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ATMOSPHERIC ADMINISTRATION

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NOTICES

This interim 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. Approval does not necessarily signify that the contents reflect the views and policies of the Department of Commerce.

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SYNTHESIS REPORT UPDATING

This volume represents an INTERIM edition of the Kodiak Shelf Synthesis Report and is intended to present a multidisciplinary overview of information relevant to possible Alaskan Outer Continental Shelf oil and gas development. OCSEAP-supported research is still continuing in the Kodiak region, making additional relevant information continually available.

In order to assist with this updating procedure, it is requested that the users of this report inform the following of major omissions or errors or of any new relevant information:

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Foreword

Expeditious development of the Outer Continental Shelf (OCS) is essential to energy requirements of the United States. The OCS oil and gas deposits may provide a national source of petroleum during a time when it is greatly needed. In each OCS area for which development is proposed, extensive environmental studies must be conducted before such development can safely proceed. As manager of the Alaskan Outer Continental Shelf leasing program, the Bureau of Land Management (BLM) has asked the National Oceanic and Atmospheric Administration (NOAA) to conduct the Outer Continental Shelf Environmental Assessment Program (OCSEAP).

This program focuses on several lease areas on the Alaskan Outer Continental Shelf, ranging from the subarctic Northeast Gulf of Alaska to the arctic Beaufort Sea. This vast geographic area encompasses extreme environmental conditions. The harsh environment and resultant severe working conditions are largely responsible for the fact that much less is known about the marine environment of the Alaskan OCS than about any other shelf and coastal area of the United States. The existence of oil under the shelf, the demand for new domestic sources of energy, and the recognition of the lack of basic environmental information have accented the need for a well-developed research program.

An essential part of a research program is the reporting of its results. OCSEAP is reproducing and widely distributing the annual reports received from each project as well as some specialized technical summaries. A listing of these reports, as well as the reports themselves, may be secured from OCSEAP's Editor, NOAA, Rx4, Boulder, CO 80303. More importantly, OCSEAP is producing synthesis reports like this one for each lease area. This current synthesis organizes all available marine environmental information pertinent to OCS development for the given lease area, tailoring the presentation to needs of the users.

A synthesis chapter is provided to tie the scientific and technical information chapters together. It presents a picture of the operation and vulnerability of the environmental system in such a way that the user, or decision maker, will have a sound basis for tract selection and location of pipelines or other facilities, will be aware of stipulations and regulations, and will know where problems exist.

The task of gathering, selecting, analyzing, and presenting needed pertinent information for the lease areas will take years to accomplish; yet the user needs information immediately. In order to resolve this dilemma and to secure a wide review of the information before the work is finished, OCSEAP provides interim syntheses, intending to update them regularly to incorporate data from current studies. These reports will be discussed at future meetings with OCSEAP staff and contract scientists to expedite the updating. The final synthesis, to be published when the OCSEAP scientific community has completed its studies in this lease area, will thus be a product tailored to current and future needs of decision makers.

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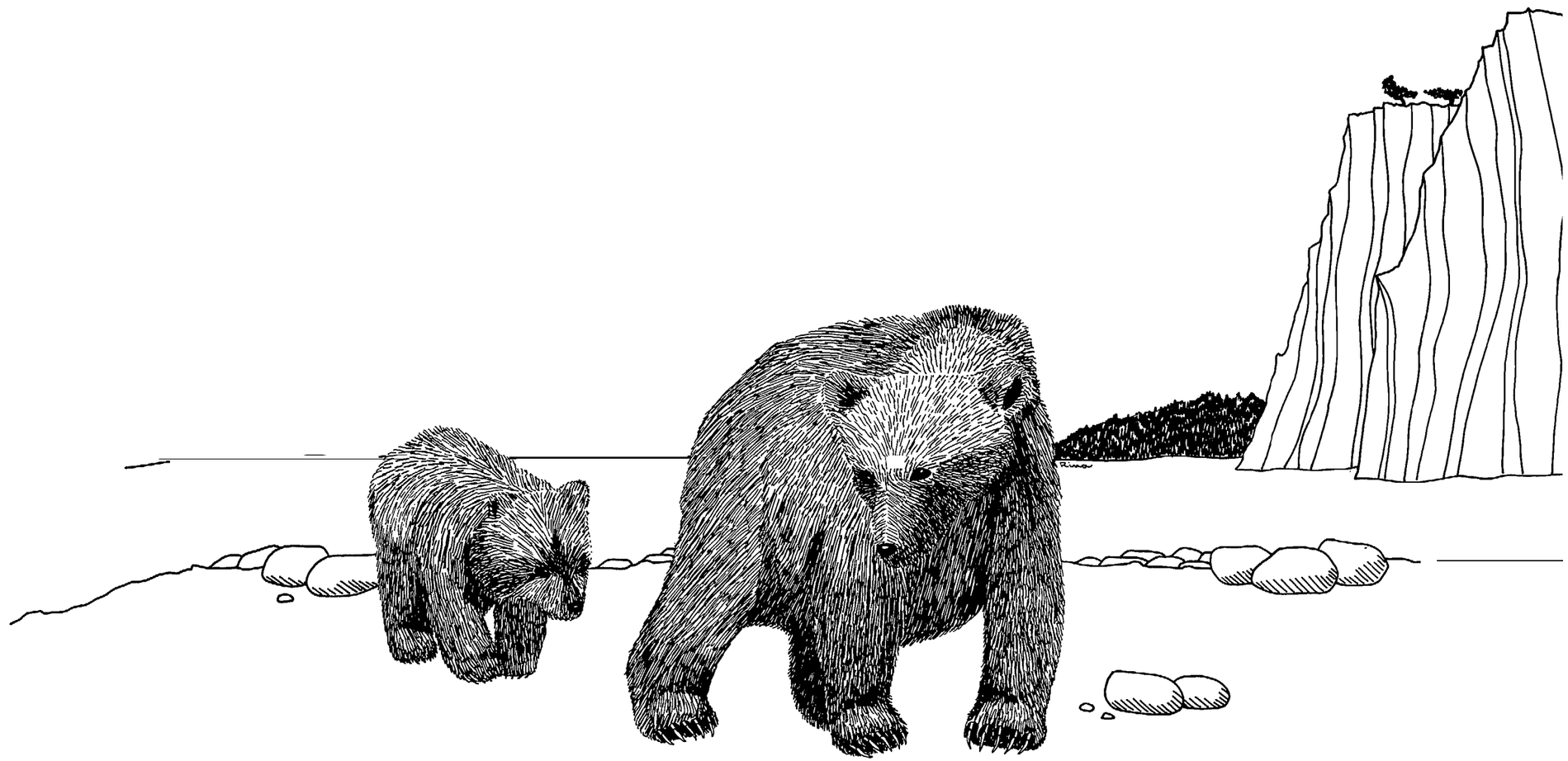
1. Introduction



CHAPTER 1 INTRODUCTION

J. G. Strauch, Jr., SAI

Origins of the Program

The Alaskan Outer Continental Shelf Environmental Assessment Program (OCSEAP) originated in May 1974, when the Bureau of Land Management (BLM), manager of the Outer Continental Shelf (OCS) oil leasing program, requested that the National Oceanic and Atmospheric Administration (NOAA) initiate an environmental assessment program in the Northeastern Gulf of Alaska (NEGOA), in anticipation of possible oil and gas lease sales in 1976. In October 1974, BLM requested that the program be expanded during 1975 and 1976 to include five additional areas of the Alaskan continental shelf. In response to a further request by BLM in December 1975, OCSEAP was expanded to include the northern Bering Sea, Chukchi Sea, and lower Cook Inlet. The Program Development Plan (PDP) (NOAA, 1976) outlined studies in progress and presented study plans for nine proposed lease areas of the Alaskan OCS. Since then the Northern Aleutian and Navarin Basin have been added to the lease schedule (Fig. 1.1).

Objectives of OCSEAP

The National Environmental Policy Act of 1969 called for the protection of the marine and coastal environment. The primary objective of OCSEAP is to obtain information on the OCS environment so that preventive or corrective measures can be taken before serious or irreversible damage to the environment occurs.

Specific objectives of the BLM environmental studies program for all OCS areas are:

- To provide information about the OCS environment that will enable the Department of the Interior and BLM to make sound management decisions regarding the development of mineral resources on the federal OCS.
- To gather information that will enable BLM to identify elements of the environment likely to be affected by oil and gas exploration and development.
- To establish a basis for predicting of the effects on the environment of OCS oil and gas activities.
- To measure the effects of oil and gas exploration and development on the OCS environment. These data may result in modification of leasing and operation regulations to permit efficient recovery of resources with maximum environmental protection.

OCSEAP divided the evaluation of potential effects of OCS oil and gas developments into six areas or tasks:

A. Existing Contaminants: Determination of background levels of potential contaminants commonly associated with oil and gas development.

B. Sources: Identification of probable sources of contaminants and environmental disturbances likely to accompany oil and gas exploration and development.

C. Hazards: Identification and assessment of environmental hazards which may affect petroleum exploration and development.

D. Transport: Determination of how contaminants move through the environment and how they are altered by physical, chemical, and biological processes.

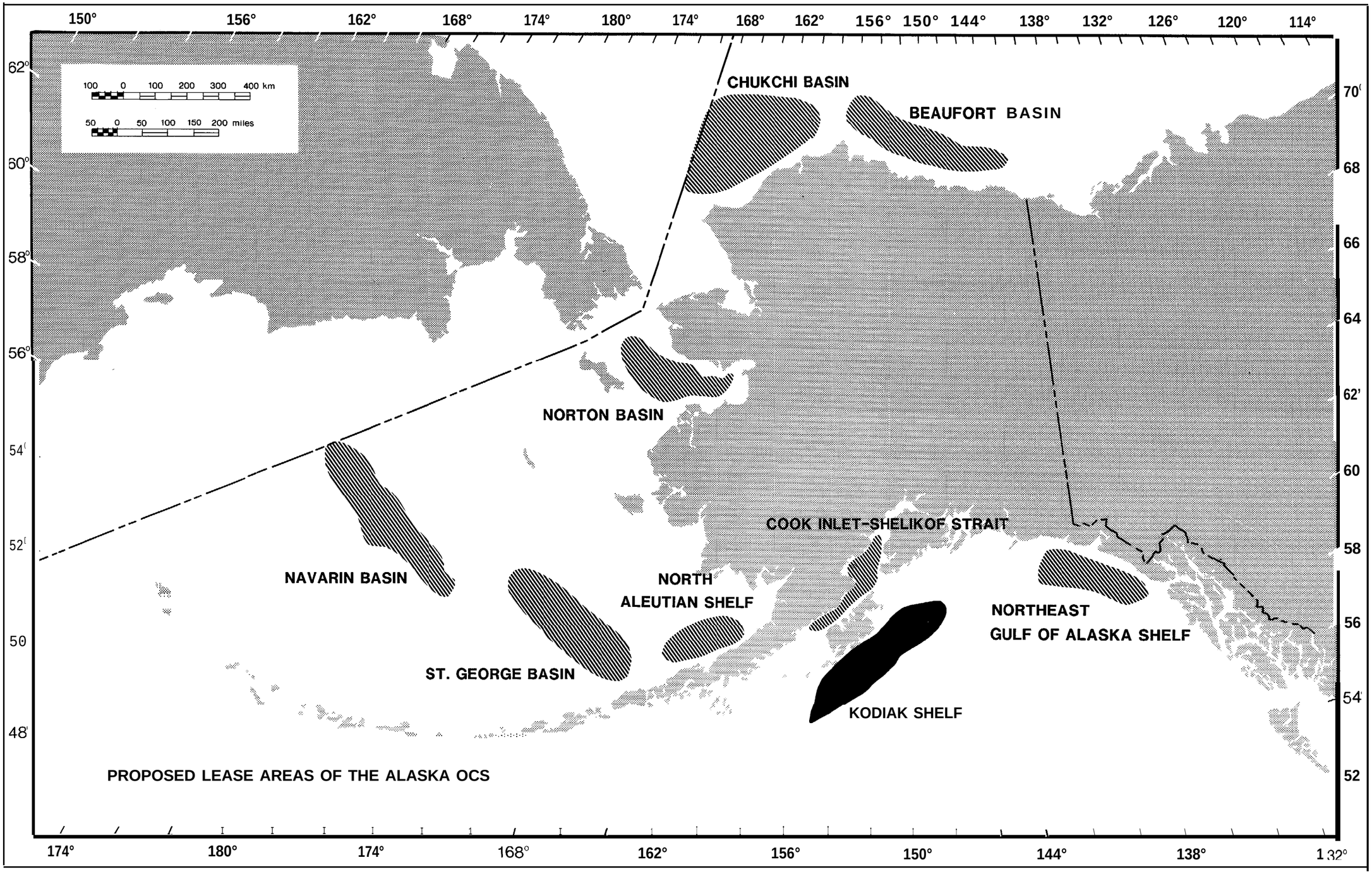
E. Receptors: Identification of the biological populations and ecological systems likely to be affected by petroleum exploration and development.

F. Effects: Determination of the effects of hydrocarbon and trace metal contaminants on ecological systems and their component organisms.

The first Kodiak Interim Synthesis Report was organized according to the list of tasks. At the Kodiak Synthesis Meeting (KSM, 1979), it became evident that this organization hindered use of the report. Therefore, the present report is organized along more traditional lines. First the physical characteristics of the environment are discussed, then the biology, beginning with microbes and ending with mammals. Each of the disciplinary chapters addresses one of the OCSEAP tasks:

Chapter 2. Geology: Task C, Hazards
Chapter 3. Physical Oceanography: Task D, Transport
Chapter 4. Chemistry: Task A, Contaminants
Chapter 5. Biology: Task E, Receptors

Chapter 6 deals with potential petroleum development (Task B) and Chapter 7 is a summary of current knowledge of the lease area. Material on Task F (Effects) has been integrated into the other chapters.


CHUKCHI BASIN
BEAUFORT BASIN
NORTON BASIN
COOK INLET-SHELIKOF STRAIT
NAVARIN BASIN
NORTH
ALEUTIAN SHELF
NORTHEAST
GULF OF ALASKA SHELF
ST. GEORGE BASIN
KODIAK SHELF
PROPOSED LEASE AREAS OF THE ALASKA OCS
100 0 100 200 300 400 km
50 0 50 100 150 200 miles

The OCS oil and gas lease sale proposed for the Western Gulf of Alaska-Kodia (USDI, 1980b includes 564 separate lease blocks covering about 1.3 million hectares (3.2 million acres) The individual lease blocks are grouped together in the eleven lease areas indicated in Fig. 1.2.

Each lease block contains 2,304 hectares. For purpose of identification and sale the blocks have been numbered, starting with the first tier north of the equator as "N 1." The first range of blocks west of the central meridian of each UTM zone is designated "E 100." Thus, a block numbered "N-200-E 96" would be the 200th block north of the equator and the 5th block west of the central meridian of the respective UTM zone.

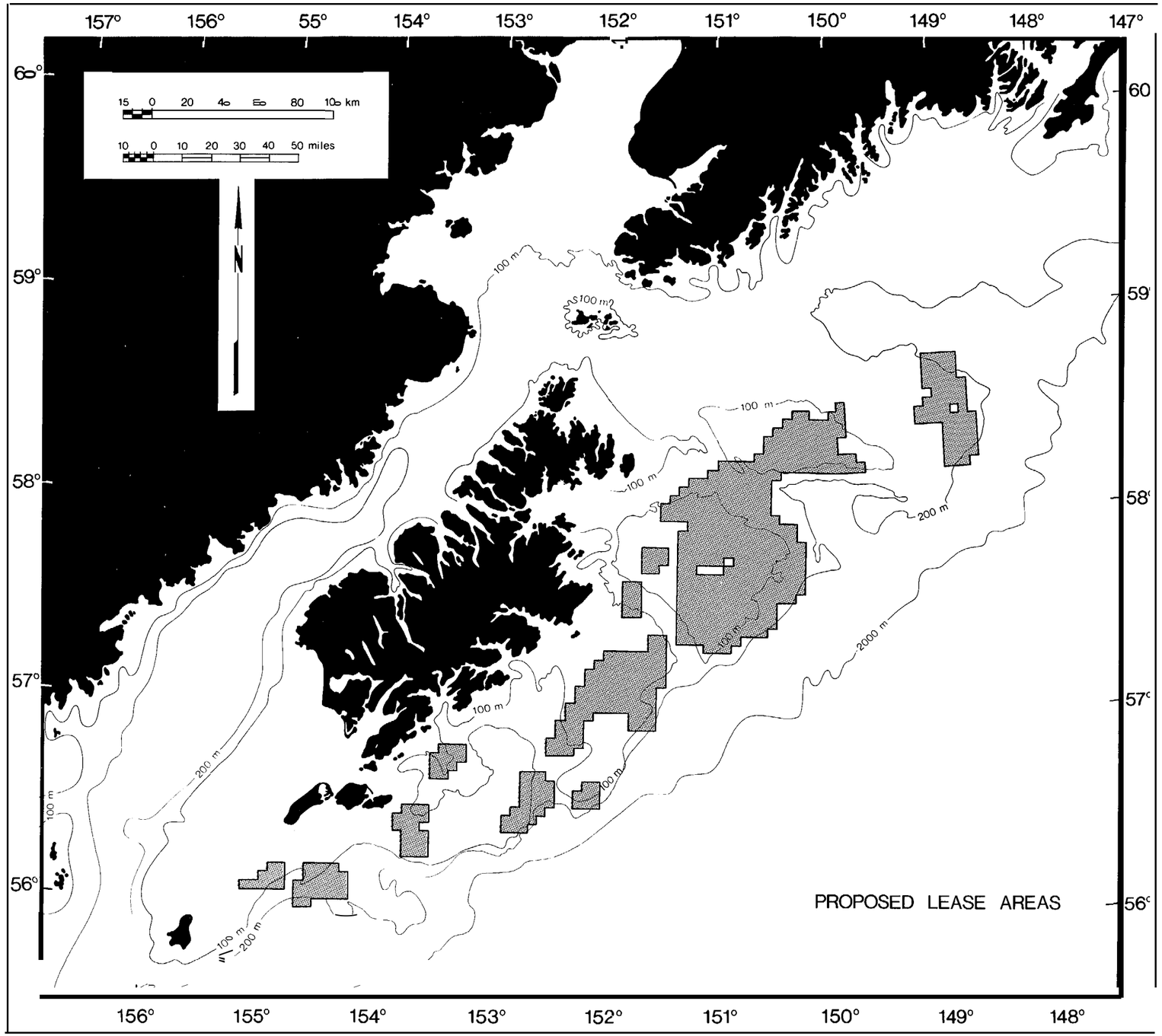


Figure 1.1 Proposed lease areas of the Alaskan outer continental shelf (USDI, 1980a).

Figure 1.2 Kodiak shelf proposed lease areas (USDI, 1980a)

Maps

Science Applications, Inc. (SAI) has produced a series of base maps for use by participants in OCSEAP. The coastline and coordinate grids were drawn by a computer plotter using World Data Base II. The computer plots were produced by the National Geophysical and Solar-Terrestrial Data Center in Boulder, Colorado. Computer smoothing of coastline contours was corrected by hand, using USGS and NOAA charts for reference.

The lease area base maps use the Universal Transverse Mercator (UTM) system. The UTM is not, strictly speaking, a projection, but rather a grid system based on the Transverse Mercator Projection. As a cylindrical, conformal projection, the Transverse Mercator provides true angles of direction at all points within the grid and true North-South measuring lines (that is, it correlates straightline coordinates of a surveying grid with the curvedline coordinates of the earth). In the UTM system central meridians define every 6° of longitude between 80°N and 80°S. A uniform rectangular grid is overlaid onto zones which extend 3° to each side of the central meridian. On the UTM grid each square in each zone represents an area of the same size on the earth's surface. The blocks of this grid are 4,800 m on a side; from them were selected the lease blocks identified by BLM for possible sale and development.

Locality map and gazetteer

Figure 1.3 is a locality map of the Kodiak region that includes all localities mentioned in the text. The, shallow banks and troughs of Kodiak's continental shelf are identified. Place-names have been listed both alphabetically and numerically.

KODIAK AREA: **Numerical** List of Placenames

1. Cape Trinity
2. Alitak Bay
3. Tanner Head (beach)
4. Middle Reef
5. Sukhoi Lagoon
6. Upper Station Region
7. Low Cape
8. Dog Salmon Creek (Frazer River)
9. Fraser Lake
10. Ayakulik River
11. Red River
12. Bumble Bay
13. Cape Ikolik
14. Halibut Bay
15. Cape Karluk
16. Karluk River
17. Larsen Bay
18. Uyak Bay
19. Alf Island
20. Zachar Bay
21. Spiridon Bay
22. Cape Ugat
23. Uganik Bay
24. Uganik Lake
25. Viekoda Bay
26. Kupreanof Strait
27. Raspberry Cape
28. Raspberry Strait
29. Malina Bay
30. Cape Paramanof
31. Blue Fox Bay
32. Big Bay
33. Latax Rocks
34. Lax Rocks
35. Sud Island
36. Ushagat Island
37. Nerd Island
38. West Amatuli Island
39. East Amatuli Island
40. Sugarloaf Island
41. Shuyak Island
42. Big Fort Island
43. Sea Otter Island
44. Seal Bay
45. Sea Lion Rocks
46. Marmot Island
47. Afognak Island
48. Izhut Island
49. Kazakof Bay.
50. Dolphin Point
51. Afognak Lake
52. Hog Island
53. Marmot Bay
54. Anton Larsen Bay
55. Whale Passage
56. Kizhuyak Bay
57. Port Lions
58. Spruce Island
59. Monashka Bay
60. Long Island
61. Pillar Mountain
62. Buskin Pass
63. Womens Bay
64. Middle Bay
65. Chiniak Bay
66. Kalsin Bay
67. Cape Chiniak
68. Narrow Cape
69. Ugak Island
70. Pasagshak Point
71. Pasagshak Bay
72. Saltery Cove
73. Ugak Bay
74. Gull Point
75. Dangerous Cape
76. Shearwater Bay
77. Kiliuda Bay
78. Cape Barnabas
79. Lagoon Point
80. Sitkalidak Strait
81. Port Hobron
82. Old Harbor
83. Three Saints Bay
84. Kaiugnak Bay
85. Sitkalidak Island
86. Ocean Bay
87. Sitkalidak Lagoon
88. Twoheaded Island
89. Cape Kaguyak
90. Horsehead Basin
91. Aliulik Peninsula
92. Geese Islands
93. Cape Sitkinak
94. Sitkinak Island
95. Tugidak Island
96. Dolina Point
97. Sitkinak Strait
98. Aiaktalik Island
99. Sundstrom Island
100. Unalaska Island
101. Unimak Island
102. Shumagin Islands
103. Mitrofania Island
104. Chirikof Island
105. Nagai Rocks
106. Semidi Islands
107. Ugaiushak Island
108. Wide Bay
109. Ukinrek Maars
110. Becharof Lake
111. Upper Ugashik Lake
112. Dry Bay
113. Puale Bay
114. Alinchak Bay
115. Kashvik Bay
116. Katmai Volcano
117. Trident Volcano
118. Dakavak Bay
119. Takli Island
120. Cape Gull
121. Kukak Bay
122. Hallo Bay
123. Village Beach
124. Big River
125. Swikshak Beach
126. Cape Douglas
127. Mount Douglas
128. Kamishak Bay
129. Augustine Volcano
130. Augustine Island
131. Iliamna Island
132. Chisik Island
133. English Bay
134. Kachemak Bay
135. Aialik Bay
136. Resurrection Peninsula
137. Barwell Island
138. Montague Strait
139. Montague Island
140. Prince William Sound
141. Middleton Island
142. Copper River
143. Cape Saint Elias
144. Kayak Island
145. Icy Bay
146. Cape Fairweather

KODIAK AREA: Alphabetical List of Placenames

47. Afognak Island
51. Afognak Lake
98. Aiaktalik Island
135. Aialik Bay
19. Alf Island
114. Alinchak Bay
2. Alitak Bay"'
91. Aliulik Peninsula
54. Anton Larsen Bay
130. Augustine Island
129. Augustine Volcano
10. Ayakulik River
137. Barwell Island
110. Becharof Lake
32. Big Bay
42. Big Fort Island
124. Big River
31. Blue Fox Bay
12. Bumble Bay
62. Buskin Pass
78. Cape Barnabas
67. Cape Chiniak
126. Cape Douglas
146. Cape Fairweather
120. Cape Gull
13. Cape Ikolik
89. Cape Kaguyak
15. Cape Karluk
30. Cape Paramanof
143. Cape Saint Elias
93. Cape Sitkinak
1. Cape Trinity
22. Cape Ugat
65. Chiniak Bay
104. Chirikof Island
132. Chisik Island
142. Copper River
118. Dakavak Bay
75. Dangerous Cape
8. Dog Salmon Creek (Frazer River)
96. Dolina Point
50. Dolphin Point
112. Dry Bay
39. East Amatuli Island
133. English Bay
9. Fraser Lake
92. Geese Islands
74. Gull Point
14. Halibut Bay
122. Hallo Bay
52. Hog Island
90. Horsehead Basin
145. Icy Bay
131. Iliamna Island
48. Izhut Island
134. Kachemak Bay
84. Kaiugnak Bay
66. Kalsin Bay
128. Kamishak Bay
16. Karluk River
115. Kashvik Bay
116. Katmai Volcano
144. Kayak Island
49. Kazakof Bay
77. Kiliuda Bay
56. Kizhuyak Bay
121. Kukak Bay
26. Kupreanof Strait
79. Lagoon Point
17. Larsen Bay
33. Latax Rocks
34. Lax Rocks
60. Long Island
7. Low Cape
29. Malina Bay
53. Marmot Bay
46. Marmot Island
64. Middle Bay
4. Middle Reef
141. Middleton Island
103. Mitrofania Island
59. Monashka Bay
139. Montague Island
138. Montague Strait
127. Mount Douglas
105. Nagai Rocks
68. Narrow Cape
37. Nerd Island
86. Ocean Bay
82. Old Harbor
71. Pasagshak Bay
70. Pasagshak Point
61. Pillar Mountain
81. Port Hobron
57. Port Lions
140. Prince William Sound
113. Puale Bay
27. Raspberry Cape
28. Raspberry Strait
11. Red River
136. Resurrection Peninsula
72. Saltery Cove
45. Sea Lion Rocks
43. Sea Otter Island
44. Seal Bay
106. Semidi Islands
76. Shearwater Bay
102. Shumagin Islands
41. Shuyak Island
85. Sitkalidak Island
87. Sitkalidak Lagoon
80. Sitkalidak Strait
94. Sitkinak Island
97. Sitkinak Strait
21. Spiridon Bay
58. Spruce Island
35. Sud Island
40. Sugarloaf Island
5. Sukhoi Lagoon
99. Sundstrom Island
125. Swikshak Beach
119. Takli Island
3. Tanner Head (beach)
83. Three Saints Bay
117. Trident Volcano
95. Tugidak Island
88. Twoheaded Island
107. Ugaiushak Island
73. Ugak Bay
69. Ugak Island
23. Uganik Bay
24. Uganik Lake
109. Ukinrek Maars
100. Unalaska Island
101. Unimak Island
6. Upper Station Region
111. Upper Ugashik Lake
36. Ushagat Island
18. Uyak Bay
25. Viekoda Bay
123. Village Beach
38. West Amatuli Island
55. Whale Passage
108. Wide Bay
63. Womens Bay
20. Zachar Bay

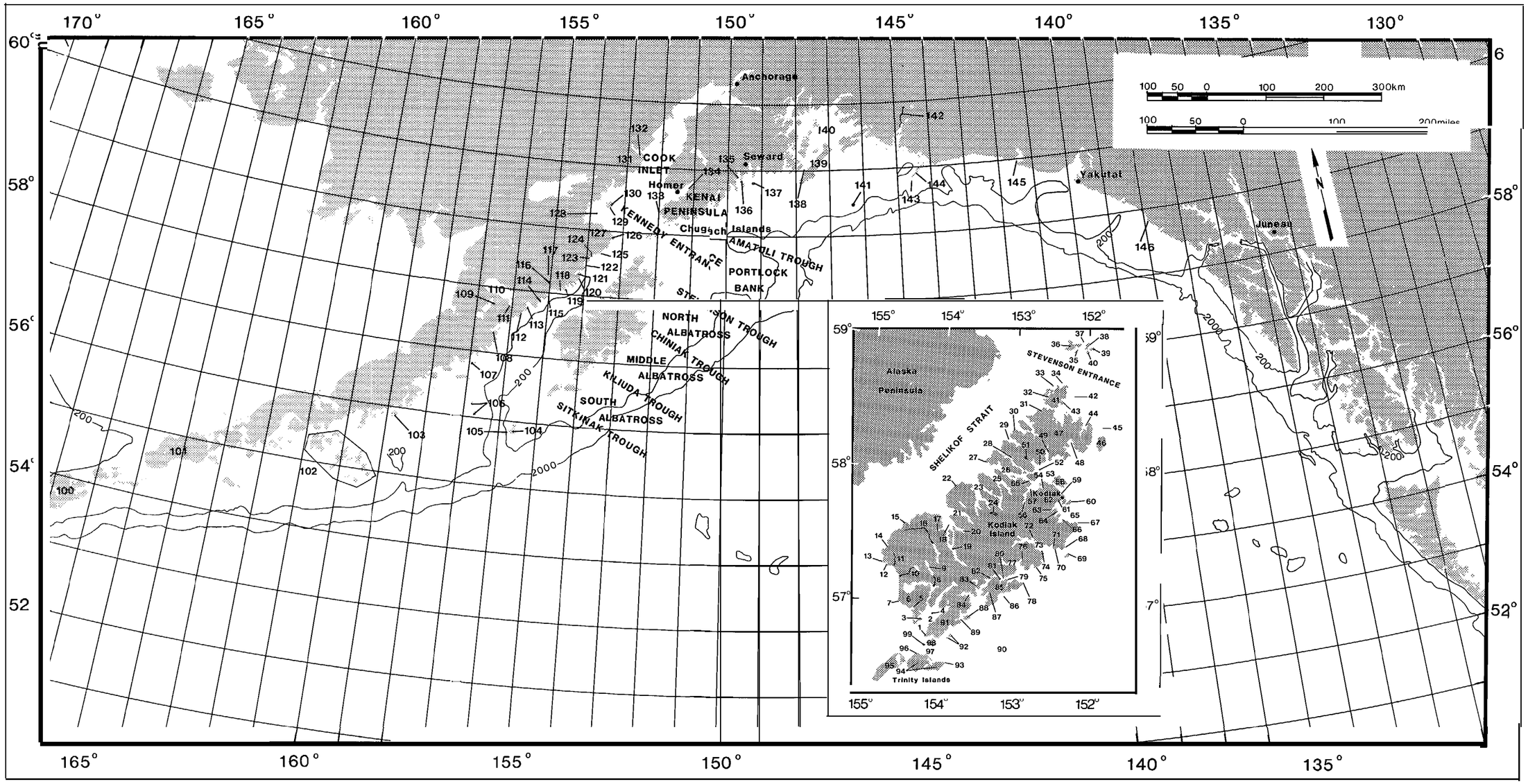
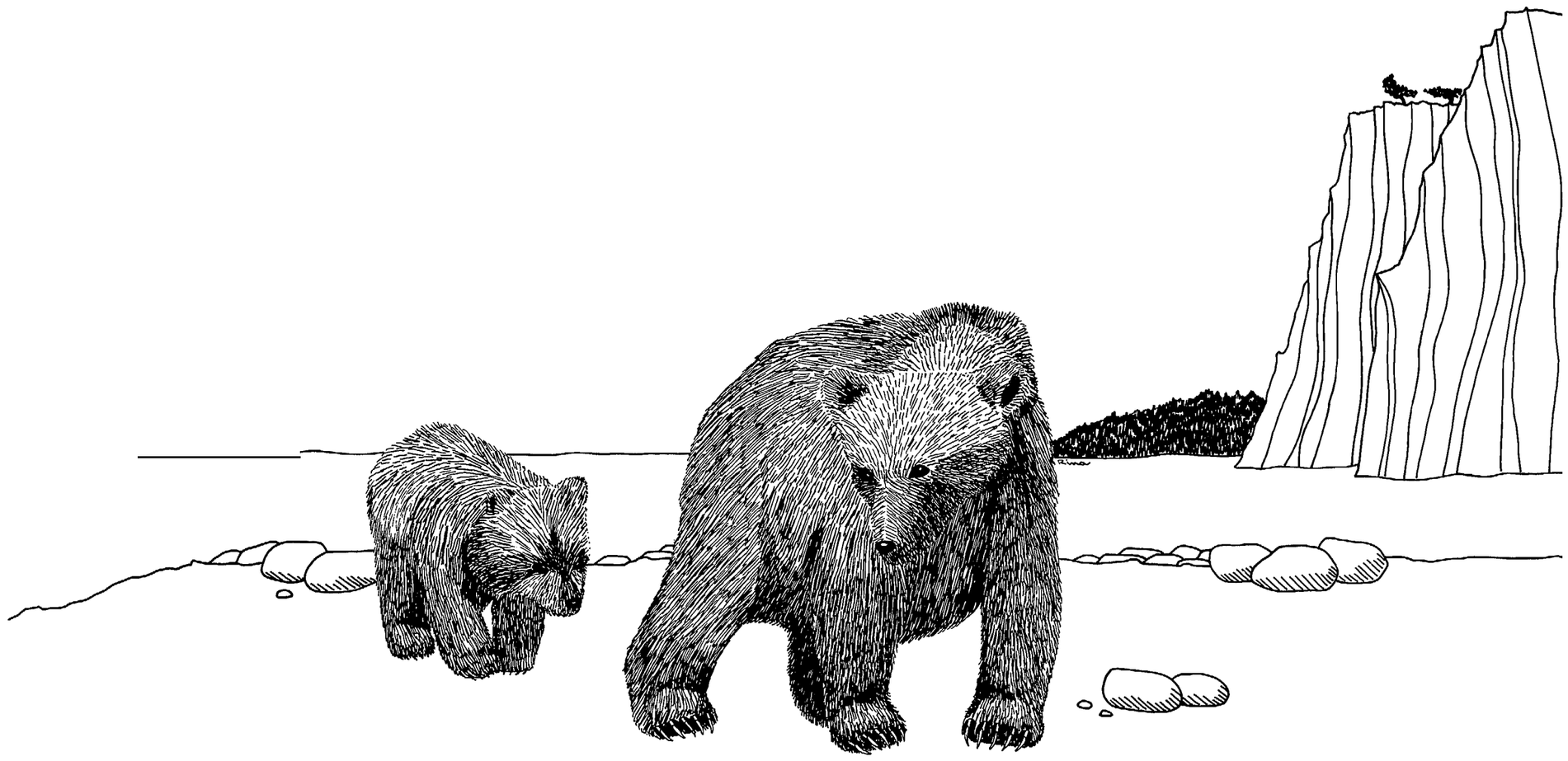


Figure 1.3 Locality map and gazetteer for the Kodiak region and the Gulf of Alaska.

2. Geology



CHAPTER 2 GEOLOGY

R. E. Peterson, SAI

2.1 INTRODUCTION

2.1.1 Relevance of geologic hazards study

The continental shelf around the Gulf of Alaska, the Alaska Peninsula, and the Aleutian Islands is situated in a dynamic tectonic environment. Several prominent crustal features are associated with this setting: the deep Aleutian Trench and Aleutian volcanoes which result from the underthrusting of the oceanic plate; rugged mountain ranges produced by compressive forces generated during the collision of the two plates; and major fault systems, which reveal the structural failure of crustal rock as the motion can no longer be accommodated by plastic deformation.

The most immediate and perhaps spectacular hazard posed by this tectonic activity involves the occurrence of earthquakes. Earthquakes have been particularly destructive in heavily populated areas, due to the variety of effects produced. Open fissures and cracks with offsets along fences and roads are dramatic, but the conflagrations resulting from ruptured natural gas lines and gasoline storage tanks and broken electrical power lines are far more destructive. Structural failure and weakening of oil pipelines, platforms, and buildings may be caused by soil liquefaction induced by earthquake shaking.

The risk of destruction by earthquakes is directly proportional to the extent of human development in a region. The probability that an earthquake will occur at a particular location may be reasonably forecast by seismologists; the risk posed to life and property is much more difficult to assess. The financial commitment in equipment, the increase in population, and the dire environmental consequences of a blowout or major pipeline break are important reasons for evaluating the earthquake risk to petroleum industry development on the Gulf of Alaska continental shelf.

Hazards due to tectonic activity are not the only ones resulting from geological processes. Rapid erosion and deposition of seafloor sediment may adversely affect pipelines, for instance, as may slumping and sliding of unstable slopes. Dispersion of sediment in the water column, along the seafloor, and along coastlines may affect the fate of spilled oil. Knowledge of the presence and location of gas-charged sediment is important, since encountering such deposits during offshore platform construction and drilling operations is a serious hazard.

A thorough understanding of geological processes in this region of anticipated petroleum industry development is essential for a complete evaluation of the risk posed to the development by the natural environment.

2.1.2 Geologic setting of Kodiak Island

Kodiak Island is located along the zone of crustal subduction caused by convergence of the northerly moving Pacific lithospheric plate and the more stationary North American plate (Fig. 2.1). The Pacific plate is underthrusting the North American plate, and the

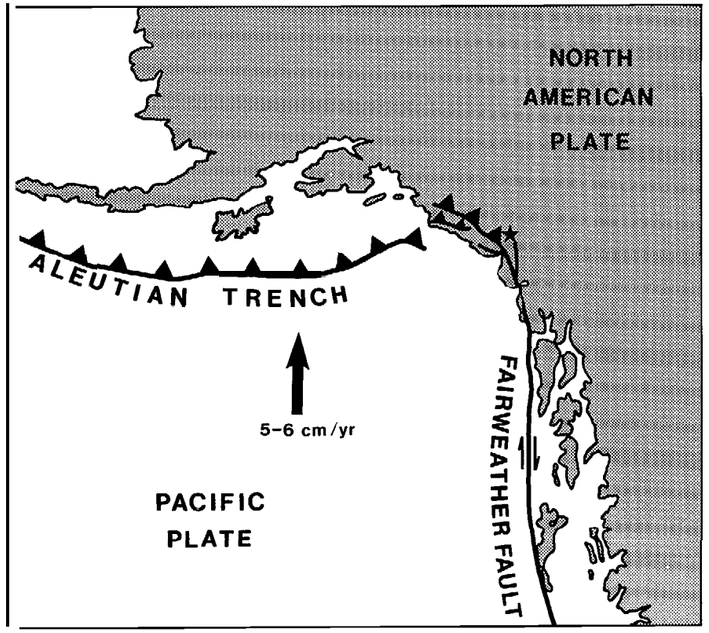


Figure 2.1 Plate tectonics relationships in the NE Pacific Ocean. Star indicates epicenter of February 28, 1979, St. Elias earthquake, the most recent large event in the region (from Lahr and Stephens, 1979).

Aleutian Trench is the surface expression of the place at which initial downwarping of the descending oceanic plate occurs (Fig. 2.2) . The interaction of these converging plates includes not only subduction and associated major thrust faulting, but also major strike/slip faulting on the eastern boundary, where relative plate motion is accommodated along the Fairweather-Queen Charlotte fault system (Fig. 2.1). The earthquake seismicity and volcanism which affect the Kodiak Island region are primarily associated with active tectonic deformation resulting from the subducting oceanic plate and continental accretion of crustal material which is "scraped off" as subduction proceeds (von Huene, 1978).

The "Benioff zone," the region of intense seismic activity associated with the subducting plate (Fig. 2.2), is usually well defined in projections of hypocenters onto vertical sections oriented perpendicular to the subduction zone axis. In the Kodiak region, Benioff zone seismicity becomes distinguishable at about 50 km depth and extends to about 200 km (refer to Fig. 2.9). The deeper earthquakes associated with subduction are generally of lesser magnitude and less hazard to life and property than are the shallower events (Pulpan and Kienle, 1979a).

Above the Benioff zone, in the zone of accretion of material onto the continental plate, there is a more diffuse pattern of earthquakes (refer to Fig. 2.6); it is in this shallow zone that the large destructive earthquakes occur. According to current ideas on subduction zone seismicity, great earthquakes occur along the main thrust plane between descending oceanic crust and overlying continental crust, at depths shallower than about 40 km (Davies and House, 1979). In this main thrust zone, seismic energy is released in great earthquakes, separated at varying time intervals

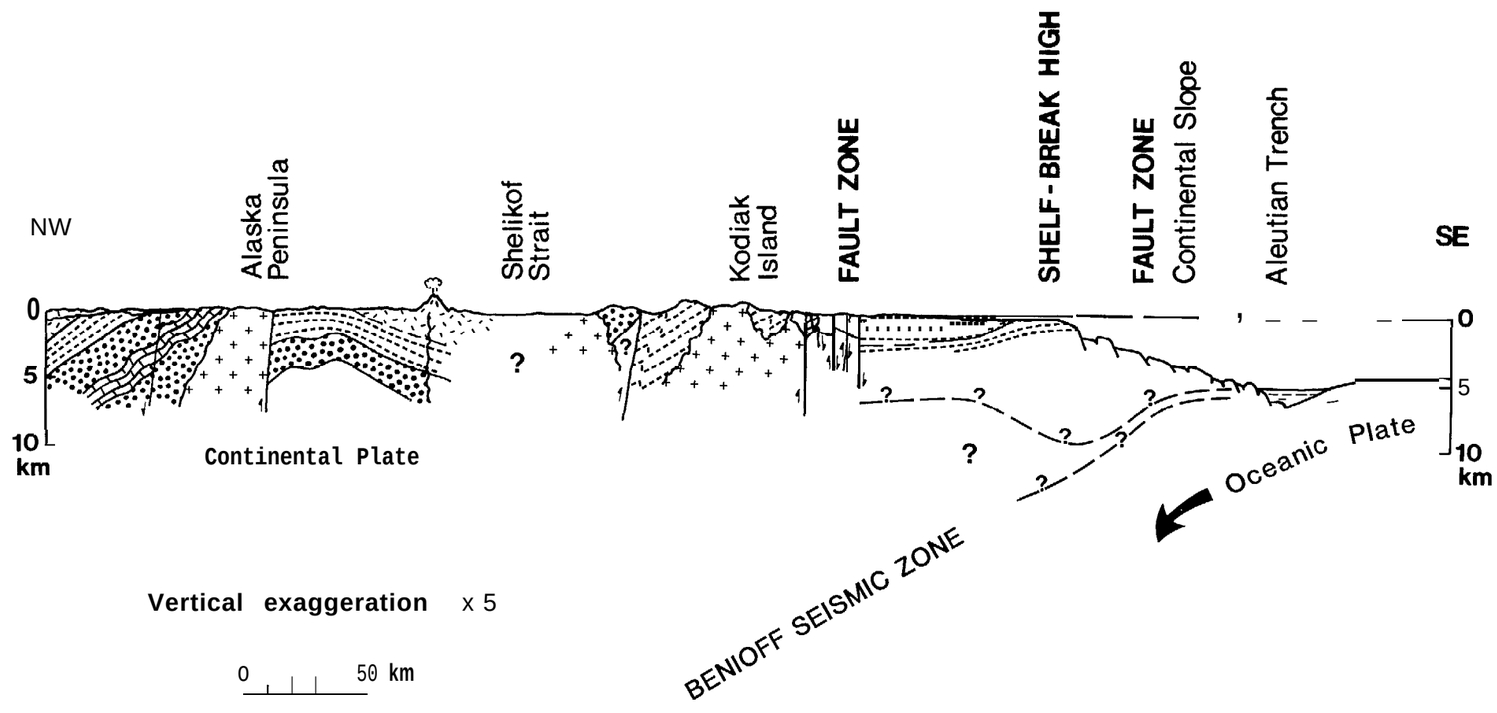


Figure 2.2 Generalized geologic cross-section across Kodiak Island and the Kodiak shelf (adapted from von Huene and Shor, 1969).

by periods of low seismic activity. Oceanic crustal segments seem to become locked to the continental block, stress builds until the strength of the rocks is exceeded, and extremely violent adjustments ensue (McCann et al., 1978). The 1964 Great Alaska Earthquake is an example of such an adjustment. Identification of the boundaries of these segments will have important significance in forecasting large earthquakes. Below 40 km in the Benioff zone, seismic energy seems to be released in a more continuous marine r (Davies and House, 1979).

Kodiak Island and its continental shelf overlie the main thrust zone just described, in a region of high earthquake risk. As the lithospheric plates converge at a rate of 5-6 cm/yr (Minster et al., 1974), the accretionary zone strata are subjected to considerable deformation--folding, faulting, and vertical motions--with accompanying earthquakes.

The volcanoes of the Aleutian Islands and Alaska Peninsula are also a result of the subduction process. As the descending oceanic plate reaches a depth where rock begins to melt, at about 100 km, magma is formed which works its way back to the surface. When the rising magma breaches the surface, a volcano is formed.

2.2 SEISMICITY

2.2.1 Earthquake catalogues

Of the more recent catalogues of earthquakes which include data for Alaska (Duda, 1965; Tobin and Sykes, 1966 and 1968; Rothé, 1969; Sykes, 1971; Kelleher et al., 1973), the file maintained by NOAA's Environmental Data Services in Boulder, Colorado, is in general the most complete. Pulpan and Kienle (1979b) estimate that the NOAA/EDS file approaches completeness for all magnitude 7 or larger events which have occurred since 1899, all magnitude 6 or larger since 1928, and all magnitude 3.5 or larger since 1969. Data for this file are obtained from a variety of sources which are described by Meyers and von Hake (1976). The main (but unavoidable) shortcomings of the file are the short time period for which instrumental records exist, the heterogeneity of magnitude determinations for some parts of the file, and the wide variation in accuracy of identifying epicenter locations.

The amount of data on Alaskan earthquakes has increased considerably since the establishment of local seismic networks to monitor the extremely active plate boundary of the southern and southeastern parts of the state. These local networks, which began operating about 1976, are capable of recording earthquakes with magnitudes as small as 1.5 in some portions of the network. The network which covers the Kodiak region is shown in Fig. 2.3. In addition to acquiring more data on smaller earthquakes in the Alaskan OCS, efforts are now being directed at producing more homogeneous data, especially calculations of magnitude and location (discussions at NOAA/OCSEAP sponsored Alaskan OCS Seismology and Earthquake Engineering Workshop, Mar. 26-29, 1979, Boulder, Colorado). Homogeneity in these data is required for studies of the distribution of seismicity in space and time (e.g., Kelleher, 1970)--studies which show the most promise for improving earthquake forecasts (see section 2.2.4).

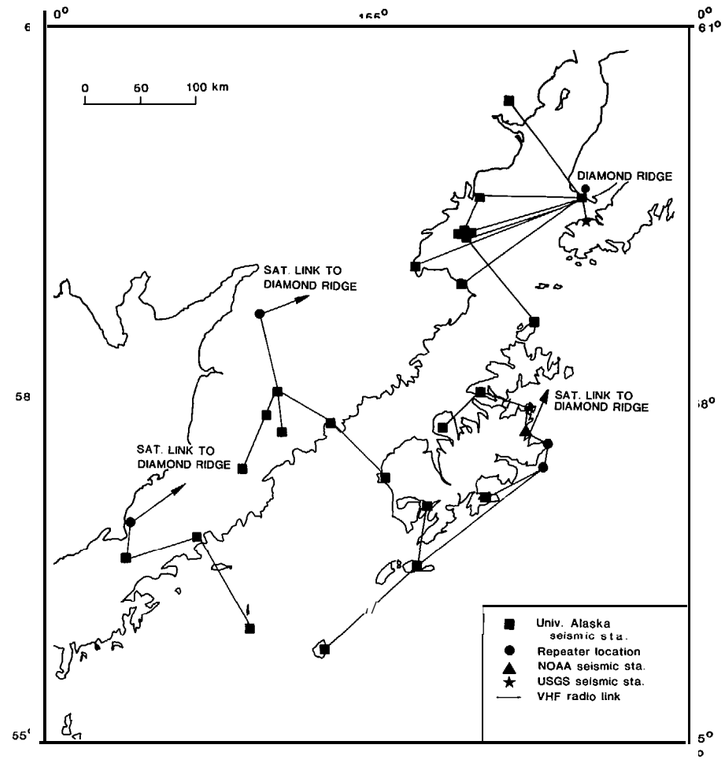


Figure 2.3 Location of local Alaskan seismic networks in Cook Inlet, Kodiak Island, and the Alaska Peninsula as of March 1979 (Pulpan and Kienle, 1979b).

2.2.2 Distribution of earthquakes

In order to present an unbiased description of the seismicity of an area via epicenter plots, it is necessary that an equal detection capability exist for the entire area of interest. During the early 1960's, coordination of worldwide seismic networks was initiated to improve this equal detection capability. About this time, the United States organized the Worldwide Network of Standard Seismographs (WWNSS; Glover, 1977) which has contributed greatly to a more homogeneous earthquake data set.

For events of magnitude 4 or greater in Alaska, equal detection capability has existed since about 1963 (Meyers et al., 1976); before then many of the smaller events went unrecorded due to insufficient seismograph station coverage. In addition, before 1963, calculation techniques were less reliable, data varied in precision, and velocity models for the crust in the region were inadequate. The epicenter plots were generated from the NOAA/EDS earthquake file; they are restricted to events larger than magnitude 4 which have occurred since 1964. They do not show events recorded by the local Alaskan seismic network.

Figure 2.4 llustrates the shallow earthquakes that are common throughout the Kodiak region; they are associated ωΞth thrust faulting in the zone of continental accretion. The arent horizontal and vertical alignments of epicenters are caused by plotting locations to the nearest tenth of a degree, an³ not by fault lineatioos Figure 2.5 shows the deeper earthquakes associated with Ben: off zone faulting along the

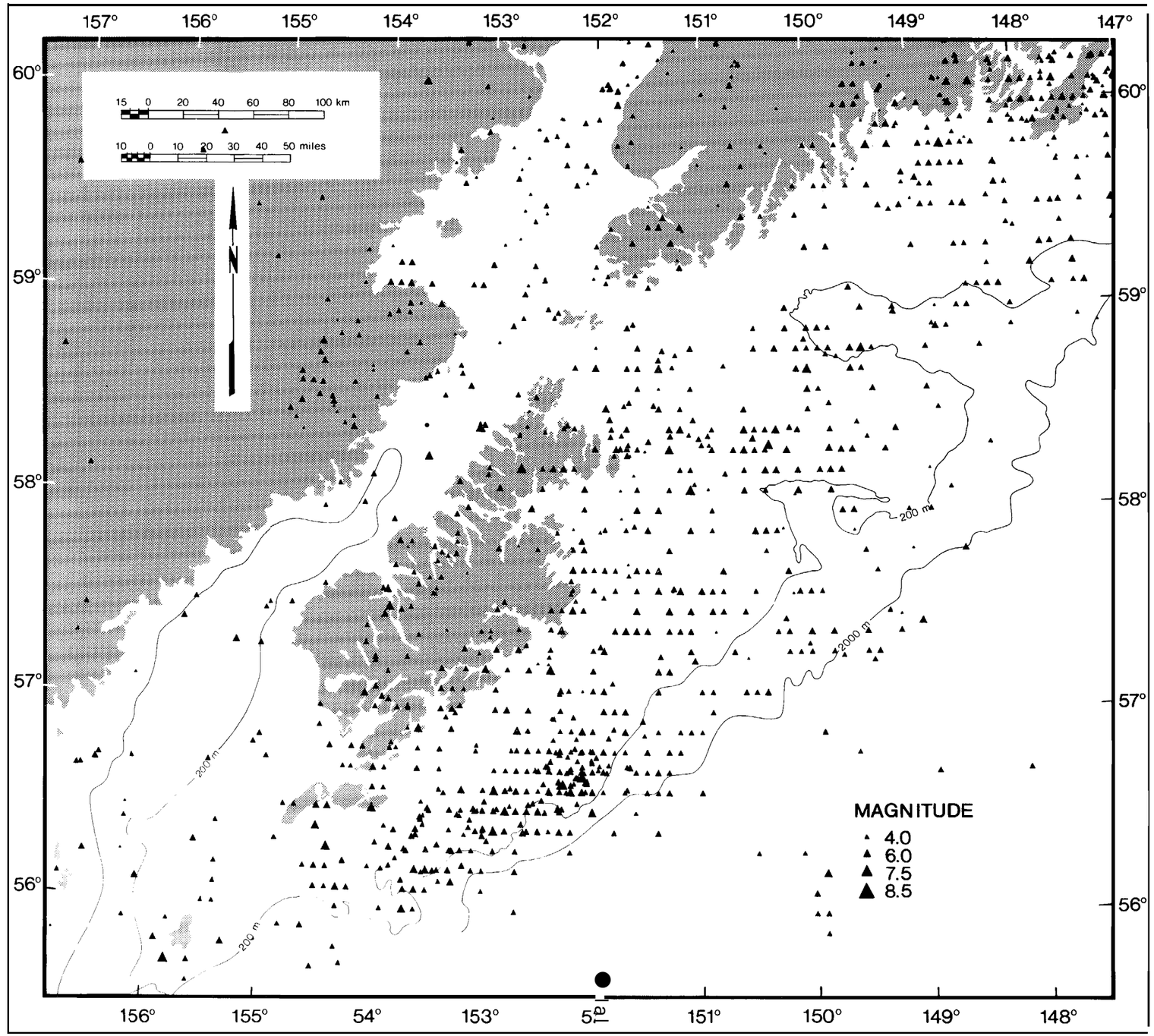


Figure 2.4 Epicenter plot of all earthquakes between 1964 and 1977 with focal depths of 70 km or less. Data are from NOAA/EDS earthquake file and do not contain local Alaskan network data. Plot produced by NOAA/EDS/NGSDC.

