructive than those in the open ocean.

6.7 INFORMATION NEEDS

The following information needs were identified by the workshop participants to improve the existing data base on fisheries and to better assess the potential effects of oil and gas development on this resource.

1. Studies are needed to evaluate avoidance capabilities of representative fishes inhabiting the Bering Sea (i.e., pollock, yellowfin sole, salmon, etc.).
2. Studies are needed to evaluate the sensitivities of invertebrate prey species including mysids, copepods, amphipods, and euphausiids.
3. If a spill occurs in Alaskan waters, a rapid on-scene response is needed to obtain information on oil concentrations and short-term biological effects.
4. A centralization of all pertinent oil and gas literature easily accessible to all users is needed.
5. Information on the subsistence use of finfish resources in the St. George Basin is needed as the present knowledge is inadequate to truly assess potential impacts of oil and gas development in this region.

6.8 SUMMARY

The southeastern Bering Sea including the St. George Basin is inhabited by more than 300 species of finfish and is the site of major U.S. and foreign fishing efforts. Because offshore drilling for oil and gas in the St. George Basin seems imminent, the potential biological consequences to the fisheries resource of such development and the likely conflicts between the petroleum and fishing industries have been discussed in this report. The implications of an open ocean spill occurring at various times of the year are given special emphasis, particularly the losses of egg, larval, and juvenile fish associated with acute exposures of oiled seawater At-sea conflicts that do not affect the resource itself include: preemption of fishery grounds; loss of or damage to gear; contamination of catch; and competition for port facilities.

The life history events of St. George Basin finfish differ in season of spawning, depth of occurrence, and migrational patterns. Eggs, larvae, juveniles, or adults of one species or another are present year-round. If a 50,000 bbl. surface spill occurred between June and August, pollock would be the single species most impacted. A winter spill of the same magnitude would be more destructive as many of the major commercial species of this region are winter spawners, and, without the presence of a thermocline oil would be mixed deeper in the water column. During winter the eggs, larvae, and juveniles of Pacific cod, pollock, rock, and flathead sole, Greenland turbot, and Pacific halibut would be most sensitive to the toxic components of spilled oil.

Well blowouts on the ocean seafloor were also considered as a potential mechanism for petroleum hydrocarbons release into the marine environments. In both summer and winter blowout situations, the expected losses to fish were similar to those described for surface spills. There may, however, be a larger kill at the point of blowout origin due to oil and water mixing from the bottom to the surface there.

The contaminated water underneath the slick produced by either summer or winter spills would contain the same concentrations of the seawater-soluble fraction of total hydrocarbons. The slick would obtain its maximal surface areal extent by the second day of the oil release. Lethal or sublethal concentrations would occur to the ichthyofauna found in the surface meter of the water column with highest toxic concentrations found in the upper one-half meter.

Although open ocean spills, such as those described in the hypothetical cases, can cause localized damage, larger spills, or spills at sites where oil can be transported to productive areas like those north of the Alaska Peninsula would be more destructive. The area fouled by the postulated spill comprises a very small fraction of the entire St. George lease area (~100 km² or .002 percent), and, because the various life stages of the finfish populations are widely distributed in both time and space, the proportions of these populations exposed to contaminated waters would be very small. There would be no devastating loss of a particular year class or stock. Consequences for commercial or subsistence fisheries would be transitory.

6.9 REFERENCES

Bakkala, R. G. 1981. Population characteristics and ecology of yellowfin sole; D. W. Hood and J. A. Calder (eds), *In: The Eastern Bering Sea Shelf: Oceanography and Resources*, OMPA, Vol. 1: p 553-574.

Clark, R. C. and J. S. Finley. 1977. Effects of oil spills in arctic and subarctic environments, 2:411-476. *In: Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms.* Academic Press, New York (D. C. Malins, ed.).

Fletcher, G. L., J. W. Kiceniuk, and U. P. Williams. 1981. Effects of oiled sediments on mortality, feeding and growth of winter flounder, *Pseudopleuronectes americanus.* Mar. Ecol. Prog. Series 4(1):91-96.

Hawkes, J. W. and C. M. Stehr. 1981. Cytopathology of the brain and retina of embryonic surf smelt *(Hypomesus pretiosus)* exposed to crude oil. Environ. res. Northw. Alaska Fish. Cent., Seattle, Wash. (in press.)

Houghton, J. P. 1981. Fate and effects of drilling fluids and cuttings discharges in Lower Cook Inlet, Alaska, and on Georges Banks. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep., Biol.

Laevastu, T. and F. Favorite. 1981. Ecosystem Dynamics in the Eastern Bering Sea. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources,* OMPA; Vol. 1:611-625

Malins, D. C. 1980. Toxicity of oil in marine habitats. Unpub. MS.

Malins, D. C., S. Chan, H. O. Hodgins, U. Varanasi, B. B. McCain, D. D. Weber, and D. W. Brown. 1981. Sublethal effects of petroleum hydrocarbons and trace metals including biotransformations, as reflected by morphological, chemical, physiological, and behavioral indices. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Ann. Rep. (in press).

National Marine Fisheries Service (NMFS). 1979. Living marine resources, commercial fisheries, and potential impacts of oil and gas development in the St. George Basin, eastern Bering Sea (Tentative Sale No. 70). NMFS, Seattle, WA and Juneau, AK. 132p.

Patten, B. G. 1977. Sublethal biological effects of petroleum hydrocarbon exposures: Fish. 2:314-335. *In: Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms,* Academic Press, New York (D. C. Malins, ed.).

Payne, J. R. 1981. Chemical properties of crude oils and petroleum products as they relate to the trajectory, dispersion and weathering of oils spilled in the marine environment. SAI Tech. Rep., La Jolla, Calif.

Pereyra, W. T., J. E. Reeves, and R. G. Bakkala. 1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Natl. Mar. Fish. Serv., Northwest and Alaska Fish Cent., Seattle, WA. Processed Rept., 619pp.

Rice, S. D., A. Moles, T. L. Taylor, and J. F. Karinen. 1979. Sensitivity of 39 Alaskan marine species to Cook Inlet Crude Oil and No. 2 Fuel Oil, pp. 549-554. Proc. 1979 Oil Spill Conference.

Serobaba, I. I. 1967. Spawning of the Alaska pollock *(Theragra chalcogramma)* (Pallas) in the northeastern Bering Sea. Izv. Tikhookean. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. (Transl. Fish. Res. Bd. Can., Transl. Ser. 3081, 27 pp.).

Smith, G. 1981. The biology of walleye pollock. *In:* D. W. Hood and J. A. Calder (eds), *The Eastern Bering Sea Shelf: Oceanography and Resources,* OMPA; Vol. 1: p 527-551.

Waldron, K. D. 1981. Ichthyoplankton. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources,* OMPA; Vol. 1: p 471-493.

CHAPTER 7

SHELLFISH RESOURCES

H. E. Curl, Jr. and C. A. Manen

With the contributions of D. Armstrong, T. Boyd, H. Feder, R. Griffiths, J. Houghton, L. Incze, S. Jewett, J. Karinen, R. Otto, and D. Somerton.

7.1 INTRODUCTION

The Southeastern Bering Sea, including the St. George Basin, supports lucrative foreign and domestic fisheries for king crab, Tanner crab, Korean hair crab, shrimp, and snails (Table 7.1). Oil and gas development in the St. George Basin could have deleterious effects on these fisheries, either directly by harming the stocks, or indirectly, by causing loss of markets, competition for harbor and dock space, etc. The participants in this workshop summarized the available information concerning the distribution and natural history of these commercially valuable shellfish and attempted to assess their vulnerability to development.

7.2 SHELLFISH RESOURCES

7.2.1 Biology

King Crab

King crabs inhabit the northern Pacific in water of 0-10°C. In the eastern Bering Sea, red king crab inhabit the continental shelf regions out to the continental slope. The area of maximum abundance extends up to 160 km offshore between Unimak Pass and Port Heiden in Bristol Bay (Fig. 7.1). In these waters, the red king crab is the most abundant species of king crab and forms the basis of the commercial fishery. The blue king crab is second in abundance, with more limited distribution in colder waters along the Asian coast from the Kurile Islands to the Chukchi Sea. Major centers of abundance for blue king crab in the Bering Sea are near the Pribilof Islands, St. Matthew Island, and St. Lawrence Island.

The annual life cycle of the red king crab is characterized by a spring mating and spawning migration and a summer and fall feeding migration. In January, female crabs move from offshore waters into shallower embayments near the Amak Island-Black Hills-Port Moller area, along the north shore of the Alaska Peninsula. Males follow a month or so later.

Female crabs must molt before mating, but males need not. Young males generally molt annually until they are about eight years old; after this they generally molt only once every two or three years. Females molt on the breeding grounds between February and May; younger (primiparous) females molt earlier in the season than older crabs. Males molt earlier than females of the same size (Gray and Powell, 1966).

King crabs copulate shortly after the females molt. Copulation must take place within several days of molting, or fertilization will not occur (Kurata, 1960). Older, non-molting males may be more important than younger males to the reproductive success of the stock because they can

Table 7.1. Commercial shellfish caught in the St. George Basin.

Common Name	Species	Fishing gear employed	Fishing season
Red King crab	*Paralithodes camtschatica*	Pot	mid-Sep.-mid-Nov.
Blue king crab	*P. platypus*	Pot	mid-Sep.-mid-Nov.
Tanner crab	*Chionoecetes bairdi* *C. opilio*	Pot Pot	mid-Jan.-May mid-Jan.-Aug.
Korean hair crab	*Erimacrus isenbeckii*	Pot	Nov.-mid-Aug. year round near Pribilof Islands
Pink shrimp Humpy shrimp	*Pandalus borealis* *P. goniurus*	Trawl	Nov.-May
Snails	*Neptunea* spp. *Buccinum* spp.	Pot	May-Sep.

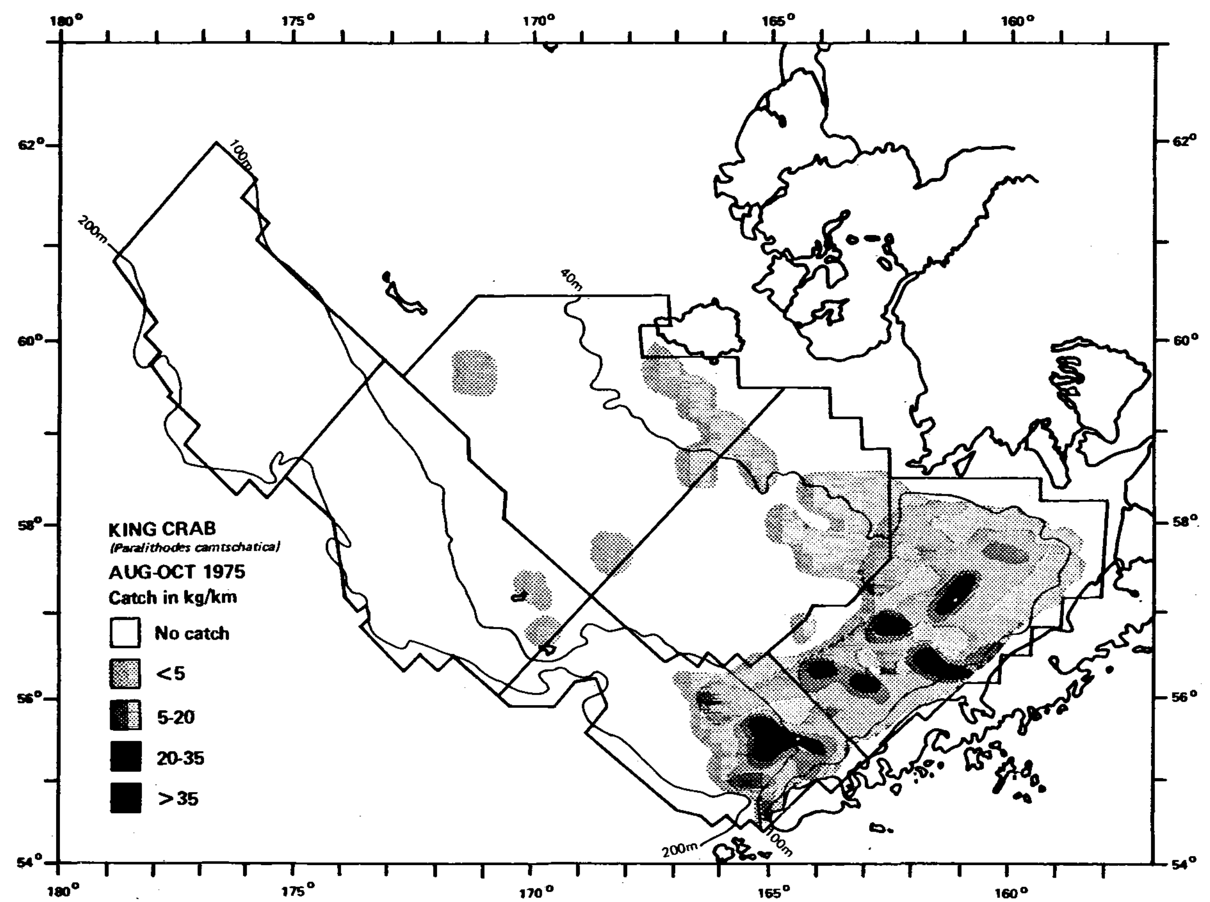

Figure 7.1. Distribution and relative abundance by weight of red king crab in the eastern Bering Sea (Pereyra et al., 1976).

mate throughout the entire season, while younger males are hampered by the stress of molting and cannot mate as often (Powell, pers. comm.).