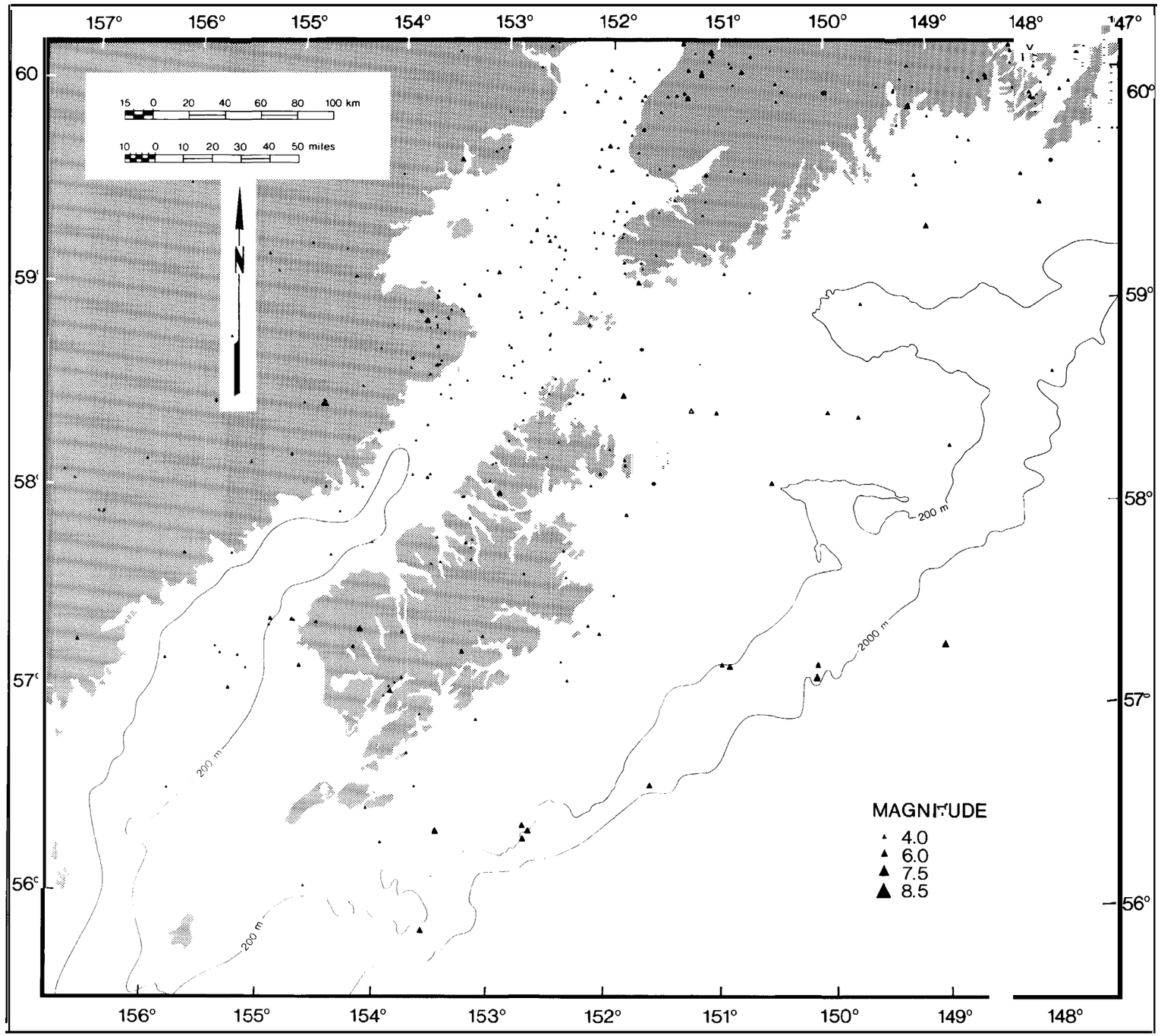


Figure 2.5 Epicenter plot of all earthquakes between 1964 and 1977 with focal depths greater than 70 km. Data are from NOAA/EDS earthquake file and do not contain local Alaskan network data. Plot produced by NOAA/EDS/NGSDC.

main thrust plane of the descending oceanic plate. The deeper earthquakes tend to be smaller in magnitude, and their stribution is displ somewhat to the of the shallow events. In Figure 2.6 these hypocenters have been projected onto a vertical plane which is oriented perpendicular to the earthquake source structure below Kodiak Island. Three features are immediately evident: first, the deep seismicity caused by the descending oceanic plate as it slides past the continental plate; second, the diffuse shallow seismicity in the zone of continental accretion where considerable strain readjustment by faulting occurs; nd third, the seismic activity associated with magma rising from the 00-km depths of the Benioff zone, which culminates in the volcanoes of the Aleutian Islands and Alaska Peninsula.

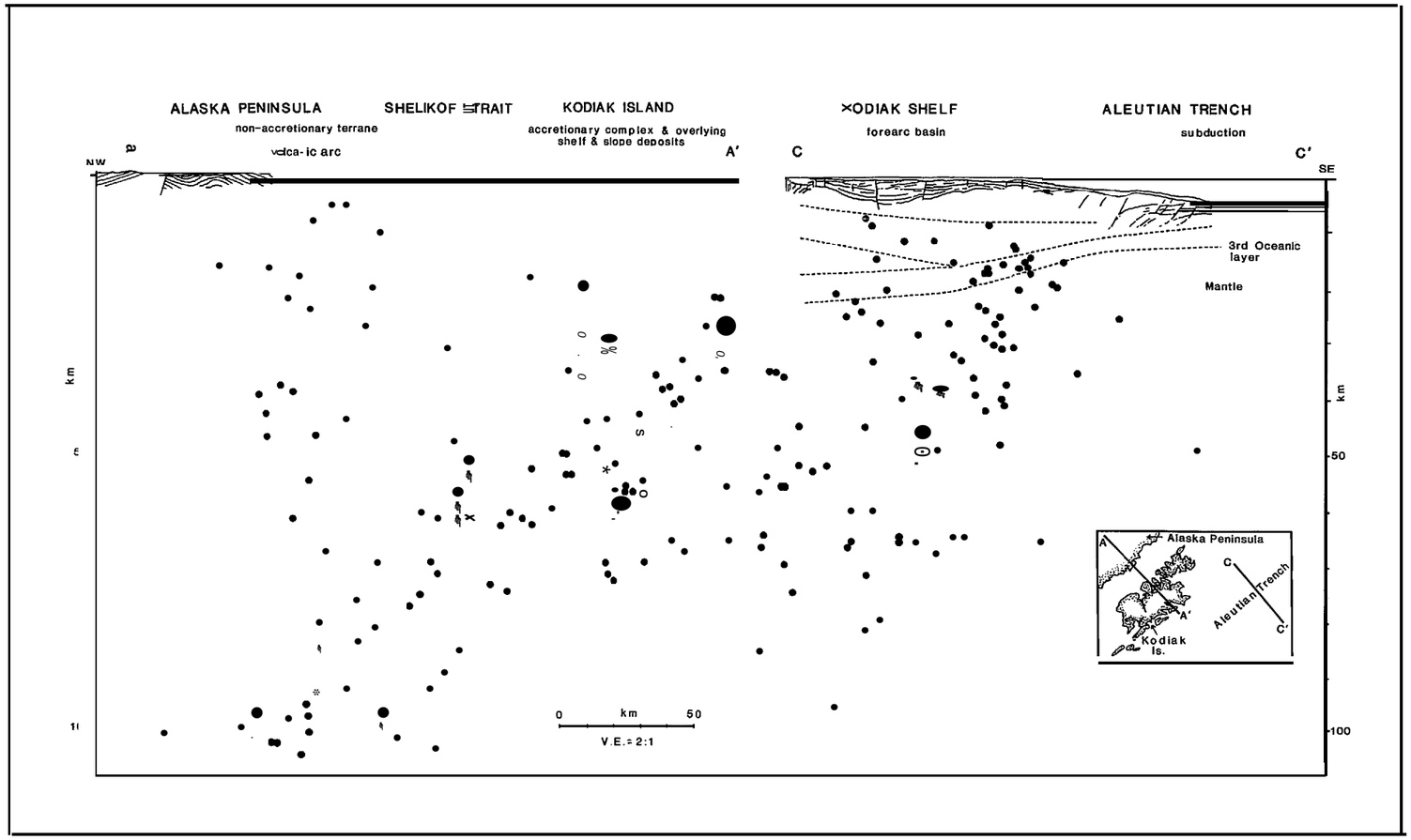


Figure 2.6 Geologic and seismicity cross-section through the Aleutian Trench and Kodiak Island. Hypocenters from an area 320 km wide have been projected onto a vertical plane (from von Huene et al., 1979).

Figure 2.7 is a plot of all seismic events of magnitude 6 or greater by depth class. Nearly equal detection capability exists for these large events throughout the entire time span of the NOAA/EDS file. Table 2.1 lists and describes each of the events plotted on Fig. 2.7.

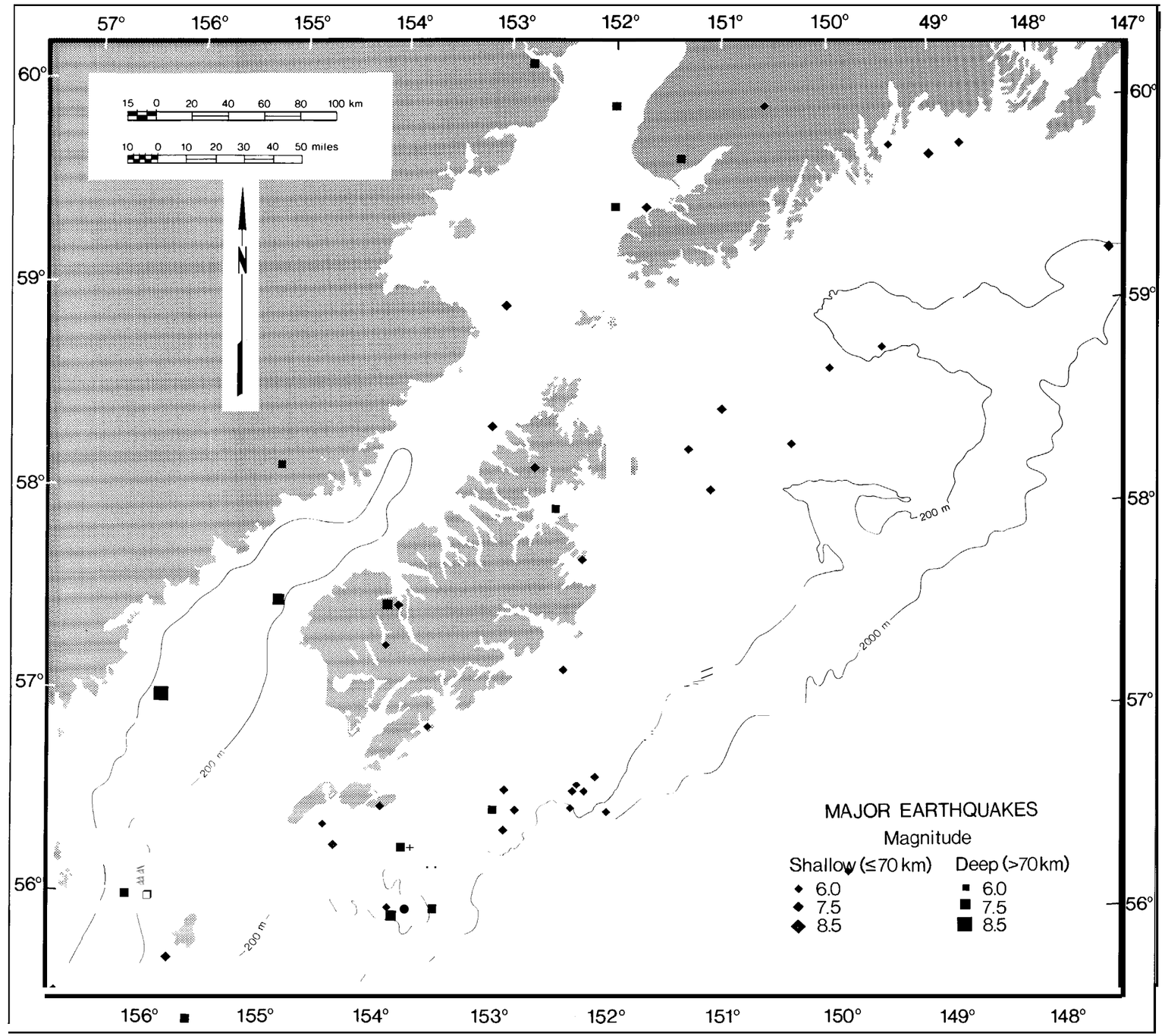


Figure 2.7 Epicenter plot of major earthquakes (magnitude greater than 6) recorded in the Kodiak Island region between 1899 and 1977. Data sources are identified in Table 2.1. Plot produced by NOAA/EDS/NGSDC.

Table 2.1 List of major earthquakes (magnitude ≥ 6) recorded from the Kodiak shelf between 1900 and 1977. Epicenters are plotted in Fig. 2.7. Maximum Mercalli intensity associated with the earthquake is also listed. Data are from the NOAA/EDS earthquake file. See text for references to other Alaskan earthquake catalogues, which may contain additional events or revised data on events listed here.

DATA SOURCE*	YEAR	MO DAY HR MIN SEC	LAT	LONG	DEPTH (km)	MAGNITUDES BODY WAVE	SURFACE WAVE	UNSPEC-IFIED	LOCAL (RICHTER)	INT MAx
CFR	1903	06 02 13 17 00.0	57.000N	156. 000W	100			8.30		
EQH	1909	09 29 19 00 00.0	60. 600N	149. 270w				7.40		v
G-R	1911	09 22 05 01 24.0	60. 500N	149. 000W	60			6.90		VIII
G-R	1912	01 31 20 11 48.0	61.000N	147. 500W	80			7.25		v
G-R	1912	06 07 09 55 54.0	59. 000N	153.000W	25			6.40		v
G-R	1912	06 10 16 06 06.0	59. 000N	153. 000W	25			7.00		
G-R	1912	11 07 07 40 24.0	57. 500N	155.000W	90			7.50		v
G-R	1912	12 05 12 27 36.0	57. 500N	154.000W	90			7.00		
G-R	1923	05 04 16 26 39.0	55. 500N	156. 500W	25			7.10		
G-R	1931	12 24 03 40 40.0	60. 000N	152.000W	100			6.25		IV
G-R	1932	09 14 08 43 23.0	61.000N	148. 000W	50			6.25		v
G-R	1933	01 04 03 59 28.0	61.000N	148. 000W	25			6.25		VI
G-R	1933	06 13 22 19 47.0	61.000N	151.000W	25			6.25		v
G-R	1934	05 14 22 12 46.0	57. 750N	152. 250W	60			6.50		VI
G-R	1934	06 18 09 13 50.0	60. 500N	151. 000W	80			6.75		v
G-R	1934	07 28 21 36 57.0	55. 500N	156. 750W	25			6.75		
G-R	1938	11 10 20 18 43.0	55. 500N	158. 000W	25			8.70		VI
G-R	1940	10 11 07 53 10.0	59. 500N	152. 000W	25			6.00		
G-R	1941	04 01 10 40 59.0	56. 000N	153. 500W				6.50		
G-R	1941	07 30 01 51 21.0	61.000N	151.000W				6.25		VI
G-R	1941	09 28 05 34 12.0	56. 500N	157. 500W	100			6.50		
G-R	1942	12 05 14 28 40.0	59. 500N	152. 000W	100			6.50		
G-R	1944	08 14 11 07 23.0	59. 000N	155.000W	100			6.25		
G-R	1945	11 03 22 09 03.0	58. 500N	151. 000W	50			6.75		
G-R	1946	01 12 20 25 37.0	59. 250N	147. 250W	50			7.20		Iv
G-R	1948	05 26 09 16 42.0	56. 000N	156. 000W				6.00		
G-R	1949	09 27 15 30 45.0	59. 750N	149.000W	50			7.00		v
G-R	1951	02 13 22 12 57.0	56. 000N	156. 000W				7.00		
1ss	1952	11 29 23 46 27.0	56. 300N	153. 800W				6.75		
1ss	1953	02 25 21 16 12.0	56. 000N	156. 200W				6.75		
1SS	1953	06 15 17 47 14.0	56. 300N	153. 800W				6.50		
CGS	1954	06 17 01 42 22.0	56. 000N	154. 500W				6.50		
USE	1954	10 03 11 18 46.0	60. 500N	151. 000W	100			6.75		VIII
1SS	1955	07 19 23 52 23.0	56. 500N	153. 000W				6.00		
CGS	1955	07 26 04 04 18.0	56. 500N	153. 000W				6.00		
CGS	1955	07 27 18 19 08.0	56. 500N	153. 000W				6.25		
1ss	1955	11 15 10 06 47.0	55. 400N	155. 600W				6.50		
1SS	1957	04 04 00 13 04.0	58. 170N	155. 040W	89			6.00		IV
1ss	1957	04 10 11 30 00.0	55.960N	153.860W				7.10		
USE	1958	01 24 23 17 29.0	60.000N	152.000W	60			6.50		IV
CGS	1959	04 19 15 03 26.0	58. 000N	152. 500W				6.25		
1SS	1959	12 26 18 19 08.0	59. 740N	151. 380w				6.25		
CGS	1960	09 01 15 37 14.4	56. 300N	153. 700W	24			6.13		
CGS	1961	01 20 17 09 15.7	56. 600N	152. 300W	46			6.38		
CGS	1961	01 31 00 48 36.5	56. 000N	153.900W	26			6.25		
CGS	1961	09 05 11 34 37.3	60. 000N	150. 600w	43			6.13		VI
CGS	1963	05 12 20 08 40.8	57. 300N	154.000W	60	6.10				
CGS	1963	06 24 04 26 37.9	59. 500N	151. 700W	52	5.70		6.75		VII
CGS	1964	02 06 13 07 25.2	55.700N	155.800W	33	5.60		6.88		v
CGS	1964	03 28 04 54 07.9	59. 800N	149. 400W	25	6.10				
CGS	1964	03 28 06 43 57.4	58. 300N	151. 300W	25	6.10				
CGS	1964	03 28 07 10 21.4	58.800N	149.500W	20	6.10		6.20		
CGS	1964	03 28 08 33 47.0	58. 100N	151.100W	25	5.60		6.50		
CGS	1964	03 28 09 01 00.5	56. 500N	152. 000W	20	6.00		6.20		
CGS	1964	03 28 10 35 38.9	57. 200N	152.400W	33	6.00		6.30		
CGS	1964	03 28 12 20 49.8	56. 500N	154. 000W	25	6.10		6.50		
CGS	1964	03 28 14 49 13.7	60.400N	147. 100W	10	5.80		6.50		
CGS	1964	03 28 20 29 08.6	59. 800N	148. 700W	40	5.80		6.60		
CGS	1964	03 30 02 18 06.3	56. 600N	152. 900W	25	5.80		6.60		
CGS	1964	04 04 17 46 08.6	56. 300N	154. 400W	25	5.70		6.50		
CGS	1964	04 04 17 59 43.3	56. 400N	154. 500W	25	5.50		6.10		
CGS	1964	04 05 01 22 13.3	56. 200N	153. 500W	25	5.40		6.00		
CGS	1964	04 12 01 24 31.2	56. 600N	152. 200W	22	5.60		6.25		
CGS	1964	04 16 19 26 57.4	56. 400N	152. 900W	30	5.50		6.63		
CGS	1964	08 02 08 36 16.9	56. 200N	149. 900W	31	5.40		6.00		
CGS	1965	06 23 11 09 15.7	56. 500N	152. 800w	33	5.70		6.38		
cGS	1965	09 04 14 32 46.7	58. 200N	152. 700W	10	6.20		6.88		
CGS	1965	12 22 19 41 23.1	58. 400N	153. 100W	51	6.50		6.88		v
CGS	1966	01 22 14 27 07.9	56.000N	153. 700w	33	5.80		6.00		
CGS	1966	04 16 01 27 13.5	56. 900N	153. 600w	23	5.70		6.25		
USE	1967	07 01 23 10 07.2	54. 400N	158.000W	33	6.20				Iv
USE	1968	04 23 20 29 14.5	58. 700N	150. 000W	23	6.30		6.13		
CGS	1968	11 15 00 07 09.7	58. 326N	150. 367w	26	5.10		6.38		
USE	1968	12 17 12 02 15.0	60. 200N	152. 800W	86	5.90		6.50		VI
USE	1969	11 24 22 51 50.1	56.200N	153.600W	33	5.50	5.7	5.70	6.00	IV
USE	1970	01 16 08 05 39.6	60. 300N	152. 700W	91	5.60		6.00		v
USE	1970	03 11 22 38 34.6	57. 500N	153. 900W	29	6.00	6.0	6.50	6.40	v
ERL	1972	03 24 03 38 27.1	56. 142N	157.180W	69	6.00				IV
GS	1974	08 01 05 07 59.0	56.516N	152.315W	10	5.20	6.1			
GS	1974	08 01 05 55 38.2	56.670N	152.105W	33	5.70	6.3			
GS	1974	08 01 07 59 56.9	56. 632N	152. 265W	33	5.20	6.0			

*Data sources for NOAA/EDS earthquake file:
EQH-Cofman and von Hake, 1973; CFR - Richter, 1958; G-R - Gutenberg and Richter, 1954; 1SS - International Seismological Summary, Kew, England; USE - United States Earthquakes, published annually by the Coast and Geodetic Survey and successor organizations from 1928 to 1972, and jointly by NOAA/USGS thereafter; CGS, NOS, ERL, and GS - Agency operating the Preliminary Determination of Epicenter (PDE) program: Coast and Geodetic Survey prior to 1970, National Ocean Survey 1970 to 1971, Environmental Research Laboratories 1971 to 1973, and U. S. Geological Survey since 1973. See Meyers and von Hake, 1976, for additional information on data sources for this earthquake file.

The local Alaskan seismic network (Fig. 2.3) has been providing a detailed description of seismic source structures by detecting much smaller events--as small as magnitude 1.5 in some areas--than those recorded at teleseismic distances. Figure 2.8 is a plot of epicenters recorded by the local network April-June 1978. Most of these events have magnitudes of 2 or 3 and focal depths of less than 50 km The cluster of small, shallow events southeast of Kodiak Island can be identified in most seismicity plots of the Kodiak region, regardless of the time interval plotted During the year following the 1964 Great Alaska Earthquake, aftershocks filled the area northeast of this cluster; presently, that area is again relatively quiet seismically (Fig 2 8

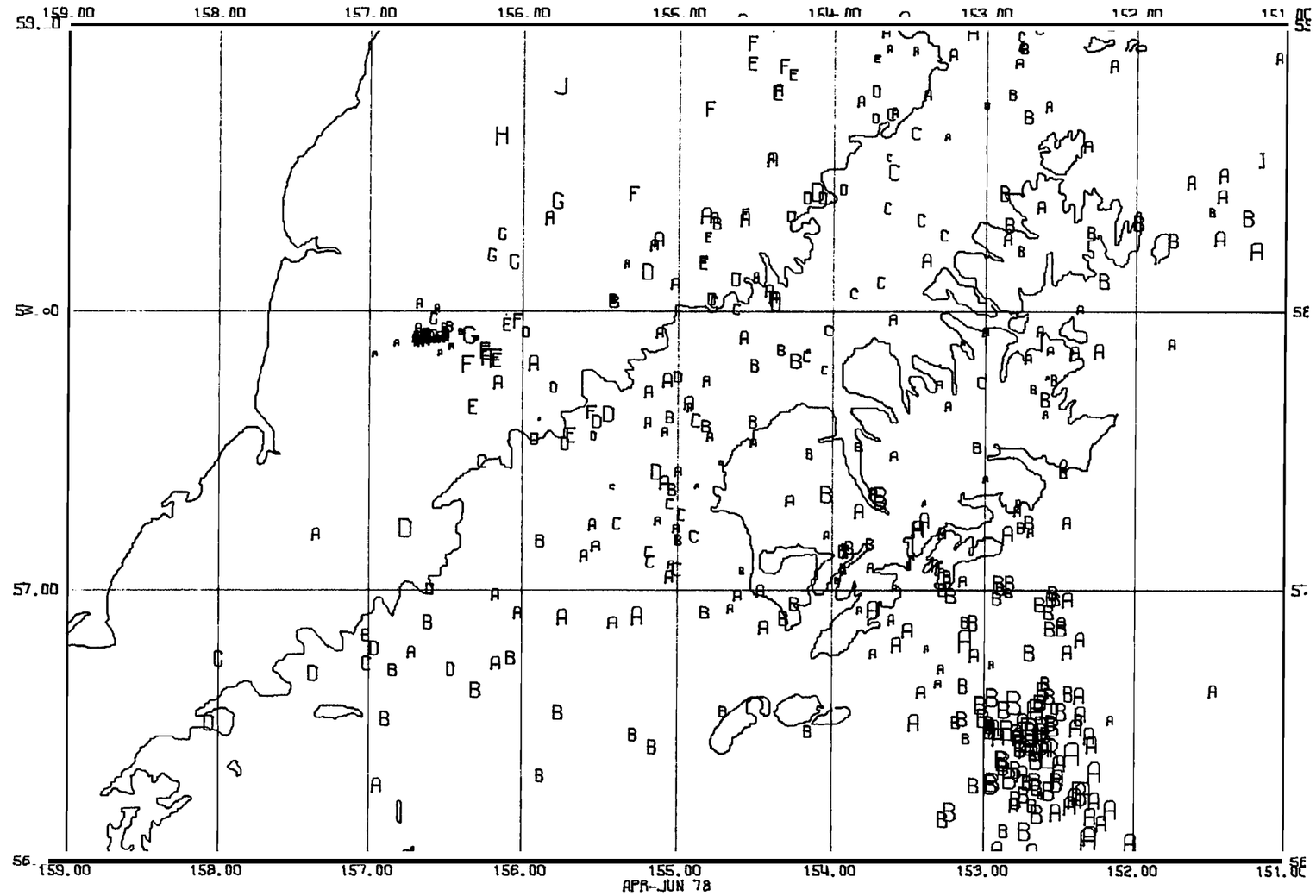


Figure 2.8 Epicenter plot of earthquakes recorded by the local Alaskan network between April and June 1978. Plot produced by University of Alaska Geophysical Institute. Size of symbol is proportional to magnitude, and letter refers to depth category (i.e., A = 0-25 km, B = 26-50 km, etc.).

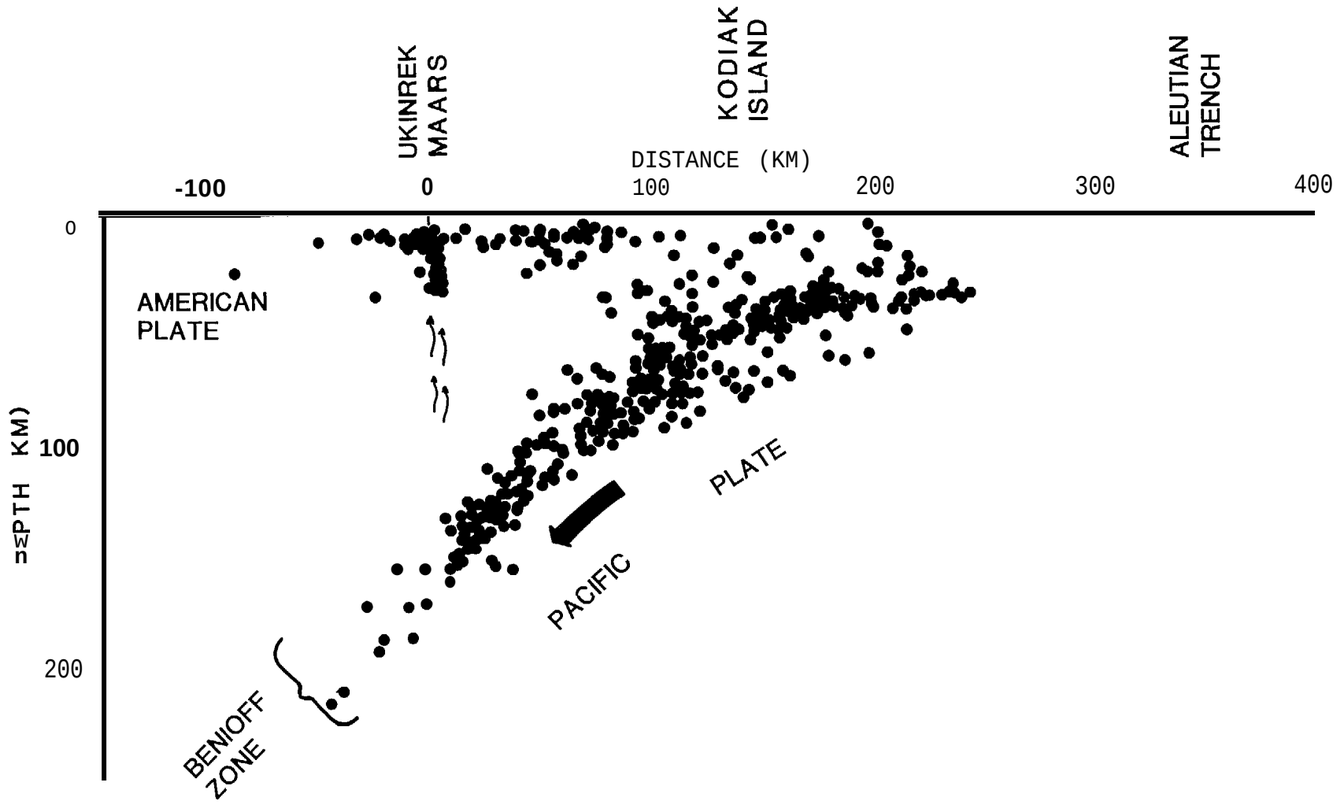


Figure 2.9 Hypocenters of earthquakes projected onto a vertical plane oriented perpendicular to the Aleutian Trench. and passing through Ukinrek Maars (Pulpan and Kienle, 1979b). Note the well-defined Benioff zone, the **shallow diffuse seismicity, and the clustering of events under Ukinrek and under the main volcanic** arc slightly east of the maars. Epicenter data are from the local Alaskan seismic network.

The cluster of small shallow events on the Alaska Peninsula in Fig. 2.8 is associated with recent volcanic eruptions at Ukinrek Maars on the Alaska Peninsula (Kienle et al., 1977). A projection of these hypocenters onto a vertical plane oriented perpendicular to the continental margin dramatically reveals the relationship between seismicity and the crustal subduction process (Fig. 2.9).

2.2.3 Major earthquakes affecting the Kodiak region

In spite of the numerous earthquakes that occur in the immediate vicinity of Kodiak Island and Shelikof Strait, none has as yet caused extensive damage by ground rupture or shaking, due in large part to the undeveloped nature of the region. If Kodiak were to become a major industrial and population center, the events that do **occur could** have more serious consequences.

However, an earthquake does not have to occur in the immediate vicinity of a region to cause extensive damage. The Great Alaska Earthquake of 1964 is an **example.** The epicenter of this (magnitude 8.5) event was located near Anchorage, yet it had a significant impact on Kodiak Island, some 320 km or so distant. The effects of this earthquake were so widespread that a special committee was established by the National Academy of Sciences to study it. Their efforts resulted in the most comprehensive and detailed account of an earthquake ever compiled (National Academy of Sciences, 1972).

Figure 2.10 shows the Mercalli scale intensities produced by that earthquake at various locations on Kodiak Island. The intensities ranged between VI and IX and indicated the following felt effects (Brazee, 1976) :

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

The earthquake produced extensive land level changes on the continental shelf off Kodiak Island (Fig. 2.11), although to date no single offshore fault

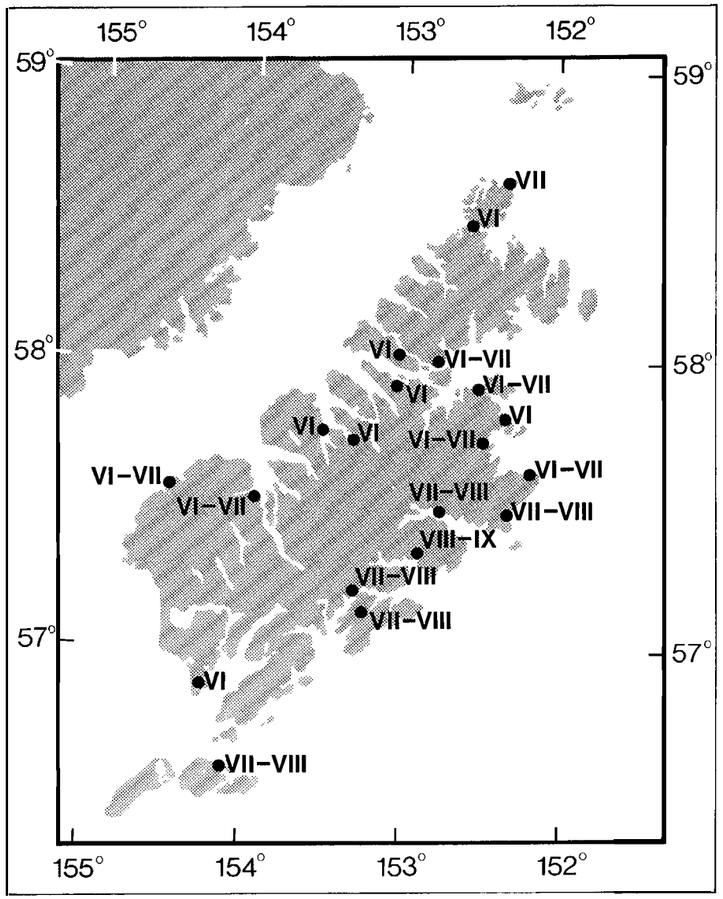


Figure 2.10 Intensities of felt effects on Kodiak Island due to the 1964 Great Alaska Earthquake (Buck et al., 1975).

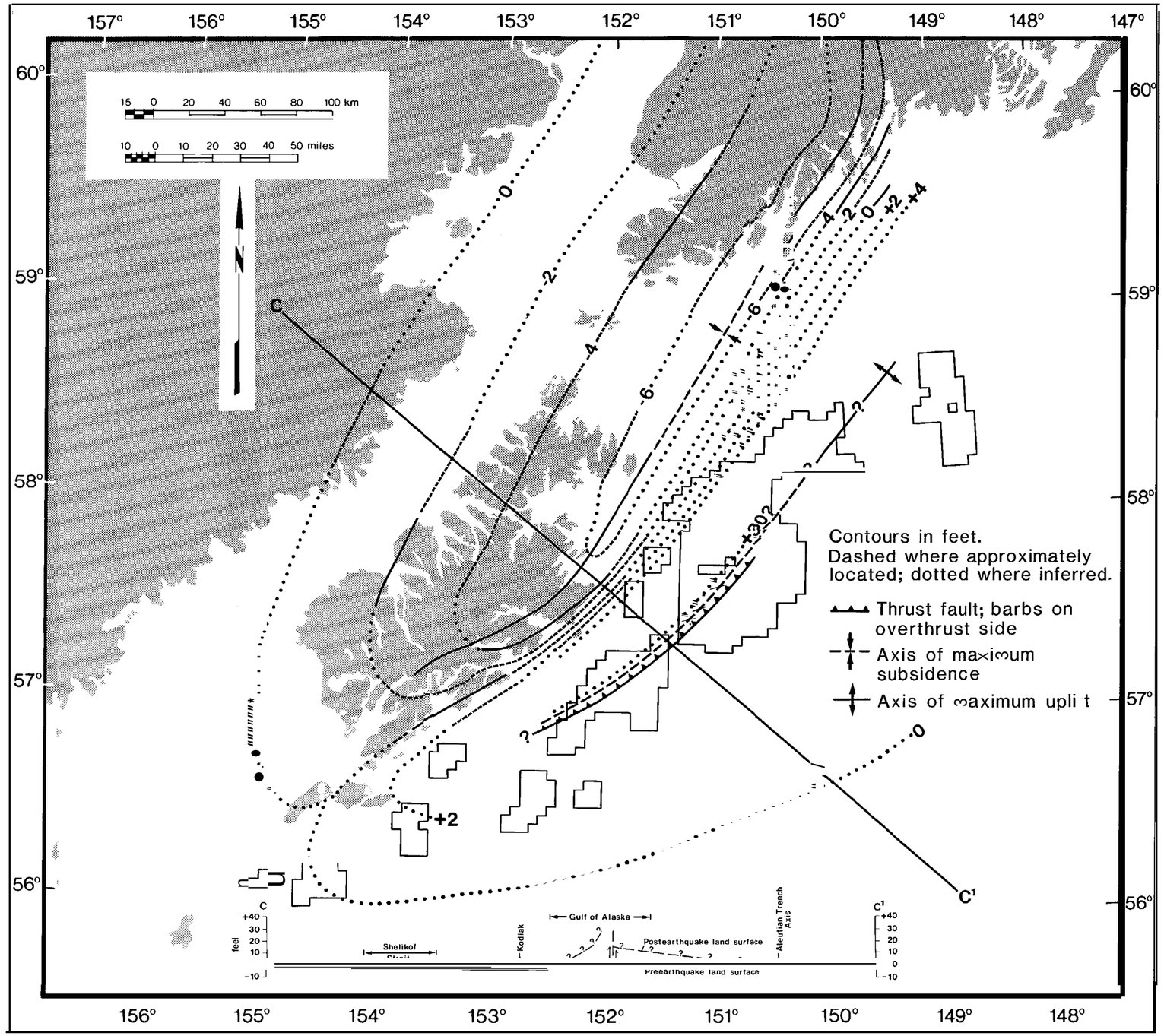


Figure 2.11 Land level changes in the vicinity of Kodiak Island due to the 1964 Great Alaska Earthquake (Plafker, 1972).

scarp on the sea floor has been positively identified as having been produced by the earthquake. The strain release map shown in Fig. 2.12 demonstrates that while the epicenter of the earthquake was in Prince William Sound, the rupture propagated to the southwest along the continental shelf, continuously releasing stress in the form of aftershocks (Wyss and Brune, 1967).

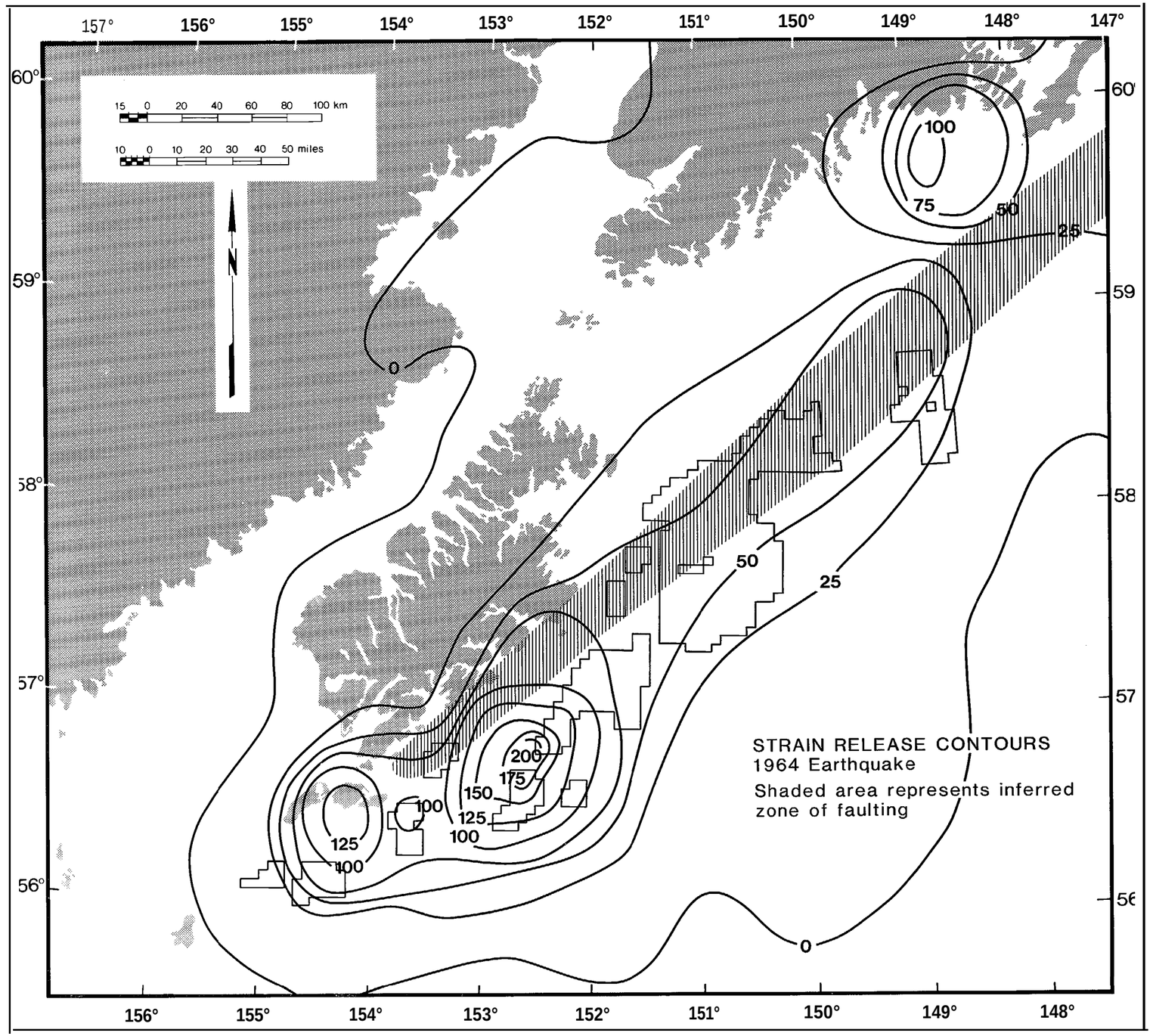


Figure 2.12 Strain release calculated from aftershock data for the 1964 Great Alaska Earthquake. Large numbers indicate greater amount of seismic energy release per unit area and time (from von Huene, 1972).

The most serious damage resulted from the seismic ea wave, or tsunami, generated by this earthquake. to fishing boats and port facilities occurred at nearly every city on Kodiak Island (Fig. 2.13), with Kodiak receiving extensive damage (Plafker and Kachadoorian, 1966; Buck et al., 1975).

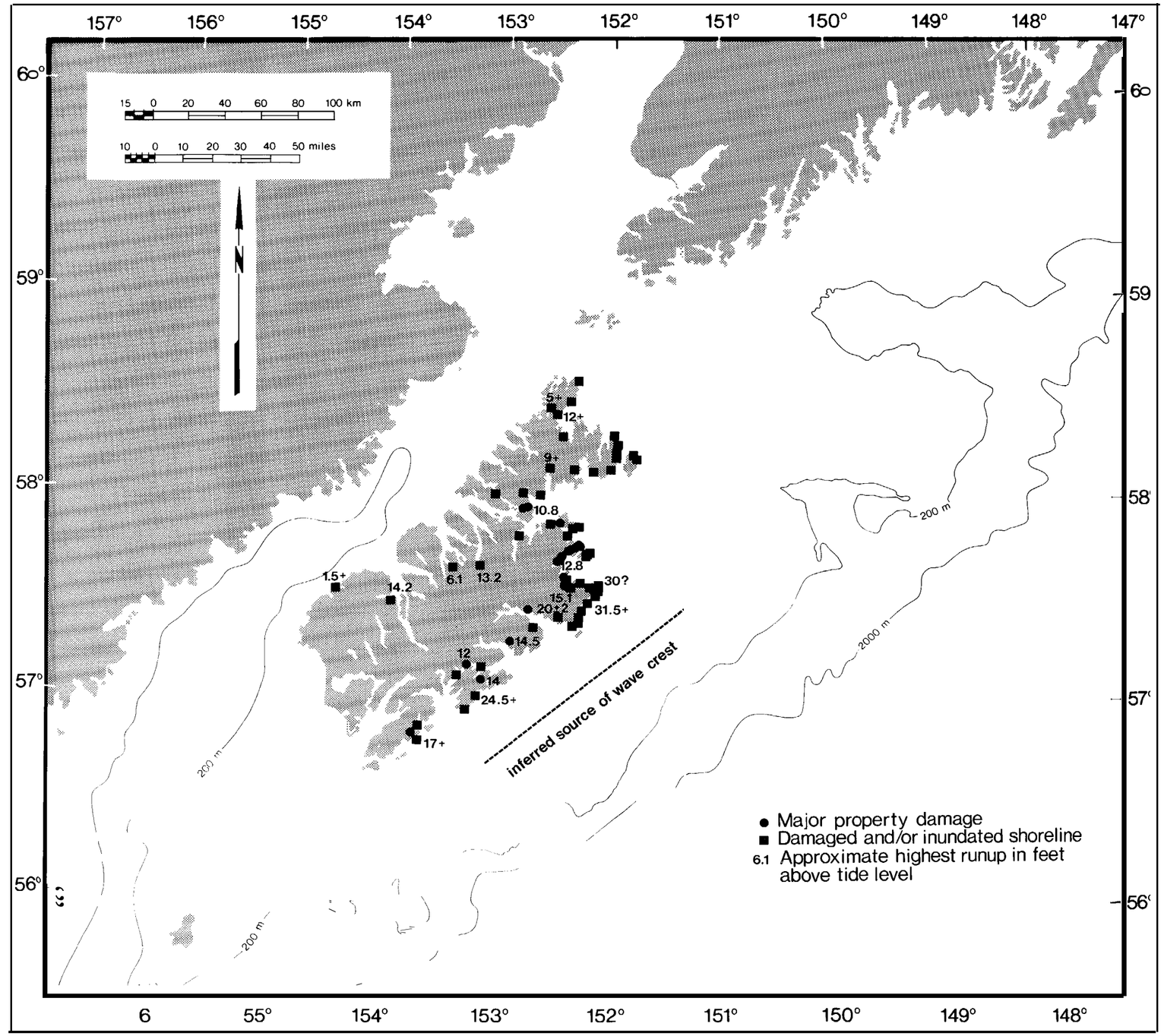


Figure 2.13 Damage on Kodiak Island resulting primarily from the tsunami generated by the 1964 Great Alaska Earthquake (Selkregg, 1974).

2.2.4 Earthquake occurrence rates

In planning for future development, it is important to make every effort to estimate the rate of occurrence and the likelihood of future occurrence of earthquakes of various magnitudes. While precise prediction of the location, magnitude, and time of large earthquakes has not yet been attained, progress has been made in "forecasting" the location, general size (e.g., great, large), and time of occurrence to within a few tens of years (McCann et al., 1978). A working hypothesis to do this involves analysis of seismicity gaps.

The seismic gap hypothesis suggests a higher earthquake potential for those segments of lithospheric plate boundaries which have experienced fewer large earthquakes in the last three decades than adjacent segments. It can be seen in Fig. 2.14 that the aftershock zones of large earthquakes tend not to overlap; the areas separating adjacent aftershock zones are designated "seismic gaps." Studies have revealed several gaps along the Aleutian Island chain and the southern Alaskan borders (Kelleher, 1970; Sykes, 1971; McCann et al., 1978; Fig. 2.14).

Both the 1972 magnitude 7.3 earthquake near Sitka and the 1979 magnitude 7.7 Mt. Saint Elias earthquake occurred within seismic gaps identified before either event by Sykes (1971). Recent study of the 1979 event indicates that the seismic gap in the NE Gulf of Alaska has not been completely filled by the aftershocks of that earthquake (Lahr et al., 1979), and therefore should still be considered an area of high potential for a large earthquake.

The Shumagin seismic gap is of particular significance in assessing earthquake risk for the Kodiak OCS. Several lines of evidence are cited by Pulpan and Kienle (1979b) to indicate that the Shumagin gap **actually extends from the southwestern tip of Kodiak Island to the eastern edge of the 1957 magnitude 8.2 aftershock zone:**

1. The segment has experienced a relatively low level of activity during historic times, and a lower level of activity compared to the Kodiak shelf as recorded by the local network in the past several years.

2. Pronounced changes in geological features and an offset in the line of Alaska Peninsula volcanoes occur at the southwest margin of the 1964 aftershock zone, suggesting the possibility of arc segmentation in which each segment accumulates and releases tectonic stresses.

3. Higher stress levels exist between Kodiak Island and the end of the Alaska Peninsula, than in other parts of the Aleutian-Alaska subduction zone arc (Archambeau, 1978).

In a recent analysis of the seismic potential of plate boundaries, McCann et al. (1978) assigned the eastern half of the Shumagin gap to their category 2, and the western half to category 3, defined as follows:

Category 2

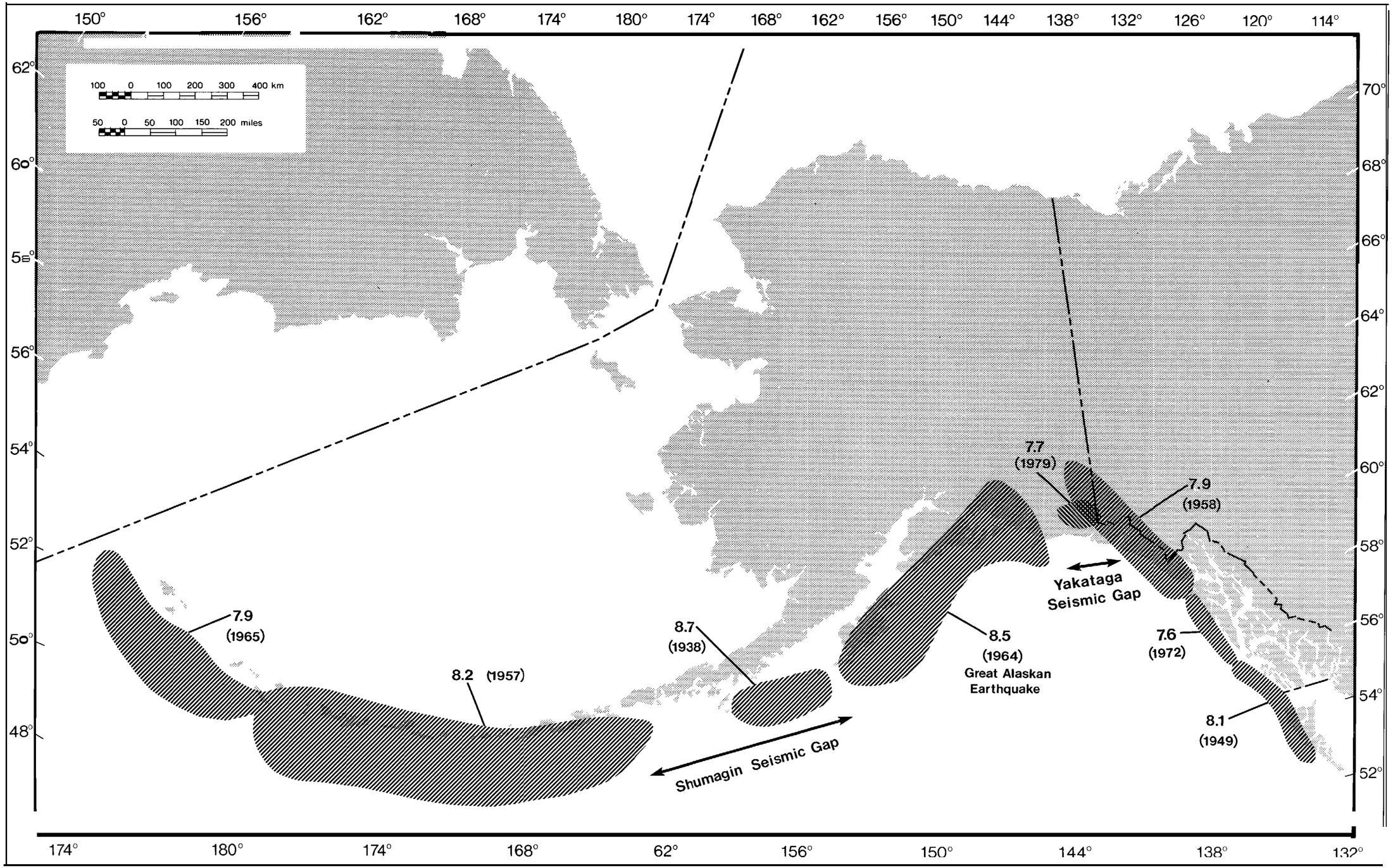
The region has experienced at least one large shock in the past with the most recent event occurring between 1879 and 1949, i.e., more than 30 years ago, but less than 100 years ago.

Category 3

The region has an incomplete history of large earthquakes. No historic event is clearly documented as having ruptured the plate boundary. There is no evidence, however, that would indicate that the region may not be the site of a future large earthquake. A comparison of the tectonic framework with that of other areas known to be sites of historic large shocks may also suggest that the region is capable of being the site of a future large shock.

Seismologists agree in general that seismic gaps have the highest potential for future large earthquakes. However, the discovery of a means to calculate the recurrence intervals of large earthquakes for a given region has proved to be an elusive goal. Estimates of recurrence intervals of very large earthquakes in Alaska range from 800 years (Plafker, 1971) to 33 years (Sykes, 1971). Recent research relating the width of the main thrust zone of the descending oceanic crust to the recurrence times of great earthquakes along the Alaskan convergence zone (Davies et al., 1979) indicates a recurrence interval on the order of 80 to 140 years for the Shumagin Islands region. It is therefore within the realm of possibility that a great earthquake will occur in the Shumagin seismic gap during the course of petroleum industry development on the Kodiak shelf.

Figure 2.14 Aftershock zones and seismic gaps along the Aleutian Island/southern Alaska plate boundary (modified from Sykes, 1971; McCann et al., 1978; Lahr and Stephens, 1979).


150°
156°
162°
168°
174°
180°
174°
168°
162°
156°
150°
144°
138°
132°
126°
120°
114°
62°
60°
58°
56°
54°
52°
50°
48°
70°
68°
66°
64°
62°
60°
58°
56°
54°
52°
100 0 100 200 300 400 km
50 0 50 100 150 200 miles
7.7
(1979)
7.9
(1958)
Yakataga
Seismic Gap
7.9
(1965)
8.7
(1938)
8.2 (1957)
8.5
(1964)
Great Alaskan
Earthquake
7.6
(1972)
8.1
(1949)
Shumagin Seismic Gap
174°
180°
174°
168°
62°
156°
150°
144°
138°
132°

The rate of occurrence of earthquakes can be described statistically by the frequency distribution of past earthquakes, principally those recorded instrumentally. This distribution follows the formula

$$\log N = a - bM$$

where N is the cumulative number of events per year greater than magnitude (M), and a and b are the intercept and slope of the equation when graphed on semilogarithmic scales. The b value is the rate parameter of interest. It has been shown to vary as a function of several earthquake source parameters: geographical region, time, depth of focus, type of shock (foreshock, aftershock, etc.), and level of stress in the rocks. Wyss (1973) provides a further discussion of the physical significance of b values. Unless the data selected for frequency distribution analysis are restricted to as few source parameters as possible (e.g., all events which occur in a geographic region defined by geological features), the frequency distribution is not a reliable indicator of frequency of occurrence.

Meyers et al. (1976) have calculated b values for Alaskan earthquakes of magnitude 4 or greater which occurred within a circle of 75 km radius about points at whole-degree increments. An example of frequency distribution for Kodiak Island is shown in Fig. 2.15. Since many of the source parameters of earthquakes, as described in the preceeding paragraph, were not considered in this analysis, the b values represent an average of the effects of several physical parameters which influence the b value; hence, these data should not be used to estimate the recurrence of specific magnitudes for discrete time intervals.

Future research is planned which will interpret b value data for all of the Aleutian/Alaska arc. Data from local seismograph networks will be assembled and standardized with respect to magnitude and location calculations, and may be useful in describing temporal and spatial variations in the recurrence rate of earthquakes in Alaska.

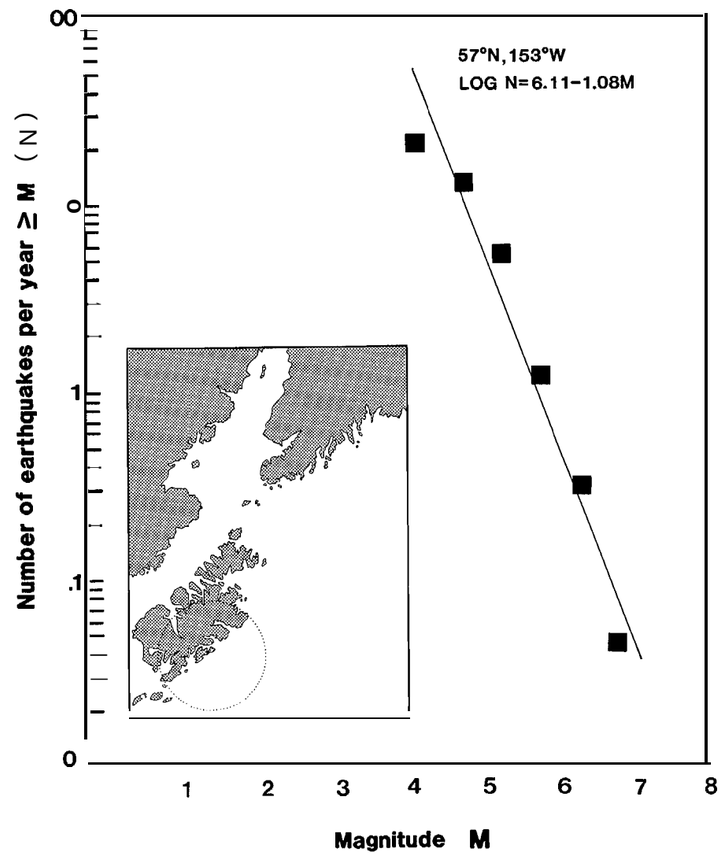


Figure 2.15 Example b value curve for an area near the Kodiak OCS. Earthquake data are from the 75 km radius circle shown in the index map inset (modified from Meyers et al., 1976).

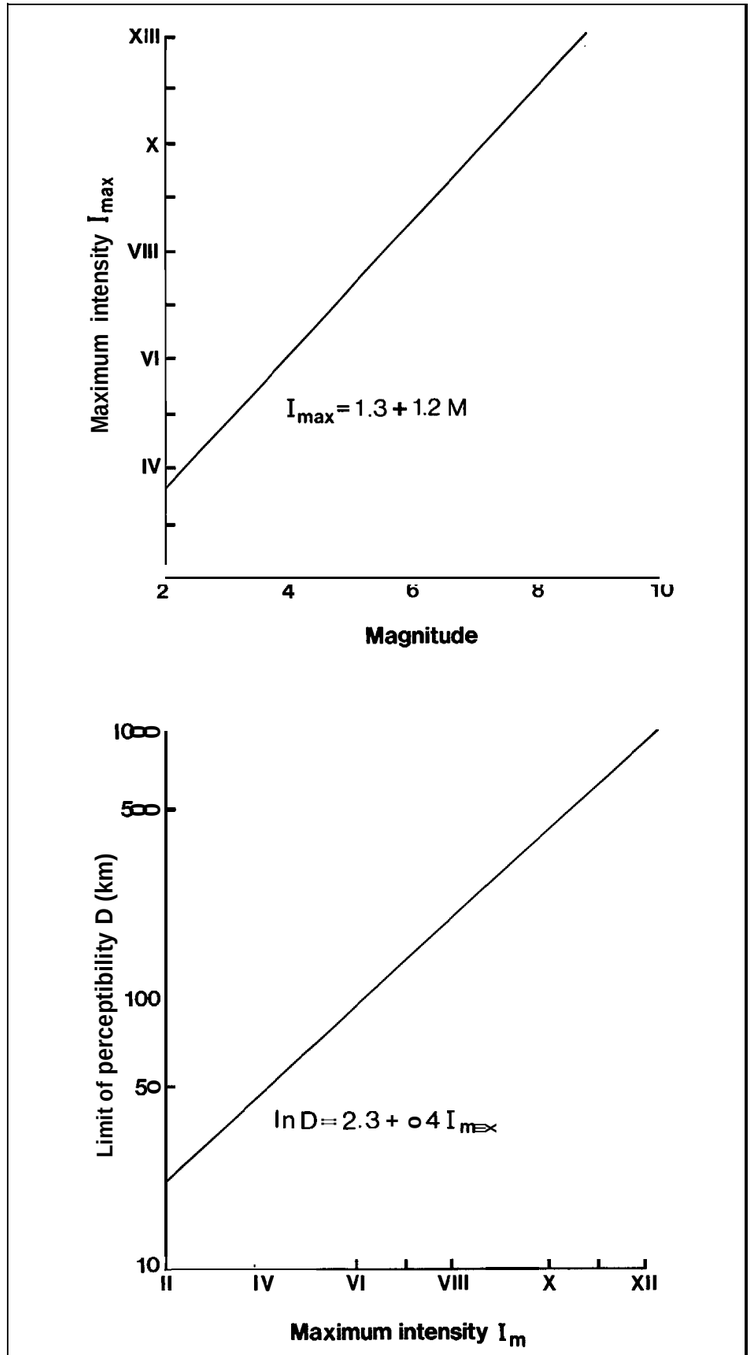
2.2.5 Attenuation of earthquake energy

The energy released as elastic shock waves at an earthquake hypocenter is dissipated by geometrical spreading and absorption by geological formations through which the waves pass. A subjective measure of the degree of attenuation at a distance from the hypocenter is referred to as intensity. It is an evaluation of felt effects of the earthquake, i.e., duration and severity of shaking, physical damage, and psychological response of the population.

The scale used today in the U.S. to quantify intensity is the Modified Mercalli Scale of 1931 (Wood and Neumann, 1931; Brazee, 1976). Surveys are made in the area experiencing an earthquake and contours, called isoseismals, are drawn connecting observation points of equal intensity. Presently, there are no means of assigning intensities to offshore areas, except for effects experienced on offshore platforms. Attenuation of earthquate energy by formations near the seafloor surface may be quite different from that on land.

Meyers et al. (1976) have completed a study which relates earthquake magnitude to intensity at distance from the epicenter, for all Alaskan data (Fig. 2.16). Note that the number of significant figures in the relationship is not indicative of precision. This type of research allows engineers to anticipate the effects on structural designs of events of various magnitudes in unpopulated areas where no intensity data exist. The primary limitation of this research comes from the subjective nature of the intensity data that were used. For engineering design purposes, a more objective, quantified approach must be taken.

A significant amount of research has been conducted as part of the Offshore Alaska Seismic Exposure



Study (OASES) in an effort to produce a seismic exposure map for the Alaskan OCS which will be useful for engineering design (Woodward-Clyde, 1978). As part of this research in modeling earthquake risk, it was necessary to define the attenuation of earthquake energy between a source and possible development site much more objectively than by simply relating felt intensity, distance, and magnitude. The measurements required for this objective approach are made by strong-motion instruments, which are triggered by an earthquake Unfortunately, since strong-motion data for Alaska are essentially non-existent, the OASES researchers had to rely on data from areas in southern California and Japan to develop their models. As more strong-motion instruments are installed in Alaska, attenuation data will become available which will further improve the output from the models, and provide engineers with the data they to design platforms, pipelines, and other structure that are as earthquake resistant as possible.

Figure 2.16 Empirical relationships between magnitude (M), maximum intensity (I_{max}), and distance (D) to the limit of perceptibility of felt effects. Equations are from Meyers et al. (1976).

2.2.6 Seismic sea waves (tsunamis)

Offshore earthquakes may produce displacements at the seafloor which result in seismic sea waves, or tsunamis. Seawater attenuates seismic wave energy much less than geologic formations, allowing these waves to travel great distances from their earthquake source at speeds of several hundred km/hr in deep water (Murty, 1977). A tsunami slows down as it enters shallower water during approach to a shoreline, and the wave height may build considerably. An extensive tsunami warning system developed at the Palmer, Alaska, Seismological Center can issue warnings in response to the occurrence of a major earthquake. Prediction of the arrival time of a tsunami is based on the distance between the epicenter and the location along the Alaskan coastline (Cox and Pararas-Carayannis, 1976)

Tsunamis can also result from major landslides which enter ocean areas or bays, as has occurred in Lituya Bay in NEGOA several times (Coffman and von Hake, 1973). The U.S. Geological Survey in Anchorage estimates that if part of Pillar Mountain slides into the Port of Kodiak entrance, a 3-m wave could be generated in the harbor that would cause as much damage as the 1964 earthquake (Geotimes, 1978). Violent volcanic eruptions may also produce tsunamis; the 1883 eruption of Mt. Augustine in Cook Inlet produced a 10-m tsunami 80 km away at Port Graham in English Bay (Kienle and Forbes, 1976).

Table 2.2 summarizes tsunamis observed around Kodiak Island and illustrates the variety of possible sources. The tsunami risk for offshore structures is low, due to the small wave heights attained during travel through deep water. However, the risk of damage to pipelines in shallow water and to shoreline facilities in bays around Kodiak Island is high. The Kodiak shoreline, particularly such bays as Marmot, Chiniak,

Table 2.2 Tsunamis observed in the vicinity of the Kodiak shelf (from Cox and Pararas-Carayannis, 1976).

Location	Earthquake or Volcanic Eruption	Remarks
Three Saints Bay, on Kodiak Is.	(unknown cause) about July 22, 1788	Effects uncertain, but included inundation, loss of life and bogs, and a ship thrown onshore; apparently a significant event, judging by the number of old reports describing it.
Three Saints Bay, on Kodiak Island	1827	"Agitation" and anomalous waves; possible offshore quake and seiche.
Kodiak	August 13, 1868 Earthquake in N. Chile	Tsunami observed, no damage
Kodiak	August 27, 1883 (Krakatoa eruption)	Small waves (0.1 m height) were generated by atmospheric pressure waves resulting from Krakatoa explosion.
Women's Bay, on Kodiak Is.	November 5, 1952 Msg. 8.25 East Kamchatka	Great tsunami ; considerable damage and some loss of life at Kamchatka; wave height 0.4 m at Women's Bay.
Women's Bay, on Kodiak Is.	March 9, 1957 Msg. 8.3 Unimak Is.	Wave height 0.2 m at Women's Bay; no reported damage on Kodiak; observed throughout Pacific, with major damage at Hawaii and Japan.
Kodiak	May 22, 1960 Mag 8.5 S. Chile	Wave height 0.7 m at Kodiak great damage in Chile, Hawaii, and Japan.
Kaguyak Old Harbor Kodiak Women's Bay	March 27, 1964 Msg. 8.5 Prince William Sound	Wave heights of 6 to 20+ m reported around Kodiak 1s ; great damage to towns, canneries , and fishing boats; 12 deaths; over $40 million in damages.
Kodiak	February 3, 1965 Msg. 8 Rat Island	Small wave (0.1 m) at Kodiak; no reported damage.

Ugak, and Kiliuda, is exposed to tsunamis generated anywhere in the Pacific, and especially to those generated in the highly earthquake-prone Aleutian/Alaska seismic belt.

2.2.7 Summary of earthquake hazards and risk analyses

Earthquakes produce a variety of effects that must be considered in any hazard analysis for a region. A generalized list of effects for the Kodiak Island coastline, the OCS, and Shelikof Strait includes the following:

Effect	Consequences
Ground shaking	Collapse of structures, weakening, and future collapse; failure of unstable terrain, landslides.
Ground rupture	Water and sewer line failures, contamination of water supplies; gas and oil line failures, fires; electrical line failures, fires, power outages; disruption of transportation lines
Tsunamis	Destruction of port facilities and boats
Population trauma	Panic, injury, loss of life; crime, looting

The proximity of the Kodiak shelf and Shelikof Strait lease areas to the active subduction zone of the Alaskan margin and its attendant seismicity places the region in a high earthquake risk category. Very large, destructive earthquakes have occurred near the Kodiak shelf, and most of the major damage resulted from tsunamis rather than ground shaking. The tectonics of the region suggest the possibility of a very large earthquake in the Shumagin seismic gap (Pulpan and Kienle, 1979b; McCann et al., 1978), so the risk of damage from severe ground shaking and tsunamis around Kodiak Island is indeed present.

The risk of disastrous destruction due to an earthquake during the exploratory phase of oil industry development is probably lower than during the later production and transportation stages. This is because the semisubmersible exploratory drilling rigs (Wills et al., 1978) are less susceptible to damage from seismic waves than are structures permanently attached to the ground, such as pipelines, tanker terminals, and storage tanks.

Statistical recurrence rates have been used along with various other parameters to produce a "seismic exposure value" for OCS development areas in Alaska (Woodward-Clyde, 1978). The results of this research, primarily useful for engineering design purposes, are given in terms of the spectral velocity of seismic waves and expected ground accelerations caused by an earthquake with an expected return period of 100 years. The seismic exposure value for Shelikof Strait and most of the Kodiak shelf is minimal relative to the other lease areas considered, and the suggestion is that the predicted value "will not significantly impact the design of typical pile-founded structures." However, the predicted values south of Kodiak Island and throughout the Shumagin seismic gap "will dominate the design of structures" (Woodward-Clyde, 1978).

A second seismic risk assessment of Alaska and the adjacent OCS has been undertaken by the U.S. Geological Survey in Denver, Colorado (Thenhaus et al., 1979). In this study, the historical earthquake record has been used along with geological information to produce maps of peak ground acceleration to be expected during periods of 10, 50, and 250 years. As in the OASES study , the USGS models produce information that is primarily used for engineering design.

2.3 VOLCANIC ACTIVITY

2.3.1 History of eruptions

The Alaska Peninsula northwest of the Kodiak OCS and Shelikof Strait contains numerous active volcanoes (Fig. 2.17), a number of which have eruptive histories during this century (Table 2.3). This volcanic arc is a direct consequence of the subduction of the Pacific plate under the North American plate, as previously described. Three of these volcanoes have produced exceptionally violent eruptions during historic times--Katmai/Novarupta in 1912, Trident in the 1950's and 60's, and Augustine in 1883, 1963/64, and 1976.

Figure 2.17 Location map for Alaska Peninsula volcanoes.

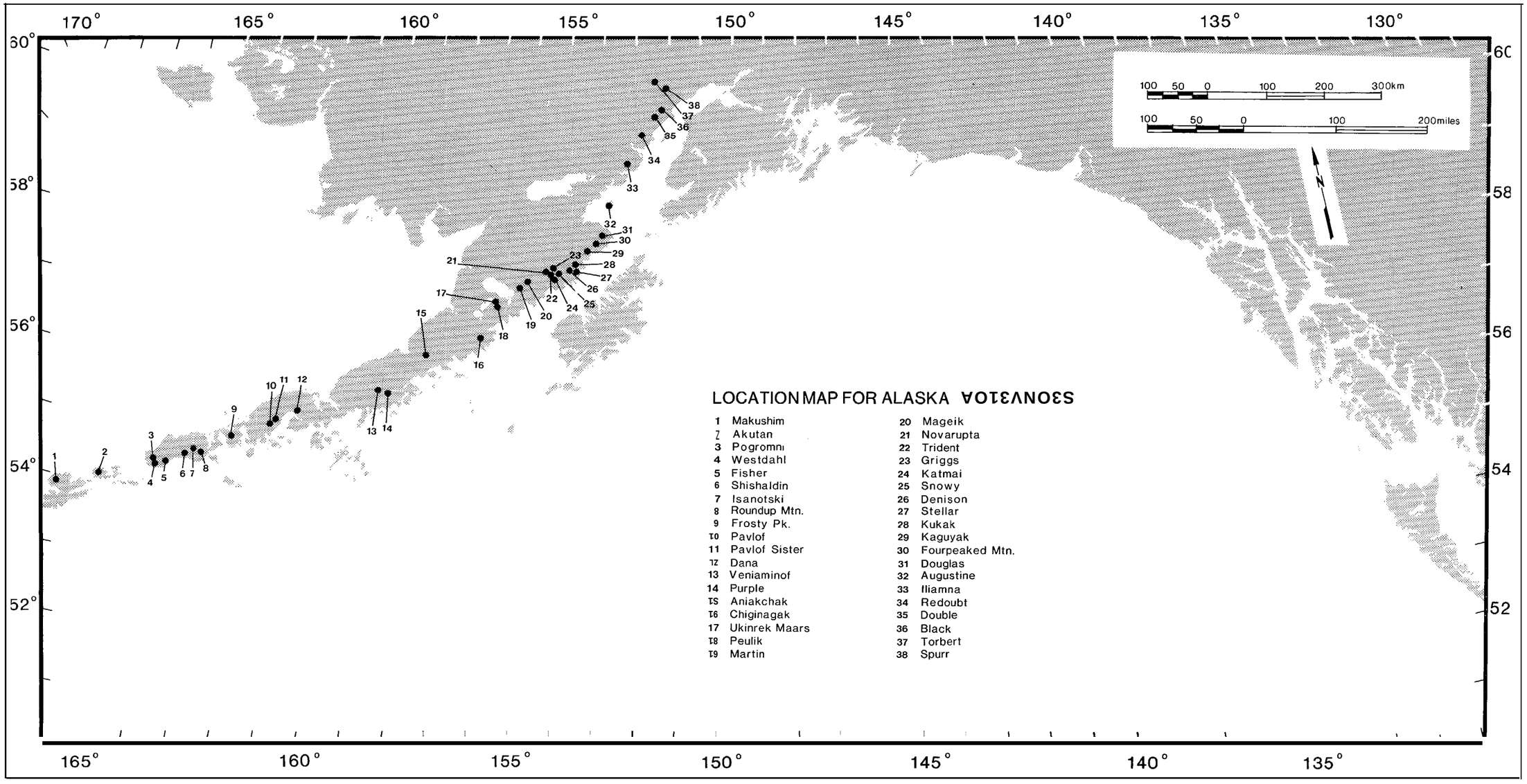


Table 2.3 Volcanic activity in the Kodiak Island region. "Historic activity" refers to the period since about 1700 (adapted from Selkregg, 1974; Kienle and Forbes, 1976; J. Kienle, University of Alaska, pers. comm.)

Number on Figure 2.17	Volcano	Description of Activity
16	Chiginagak	Smoke, steam--1976, 1954, 1929, 1852 Fumaroles on flank
17	Ukinrek	Explosive maar eruption--1977
18	Peulik	Ash eruptions--1852, 1814
19	Martin	Possible ash eruption--1912 Smoke, steam--intermittently since 1912
20	Mageik	Ash eruptions--1953, 1936, 1927, 1912 Smoke, steam--1946, 1929
21	Novarupta	Explosive eruption--1912* *Vent believed to be one of the main sources for ash and pumice flows in the Valley of Ten Thousand Smokes.
22	Trident	Explosive eruptions--1968, 1967, 1964, 1963, 1962 thru 1957, 1954, 1953, 1951; Fumarole activity
23	Griggs	Sulfurous fumaroles on summit and flanks; No known historic eruptions
24	Katmai	Major explosive eruption--1912* Smoke, steam--1931 *Vast pumice and ash deposits accompanied by caldera collapse caused extensive damage to crops and buildings on Kodiak Island, and corrosive rains at Seward and Cordova
25	Snowy	No known historic activity
26	Denison	No known historic activity
27	Stellar	No known historic activity
28	Kukak	Fumaroles on summit and flanks; No known historic eruptions
29	Kaguyak	No known historic activity
30	Fourpeaked Mtn.	No known historic activity
31	Douglas	Fumaroles on summit; No known historic eruptions
32	Augustine	Explosive eruption--1976, 1964-63, 1935, 1884-83*, 1812 Smoke, steam--continuous in recent years, 1971, 1902, 1895, 1885 *Generated a ten meter tsunami at Port Graham in 1883

The 1912 Katmai/Novarupta eruption was one of the most severe in recorded history. Over a period of only two days, it ejected over 25 km^3 of pyroclastic material (AEIDC, 1974), some of which flowed down a valley to form the Valley of Ten Thousand Smokes. A great quantity of ash was ejected into the atmosphere, and a significant amount was deposited on Kodiak 160 km away (Fig. 2.18). Novarupta appears to have been the main source of eruptive material; it has been suggested that Novarupta acted as a relief valve for the pressures and magma building up under Mt. Katmai (Alaska Geographic Society, 1976). The release of pressure and subsequent draining of magma reservoirs under Katmai during the eruption caused the mountain to collapse and form the deep caldera of Mt. Katmai that is visible today.

In 1953, Mt. Trident burst into activity with a 30,000-foot column of smoke and ash (Ray, 1967). During the 1950's and 60's, it was the most active volcano in the Katmai area, having discharged several lava flows and produced major eruptive columns in 1960, 1962, 1963, and 1964. No damage to property or loss of life has been attributable to eruptions of Trident, however

Most recently, Augustine volcano in Inlet erupted during January, February, and April 1976, producing eruptive columns up to 11 km high, glowing debris avalanches with nuées ardentes, regional ash falls, and a lava dome at the summit. This most recent activity has been described in detail by Kienle and Shaw (1979), and Kienle and Forbes (1976).

The main eruption began on January 23 and consisted of major explosions and ash falls characteristic of the vent-clearing phase. Pyroclastic debris flows, nuées ardentes, and additional explosions continued into early February. Extrusion of a lava dome began about February 12, heralding the decline of explosive activity. A second extrusive phase occurred between April 13 and 18, 1976, and was the last of the major eruptive phases (Kienle and Shaw, 1979). Post-eruptive stages at Augustine consist of gas and steam expulsion, and relatively quiet seismicity.

Eruptions characterized by violent ejection of solid or semi-solid hot rock fragments, glowing avalanches, and short, thick lava flows or lava domes are termed "Peléean" eruptions. The previous eruptions of Augustine (since its discovery in 1778), probably all Peléean in nature, occurred in 1812, 1883, 1935, and 1963-64. The 1883 eruption was violent enough to produce a 10-m tsunami at Port Graham in English Bay during one blast, causing considerable damage to fishing boats and docking facilities (Davidson, 1884).

Researchers from the University of Alaska's Geophysical Institute have assembled a large amount of information on Augustine volcano, and have a good understanding of its eruptive history, geology and geochemistry, internal structure, and associated seismic activity (Pulpan and Kienle, 1979b). Seismic activity is particularly noteworthy in that shallow seismic activity under the volcano appears to precede eruptions. The 1976 eruption, for example, occurred after eight months of precursor seismicity.

In April 1977, volcanic activity began at the Ukinrek Maars between Becharof Lake and Upper Ugashik Lake, slightly to the west of the main arc of Aleutian volcanoes (Fig. 2.17). This activity apparently resulted from the heating of groundwater from below by hot basaltic magma, causing violent steam and gas eruption, and eventually extrusion of lava (Kienle et al., 1977). Recent geochemical research on gases emitted at the maars (Barnes and McCoy, 1979) indicates that explosive release of mantle-derived carbon dioxide from a basaltic magma may also have been instrumental in their formation cal and petrologic data (discussed in Kienle et al., 1980) support the hypothesis that the basalt has a deep origin, 80 km or greater, in the mantle. Continuing shallow seismicity is associated with the volcanic activity at Ukinrek Maars Fig 2.9).

The inferred conduits between the deep mantle source area and the surface eruptions are ase.smic (Pulpan and Kienle, 1979b).

2.3.2 Summarv of volcanic hazards

The phenomena associated with volcanic eruptions that should be considered in assessing volcanic hazards in Shelikof Strait, Kodiak Island, and the Kodiak OCS are:

- Violent, explosive eruptions, directed blasts, glowing avalanches with nuées ardentes, heavy debris falls, and volcanically induced tsunamis.
- Hazardous atmospheric phenomena, including turbulent ash clouds, noxious gas clouds, ash falls, corrosive rains, and lightning discharges.
- Pyroclastic flows, lava flows, and mudslides.

Most of the above phenomena occurred during Katmai's eruption, and may occur in future eruptions of Augustine and other Alaska Peninsula volcanoes. S.nce the risk to facilities and offshore development decreases rapidly with increasing distance from the volcano, vo canic hazards are significantly greater in Shelikof Strait than in the Kodiak OCS lease areas.

However, the effects of airborne ejecta can be serious throughout the Kodiak region. Airborne ash can easily be transported from volcanoes such as Katmai to Augustine and the Kodiak OCS region. The 1912 Katmai eruption deposited about 0.3 m of ash on the city of Kodiak, some 160 km distant, and acid rains fell on Cordova, at a distance of 750 km (AEIDC, 1974; Fig. 2.18).

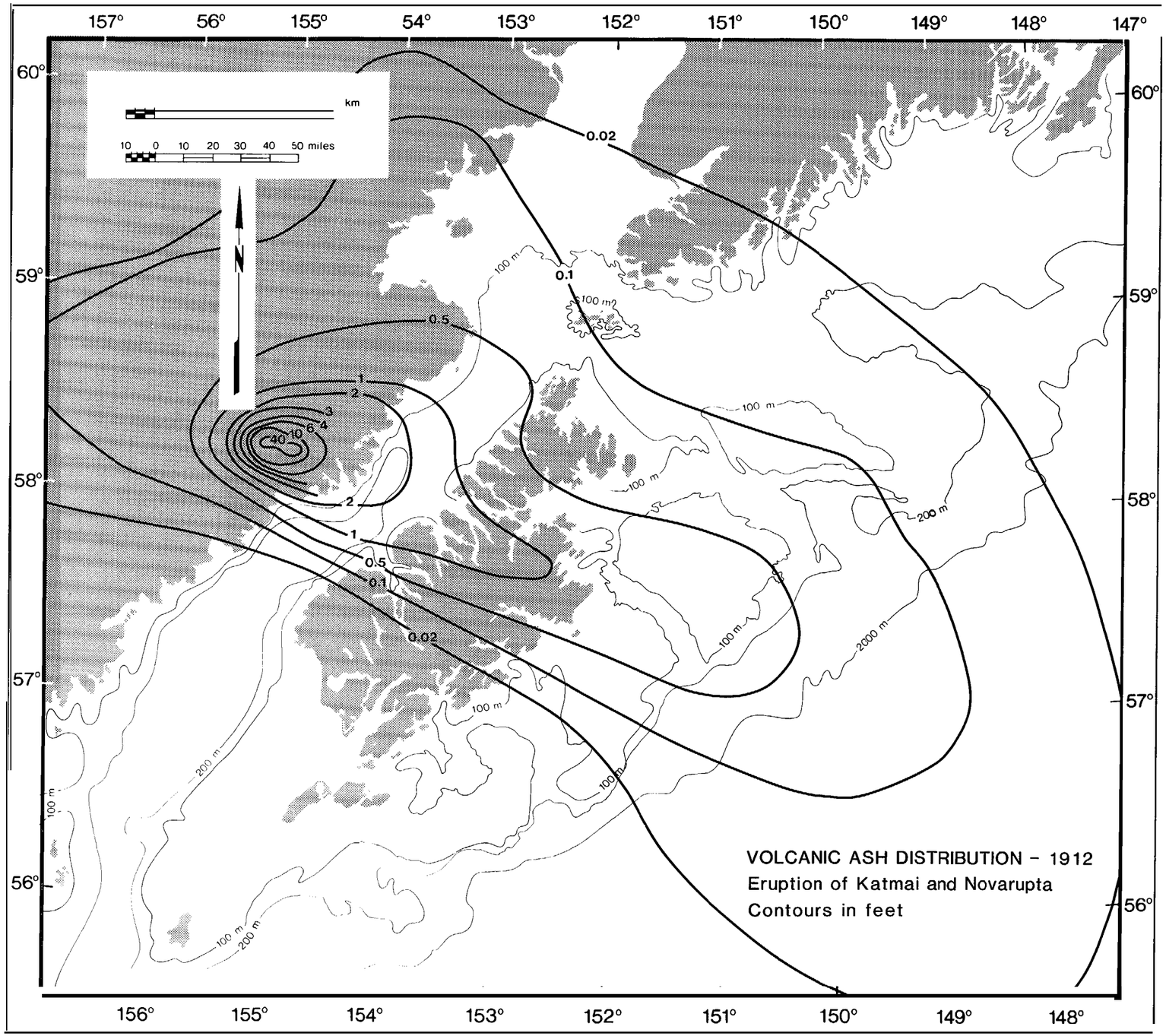
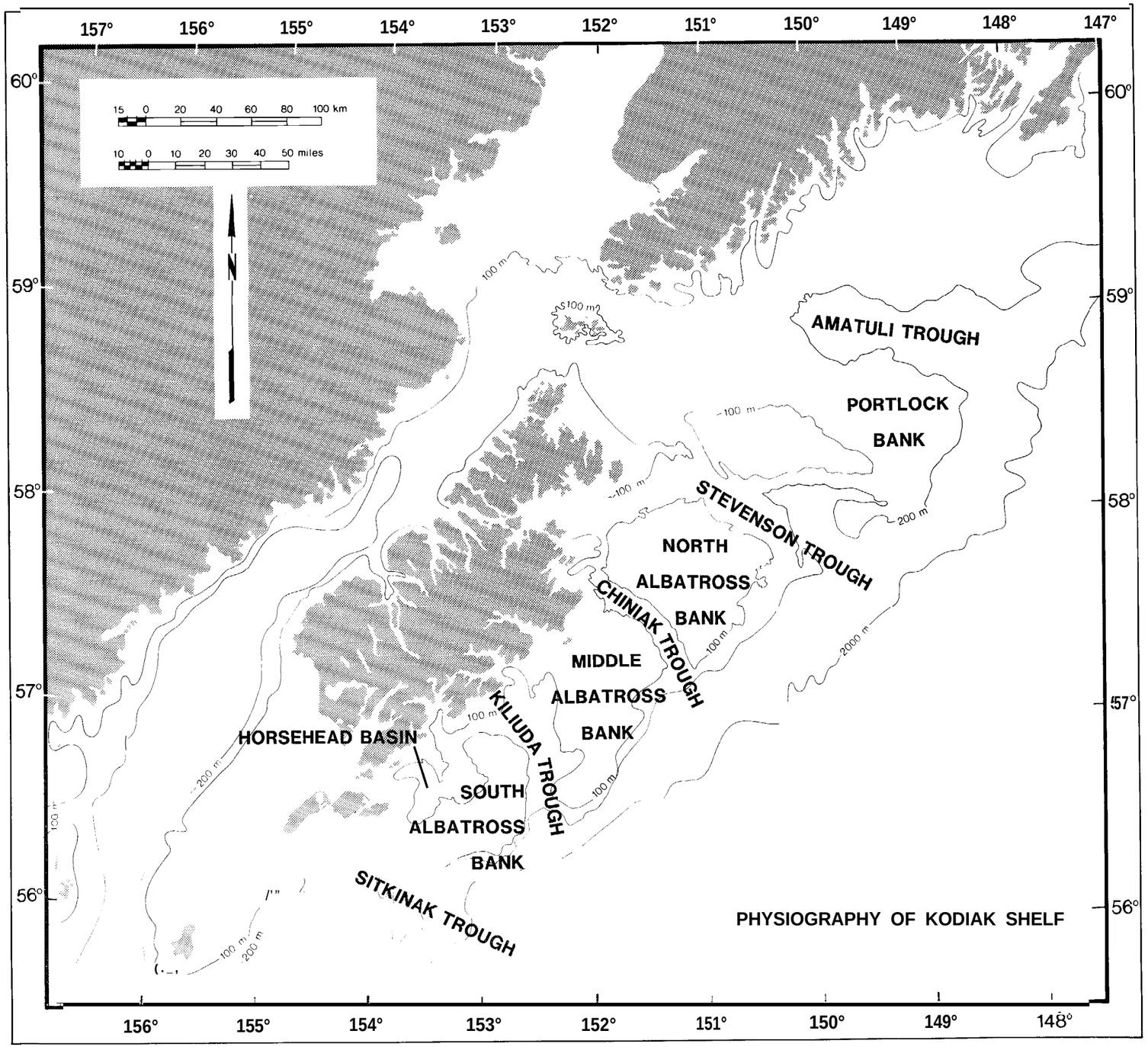


Figure 2.18 Distribution of volcanic ash from the 1912 eruption of Mt. Katmai and Novarupta (from Wilcox, 1959).



Heavy ash falls produce physically uncomfortable conditions; water supplies may become laden with ash or turn excessively acid. Corrosive rains formed by acidic volcanic gases combining with precipitation may accompany eruptions and damage equipment. In addition, ash clouds, corrosive rains, and lightning storms, all atmospheric phenomena accompanying an eruption, could pose hazards to aircraft. Radio communications may also be impaired by these atmospheric phenomena.

2.4 OFFSHORE SURFACE GEOLOGY

2.4.1 Surface sediments

The distribution of unconsolidated surface sediment on the Kodiak shelf is strongly related to the physiography of the seafloor, shown in Fig. 2.19. The physiography, in turn, is a product of past glacial activity and geomorphic processes that have been occurring since the retreat of glaciers about 10,000 years ago. As sea level rose after the last glacial period, wave activity and the influence of longshore currents sorted and redistributed the sedimentary deposits associated with the glaciers. This sorting continues today on the shelf, although probably with less intensity than when sea level was at a lower stand. Estimates of the thickness of unconsolidated surface sediment have also been made by the USGS (Fig. 2.20; Hampton et al., 1979b).

Figure 2.19 Location map for the Kodiak shelf, showing the major physiographic features (modified from Hampton et al., 1979b).

A map of surface geologic units on the Kodiak shelf has recently been assembled by the U.S. Geologica Survey (Fig. 2.21). The map has been constructed by delineating different characteristics on seismic reflection records and correlating the seismic characteristics with sediment samples from the same areas The seismic profiling records were obtained by Petty-Ray Geophysical in 976 and 1977 and were recently released to the public (Thrasher, 1979). The sediment samples that were used to correlate with the seismic records were obtained by Wright (1970) and by Bouma and Hampton (1976 and 1978) as part of OCSEAP The legend for this map includes a narrative description of sediment types found on the shelf, and illustrates the variety in composition and textural characteristics of the unconsolidated material.

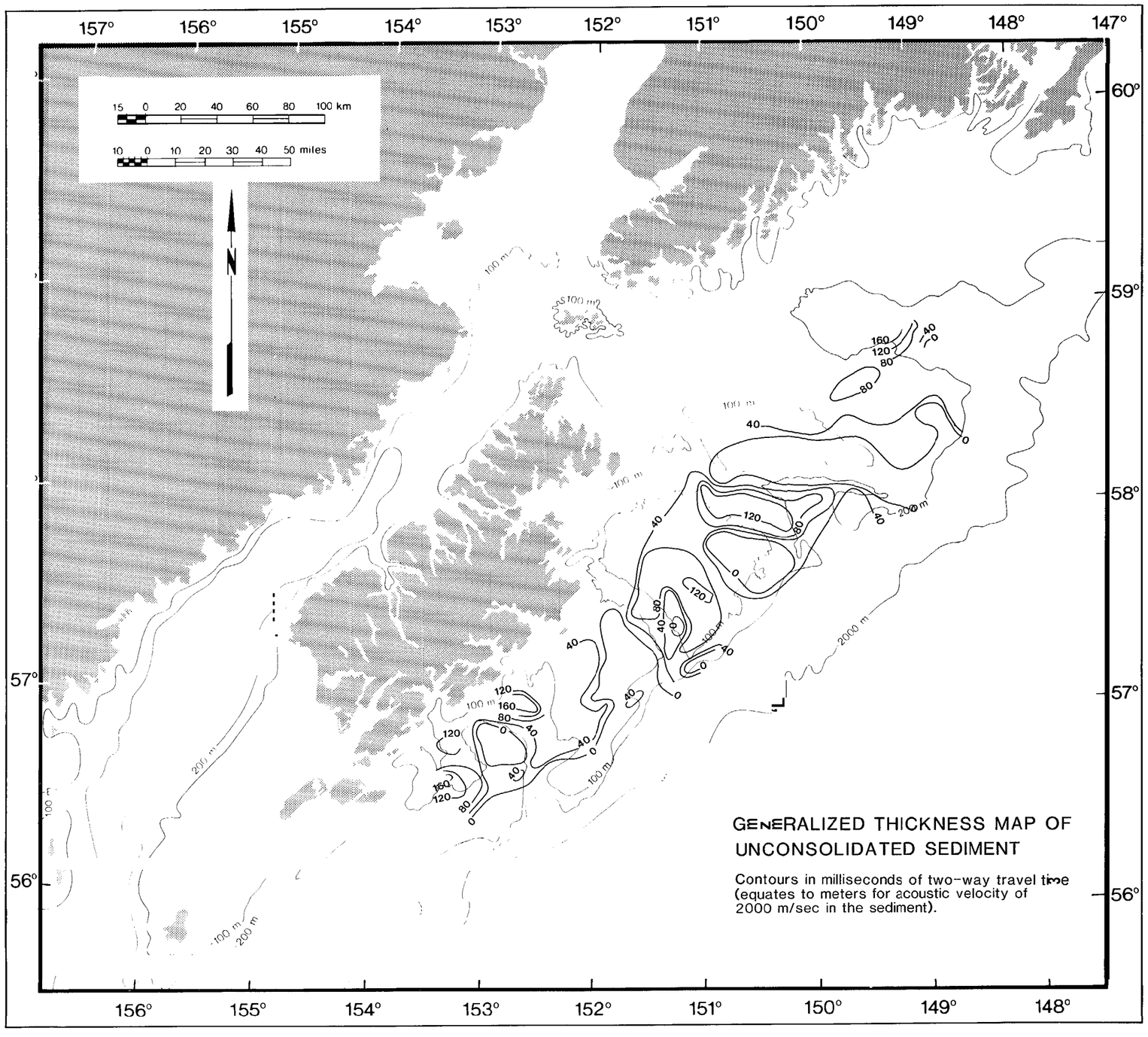


Figure 2.20 Generalized isopach map of unconsolidated sediment on the Kodiak shelf, constructed from seismic reflection data (Hampton et al., 1979b).

Qs Holocene Soft Sediments Shallow basins (profile) well-defined, continuous, horizontal reflectors. These deposits (thin, rarely exceed 100 msec of two-way travel-time (approximately 75 m) in thickness, allow excellent penetration of the 3.5 kHz subbottom profiler signal. Side-scan monographs over this unit are generally featureless with occasional grainy texture, boulders, and water column anomalies. In Stevenson Trough, however, large areas of these deposits show indistinct scattered dimples or blemishes, 5-10 m in diameter, on the sonographs. These features are of unknown origin. Samples are mostly gray-green, ash-rich silts and clays, with occasional sands, pebbles, shells, and glass shards.

Qb Holocene Bedforms and Sand-Fields Mappable regions of bedforms and, where possible, the massive sand unit with which they correlate. Bedforms and sand units identified by cross section on sparker records, by "side-scan" sonographs, or both. Subbottom profiler penetration is nonexistent. All samples recovered from this unit consist of clean, well-sorted sand of various grain sizes.

Qu Holocene Undifferentiated Deposits In seismic profile these deposits exhibit well-developed, nonhorizontal, parallel layering, with occasional indications of internal deformation. Sparker records show the upper layers conformable to the seafloor and often show poorly resolved internal reflectors. The 3.5 kHz subbottom profiler records indicate occasional poor penetration, with fair penetration in the Chiniak Trough deposit. Sample lithologies are diverse, ranging from green muddy ash to gravelly sand.

Qgm Pleistocene Glacial Lateral and Terminal Moraines These fairly linear deposits are generally located along the sides and across the mouths of sea valleys that cut across the continental shelf. There is no subbottom profiler penetration in these "nits. Sparker records indicate no, or very little, internal structure, and thicknesses are rarely more than 100 msec. The few observable side-scan sonograph features are mainly lateral variations of sediment type (> 5 m texture variations on the monographs.) with occasional boulders, water column anomalies, and trawl marks. Dominant sample lithology is gravelly sand, with rare samples of volcanic ash or stiff gray mud.

Qgg Pleistocene Glacial Ground Moraine Sparsely exposed deposits with no internal structure in seismic profile and no subbottom profiler penetration. These fairly thin (generally 100 msec thick) deposits commonly lie in troughs and, in most cases, are overlain by Holocene soft sediments (Qs). The upper surface is hummocky and often constitutes the 3.5 kHz acoustic basement in areas of Holocene sediment fill. Monographs obtained over these deposits exhibit coarse bouldery bottom. Samples from this unit are predominantly muddy sands to sandy muds, with occasional ash, shards, shell fragments, and pebbles.

Qgf Pleistocene Glacial-Fluvial and Glacial-Marine Deposits Thick deposits (often exceeding 100 msec) exposed on bank areas of the continental shelf. In seismic profile these deposits exhibit some discontinuous, nonparallel, nonhorizontal reflectors. The surface is generally smooth and gently sloping with occasional ridges and scarps. The 3.5 kffz subbottom profiler exhibits only scattered, very poor penetration. On side-scan monographs this unit is almost completely covered with fine to coarse texture variations (< 5 m to > 50 m) and has very numerous scattered bedforms (ripples, comet marks, ribbons, and sand waves) fled forms are more numerous on the southern banks than on the northern banks. Trawl marks, boulders, and boulder patches are also commonly observed on the sonographs. Samples recovered from this unit are diverse in lithology, which is mainly sandy, and contain considerable shell debris. Pebbles, gravel, ash, and mud are also common.

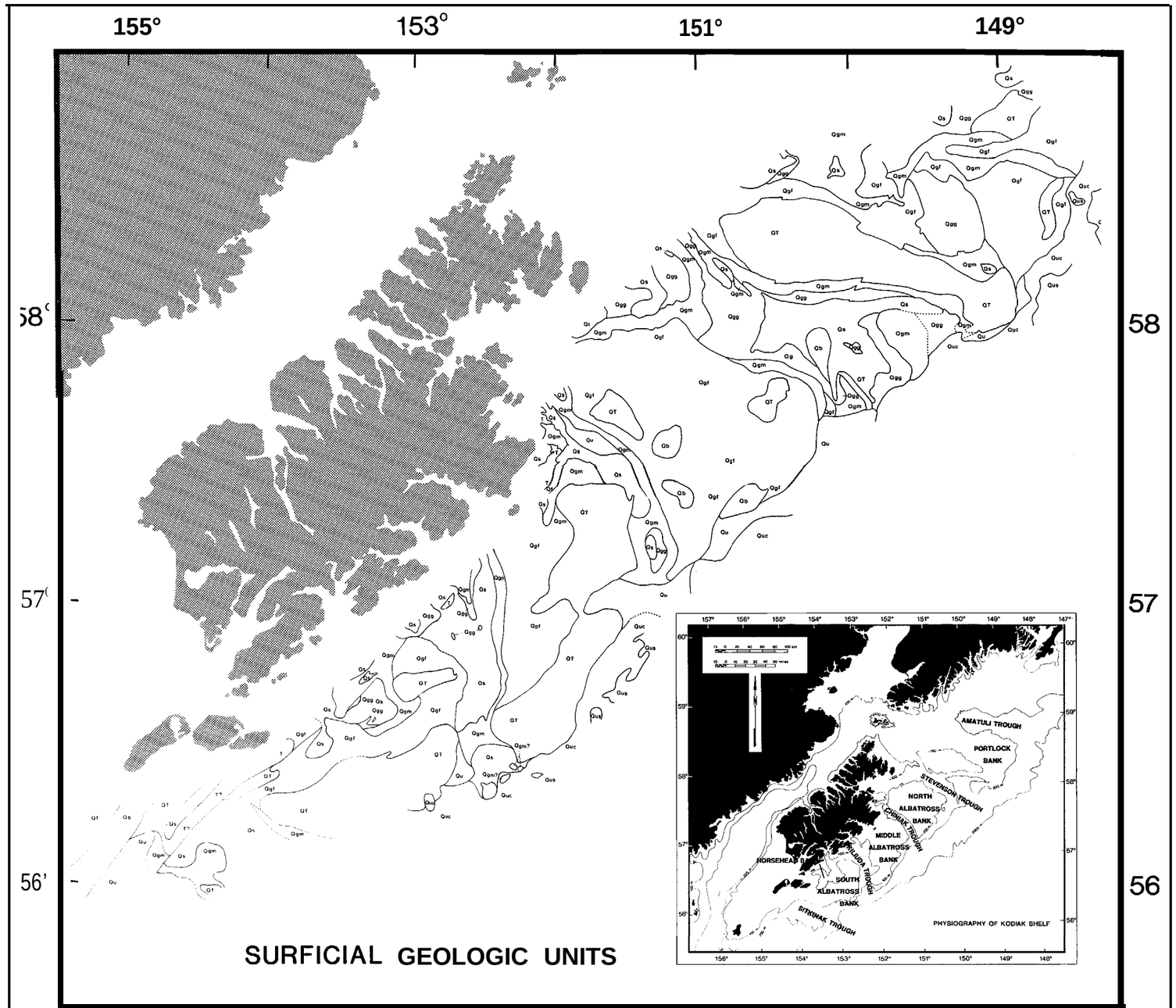
QT Plio-Eocene Sedimentary Rocks Exposures of gently dipping, truncated sedimentary rocks that exhibit well-developed, parallel, internal reflectors. Numerous folds and faults deform the unit internally. The upper surface of this map unit is a regional angular unconformity that underlies the entire outer shelf. Side-scan monographs show all sizes of texture variations, much of it in linear patterns. Numerous hogback ridges, scarps, and boulders are also identified on the sonographs as well as numerous, scattered, diverse bedforms. Most of the bottom samples recovered from exposures of this unit were claystones and siltstones. In some areas, the mapped exposures of this "n, t are covered by a very thin layer of recent sediment and debris. The dominant lithology of nonbedrock samples was pebbly, shelly sand, or sandy gravel. Occasional samples of silty sand, ash, and shell debris have also been recovered.

Between Tugidak and Chirikof Islands, this unit corresponds with the Pliocene Tugidak Formation exposed on both islands (Moore, 1967). In the northeast corner of the mapped area (sheet 1), this unit may correlate with the Yakataga Formation of late Tertiary to Quarternary age, as exposed on Middleton Island to the east (Plafker, 1967). This unit may contain, as does the Yakataga Format, on (Plafker, 1967), some Miocene rocks (Michael Fisher, . ral communication, 1)71)

T Tertiary Sedimentary Rocks These rocks are observed only in small outcrops along the landward edge of the mapped area and have no seismically determinable internal structure. The ocean floor is highly reflective, allowing no 3.5 kHz subbottom profiler penetration, and only a few reflections are returned from below the ocean floor on the sparker system. Side-scan sonographs show coarse, irregular bottom on some lines and well-defined, jointed and folded, outcropping beds on other lines. All the exposures are adjacent to capes and islands, and hence, these rocks probably correspond to the exposed formations. The outcrops adjacent to Sitkinak, Sitkalidak, and Uganik Islands may correspond to the Eocene-Oligocene Sitkalidak Formation, and outcrops adjacent to Cape Chiniak may correspond to the Paleocene Ghost Rocks Formation (Moore, 1967; 1969). There are no samples available from the offshore exposures.

Qu Quaternary Undifferentiated Continental Slope Deposits Large seismic vertical exaggeration and steep slopes seaward of the continental shelf edge preclude accurate mapping on the continental slope. Water depths are too great for subbottom profiler or side-scan sonar operation. Samples from these deposits are highly variable, ranging from olive-green mud through coarse pebbly sand. Some of these deposits, especially near Kiliuda Trough, appear to be in active mass movement.

Qus Quaternary Undifferentiated Sediment Basins on the Upper Continental Slope Basins of sediments that exhibit well-defined, near-horizontal, continuous reflectors in seismic profile.

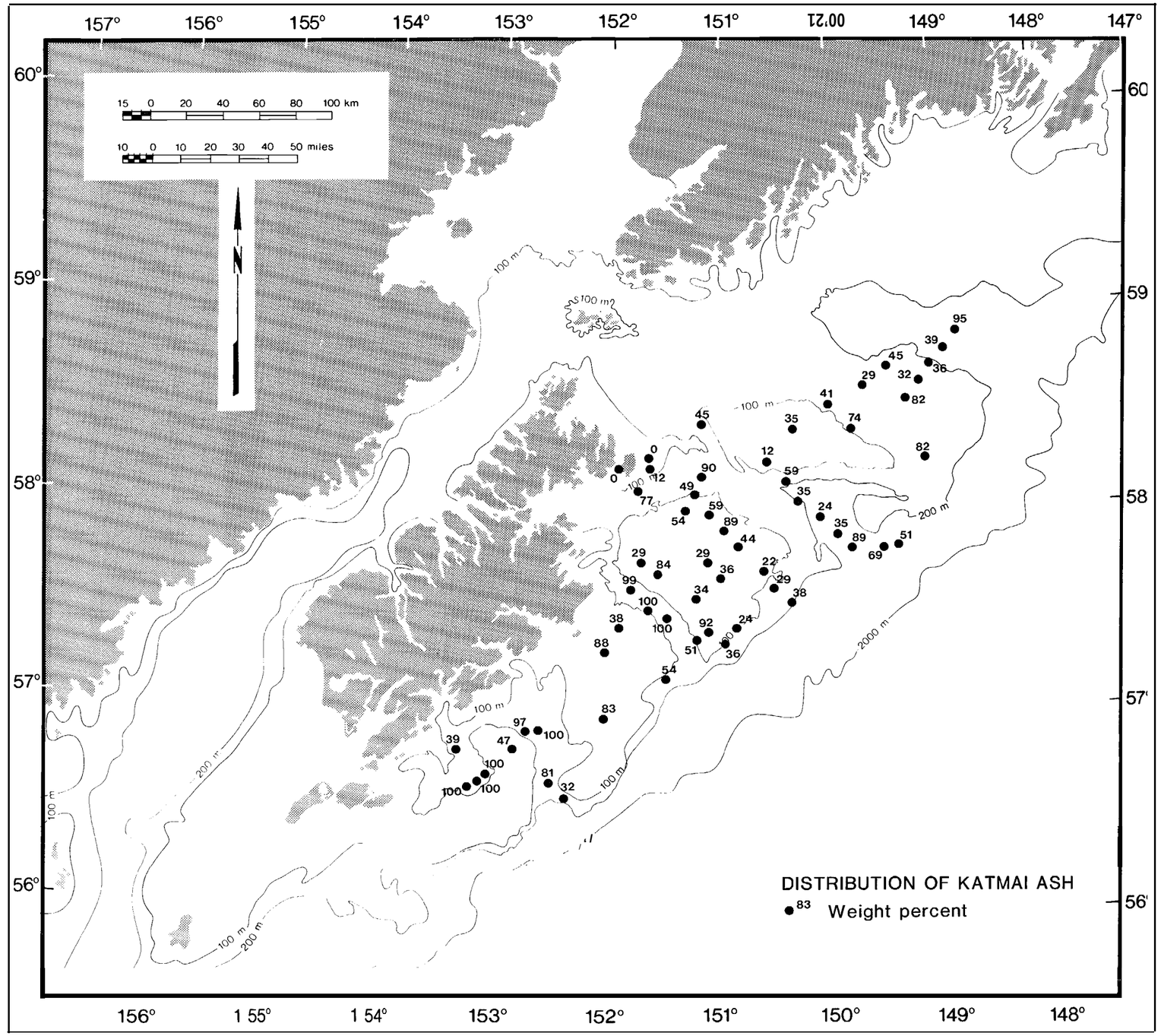


By volume, most of the surface sediment consists of Pleistocene glacial material that is being reworked under the present sedimentary regime. The influx of additional sediment to the shelf is low due to a lack of nearby sources of detritus. However, several sources are currently providing small amounts of detrital material to the shelf, and some of this material can be traced as it is incorporated into shelf sediment. The distribution of volcanic ash from the 1912 eruption of Mt. Katmai is a good example of the fate of modern detritus influx. This ash behaves as fine-grained, low density particulate matter, and is presently accumulating in some of the troughs and depressions on the shelf (Fig. 2.22). There are major ash accumulations in Kiliuda, Chiniak, and Amatuli Troughs, and minor accumulations in Stevenson and Sitkinak. The troughs are characterized by a hydraulic regime of lower energy than that of the intervening banks, where deposition and preservation of fine sediment are prevented by current and storm wave activity. The ash is an excellent indicator of present-day sediment dispersal patterns (Hampton et al., 1979a).

Other modern sources of detrital influx to the shelf are the Copper River and, to a lesser extent, the erosion of seafloor outcrops and runoff from Kodiak Island (Hampton et al., 1979b; Hein et al., 1977). These sources provide fine-grained clay minerals, which are good indicators of source rock (provenance). Biological production in the water column is a source of siliceous and carbonate detritus.

Figure 2.21 Surface geologic units on the Kodiak shelf (Thrasher, 1979).

Figure 2.22 Weight percent of volcanic ash, relative to the total terrigenous fraction, in surface sediment of the Kodiak shelf (Hampton et al., 1979a). Ash is from 1912 Katmai/Novarupta eruption.



The direction of sediment transport on the Kodiak shelf is generally from the banks into the troughs. The blanket of fine-grained surface sediment in Kiliuda, Chiniak, and Amatuli Troughs reaches 20 m in thickness (Hampton et al., 1979b; Fig. 2.21) and is predominantly Katmai ash. Accumulation in these troughs is enhanced by the presence of sills which are about 30 m shallower than adjacent landward sections of the troughs (Hampton et al., 1979a) and prevent seaward transport of trough sediment. These sills are primarily the result of tectonic uplift along the outer continental shelf, although some of the sills are formed by glacial moraines as shown by the location of Qgg deposits in Fig. 2.2o.

An exception to the general dispersal pattern is Stevenson Trough, which contains abundant sand-sized material, sandwave bedforms, and low percentages of Katmai ash compared to other troughs (Fig. 2.22). In addition, the sediment on the slope off Stevenson Trough is similar to that in the trough, suggesting seaward transport of material (Hampton et al., 1979a). These features are all evidence that Stevenson Trough is a route for high-energy bedload transport of sediment across the Kodiak shelf. The region between Chirikof and Trinity Islands also contains bedforms of well-sorted sand-sized material. Data from the 1979 field season reveal an asymmetry in sandwaves, which are oriented northeast-southwest, that suggests a bedload transport direction towards the Alaska Peninsula (M. A. Hampton, USGS, Menlo Park, pers. comm.).

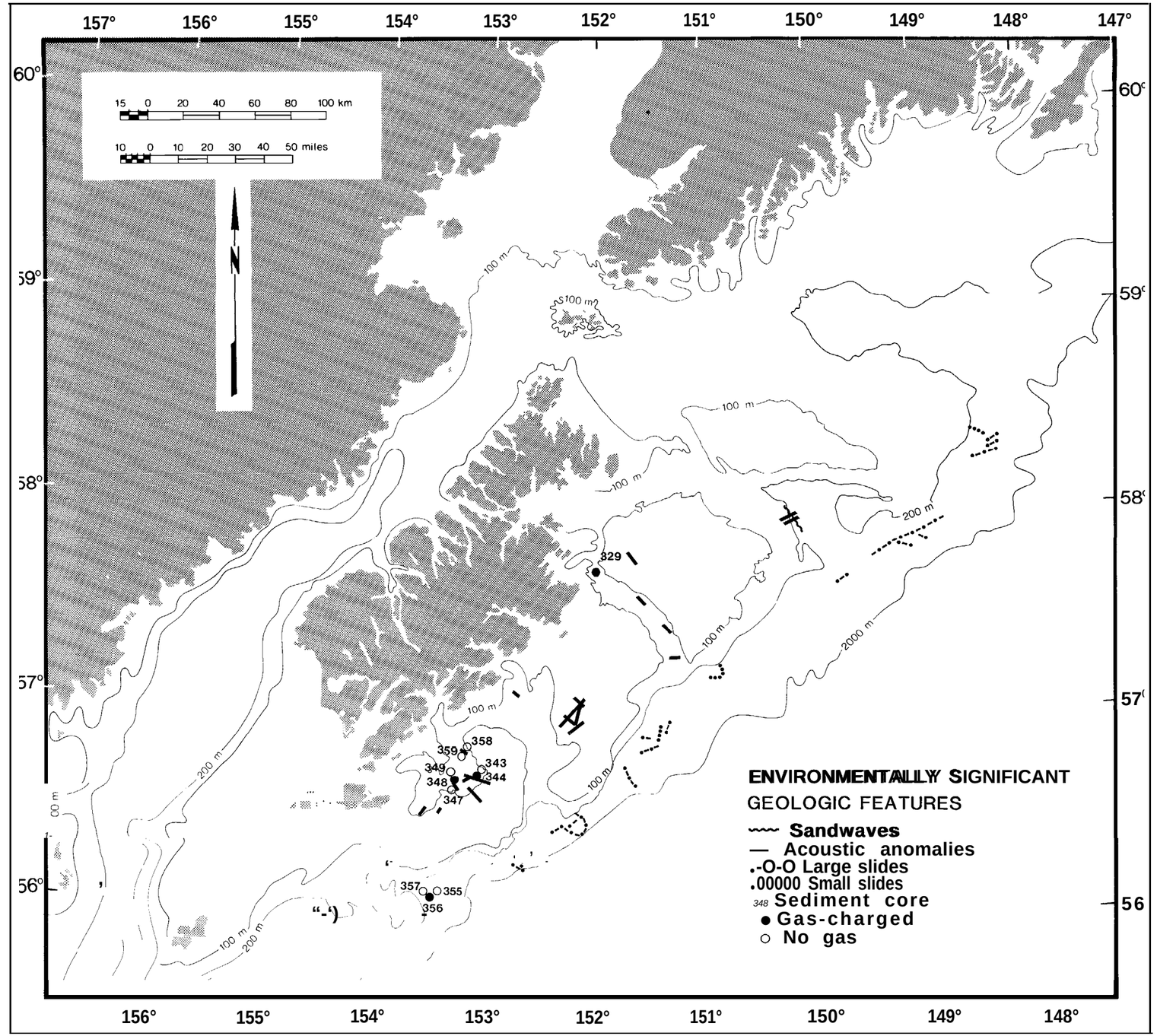


Figure 2.23 Locations of environmentally significant geologic features on the Kodiak shelf (modified from Hampton et al., 1979b). The maximum length of the sediment cores analyzed for methane gas was about 3.5 m.