Ova are extruded, fertilized, and then carried by the female for about 11 months. Fecundity increases with the size of females; the largest females may produce up to 400,000 eggs (Eldridge, 1972). Free-swimming zoea larvae are released the next seson when the females return to their breeding grounds. The zoea molts through four instars, sinking lower in the water column with each molt, and then metamorphoses into a glaucothoe larva. The glaucothoe molts into a juvenile stage that resembles the adult.

In the eastern Bering Sea, larval hatching and peak larval abundance occur from early May through mid-July. Larvae are concentrated along the North Aleutian shelf from Unimak Island into Bristol Bay (Fig. 7.2). During larval development, approximately 10 weeks, the center of peak abundance may move northeastward along the North Aleutian Shelf towards Bristol Bay (Fig. 7.3) (Haynes, 1974; Armstrong et al., 1981).

Shallow coastal areas, depths less than 30 m, are primary settling and rearing areas for juvenile (< 100 mm) king crabs. Young crabs that have settled to the sea bed live solitarily under rocks and debris in the intertidal zone, in association with bryozoans, algae, molluscs, and echinoids. During their first year, juvenile crabs may molt 11 times while growing from about 2 mm to 11 mm in carapace length. During the next two years, they molt eight more times and grow to about 60 mm long.

In their second and third years, juveniles larger than about 15 mm form large aggregations called "pods." Pods of up to several thousand individuals of both sexes are commonly observed close to shore, in water less than 30 m deep. Sometimes the water is barely deep enough to cover them at low tide. Podding continues at least into the fourth year, when the crabs again disperse and, like adults, move offshore to feed in summer and fall, returning to shallower waters in spring.

King crabs reach sexual maturity at four to six years of age. Males reach legal commercial size at about seven years. Most commercially caught males are eight or nine years old and, on the average, weigh about 3 kg each. Individuals 15 years old and weighing 11 kg have been harvested. Females may not be taken.

Larval crabs are planktonic feeders, utilizing phytoplankton and smaller zooplankton. In the glaucothoe stage, they settle to the bottom, where they feed on bottom species and organic detritus (Feder et al., 1980).

Juvenile and adult king crabs are bottom-foraging omnivores. Diatoms are a principal ele-

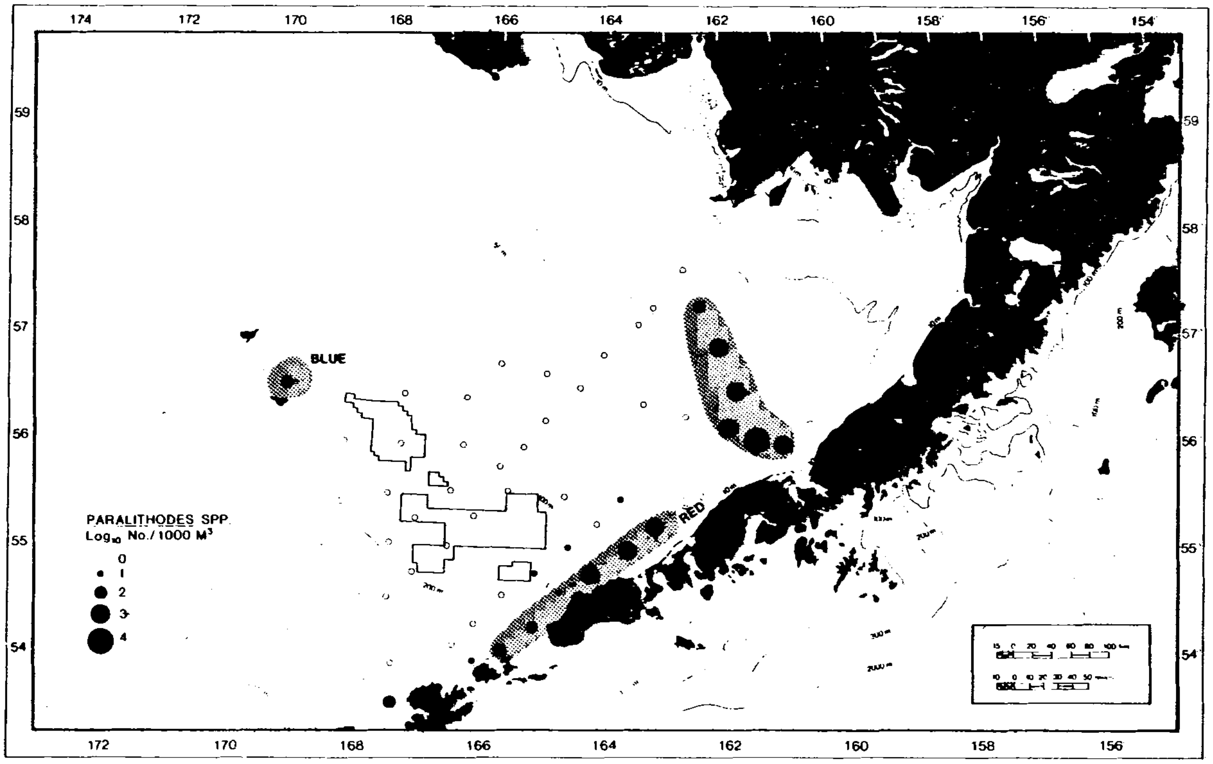

Figure 7.2 Distribution of king crab larvae from combined data collected May-June 1977 and 1980 (Armstrong et al., 1981).

ment in the diet of juveniles, occurring in 40 percent of stomachs analyzed. Other juvenile foods include protozoa, ostracods, algae, echinoderms, small molluscs, hydroids, and sponges (Bartlett, 1976). Adult king crabs feed on cockles, snails, clams, brittle stars, polychaete worms, and Tanner crabs (Feder and Jewett, 1980) (Fig. 7.4). In turn, king crabs are fed upon by sculpins, Pacific halibut, and sea otters. (Feder and Jewett, 1981).

Little is known about the biology of the blue king crab. It has been assumed to be similar to that of the red king crab, except that in the southern Bering Sea the population of blue king crabs is concentrated around the Pribilof Islands. However, recent data indicate that, unlike red king crabs, blue king crabs may spawn biennially, and blue king crab juveniles have not been observed to form pods (Wolotira, pers. comm.).

Tanner Crabs

Tanner crabs, also called snow crabs, have a circumarctic distribution that extends into the temperate waters on the east and west coasts of North America and Eurasia, respectively. In the eastern Bering Sea, Tanner crabs are broadly distributed over the continental shelf from the intertidal zone to at least 450 m. However, the two species of Tanner crab, *Chionoecetes opilio* and *C. bairdi* appear to be segregated by water temperature. *C. bairdi* usually are found in the warmer slope and outer continental shelf waters (4.5°C average) of the southern Bering Sea (Fig. 7.5a), whereas *C. opilio* prefer the colder waters (2.4°C average) to the north (Fig. 7.5b) (Somerton, 1981).

Although little information is available on the migration and behavior of these crabs in the eastern Bering Sea, they appear to make seasonal, sexually segregated movements related to reproduction. Young crabs of both sexes congregate by age groups. After reaching maturity and mating, males leave the aggregation, whereas the females that have recently reached maturity remain together throughout their lives.

The mating season of Tanner crabs in the Bering Sea is from February to early June. After mating, the female crabs carry the fertilized eggs for about 11 months. Gravid females brood an average of 30,000-80,000 eggs, although egg masses of up to 318,000 (Eldridge, 1972; Hilsinger, 1976) have been reported. The period of peak hach in the eastern Bering Sea appears to be mid-May for *C. bairdi* and mid-April for *C. opilio* (Somerton, 1981). The larvae have a fairly long pelagic life. Best estimates, based on both laboratory and field observations, indicate a total pelagic time of three months for two zoeal and one megalops stage (Incze et al., 1981). The rate of development is influenced by the availability of food and ambient temperatures. Juvenile Tanner crabs, which resemble adults, are bottom dwellers. Larval and juvenile crabs are found throughout the ranges of both species (Fig. 7.6).

The frequency of molting and growth in juveniles decreases with age. Males and females

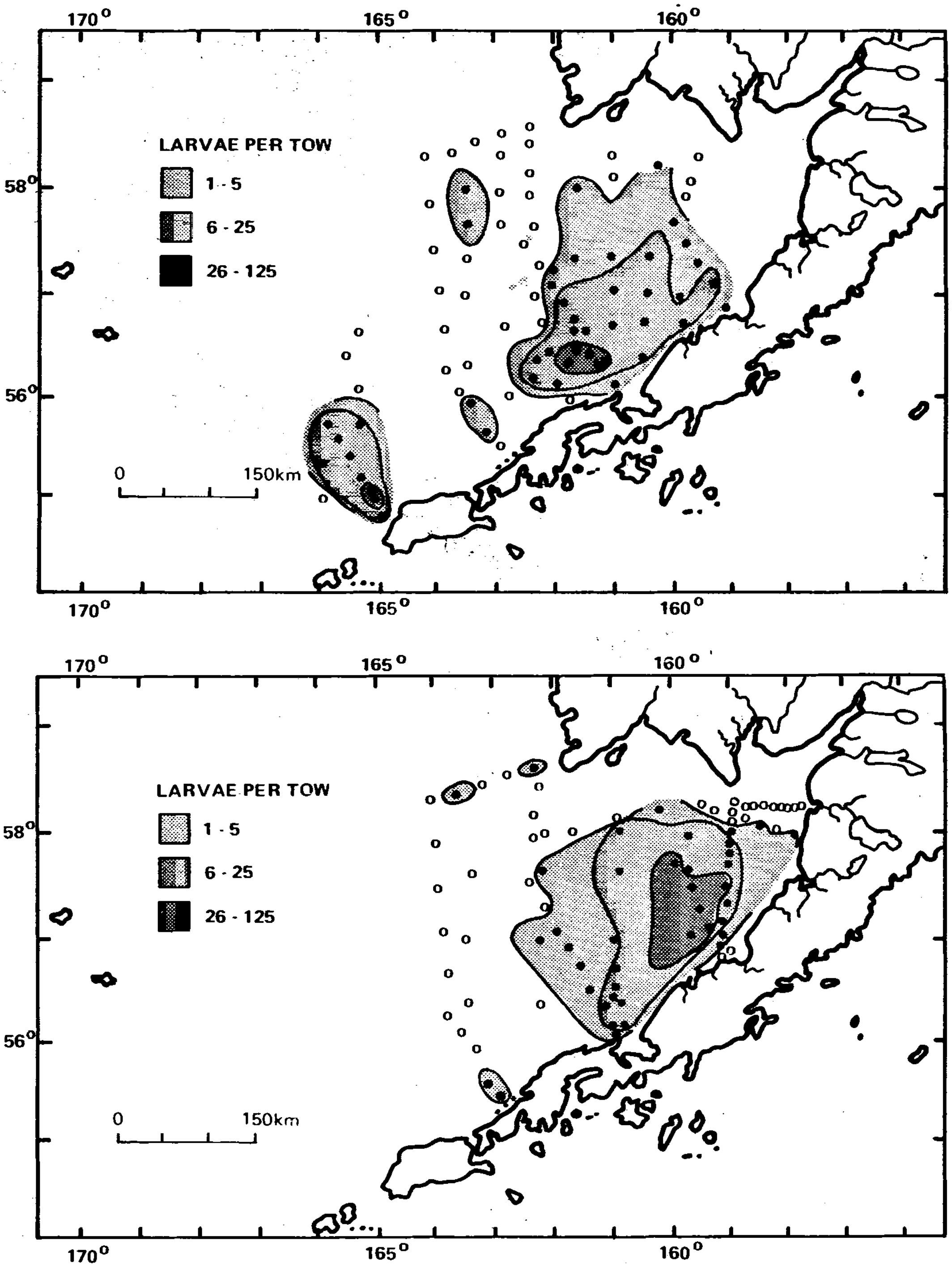

Figure 7.3. Distribution and abundance of king crab larvae in May (1969 & 1970, top) and June (1969 & 1970, bottom) (Haynes, 1974). Note that there were no sampling stations west of Black Hills or around the Pribilof Islands.

have similar growth rates until sexual maturity, at about five to six years of age. Commercially harvested males are usually 7-11 years old and weigh 0.9-1.8 kg each. Tanner crabs have an estimated maximum age of 14 years.

Free-swimming Tanner crab larvae consume phytoplankton and small zooplankton (Paul et al., 1979). After metamorphosis and settling, they consume benthic diatoms and other algae, hydroids, and detritus. It has been reported that adults in the Bering Sea feed on dead and decaying molluscs, crustaceans, and other organisms that accumulate on the ocean floor. This behavior probably reflects extensive commercial fishing and the resulting availability of dead organisms. The adults also prey on polychaetes, clams, hermit crabs, and brittle stars (Feder and Jewett, 1981). Tanner crabs in turn are fed upon by king crabs, at least six species of fishes (walleye pollock, Pacific cod, great sculpin, Pacific halibut, rex sole, and rock sole) and two marine mammals (walrus and bearded seal) (Feder and Jewett, 1981).