Recent data suggest that natural gas (methane) is common in marine sediment on the Kodiak shelf (Hampton and Bouma, 1979). The locations where sediment cores containing methane-charged sediment were recovered are shown in Fig. 2.23, and the data for all cores analyzed are listed in Table 2.4. The source of the gas is probably decomposition of organic detritus in the sediment, rather than seepage from deeper petroleum or gas reservoirs (Kvenvolden and Redden, 1978). A high correlation between gas-charged sediment cores and acoustic anomalies in seismic reflection records suggests a cause-and-effect relationship; hence the frequent appearance of these anomalies in areas where core samples are not available allows us to infer that shallow gas-charged sediment is fairly common (Hampton and Bouma, 1979).

The high concentrations of methane in the cores recovered from Chiniak Trough (core 329, Fig. 2.23) and Horsehead Basin (cores 348 and 344, Fig. 2.23) correspond to high concentrations observed in the near-bottom waters (Fig. 4.2; Cline et al., 1978). It is possible that methane seepage from the sediment is responsible for the high levels observed in the water column in some areas. A gas seep was recently detected on seismic reflection records in Kiliuda Trough, in an area of acoustic anomalies (M. A. Hampton, USGS, Menlo Park, pers. comm.). Gas bubbles were observed emanating from a moundlike structure on the seafloor, and trailing off in a down current direction in the water column.

Table 2.4 Methane levels in sediment cores. Measurement by gas chromatography, on board ship, immediately after core recovery. Analyses by George Redden and Keith Kvenvolden (Hampton and Bouma, 1979). Core locations are plotted in Fig. 2.23.

Station Number	Location	Water Depth (m)	Distance Below Top of Core (cm)	Methane (x106 nl/l)
329	57° 39.0'N 151° 57.8'W	218	0-10 50-60 100-110 200-210	0.301 42.070 32.093 36.250
343	56° 40.0 'N 153° 05.5 'W	153	0-10 65-75 110-120 187-197	0.003 0.073 0.112 0.237
344	56° 39.6'N 153° 05.6'W	155	0-10 50-60 117-127 200-210	0.022 0.640 2.075 31.300
347	56° 36.6'N 153° 17.8'W	138	0-10 50-60 100-110	0.003 0.105 0.227
348	56° 37.3'N 153° 18.6'W	143	0-10 50-60 100-110 200-210	0.002 0.148 0.443 2.110
349	56° 38.0 'N 153° 19.4'W	145	0-10 50-60 100-110 197-207 300-310	0.001 0.034 0.127 0.288 0.696
355	56° 08.8'N 153° 29.6'W	314	0-10 50-60 206-216 348-358	0.011 0.002 0.004 0.039
356	56° 05.6'N 153° 31.3'W	250	56-66 175-185 310-320	0.439 51.492 29.375
357	56° 07.6'N 153° 38.4'W	233	0-10 50-60 129-139	0.005 0.011 0.026
358	56° 47.2'N 153° 11.6'W	122	0-10 48-58 100-110 150-160	0.003 0.006 0.005 0.008
359	56° 46.6'N 153° 10.7 'W	152	0-10 56-66	0.002 0.049

2.4.2 Surface faults

Surface faults that have been located on the Kodiak shelf are shown in Fig. 2.24. The map was produced primarily from the seismic profiling data that were used to develop the surface geology map in Fig. 2.20 (Thrasher, 1979). It is based on interpretation of the most recently available data. A zone of near-surface faults is apparent along the inner shelf off Kodiak. This zone roughly coincides with the zone of abundant aftershocks from the 1964 earthquake (refer to Fig. 2.14), with a map of strain release calculated on the basis of aftershock data (Fig. 2.12), and with the northeasterly trending axis that separates subsidence from uplift resulting from the 1964 earthquake (Fig. 2.11). To the northeast, the zone goes onshore at Montague Island where Plafker (1972) found two steeply dipping reverse faults with northwestern sides raised about 6 m during the 1964 earthquake. The maximum vertical offset observed on these faults is on the order of 20 m (Thrasher, USGS, Anchorage, pers. comm., 1979).

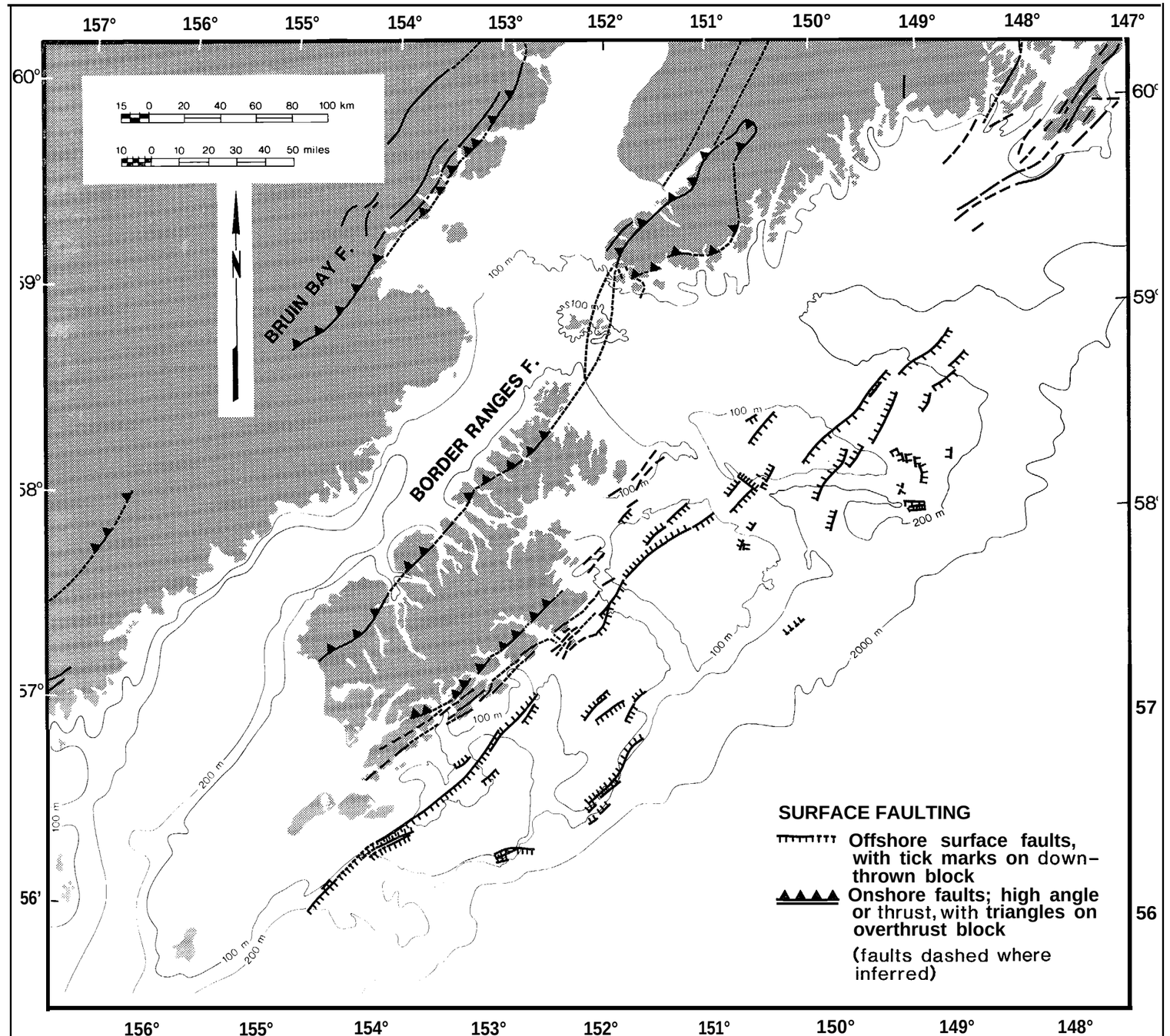


Figure 2.24 Surface faulting on the Kodiak shelf (from Thrasher, 1979; USDI, 1976a).

To date, no single offshore fault scarp has been positively identified as having been formed during the 1964 earthquake. One of the objectives of the 1978 field season of OCSEAP research by the USGS was to determine how recently these faults had moved. Unfortunately, the data collected did not provide conclusive evidence for the age of movement (Hampton and Bouma, 1979). However, the faults appear to cut sediment deposited during the last 10,000 years.

Seaward of the Kodiak OCS on the upper continental slope, short faults are present which are probably related to tectonic activity (uplift, folding, faulting, and earthquakes). The relatively steep slopes in this area, along with a triggering mechanism such as tectonic deformation, enhance the potential for slumps and gravity slides of unconsolidated sediment, which may also appear as short faults on seismic records (Hampton and Bouma, 1977; Figs. 2.23 and 2.24).

2.4.3 Seafloor instability

The upper slope off Kodiak is the area of greatest seafloor instability, by reason of the slumps and slides just described (Fig. 2.23). To date, no significant slumps or slides have been identified on the shelf. Some localized slope failures in the vicinity of Sitkinak Trough have been reported by Self and Mahmood (1977), but subsequent study of that area has revealed no large-scale or widespread occurrences (Hampton et al., 1979b).

Relative slope stability on the Kodiak shelf has been evaluated using as criteria slope steepness, sub-bottom soil type, and evidence of past mass movement (Self and Mahmood, 1977). The mapping is based on seismic reflection surveys and sediment sampling completed by private industry before the work performed by the USGS (described above). The principal conclusion reached by the Self and Mahmood study (1977) is that the areas of greatest concern for potential slope failure are the banks of the major troughs crossing the shelf and the upper slope.

Seafloor instability due to rapid erosion or deposition will probably not be a major concern on the Kodiak OCS. The bedload transport occurring in Stevenson Trough (refer to section 2.4.1) and possibly a similar sand wave region between Chirikof Island and the Trinity Islands (Hampton et al., 1979b) are the only areas of known potential risks to structures or pipelines associated with undermining or loading problems.

2.4.4 Summary of surface geology hazards

In a geo-environmental assessment of the Kodiak shelf, Hampton et al. (1979b) have found risks posed by active tectonic deformation and earthquake shaking to be more significant than the hazards from surface geology features described above. The main problems associated with seafloor sediment and sediment dispersal will involve the fate of pollutants rather than risks to platforms and pipelines. However, the apparently widespread occurrence of gas-charged sediment may have consequences for platform design and drilling operations.

A list of geo-environmental concerns on the Kodiak shelf includes (Hampton and Bouma, 1979):

1. Shallow faulting with probable present-day activity and future seafloor offset.
2. Storage sites for fine-grained sediment (and possibly pollutants) in Kiliuda, Chiniak, and Amatuli Troughs.
3. Localized transport routes of sediment (and possibly pollutants) across the shelf break, especially on northern Albatross Bank and in Stevenson Trough.
4. High-energy sediment transport, with possible scour and fill problems, in Stevenson Trough and between Chirikof and Trinity Islands.
5. Localized deposits of volcanic ash in Kiliuda, Chiniak, and Amatuli Troughs, with possible abnormal compaction during loading. Also thick deposits of fine sediment in Sitkinak Trough, which may be weak and/or compressible.
6. Coarse-grained unconsolidated and fine-grained semiconsolidated sediments on Albatross and Portlock Banks that appear to be stable foundation material but may pose some problems to drilling because of the presence of boulders.
7. Lack of sediment slides on the shelf except for some apparently localized occurrences reported by Self and Mahmood (1977).

2.5 COASTAL GEOLOGICAL HAZARDS

2.5.1 Shoreline description

Hayes and Ruby (1979) provide the most recent and complete description of the Kodiak shoreline; the following is a summary of their report. The southeastern coastline of Kodiak Island consists of numerous wide estuarine embayments that have formed partially in response to tectonic activity associated with crustal subduction; these embayments have also been modified by glacial activity. The igneous and metasedimentary rocks comprising Kodiak Island result in a youthful topography and rugged coastline, typically consisting of steep rocky cliffs and headlands, with small intervening pocket beaches of boulders or coarse gravel. The shoreline reflects exposure to severe fall and winter storms in the Gulf of Alaska. The coastline of Afognak Island is similar to the southeastern coast of Kodiak, but less rugged.

The side of Kodiak Island facing Shelikof Strait is different from the southeast coast in that it shows the effects of Pleistocene glaciation more dramatically. The shoreline is characterized by narrow fiords and U-shaped valleys, which lie perpendicular to the trend of the mountains and which formed during mountain glaciation. Straight, narrow gravel beaches backed by steep valley walls occur along the numerous fiords.

The southwest tip of Kodiak Island has been subjected to continental glaciation, which has produced relatively gentle topography and deposits of glacial till. This material is more easily eroded than the rock outcrops on other parts of the island, and results in beaches of sand, gravel, and large glacial erratics.

In general, the Kodiak coastline is erosional, although a few depositional features such as spits and sand bars occur. Salt marshes and tidal flats are present at the heads of some fiords. Rivers draining the island contribute little sediment to the shoreline, but they do add to the deposits at the heads of fiords. A generalized map of substrate types in the intertidal zone (Fig. 2.25) illustrates the predominance of bedrock and boulder substrates (Sears and Zimmerman, 1977).

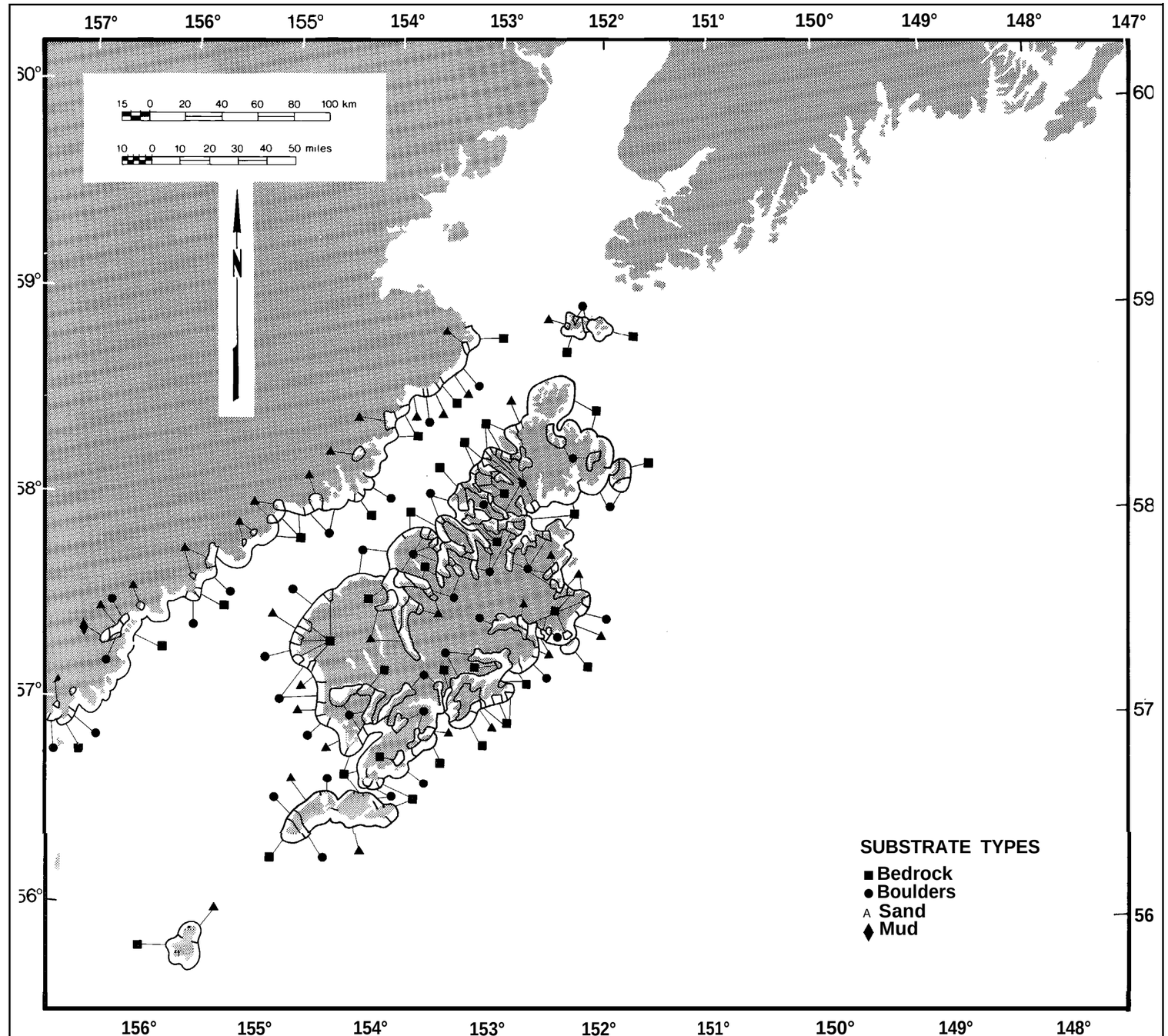


Figure 2.25 Major substrate types in the Kodiak Island intertidal zone (adapted from Sears and Zimmerman, 1977).

2.5.2 Oil spill vulnerability of the coastline

A much more detailed analysis of coastline dynamics, beach sediments, and susceptibility to long-term oil residence has now been completed by Hayes and Ruby (1979). Their approach to assigning an oil spill vulnerability index (OSVI) to a coastline relies primarily on estimating the residence time of spilled oil, and considers the controls that beach morphology, sediment grain size, and incoming wave energy have on longevity. Details on the development of their OSVI can be found in Ruby and Hayes (1978) and Ruby (1977).

The primary product of the research by Hayes and Ruby (1979) is a set of 42 USGS topographic quadrangle maps upon which the entire Kodiak coastline is classified according to the OSVI. The detail presented on these maps precludes a single-figure representation of all the information. However, a narrative description of the characteristics of each of the vulnerability classes, and the percentage of shoreline in each class, is presented in Table 2.5. A sample OSVI map (Fig. 2.26) shows the shoreline around Chiniak Bay, and is a

Table 2.5 Abundance and characteristics of shoreline types for the Kodiak Archipelago, classified according to Oil Spill Vulnerability Index (OSVI; Hayes and Ruby, 1979).

Kilometers of Shoreline	Percent Total Shoreline	OSVI	Discussion
1083.2	25.3	1 & 2	Oil easily removed by wave action. Some problems in areas of gravel accumulation and in tidal pools. Pocket beaches may be particularly hard hit. Do not recommend human intervention once oil is on beach.
38.6	0.9	3, 4, & 5	Generally low risk areas; quite rare in the study area. Fine sands and sands and mud tidal flats will not permit much penetration of oil. Low wave energy areas will require as much as a year for natural cleaning. Mechanized cleaning on sand beaches is quite feasible but represents a very small area. Recommend no human effort in these areas.
942.4	22.1	6	Sand and gravel beaches represent a large percent of the shoreline and tend to be relatively high risk beaches. They permit rather deep burial of oil and can retain oil for about 2 years, especially if it is emplaced high on the beach face (as during a spring tide). Mechanized clean up can be very difficult due to low bearing strength of the sediments. Removal of sediments may accelerate erosion.
634.2	14.9	7	Pure gravel beaches will permit immediate deep burial of oil. Retention periods, especially in a lower wave energy area can be many years. Mechanized clean up will be impossible without removal of sediment and increased erosion. The increased erosion, may not be of particular importance in uninhabited areas.
1462.0	34.2	8	Sheltered rock headlands and their associated gravel pocket beaches will be highly damaged in the event of a spill. They occur primarily in fjords and on the very irregular areas on Afognak Island. These areas should receive first protection priority in the event of a spill. All possible means should be used to prevent oil from entering these areas (booms, skimmers, etc.). Once these beaches are oiled, expect severe biological damage, deep penetration, difficult clean up and longevity up to 8 years.
109.8	1.6	9 & 10	These bayhead and river mouth systems are highly vulnerable. They are, however, rare in the study area. Further, they occur in areas which will receive maximum protection from river flushing. If oiled, biodamage will be extreme, recovery slow and spill longevity up to 10 years.

composite of four quadrangles. Exact photographic reproductions of their detailed coastline classification have been produced, and are available from Science Applications, Boulder, Colorado. These reproductions should be extremely useful, when combined with data on the shoreline biota, in further assessing environmental risk due to oil spills.

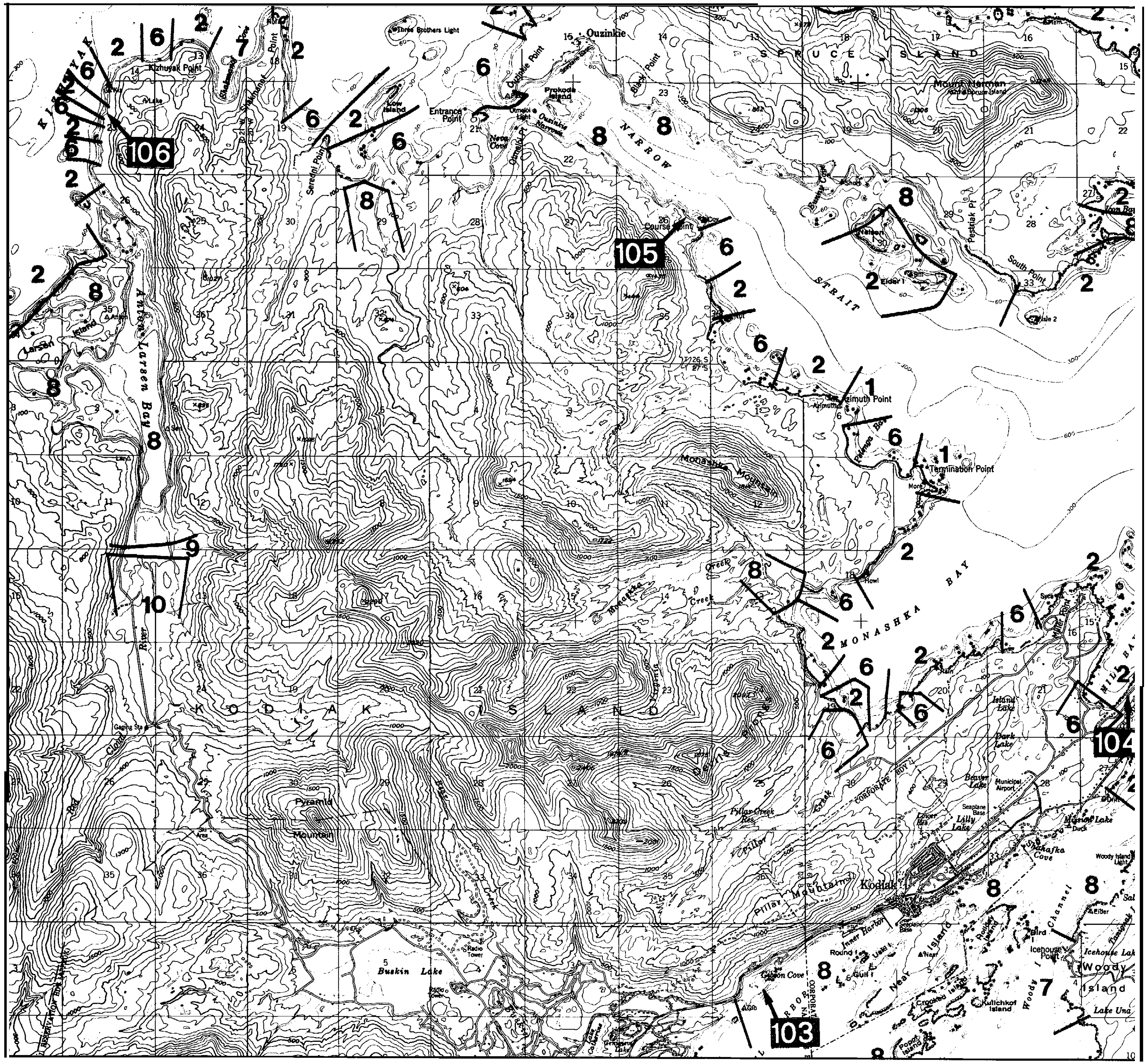


Figure 2.26 Oil Spill Vulnerability Index as applied to the NE coastline of Kodiak Island in vicinity of Chiniak Bay (Hayes and Ruby, 1979). The numbers in boxes refer to locations where beaches were studied in detail. See Table 2.5 for an explanation of the OSVI.

2.5.3 Coastline subject to slope failure

During the 1964 Great Alaska Earthquake, numerous landslides were generated along the southeastern coast of Kodiak Island (Fig. 2 27). Although unstable s.opes have perhaps been reduced to a stable configuration by that earthquake, it s also possible that the jolt placed other areas in a more unstable posture, ust short of failure. thus creating a potent.al hazard to industrial or residential developments during future shocks

The landslide alert issued by the U.S. Geological Survey's Alaska branch regarding Pillar Mountain (Geotimes. .978) identifies the potentially most dangerous unstable slope near a coastline development today. Analyses of steep s.opes, and of fractures within the bedrock forming them, will be required before shoreline facilities are built in undeveloped areas.

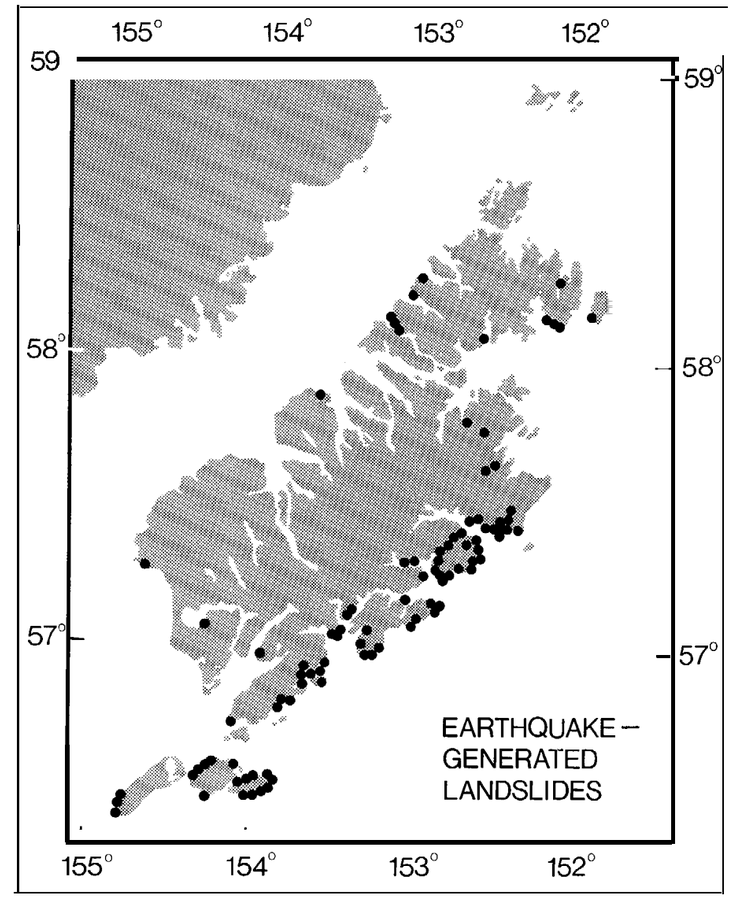
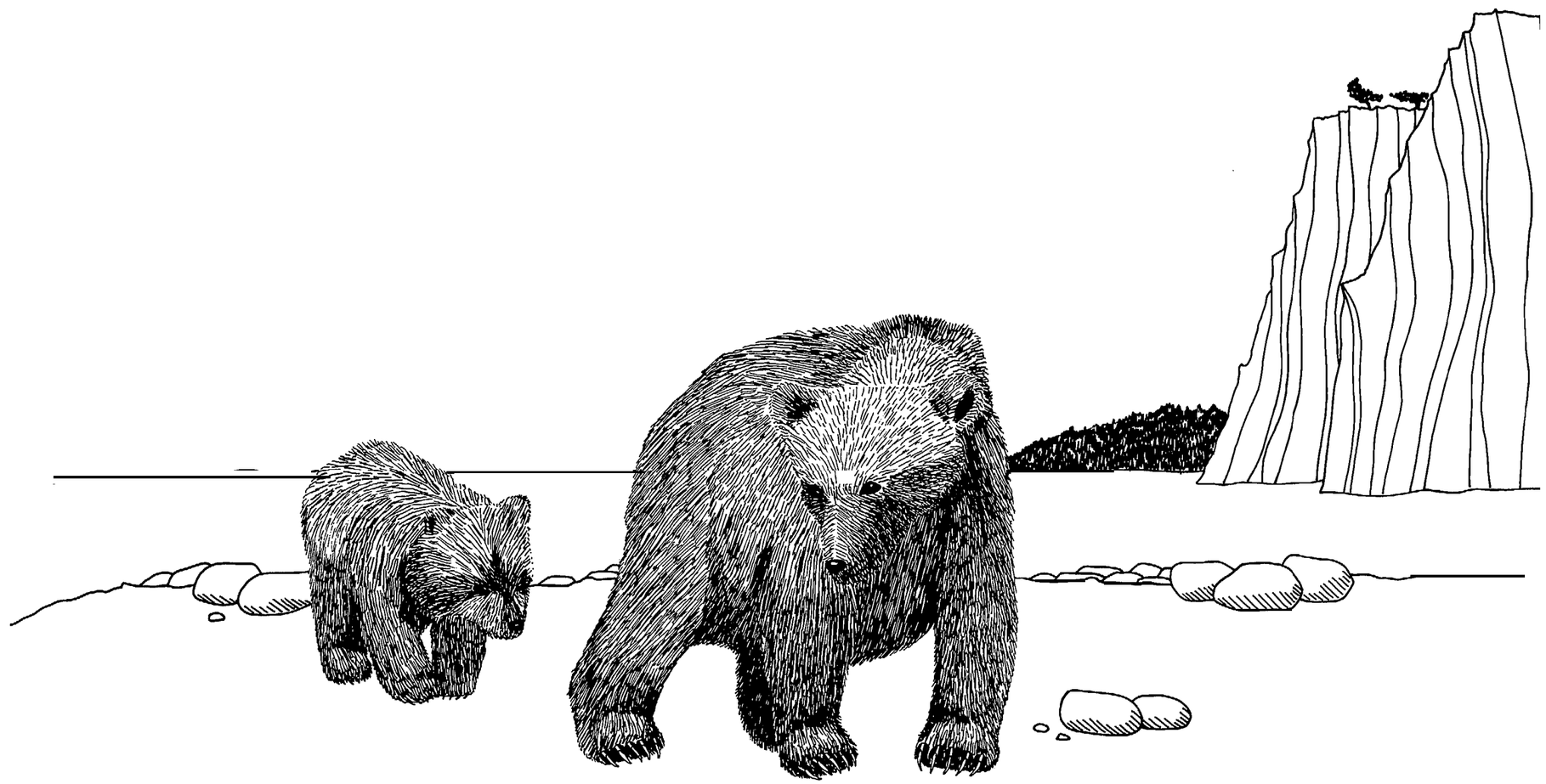


Figure 2.27 Locations where landslides were generated by the 1964 Great Alaska Earthquake (Buck et al., 1975).

3. Physical Oceanography



CHAPTER 3 PHYSICAL OCEANOGRAPHY

E. J. C. Sobey, SAI

3.1 INTRODUCTION

3.1.1 Transport of oil in the marine environment

Oil spilled in a marine environment is subject to a multitude of forces that control its subsequent history. These forces can be categorized as transformation and transportation processes. Transformation processes are those that affect the physical and chemical properties of the oil. Examples are evaporation, emulsification, photochemical oxidation, and solution. Although dependent on environmental conditions, these processes are not specific to individual lease areas. Thus transformation processes will not be discussed here. They have been summarized by Payne and Jordan (unpubl. MS).

Transport of an oil slick has two components: spreading and drift. Spreading is controlled by gravitational, hydrostatic, and surface forces, which are not site-specific, and by turbulent mixing, which is site-specific. Mixing and drift are highly specific to the location of the slick and are the subject of this chapter.

By oil drift is meant the movement of the center of mass of the slick. Winds, waves, and currents all contribute to drift and interact in ways that are not fully understood. Wind-induced drift generally is accepted to be about three percent of the wind speed at a small angle (e.g., 20°) to the right of the wind. Oil is assumed to move in the same direction and at the same speed as surface currents (neglecting wind drift). Furthermore the effects of wind drift and surface currents are assumed to be additive.

None of these assumptions is entirely true; all are approximations that work reasonably well. For example, Schwartzberg (1970) showed that oil is not advected at the same rate as wooden chips (used as a reference) because of the difference in the depth of penetration (draft). When waves were added to his laboratory experiments, however, the two materials were advected at nearly the same rates. He also showed that the coupling between surface currents and an oil slick is reduced in the presence of wind. Reisburg (1973) showed that drifts induced by waves and wind are not strictly additive. For high wind speeds, waves "cause a net decrease in the coupled drift velocity"; this decrease continues as wind speed increases.

Further complicating the transport of oil are the effects that the oil itself has on the environment. That oil calms surface water (by reducing capillary waves) has been known by sailors for centuries. However, the mechanisms by which surface oil affects the transfer of energy between wind and currents have received only limited attention (Liu and Lin, 1979).

To predict where oil will go, data on ocean circulation are used. The problem of determining where the the oil will go has been reduced to determining where the water will go. Predicting oil motion even when circulation and winds are known is inexact, at best. However, experiments have shown that standard oceanographic techniques can reliably predict oil movement (e.g., Audunson, 1978). Thus we will assume that oil movements follow ocean circulation.

3.1.2 The Kodiak environment

The dominant physical phenomenon in the Gulf of Alaska is the seasonal change in the position of the Aleutian Low, the center of which moves clockwise through the year. In early autumn the Aleutian Low migrates out of the northern Bering Sea and crosses the Alaska Peninsula. In winter the low is usually located in the Gulf of Alaska (about 55°N, 155°W). The winds at Kodiak, which are caused by the low in this position, are from the northeast.

The bathymetry of the Kodiak Island continental shelf is rugged. On the eastern side of Kodiak Island is a series of shallow banks (as shallow as 50 m) separated by troughs. These troughs lie approximately perpendicular to the shelf break and act as corridors between Kodiak Island and the edge of the shelf.

On the western side of Kodiak Island is Shelikof Strait. Through it flow the waters leaving Lower Cook Inlet. The depth of the Strait varies from about 165 m at the northeast end to 275 m at the southwest end.

The influx of fresh water along the coast might be expected to have an important role in the circulation. Large quantities of fresh water are introduced "upstream" of the Kodiak lease area. By lowering coastal surface salinities (and their densities) this fresh water contributes to the baroclinic component of flow.

The circulation throughout the Gulf of Alaska is dominated by the Alaska Stream (or Current). It flows counterclockwise, advecting warm water from the south. Off Kodiak Island the flow is intensified. Farther to the southwest, part of the current enters the Bering Sea and the rest continues westward, parallel to and north of the North Pacific Current.

An estimate of the mean surface circulation is shown in Section 3.6. In that section all of the available data are summarized to give a conceptual model of the transport in the Kodiak Island region.

3.2 FORCES CONTROLLING CIRCULATION

3.2.1 Tides

Tides in the Kodiak lease area are mixed semi-diurnal. The mean range at Kodiak (the difference between mean high water and mean low water) is about 2 m and the diurnal range (the difference between mean higher high and mean lower low water) is about 2.6 m. The maximum range between higher high and lower low water is predicted to be over 4 m and the minimum diurnal range is about 0.4 m. The highest tide predicted (above mean level, using 1973 data) is about 3.3 m and the lowest tide is -0.9 m (Brewer et al., 1977).

The semidiurnal principal lunar (M_2) and diurnal soli-lunar (K_1) components progress counterclockwise in the Gulf of Alaska. Tides progress along the seaward side of Kodiak Island from the northeast to the southeast. Although in NOS (1978) tidal progression appears to be in the opposite direction, this is probably due to the location of the gauges in bays and estuaries (Pearson, pers. comm.). On the western side of Kodiak Island tidal progression is northeastward from lower Shelikof Strait but southwestward from upper Shelikof Strait (Pearson, pers. comm.).

The largest components of tidal forcing on Middle Albatross Bank are the K_1, diurnal principal lunar (O_1), and diurnal principal solar (P_1) components, according to spectral analyses of current meter data from the continental shelf (Schumacher et al., 1979b). However, semidiurnal tides are dominant on the adjacent banks to the northeast and southwest (Schumacher, pers. comm.).

3.2.2 Winds

Monthly mean winds

Monthly scalar-averaged wind speeds exhibit a large seasonal fluctuation (Fig. 3.1). Means in Marine Areas B and C (areas covering the Kodiak Island Shelf; see the insert on Fig. 3.1) show the same seasonal pattern. Scalar-averaged winds are at a maximum in fall and winter (October through February) and at a minimum in June or July.

Monthly means of vector wind speeds are not as clearly seasonal. However, the mean vector wind direction shows strong variation. Winds are from western points of the compass for each month except June. Predominant winds are from the north to west-northwest from fall through mid-spring (October through April). Winds during the rest of the year (May through September, except June) are from the southwest. In June winds are from the south-southeast.

By comparing the scalar mean wind speed to vector mean speeds one can obtain a qualitative estimate of the directional variability of winds during each month. In winter (January through March) the scalar mean speeds are high while the vector mean speeds are low. The conclusion is that wind direction is highly variable in winter. Winter storms are probably responsible for winds and variable direction. Wind direction is most consistent in July and August, when storms are few and meteorological conditions are governed to a large degree by the North Pacific high pressure cell located at about 43°N, 143°W.

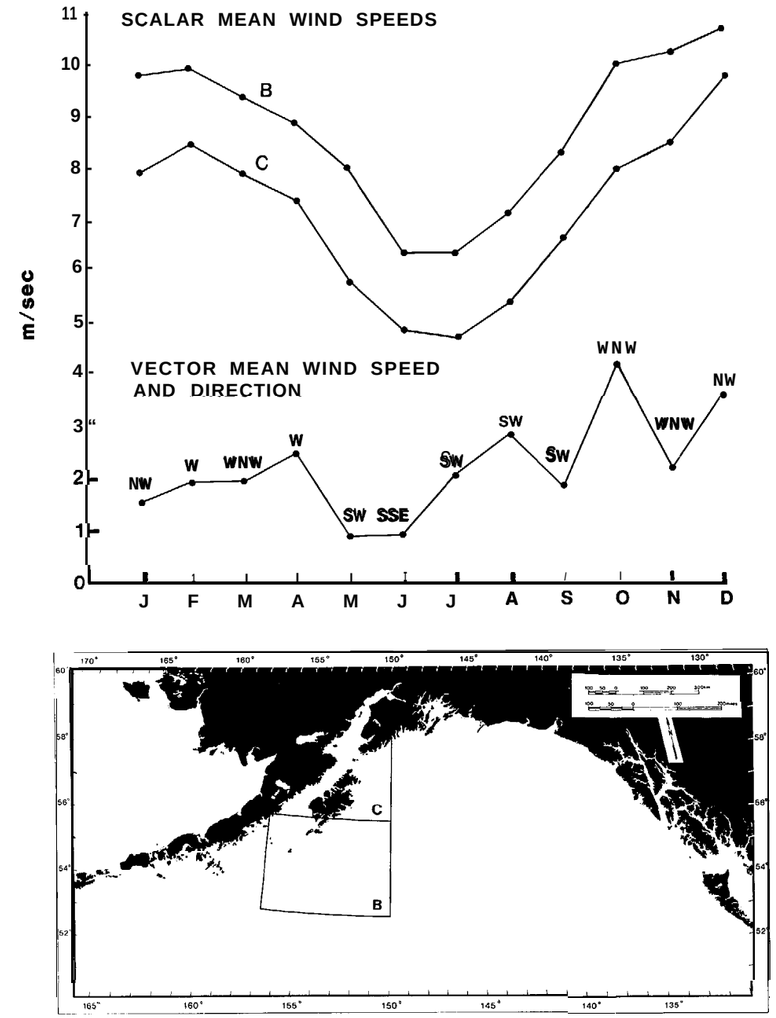


Figure 3.1 Vector mean wind speed and direction (for marine area B) and scalar mean wind speed (for marine areas B and C). For January the vector mean wind was about 1.6 m/see from the northwest. Marine areas B and C are shown in the inset. Values obtained from surface marine observations are archived at the National Climatic Center (Brewer et al., 1977).

Climate types

Overland and Hiester (1978) have developed a set of six climate types (Fig. 3.2) of the Northern Gulf of Alaska (Yakutat to Kodiak Island). A climate type is a subjectively defined pattern of sea-level atmospheric pressure distribution which represents a generalized, quasi-steady state of atmospheric circulation. Each type represents a distribution pattern that is frequently observed. The types were identified and classified by a meteorologist from daily weather maps. The types selected are modifications of those reported by Sorkina (1963) and Putnins (1966). Any pattern of sea-level pressure can be approximated by one of the climate types. A set of twelve subtypes showing slight variations in location or intensity were also identified (Overland and Hiester, 1978), but are not discussed here.

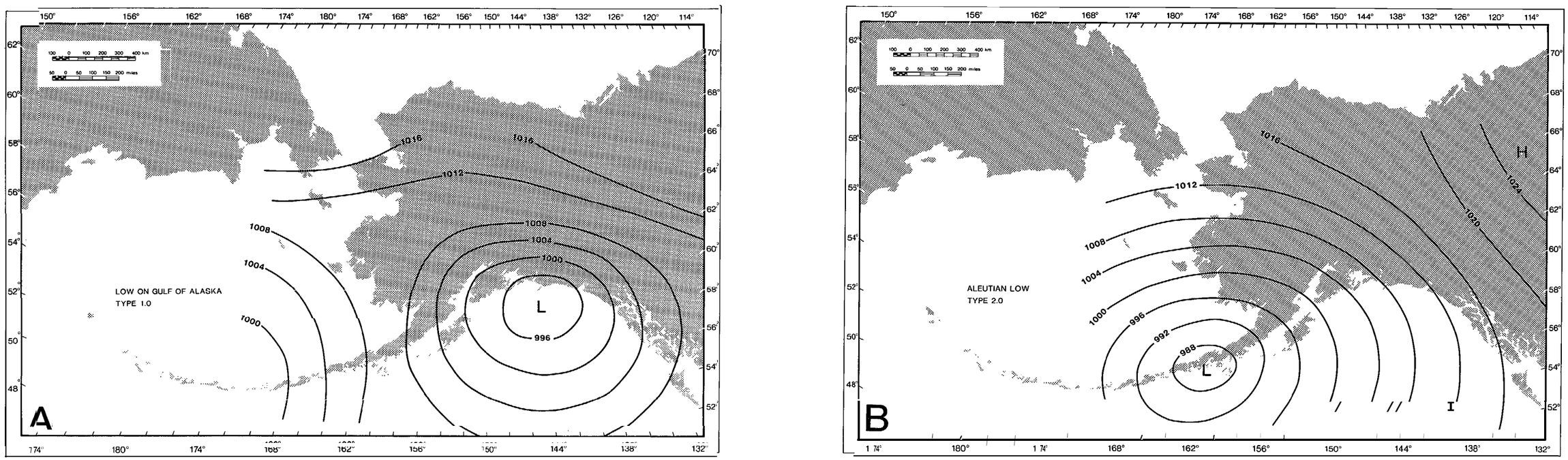
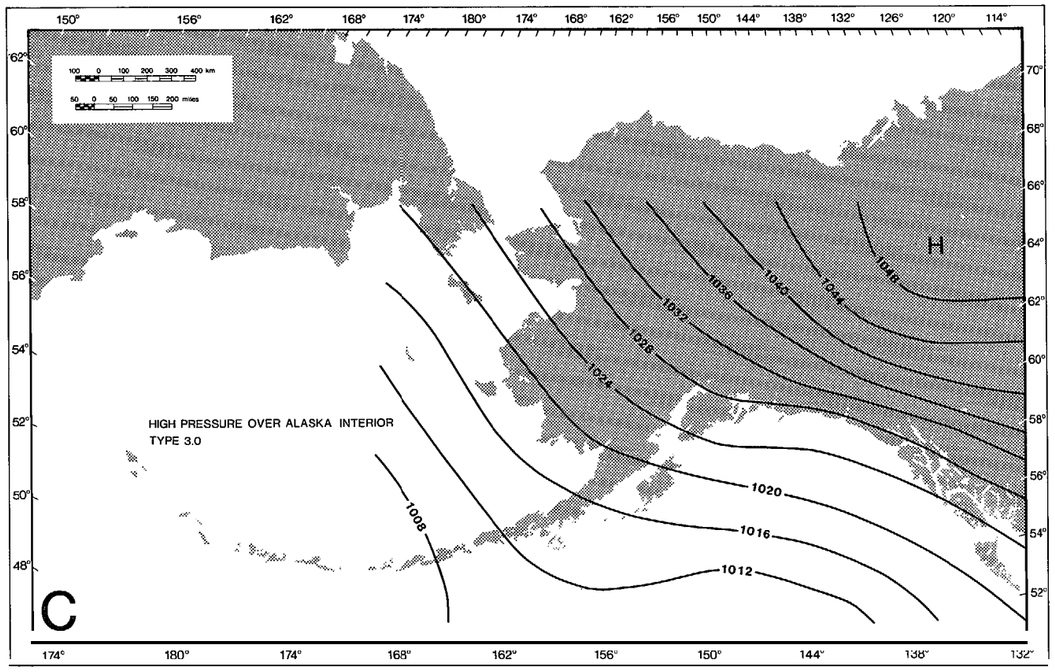


Figure 3.2 Climate types for northeastern Pacific Ocean. Surface weather charts can be described as some combination of these six climate types. Slight variations in the patterns of these climate types, called subtypes, also have been described by Overland and Hiester (1978). Contours are of surface atmospheric pressure in millibars.


HIGH PRESSURE OVER ALASKA INTERIOR
TYPE 3.0
H
1048
1044
1040
1036
1032
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1024
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1016
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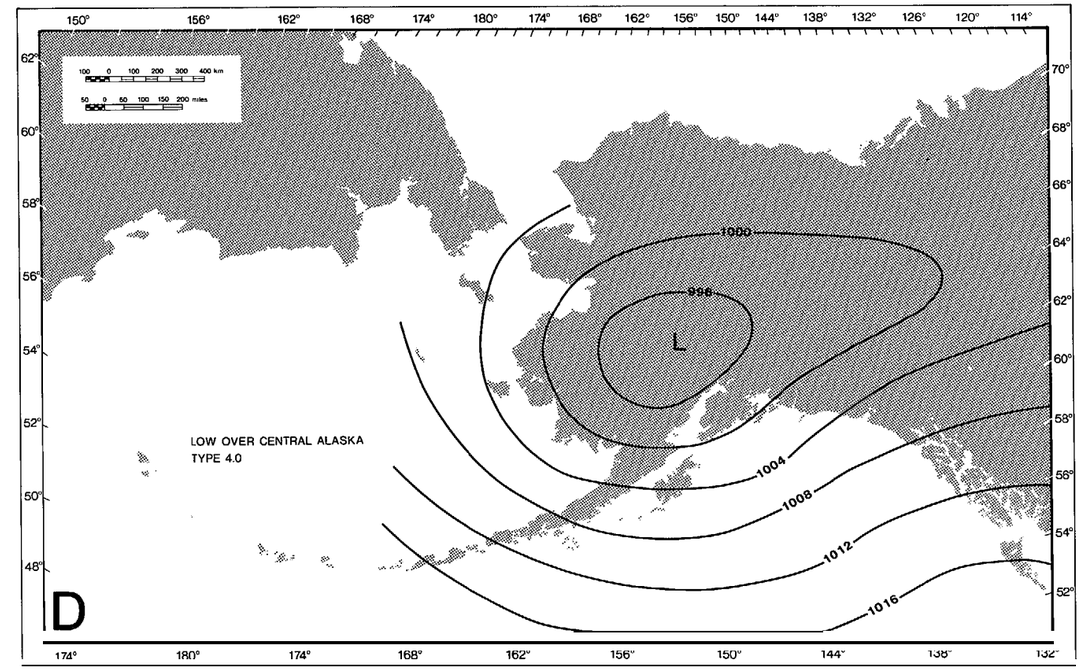
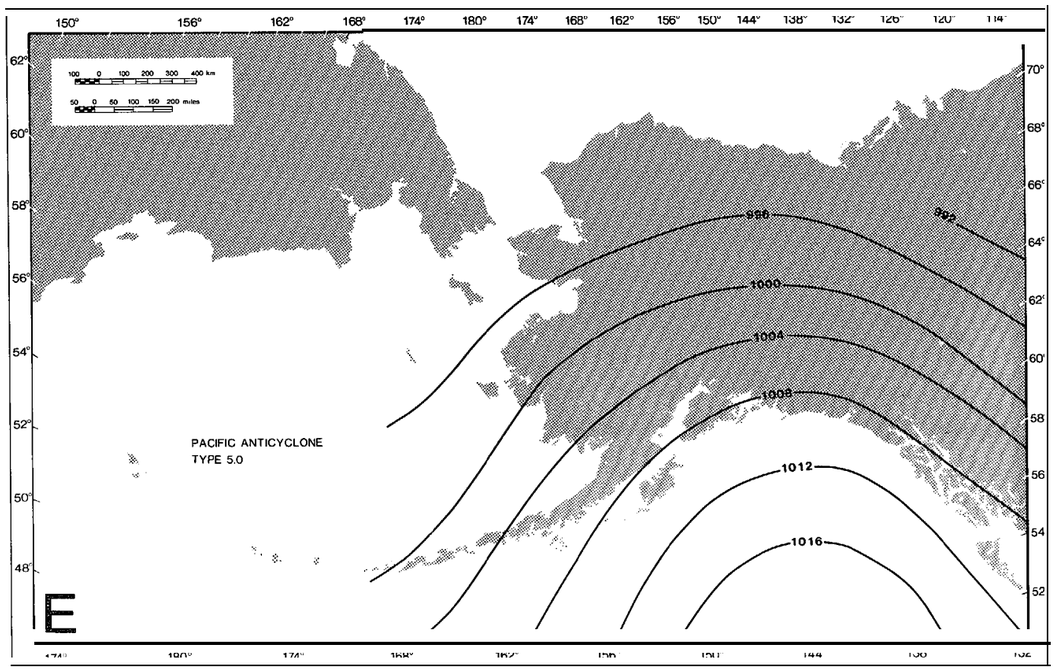
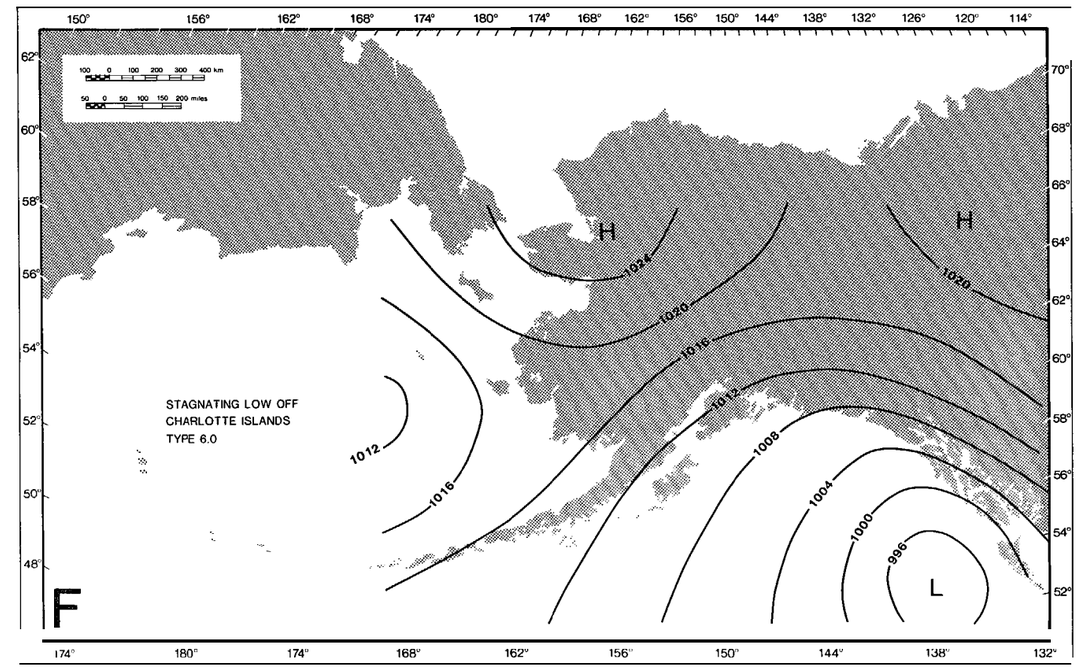
1008
C


LOW OVER CENTRAL ALASKA
TYPE 4.0
L
996
1000
1004
1008
1012
1016
D


PACIFIC ANTICYCLONE
TYPE 5.0
992
996
1000
1004
1008
1012
1016
E


STAGNATING LOW OFF
CHARLOTTE ISLANDS
TYPE 6.0
H
H
L
1024
1020
1016
1012
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1004
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996
F

Climate type 1.0 represents the condition of a low in the Gulf of Alaska. This distribution is mm in a seasons except summer (Fig. 3.3 Lows tend to stagnate due to high coastal mountain ranges around the Gulf and the cooler air over Alaska

Type 2.0 is the Aleutian Low. This is the dominant pattern throughout the year, but it is at a maximum in spring In summer, the ow is usual y about 400 km to the northeast of this position shown for type 2.0. This alternate pattern is a subtype of the Aleutian Low

Type 3.0 is at a maximum in winter. It s a high pressure cel over the interior of Alaska caused by air cooled over the tinental land mass When cyclones are absent along the coast in winter this type is dominant.

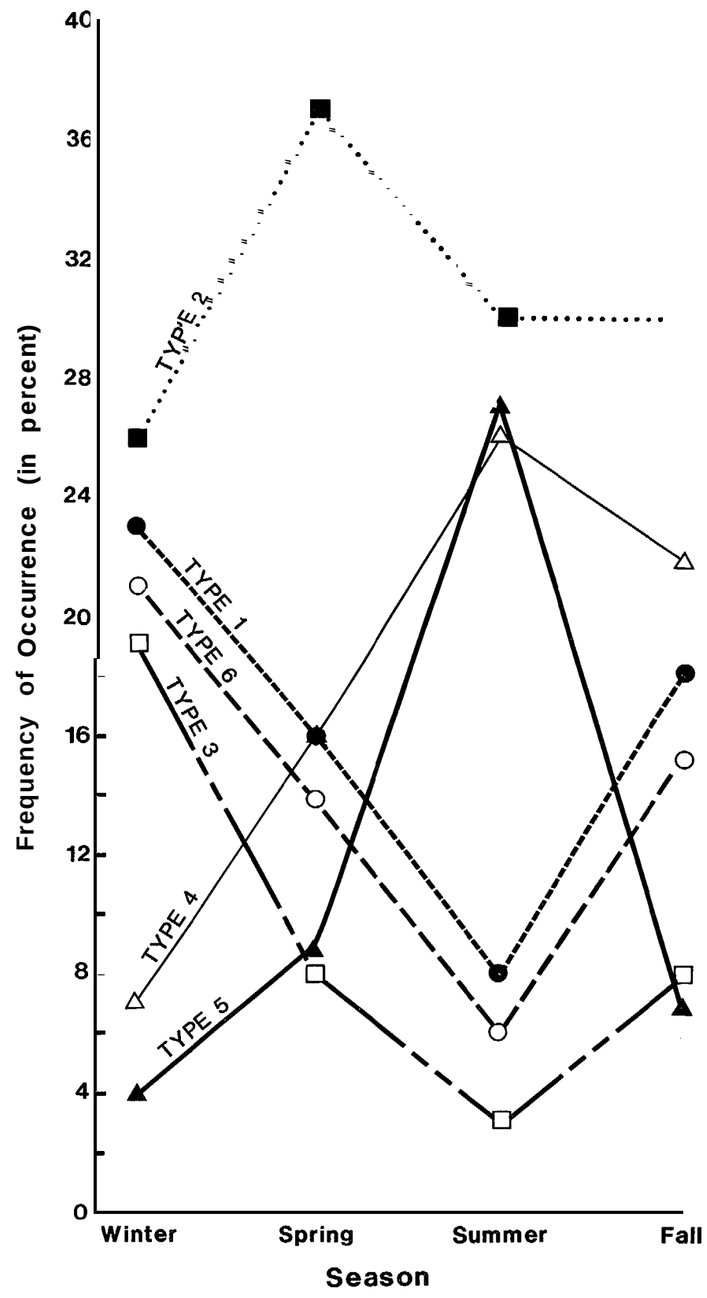


Figure 3.3 Seasonal frequency of occurrence curves for the six climate types shown in Fig. 3.2. For example, Type 2 (Aleutian low) occurs on the average 37 percent of the time during spring (Overland and Hiester, 1978).

In summer, cyclones or lows are typically found farther to the north than in winter. This situation is represented by type 4.0. This pattern occurs rarely in winter (7 percent of the time) but fairly frequently (26 percent of the time) in umm r.

Type 5.0 is the north Pacific high-pressure cell. This distribution is seldom encountered in umm In subtype 5.1 the axis of the high pressure ridge is farther to the west, south of Kodia Island.

Type 6.0 is a stagnating low off the Queen Charlotte Islands. This condition is most frequently encountered in winter. Associated with it is a high pressure cell over northeast Alaska and another over the Bering Sea.

Overland and Hiester (1978) found that 75 percent of the patterns on daily weather charts (from 1969 to 1974) correlated with one of the climate types with a correlation coefficient equal to or greater than 0.7. The seasonal frequency of occurrence of each type is shown in Fig. 3.3

Upwelling indices

Upwelling indices reflect the alongshore coastal wind field. Winds favorable for upwelling are those that blow to the northeast along the Kodiak Island coast and force surface waters offshore. Winds favorable for downwelling are in the opposite direction and force surface waters onshore. The indices show coastal upwelling and thus are a measure of potential biological productivity.

Ingraham et al. (1976) characteri various coastal regions around the Gulf of Alaska according to the seasonal dominance of divergence (upwelling) or convergence (downwelling). An area northeast of Kodiak Island (59°N, 151°W) has a nearshore convergence and offshore divergence for eight months of the year. This

dominant situation can be visualized (looking southwestward along the coastline) as a clockwise (in an offshore-vertical plane) circulation. Southwest of Kodiak Island the same circulation pattern is dominant only six months of the year. In general, the proportion of time when upwelling occurs increases to the southwest of Kodiak Island and decreases to the northeast.

Coastal upwelling indices for two regions near Kodiak Island (as reported by Ingraham et al., 1976) are shown in Fig. 3.4. Strongly negative (downwelling) values are encountered during winter months; only weak positive values are encountered from June to September. Numerical values of the index correspond to the vertical velocity (mm/day) through the bottom of the Ekman layer required to balance the divergence (or convergence) in the surface layer caused by the wind.

Winds on Kodiak Island versus those on the shelf

Reynolds (1978) showed that marine winds within 100 km of the coast in the northeast Gulf of Alaska are severely affected by the mountainous coast. He noted two types of effects: diurnal winds, which could be either katabatic winds or sea-land breezes, and mechanical blocking by coastal mountains. On Kodiak Island mountain ridges lie mainly perpendicular to the coastline and funnel coastal winds. Kodiak Island has lower topographic features than the Northeast Gulf. The difference in height could be important for wind blocking and for the generation of katabatic winds. The lower elevations are less likely to maintain extensive snow fields that generate katabatic flows. However, whether winds measured on Kodiak Island are representative of winds over the continental shelf must be questioned.

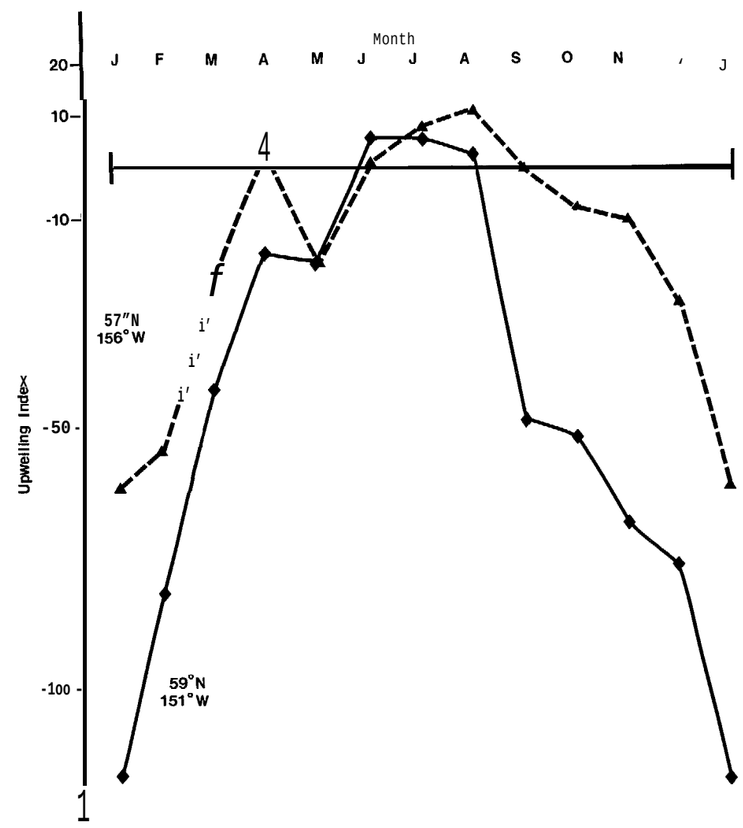


Figure 3.4 Upwelling indices for two locations in the Gulf of Alaska. The vertical axis is the vertical velocity in mm/day through the bottom of the Ekman layer. Values are computed from geostrophic winds derived from charts of surface atmospheric pressure. Wind-induced divergence and convergence in the surface layer can cause upwelling and downwelling, respectively (Ingraham et al., 1976).

Reynolds et al. (1979) compared wind observations of the National Weather Service on Kodiak Island to winds measured at a data buoy (EB-46008 at 51°7'N, 151°45'W) situated 75 km east-southeast of Kiliuda Bay. Data from three months (January, March, and June) were examined.

For January the buoy data and Kodiak Island data are similar. Winds on Kodiak Island are weaker than on the shelf. Vector mean speeds were 3.4 m/sec and 6.0 m/sec. March winds are less similar with lower speeds still observed on Kodiak Island: 1.4 m/sec compared to 2.4 m/sec. There is little similarity in June. Vector mean speeds were 0.5 for Kodiak Island and 3.4 for the data buoy.

Wind data from January, March, and June for Kodiak Island and an environmental buoy are shown in fabric diagrams (Fig. 3.5). Contours on the diagram represent the probability of occurrence of winds of various wind speeds (radial distance from the center) and wind direction (direction from which the wind was blowing).

For January the two wind diagrams are similar. However, Kodiak Island winds have a substantial probability of coming from the west-northwest not found in the buoy winds. This is caused by orographic control (Buskin Pass). In March the buoy winds are much more variable while Kodiak Island winds appear to be dominated by orographic effects.

Buoy winds during June are much less variable than in previous months and less variable than June winds on Kodiak Isand (see Fig. 3.1). The predominantly northwest-southwest winds on Kodiak Island could indicate sea-land breeze effects or katabatic winds.

To test the blocking effects of coastal mountains Reynolds et al. (1979) computed a parameter to suggest persistence of wind direction. The parameter "r" is

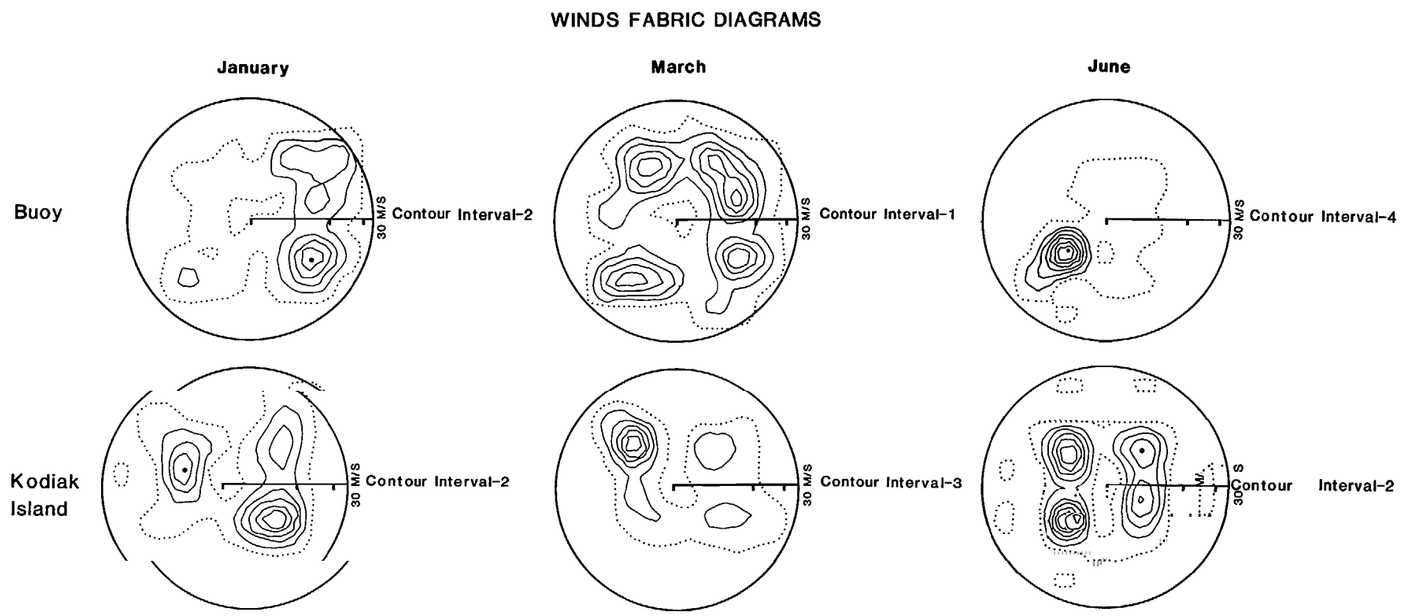


Figure 3.5 Fabric diagrams for winds observed at an offshore buoy and on Kodiak Island (lower figure) for January, March, and June. Wind speed is represented as radial distance from the center. Wind direction corresponds to the azimuth direction; the probability of occurrence is represented by the contours (Reynolds et al., 1979).

the ratio of vector mean wind speed to scalar mean speed. The more persistent a wind direction, the larger the vector mean speed will be relative to the scalar mean speed. Conversely, for winds that are variable in direction, r is low. Winds that blow consistently from one direction will have an r value near 1.0.

To compute r, average wind data were obtained from the Climatic Atlas (Brower et al., 1977). In winter, when Kodiak Island winds were strongest, winds were consistent in direction (r = 0.47). In the summer this consistency disappeared. An unexplained high value (0.32) was recorded for Marine Area B (see Fig. 3.1) in July, however. In winter Kodiak winds appear to be somewhat controlled by orography (in this case Buskin Pass, which is near the observation site).

Reynolds et al. (1979) concluded that Kodiak Island winds do not represent offshore conditions. The meteorological environment at the buoy site (51°7'N, 151°45'W) seems to be beyond the area of land influence.

Summary of Kodiak marine climatology

Since winds observed on Kodiak Island are not representative of winds over the continental shelf, it is necessary to obtain information from ships and buoys to describe winds over the lease area.

Wind climatology can be seasonally classified into two types. In winter (roughly October through April) the predominant regional patterns are Overland and Hiester's (1978) types 2.0, 4.0, 1.0, and 6.0 (see Fig. 3.2). Vector mean winds are from the northwest (Fig. 3.1) and wind speeds are high. These conditions favor downwelling at the coast (Fig. 3.4). Directional variability is high, probably the result of frequent passage of storms.

In summer (May through September) winds are mainly from the southwest; types 2.0, 4.0, and 5.0 dominate. Wind speed is lower than in winter with minimum winds occurring in June and July. Directional consistency is high.

3.2.3 Coastal influx of fresh water

Royer (1979) has shown that the influx of fresh water at the coast greatly influences dynamic heights measured on the shelf as well as coastal sea level. A cross-shelf pressure gradient results from the coastal influx of fresh water, and this drives a longshore, baroclinic coastal current. In the Northeast Gulf of Alaska, where this work was performed, the baroclinic coastal current is an important advective system. Similar conditions occur along the Kenai Peninsula (Schumacher et al., 1978, 1979c). Thus we may expect the similar forcing of a coastal current along Kodiak Island.

The great influence of precipitation and runoff on dynamic heights in the Northeast Gulf of Alaska has several causes. There is a high annual pulse of precipitation and runoff (see Roden, 1967, for monthly mean discharge of major rivers in the Gulf of Alaska). This runoff occurs over much of the long Alaskan coastline; the more fresh water remains near the shore, the larger

the dynamic heights downstream because of the accumulation of fresh water. Low temperatures also contribute to this effect, since at low temperatures changes in density are controlled largely by changes in salinity (Royer, 1979).

Off Seward the dynamic heights on the shelf are highly correlated with sea level at Seward. Over 80 percent of the variation in sea level can be accounted for by changes in the 0-200 db dynamic height. Variations in the upwelling index can account for only 4 percent of the changes in the shelf dynamic height (0-200 db) but account for 70 percent of the variation in the deep, off-shelf dynamic height (200-1000 db). Thus fresh water effects appear to mask the effects of winds on dynamic heights for the continental shelf off Seward.

At Yakutat the correlation between sea level and the 0-200 db dynamic height was weaker (0.587) than at Seward (0.934). However, the correlation using 200-1000 db dynamic heights was higher at Yakatut (0.478) than at Seward (0.132). These differences in the correlations could be caused by either the narrower shelf at Yakutat or the location downstream from Yakutat of several major rivers that influence the shelf off Seward (Royer, 1979).

Predicting the influence of fresh water influx at Kodiak Island is difficult. Precipitation is less there (137 cm/year) than at Seward .(170 cm/year) or Yakutat (335 cm/year) (Royer, 1979). There are major sources of fresh water (e.g., the Susitna River) that could influence Kodiak Island but not Seward. However, this water and much of the water of low salinity advected by the Coastal Current probably pass Kodiak Island via Shelikof Strait. Since there are no large sources of fresh water on Kodiak Island, and since much of the fresh water contributed upstream of Kodiak Island travels through Shelikof Strait, it is unlikely that the continental shelf east of Kodiak Island is heavily influenced. Thus, although Kodiak Island and Kenai Peninsula are adjacent, the continental shelves off these coasts may be influenced differently by the influx of coastal fresh water. When analyses like those carried out off Seward are repeated off Kodiak Island the role of coastal fresh water in the circulation around Kodiak Island will be better understood.

3 ≥ CIRCULATION DETERMINED BY INDIRECT METHODS

3.3.1 Temperature and salinity distributions

Winter itions

Surface temperatures for March 1977 (Fig. 3.6) show the influence of mixing over shoal regions. The coldest surface temperatures (< 5°C) occurred over North Albatross and Middle Albatross Banks. The warmest temperatures (> 6°C) occurred over Stevenson Trough and Kennedy Entrance.

A similar pattern occurs in bottom (or 200 m) temperatures (see Schumacher et al., 1978). The coldest water was found on the banks and seaward of the shelf break and the warmest water was found in the troughs. Thermal stratification (the temperature difference between surface values and those at the bottom, or 200 m) was small or nonexistent over North and Middle Albatross Banks. Over Kiliuda and Chiniak Troughs and over the Amatuli Trough/Kennedy Entrance, thermal inversions as large as 0.6°C occurred (Schumacher et al., 1978).

The inversions resulted from surface cooling. Since salinity is the major factor determining water density, these thermal inversions did not cause gravitational instability. Over the banks tidal energy and storm winds were strong enough to cause mixed conditions. However, over the deeper troughs the available energy was insufficient to mix the water column completely.

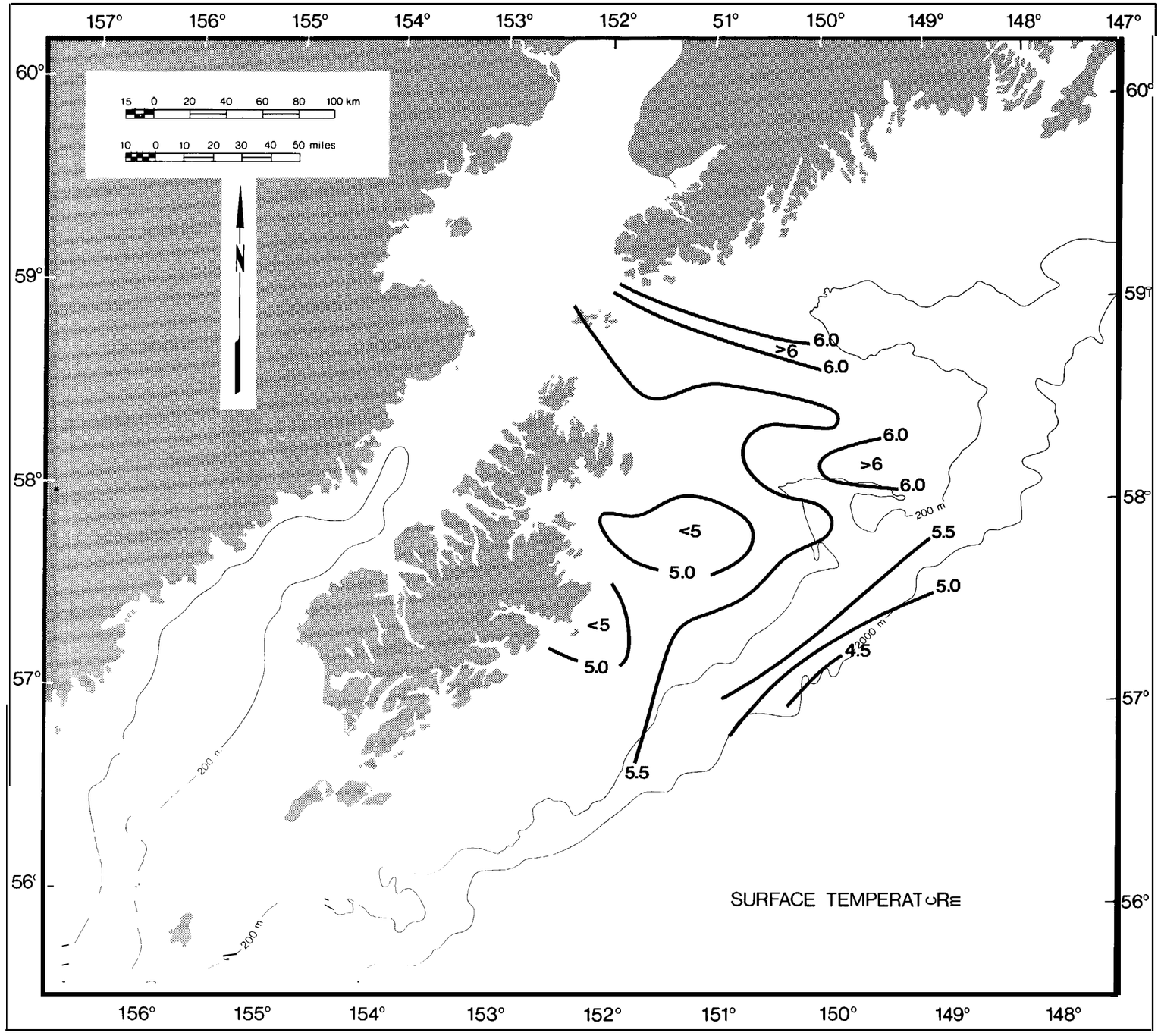


Figure 3.6 Surface temperature contours in degrees C for 2-10 March 1977 (Schumacher et al., 1978).

Surface salinities from March 1977 (Fig. 3.7) had two bands of low values: along the shelf break and along the southern end of the Kenai Peninsula. The band of low salinity at the shelf break off Kodiak was reported by Favorite and Ingraham (1977) from hydrographic data taken in May 1972. Royer and Muench (1977) also reported a "streamer-like lens of low density water" near the shelf break off Kodiak. Their infrared data (obtained by NOAA 3 and 4 satellites) suggest that nearshore water flows around Kayak Island and some of it is diverted offshore by this island. These less saline waters travel counterclockwise around the Gulf of Alaska with the Alaska Current. This band may be a continuous feature in the western half of the Gulf of Alaska.

The second region of low salinity (as low as 29.0 g/kg) is near the southern edge of the Kenai peninsula. This region consistently has low salinities throughout the year (see Figs. 3.9 and 3.12). Fresh water contributed by rivers and glacial storms throughout the Gulf of Alaska, Southeastern Alaska, and British Columbia and accumulating along the coast is the source of this low salinity.

Between these two regions of low salinity is an area of higher salinities (as high as 32.3 g/kg). Seaward of the shelf break salinities increase to the maximum value observed in this data set, 32.6 g/kg.

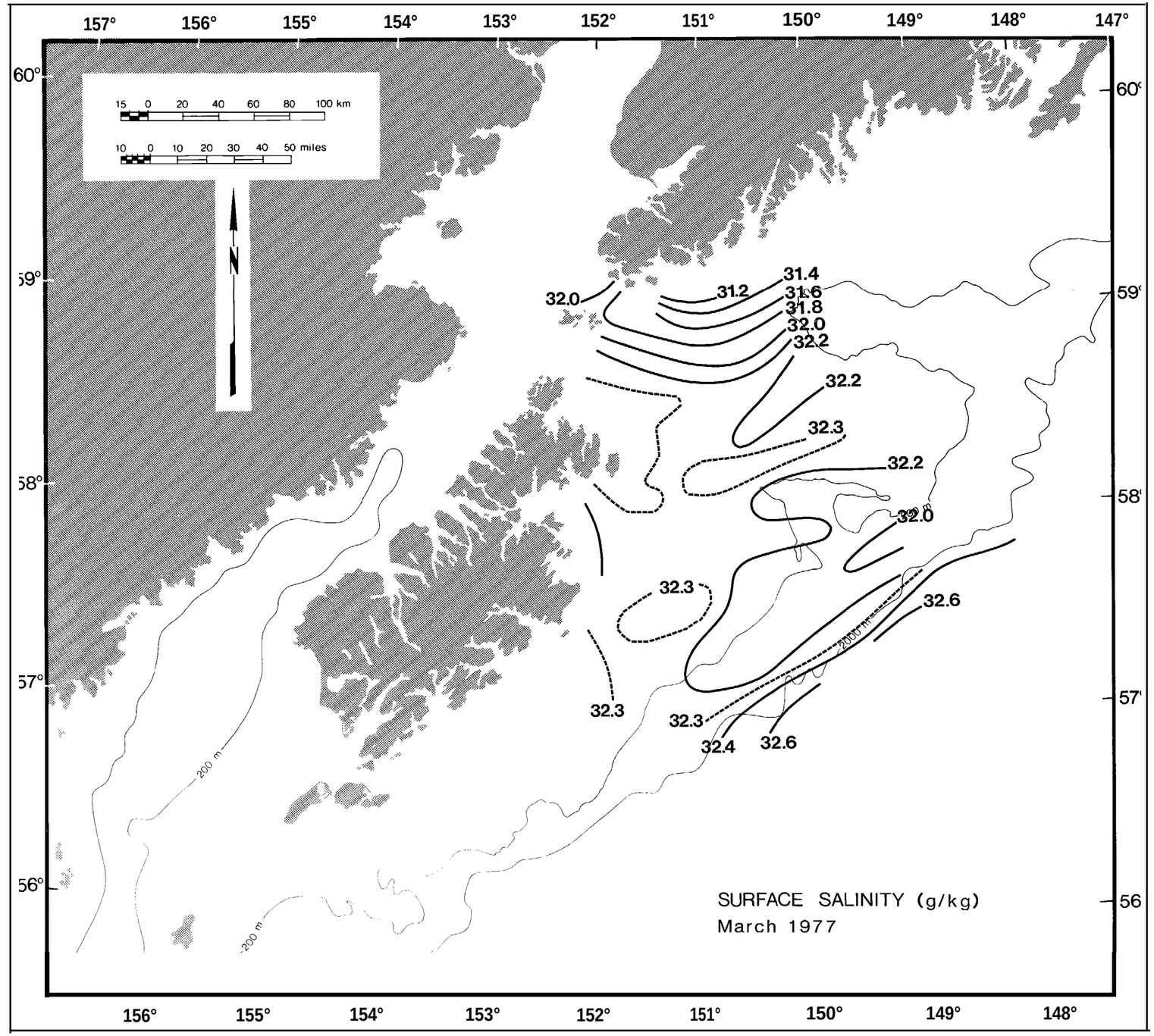


Figure 3.7 Surface salinity contours in g/kg for 2-10 March 1977 (Schumacher et al., 1978).

Salinity data from the bottom (or 200 m) show three features. There are high salinities (> 32.6 g/kg) in the troughs (Fig. 3.8). These can be seen in the Amatuli, Stevenson, and Kiliuda Troughs. In Chiniak Trough there is a suggestion of a high-salinity intrusion which could indicate circulation up the troughs toward Kodiak Island and Lower Cook Inlet (see Section 3.4 for further evidence of this circulaton)

Portlock, North Albatross, and Middle Albatross Banks all are identifiable by the lower salinity (32.4 g/kg) contours. Since salinity increases with depth, the increased tidal mixing over the banks lowers the bottom salinities.

A second feature of the bottom salinity contours is the region of low salinity near the southern edge of the Kenai Peninsula. This corresponds to the low values for surface salinity in this region.

There is also a low-salinity band and dense packing of salinity contours along the shelf edge. This area could be expected to have great variation in horizontal density corresponding to the Alaska Current. Figure 10 of Schumacher et al. (1978) confirms this prediction.

The same pattern seen in the bottom salinity contours can be seen in the differences between surface and bottom salinities (Fig. 8, Schumacher et al., 1978). Over the banks mixing has reduced the difference to a small value (typically 0.2 g/kg). Greater differences occur off the Kenai Peninsula and along the shelf break. Along the shelf break the contours of

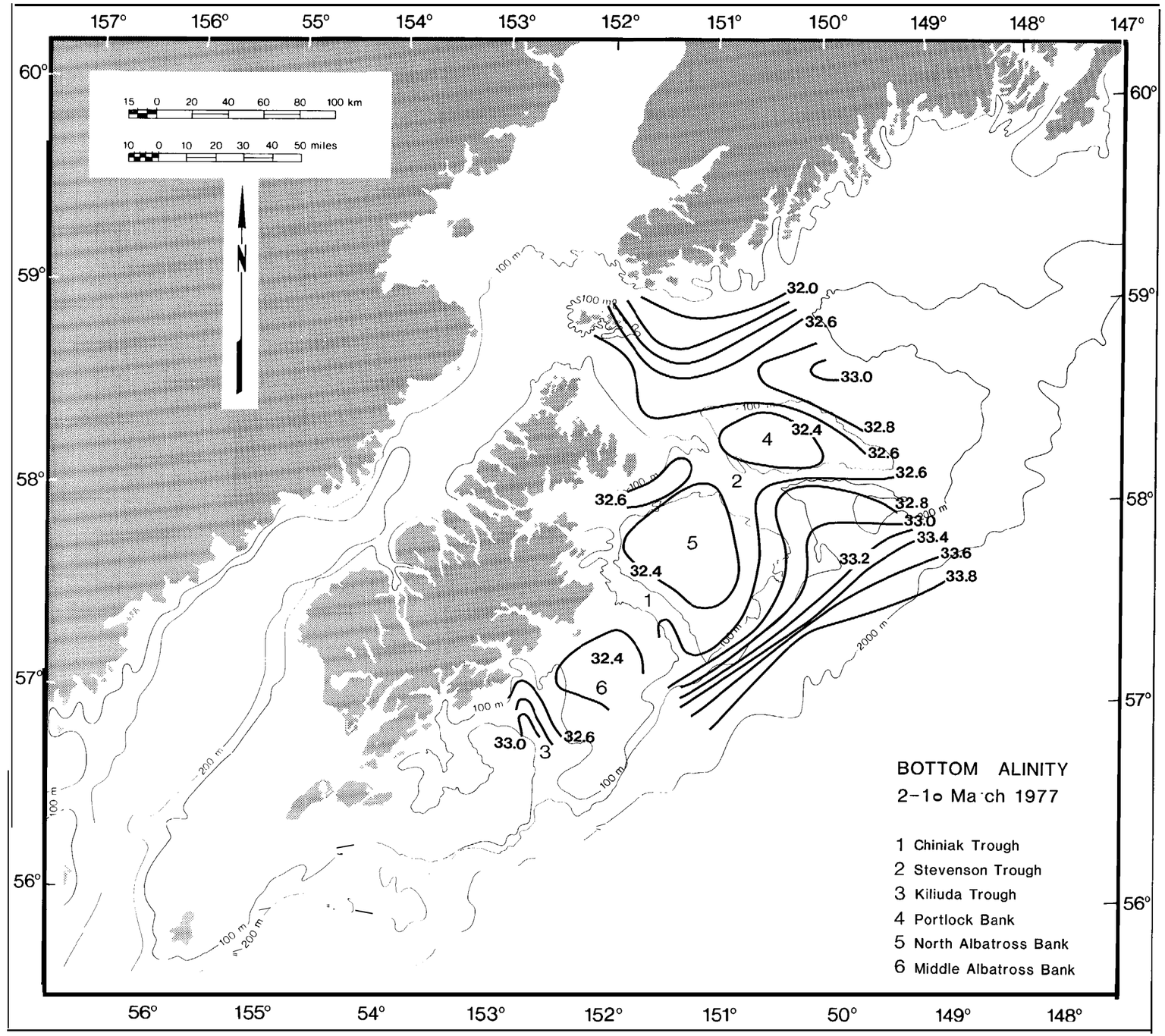


Figure 3.8 Contours of near bottom salinity in g/kg for 2-10 March 1977. These data were obtained just above the bottom or at 200m depth, whichever was more shallow (Schumacher et al., 1978).

surface-bottom salinity difference are crowded and reach 1.6 g/kg at this seaward edge of the study area (approximately over the 2,000 m isobath).

Surface salinities from March 1978 show no major differences from those of March 1977 (Fig. 3.7). (See Fig. 2(c) in Reed et al., 1979; unfortunately, their data set does not include stations on the shelf and thus we can compare only contours at the shelf break.) The 1978 data show contours of surface salinity to be clustered near the shelf break and parallel to it.

Spring conditions

Surface salinities from late spring (26 May to 6 June) 1978 were very similar to those from March 1978 along most of the shelf break (Reed et al., 1979). One difference is a disruption of the southwest-tending contours seaward (southeast) of Stevenson Trough, where an intrusion of low-salinity water (32.4 g/kg) extends well offshore of the shelf break (Fig. 3.9). This intrusion apparently developed between the March and mid-May hydrographic cruises. The 0/1000 decibar dynamic topography (see Fig. 3(b) in Reed et al., 1979) shows this feature as an anticyclonic (clockwise) eddy or eddy-like feature. It apparently formed inshore over Stevenson Trough, intensified, and moved southeastward toward the shelf break. No subsequent data are available.

Surface salinities for May 1972 were sampled in the near coastal waters of Kodiak Island and the upper end of Shelikof Strait (Favorite and Ingraham, 1977).

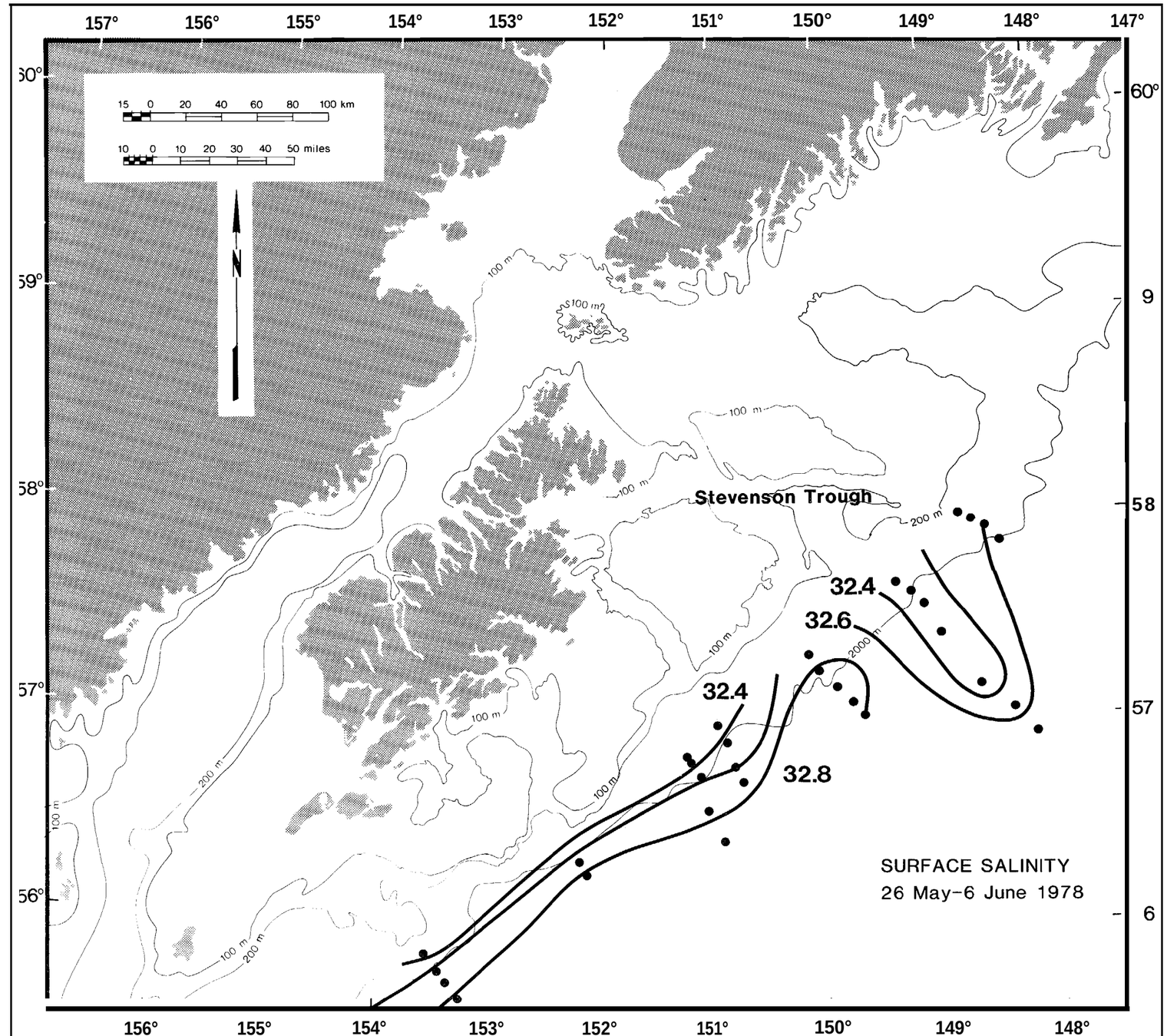


Figure 3.9 Surface salinity contours in parts per thousand for 26 May to 6 June 1978 (Reed et al., 1979).

A region of very low surface salinities off Cape Douglas probably reflects low-salinity water flowing out of Lower Cook Inlet along its western side. A salinity maximum occurs over the shelf. Farther offshore is another continuous band of water of lower salinity. This zone of minimum salinity lies approximately over the shelf break. Favorite and Ingraham (1977) state that this band separates the maximum salinities of the shelf (due to vertical mixing) from the high salinities offshore in the oceanic region. They also note a perturbation in the contours of surface salinity and speculate that this eddy-like feature formed on the inshore side of the Alaska Stream. This "eddy" was at 56°N, 153°W, southwest of the one shown in Fig. 3.9 (see Figure 8, Favorite and Ingraham, 1977).

Favorite and Ingraham (1977) also recorded continuous surface salinities across the region from the observed salinity minimum to the offshore salinity maximum. A surface salinity front was shown clearly. As one traveled offshore, the salinity rose from about 32.65 g/kg to 32.75 g/kg over 1-3 km. During the 30-hour period of observations the front moved seaward about 10 km. Horizontal oscillations of the front with an estimated period of 8-10 hours and an estimated amplitude of 3-5 km were reported.

Water temperatures for May-June 1972 (Fig. 3.10) were generally lower inshore and higher (> 5.0°C) seaward of the shelf break. These data contradict the values for bottom temperatures (from March 1977) shown

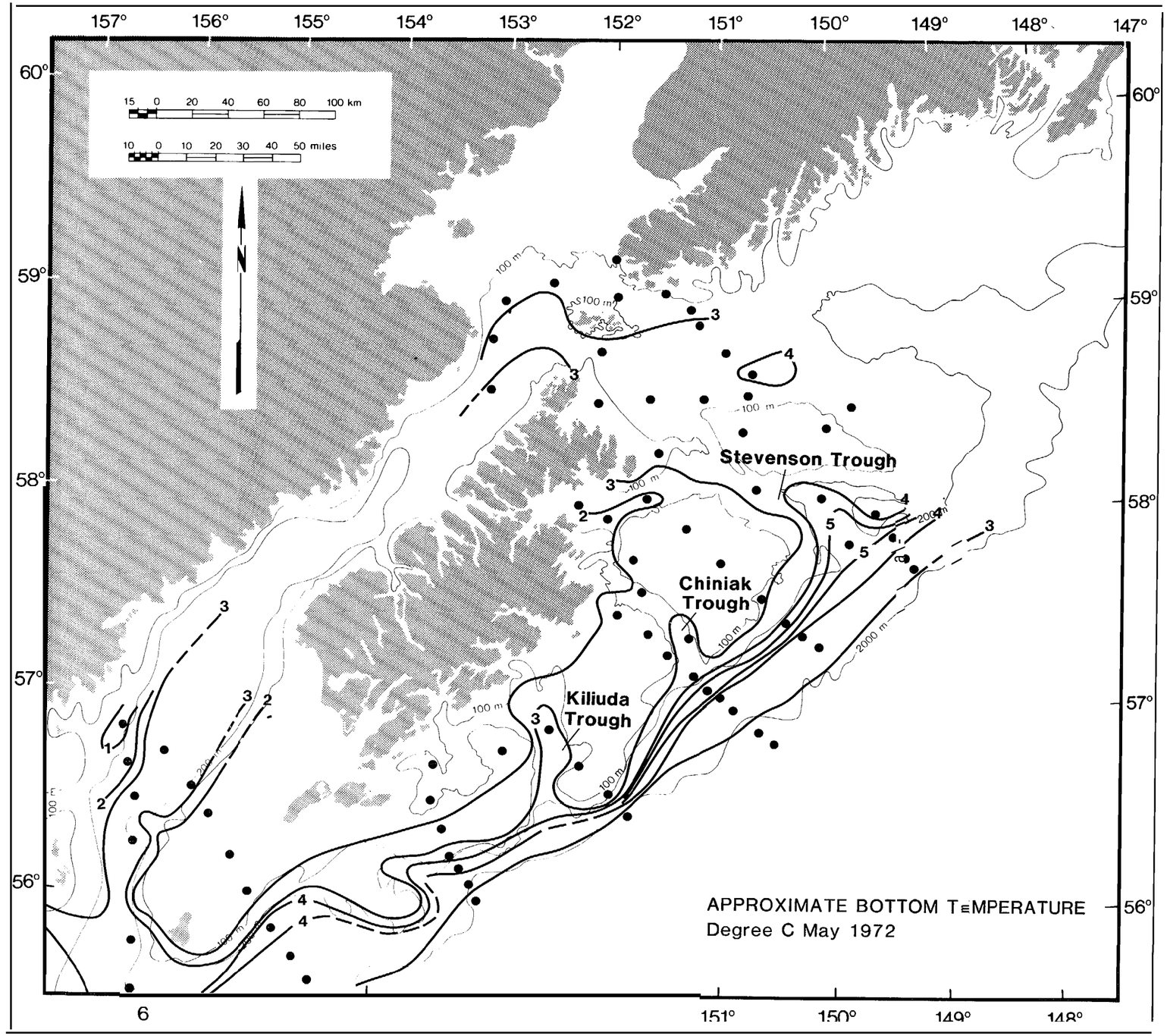


Figure 3.10 Approximate bottom temperatures in degrees C for May 1972 (Favorite and Ingraham, 1977).

(Fig. 4) in Schumacher et al. (1978). They are supported by the distributions of sea surface temperatures reported by Royer and Muench (1977), however. The coldest water (< 1°C) was found in southern Shelikof Strait. Water colder than 2°C occurred at the bottom along the east coast of Kodiak and Afognak Islands. Water this cold was found only adjacent to the coast (Favorite and Ingraham, 1977).

Water farther south and southwest of Kodiak Island was 2-3°C colder than water north and east of Afognak Island. Favorite and Ingraham (1977) speculated that this temperature difference might be due to atmospheric cooling at the surface. Meteorological data that could substantiate or refute this hypothesis were not presented.

Bottom temperatures for May 1972 are shown in Fig. 3.10. (See Favorite and Ingraham for an explanation of how these temperatures were derived.) Warm water extended offshore up into Stevenson, Chiniak, and Kiliuda Troughs. Cooler water dominated the banks. Warm water also occurred at each end of Shelikof Strait. Other observations (Fig. 3.15) suggest an inflow of warm water along the bottom through the southwestern entrance of Shelikof Strait.

A thermal front overlies the shelf break. The temperature contours closely parallel the bathymetry. The small bank seen in the 200 m isobath south of South Albatross Bank is outlined by temperature contours. This is also the approximate location of the eddy-like feature seen in Favorite and Ingraham's (1977) surface salinity distribution. (This distribution was discussed above but is not shown. Refer to Figure 8 in Favorite and Ingraham.)

umm r conditions

Surface temperatures for September, 1977 (Fig 3.11) were warmer than those of March of the same year (Fig 3.6 Surface waters were relatively warm -14°C) throughout the region with highest temperatures rd of the shelf break and near the Kenai Peninsula In general, cooler waters overlay the banks however, sampling was inadequate to show possible temperature differences between troughs and adjacent banks No differences were expected

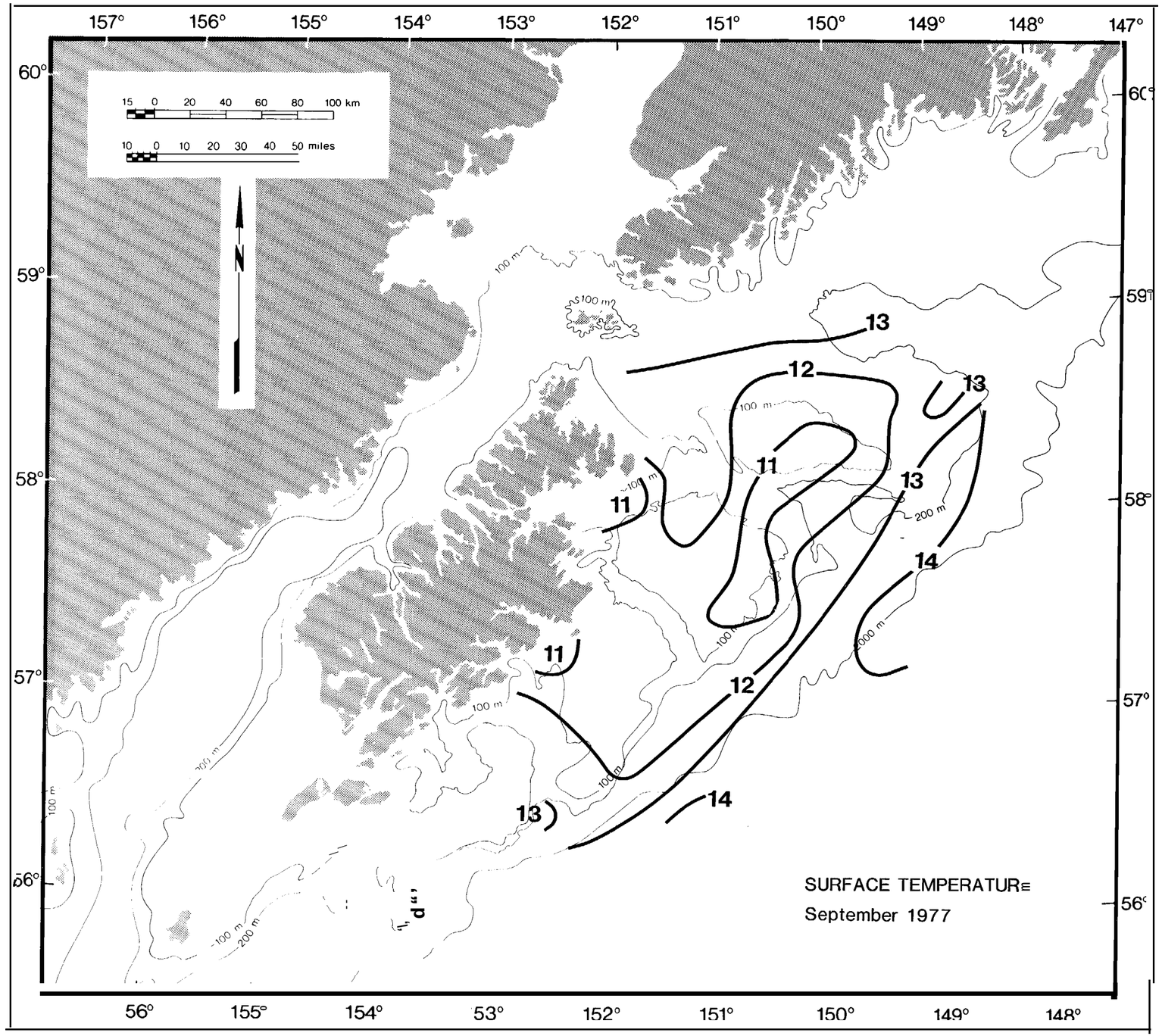


Figure 3.11 Surface temperature contours in degrees C for September 1977 (Schumacher et al., 1979c)

Surface salinities were low (28.5 g/kg) (Fig. 3.12) in September 1977. The lowest values for September, as for March (Fig. 3.7) and October-November (Fig. 21 in Schumacher et al., 1979c), occurred off the Kenai Peninsula. In general, September salinities were lower than those in March, May-June (Fig. 3.9), and October-November. (Note that the May-June data are from 1978, the other data from 1977.) The 32.0 g/kg contour closely follows the 200-m isobath. The contour shows onshore intrusions of water of higher salinity (32.0 g/kg) in Stevenson and Kiliuda Troughs. The highest salinity observed (32.5 g/kg) in September was seaward of the 2,000 m isobath.

Unlike the surface salinity distributions for March (Fig. 3.7) and for May (Favorite and Ingraham, 1977), the September salinities increase seaward from Kodiak Island, and no region of minimum salinities was observed. (Contour intervals are different for the different data sets, but the lack of a region of minimum salinities does not appear to be an artifact of the contour interval.) Neither is there a zone of minimum salinity in the October-November 1977 data (Fig. 21 in Schumacher et al., 1979c).

In his September salinity data, Schumacher (pers. comm.) found a slight surface minimum. The minimum extends only as far south as a line drawn southeast from the northern end of Afognak Island. In his October data he found a weak salinity minimum over Stevenson Trough. Data collected in March and May/June 1978 showed a region of minimum salinity but Schumacher considered it too limited to affect flow dynamics.

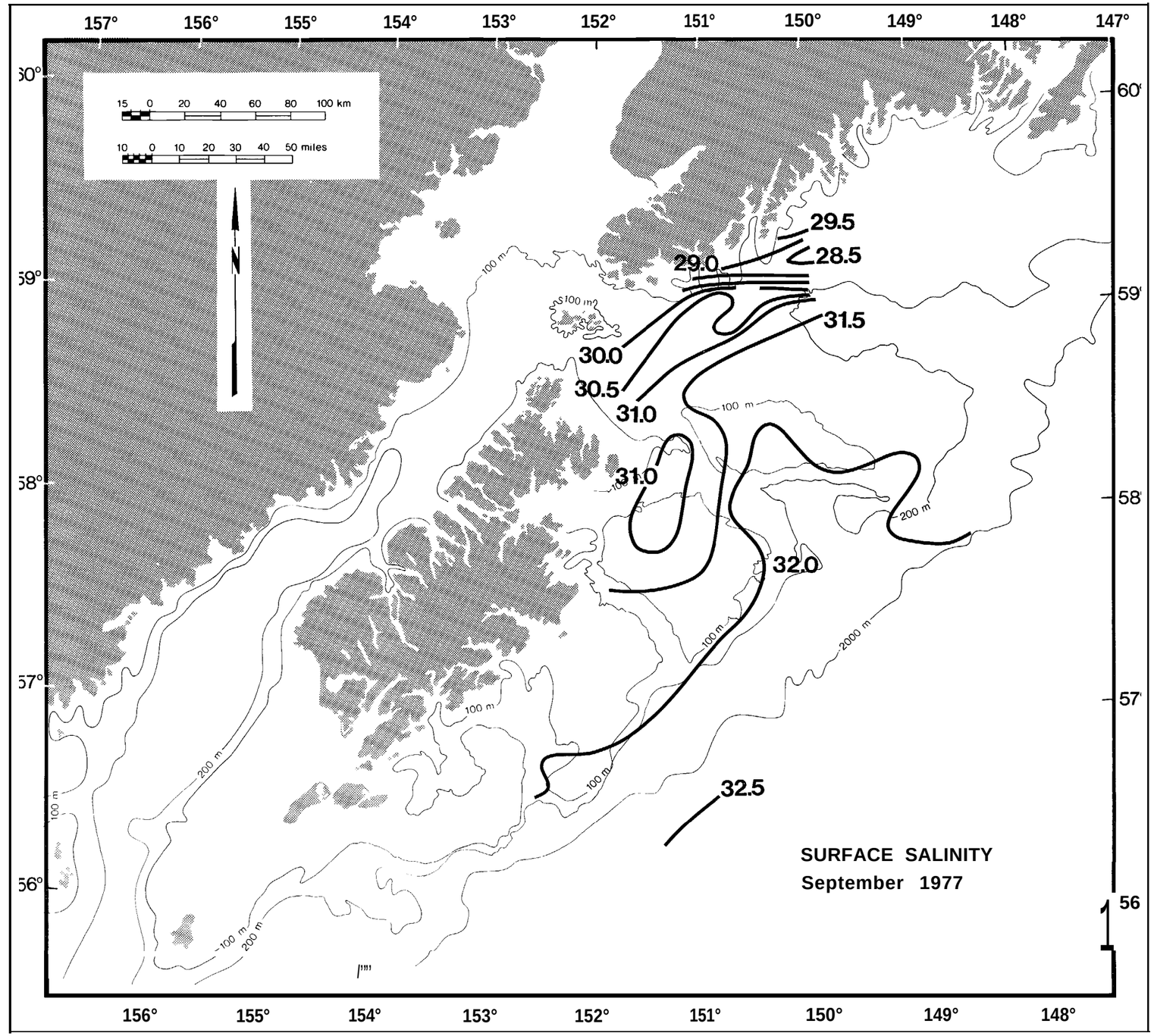


Figure 3.12 Surface salinity contours in g/kg for September 1977 (Schumacher et al., 1979c).

Autumn conditions

By mid-October to early November 1977 (see Fig. 20 in Schumacher et al., 1979c) surface temperatures had lowered by 4°C or more. The warmest temperature recorded was 10°C along the eastern side of the Kenai Peninsula. Warm waters were found both along the peninsula and east of Afognak Island along the edge of the shelf. Cooler water (7°C) was found between these areas of warm water. Temperatures were 2-3°C cooler in March (Fig. 3.6) than in October-November.

The salinity distributions for September and October-November are similar. September values inshore along Kodiak Island were slightly (0.5 g/kg) lower in salinity while those near the edge of the shelf were higher by about 0.5 g/kg.

The distribution for bottom (or 200 m) salinities observed in October-November 1977 (Fig. 37 in Schumacher et al., 1979c) was similar to the distribution of March 1977 (Fig. 3.8). However, salinities later in the year were lower by as much as 0.4 g/kg. Minimum salinities in October-November occurred along the Kenai Peninsula and over North and Middle Albatross Banks (32.0 g/kg) and over Portlock and South Albatross Banks (32.5 g/kg). The highest salinities (33.5 g/kg) were found over Amatuli Trough and along the shelf edge. Intrusions of high salinity bottom water can be seen clearly in Stevenson, Chiniak, and Kiliuda Troughs.

Vertical sections of temperature (Schumacher et al., 1979c) show two regions of warm temperatures: inshore and over the shelf break. These surface temperature maxima appear to be continuous along the Kenai Peninsula and Kodiak Island. In each band of temperature maxima cooler temperatures occurred farther to the southwest.

Storm-induced changes in temperature and salinity

Sampling at two stations on Portlock Bank immediately before and after high winds (approximately 50 knots) in October 1977 (Schumacher et al., 1979c) showed decreases in surface temperature (about 1°C at one station and almost 1.5°C at the other) and a significant increase in surface salinities (by about 0.5 g/kg) over 41-42 hours. The water column at each station showed both thermal and haline stratification before the winds. Afterwards the water columns were isothermal and isohaline. The authors attribute the changes in temperature and salinity over Portlock Bank to localized upwelling. Regardless of the mechanism, it is apparent that meteorological events can greatly influence physical conditions and the distribution of petroleum within the water column on the shelf.