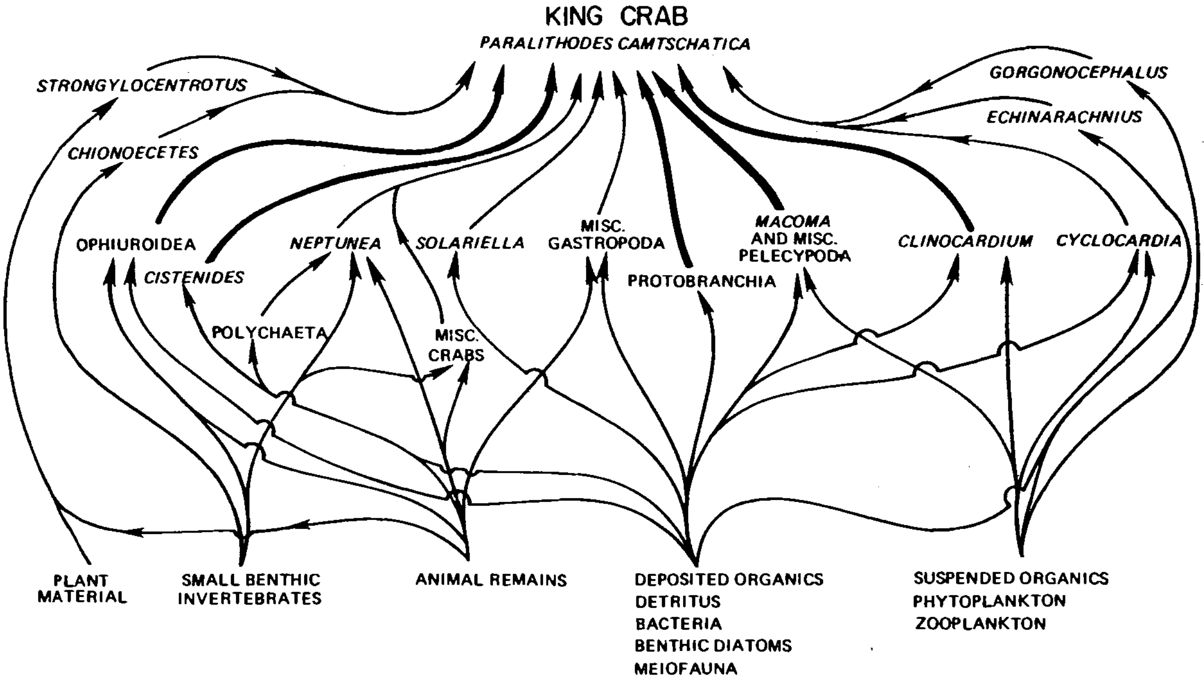

Figure 7.4. A food web for the king crab in the southeastern Bering Sea (Feder and Jewett, 1980).

Korean Hair Crab

The Korean hair crab is found throughout the Aleutian Islands and as far north as St. Matthew Island; the largest concentrations are found in the shallow waters along the northern shore of the Alaska Peninsula and around the Pribilof Islands.

The National Marine Fisheries Service has been collecting age, growth, and reproductive data on this species in the Bering Sea for the past four years, but few females have been caught so far. During the 1978, 1979, and 1980 trawl surveys more than 2000 males were caught but only 150 females. The low catch of females was probably due to selectivity of the gear; female hair crab are usually small, and very few reach or exceed 8 cm in length (Sakurai et al., 1972). Most of the females caught during the summer trawl surveys were in prespawning condition. About 20 percent of the females were carrying empty egg cases, and some females were observed in this condition during every month of the survey, from late May through mid-August. Only three spawning females were observed. These were taken during the latter half of May 1980, at about 64 m. The three females were brooding between 30,000 and 120,000 eggs apiece.

Females reach sexual maturity at two years of age (4 cm long), males at four (7-8 cm long) (Sakurai et al., 1972). Males may reach 12 to 13 cm in length. The maximum length of females is approximately 10 cm. Males over 8 cm (four years old) are harvested commercially.

Shrimp

Several species of pandalid shrimp inhabit the eastern Bering Sea, but only the pink shrimp (*Pandalus borealis*) and the humpy shrimp (*P. goniurus*) are of commercial interest. These species are most abundant along the central outer shelf and slopes of the Bering Sea on relatively smooth sand and mud bottoms (Fig. 7.7).

The life histories of *P. goniurus* and *P. borealis* are similar. Pandalid shrimp are protandric hermaphrodites. *P. borealis* become sexually mature as males when two or three years old and mate for the first time. By the fifth year, most individuals have changed into breeding females. However, individuals called "primary females," which never function as males, are believed to exist in every shrimp population.

Pink shrimp live six to seven years. Breeding takes place in September and October. Just before spawning, the female molts and grows a shell specialized for carrying the eggs. The eggs are fertilized as they are extruded from the female and are attached to specialized setae on the abdominal appendages. Pandalid shrimp produce 900 to 3,000 eggs per brood. (Fox, 1972). The eggs are carried for seven to eight months and hatch in the spring.

After release, the free-swimming larvae rise to the surface and spend up to three months drifting passively or swimming weakly and feeding on plankton. The larvae molt about six times during this period. By the end of the summer, the young

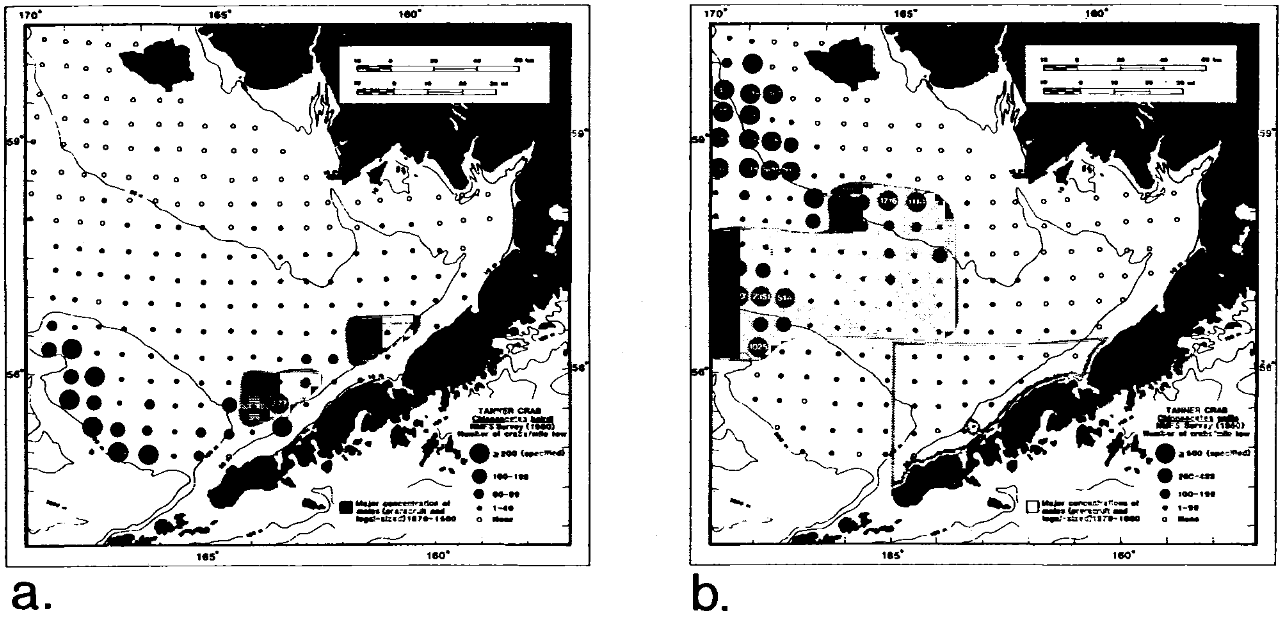

Figure 7.5. Distribution and abundance of Tanner crab, (Otto, 1981) a) *C. bairdi;* **b)** *C. opilio*

closely resemble miniature adults and spend part of their time feeding in the water column and the remainder on the bottom. The juvenile shrimp then develop into males.

Adult pink and humpy shrimp feed primarily on benthic organisms such as polychaetes, clams, and small crustaceans (Feder and Jewett, 1981). Pink shrimp are consumed by many demersal fishes, including walleye pollock, Pacific cod, rex sole, yellowfin sole, flathead sole, and arrow-tooth flounder.

Snails

At least 35 species of large marine gastropods inhabit the eastern Bering Sea shelf. By far the most important commercially utilized species is *Neptunea pribiloffensis.* (Seventy percent by weight of the Japanese snail catch in the eastern Bering Sea in 1973 was this species.) Other abundant species are *Buccinum scalariforme* (16 percent) and *B. angulosum* (11 percent).

The National Marine Fisheries Service assessed the snail resources of the Bering Sea shelf in the summer and fall of 1975. Snail distribution was patchy (Fig. 7.8), and the areas of highest density also supported a high biomass of fish and invertebrates other than snails. Snail biomass in some areas exceeded 35/km^2 and composed 1.7 percent of the total biomass and 6.6 percent of the invertebrate biomass in the survey area (MacIntosh, 1976).

The life histories of these large gastropods are similar. They spend their entire lives, which exceeds 10 years for *Neptunea,* on the bottom. Clusters of egg capsules are produced between May and October; they are usually deposited on large snail shells, either living or dead. Freshly laid egg clusters and capsules containing snails ready to hatch are numerous in the eastern Bering Sea in July. The newly hatched snails immediately take up a benthic existence.

These snails prey or scavenge on invertebrates such as sponges, marine worms, cockles, mussels, and shrimp. In turn, snails are preyed upon by crabs, including king crabs (MacIntosh, 1976).

7.2.2 Fisheries

Commercial

Since the decline of crab stocks in the Gulf of Alaska during the late 1960's, U.S. fishing activity in the Bering Sea has increased each year. More than 230 vessels produced a record catch of red king crab in 1980-81 valued at more than $118 million (Table 7.2). Other shellfish harvested include blue king crabs, Tanner crabs, Korean hair crabs, and several species of pandalid shrimp. Together, the Bering Sea shellfish resources are worth more than $150 million annually. They represented nearly 70 percent of the estimated ex-vessel value of the all-Alaska shellfish catch in 1980. In addition to the domestic fishery, foreign draggers operating in the Bering Sea annually harvest millions of crabs as a by-catch with pollock and other groundfish.

Red king crabs are the most valuable shellfish in the Bering Sea and have been harvested there by U.S. crabbers since 1947. Because crabbing is done during severe winter weather, most of the more than 200 vessels fishing today have mean keel lengths of more than 30 m. The crabs are fished most heavily within Bristol Bay and south of the Pribilof Islands, especially in the region bounded by latitude 56° to 57.5°W and longitude 163° to 166°W (ADF&G, 1981) (Fig. 7.9). This area produces more than 18,149 t annually and

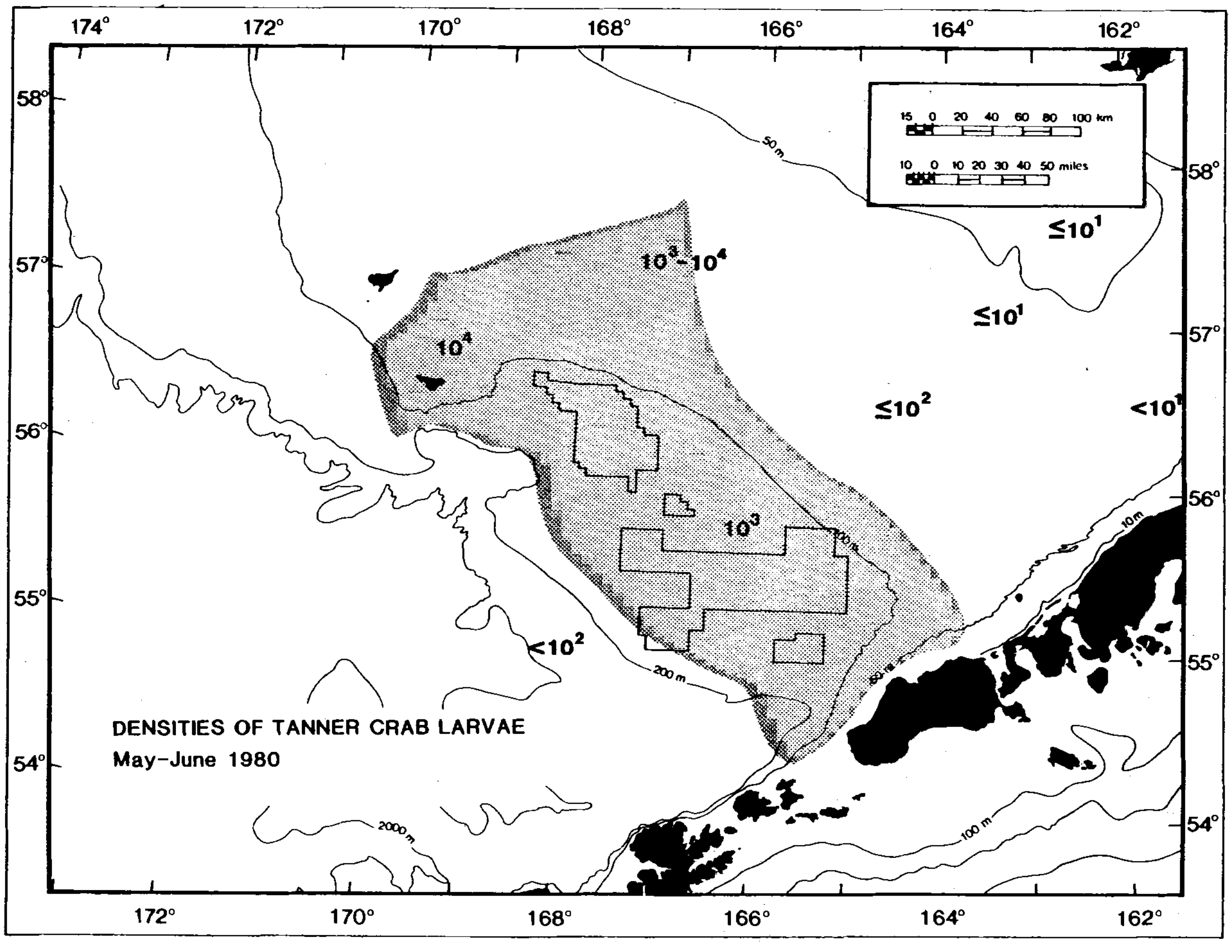

Figure 7.6. Densities of Tanner crab larvae expressed as number per 1,000 m^3 in the upper 60 m of the water (Incze et al., 1981).

encompasses the easternmost waters (between longitude 165° and 166°W) of the St. George Basin lease area. More than 37 percent of the 1980-81 Bering Sea red king crab catch was taken in the St. George Basin; over 6 percent was taken in the areas that have been proposed for sale.