Temperature environments near Kodiak Island

Favorite and Ingraham (1977) categorized bottom temperature environments around Kodiak Island according to temperature distribution. One environment is over shoal regions where the depth is less than 100 m. Winter overturning occurs to this depth and mixing by tides and winds ensures that water is nearly isothermal over the shoals throughout the year. Temperatures as low as 1-2°C occur in winter and as high as 6-9°C in summer.

In the troughs, at depths greater than 150 m, overturning and mixing do not occur throughout the water column. Thus the difference between surface and near-bottom temperatures is at a maximum over troughs.

At the shelf break bottom temperatures are constant throughout the year: 4-5°C.

The fourth thermal environment is Shelikof Strait. Here winter temperatures are influenced by the influx of warm water from the continental shelf and by cold water from Lower Cook Inlet.

Favorite and Ingram (1977) represented these four environments on a T-S diagram (their Fig. 12). The characteristics of waters seaward of the shelf edge, of those in Stevenson Trough, and of those overlying shoals near Portlock Bank all lie along a straight line on the T-S diagram. It is tempting to infer that water would move onto the shelf into troughs and mix with the lower-salinity and cooler (in winter) water that is probably moving offshore. Additional mixing would result in the water characteristics observed on the shoals. Thus the differences in thermohaline properties among the four environments could reflect differing contributions of the two water types.

Shelikof Strait

Temperature and salinity sections (Fig. 3.13) were also obtained across the northeast and the southwest ends of Shelikof Strait in March 1977. Strong stratification was found near the surface along the Alaska Peninsula side of the northeast section, the result of outflow from Lower Cook Inlet. The maximum salinity observed along this cross-section was 32.19 g/kg at the eastern side of the Strait. Throughout almost all of the northeastern section salinities were less than or equal to 32.0 g/kg. At the southwest end of the Strait only weak stratification was noted across the section. Maximum salinities in the section were greater than 32.75 g/kg.

The water of highest salinity (> 32.0 g/kg) did not originate at the northeastern end of the Shelikof Strait, where highest salinities were 32.0 g/kg or less. Rather it probably entered the Strait from the southwest. Schumacher et al. (1978) suggest that this

inflow of deep water occurs to balance the loss of deep water entrained by the outflowing shallow water.

Temperatures were, in general, higher at the southwestern section. The difference in temperatures between the two sections might have been caused by a change in the temperature of the source water which was being advected past only the northeastern stations at the time of the survey. The warmest waters in either of the sections were found near the bottom of the southwestern section.

The absence of inclined isohalines in these sections (except for the near-surface stratification at the northeast end) suggests that the flow through Shelikof Strait is predominately barotropic. For baroclinic current shears to exist, a tilting of isopycnals relative to a level surface would have to occur. Since salinity largely determines density in this region, the isohalines would have to tilt. Current meter data in Shelikof Strait indicate some current fluctuations that may be associated with winds. The presumably barotropic mean flow is probably driven by a pressure (sea elevation) difference between the two ends of the Strait and, to a lesser degree, by local wind forcing.

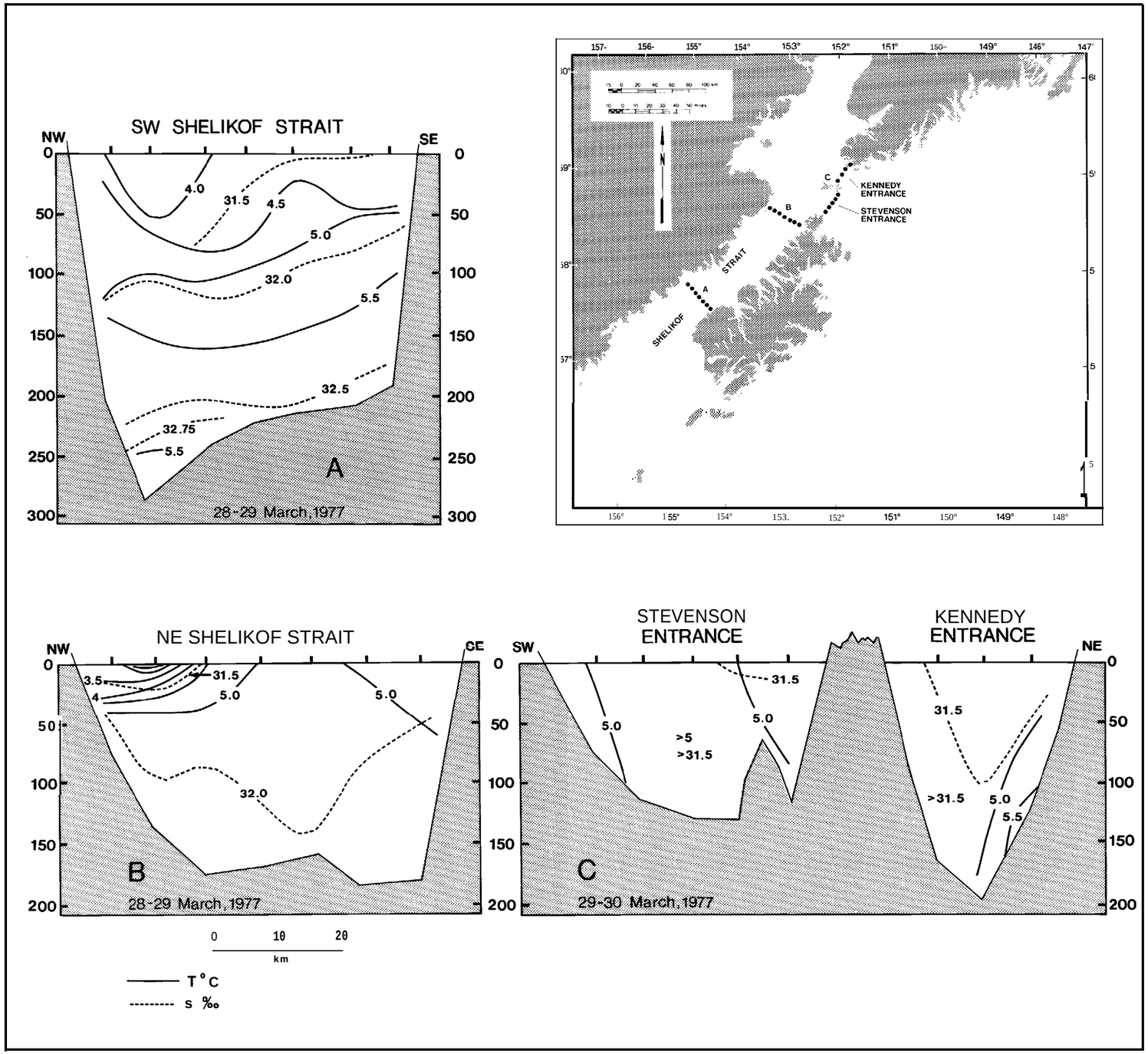


Figure 3.13 Temperature and salinity vertical profiles along transects across southeastern Shelikof Strait (A), northeastern Shelikof Strait (B), and across Kennedy and Stevenson Entrances (C) (Schumacher et al., 1978).

Kennedy and Stevenson Entrances

A temperature and salinity section for March 1977 through the Kennedy and Stevenson Entrances of Cook Inlet is shown in Fig. 3.13. There is very little thermal or haline stratification. In general, the water in Kennedy Entrance is cooler and less saline than that in Stevenson Entrance. However, a small core of warm water was observed along the Kenai Peninsula at a depth of about 130 m.

Conclusions

Warm waters of low salinity flow near shore along the Kenai Peninsula and appear to enter Lower Cook Inlet through Kennedy Entrance. Dilution by coastal rivers probably accounts for the low salinity, while insolation on the shallow, inshore areas may cause the high temperatures.

Warm water of low salinity is also found along the shelf edge. Several authors (Royer and Muench, 1977; Favorite and Ingraham, 1977) have discussed the continuity of this band along the shelf break off Kodiak Island and in the Northern Gulf of Alaska. Favorite and Ingraham (1977) suggest that the surface salinity front where oceanic water of high salinity lies next to the waters of minimum salinity may be a navigational aid for migrating fish. Royer and Muench (1977) suggest that this band of low-density water may augment baroclinic flow toward the southwest on its seaward side and retard it on its shoreward side This band was not observed during hydrographic cruises in September and October-November 1977, but this may have been caused by inadequate sampling.

Flow occurs along the shelf break. Isolines are generally densely packed in this region. In most data sets the isolines closely parallel the bathymetry. However, perturbations were observed in two data sets. These eddy-like features probably originate on the shore side of the Alaska Current.

Saline water appears to flow shoreward in the troughs that cut perpendicularly across the Kodiak Island shelf. Over the banks and shoals the water column is nearly isothermal and isohaline as a result of thorough mixing. Over the deeper troughs mixing is incomplete, and thermal and saline stratification is the result.

3.3.2 Baroclinic geostrophic circulation

Temperature and salinity profiles across the continental shelf indicate the direction and strength of currents relative to some specified level by means of the geostrophic assumptions. The data presented in this section are contours of dynamic topography. The geostrophic component of flow parallels these contours. In the Northern Hemisphere highest dynamic heights are on the right when the observer faces downstream. The speed of the flow is inversely proportional to the spacing between adjacent contours.

The problem in using dynamic topography is deciding what level to use as a reference. (For a discussion of reference levels, see Fomin, 1964, or Neumann and Pierson, 1966.) It is generally assumed that for surface dynamic heights, a reference level of 1500 decibars (db) is sufficient to represent both temporal and spatial variations, although estimates of volume transport will be in error (Reed et al., 1979). On the continental shelf, where depths are much less, a reference level of 1500 db cannot be used directly. The simplest solution is to choose an arbitrary reference level (e.g., 100 db) that is attained in the hydrographic data. The geostrophic assumptions are probably invalid in shallow water, as on the Kodiak Island continental shelf. However, the dynamic topography can be interpreted as baroclinic flow or as lenses of water of varying density. The dynamic height of the water column then is a measure of the density of water integrated over the column. Interpreting the topographies as currents appears to be valid in the Kodiak lease area. Directions of flow are representative in many cases although the speed of the flow may not be. It has not been shown that the dynamic method represents currents on the Kodiak Island shelf accurately, but it has been demonstrated to be accurate elsewhere (e.g., off Oregon: Huyer et al., 1978).

A second solution is to project, with a chosen algorithm, the slope of isopycnals near the bottom onto shallower depths. Comparisons of dynamic heights can then be made between inshore and offshore areas by use of deep reference levels. The algorithm selected by Reed et al. (1979) is the method of Jacobsen and Jensen (Fomin, 1964). This method assumes that the isopycnals are parallel to the isobars at some depth (1500 db for this study). The difference between specific volume anomalies at the deepest level common to two adjacent stations is multiplied by the difference in depths between the common level and 1500 db. (This value is multiplied by 0.5 to represent the dynamic height midway between the two stations.) This adjustment is then added to the surface dynamic height relative to the common level.

Deep reference levels

The dynamic topography of the sea surface, relative to 1500 db, for the entire Gulf of Alaska was developed by Roden (1969). The baroclinic geostrophic flow is cyclonic (counterclockwise) toward the southwest off Kodiak Island. The contours are compressed off Kodiak Island, representing an increase in the speed of the flow. (For a discussion of the theory on

the intensification of the Alaska Stream near Kodiak Island, see Thompson, 1972.) Roden estimated that maximum speeds of about 20 cm/sec occur near the shelf edge. However, his data were few and his estimates of speed appear to be low.

In a dynamic topography (0/1000 db) for early March 1978 (Reed et al., 1979) the contours are parallel to the bathymetry and no large perturbations exist. Baroclinic geostrophic surface flow, relative to 1000 db, is toward the southwest. In a 0/1000 db dynamic topography for late May/early June (Reed et al., 1979), the values of dynamic height are lower by about 0.20 dynamic meters than in March. Although the May-June data contours largely parallel the bathymetry, a large perturbation is centered at 57°30'N, 149°30'W. The distribution of surface salinity shown in Figure 3.9 shows this perturbation. The eddy-like feature has a maximum value of dynamic height, and an anticyclonic (clockwise) circulation is inferred around this maximum. Reed et al. (1979) noted that the center of this feature was almost 0.1 dynamic meters higher than the dynamic height at the same location eight days before. In addition the isolines had deepened by almost 100 m.

Data (0/1000 db) from May 1972 (Favorite and Ingraham, 1977) show almost uniform flow along the shelf break. Minor perturbations are suggested at the extreme northeastern and southwestern inshore ends of the data set. More interesting is a potential flow reversal, with flow of about .4 cm/sec to the northeast (relative to 1000 db) at about 55*N, 152°30'W, 96 km miles seaward of the shelf break. This is well offshore of the zone of minimum salinity reported by Favorite and Ingraham. These are the only hydrographic data that show a flow reversal in this region.

The only other data with a deep reference level were reported by Schumacher et al. (1979c). They used a 500 decibar reference level for the surface topography. Data for September 1977 show uniform flow towards the southwest, parallel to the shelf break. In the October-November data the flow was also fairly uniform.

Shallow reference levels

Several calculations use shallow reference levels so that dynamic topographies near shore can be computed. Favorite and Ingraham (1977) used a reference level of 50 db for surface dynamic heights. These data (from May 1972) show a westward surface flow north of Afognak Island which brings low-salinity water into Lower Cook Inlet through Kennedy Entrance and directly into Shelikof Strait through Stevenson Entrance. East of Afognak Island is a region of weak cyclonic circulation. The densest packing of contours, and thus the highest speeds, occur just seaward of the shelf break. Here dynamic heights are at a maximum. Between this maximum and the high values along Kodiak Island is a decrease in dynamic height. This trough lies generally shoreward of the 150-m isobath. A flow reversal, or flow towards the northeast, which results from this trough extends continuously along (inshore of) the shelf break .

The dynamic topography correlates well with the surface salinity. The trough corresponds to the surface salinity maximum, and the ridge corresponds to the band of minimum salinities reported by Favorite and Ingraham (1977). At about 55°30'N, 155°W, a perturbation appears which has been contoured as a cyclonic eddy.

East of Portlock Bank is an indication of an anticyclonic eddy. In general, the dynamic height contours over the shelf do not strictly parallel the bathymetry but oscillate shoreward and seaward.

The 0/100 db dynamic topography for September differs substantially from the 0/50-db topography for May. The September data do not show a trough in dynamic heights; the largest values occur inshore, and values decrease seaward (Fig. 3.14). Flow toward the southwest occurs near the shelf break. As in the data discussed above, there is a westward flow around the southern end of the Kenai Peninsula. East of Afognak Island is a well-developed anticyclonic (clockwise) gyre (Schumacher et al., 1979c). Favorite and Ingraham (1977) reported a weak cyclonic gyre in this area.

In September the anticyclonic gyre was situated over Stevenson Trough. Water flowed eastward along the southern edge of Portlock Bank and westward along the northern edge of North Albatross Bank. Schumacher et al. (1979c) suggest that the gyre may have resulted from a southerly offshoot of the westward flow along Kenai Peninsula (see the 0.29-dynamic meter contour in Fig. 3.14). The distributions of surface temperature and salinity (Figs. 3.11 and 3.12) support this hypothesis. If water of low density were advected into the trough, it could be constrained from flowing out onto the shelf by the southwesterly flow on the shelf (Schumacher et al., 1979c).

Values of dynamic height were lower on the Kodiak Island shelf in October-November 1977 than they were in September. However, they were higher along the Kenai Peninsula in October-November (see Fig. 19 in Schumacher et al., 1979c). The volume transport was 0.4×10^6 m^3/sec in September and 1.0×10^6 m^3/sec in October-November, more than double the September value.

A combination of increased discharge of fresh water along the coast and wind-caused coastal convergence appear to be responsible for the increased transport. Rainfall is usually heavier later in the fall, but surface salinities for the two periods are similar;

no large decrease in salinity occurred near Kenai Peninsula in October-November. However, the ow-salinity near-surface layer deepened (compare Figs .6 and 31 in Schumacher et al., 979c). Before the October-November hydrographic cruise there were two periods of strong winds from the northeast which could have caused coastal convergence and a ing of the low-salinity ayer. f the ncreased transport along the Kenai Peninsula were due olely to wind convergence, comparable changes in the dynamic topography along Kodiak Is and would be expected Since the atter did not occur, the increased runoff from the Alaska ma nland, along with the winds ust have been responsible for the increased volume transport.

An anticyclonic eddy was still evident over Stevenson Trough in October-November. However, some o the contours extend the length of the trough and indicate eaward flow in the trough. A flow from the western end of Amatuli Trough into the western end of Stevenson Trough, which may supply low-density water that contributes to the arge dynamic heights, is sti l evident

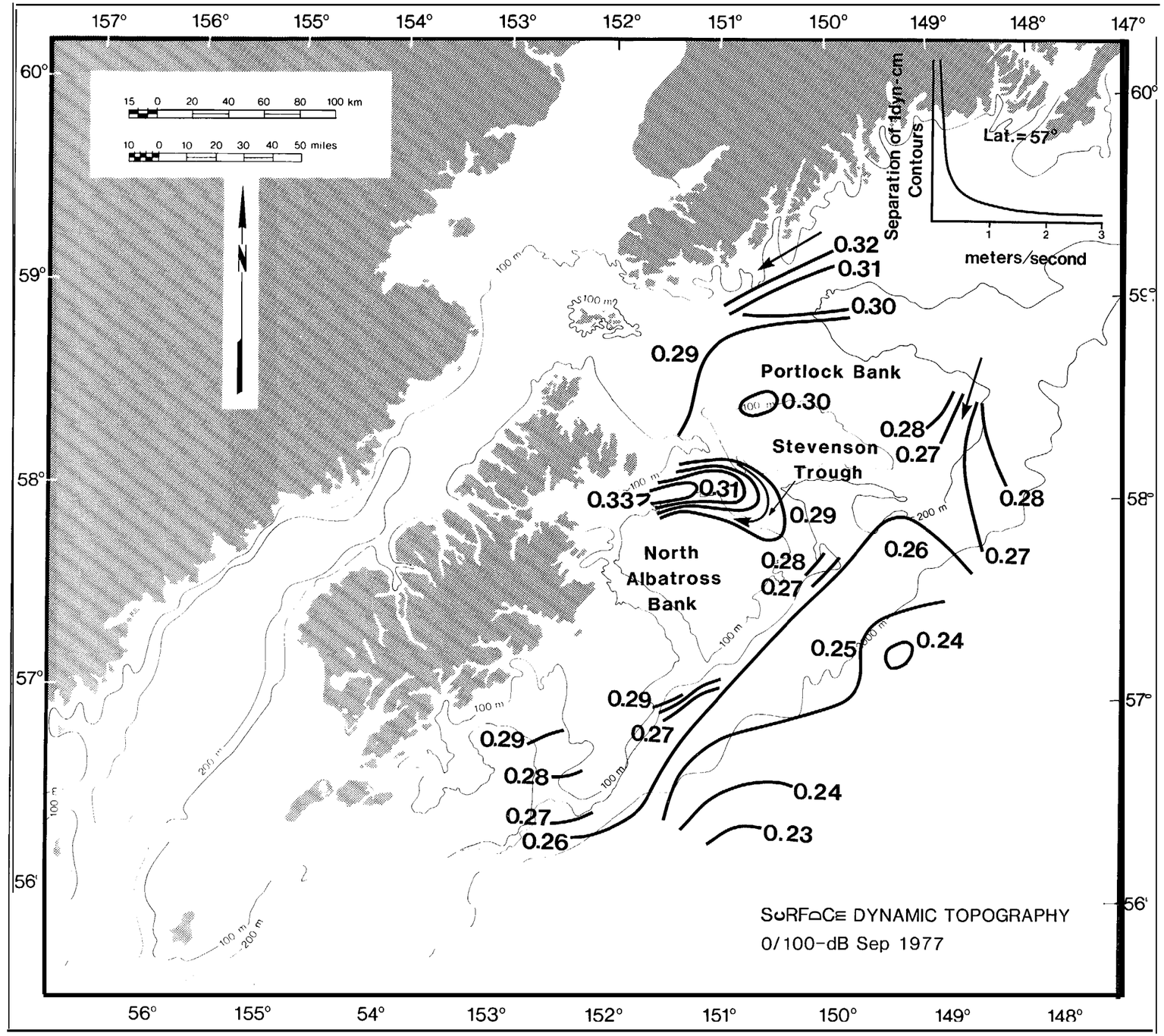


Figure 3.14 Surface dynamic topography, relative to 100 dB, for September 1977 (Schumacher et al , 1979c).

Transport of the Alaska Stream

Reed et al. (1979) studied the seasonal variability of the baroclinic transport of the Alaska Stream off Kodiak Island. Apparently, large gains or losses of water do not occur there between the Alaska Stream and the oceanic region. The authors assumed little variation in the volume transport between different locations along the Alaska Stream. (Royer (pers. comm.) disagrees. He found a smaller transport across a hydrographic line southwest of Kodiak Island than on a line off Lower Cook Inlet.) This assumption allows the comparison of data taken at different times regardless of its exact location.

The assumption of no gain or loss of water is plausible. The dilute warm band of water associated with the Alaska Stream shows no large shoreward or seaward tendencies that might represent losses or gains (Reed et al., 1979).

Use of a reference level of 1500 db instead of 3000 db (where horizontal gradients of geopotential typically vanish) probably reduces the calculated transport by $5 \times 10^6 m^3/sec$. However, the direction of flow and spatial and temporal variations in flow are probably depicted accurately when 1500 db (Reed et al., 1979) is used.

For stations where the hydrographic data do not extend down to a 1500 db reference level, the method of Jacobsen and Jensen was used. However, transport in water of 300-m depth or less was neglected by Reed et al. (1979). Neglecting this flow probably results in an underestimate of the volume transport by about 1×10^6 m^3/sec.

The mean adjusted transport is $11.6 \times 10^6 m^3/see$, while the unadjusted transport is $9.4 \times 10^6 m^3/sec$. The **variability in both transport values is about the same (standard deviation of about $2.2 \times 10^6 m^3/see$). However,** the variability between values computed at the same time at adjacent locations is slightly less for the adjusted transport than for the unadjusted transport.

The maximum adjusted transport, $17 \times 10^6 m^3/sec$, occurred in July 1976. The minimum, 8×10^6 m3sec, occurred in June 1978. Variation is large, but there are no apparent seasonal trends. In a more recent study Royer (pers. comm.) found a seasonal variation in transport values. The differences between the results of these two studies have not been resolved.

The lack of a seasonal pulse in the transport is unexpected, since the wind stress transport has such a strong seasonal peak. Wind stress typically has values during October-February that are an order of magnitude (or more) greater than spring and summer values.

3.3.3 Seasonal sea level variations

Variations in sea level can be used to estimate the condition of the baroclinic or barotropic components of flow along the coast. Off Seward, Royer (1979) found that seasonal variations in sea level can be accounted for by changes in local dynamic height. He inferred no seasonal change in the barotropic component. The changes in dynamic height off Seward are caused by seasonal fluctuations in the influx of coastal fresh water.

It is not known if the influx of fresh water is as important along Kodiak Island as it is off Seward. Since much of the fresh water accumulated along the Gulf of Alaska coast passes through Kennedy or Stevenson Entrance and through Shelikof Strait, sea level at Kodiak may reflect changes in the barotropic component of alongshore currents. Direct observations over periods long enough to determine whether there is a seasonal signal in the shelf currents are unavailable.

A twenty-five-year mean of monthly sea levels (adjusted for atmospheric pressure) for Kodiak Island (Fig. 3.15) shows a seasonal pulse. Sea levels in the summer are low while winter values are about 20 cm higher.

If all of the seasonal variation in sea level were attributable to changes in the barotropic component of flow, seasonal changes in the latter would be about 20 cm/sec. Maximum barotropic flow toward the southwest would occur in late fall and winter; minimum flow in this direction would occur in mid-summer. Wind speed, coastal upwelling indices (Ingraham et al., 1976), and the curl of the windstress all have similar seasonal cycles.

While it is unlikely that all of the seasonal variations in sea level are associated with changes in the barotropic component of the longshore flow, it is also unlikely that they are entirely attributable to influx of fresh water along the Kodiak Island coast as they are off Seward.

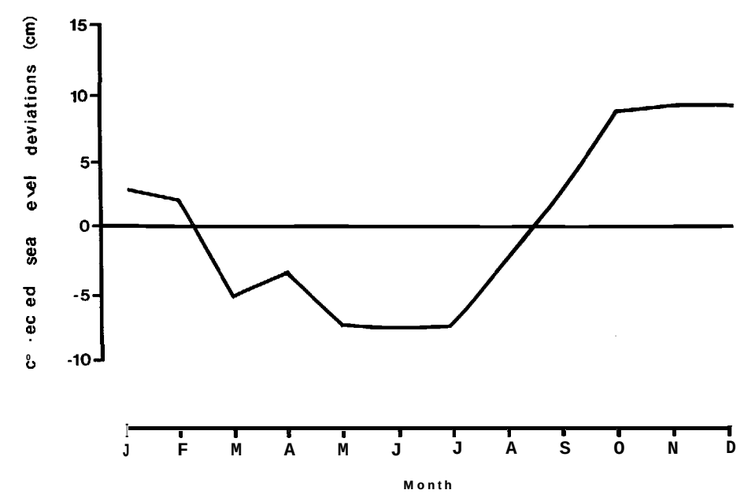


Figure 3.15 Twenty-five-year means of monthly sea level at Kodiak Island. Sea level has been corrected for atmospheric pressure (Ingraham et al., 1976).

3.3.4 Distribution of suspended matter

In the Lower Cook Inlet/Shelikof Strait region large horizontal variations in the concentration of total suspended matter exist which give some clue to mean circulation.

Gulf of Alaska water, flowing into Lower Cook Inlet around the Kenai Peninsula, has little suspended matter (0.5-5.0 mg/1). Water exiting Lower Cook Inlet on the western side has a high concentration of suspended matter (typically 5.0-200 mg/1). Much of this heavy suspended load is deposited in Kamishak Bay. However, water flowing past Cape Douglas has a higher concentration of suspended matter than the water farther to the north (Feely and Cline, 1977).

The distribution of total suspended matter near the bottom (Fig. 3.16) suggests a flow from Lower Cook Inlet towards the southwest along the western side of Shelikof Strait. The Gulf of Alaska water enters Lower Cook Inlet and then flows southwestward into Shelikof Strait or travels westward into Shelikof Strait along the northern coast of Afognak Island.

Data from other cruises (see Burbank, 1974) show slightly different distributions, but all show a continuity of suspended matter from Lower Cook Inlet into Shelikof Strait. The horizontal distribution of salinities indicates a circulation similar to that of the distribution of suspended matter (Feely and Cline, 1977).

Figure 3.16 Distribution of total suspended matter, 5 m above the bottom (Feely and Cline, 1977).

3.3.5 Circulation inferred from indirect observations

Along the outer continental shelf of Kodiak Island the flow is toward the southwest (see Fig. 3.17). The coastal influx of fresh water into the Gulf of Alaska supplies water of low salinity to the shelf. The resulting increase in dynamic heights found on the shelf (compared to those seaward of the shelf) contributes to the baroclinic flow, counterclockwise around the gulf. Surface fronts of temperature and salinity have been reported near the shelf break.

The dense packing of dynamic contours off the Kenai Peninsula suggests a large baroclinic coastal flow to the southwest. Much of this water probably passes through Kennedy Entrance and into Shelikof Strait. Also, a plume of low density water enters Shelikof Strait by Cape Douglas. The fact that no vestige of the plumes remains at the southwestern end of the strait indicates mixing. Unlike the flows along Kenai Peninsula and the shelf break, the flow through Shelikof Strait is largely barotropic.

Onshore bottom flows in the troughs leading to Kodiak Island are probable. There is also evidence of a bottom flow toward the northeast, into the lower end of Shelikof Strait.

Eddies which have been found on the continental shelf could play a significant role in determining the distribution of contaminants.

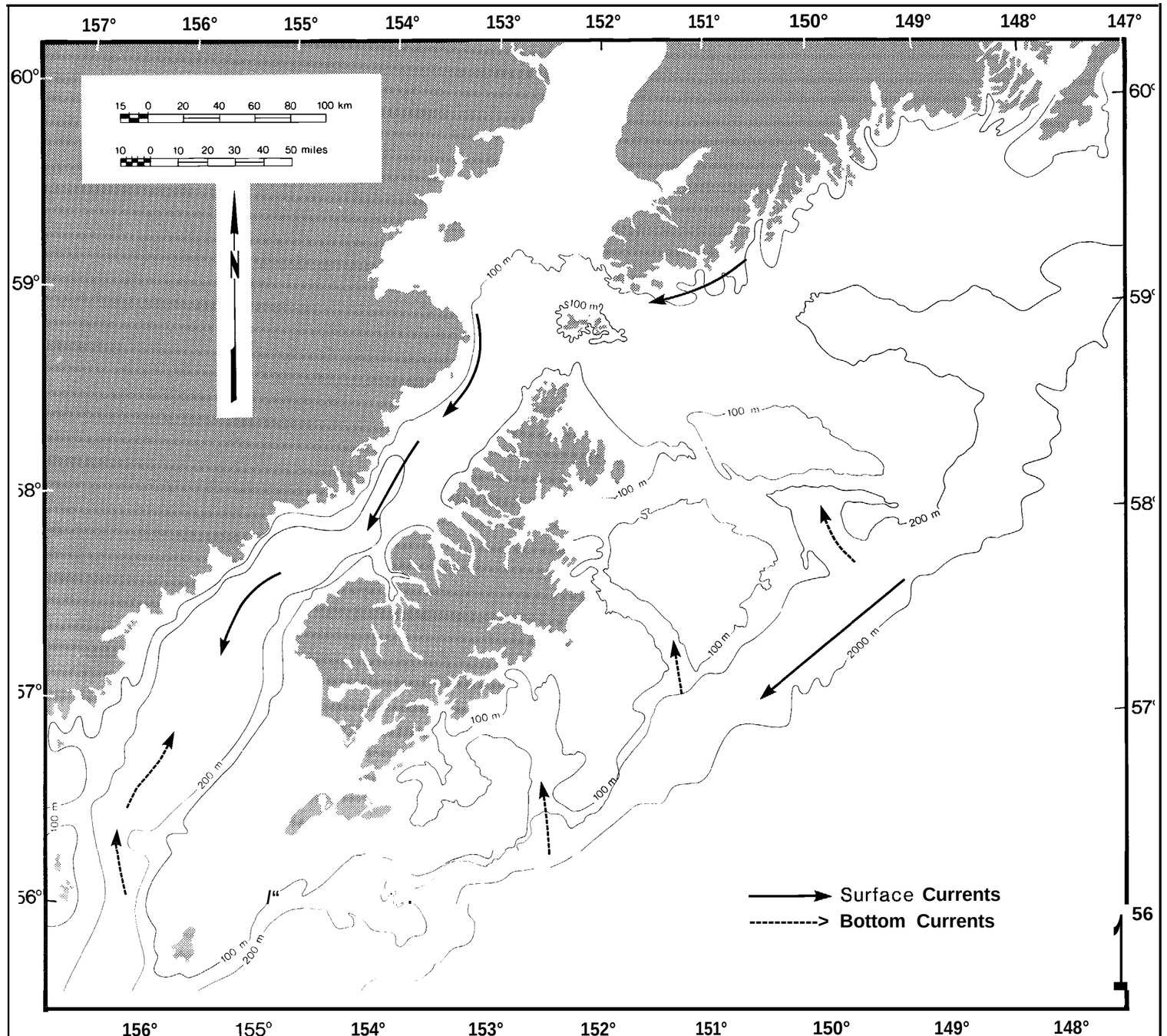


Figure 3.17 Circulation based on indirect evidence.

3.4 CIRCULATION DETERMINED BY DIRECT METHODS

3.4.1 Lagrangian methods

Lagrangian current-tracking devices are drogues or drifters advected by the current. A "parcel" of water can be tracked either by locating the device periodically or by recovering it if it makes a landfall. It is assumed that a pollutant released at the same location and time (and staying at the same vertical position as the drogue) will follow the trajectory of the drifter.

Determining the trajectories of pollutants floating on the ocean surface is difficult if not impossible. Expendable devices such as drift cards and drift bottles probably follow paths most similar to those a pollutant would follow, because they have little sail area exposed to the wind and they do not extend deep into the water column where currents may differ in speed and direction from those of the surface. However, drift bottles or cards give no information on trajectories; we know only the starting and ending locations. Trackable buoys give trajectories but are influenced by winds and non-surface currents. Their trajectories, however, imply circulation that is generally similar to circulation estimated by other methods.

Drift cards

About 4,500 drift cards were released in three batches (early March, late May, and early October, 1978) (Schumacher et al., 1979b). Approximately 3 percent have been reported.

The March drift cards were released at five sites northeast of Afognak Island and at eight sites (mainly in a straight line parallel to the bathymetry) east of Afognak and Kodiak Islands. Cards released northeast of Afognak were recovered mainly along the western coasts of Afognak and Kodiak Islands. The release site closest to the Kenai Peninsula produced the only recovery in Lower Cook Inlet (north of Cape Douglas). Apparently most of the cards were advected directly into Shelikof Strait and did not enter Lower Cook Inlet (hence the recoveries on the east side of the strait).

Cards released on the continental shelf east of Kodiak and Afognak Islands were advected to the southwest. Cards were recovered along the east shore of Kodiak Island. Several cards were recovered in the Bering Sea.

In May cards were released along a line extending south and east from the Kenai Peninsula. Although recoveries were concentrated densely in Kamishak Bay, those around Kodiak and Afognak Islands were widely distributed.

The pattern of recoveries is puzzling in that some cards released at offshore locations seem to have been advected to the west (into Lower Cook Inlet), while some cards released farther inshore landed on the eastern side of Kodiak Island.

Concurrent with, and shortly after, the release of drift cards in May, satellite-tracked drogues were deployed near the card release sites. All of the buoys moved toward the entrances to Lower Cook Inlet, and three (the one released nearest to shore and the two released farthest from shore) entered the inlet. After a month in Lower Cook Inlet, one of the buoys drifted through Shelikof Strait. Of the other two buoys, one malfunctioned and the other was advected southward along the Afognak and Kodiak Islands coast. (See the section on satellite-tracked drifters.)

Cards released near Kenai Peninsula in October were found mainly on the west coast of Kodiak Island. Those released over the central Kodiak shelf were recovered south of Sitkalidak Island.

The data show that material released on the water near the Kenai Peninsula probably will enter Lower Cook Inlet. Within the inlet landings can be anywhere but are most probable in Kamishak Bay. Material that beaches in Shelikof Strait will probably land on the west coastline of either Kodiak or Afognak Island. Releases made east or northeast of Kodiak Island could land in the embayments along the eastern side of Kodiak Island. They are less likely to land in the southeastern Bering Sea.

In drift card studies in Lower Cook Inlet by the Alaska Department of Fish and Game (Burbank, 1977), cards were released at several locations throughout Lower Cook Inlet; recoveries were common on either side of Shelikof Strait. Of two releases in Kennedy Entrance (in April and June 1976), most of the subsequent recoveries occurred in Kamishak Bay or Shelikof Strait, but a few cards apparently did not enter Lower Cook Inlet. One was recovered on Spruce Island just north of Kodiak Island and two were recovered on the northern shore of Afognak Island.

Cards released over Portlock Bank were recovered in Shelikof Strait and along the east side of Kodiak and Afognak Islands as well as in the straits between these two islands (Fig. 3.18). The latter recoveries were the first to be reported (about two weeks after release).

One drift-card experiment conducted in June 1976 yielded an unexpected recovery. Most of the cards released in Southern Lower Cook Inlet were recovered in Kamishak Bay and along the western side of Shelikof Strait. However, one card was recovered in Shearwater Bay, on eastern Kodiak Island. The trajectory of these cards is unknown.

Drift bottles

Drift bottles released by Thompson and C: eve 1936) east of Kodiak Island were recovered only along the south coast of Kodiak Island and along the Alaska Peninsula, north and west of Kodiak Island Ingraham, et al., 1976)

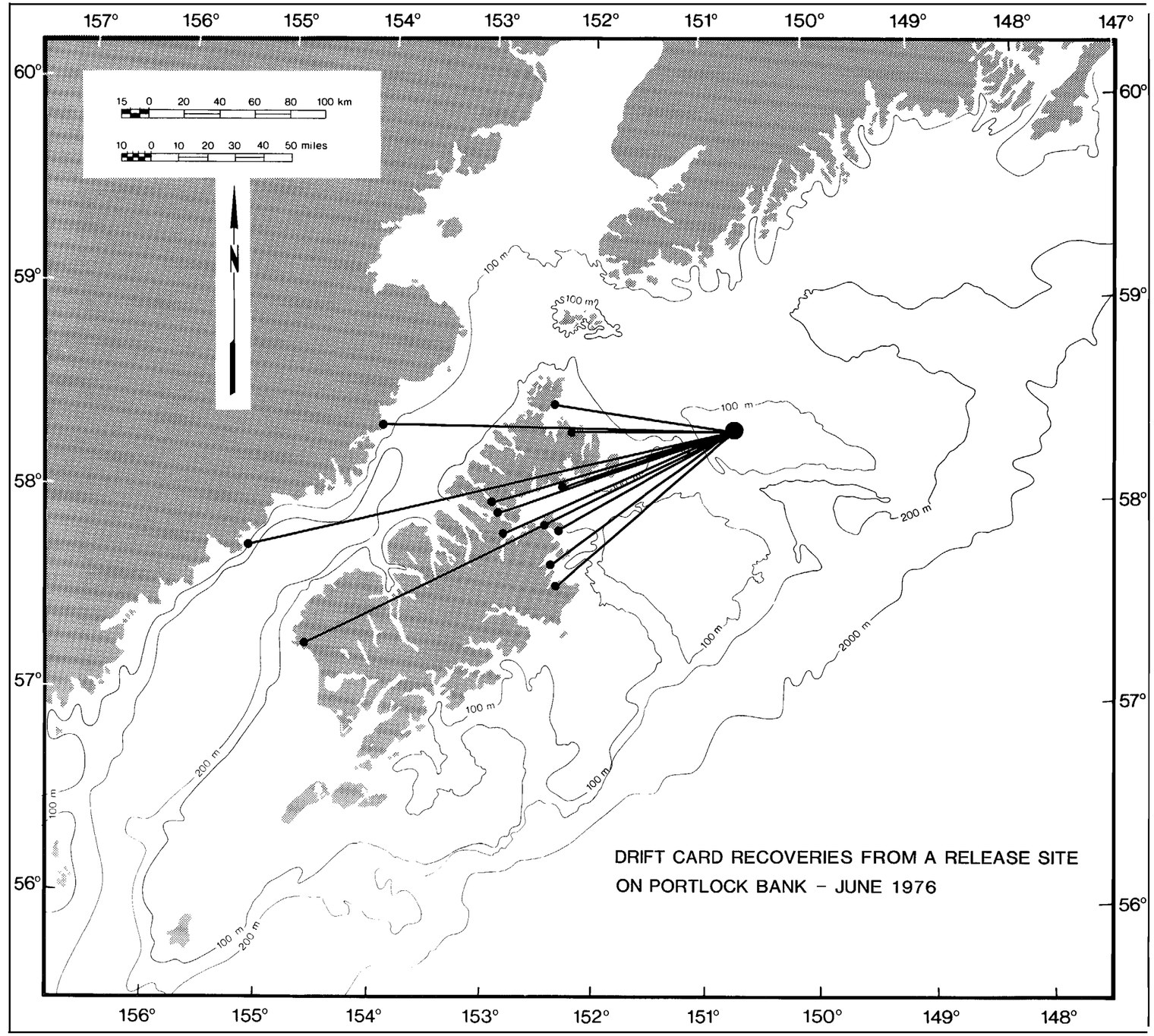


Figure 3.18 Drift card recoveries from a release on Portlock Bank, June 1976 (Burbank, 1977).

Se -bed drifters

Sea-bed drifters were released (Fig. 3.19) northeast of Kodia Island by Ingraham and Hastings (1974). Of the 475 released only 16 were recovered. Most of these had a net drift southwestward at a minimum average speed of 0.4 km/day. One drifter released over Portlock Bank moved nort tward On y those that were rel inshore of the shelf break were recovered. It is assum that the remainder were entra ned in the Alaska Stream and advected southwestward.

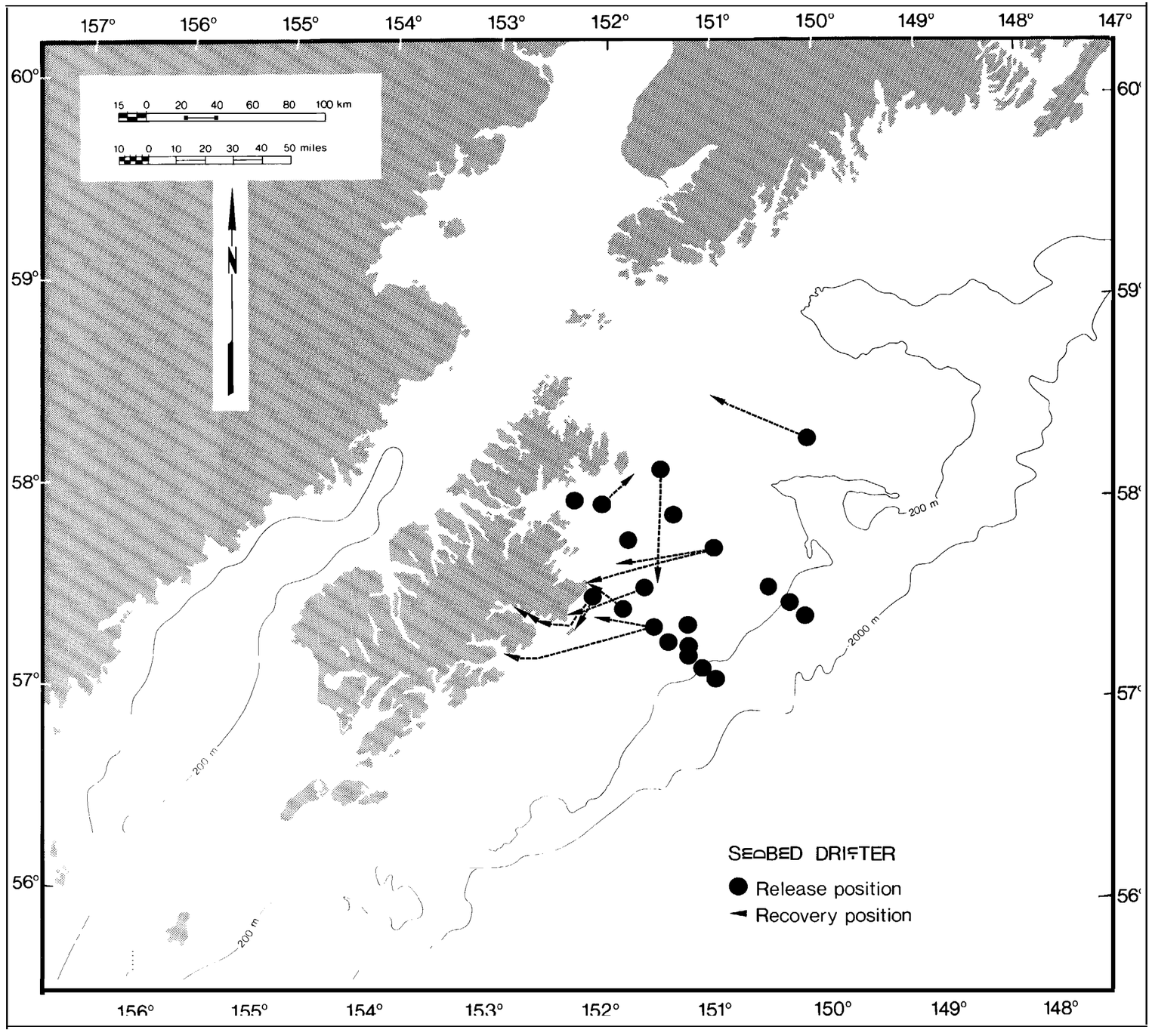


Figure 3.19 Sea-bed drifter release and recovery sites Ingraham and Hastings, 1974).

Another group of sea-bed drifters were released between November 1977 and November 1978 (Dunn et al., 1979a). Of the 3,536 drifters released, 33 were recovered (Fig. 3.20). Recoveries were generally made inshore and southwest of release points. The three recoveries of drifters released from Middle Albatross Bank were made in Kiliuda Trough. Three drifters recovered at the head of Chiniak Trough had been released at the seaward edge of that trough.

Recoveries were made in Kaiugnak Bay from releases just offshore. The data show a generally onshore flow in the troughs and a southwesterly flow over the banks.

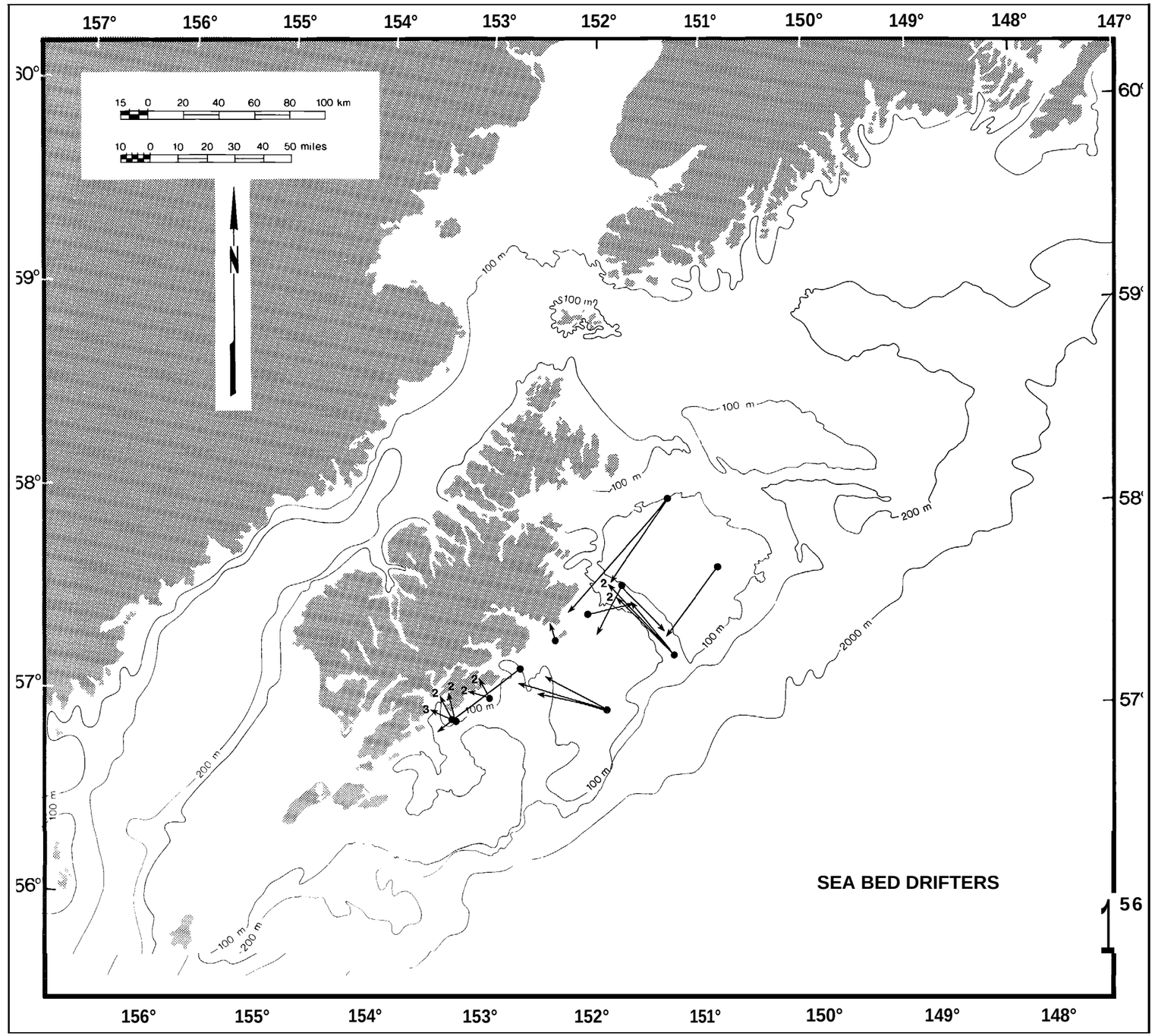


Figure 3.20 Sea-bed drifter release and recovery sites. Releases were made between November 1977 and November 1978 (Dunn et al., 1979a).

Satellite-tracked drifters

Hansen (1977) launched three satellite-tracked Lagrangian drifters northeast of Kodiak Island in October 1976. The drogues attached to the drifters were set at a depth of 30 m. The resulting trajectories are shown in Fig. 3.21.

The drifters were deployed in a line tending southwest from the Kenai Peninsula. The two drifters deployed on the continental shelf rotated counterclockwise, indicating the possibility of an eddy over Portlock Bank. The drogue deployed farthest offshore meandered generally southwestward.

Nine drifters were released in May and July 1978 (Hansen, 1978). A buoy released east of the southern end of the Kenai Peninsula went into Lower Cook Inlet through Kennedy Entrance (at an approximate speed of 20 km/day). Apparently it remained about two weeks in southern Lower Cook Inlet before entering Shelikof Strait, where it had an approximate speed of 16 km/day. It drifted eastward out of the strait. This trajectory supports the conceptual model of circulation in which Gulf of Alaska water enters Lower Cook Inlet and leaves via Shelikof Strait.

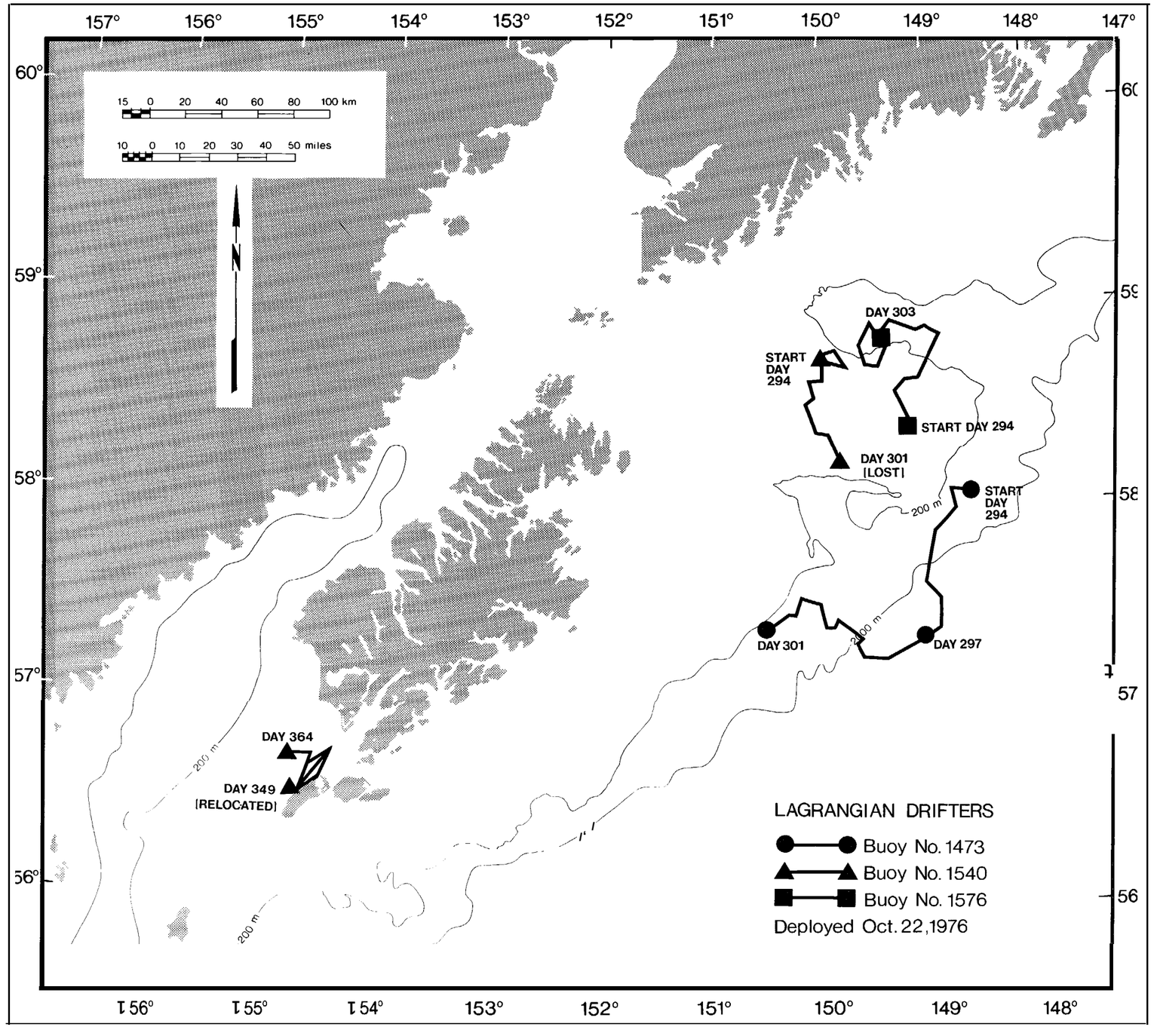


Figure 3.21 Trajectories of surface Lagrangian drifters (Hansen, 977).

Three other buoys also support this model. One launched due east of the Barren Islands on the 150th meridian functioned for only a week, but during that time it travelled almost due west, toward the entrances to Lower Cook Inlet. Its net speed was about 16 km/day. The other two buoys were launched near the 50th meridian but farther to the south (at about 58°30'N and 57°20'N). Both were advected into Lower Cook Inlet. The buoy released at the more northern site probably went through Kennedy Entrance and on into Lower Cook Inlet. The other buoy travelled (Fig. 3.22) through Stevenson Entrance towards Cape Douglas and went south, then east into the strait between Kodiak and Afognak Islands. The buoy travelled at a net speed of about 51 km/day, or roughly one knot.

The direction and speed of this last buoy seem remarkable. However, Fig. 3.9 sheds some insight on the trajectory. (The same day the buoy was aunched a hydrographic survey was begun.) The buoy launch site (approximately 57°20'N, 149°45'W) was on the left flank of a strong, anticyclonic eddy. The buoy was advected to the northwest, up Stevenson Trough and then into Stevenson Entrance. The buoy s initial trajectory corresponds to the inferred direction of flow of the 0/1000-db dynamic topography given in Reed et al. (1979). Unfortunately, since the hydrographic survey did not extend farther inshore no comparisons could be made with the later part of the trajectory.