The blue king crab fishery is concentrated in the shallow waters around the Pribilof Islands (Fig. 7.9). This fishery was started in 1973 during the summer when red king crab fishing was closed. The 1980-81 season began on September 15 and closed on November 15. With most fishermen going after red king crabs in Bristol Bay, only 15 vessels participated in the blue king crab fisheries during September and October, and the catch was low (1,407 t). After Bristol Bay was closed to fishing in October, more than 100 vessels moved to the Pribilof area, and 3,584 t or blue king crab were landed in less than two weeks (ADF&G, 1981). Although some blue king crabs were harvested in the waters north of the St. George Basin, about 75 percent of the total 1980-81 catch came from the fishing grounds surrounding St. Paul and St. George Islands and 14.5 percent from the western sale areas due east of the Pribilofs.

Tanner crab were first caught in the Bering Sea in 1968, incidental to the king crab fishery. In 1974, a *C. bairdi* fishery began. Although *C. opilio* was taken incidentally to the *C. bairdi* catch, it was not until the 1977-78 season when *C. bairdi* stocks declined sharply that the commercial fleet shifted its effort to *C. opilio*. Fishermen delivered over 14,065 t of *C. opilio* in 1979 and 17,695 t in 1980. More than 80 vessels participated in the Bering Sea Tanner crab fishery between January and August 1980.

Both *C. bairdi* and *C. opilio* are captured in abundance along the eastern and northern portions of the St. George Basin and over much of the region that has been proposed for sale (Fig. 7.10 and 7.11). A large part of the fishing grounds for the more commercially valuable *C. bairdi* are due east of the St. George Basin (to 163°W) in offshore waters north of the Alaska Peninsula (Fig. 7.10). This region is also planned for OCS leasing for oil and gas development.

Since 1979, foreign fleets have been prohibited from taking king and Tanner crabs off Alaska. Nevertheless, many crabs are taken as a by-catch of trawling for pollock and other demersal fish (Morris, 1981). The St. George Basin is a major area for these by-catches within the Bering Sea

Table 7.2. Commercial U.S. and foreign shellfish catch and value (dollars), for the 1980-81 season in the southeastern Bering Sea.[1]

	Southeastern Bering Sea			St. George Basin call area			Proposed St. George Basin sale area		
Resource	**Number**	**Metric tons**	**Estimated ex-vessel value**	**Number**	**Metric tons**	**Estimated ex-vessel value**	**Number**	**Metric tons**	**Estimated ex-vessel value**
King crab									
Red	23,307,140	59,846	$118,710,000	6,863,329	22,484	$44,610,874	430,556	1,406	$2,700,000
Blue	1,530,263	5,044	10,564,454	1,138,607	3,779	7,914,217	155,844	544	1,200,000
Tanner crab[2]									
C. *bairdi*	15,175,125	17,137	19,646,460	1,831,341	2,062	2,364,359	720,000	816	900,000
C. *opilio*	25,286,777	17,845	8,261,888	9,706,408	6,836	3,164,733	7,065,868	5,352	2,500,000
Foreign catch[3]									
King crab	1,162,949	3,798	7,619,642	639,760	2,089	4,191,708	-	-	-
Tanner crab	18,269,582	13,259	8,769,399	13,327,721	9,673	6,397,306	-	-	-
Korean hair crab	25,417	26	31,000	24,937	25	30,418	966	0.9	1,119
Pandalid shrimp	0	698	446,559	0	698	446,559	0	0	0
Totals: U.S.			$157,660,361			$58,531,160			$7,301,119
Foreign			16,389,041			10,589,014			

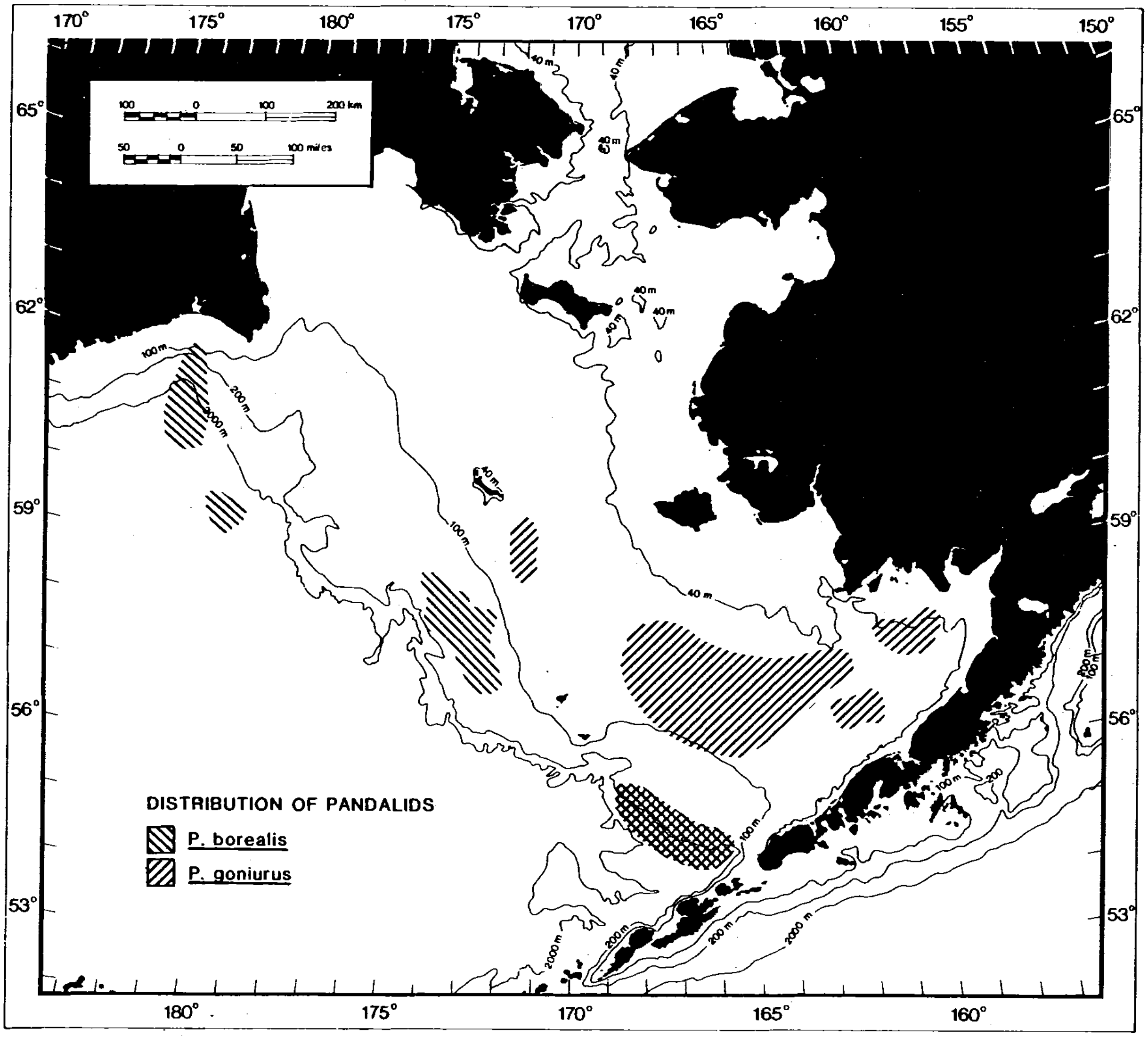

Figure 7.7. Distribution of pandalids in the eastern Bering Sea, August-November 1975 (NMFS, 1976).

(Table 7.2). Over 70 percent of the foreign catch of Tanners (more than 13 million crabs) and 55 percent of king crabs (about 640,000 crabs) are incidentally captured by foreign nations trawling between the 100-m and 200-m isobaths in the St. George Basin. The loss to American fishermen in 1980 was estimated at more than $16 million.

A fishery for hair crabs was initiated around the Pribilofs in 1979 and is rapidly expanding. The fishery has run concurrently with the Tanner crab season, except within 5 km (3 mi) of the islands, where it is open year round to allow local residents to have a summer fishery. In 1980, almost 98 percent of the total catch, or 25,000 crabs, were harvested within the St. George Basin by U.S. fishermen using king and Tanner crab pots. Although these pots are less efficient than those used by Japanese elsewhere (pots similar in size to those used to capture Dungeness crabs), the domestic catch was nearly 27 t in 1980. By July 1981, over 907 t of hair crabs with an estimated value of more than $1.7 million had been harvested (K. Griffen, pers. comm.). Most of this catch came from around the Pribilofs, although some crabs have been taken in the shallower waters north of the eastern Aleutian Islands. National Marine Fisheries Service estimates almost 14 million male crabs of harvestable size in the Bering Sea.

The number of red king crabs caught in the Bering Sea is expected to decline in coming years, because fishermen have harvested an exceptionally strong year class during the past two seasons. However, red king crab stocks, as well as blue king crab stocks, are thought to be stable. Year-class strength of red king crabs may be weaker than in recent years because of poor larval survival, attributed to unfavorable environmental conditions. Additionally, poor larval survival has been correlated in the past with years of exceptionally large salmon runs into Bristol Bay (as in 1980) and may reflect predation of larvae by pollock and emigrating smolts. Although *C. bairdi* stocks have been depressed in

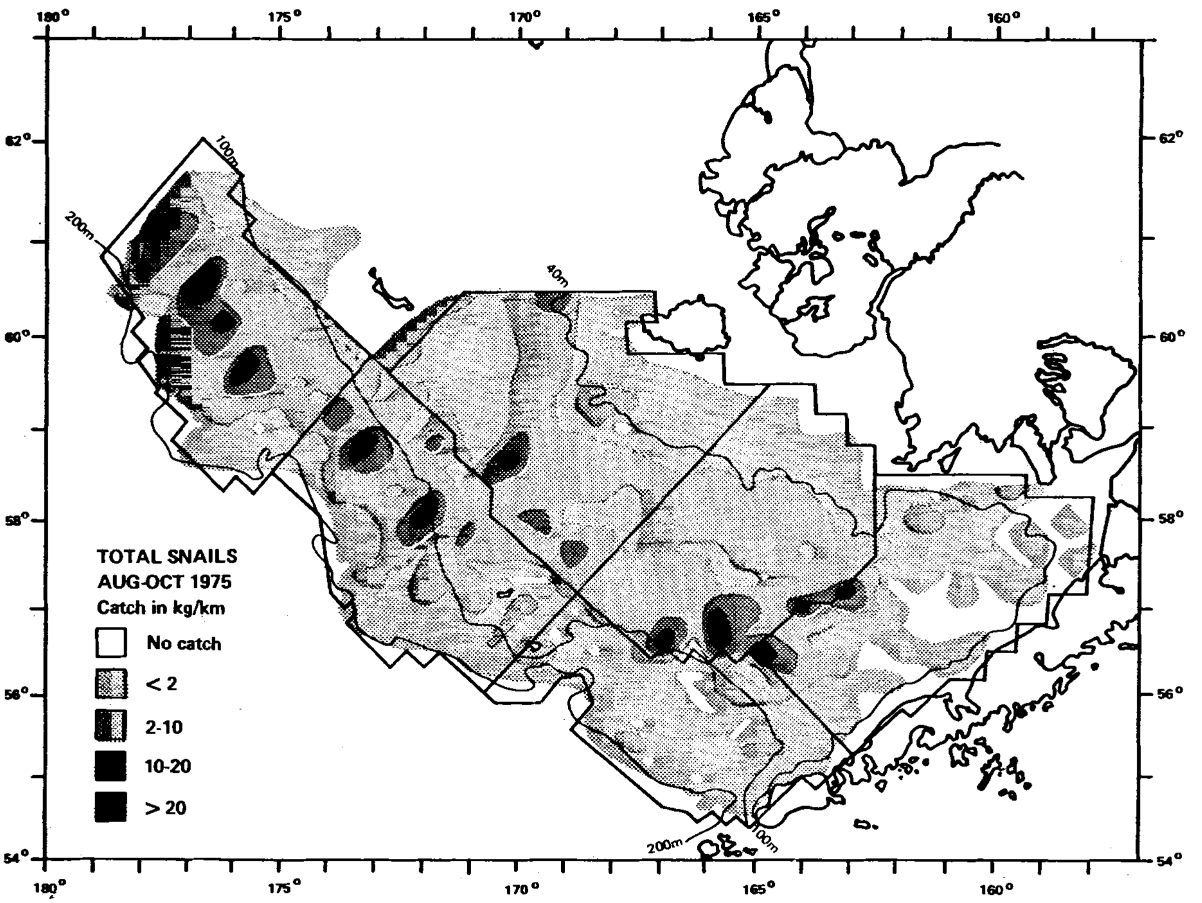

Figure 7.8. Distribution and relative abundance by weight of snails in the eastern Bering Sea (Morris, 1981).