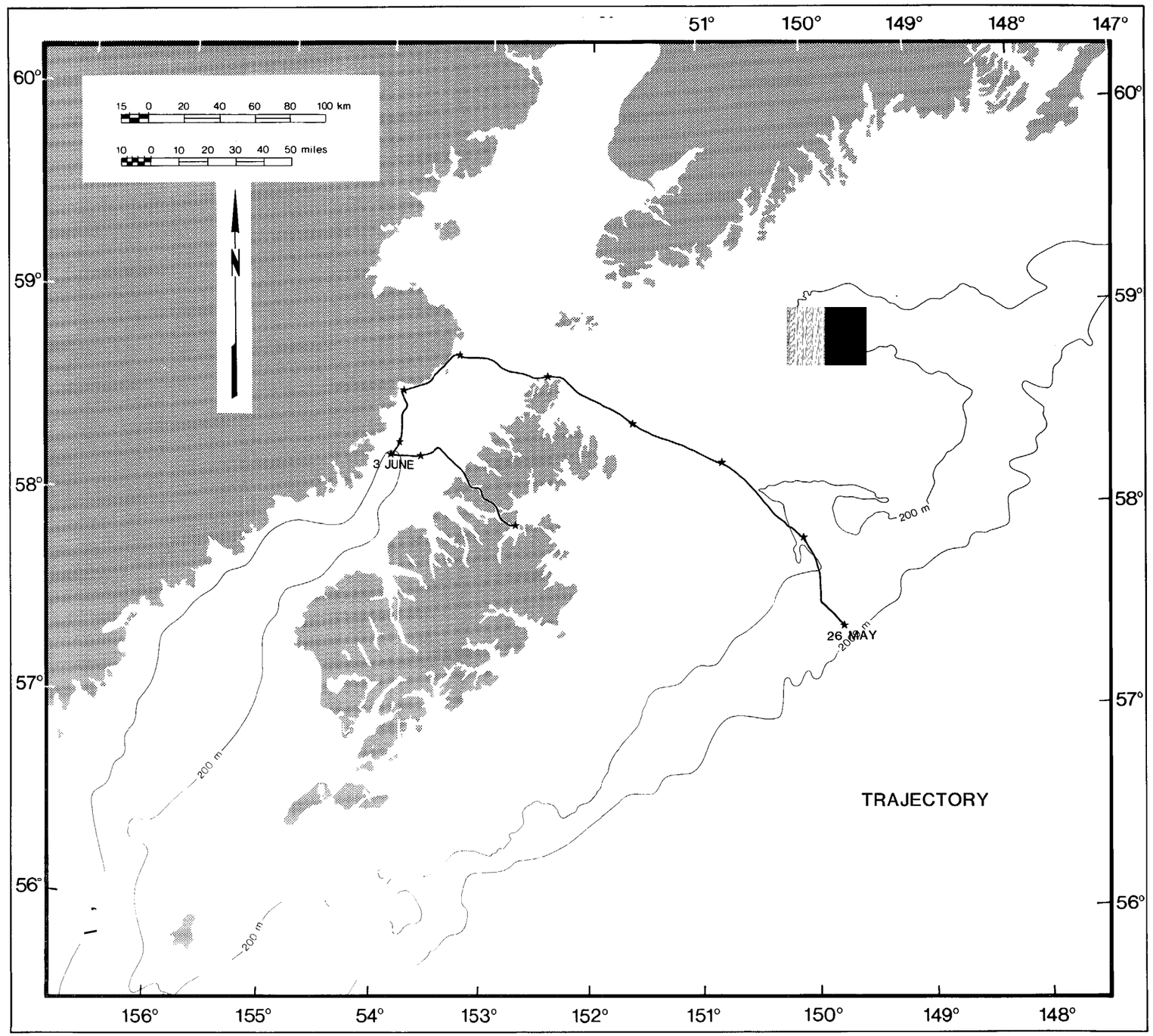
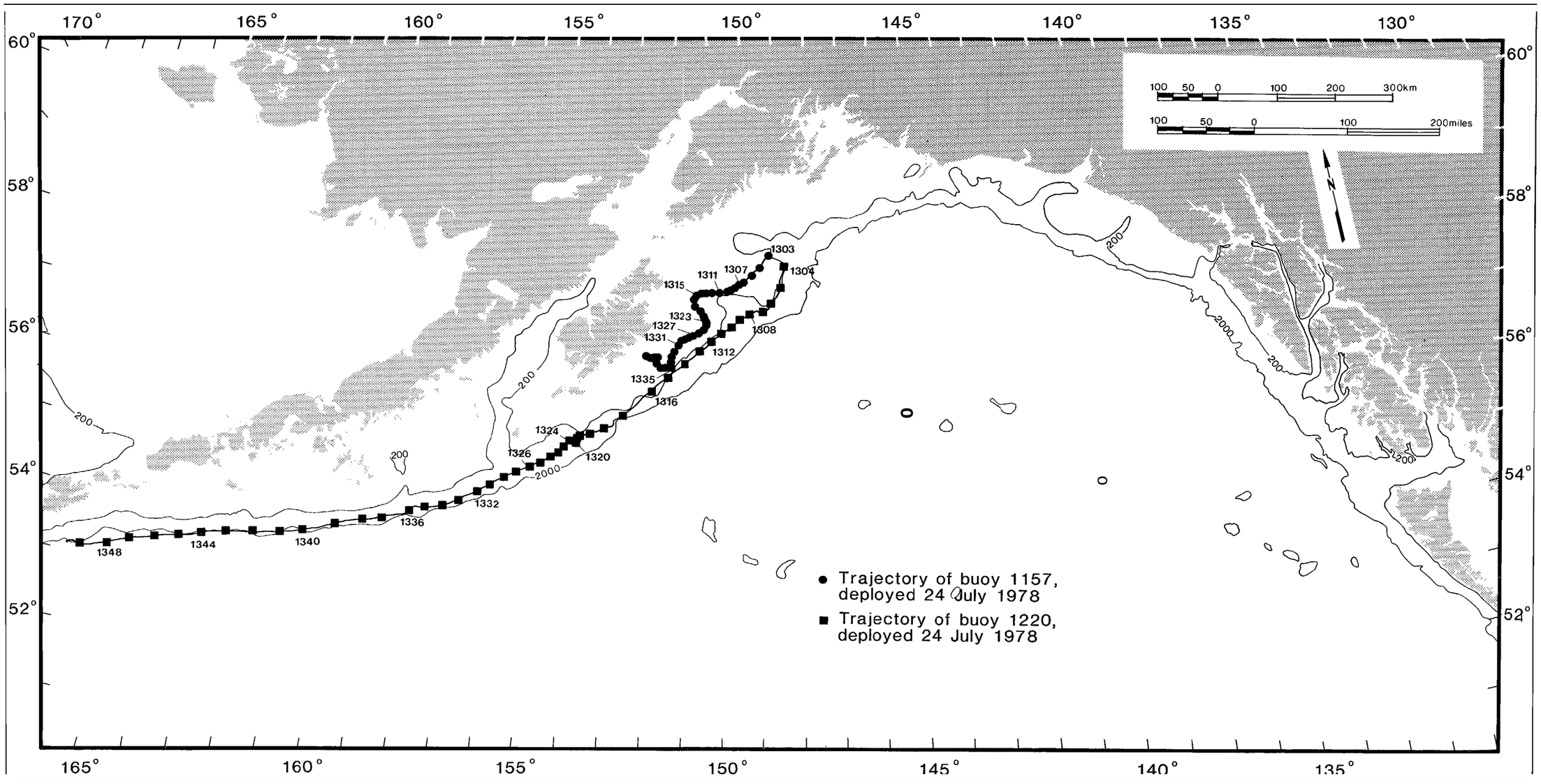


Figure 3.22 Trajectory of a satellite-tracked drifter buoy deployed on 26 May, 1978. Marks along the trajectory show the passage of a day (Hansen, 1978).

Two more buoys (Fig. 3.23) were deployed at nearly the same location but had different trajectories Both were deployed between 58 and 59°N on the 200-m isobath; one was on the 149th meridian and the second was farther to the east at about 148°30'W. The buoy released farther to the west was advected slowly (net speed of about 9 km/day) towards the southwest. Its trajectory undulated westward and eastward. The second buoy was more quickly advected southwestward on an almost straight path. While travelling next to Kodiak Island, this buoy had a net speed of almost 30 km/day.

The buoy released farther to the east probably was advected by a weak flow inshore of the Alaska Stream. The other buoy continued southwestward along the Aleutian Islands; its trajectory probably traces the flow at 30 m depth in the Alaska Stream.

Figure 3.23 Trajectories of two satellite-tracked drifter buoys (Hansen, 1978).



Summary

Many of the drifters released east or northeast of Afognak Island entered Lower Cook Inlet and Shelikof Strait. Those that did not were advected to the southwest. Drifters released in Lower Cook Inlet left the inlet along the western side and passed through Shelikof Strait. Some buoys on the continental shelf east of Kodiak Island had trajectories that imply the presence of eddies. Sea-bed drifters moved onshore, and up the troughs that lead to Kodiak Island.

3.4 2 Current meter data

Shelikof Strait

The mean flow through Shelikof Strait is parallel to the bathymetry (Figs. 3.24 and 3.25). Scatter diagrams for the low-pass filtered currents (Schumacher et al., 1978) show that the flow had relatively little scatter about its southwesterly mean, especially at the K2A mooring. There is little shear between the shallow (20-m) currents and the deep (100-m) currents except at mooring C10. Weak reversals did occur, but only infrequently.

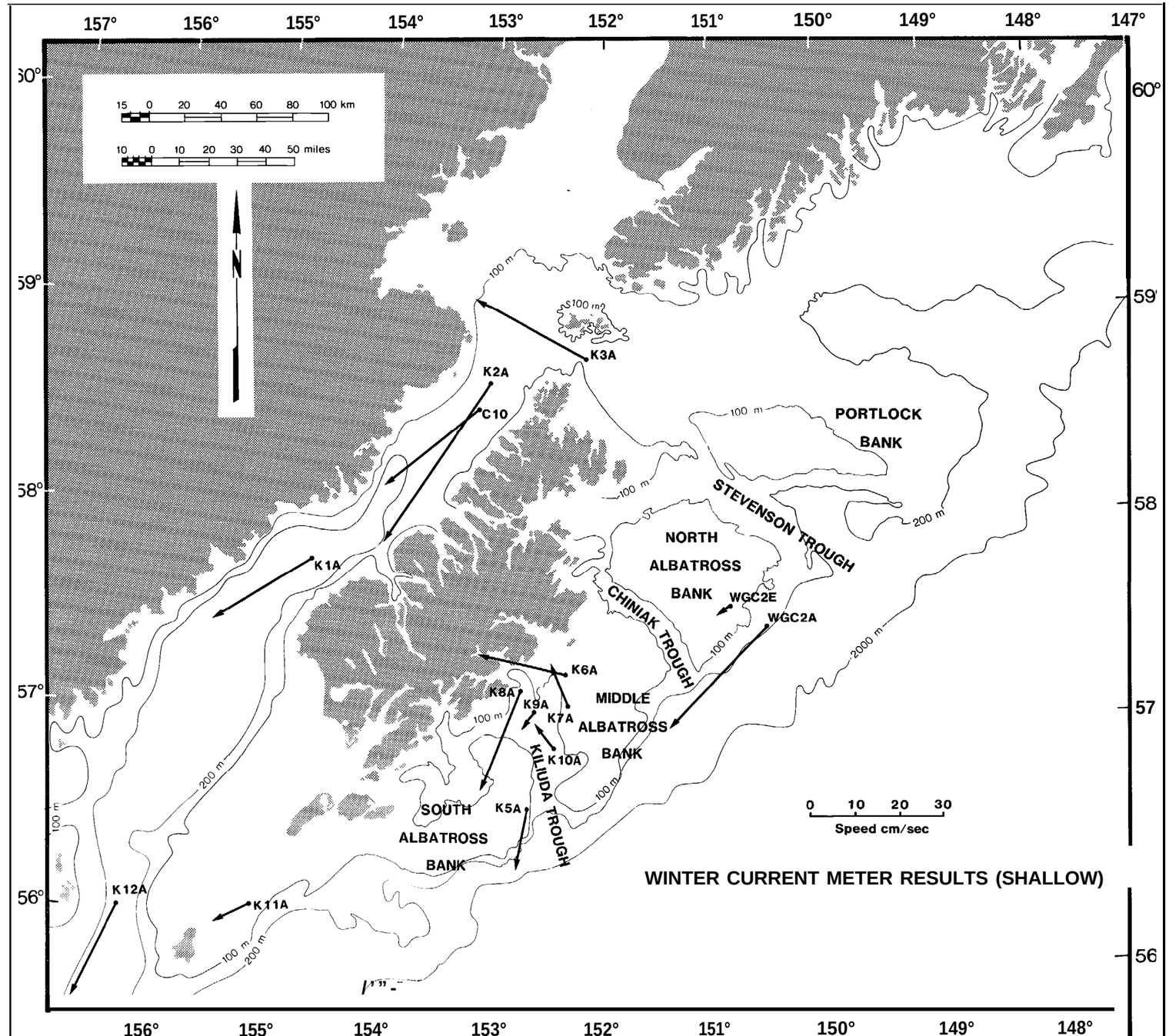


Figure 3.24 Mean currents from current meters moored at shallow depths in winter. The data are from different sampling periods (Schumacher et al., 1978 and 1979b).

The mean currents in Shelikof Strait (approximately 30-40 cm/sec) are faster than the net speed of the satellite-tracked drifter (about 19 cm/sec). However, the period when the current meters were in use (mid-October 1976 to late March 1977) coincides with the seasonal increase in sea level (see section 3.33 and Fig 3.15). Thus the higher mean speed is expected. Also, since the drifter did not travel in a straight line, the computed net speed is less than the average speed of its movements.

The lack of vertical shear in the current meter records suggests that the mean flow is largely barotropic. Schumacher et al. (1978) calculated the surface baroclinic component of flow relative to 150 db. At the northeast end of Shelikof Strait the calculated flow was about 5 cm/sec toward the northeast. This flow was opposite in direction to the mean flow and was a fraction of the obs speed. At the southwest end, the 0/250 db flow was 10 cm/sec toward the southwest. This was much less than the long-term mean (roughly 27 cm/sec) at mooring K1. Thus the flow through Shelikof Strait is largely barotropic.

Schumacher et al. (1978) discount wind forcing as the dominant driving force for the waters in Shelikof Strait. They suggest that the most important forcing mechanism is a longitudinal pressure gradient established by the coastal flow through Stevenson and Kennedy Entrances

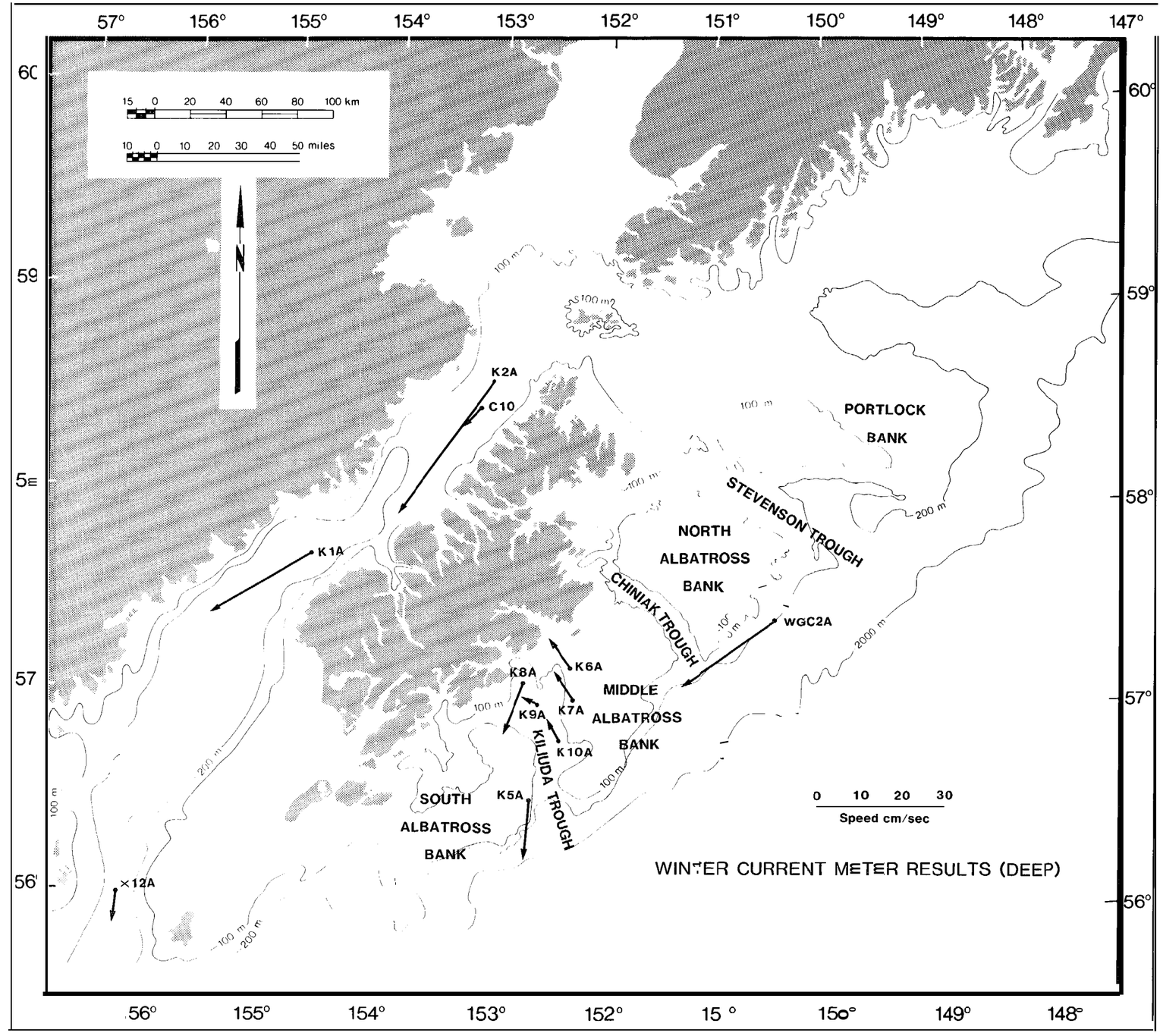


Figure 3.25 Mean currents from current meters moored in deep water in winter. The data are not from simultaneous periods (Schumacher et al., 1978 and 1979b).

Stevenson Entrance

A 37-day record (28 October to 15 November 1976) of 20-m deep currents was obtained in Stevenson Entrance. The mean velocity of these currents was 30 cm/see, towards the northwest. The maximum speed recorded was about 70 cm/sec. Weak currents to the southeast were observed for a few days at mooring K3A. During the same period, currents at mooring K2A were very weak also (Schumacher et al., 1978).

The baroclinic geostrophic current component in Stevenson and Kennedy Entrances for March 1977 was calculated by Schumacher et al. (1978). For Stevenson Entrance a speed of 15 cm/sec (0/116 db) towards the northwest was calculated. The mean current at Mooring K3A had twice that speed (the sampling periods do not overlap, however). The calculated surface speed through Kennedy Entrance was 11 cm/sec using a 116 db reference level.

Current meter data in Stevenson Entrance and Shelikof Strait strongly suggest that flows in these areas are closely coupled. Lagrangian current records (Fig. 3.22) support this hypothesis.

Northern continental shelf

Currents on North Albatross Bank measured at mooring WGC-2E were weak (see Figs. 3.24 and 3.25). During October and November 1977 they were mainly southwesterly with speeds of approximately 15 cm/sec. In February, however, the direction was variable; flow reversals (from the mean direction) which usually lasted two to three days occurred several times. Currents with maximum speeds (about 30 cm/see) were oriented parallel to the local bathymetry.

The weak mean currents on North Albatross Bank contrast with the strong means at mooring WGC-2A. The mean speed of near-surface currents at WGC-2A was over 30 cm/sec and that for deeper currents was about 25 cm/sec.

The currents at two moorings (WGC-2C and WGC-2D, not shown) about 15 km apart were compared. The positions of these moorings correspond to those of WGC-2E and WGC-2A. The mean speed of each of the near-surface currents (at WGC-2C and WGC-2D) is approximately 30 cm/sec. However, the net drifts are quite different: 3 cm/sec on North Albatross Bank (WGC-2C) and 22 cm/sec on the shelf seaward of the bank (WGC-2D). (Net drift is the vector average of currents and represents the mean motion along a straight line between the start and finish points of a progressive vector diagram. Mean speed is the scalar average, regardless of the direction of flow.) Thus the mean flow at the shelf break was less variable in direction than that on the bank.

The contribution to the variance for each of the current records was analyzed. The total variance of the current record on North Albatross Bank (WGC-2C) was more than twice (1412 cm^2/sec^2) that of the shelf break record (604 cm^2/sec^2) but the net drift at the shelf break was more than seven times that on the bank (Hayes and Schumacher, 1977). This difference is caused by the much higher level of high-frequency (every 6 to 25 hours) variance on the bank (1400 cm^2/sec^2) than at the shelf break (140 cm^2/sec^2). This high-frequency variance contributes 91 percent of the total variance on the bank but only 67 percent at the shelf break.

Tides are the dominant driving force in the high-frequency part of the current variation. Thus, we can assume that tidal energy concentrated on the relatively shallow bank is responsible for the high level of variance there compared to that of the shelf break. Tidal energy also accounts for the mixing of waters over the banks in contrast to the more stratified water in the deeper troughs.

Kiliuda Trough

Between October 1977 and March 1978 Schumacher et al. (1979b) investigated processes affecting circulation over a bank-trough environment. Five moorings (K6A through K10A) were placed on Middle Albatross Bank and in Kiliuda Trough.

Current meters had been placed at mooring K5A at 20 m and 80 m during an earlier experiment (October 1976 to March 1977). Currents at both meters were predominantly aligned with the bathymetry. The mean flow was seaward. However, fluctuations in the current record suggest that wind-induced flow reversals or shifts in boundaries of currents did occur. Such changes in the currents could carry water of high salinity (> 32.5 g/kg) from the shelf into Kiliuda Trough (see Fig. 3.8) (Schumacher et al., 1978).

At the moorings on Middle Albatross Bank (K6A and K7A) the flow was generally onshore with typical speeds of 10 cm/sec. However, the near-surface currents at K6A were divided about equally between onshore and alongshore flow. The four current meter records from the bank area are similar but those from moorings over the trough differ substantially. Mean directions and speed also differ greatly among current meters at these three moorings.

Tidal variance was higher (by a factor of 3 to 4) on the banks than in the troughs and contributed a larger percentage of the total variance (50-60 percent of the total) than that in the troughs (20-40 percent). Subtidal variances were similar in both environments although total variances were about twice as large on the bank as in the trough. Thus, tidal forces are

responsible for the higher energy levels on Middle Albatross Bank. This is further evidence that the water column over banks is mixed more thoroughly than that of troughs and that the energy source for this mixing is the tides.

Southwestern continental shelf

The flow at mooring K12a appears to be a continuation of the Shelikof Strait flow. The trajectory of buoy 1775 (Fig. 2 in Hansen, 1978) provides further evidence for this hypothesis. The buoy followed a path parallel to the bathymetry through Shelikof Strait and out into the Kodiak Island Continental Shelf. The vertical shear in the mean currents was much larger at K12A than at the moorings in Shelikof Strait. The presence of water of high salinity in southwestern Shelikof Strait (see Fig. 3.13) has led to the theory that a northeasterly flow might occur along the bottom. High-salinity water was not found in the northeastern salinity sampling and the only other source would be water from seaward of the continental shelf. Deep water could be entrained by the high-speed flow out of Shelikof Strait, thus causing a shoreward replacement flow.

3.5 SIMULATIONS OF CURRENTS

3.5.1 Diagnostic models

Galt (1977) employed a steady-state diagnostic model to simulate the circulation of the Kodiak Island/Shelikof Strait region. The model was described by Galt (1975, 1978). It is a linear combination of geostrophic and Ekman dynamics and includes the effects of bathymetric variations and bottom friction. Geostrophic currents are composed of barotropic and baroclinic components. The barotropic component is generated by calculating the wind-driven sea surface set-up. A bathystrophic balance is assumed in which the cross-shelf sea surface slope is considered to be proportional to the alongshore component of wind stress. It is assumed that the barotropic component instantaneously responds to wind forcing on a time scale which is short compared with the period of baroclinic adjustment. The baroclinic component is computed from available hydrographic data. Frictional Ekman boundary layers at the surface and at the bottom are determined from observed surface winds and bottom geostrophic flow, respectively. The model can, in principle, simulate circulation at any depth in the water column. To date, however, simulations have been made only for surface and bottom currents.

Since the wind-driven flow is represented by classical Ekman dynamics, the model is restricted to water depths that exceed the local Ekman depth. Additional restrictions are that shelf waves are not included and that high-frequency motions (time scales shorter than the geostrophic adjustment period) are not represented. The importance of shelf waves in the Kodiak Island region has not been assessed; however, the rugged bathymetry suggests that shelf waves are probably scattered by the bathymetry and are not important. Verification of the simulated currents by comparison with actual field observations has not yet been accomplished.

The two simulations reported here (Figs. 3.26 and 3.27) depict the surface and the bottom currents under the influence of a wind stress of 1 dyne/cm^2 (which corresponds to a windspeed of approximately 7 m/sec) from the northeast. Several interesting features of these simulations were noted by Galt (1977). Along the edge of the continental shelf, flow is dominated by the Alaska Stream. The stream appears to intensify toward the southwest and it broadens southwest of the Trinity Islands, possibly because of the bathymetry upstream of the islands. The dynamic topography for April 1976 (see Royer, 1977) also suggests an intensification of the flow in this region.

The deep channels that cross the shelf tend to have onshore flow when winds are blowing toward the southwest. When the winds are toward the northeast, no flow through the channels is observed.

Between Cape Trinity and Dangerous Cape the well-developed coastal current approaches speeds of two knots when there are strong winds to the southwest. With winds toward the northeast, the coastal flow is

reversed. The strongest flow (about half a knot) occurs off Dangerous Cape, apparently in association with the channel across Albatross Bank.

Weak counterclockwise eddies appear both northeast and southwest of Kodiak Island. A third, weak counterclockwise eddy may exist between the nearshore and offshore southwesterly flow. Dynamic topographies indicate weak flows in these locations. Eddies can also be inferred from dynamic topographies and Lagrangian current data (e.g., Fig. 3.21).

The simulated flow in Shelikof Strait is toward the southwest, but it has current reversals and components that cross bathymetric contours. In addition, bottom currents flow eastward through Stevenson Entrance (Fig.3.27); in Fig. 3.26 the direction of surface flow through this entrance is not clear.

Cross-sections of hydrographic data (Fig. 3.13) do not indicate a baroclinic current reversal. Furthermore, current meter observations (Schumacher et al., 1978) indicate that the currents in Shelikof Strait are aligned with the axis of the strait and have few reversals. The current vector that is oriented toward the southeast (south of Kodiak Island) has not been corroborated by observational evidence. It and the flow reversal in Shelikof Strait indicated by an arrow probably are caused by boundary effects.

The simulated bottom currents (Fig. 3.27) are similar to the surface currents, but weaker. The direction of the bottom currents is oriented (across the local bathymetry) so that the flow compensates for

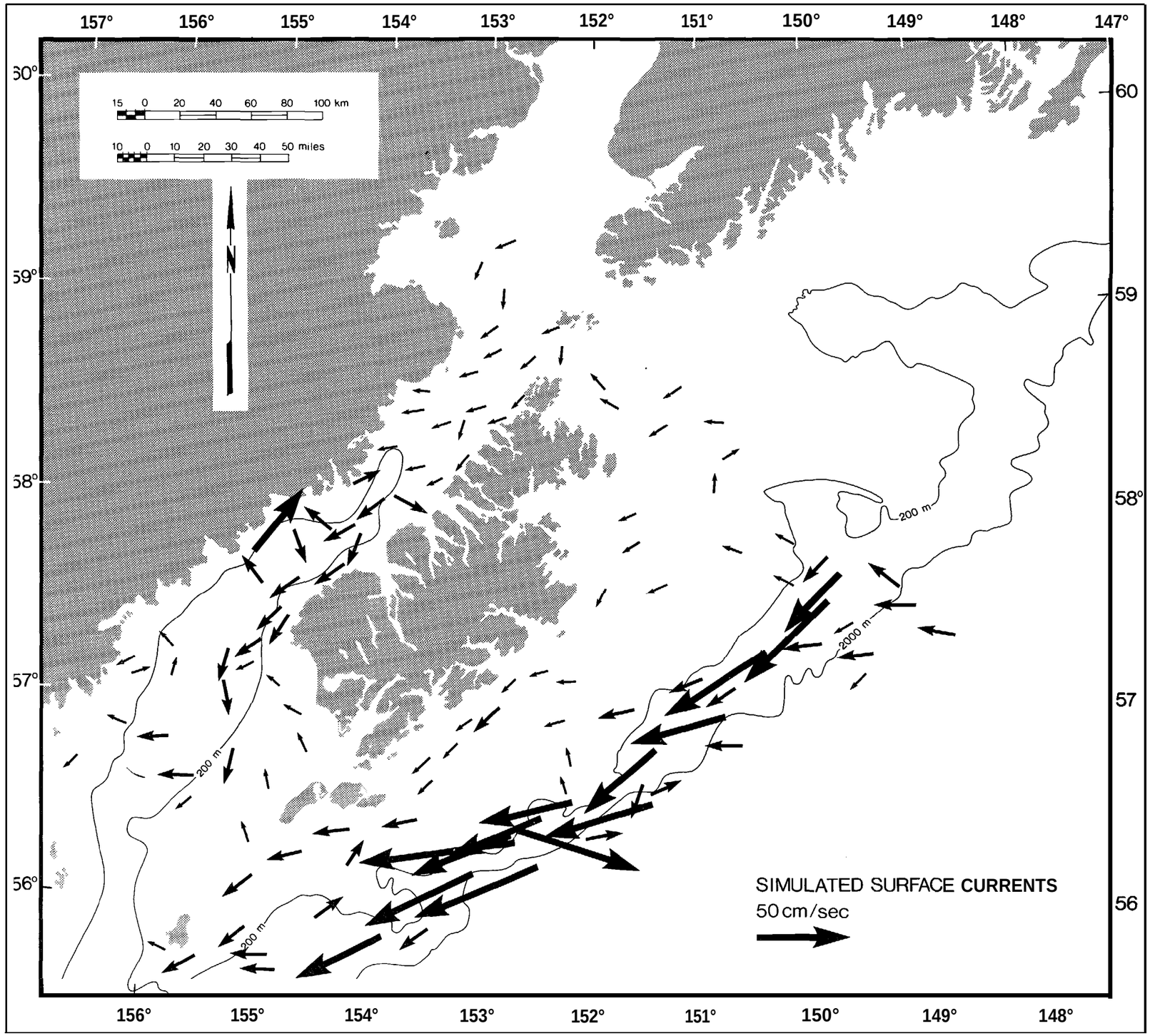


Figure 3.26 Computed surface current field from a diagnostic model using data from spring, 1976. Surface wind stress is 1 dy/cm^2 from the northeast (Gait, 1977).

the surface Ekman flow. No reversals are seen in the bottom currents except south of Portlock Bank.

The results of the simu.ation agree qualitatively with the field observations on which the model is based and with current-meter results (Figs. 3.24 and 3.25). Simulations using winds toward the southwest have currents in Kiliuda Trough similar to the mean currents shown in Figs. 3.24 and 3.25. When winds from the southwest are used, the current flow in Kiliuda Trough reverses (see Figs. 4 and 8 in Galt, .977).

Harding (1976) calculated tidal heights and associated currents for a two-layer region extending from eastern Kodiak Island to Unimak Pass. Wind forcing, in addition to tidal forcing, was simulated in some cases. An interesting result of the simulations with no wind stress is an apparent convergence zone in the southwestern region of Shelikof Strait. Such a convergence zone is suggested by drift bottle data reported by Ingraham et al. (.976)

3.5.2 Oil spill risk analysis trajectory simulation

The USGS used a model to determine the risks of oil insulting the Kodiak Is.and coastline from releases within proposed lease areas and along two transportation corridors (Slack et al., 1977). The objectives were to determine the probabi.ity of a spi l, to determine likely trajectories for spilled oil, and to determine the location of vulnerable resources. This study was recently updated by USGS (Lanfear, pers. ( ). Results probably will be available in 1980.

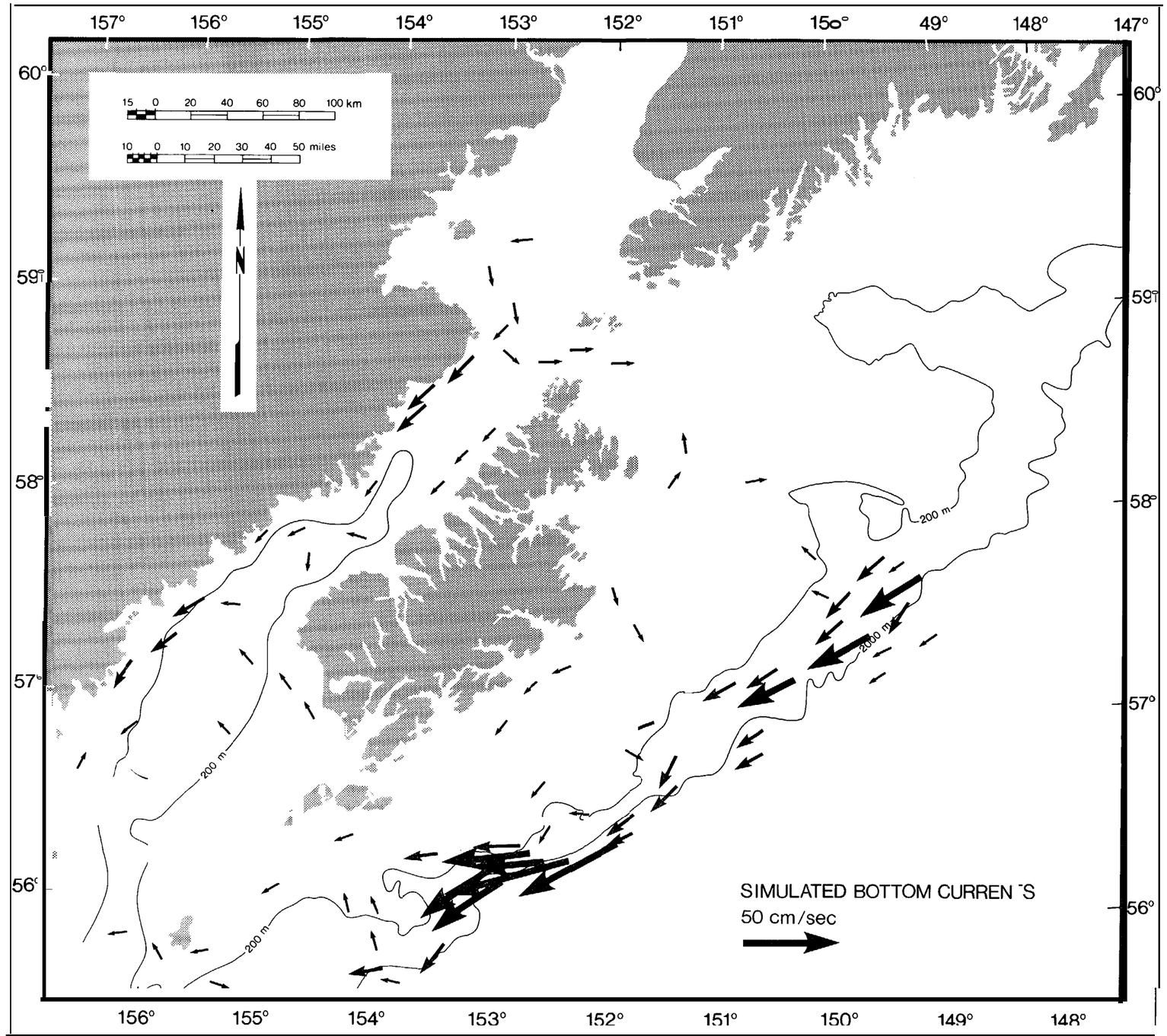


Figure 3.27 Computed bottom current field from a diagnostic model using data from spring, 1976. Surface wind stress is 1 dy/cm^2 from the northeast (Galt, 1977).

3.6 CIRCULATION SUMMARY

All the available data have been used to summarize the surface circulation around Kodiak Island (Fig. 3.29). This summary is based, in part, on preliminary analyses of data and unverified results of numerical models and thus is speculative.

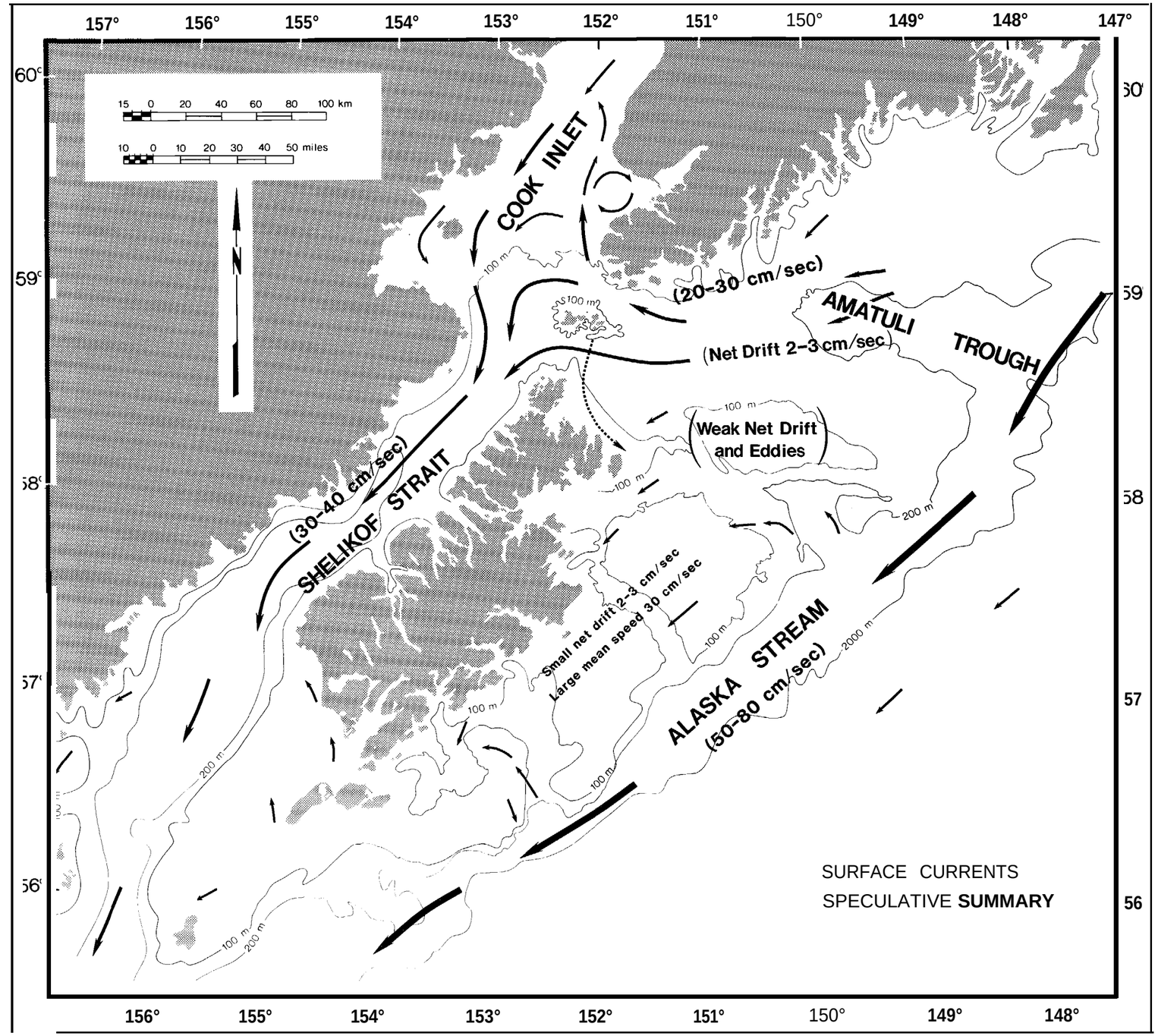


Figure 3.28 Speculative summary of surface currents based on all available information.

Source waters

The general circulation in the Gulf of Alaska is a counterclockwise gyre. Thus the water in the Kodiak Island lease area comes largely from shelf areas lying to the northeast. In the eastern Gulf of Alaska the Alaska Current overlies the shelf break and is separated from the (nearshore) coastal current. Kayak Island deflects the coastal current seaward, and it continues towards the west along with the Alaska Current. Middleton Island shoals direct the Alaska Current farther seaward. The Alaska Stream lies just seaward of the shelf break off Kodiak Island. In the northwestern Gulf of Alaska a coastal current generated by the influx of local fresh water, especially from the Copper River, flows along Kenai Peninsula into Lower Cook Inlet.

A band of warm water of low salinity extends throughout the western Gulf of Alaska. The temperature signal has been tracked as far east as Kayak Island. Off Kodiak Island this band is found along the shelf break. The low-salinity band has not been found in samples taken in late summer and autumn, probably because of sampling problems.

The Alaska Current appears to bifurcate near Amatuli Trough (Schumacher et al., 1978). One part of the flow moves up the trough toward the Barren Islands while the second continues toward the southwest along the shelf break.

Meteorological influence

It is to be expected that meteorological conditions, and especially winds, would play a dominant role in determining the circulation. These conditions are controlled seasonally by the migration of the Aleutian Low and the North Pacific High. Winds off Kodiak Island are generally from the northwest quadrant during winter (October-April) and from the southwest quadrant in summer (May-September). Unfortunately, we do not know how these conditions affect circulation.

Undoubtedly, the strong seasonal variation in the influx of coastal fresh water (due to precipitation and runoff from snow melt) influences the circulation. It has been shown that the influx of fresh water east of Kodiak Island is a major driving force for coastal circulation in the Gulf of Alaska (Royer, 1979). Whether fresh water added along Kodiak Island or the adjacent Alaska Peninsula is important to circulation is not known.

Although the curl of the wind stress over the Gulf of Alaska varies seasonally by an order of magnitude, no corresponding seasonal change in the baroclinic transport of the Alaska Stream is evident. The lack of response of the Alaska Stream could be an inability to adjust baroclinically to a seasonal time scale. Seasonal changes in coastal sea level elevations do occur, however.

The baroclinic transport around Kenai Peninsula can change dramatically from month to month. In one instance a combination of winds and the influx of fresh water appeared to be responsible for a doubling of the transport. Two episodes of strong winds favoring convergence kept waters of low salinity and low density near the Kenai Peninsula, thus increasing the baroclinic component of geostrophic flow. The net speed of the Kenai Peninsula current is typically 10-20 cm/sec. Peak speeds can be greater than 100 cm/sec (Schumacher, 1979, pers. comm.).

On a smaller scale, it has been shown that winds measured on Kodiak Island are not representative of winds over the continental shelf. Orographic and diurnal effects contaminate the Kodiak Island measurements. The difference between winds measured onshore and those measured offshore illustrates the need for measurements of atmospheric parameters over the shelf.

Kenai Peninsula coastal current

The coastal current lies inshore, close to the Kenai Peninsula. Most dynamic topographies in this shallow water depict the baroclinic geostrophic current as flowing around the peninsula and into Lower Cook Inlet. Low surface salinities (as low as 28 g/kg) and large relative dynamic heights are found adjacent to the coast. Thus, there appears to be a contribution of fresh water to this flow. This fresh water originates in coastal streams and rivers along the peninsula and as far east as the Copper River. In general, surface contaminants near Kenai Peninsula (probably within 100 to 200 km of the peninsula) may be expected to enter Lower Cook Inlet. Once in Lower Cook Inlet, they are most likely to beach in Kamishak Bay. (They could, however, be widely dispersed and land almost anywhere in Lower Cook Inlet or along either side of Shelikof Strait. See Burbank (1977) for drift card results in Lower Cook Inlet.)

Water leaves Lower Cook Inlet on the western side and enters Shelikof Strait. There it mixes with Gulf of Alaska water entering directly into the strait, probably via Stevenson Entrance. Although the water from Lower Cook Inlet has low salinity adjacent to the coast, traces of it are obliterated by tidal mixing. The Lower Cook water also carries a high concentration of suspended matter.

The transport of the coastal current adjacent to Kenai Peninsula varies with the contribution of fresh water and with winds. Winds from the northeast tend to cause coastal convergence that augments the geostrophic flow. An increased influx of fresh water also probably augments this flow.

Although the conceptual model of circulation shows the coastal current flowing into Lower Cook Inlet and Shelikof Strait, it sometimes actually flows toward the southwest instead, across the entrances to Lower Cook Inlet. In these instances the low-density water accumulates over Stevenson Trough, possibly blocked from entering the shelf by the Alaska Stream. An anticyclonic gyre can form here over a period of about two months. These gyres have high velocities and greatly affect the direction and speed of surface contaminants. Instead of having relatively weak net currents, the area east and north of Afognak Island develops fairly intense currents that could draw surface contaminants from the area into Lower Cook Inlet or Shelikof Strait.

Shelikof Strait

Water in Shelikof Strait comes either from the Gulf of Alaska, via Stevenson Entrance or Kennedy Entrance and Lower Cook Inlet, or from fresh-water sources in Upper and Lower Cook Inlet. Water from the Gulf of Alaska is of relatively high salinity and has low levels of suspended matter, while water from Lower Cook Inlet has been diluted with fresh water that has high loads of suspended matter.

The baroclinic component of flow in Shelikof Strait appears to be small compared to the barotropic component. The dominant force appears to be an alongshore pressure gradient between Kennedy and Stevenson Entrances and the southwestern end of Shelikof Strait. This force can ultimately be attributed to the wind patterns that dominate the Gulf of Alaska. Forcing by local winds also may be important in augmenting or retarding the southwesterly flow. Flow reversals in Shekilof Strait occur rarely, if at all. However, an inflow of water of high salinity along the bottom of the southwestern end of Shelikof Strait is apparent.

Water leaves Shelikof Strait at the southwest end. Mean currents (Fig. 3.24) tend to follow the bathymetry. The presence of water of high salinity (> 32.5 g/kg) near the southwestern end suggests that shelf water enters the strait from this end along the bottom. If this occurs it is probably the result of episodic flows along the bottom rather than a mean near-bottom flow into the strait (see Fig. 3.25).

Alaska Stream

The Alaska Current appears to intensify as it becomes a western boundary current (the Alaska Stream) in the western Gulf of Alaska. The Alaska Stream lies just seaward of the shelf break off Kodiak Island. As indicated by the position of the surface salinity front, the Alaska Stream can move laterally 3-5 km in about 10 hours. It has baroclinic geostrophic currents estimated at 50-80 cm/sec.

The mean baroclinic transport of the Alaska Stream is estimated to be about 12×10^6 m^3/sec (with a standard deviation of about 2×10^6 m^3/see), relative to 1500 db. Large variations from this mean do occur; the maximum estimate for transport is about 17×10^6 m^3/see and the minimum is 8×10^6 m^3/sec. The variations in baroclinic transport do not appear to be seasonal, which is surprising. The barotropic component of the Alaska Stream probably does have a seasonal signal, the result of the seasonal wind pattern.

Kodiak Island shelf

The net alongshore flow on the Kodiak Island shelf is small. However mean speeds (a scalar description of currents as opposed to a vector description) can be substantial (30 cm/see).

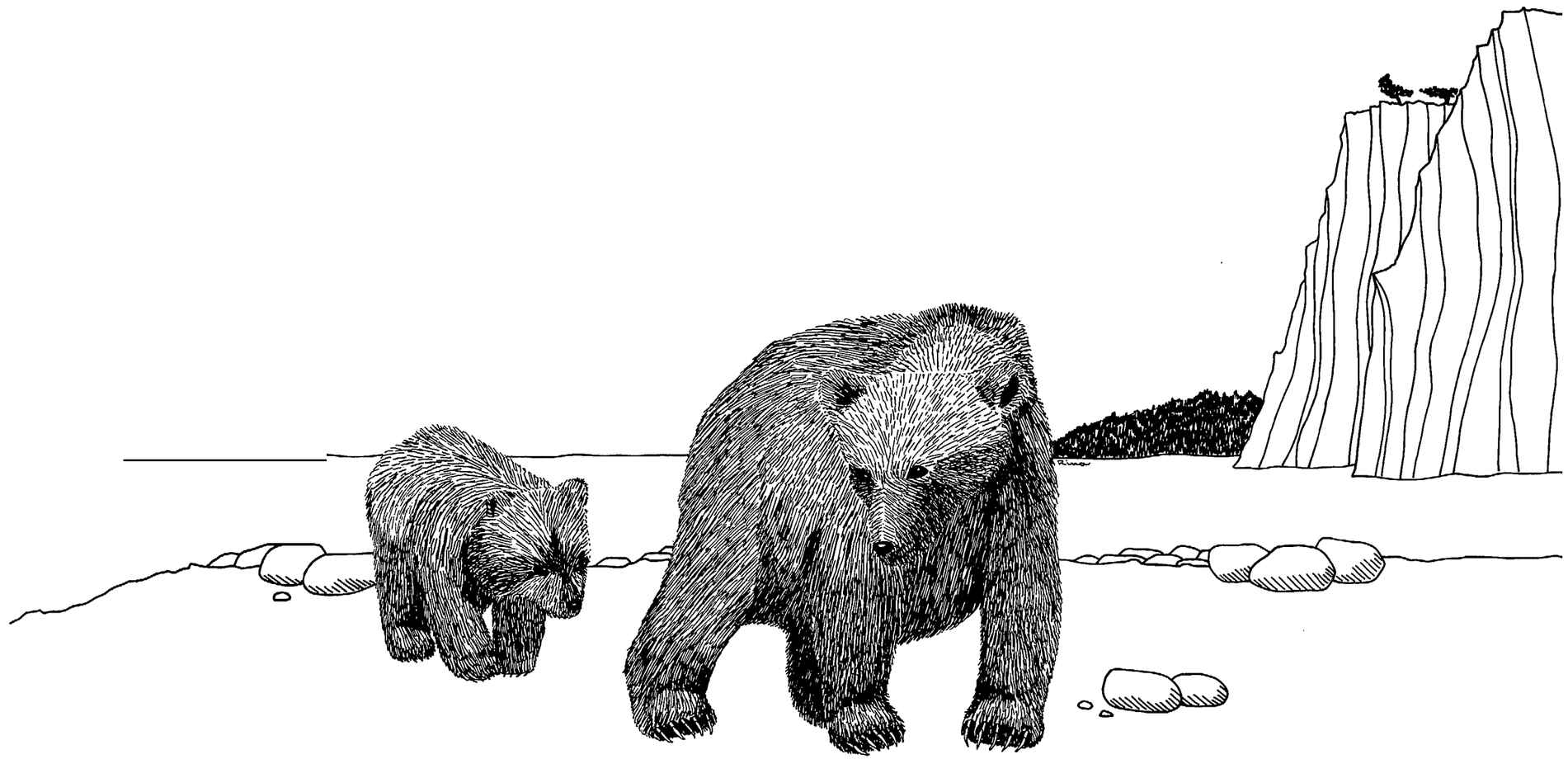
The bathymetry of the shelf creates two distinct shelf environments. Over the relatively shallow banks (depths less than 100 m) tidal mixing plus wind-induced mixing and thermal convection overturning effectively mix the water column. Surface contaminants of negligible buoyancy could be mixed downward over the banks. Currents 15-20 km apart on the banks appear to be correlated.

Over the troughs the water column is stratified. Mixing by winds and winter overturning do not penetrate to the bottom (at depths greater than 150 m) and mixing by tides is not complete throughout the longer water column. Currents in the troughs seem to be highly variable. There is little correlation among currents even over horizontal separations of 20 km or less. Onshore flow into the troughs appears to be the agent that introduces water of high salinity. In at least one instance, circulation in a trough was dominated by an anticyclonic gyre apparently fed by low-density waters from the Kenai Peninsula Current.

Speculative summary of surface currents

A speculative summary or model of surface currents is shown in Fig. 3.28. Lengths and breadths of arrows indicate relative strengths of mean currents (net velocity not speed). The model has much greater detail in Kiliuda Trough than in other troughs because more data were gathered there. (The bank-trough experiment was conducted there.) The dotted arrow northeast of Afognak Island indicates that a baroclinic flow was observed there but that it was not permanent. The ephemeral gyre over Stevenson Trough is not shown.

4. Chemistry



CHAPTER 4 CHEMISTRY

K. W. Fucik, SAI

4.1 INTRODUCTION

Hydrocarbons in the marine environment may be either terrigenous, biogenic, or petrogenic. Terrigenous and biogenic hydrocarbons are naturally occurring compounds. One of the goals of OCSEAP is to assess changes in the environment of Alaskan waters resulting from offshore petroleum development. First, however, it is necessary to identify present levels of hydrocarbons and their probable origins.

Hydrocarbons in the water are likely to increase during the exploration, production, and transportation phases of development. Because some of the hydrocarbons common to petroleum are also produced by marine organisms, natural background levels of hydrocarbons must be established before contributions from petroleum development can be determined. Techniques developed for tracing the sources of hydrocarbons will also be valuable in future monitoring and assessment programs.

The few studies of the chronic effects of petroleum operations on marine environments have reported little damage. In a comprehensive study of the effects of almost 30 years of petroleum operations on the estuarine and offshore waters of Louisiana, the Gulf Universities Research Consortium (GURC) Offshore Ecology Investigation (OEI) found that concentrations of all compounds associated with drilling or production were too low to be a persistent biological hazard; the region, which is very productive, appears to be ecologically healthy; and study sites in Timbalier Bay showed no significant ecological change as a result of petroleum operations, which began in 1952 (Oppenheimer, 1977).

Another study has been monitoring the effects of an oil and gas field in approximately 60 feet of water off Galveston, Texas. Although production and development began in 1960, petroleum operations appear to have had little effect on the local environment. Hydrocarbon levels in the water have been low (<35 ppb), and petroleum hydrocarbons have been detectable in the sediments only in the immediate vicinity of the platforms (Jackson et al., 1978).

In the same area, Armstrong et al. (1979) examined the effects of an oil separator platform in the shallow waters (≅2 m) of Trinity Bay, Texas. Reduced benthic populations near the platform were correlated with naphthalene concentrations in the sediments. The most drastic changes were noted within 150 m of the platform. Total concentrations of naphthalenes ranged from 6 ppm to 22 ppm. No changes were evident 500 m from the platform.

The effects of major oil spills have been variable. The Argo Merchant spill appears to have had little lasting effect on the environment (Kuhnhold, 1978; Morson, 1978), probably because the oil remained in open waters and did not come ashore. The ultimate impact of the Metula spill is as yet unknown but may be significant at heavily oiled sites (Straughan, 1978). The Amoco Cadiz spill immediately contaminated littoral communities (Hess, 1978); the long-term effects of this spill are under study. Studies of the effects of the IXTOC I blowout in the Gulf of Mexico have just begun.

In gas and oil field operations heavy metals can enter the marine environment in formation waters, drilling muds, crude oil, or sediments. Studies in the Buccaneer oil and gas field off the Texas coast showed elevated levels of barium, lead, strontium, and zinc in the sediments; these may have come from petroleum operations (Anderson et al., 1979). If these toxic metals are incorporated into the marine food web, they may ultimately contaminate human food and are thus a potential health hazard to man. They may also cause permanent changes in local animal communities. Knowledge of the present concentrations of heavy metals in the water, sediments, and biota of Alaskan marine waters is required before oil development begins so that future changes in metals concentrations can be accurately measured.