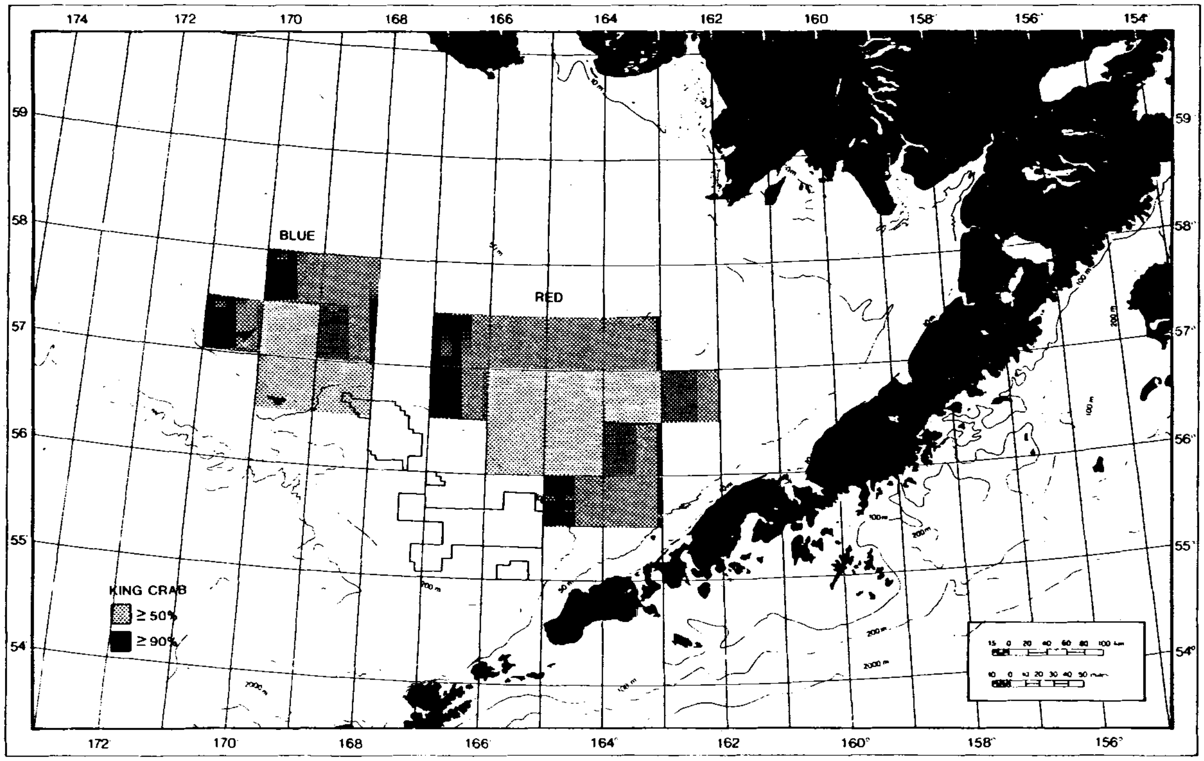

Figure 7.9. Major king crab catch areas relative to St. George Basin lease area (Otto, 1981).

Original was poor quality

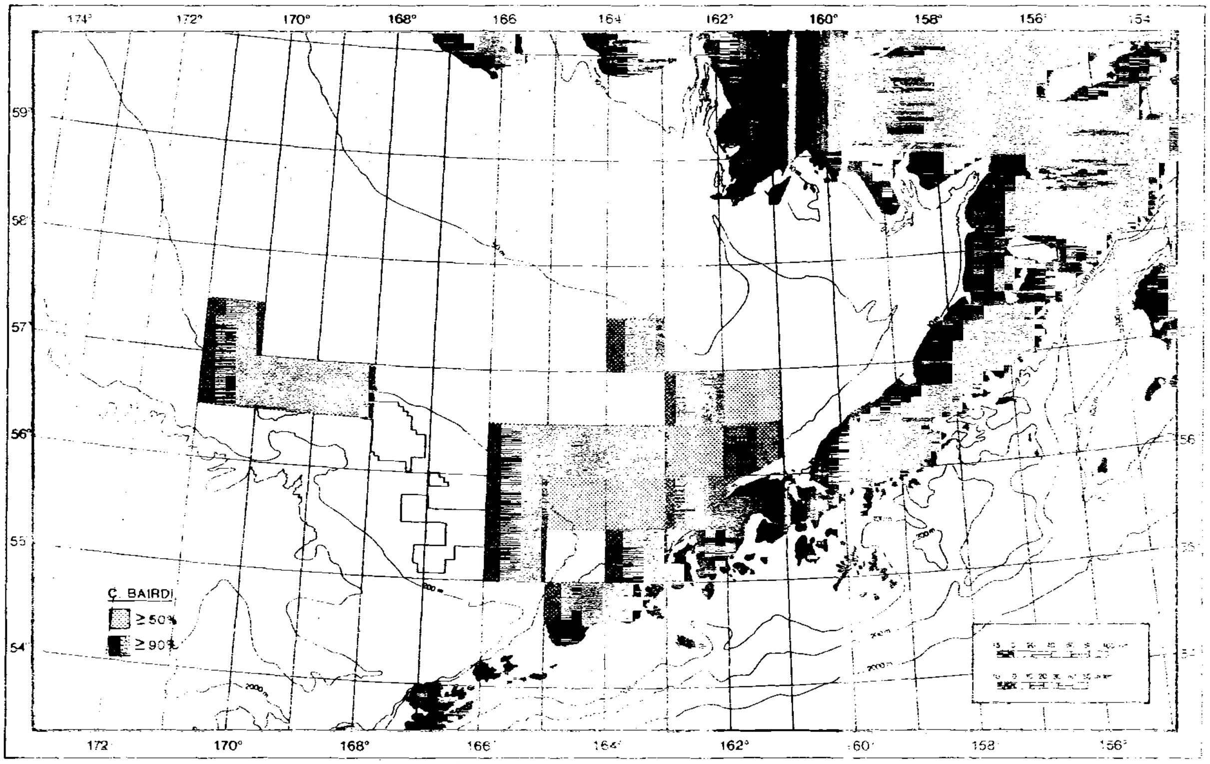

Figure 7.10. Major fishing grounds for *C. bairdi* relative to St. George Basin lease area (Otto, 1981).

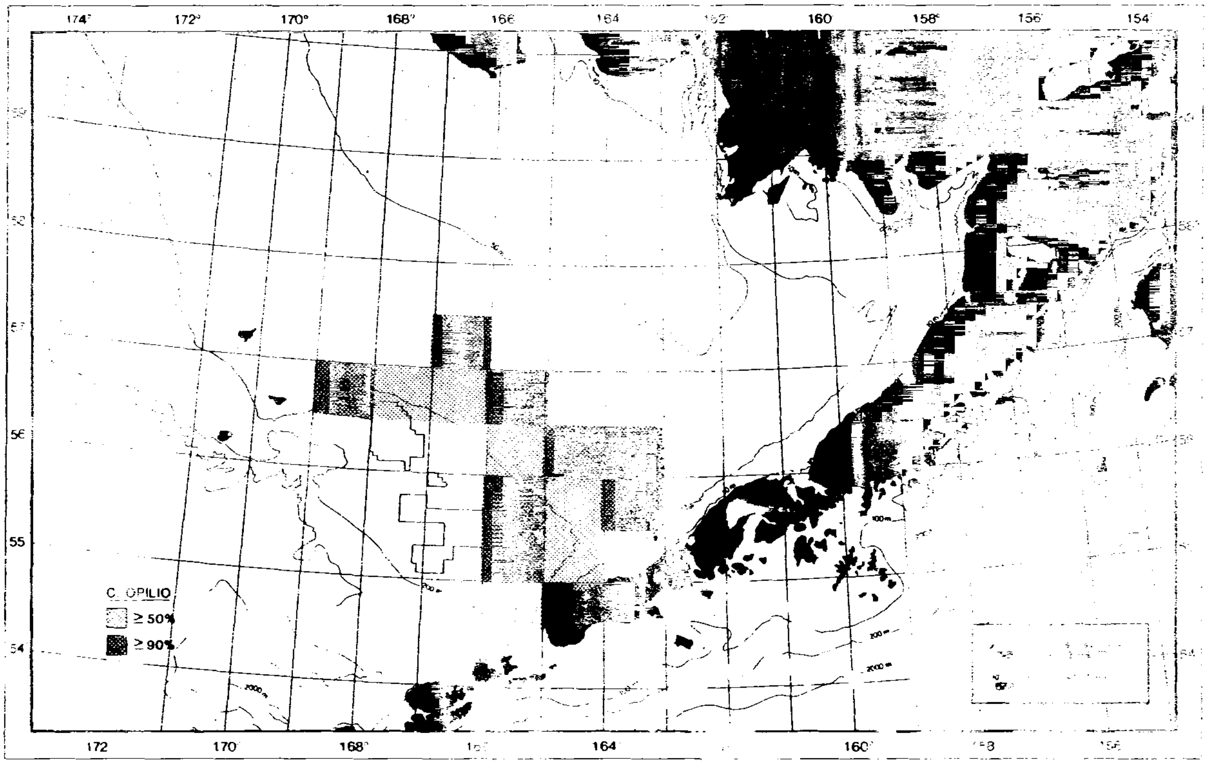

Figure 7.11. Major fishing grounds for *C. opilio* relative to St. George Basin lease ar[illegible] Otto, 19[illegible]

th[illegible] St. George Basin since 1977-78, recent evidence indicates that they may be increasing in the southern Bering Sea. On the other hand, the catch of *C. opilio* will probably continue to decline, as the fishery has been concentrated on one or two strong year-classes. A 1980 NOAA summer survey e[illegible] bio[illegible] 6,80[illegible] of hair crab around t[illegible] and these stocks appear to be h[illegible]lth[illegible] although little is known about their biolo[illegible] or migratory behavior.

The [illegible] pa[illegible]se began [illegible] fishery northwest of the Pribilof Islands (F[illegible] in 19[illegible] and were

Original was poor quality

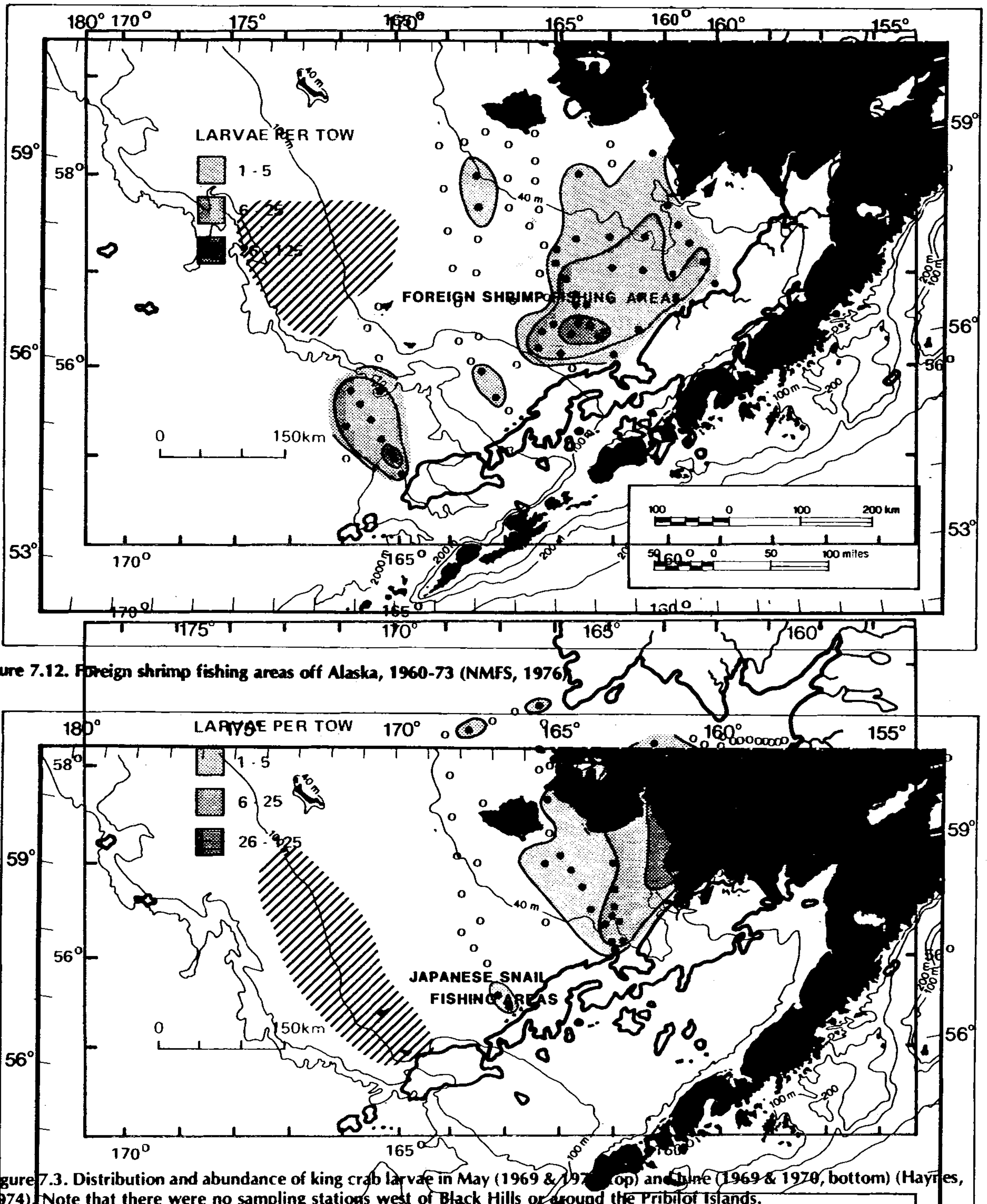

Figure 7.12. Foreign shrimp fishing areas off Alaska, 1960-73 (NMFS, 1976).

Figure 7.3. Distribution and abundance of king crab larvae in May (1969 & 1970, top) and June (1969 & 1970, bottom) (Haynes, 1974). Note that there were no sampling stations west of Black Hills or around the Pribilof Islands.

have similar growth rates until sexual maturity at about five to six years of age. Commercially harvested males are usually 7-11 years old and weigh 0.9-1.8 kg each. Tanner crabs have an estimated maximum age of 14 years.

Free-swimming Tanner crab larvae consume phytoplankton and small zooplankton (Paul et al., 1979). After metamorphosis and settling, they consume benthic diatoms and other algae, [illegible] [illegible] adults in the Bering Sea feed on dead and decay-

ing molluscs, crustaceans, and other organisms that accumulate on the ocean floor. This behavior probably reflects extensive commercial fishing and the resulting availability of dead organisms. The adults also prey on polychaetes, clams, hermit crabs, and brittle stars (Feder and Jewett, 1981). Tanner crabs in turn are fed upon by king [illegible] Jewett, 1981).

Figure 7.13. Distribution of Japanese snail-fishing effort in the eastern Bering Sea (NMFS, 1976).

joined briefly by six Soviet trawlers in 1963. Japanese catches peaked that year at 27,000 t. By 1968 the Japanese had removed a total of 85 million t and had exhausted shrimp stocks around the Pribilofs. Today the only commercial shrimping in the southeastern Bering Sea is done by a few U.S. trawlers in Makushin and Skan Bays, in the southern portion of the St. George Basin. Pink shrimp compose 80-90 percent of the catch of this minor fishery, which harvested 681 t of shrimp in 1980 (Table 7.2). Pandalid stocks in the Bering Sea are considered "distressed" (ADF&G, 1981), and it is unknown whether their condition is improving.

In 1971, Japan began to fish for snails on the continental shelf around and northwest of the Pribilof Islands (Fig. 7.13). About 3,000 t of edible meat per year were harvested between 1972 and 1975 (MacIntosh, 1980). The snails are caught from May through October in pots similar to those used for Tanner crabs. Meats are extracted aboard the catcher vessel and frozen raw. There is no present U.S. fishery, but the resource and the harvesting capacity exist and there is promise of a potential off-season operation in the next few years using existing domestic crab vessels.

7.2.3 Subsistence

Although subsistence use of the shellfish resources of the St. George Basin has not been measured quantitatively, the inhabitants of the Aleutians and Pribilofs are known to depend on the marine environment. Subsistence use of the major shellfish species in the St. George Basin area is probably as follows:

Subsistence species	Location	Gear used	Greatest use
Red king crab	Eastern Aleutians	Pots	Spring,summer
Blue king crab	Pribilofs	Pots	Year round
Hair crab	Eastern Aleutians, Pribilofs	Pots	Year round?
Tanner carb	Eastern Aleutians, Pribilofs	Pots	Year round

7.3 EFFECTS OF PETROLEUM HYDROCARBONS

When petroleum is transported into or obtained from coastal or off-shore areas, some inevitably escapes into the marine environment. This spilled oil can harm marine resources by causing:

1. immediate death of organisms, especially larval and juvenile forms, by asphyxiation, contact poisoning, or exposure to water-soluble toxic components of oil at some distance in space and time from a spill;
2. incorporation of sublethal amounts of petroleum hydrocarbons into organisms, resulting in reduced resistance to infection and other stresses and in failure to reproduce and grow at normal rates;
3. exposure to carcinogens and mutagens, resulting in tumors and morphological abnormalities affecting survival and commercial value;
4. low-level (sublethal) effects that may interrupt the feeding, migration, and propagation of the species or impair the survival of those species which are higher in the marine food web;
5. contamination of marine food resources rendering them unfit for human consumption.

Some of these effects, such as immediate death or acute toxicity, are much easier to measure and quantify than others. Toxicity is measured in the laboratory as LD_{50}, the concentration required to cause mortality in one-half of the organisms exposed to the substance being tested for a given time, usually 96 hours. Originally LD_{50}'s were measured in static systems, but because the hydrocarbon mixture is constantly changing as a consequence of weathering and the uptake and metabolism of the toxicants by the experimental organisms, actual exposures can change dramatically during the 96-hour assay period. Currently, LD_{50} values are determined in flow-through systems, so that the concentration of the toxicant remains fairly constant throughout the experiment. This is more realistic but poses logistical problems for large, active organisms. Other problems with measurements of acute toxicity include: unrealistically high LD_{50} values due to delayed mortality; the difficultyof correlating laboratory determinations with field observations since the toxicity of oil changes as it weathers; differences in the toxicity of different crude and refined oils; and the differing sensitivities of each life stage. Some of these problems, for example the effects of different oils on different life stages, are illustrated in Table 7.3.

In general, tests for acute lethality are properly used for initial, rapid evaluations of toxicity. They cannot easily be used to predict the ecological consequences of oil spills as major ecological changes are likely to arise from biological dysfunctions occurring at sublethal concentrations.

For the purpose of assessing possible effects of OCS oil and gas development, the minimum concentrations of petroleum hydrocarbons causing lethal and sublethal effects are summarized in Table 7.4. This table again illustrates the increased sensitivity of larval and juvenile forms to petroleum hydrocarbons. This may reflect differences in (1) size, since smaller forms have more surface area per unit mass than larger forms and would be more sensitive to water-borne pollutants; or (2) metabolic rates, since actively growing larvae have higher metabolic rates. For

Table 7.3. Some static LD_{50} values for red king crabs (Karinen, 1981).

Life stage	Oil	96 h LD_{50} (ppm)
Juvenile	SWSF Cook Inlet crude	3.69
	SWSF No. 2. fuel oil	1.02
Larva, stage 1	SWSF Cook Inlet crude	1.80
Larvae, molting 1-2	SWSF Cook Inlet crude	1.30

crustaceans, the increased sensitivity of larval forms can also be correlated with molting frequency; the increased permeability of the exoskeleton during molting facilitates penetration of toxins into the tissues.

Typically, oil concentrations of 1-4 ppm are lethal to a large fraction of both adult and larval crabs and shrimps after 96 hours of exposure. Shrimp are twice as sensitive as crabs. In general, the larvae of both shrimp and crab are two to three times more sensitive than adults to lethal doses. However, there are no toxicity data on adult king crab and only limited information on effects of fresh oil on juvenile crabs. Toxicity data are also sparse for snails, but the impermeable egg capsule and non-pelagic mode of larval development of these large snails minimize natural mortality by protecting the larvae from environmental hazards. The resulting high survival rate of the larvae is offset by the small number of larvae initially produced. Snails at all stages of development could be affected directly or indirectly by oil contamination of sediments or food organisms.

The sublethal effects of petroleum hydrocarbons may be obvious physical changes (Tanner crabs exposed to the seawater-soluble fractions of Cook Inlet crude oil (32 ppm) spontaneously shed one or more legs (Karinen and Rice, 1974), or may be subtle alterations in behavior or physiology. These effects are much more difficult to quantify and interpret. For example, increasing evidence indicates that, in aquatic ecosystems, behavior such as feeding, mating, habitat selection, migration, escape, and orientation may depend on the detection of trace amounts of certain organic compounds called pheromones. Petroleum contamination of even a few parts per billion may disrupt these chemically-mediated behavior patterns by masking or mimicking these compounds or by disrupting sensory mechanisms. Boesch (1973) found that exposure of the intertidal crab *Pachygrapsus crassipes* to the seawater-soluble extracts of crude oil (ppb) inhibited the feeding response and the mating stance of males exposed to the female's sex pheromone. Moreover, after the West Falmouth oil spill, male and female fiddler crabs (*Uca pugnax*) exhibited breeding display colors, and males assumed threat postures, even though the breeding season was over (Krebs and Burns, 1977). Exposure to 0.1-1.0 ppm of the seawatersoluble fraction of No. 2 fuel oil interfered with chemoreception in lobsters (*Homarus americanus*), causing inappropriate feeding, searching, escape, and aggressive behavior, and abnormal neuromuscular control (Atema, 1977). Failure to find food, inappropriate responses to environmental stimuli, failure to find mates, and change in time of spawning could result in significant declines in crab and shrimp populations.

Shellfish can accumulate petroleum hydrocarbons from the water or from their food. In heavily contaminated areas, crabs, bivalves, and bryozoans have been reported to exhibit lesions and neoplasms in several different tissues. These abnormalities are postulated to be the result of petroleum hydrocarbon accumulation and metabolism. However, attempts at inducing neoplasms by exposing organisms to petroleum products in the laboratory have been unsuccessful (Yevich and Barszcz, 1977).

Accumulation of hydrocarbons in shellfish tissue may not only harm the animals, it may also make them unfit for human consumption. As an example, crude oil contains small quantities of known human carcinogens, e.g., benzo(a) pyrene (Blumer, 1971). Also, "tainting," the perception of an objectionable oily taste or odor in seafood as the result of petroleum contamination, is of great concern to fishermen due to the fear that tainted catches will be refused. Although acutely contaminated organisms can depurate rapidly once placed in clean water, this process is not

Table 7.4. Generalized sensitivities (minimum) of marine organisms to the seawater-soluble fractions of petroleum (Moore and Dwyer, 1974).

Concentration	Effect	Life stage
1-100 ppm	lethal	adult
0.1-1.0 ppm	lethal	larval, some eggs
0.01-1.0 ppm	sublethal	adult
0.001-0.1 ppm	sublethal	larval

necessarily complete. Analysis of tissues for petroleum hydrocarbons is still an art; a minor, undetectable component of the oil may be the major taint-producing compound.

7.4 HYPOTHETICAL OIL SPILLS

Two hypothetical spill case studies were discussed at the meeting; they specified the release of oil at latitude 55.5°N, longitude 166°W, either 50,000 bbl at the surface at once or 5,000 bbl/d for 10 days, as in a well blowout.

The instantaneous spill of 50,000 bbl at the surface would produce an oil slick which could cover about 100-300 km² within 24 hours of release and could remain this size for at least 10 days. (Chapter 2). The seawater-soluble fraction of the oil could form (1) a 50 m-wide band at the origin of the spill containing 5 ppm of soluble hydrocarbons mixed to a depth of 20-30 m in the summer, 75-100 m in winter; (2) a 5 km-wide band originating in the source in which the oil concentration gradually declines from 5 ppm to 1 ppm and is mixed to a depth of 20-30 m in the summer, 75-100 m in winter; and (3) a band from 5 km to the outer edge of the spill (20 km) in which the oil concentration would decline from 1 ppm to 80 ppb with similar mixing. These concentrations were derived from studies using Prudhoe Bay crude and are similar to those reported from the IXTOC-I spill (Boehm and Fiest, 1980).

A subsurface release of oil, however, could spread dissolved oil of about 20 ppb over an area between 100 and 300 km² after 10 days (chapter 2).

Oil released from the designated site in summer (June-August) would move in an eastward direction, approximately 200 km and could approach the Alaska Peninsula from Unimak Island. Predicted oil spill trajectories from release sites south of 55.5°N, 166°W indicate that the oil could reach this shoreline (see Figs. 2.18 and 2.19, chapter 2).

In winter (December-May), however, oil released from the designated site would be transported toward the west and would not reach the coast. If the release site were shifted north of 55.5°N 166°W, the slick could reach the Pribilof Islands (see Figs. 2.20 and 2.21, Chapter 2).

7.5 POTENTIAL IMPACTS

7.5.1 Lethal Effects

The concentrations of the seawater-soluble oil fractions resulting from the hypothetical oil spills are sufficient to kill all pelagic larvae in the 100-300 km² area of the spill. However, this area is about one percent of the St. George Basin lease area and less than 0.002 percent of the total area of the St. George Basin. A spill of 50,000 barrels would not significantly affect the area's pelagic shellfish larvae.

Most crude oils and refined petroleum products have specific gravities less than 1 so that they float when released into the marine environment. However, after release the oil can be acted upon by several processes all of which result in the transfer of the oil from the water column to the benthos. Some oils have an initial density close to that of water (e.g., Bunker C). These may lose volatile or soluble components as the result of "weathering", and sink (Conomos, 1975). Sinking apparently occurred after a Bunker C spill in cold water off the coast of Greenland (Mattson and Grose, 1978). The sinking of spilled oil as the result of changing density is a difficult process to predict and quantify because it depends on the characteristics and weathering of the spilled oil.

Oil may be ingested by zooplankters and excreted and transported as fecal pellets. Shaw (in press) calculated the rate of transfer of spilled oil from the water column to the benthos by copepods for the southern Bering Sea. If copepod behavior and metabolism, including fecal pellet production rate, are unchanged in the presence of oil, and if copepod abundance is maximum (Else, 1981), 20 mg oil/m³/d could be ingested and excreted as fecal pellets. If this concentration of oil is mixed 1 cm deep into the sediments, the resulting oil contamination would be 6.7 ppt over 100-300 km². This agrees well with the concentration of 7 ppt observed in the particulate matter settling out of the water column after the *Tsesis* spill (Boehm et al., 1980). After the *Tsesis* spill, decline in benthic macrofauna abundance was observed, the result of the disappearance of two species of motile amphipods *(Pontoporeia affins* and *P. femorata)* and polychaete *(Harmothoe sarsi)*. There was little change in biomass, however, since the dominant *Macoma balthica* did not decrease in abundance (Elmgren et al., 1980).

Oil may be transported to the benthos by adsorption to bottom sediments that have been resuspended by storms. A severe storm in 60 m of water would stir oil downward into the water column and bottom sediments upward into the water column. Under these conditions and neglecting the evaporative losses and advection of the oil slick from the spill site, it was calculated that oil could reach the benthos in concentrations on the order of g/m² over an area of about 100 km² (see section 2.4.4). Lesser concentrations would occur over hundreds of square kilometers. If the concentration of oil delivered to the bottom is 10 g/m² and is mixed 1 cm deep, the resulting crude oil concentration would be 3-4 ppt. (Curl, pers. comm). This concentration would probably kill many snails, crabs, and clams. As mentioned above, however, 100 km² is less than 1 percent of the St. George Basin lease area and less than 0.002 percent of the total area of the St. George Basin. A spill of 50,000 barrels from 55.5°N 166°W would not significantly affect the benthic shellfish resources.

7.5.2 Sublethal and Indirect Effects

Sublethal effects of oil contaminations on the benthos are likely but difficult to assess. Benthic contamination may alter shellfish behavior or may interfere with the detrital food chain. The total amount of available nutrients cycled through the detrital food chain in the subarctic marine environment ranges from 50 to 90 percent. One part per thousand of crude oil incorporated into the sediments will decrease the production of bacterial biomass (the basis of this food chain) by at least 50 percent for as long as a year. This amounts to a reduction of 25 to 45 percent in the amount of food available to higher trophic levels (Griffiths and Morita, 1981).

Possible negative effects on the fisheries from spilled oil are not limited to the destruction or reduced productivity of the resource. A major oil spill could damage or ruin fishing gear. Oil would foul not only crab pots, longlines, purse seines, and other gear, but the fishing vessels themselves. Bering Sea crab vessels hold their catch in tanks of circulating seawater. Contamination of incoming water could result in losses of up to $300,000 per spill for king crab and $200,000 per spill for Tanner crab. Further losses would be incurred due to time spent cleaning the hold. Concurrently, the marketability and monetary return to the fishing and processing industries might be significantly reduced for a while because of real or imagined tainting.

7.5.3 Alternate Scenarios

Spills larger than 50,000 barrels would exhibit concentration gradients similar to those discussed above but over proportionally larger areas. For example, a spill of 500,000 barrels could form a slick covering 1,000-3,000 km². Hydrocarbon concentrations in the affected area (10 percent of the sale area) might be great enough to kill all pelagic larvae in the affected area. This great a larval mortality would significantly affect the shellfish populations.

Tanner crab larvae in the St. George Basin have a strong diel vertical migration (Armstrong and Incze, pers. comm.). Nocturnal surface tows during July 1981 collected megalopae at densities of 10,000-24,000/1,000 m³, some of the highest densities recorded for any larval stage of this species (see Fig. 7.6). Most important, this great abundance was recorded from the upper meter, where hydrocarbon concentrations would initially be highest in a surface spill. Megalopae represent survivors of the year's larval hatch (the natural mortality of zoeal stages 1 and 2 is thought to be very high); vertical migration of megalopae to the surface after a spill could expose a significant fraction of these survivors to toxic concentrations of hydrocarbons. Although only 10 percent of the total sale area would be affected and data on the distribution of the megalopa stage are virtually nonexistent it is possible that a very large proportion or an entire year-class of Tanner crab might be affected by such a spill.

If the oil release site is moved south of 55.5°N, 166°W, a spill occuring during June-August could affect the Alaska Peninsula from Unimak Island eastward (Chapter 2). Spilled oil which reaches the nearshore zone could be transported to the benthos by adsorption onto suspended particulate matter. Incorporation of oil into the nearshore sediments along the Alaska Peninsula could adversely affect red king crab stocks for a long time. One ppt of crude oil in sediments reduces the microbial detrital food chain activity by 50 percent, resulting in a 25 to 40 percent loss of detrital food (Griffiths and Morita, 1981). Twenty parts per thousand could severely damage detrital food chains and juvenile and young crab which rely on the members of this chain for both food and shelter. Concentrations of 110 ppt were reported in the sediments along the coast of France following the *Amoco Cadiz* spill (Vandermeulen et al., 1978). Moreover, oil incorporated into the sediments at concentrations greater than 1 ppt is degraded very slowly, particularly in fine-grained sediments in low-energy environments such as that of the St. George Basin. Weathering experiments conducted *in situ* with Cook Inlet crude oil incorporated into Kasitsna Bay sediments, indicate that fresh or weathered crude oil incorporated into the sediment at a concentration of 50 ppt had changed little in composition and quantity by the end of one year. Sediments containing concentrations of 1 ppt crude oil did show selective utilization of aliphatic hydrocarbons. The aromatics were unchanged. At the end of one year, sediments originally containing 0.1 ppt crude oil appeared to contain only biogenic hydrocarbons in quantities similar to those observed in the non-treated control sediments (Payne, 1982). Thus, oil in the sediments would seriously affect the food, shelter, and behavior of young and juvenile crabs, the most sensitive stages; these effects would be felt by year classes 0-5 for more than one year and by females migrating into nearshore areas to spawn.

Alternatively, if the oil release site is moved north of 55.5°N, 166°W, a spill occuring during

December-May could reach the Pribilof Islands. The incorporation of oil into the nearshore sediments around the Pribilof Islands could severely affect the blue king crab and Korean hair crab as described above for the red king crab.

7.6 INFORMATION NEEDS

As a result of this workshop, the participants agreed that more information, in several areas, was required for a better assessment of the possible impact of oil and gas development. These areas include:

1. Reproductive biology of red king crab along the North Aleutian Shelf.
    a. Effects of chronic exposure to petroleum hydrocarbons on maturing eggs, i.e. abnormalities, growth rate, hatching success and larval survival.
    b. Larval distribution, including centers of abundance, time of greatest hatch, and duration of larval stages. It should be noted that Figs. 7.2 and 7.3 are based on on sporadic sampling from ships of opportunity.
    c. Nearshore biology and ecology of larval and juvenile crabs.
    d. Effects of chronic exposure to petroleum hydrocarbons on the ability of adult crabs to mate successfully.
2. Effects of petroleum hydrocarbons on North Aleutian Shelf microbial processes and the resultant effects on benthic community metabolism.
3. Biology of the Korean hair crab.
4. Biology of the blue king crab, including time and place of breeding, timing of larval release, larval distribution, life history, and utilization of the more vulnerable nearshore areas by adults and juveniles.
5. Toxicity and sublethal effects of petroleum hydrocarbons on *Neptunea* spp., including juveniles.

7.7 SUMMARY

The shellfish fisheries in the Southeastern Bering Sea are either among the most lucrative of U.S. fisheries, or have the potential for becoming very valuable. For example, the 1980 king crab catch from the southeastern Bering Sea had an estimated value of $129 million. Not only are these shellfish of major commercial value but they are also of important subsistence value to the local residents. Any or all of these fisheries could be subject to loss as a result of oil and gas development in the St. George Basin. In order to assess the extent of possible loss, the participants in this workshop considered the fisheries, the shellfish stocks, and the effects of spilled oil.

With the exception of the shrimp, which have suffered from overfishing, shellfish stocks in the southeastern Bering Sea are thought to be "healthy" and capable of producing near maximum sustainable yields. However, catch of both red king crab and the smaller Tanner crab *(C. opilio)* will probably remain low for several years.

The early developmental stages of crustaceans, either pelagic or benthic, are the most sensitive to spilled oil. Discussion indicated that a spill which occurred either at the surface or on the sea bottom could have similar acutely toxic effects on the pelagic larvae. But spills of 50,000 barrels were thought to be too small, forming a slick of approximately 300 km² or 1 percent of the area of the St. George sale area, to cause any significant loss of pelagic larval. A spill on the order of 500,000 barrels or larger, which occurred in an area of maximum larval abundance, could conceivably kill an entire year class of larvae, with long lasting effect to the stock and corresponding fishery.

Because the sediments are the ultimate sinks for the residual components of spilled oil, concentrations of petroleum hydrocarbons in the sediments may reach the ppt level. Moreover, in cold waters the degradation of these components occurs very slowly. Benthic organisms, therefore, may be exposed to petroleum hydrocarbons for long periods of time. It was estimated that a spill of 50,000 barrels in 60 m of water could cover 100 km² of bottom with oil concentration in ppt. This would kill many of the benthic organisms, but 100 km² is less than 1 percent of the St. George Basin lease area, so there would be little, if any, long term effect on the fisheries. If, however, the area containing the oil was along the north shore of the Alaska Peninsula and included the prime mating and nursery areas of the king crab, the effects on the fishery could be long-term and severe.

OCS oil and gas development in the St. George Basin may affect the shellfish fisheries without impacting the resource itself. This would happen by increased competition between fishing and petroleum industries for limited dock and harbor space in this remote region. The placement of rigs and establishment of safety zones may result in minor losses of fishing areas, and in the case of a spill, markets for shellfish products might be lost through real or perceived belief that tainting has occurred. Gear could also be fouled by spilled oil. Finally, increased vessel traffic in the St. George Basin may result in greater numbers of pots being lost, as marking buoys are overrun, punctured, and rendered unrecoverable.

7.8 REFERENCES

Alaska Department of Fish and Game (ADF&G). 1981. Westward region shellfish report to the Alaska Board of Fisheries, March 1981. Div. Comm. Fish., Westward Regional Off., Kodiak.

Armstrong, D., L. Incze, J. Armstrong, and D. Wencker. 1981. Abundance of larval king crab and other decapod larvae in the eastern Bering Sea and their relationship to oil and gas develoment in St. George Basin. St. George synthesis meeting. Unpub. MS.

Atema, J. 1977. The effects of oil on lobsters. Oceanus 20:67-73.

Bartlett, L. D. 1976. King crab (Family Lithodidae), pp. 531-545. *In:* W. T. Pereyra, J. E. Reeves, and R. G. Bakkala (eds.), Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. NOAA/NMFS, Northw. Alaska Fish. Cent., Seattle, Wash.

Blumer, M. 1971. Scientific aspects of the oil spill problem. Environ. Aff. 1:54-73.

Boehm, P. D., J. Barak, D. Fiest, and A. Elskus. 1980. The analytical chemistry of *Mytilus edulis, Macoma balthica*, sediment trap and surface sediment samples, pp. 19-274. *In:* J. J. Kineman, R. Elmgren, and S. Hansson (eds.), The Tsesis Oil Spill. U.S. Dep. Comm.

Boehm, P. D., and D. L. Fiest. 1980. Surface water column transport and weathering of petroleum hydrocarbons during the IXTOC-I blowout in the Bay of Campeche and the relation to surface oil and microlayer compositions, pp. 267-340. *In:* Proc. symposium on preliminary results from the September 1979 Researcher/Pierce IXTOC-I cruise, Key Biscayne, Florida, June 9-10, 1980. NOAA/OMPA, Boulder, Colo.

Boesch, D. 1973. Biological effects of chronic oil pollution on coastal ecosystems. Background information for Ocean Affairs Board Workshop on Inputs, Fates, and Effects of Petroleum in the Marine Environment, pp. 373-383.

Conomos, T. J. 1975. Movement of spilled oil as predicted by estuarine non-tidal drift. Limnol. Oceanogr. 20:159-173.

Eldridge, P. 1972. The king crab fisheries in the Gulf of Alaska, pp. 211-266. *In:* D. H. Rosenberg (ed.). A review of the oceanography and renewable resources of the Northern Gulf of Alaska. Inst. Mar. Sci., Fairbanks. Rep R72-23.

Elmgren, R., S. Hansson, U. Larsson, and B. Sundilin. 1980. Impact of oil on deep soft bottoms, pp. 97-126. *In:* J. J. Kineman, R. Elmgren, and S. Hansson (eds.), The Tsesis Oil Spill. U.S. Dep. Comm.

Else, P. V. 1981. The prediction of hydrocarbon transport via copepod fecal pellets. M.S. Thesis, Univ. Alaska, Fairbanks.

Feder, H. M., and S. C. Jewett. 1980. A survey of the epifaunal invertebrates of the southeastern Bering Sea with notes on the biology of selected species. Inst. Mar. Sci., Fairbanks. Rep. 78-5.

Feder, H. M., and S. C. Jewett. 1981. Feeding interactions in the eastern Bering Sea with emphasis on the benthos. *In:* D. W. Hood and J. A. Calder (eds.), *The Eastern Bering Sea Shelf: Oceanography and Resources*. NOAA/OMPA, Seattle, Wash. Vol. 2:1229-1262.

Feder, H. M., K. McCumby, and A. J. Paul. 1980. The food of post-larval king crab, *Paralithodes camtschatica*, in Kachemak Bay, Alaska (Decapoda, Lithodidae). Crustaceans 39:315-318.

Fox, W. W., Jr. 1972. Shrimp resources of the northeastern Pacific Ocean, pp. 313-338. *In:* A review of oceanography and renewable resources of the northern Gulf of Alaska. Inst. Mar. Sci., Fairbanks. Rep. R72-73.

Gray, G. W., and G. C. Powell. 1966. Sex ratios and distribution of spawning king crabs in Alitak Bay, Kodiak Island, Alaska (Decapoda, Anomura, Lithodidae). Crustaceana 10:393-309.

Griffiths, R. P., and R. Y. Morita. 1981. Summary of data related to the petroleum of crude oil effects on carbon cycling. St. George synthesis meeting. Unpub. MS.

Haynes, E. 1974. Distribution and relative abundance of larvae of king crab, *Paralithodes camtschatica*, in the southeastern Bering Sea, 1969-1970. Fish. Bull. 72:804-812.

Hilsinger, J. R. 1976. Aspects of the reproductive biology of female snow crabs, *Chionoecetes bairdi*, from Prince William Sound and the adjacent Gulf of Alaska. Mar. Sci. Comm. 2:201-225.

Incze, L. S., D. A. Armstrong, D. L. Wencker, and J. Armstrong. 1981. Tanner crab larvae in the southeastern Bering Sea: Spatial and temporal patterns of distribution and abundance. St. George synthesis meeting. Unpub. MS.

Karinen, J. F. 1981. Potential effects of OCS development on shellfish resources of the St. George Basin. St. George synthesis meeting. Unpub. MS.

Karinen, J. F., and S. D. Rice. 1974. Effects of Prudhoe Bay crude oil on molting Tanner crabs, *Chionoecetes bairdi*. Mar. Fish. Rev. 36:31-37.

Krebs, C. T., and K. A. Burns. 1977. Long-term effects of an oil spill on populations of the salt marsh crab *Uca pugnax*. Science 197:484-487.

Kurata, H. 1960. Studies on the larvae and post-larvae of *Paralithodes camtschatica*: 3. The influence of temperature and salinity on the survival and growth of larvae. Bull. Hokkaido Reg. Fish. Res. Lab. 21:9-14.

MacIntosh, R. A. 1976. Snails, pp. 553-559. *In:* W. T. Pereyra, J. R. Reeves, and R. G. Bakkala (eds.), Demersal fish and shellfish resources of the Eastern Bering Sea in the baseline year 1975. NOAA/NMFS, Northw. Alaska Fish. Cent., Seattle, Wash.

MacIntosh, R. A. 1980. The snail resource of the eastern Bering Sea and its fishery. Mar. Fish. Rev. May 80:15-20.

Mattson, J., and P. Grose. 1978. Impact assessment of the USNS POTOMAC oil spill. Interim Final Rep. NOAA.

Moore, S. F., and R. L. Dwyer. 1974. Effects of oil on marine organisms; a critical assessment of published data. Water Resources 8: 819-827.

Morris, B. F. 1981. An assessment of the living marine resources of the central Bering Sea and potential resource use conflicts between commercial fisheries and petroleum development in the Navarin Basin, Proposed Sale #83. Nat. Mar. Fish. Serv., Anchorage, Alaska.

National Marine Fisheries Service (NMFS). 1976. Shrimp of the eastern Bering Sea and Gulf of Alaska. Final environmental impact statement/preliminary fishery management plan. Juneau, Alaska.

Otto, R. I. 1981. Eastern Bering Sea king and Tanner crab fisheries and the relationship to proposed oil and gas leases in the St. George Basin. St. George synthesis meeting. Unpub. MS.

Paul, A. J., H. M. Feder, and S. C. Jewett. 1979. Food of the snow crab, *Chionoecetes bairdi*, Rathbun 1924, from Cook Inlet, Alaska. Crustaceana, Suppl. 5:62-68.

Payne, J. R. 1982. Chemical weathering of petroleum hydrocarbons in subarctic sediments. Results of chemical analysis of naturally weathered sediment plots spiked with fresh and artifically weathered Cook Inlet crude oil, Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep.

Pereyra, W. T., J. E. Reeves, and R. G. Bakkala. 1976. Demersal fish and shellfish resources on the eastern Bering Sea in the baseline year 1975. NOAA/NMFS, Northw. Alaska Fish. Cent., Seattle, Wash.

Sakurai, M., S. Yamashiro, S. Kawashima, H. Omi, and K. Abe. 1972. The fish and fishing industry of Kushiro. Kushiro Serial 13, Kushiro City Pub.

Shaw, D. G. In press. Hydrocarbons: Natural distribution and dynamics on the Alaskan Outer Continental Shelf. Environmental Assessment of the Alaskan Continental Shelf. NOAA/OCSEAP, Final Rep.

Somerton, D. 1981. Factors affecting the productivity of Tanner crab in the eastern Bering Sea. St. George synthesis meeting. Unpub. MS.

Vandermeulen, J. H., D. E. Buckley, E. M. Levy, B. F. N. Long, P. McLaren, and P. G. Wells. 1978. Sediment penetration of *Amoco Cadiz* oil, potential for future release and toxicity. Mar. Poll. Bull. 9:292-293.

Yevich, P. P., and C. A. Barszcz. 1977. Neoplasms in softshell clam, *Mya arenaria,* collected from oil-impacted sites. Ann. Acad. Sci. N.Y. 298:409-426.

LIST OF ATTENDEES

Al Allen
ABSORB
6700 Arctic Spur Road
Anchorage, AK 99502

David Armstrong
College of Fisheries WH-10
University of Washington
Seattle, WA 98195

Patricia A. Baird
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Ed A. Baker
Pacific Marine Environmental
Laboratory
3711 15th Ave., N.E.
Seattle, WA 98105

Richard G. Bakkala
NWAFC/NMFS
2725 Montlake Blvd., East
Seattle, WA 98115

Marsha Bennett
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Ed Best
International Pacific Halibut
Commission
P.O. Box 5009, University Station
Seattle, WA 98105

Reed Bohne
NOAA/CZRC
3300 Whitehaven, Street, N.W.
Washington, D.C. 20235

Tom Boyd
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Howard W. Braham
NMFS/NWAFC/NMML
7600 Sand Point Way, N.E., Bldg. 32
Seattle, WA 98115

Bob Brock
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Chuck Chamberlain
Fugro, Inc.
P.O. Box 7765
Long Beach, CA 90807

Joel Cline
Pacific Marine Environmental
Laboratory
3711 15th Ave., N.E.
Seattle, WA 98105

Rod Combellick
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Drew Comer
USGS Conservation Division
800 A Street
P.O. Box 259
Anchorage, AK 99510

Daniel P. Costa
Long Marine Laboratory
CCMS
University of California
Santa Cruz, CA 95064

Cleve Cowles
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Herb Curl, Discussion Leader,
Shellfish Resources
NOAA/NMFS/PMEL
7600 Sand Point Way N.E., Bldg. 32
Seattle, WA 98115

John Davies
Lamont-Doherty Geological
Observatory
Columbia University
Palisades, NY 10964

Ray Emerson
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Raymond Everett, Jr.
Crowley Environmental Services Corp.
3812 Spenard Rd.
Anchorage, AK 99503

Francis H. Fay
Institute of Marine Science
University of Alaska
Fairbanks, AK 99701

Howard M. Feder
Institute of Marine Science
University of Alaska
Fairbanks, AK 99701

R. Glen Ford
Department of Biology
University of New Mexico
Albuquerque, NM 87131

Douglas J. Forsell
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Charles Fowler, Discussion Leader,
Marine Mammals
NOAA/NMFS/NMML
7600 Sand Point Way N.E., Bldg. 32
Seattle, WA 98115

Kathy Frost
Alaska Dept. of Fish & Game
1300 College Road
Fairbanks, AK 99701

Jim Gardner
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

Robert G. Gill, Jr.
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Judy Gottlieb
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Patrick J. Gould
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Robert P. Griffiths
Oregon State University
Dept. of Oceanography
Corvallis, OR 97330

M. Jawed Hameedi, Meeting Chairman
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Don Hansen
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Joyce Hawkes
Environmental Conservation Div.
NWAFC/NMFS
2725 Montlake Blvd., East
Seattle, WA 98112

Roger Herrera
SOHIO Alaska Petroleum Company
Pouch 6-612
Anchorage, AK 99502

Pauline Hessing
U.S. Fish & Wildlife Service
Pouch 2
Cold Bay, AK 99571

W. Neil Holmes
Dept. of Biological Sciences
University of California
Santa Barbara, CA 93106

David Hopkins
Quaternary Research Center
University of Washington
Seattle, WA 98195

Jonathan P. Houghton
Dames & Moore
155 N.E. 100th Street, Suite 500
Seattle, WA 98125

Joel D. Hubbard
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

George L. Hunt, Jr., Discussion
Leader, Marine Birds
Department of Ecology and Evolutionary Biology
University of California
Irvine, CA 92717

Lew Incze
College of Fisheries
Shellfish Unit
University of Washington
Seattle, WA 98195

Laurie Jarvella
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Bill Jensen
North Pacific Fishing Vessel Owners
Assoc.
Fishermen's Terminal
C-3, Room 133
Seattle, WA 98119

Steve C. Jewett
Institute of Marine Science
University of Alaska
Fairbanks, AK 99701

Jerry L. Kaiwi
Department of Ecology and Evolutionary Biology
University of California
Irvine, CA 92717

Bruce Kirstein
Science Applications, Inc.
476 Prospect Street
La Jolla, CA 92038

John Karinen
National Marine Fisheries Service
Auke Bay Fisheries Laboratory
P.O. Box 155
Auke Bay, AK 99821

Sid Korn
National Marine Fisheries Service
Auke Bay Fisheries Laboratory
P.O. Box 155
Auke Bay, AK 99821

Jan Leendertse
Rand Corporation
1700 Main Street
Santa Monica, CA 90406

David Liu
Rand Corporation
1700 Main Street
Santa Monica, CA 90406

Seelye Martin
Dept. of Oceanography
University of Washington
Seattle, WA 98195

Byron Morris
Environmental Assessment Div.
National Marine Fisheries Service
632 West 6th Avenue, #408
Anchorage, AK 99501

Larry Moulton
Alaska Dept. of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

David N. Nettleship
Canadian Wildlife Service
Box 1006
Bedford Institute of Oceanography
Dartmouth, Nova Scotia
Canada B2Y 482

Tom Newbury
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

David Nysewander
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Guy Oliver
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Robert Otto
NOAA/NMFS
P.O. Box 1638
Kodiak, AK 99615

Jim Overland
Pacific Marine Environmental Laboratory
3711 15th Ave., N.E.
Seattle, WA 98105

Jim Payne
Science Applications Inc.
476 Prospect Street
La Jolla, CA 92038

Maurie Pelto
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

John Prince
Exxon Production Research
P.O. Box 2189
Houston, TX 77001

Jim Ray
Shell Oil Company
P.O. Box 4320
Houston, TX 77210

Bill Sackinger, Discussion Leader, Environmental Hazards
Geophysical Institute
University of Alaska
Fairbanks, AK 99701

Gerald A. Sanger
U.S. Fish & Wildlife Service
1011 East Tudor Road
Anchorage, AK 99507

Dave Schneider
Department of Ecology and Evolutionary Biology
University of California
Irvine, CA 92717

Karl Schneider
Alaska Dept. of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Jim D. Schumacher, Discussion Leader, Transport and Fate of Spilled Oil
Pacific Marine Environmental Laboratory
3711 15th Ave., N.E.
Seattle, WA 98105

Fred Sieber
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

David Somerton
Center for Quantitative Sciences
College of Fisheries, HR-20
3737 15th Ave., N.E.
Seattle, WA 98195

Gil Springer
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Richard Straty
NOAA/NMFS/ABL
P.O. Box 155
Auke Bay, AK 99821

Joseph G. Strauch, Jr.
Science Applications Inc.
2760 29th Street
Suite 209
Boulder, CO 80301

Bill Stringer
Geophysical Institute
University of Alaska
Fairbanks, AK 99701

Fredrik Thorsteinson, Discussion Leader, Finfish Resources
Box 287
Auke Bay, AK 99827

Lyman Thorsteinson
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Lance L. Trasky
Alaska Dept. of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Tom Warren
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Bob Wienhold
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Burl Wescott
NOAA/OMPA
U.S. Court House and Federal Bldg.
701 "C" Street
Box 54
Anchorage, AK 99513

Robert Wolotira
NOAA/NMFS
P.O. Box 1638
Kodiak, AK 99615

Rick Wright
State of Alaska Liaison
OCSEAP
P.O. Box 1808
Juneau, AK 99802

Steve Zimmerman
NOAA/OMPA/OCSEAP
P.O. Box 1808
Juneau, AK 99802