4.2 DISTRIBUTION AND CONCENTRATION OF PETROLEUM HYDROCARBONS

4.2.1 Horizontal and vertical distributions of petroleum hydrocarbons in the water column

The distribution of hydrocarbons in surface waters has been studied throughout the Gulf of Alaska and Cook Inlet by Shaw (1975, 1976, 1977). The hydrographic stations sampled near Kodiak are shown in Fig. 4.1. Concentrations were low throughout the Gulf of Alaska, with measured hydrocarbon concentrations generally less than 1 ppb. These values are as low as or lower than hydrocarbon levels in other unpolluted areas of the

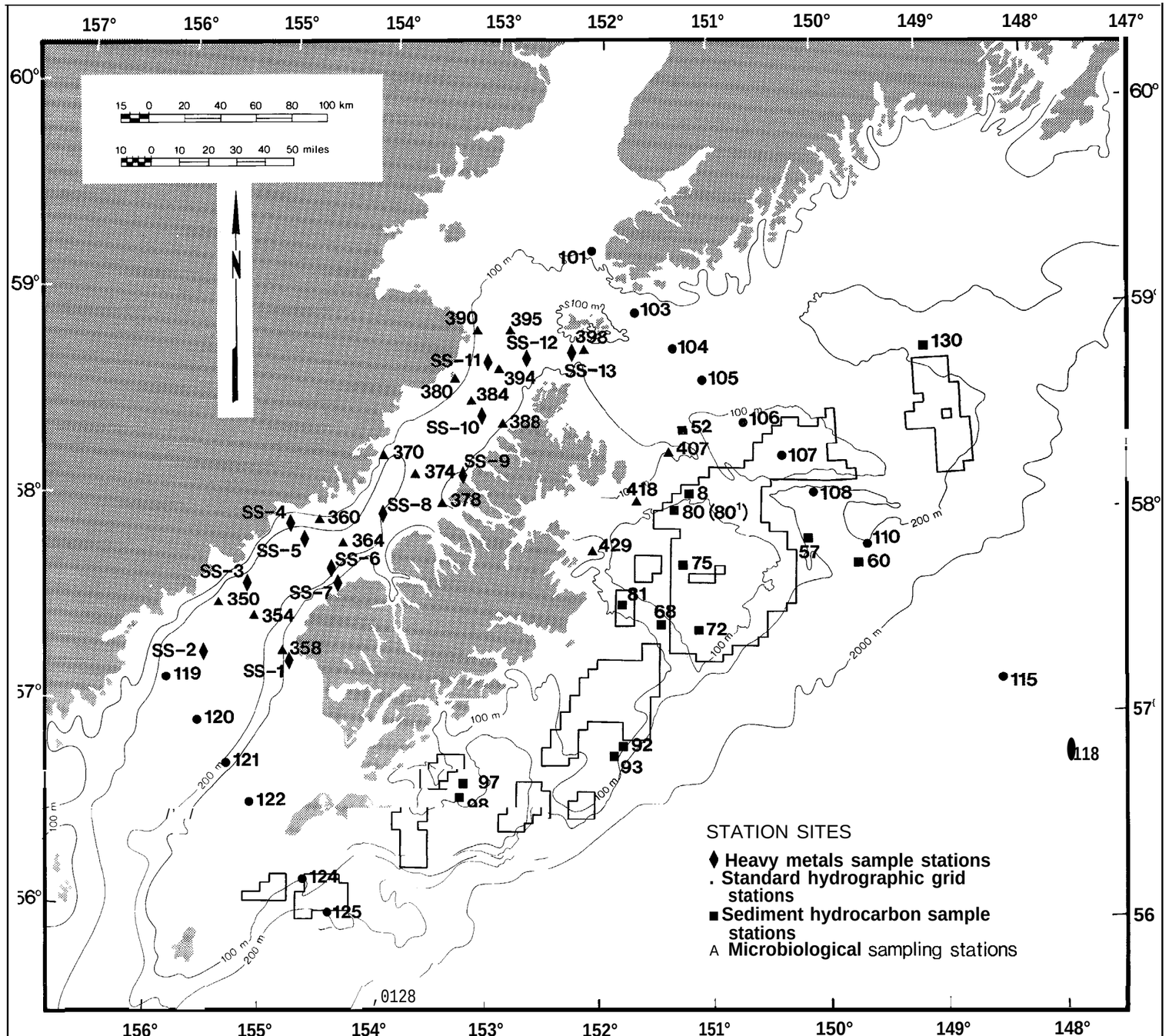


Figure 4.1 Sampling locations for hydrocarbons, trace metals, and microbiological parameters in the Kodiak region (see text for sources).

world s oceans (Table 4.1) (for a mm of these eve s, see Clark and MacLeod, 977). Hydrocarbon concentrations of April samp es were generally highe than those of February samp es but seasonal trends have not been establ shed The higher leve s in April are correlated with the spring plankton bloom, supporting the theory that the hydrocarbons are biogenic.

Table 4.1 Concentrations of hydrocarbons of low molecular weight in surface waters of the open ocean and contaminated coastal waters of the world's oceans (Swinnerton and Lamontagne, 1974).

	Hydrocarbon type	Hydrocarbon (mean)	content (nl/l)
Clean open water (n=452)	CH_4	31-80	(495)
	C_2H_6	0.1-1.7	(0.5)
	C_3H_8	0.05-1.4	(0.34
	C_4H_{10}		(0 05
	C_2H_4	0.7-12.	(4 8
	C_3H_6	0.1-5.8	(1
Contaminated coastal waters (n=452)	CH_4	103-3800	(12500
	C_2H_6	1.4-650	(71)
	C_3H_8	1.0-1100	(95)
	C_2H_4	1.9-35	(11.0)
	C_3H_6	0.1-16	(2.8)

F oating tar was collected in three of 9 seston tows in the Gulf of Alaska (Shaw, 1977). An average of 8.5 x 10^{-3} mg/m^2 of tar was obtained. This level is two to three orders of magnitude less than tar residues measured in other parts of the world s oceans (see Clark and MacLeod 1977).

4.2.2 Distribution of petroleum hydrocarbons in bottom sediments

In aquatic ecosystems the sediments are the ultimate sink for many contaminants. Processes that increase the specific gravity of petroleum, causing it to sink, are (1) evaporation and dissolution, (2) degradation and oxidation, (3) formation of dispersed particles and subsequent agglomeration, (4) absorption and adsorption by particulate matter, and (5) uptake of seawater during emulsif cation (Clark and MacLeod, 1977). Several examples in which the incorporation of petro eum hydrocarbons into the sediments has resulted in chronic pollution have been reported (e.g., Armstrong et al., 1979; Blumer and Sass, 72; Vandermeulen and Gordon, 1976).

Present levels of hydrocarbons in the sediments of the Gulf of A aska are those of a pristine environment. Sediment hydrocarbon levels measured near Kodiak (Fig. 4.1) during 1975 ranged from <1 to 27 mg/g dry sediment (Table 4.2; Kaplan et al., 1977). These values are low; petroleum levels of unpolluted coastal sediments elsewhere are usually below 70 ppm (Clark and MacLeod, 1977). Hydrocarbon levels of polluted coastal sediments may range from 100 to 12,000 ppm. The range of concentrations observed near Kodiak may be due to variations in sediment grain size and organic carbon content, with higher hydrocarbon concentrations in fine-grained sed ments near the shelf edge and lower concentrations in coarse-grained sediments close to shore.

Additional samp es collected during the summer of 1976 at 14 stations on the Kodiak she f (Fig. 4 1) (Kaplan et al., 1978) showed hydrocarbons much lower than 1975 leve s (Table 4.2). Gas chromatographic analyses indicated that levels of terrigenous hydrocarbons were much lower than those from marine sources (Kaplan et al., 1979). Distinct patterns in hydrocarbon distributions were not found, although the highest hydrocarbon levels and percentages of organic carbon were found at the southernmos stations. Overall, hydroc rbon levels in the Kodiak area sedi ts were similar to or lower than those in other Alaskan sediment (Kaplan et al., 1978).

Table 4.2 Hydrocarbon levels (ppm) in the sediments of the northwest Gulf of Alaska near Kodiak Island (Kaplan et al., 1978).

Station	Organic Carbon %	Nonsaponifiable	Aliphatic	Aromatic	Total Hydrocarbons*
1975					
103	0.53	242.0	4.0	3.2	7.2
104	0.39	110.0	5.6	17.8	23.4
105	0.76	166.7	6.7	3.8	10.5
119	0.74	188.4	5.8	14.3	20.1
120	-	382.2	6.5	12.5	19.0
121	0.13	270.1	13.5	13.2	26.7
122	0.18	36.6	0.6	n.d.	n.d.
124	0.92	201.6	6.4	11.9	18.3
1976					
52	0.34	42.2	1.2	2.1	3.3
57	0.36	28.3	1.4	1.4	2.8
60	0.31	37.7	2.1	2.8	4.9
68	0.60	69.5	2.3	1.4	3.7
72	0.23	22.3	1.6	0.9	2.5
75	0.33	33.2	2.1	0.4	2.5
80	0.35	13.0	0.5	0.5	1.0
81	-	24.9	0.7	0.6	1.3
81	0.50	71.1	2.7	2.9	5.6
87	0.45	29.2	0.8	1.5	2.3
92	1.17	130.9	5.1	6.6	11.7
93	1.01	26.1	1.9	2.3	4.2
97	2.45	98.7	4.2	5.2	9.4
98	2.15	205.1	7.8	10.9	18.7
130	0.91	36.6	1.9	3.0	4.9

* Total hydrocarbons aliphatic+ aromatic fractions
n.d. = not determined

From analysis of sediments from south-central Alaska waters, Shaw (1978) determined that adsorption of hydrocarbons onto the sediments is unlikely to be a major factor in the dispersal of spilled oil. In the immediate vicinity of oil spills, however, oil droplets may coat sediments and sink, thereby increasing concentrations of oil in the sediments.

4.2.3 Distribution of petroleum hydrocarbons in selected marine organisms

Marine organisms accumulate petroleum hydrocarbons either directly from the water or by ingestion. Laboratory and field studies have shown that some organisms continued to accumulate hydrocarbons until they died or were removed from the hydrocarbon source. Once removed from the source, most organisms could rid themselves of the hydrocarbons accumulated in their tissues. Crustaceans and fish can also metabolize hydrocarbons. Little is known of fate or effects of the metabolic products of hydrocarbons on organisms.

Petroleum hydrocarbons may be acutely lethal or chronically sublethal to marine organisms. Their effects vary with the species, life stage, level of exposure, the nature of the oil (i. e., crude or refined), and the duration of exposure (Rice et al., 1977). Most of our present knowledge has been derived from laboratory studies.

In one of the few field studies on the subject carried out in Kodiak nearshore waters, mussels *Mytilus edulis* from Sitkalidak Lagoon were collected and their tissues analyzed for hydrocarbons (Shaw, 1977). Gas chromatography (GC) showed low levels of hydrocarbons, suggesting that no petroleum has entered the waters of the Kodiak and Aleutian region (Table 4.3). Similar levels have been obtained from organisms from other Alaskan waters.

Table 4.3 Concentrations of total hydrocarbons in the mussel *Mytilus edulis* from the Aleutian Islands and Kodiak Island (from Shaw, 1977).

Station Location	Hydrocarbon Concentration mg/kg	
	Fraction 1	Fraction 2
Unimak Island (Sennett Pt.)	<.01	4.3
Unimak Island (Cape Lupin)	0.4	5.2
Unalaska Island (Ercter Pt.)	0.6	7.3
Sitkalidak Lagoon (Kodiak Is.)	0.4	5.5

Fraction l--saturated and olefinic hydrocarbons

Fraction 2--unsaturated hydrocarbons, aromatics, and some non-hydrocarbon organic compounds

4.2.4 Distribution of methane, ethane, propane, butane, and olefinic homologs in the water column

Low-molecular-weight hydrocarbons (LMWH) are ubiquitous in the Alaskan shelf regions (Cline et al., 1978). Methane is found in moderate concentrations and the C_2-C_4 hydrocarbons in low concentrations (except in localized areas of Cook Inlet and Norton Sound) (Table 4.4). These compounds can be used to identify the source of hydrocarbons and to trace mesoscale circulation (Cline et al., 1978). The distribution of methane, for example, adds evidence to support the cyclonic circulation in the outer part of Norton Sound and the clockwise gyre south and west of Kayak Island in the Gulf of Alaska.

The LMWH distributions discussed below come from a July 1977 survey of the Kodiak region.

Table 4.4 Typical seasonal range of hydrocarbon concentrations observed in the near-bottom waters of selected OCS areas. Unusually high concentrations occurring singly have not been included in the ranges. Number of observation periods in each survey area is given in parentheses (data from Cline et al., 1978).

Region	NEGOA (3)	LCI[2] (2)	Bristol Bay (2)	Norton Sound[1] (1)	Chukchi Sea (1)	Kodiak Shelf (1)
Component	nl/l (STP)					
Methane	100-1500	100-900	60-600	200-2000[3]	200-3000[3]	150-2000
Ethane	0.2-1.0	0.3-0.8	0.5-2.0	0.3-1.3	0.3-3.0	0.2-0.8
Ethene	0.5-3.0	0.5-5.0	0.5-5.0	0.3-4.0	1-4.0	0.5-3.5
Propane	0.2-0.6	0.1-0.6	0.2-0.7	0.2-0.5	0.2-1.3	0.1-0.5
Propene	0.2-0.6	0.2-0.8	0.2-2.0	0.2-0.9	0.3-0.8	0.8-2.0
Isobutane	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05
n-Butane	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05	$\leq$ 0.05
$C_{2:0}/C_{2:1}$	< 0.5	$\leq$ 0.5	< 1	< 0.5	< 1	< 0.5

[1]The range does not include observations from region of gas seep

[2]The range does not include observations from the region north of Kalgin Island.

[3]The upper value is the result of strong thermal stratification that existed at the time of the measurements.

Methane

Methane concentrations in surface waters were highest along the southern coast (200 to 300 nl/l) with an elongated distribution northward. This distribution may be related to biological activity or the result of a countercurrent along the inner shelf (Cline, pers. comm.). Favorite and Ingraham (1977) have hypothesized the presence of a cyclonic gyre along the southern Kodiak shore, but existing data on circulation do not support this hypothesis (see Chapter 3). A gyre could cause materials to be trapped and concentrated in this area. Near-bottom concentrations were distributed similarly to surface concentrations (Fig. 4.2).

Methane concentrations were highest over sediments rich in clay (e.g., Kiliuda Trough). These sediments contain organic material which supports the microbial production of methane. The highest value (1880 nl/l) was obtained from the Chiniak Trough. The high methane concentrations in the waters of Chiniak Trough were an exception, as sediments here are sand and silt in a 3:1 ratio. This suggests that high bottom values are a result of either strong biological activity at the sea/bottom interface or gas seepage from the sediments. Redden and Kvenvolden (in Hampton and Bouma, 1979) found high methane values in the sediments in this area, lending support to the latter hypothesis (Chapter 2). Concentrations were lowest over Portlock Bank, where sediments are mainly coarse sands and gravels.

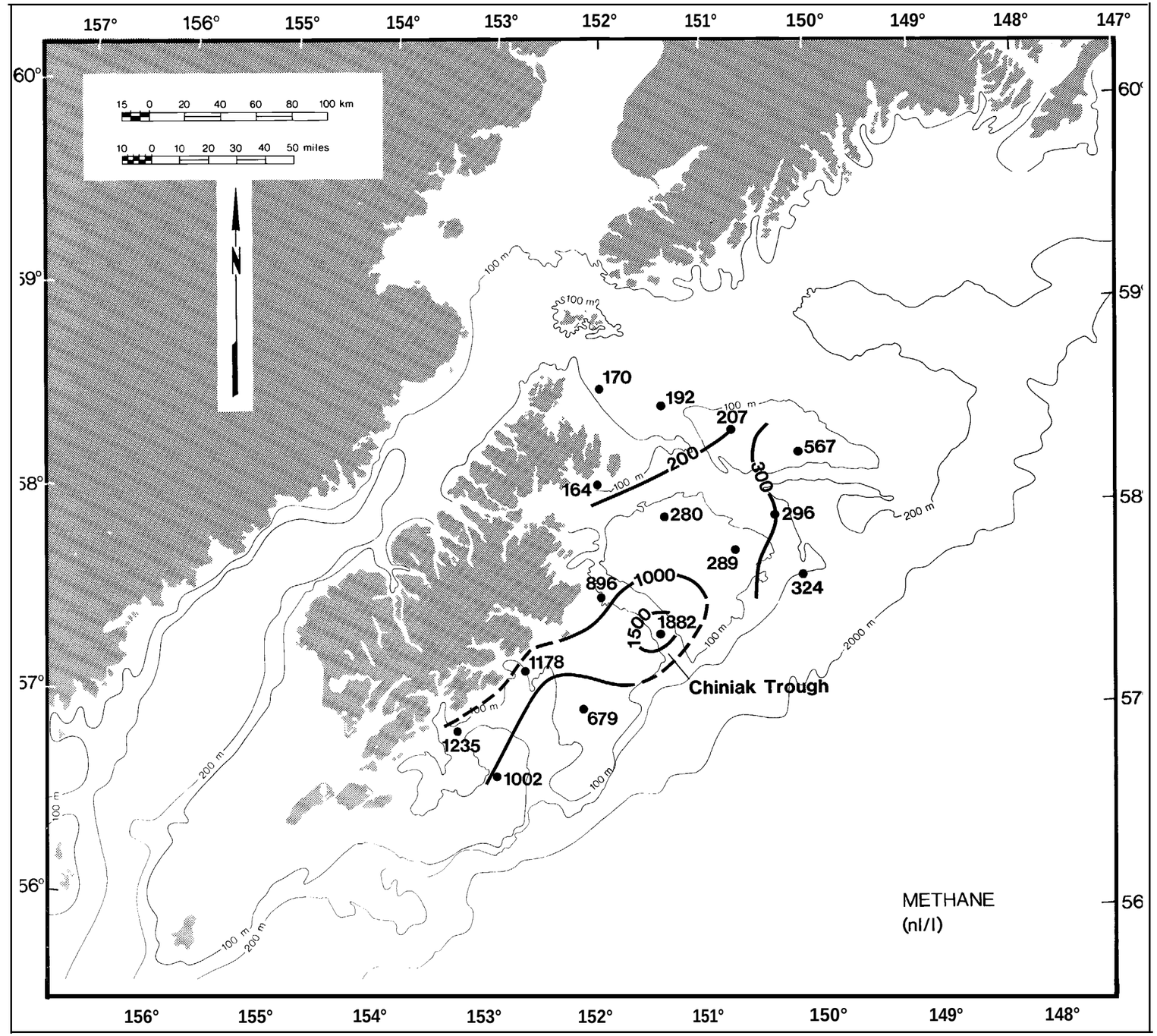


Figure 4.2 Methane distributions within 5 m of the bottom, July 1977 (Cline et al., 1978).

Ethane/ethene

Ethane concentrations in the surface waters were distributed like those of methane (Fig. 4.3). A maximum concentration of 0.3 nl/l was measured in the waters along the southern coast. The lowest values were found in the north, where the minimum concentration was 0.4 nl/l. Bottom concentrations ranged from 0.2 to 0.8 nl/l, with a mean of 0.5 nl/l. They were highest near the coast and decreased off shore.

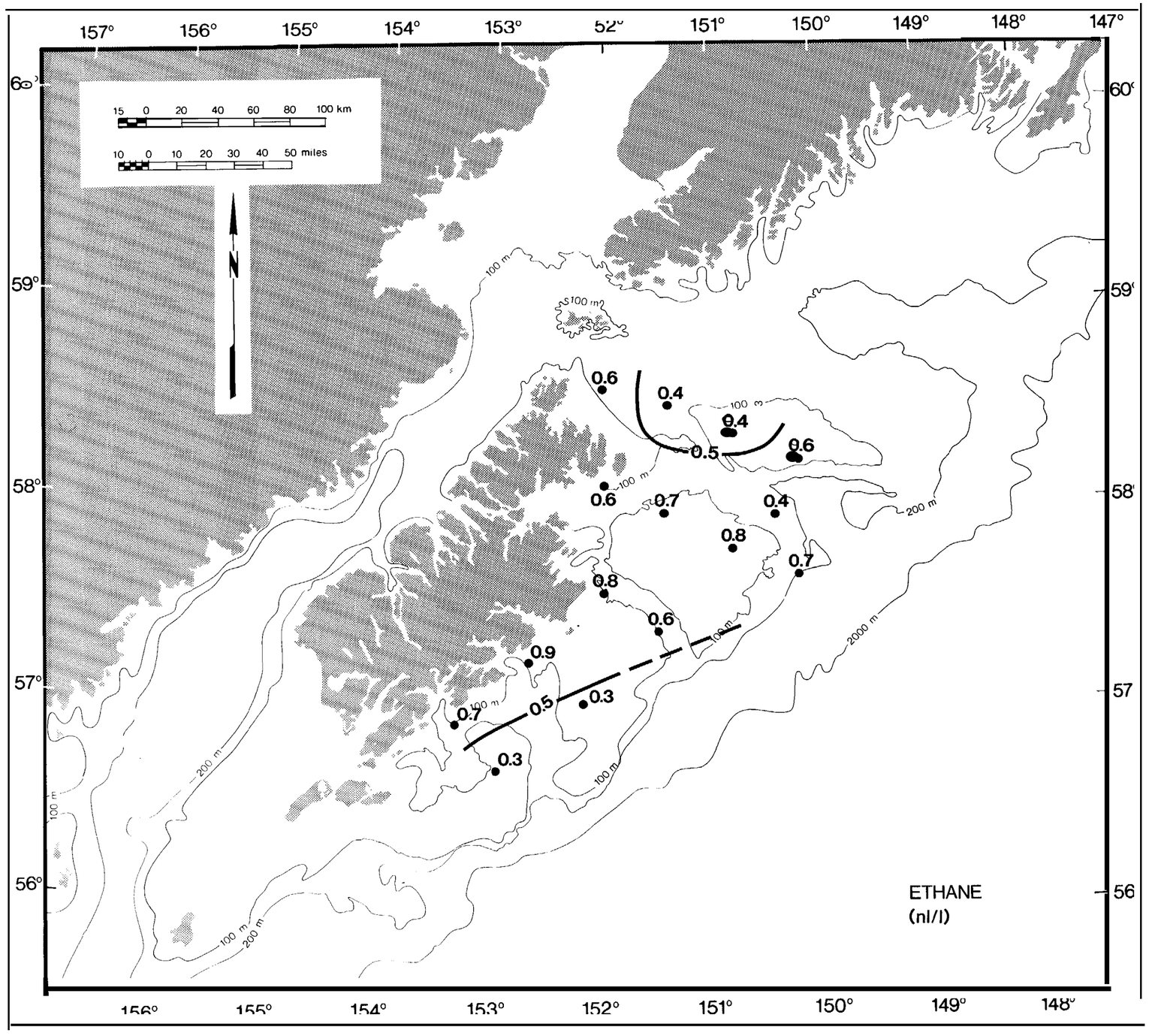


Figure 4.3 Surface ethane distributions, July 1977 (Cline et al., 1978).

Ethene concentrations were uniformly high in the surface waters over the shelf (Fig. 4.4; Cline et al., 1978), where they ranged from 3.2 nl/l in the north to 5 nl/l off Marmot Bay. The highest concentrations extended south along the coast from Sitkalidak Island to just off Marmot Island. The bottom concentrations were higher near the coast, with a high of 3.4 nl/l on Portlock Bank.

The distribution of ethene in the Kodiak region appears to be controlled by primary productivity or by processes related to primary productivity (Cline et al., 1978). Thus, the high ethane levels observed in the surface layers near the coast could be related to the rate of production of ethene. This hypothesis has not yet been confirmed, however.

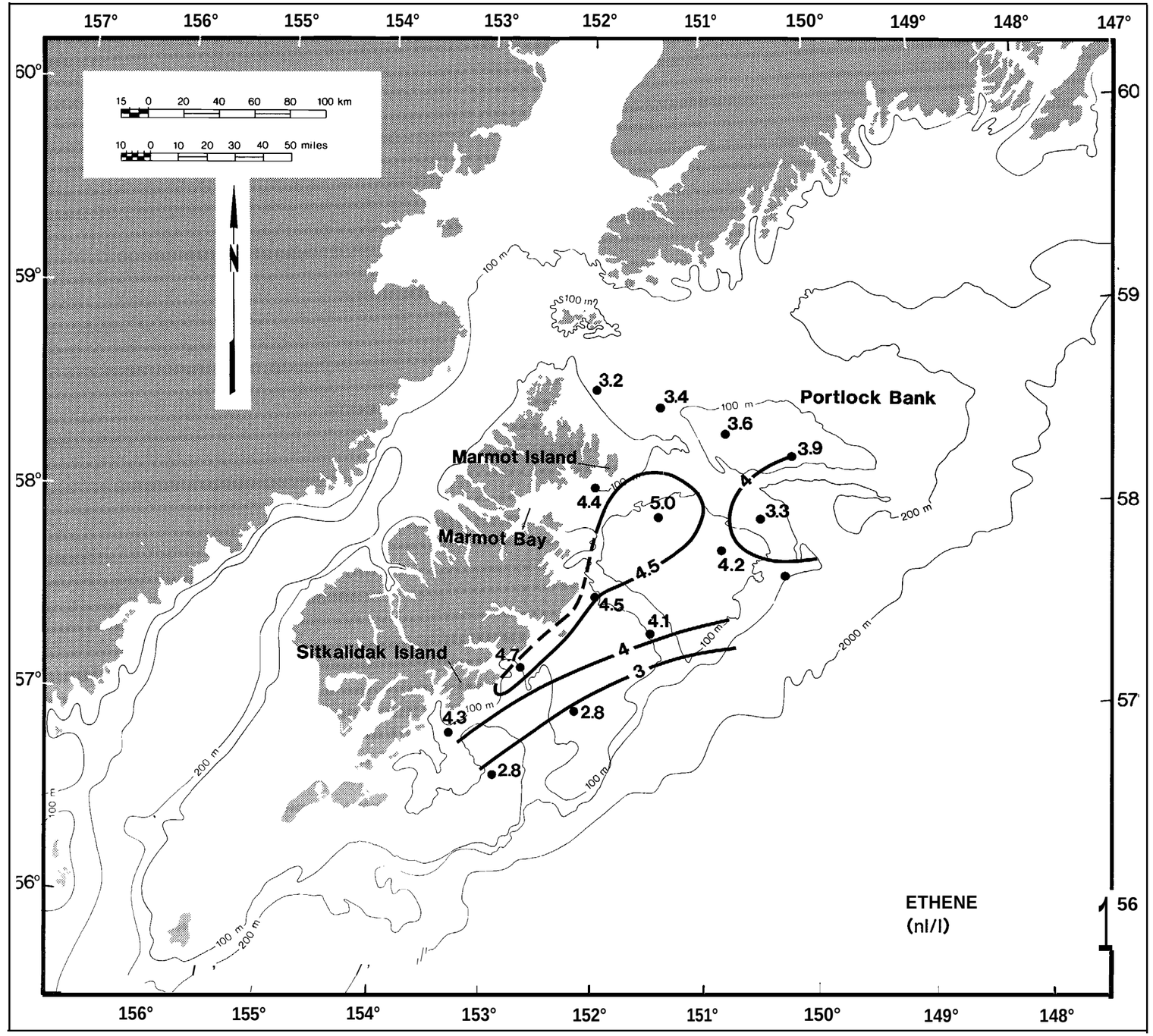


Figure 4.4 Surface ethene distributions, July 1977 (Cline et al., 1978).

Propane/propene

Propane concentrations of 0.5-0.8 nl/l were found nearshore and 0.3-0.5 nl/ offshore (Fig. 4.5). Surface concentrations averaged 0.5 nl/l. Bottom concentrations were variable with eve.s north of Afognak Island ranging between 0.1 n./l and 0 3 nl/l. The maximum bottom concentration was 0 5 nl/l measured along the southern coast of Kodiak.

The distribution of propene was simi.ar to that of ethene. Surface concentrations ranged from 0 8 nl/ to 2 nl/l, while near-bottom level ranged from trace amounts <0.5 nl/l to nearly nl/l.

Butane

Butane concentrat.ons were below the imit of detection of 0.05 n./ throughout the area.

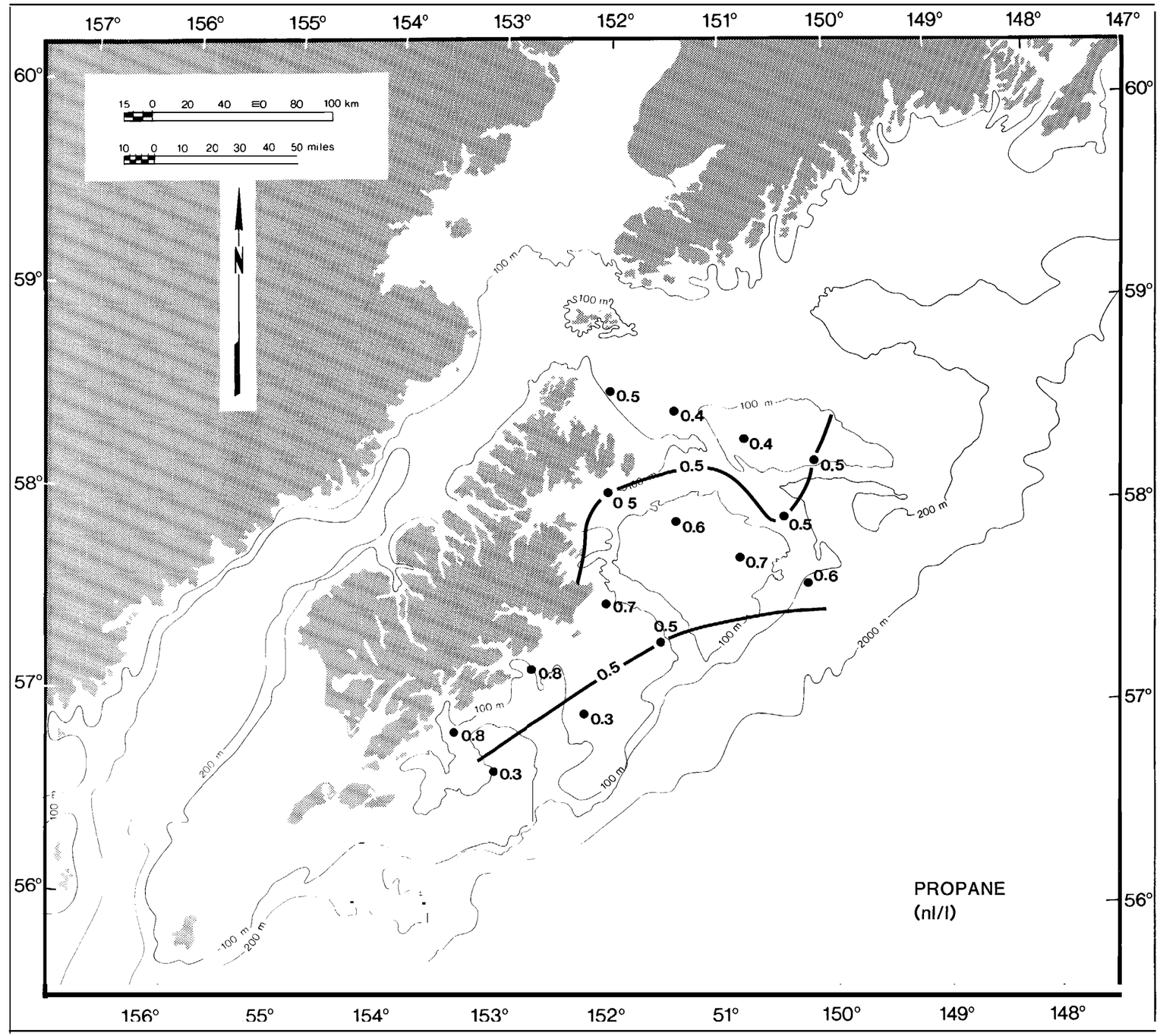


Figure 4.5 Surface propane distributions, July 1977 (Cline et al., 1978).

4.3 DISTRIBUTION AND CONCENTRATION OF TRACE METALS

4.3.1 Distribution of trace metals in the water column

Water for analysis of heavy metals (Cd, Cu, Zn, Se, Cr, Pb, Ni, Hg, and V) was sampled at several stations along two transects northeast and southwest of Kodiak Island (Fig. 4.1; Burrell, 1976, 1977, 1978). Concentrations of dissolved manganese and vanadium from a few locations in the Shelikof Strait were also measured (Robertson and Abel, 1979).

Concentrations of heavy metals in the water column of the western Gulf of Alaska are low and are distributed uniformly (Table 4.5). They are generally below the oceanic mean:

Element	Gulf of Alaska mean µg/l	Oceanic mean µg/l
Ag	0.009	0.04
Cd	0.03	0.1
Cu	0.2	0.5
Hg	0.007	0.03
Ni	0.65	1.7
Pb	0.04	0.03
V	1.5	2.5
Zn	0.3	5.0

Table 4.5 Trace metals concentrations (µg/l) measured in the water of the northwest Gulf of Alaska near Kodiak Island (data from Burrell, 1976, 1977; 1978).

Station No.	Depth (m)	Cd	Pb	Cu	Zn	Hg*	V	Se	Cr
104	0	0.03	0.04	0.20	0.28		1.6		
	95	0.05	0.05	0.24	n.d.		1.4		
106	81	0.025	0.035	0.16					
108	10		0.07	0.16	n.d.		1.5		
	226	0.025	0.025	0.15	n.d.	4(4)*	1.6		
110	10	0.03	0.025	0.15	0.20	3.9±0.4(9)*			
	175				n.d.				
	273					9(6)*			
119	0	0.02	0.025	0.26	n.d.			n.d.	0.23
	240	0.03	0.035	0.16	n.d.		1.5	n.d.	n.d.
120	0	0.04	0.13	0.42	0.50				
	280	0.06	0.06	0.26	n.d.				
121	0	0.04	0	0.26	0.42		1.3		
	220	0.04	0.05	0.33	n.d.		1.7		
122	0	0.025	0.08	0.28	0.24				
	40	0.03	0.07	0.23	0.20				
124	0	0.025	0.15	0.28	0.40		1.6	n.d.	n.d.
	105	0.05	0.10	0.24	n.d.		1.7	n.d.	0.06

* rig/l first number is inorganic Hg; number in parentheses is total Hg.

The particulate metals fraction is correlated with the overall concentration of suspended particulate matter It is thus highest in nearshore and near-bottom waters (Table 4.6).

Table 4.6 Selected heavy metals and total major cation (Al) contents (μg/l) of suspended sediments of the northwest Gulf of Alaska near Kodiak Island (data from Burrell, 1976; 1977; 1978).

Station No.	Depth (m)	Cr	Mn	V	Al	Ti	Na
103	1		0.13±0.04	<0.020	3.79±0.43		
	125		0.26±0.02	0.021±0.012	7.40±0.19		
104	1		0.061±0.010	<0.0056	2.46±0.08		
	96		0.67±0.03	0.059±0.014	27.38±0.13		
106	81		0.54±0.12	<0.057	26.3±1.0		
108	10		0.19±0.12	<0.052	4.53±0.86		
	226		0.33±0.13	<0.055	30.1±0.8		
110	10		0.17±0.10	<0.046	4.42±0.82		
	173		0.27±0.20	<0.080	17.1±1.5		
119	1		0.68±0.09	0.070±0.051	32.4±1.0		
	204	n.d.	6.48±0.08	0.094±0.045	35.3±0.8		
120	1		0.38±0.07	<0.036	16.5±0.6		
	281		7.10±0.09	0.224±0.063	103±1		
121	1		0.26±0.04	<0.025	15.0±0.6		
	220		2.64±0.08	0.148±0.051	69.9±0.8		
122	1		0.24±0.04	<0.036	15.1±1.0		
	35		0.35±0.04	0.053±0.024	28.3±0.5		
124	1	Tr	0.28±0.03	0.028±0.020	14.6±0.4		
	105		0.30±0.04	0.030±0.029	25.5±0.6		
SS-2			14.6±0.5	0.66±0.14	411±11	24.2+9.0	680±50
SS-4			0.93±0.04	0.11±0.03	37.7±1.7	<4.0	170±10
SS-6			11.4±0.4	0.27±0.09	142±6	42	510±30
SS-11			5.±3	<0.06	21.2±1.5	3.3± .6	150±10
SS-13			6.5±0.2	0.15±0.05	74±3	<6.2	260±20

n.d.--not detectable above background
Tr--0.04-0.10 μg/l above background

4.3.2 Distribution of trace metals in seafloor sediments

Sediment samples for analysis of trace metals were collected from transects northeast and southwest of Kodiak Island (Burrell, 1976, 1977, and 1978) and in Shelikof Strait (Robertson and Abel, 1979). The metals content of these sediments is related to mineralogy and grain size. Metals are adsorbed onto the coarser sediments of the western gulf much less readily than they are onto the fine-grained sediments of the northeast Gulf of Alaska. The ranges of metals concentrations measured in the sediments are shown in Table 4.7. No unusually high concentrations of metals were found. Similar data have been obtained in all areas of the Alaskan Gulf. These data are similar to levels obtained in unpolluted areas of the continental shelf.

The available fraction of trace metals in surficial sediments is defined as the fraction leached by dilute solutions of H_2O_2 and HCl (Robertson and Abel, 1979). Determinations of the available metals fraction show that generally less than 1 percent of the metals examined are associated with organic phases. The extractable metals fraction in the Shelikof Strait was lower and more uniform than that measured in the eastern and western Gulf of Alaska. This may be due to differences in sediment types and textures.

Table 4.7 Ranges of heavy metals concentrations of sediment extracts and total metals content of bottom sediments from the northwest Gulf of Alaska near Kodiak Island (data from Burrell, 1977 and Robertson and Abel, 1979).

Surface Sediment Extracts (μg/g)	
Sc	nd-0.20
Cr	nd-1.3
Al	117-599
V(%)	10-14
Mn(%)	37-51
Total Heavy Metals Content (μg/g)	
Mn	312-1074
V	27-167
As	1.8-14.1
Ba	260-1100
Co	3-21
Cr	15-192
Fe(%)	0.83-5.22
Sb	0.17-1.27
Al(%)	7.59-8.21
Ti(%)	0.34-0.54
Na(%)	3.00-3.82
K(%)	1.39-1.85
La	15.1-23.1
Sm	3.3-4.4
Sc	16.20-18.45
Cs	2.17-5.02
Eu	0.91-1.05
Tb	0.35-0.53
Ta	0.30-0.84
Tn	3.50-6.64

4.3.3 Distribution of trace metals in benthic organisms

Samples of a mussel (*Mytilus* sp.) and a rockweed (*Fucus* sp.) from Kodiak intertidal waters were analyzed for Se, Cr, Cd, Cu, Ni, and Zn (Table 4.8; Burrell, 1976; 1977; 1978; Robertson and Abel, 1979). Total metals concentrations in these organisms were low and showed no metals contamination. The levels observed are similar to levels throughout the' Gulf of Alaska. They are as low as or lower than those reported for more temperate regions.

Table 4.8 Heavy metals content (μg/g dry weight) in *Mytilus* and *Fucus* specimens collected in Summer 1976 from Kodiak and intertidal waters. Numbers represent a mean of duplicate samples (data from Burrell, 1976; 1977; 1978).

Locality	Cd	Cu	Ni	Zn	V[1]
Mytilus sp.					
Sundstrom Island	10.3	8.0	3.4	107	
Sundstrom Island*	5.2	8.4	<5		
Three Saints Bay*	6.1	10.2	<5		
Lagoon Point	5.8	9.6	1.3	102	
Pasagshak Point	2.5	9.3	1.6	115	
Fucus Sp.					
Sundstrom Island					483±13
Sundstrom Island*	2.3	2.0	5.3	8	
Sundstrom Island	3.0	3.8	6.1	19	
Three Saints Bay*	3.1	3.5	5.5	18	
Lagoon Point	3.9	1.5	6.7	17	
Pasagshak Point	3.5	1.8	4.3	23	

*Summer 1975

[1]μg/g dry weight

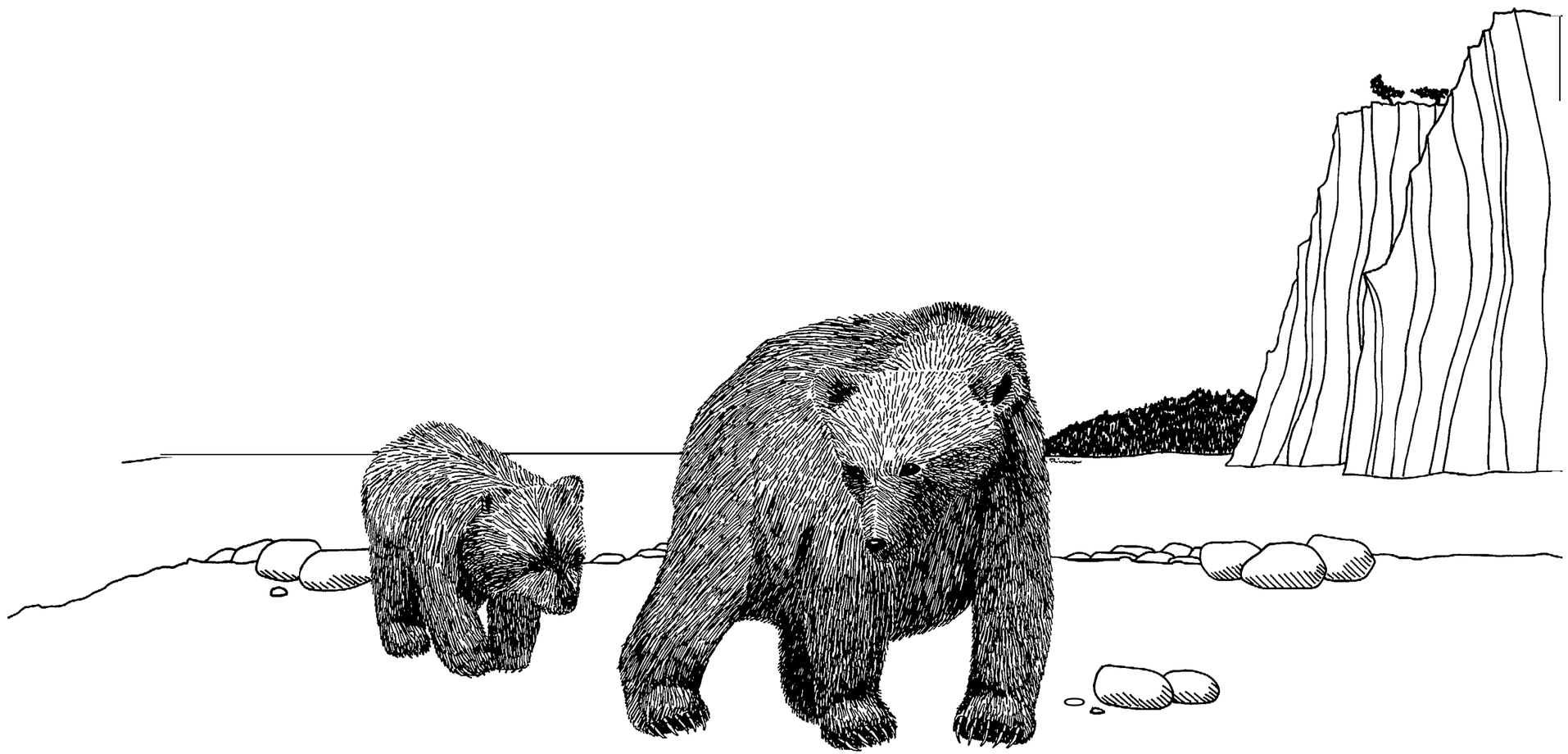
4.4 SUMMARY

Sampling of concentrations of hydrocarbons and metals on the Kodiak Shelf have been too limited to show clear seasonal and spatial trends. As in other areas of the Alaskan OCS, however, the measured levels indicate an essentially unpolluted environment. Levels of soluble hydrocarbons and of floating tar were as low as or lower than those reported in open ocean waters elsewhere. Hydrocarbon levels were also low in the sediments and in certain organisms.

Low-molecular-weight hydrocarbons (LMWH) were sampled only once, in July. Their composition indicated them to be biogenic rather than petrogenic. The levels of LMWH were within the range of concentrations measured in other areas of the Alaskan OCS and other unpolluted regions of the world's oceans.

Limited sampling of the water, sediments, and biota of the Kodiak area indicated no contamination by trace metals.

5. Biology



CHAPTER S BIOLOGY

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5.1 INTRODUCTION

OCSEAP has as its underlying objective the protection of the environment compatible with oil and gas development. Alaskan ecosystems have evolved over millions of years with minimal human influence. Many of the interactions in these systems are not understood; it is often difficult to assign them precise quantitative values, anticipate the impact of human activities, and determine to what extent perturbations are inevitable.

With increasing industrial expansion and rapid population growth, resulting in a greatly increased need for food, living space, and energy, the world is rapidly losing natural habitat areas. In Alaska there remains a great opportunity to plan for development so that environmental damage is minimized or possibly completely avoided. The data base necessary for such planning, however, is scanty.

Before the impact of oil and gas development on the marine biota of Alaska can be predicted, it is necessary to establish its distribution and interactions. Distributional data, as well as information on the breeding biology, feeding behavior, physical requirements, and the physiology of different species can be used to estimate vulnerability at specific locations and times of the year.

The cycling of nutrients and energy through biological communities depend on complex predator-prey relationships or food webs. Microbes, plankton, and larger species are all integral parts of these food webs. Both marine and terrestrial species may be important members of the same food web. The loss or drastic population reduction of even one key member of these webs could have detrimental effects on many other species. The details of these interrelationships are little understood and some key species remain unidentified.

The fishing industry represents an important component of the economy of the State of Alaska. In addition Japan, Russia, and Korea exploit a large portion of the Alaskan fisheries. The recent establishment of a 200-mile territorial limit will have significant effects on both international relations and the Alaskan economy. Wise ecological studies are needed if serious political and resource-conflict problems are to be avoided.

The material presented here represents a significant increase over previous knowledge of Alaskan ecosystems. Of necessity much of it is preliminary, incomplete, and descriptive in nature. It does, however, represent a first step toward a better understanding of what needs to be done in the future. Some OCSEAP work toward understanding the dynamics of these natural systems is already in progress, but much more needs to be done. Work to date has demonstrated the rich and pristine nature of the Alaskan marine environment. Such information can help planners to preserve this heritage.

5.2 MICROBIOLOGY

Microorganisms are essential members of marine ecosystems. The productivity of a region is strongly dependent on the distribution, diversity, and abundance of its microbial communities. A source of food for many organisms, microorganisms also convert organic and inorganic compounds into nutrients essential to the primary producers. Certain bacteria capable of degrading petroleum are important in the cycling of pollutants in areas of acute or chronic pollution.

Microbial populations at several stations around Kodiak (see Fig. 4.1) were sampled during October 1975 (Atlas, 1976). The results of both direct counts and indirect plate counts are summarized in Table 5.1. Direct microbial counts from water samples ranged from 1.8×10^5/ml to 4.3×10^5/ml. Direct counts give the best estimates of the numbers of microorganisms present but do not differentiate between living and dead organisms. In contrast the viable counting method is selective for a given population capable of growth under sampling conditions. The direct method thus tends to overestimate microbe populations whereas the viable method greatly underestimates them. Less variation and much lower numbers were obtained by viable (plate) counts. The numbers of culturable mesophilic, psychrophilic, and psychrotrophic heterotrophs were similar throughout the Kodiak area, although the heterotroph counts in the water increased slightly from Kodiak toward Unimak Pass in the Aleutians. Counts in the sediments of 10^5-10^6/g were observed, but sediment samples were insufficient to determine distributions. Four samples taken from the Kodiak shelf in April 1977 were counted, using epifluorescent microscopy (Griffiths and Morita, 1978). Counts in the water were similar to the direct counts of Atlas's October 1975

Table 5.1 Counts of various microbes isolated from water and sediments in the vicinity of Kodiak Island. (Atlas, 1976) .

	Water (per ml)	Sediment (per gram dry sediment)
Direct Count	1.8-4.3 X 10^5	---
Aerobic Heterotrophic Psychrophiles & Psychrotrophs	35-97	1.1 x 10^6
Aerobic Heterotrophic Mesophiles	43-80	8.4 x 10^5
Psychrophilic & Psychrotrophic Fungi	1.0-8.7	2.8 X 10^4
Mesophilic Fungi	7.0-12	1.5 x 10^4
Pseudomonades	< 0.1	< 100
Salmonella-Shigella	< 0.1-1	< 100
Enteric Bacteria	< 0.1	< 100
Vibrio **Mesophiles**	12-15	4 x 10^4
Oil-utilizing **Psychrophiles &** Psychrotrophs	0.5-15	< 100
Oil-utilizing Mesophiles	1 - < 10	< 100

samples but sediment counts were about 10^9/g. Bacterial counts by epifluorescent microscopy are easily misinterpreted, however. Although microbial populations in the northwest Gulf of Alaska appear to be lower than those in the northeast Gulf (Table 5.2), this conclusion is very likely erroneous, since samples were obtained in different seasons and different years and since marine microbial populations demonstrate a marked seasonal dependence in the Arctic (Button, in litt.).

Counts of culturable fungi in the water were generally less than 10/ml, whereas the sediment counts were generally greater than 104/ml. Counts of mesophilic fungi were about the same as those of the psychrophilic and psychrotrophic fungi.

Table 5.2 Direct bacterial counts in the water and sediments of the northeast Gulf of Alaska measured in March 1976 (Morita and Griffiths, 1977).

Station No.	Cells/ml x 10^5	Cells/g Dry Weight Sediment x 10^9
d	2.0	0.02
1	1.4	2.2
4	1.4	1.4
7	1.9	1.9
68	1.6	
59a	2.0	1.4
57	1.2	2.1
55	2.6	
e	2.0	
53a	1.2	
53b	1.6	1.4
52	1.6	2.6
50	1.5	3.0
42	2.3	1.6
44	2.0	
37	2.3	0.1
41	1.8	3.1
30	2.7	0.3
32	2.0	1.3
f	1.5	0.01
g	2.2	
29	1.6	
28	2.1	1.2
27	2.2	2.4
a	2.5	0.9
b	2.7	1.7
c	2.4	
Average Values	1.9	1.5

Counts of oil-utilizing microorganisms were generally low in both water and sediments throughout the Gulf of Alaska, but were somewhat higher just south of Kodiak and near Unimak Pass than in other areas of the Gulf (Atlas, 1976). However, some workers believe that a substantial oil-utilizing population exists which remains undetected by present methods (Button, in litt.) .

Microbial isolates were obtained from the tissues of Tanner and Dungeness crabs collected from Chiniak and Ugak Bays. These crabs had higher bacterial counts than crabs taken from the Bering Sea. Bacterial concentrations were highest in the gill (9.0 x 10^2-1.66 x 10^5) and muscle (50-3.8 x 10^3) tissue. High levels of gram-negative microorganisms were found in crabs taken near Kodiak Island Harbor. (Table 5.3). The presence of many species of gram-negative bacteria is indicative of human pollution. Fewer gram-negative isolates were observed in Ugak Bay, which is farther from human activity.

Bacterial populations in the Gulf of Alaska are highly diverse (Atlas, 1977). In a study of the utilization by bacteria of various nutritional substrates, more populations of bacteria from Kodiak samples than from Aleutian samples were found to use test substrates. Kodiak bacteria also utilized more kinds of substrates, suggesting a wider tolerance to varying environmental conditions.

In a study measuring the tolerance of bacteria to changes in temperature, salinity, and pH, water populations were more tolerant of high temperatures than sediment populations, but both were intolerant to changes in salinity from 3 percent to either 0.5 or 5 percent NaCl. Both groups tolerated a pH range of 7 to 9 or 10.

Various microbiological characteristics were

Table 5.3 Microbial species isolated from Dungeness and Tanner crabs collected in Kodiak waters (Atlas, 1976).

Isolated from	Gill	Muscle	Eggs
Dungeness Crab	Acinetobacter calcoaceticus Pseudomonas maltophilia Pseudomonas fluorescens Group D streptococcus, including one isolate--Enterococcus Enterobacter agglomerans Citrobacter freundii Klebsiella pneumoniae, possibly K. ozonae Aeromonas hydroxyla Staphylococcus epidermidis (Coag. neg.) Sarcina spp. Yersinia enterolitica Alcaligenes spp. Moraxella spp. Pasteurella spp.	Staphylococcus epidermidis Sarcina spp. Group D streptococcus Pseudomonas spp. Alcaligenes spp. Moraxella spp. Pasteurella spp. Acinetobacter calcoaceticus Micrococcus spp.	
Tanner Crab	Staphylococcus epidermidis Micrococcus spp. Alcaligenes spp. Moraxella spp. Acinetobacter calcoaceticus	Staphylococcus epidermidis Micrococcus spp.	Staphylococcus epidermidis Micrococcus spp. Sarcina spp. Alcaligenes spp. Acinetobacter calcoaceticus Pseudomonas fluorescens

measured during November and Apri 1977 and April 1978 at a series of stations around Kodiak island (Griffiths and Morita, 1978; Table 5.4). The samples were taken as part of a ling program which included Cook Inlet. In the Kodiak area, the majority of the samp.es were taken from Shelikof Strait.

Relative microbial activity in samples from Kodiak waters was quite variable and showed no spatia or temporal patterns. High activities were found in water from the Kodiak side of Shelikof Strait in Apr ; their cause is unknown. Activity in sediment samples was higher than that in water samples. Overall, microbial activity was lower than that observed in northern Cook Inlet and similar to those in the northeast Gulf and

Table 5.4 A summary of microbial characteristics from Shelikof Strait and around Kodiak in April and November 1977 and April 1978. Numbers in parentheses refer to sample size (Griffiths and Morita, 1978; 1979)

	Microbial Activity[a]	Respiration (percent)	Nitrogen Fixation[b]	Crude Oil Degradation Potential[c]
WATER				
Shelikof Strait				
Apr	2.8±2.8 (12)	65±9.8 (10)	-----	
Nov	0.8±0.3 (12)	64±6 (09)	-----	-----
S. E. Kodiak				
Apr	7.6±11 (03)	71±7.8 (03)	-----	-----
Nov	1.1±0.3 (03)	62±5 (03)	-----	-----
SEDIMENT				
Shelikof Strait				
Apr	15.3±10.6 (10)	55.4±13.1 (05)	0.38±0.07 (02)	74±18 (20)
Nov	22±5 (11)	58.5±2.1 (02)	1.1±1.1 (19)	272±188 (12)
S. E. Kodiak				
Apr	9.5±2.1 (02)	-----		-----
Nov	68±10 (02)	56±2 (02)	0.5±0.3 (05)	542±235 (02)

[a] in terms of Glutamic Acid uptake, units = ng Glutamic Acid/liter/hr
[b] units = ng/dry wt/hr
[c] units = DPM/g dry wt

Lower Cook Inlet. Respiration percentages exceeded 50 percent in both sediment and water samples, suggesting that the Kodiak bacterial populations are stressed by their environment since they respire most of the carbon they assimilate.

The nitrogen fixation rates measured in Shelikof Strait were much higher than rates measured in Kamishak Bay but lower than those measured in Kachemak Bay. They indicate a high rate of microbial productivity in the Strait.

Microorganisms which degrade petroleum are found universally. Hydrocarbon utilizing microbes have been identified wherever careful attempts have been made to isolate them; their populations are denser in areas where oil is present (Karrick, 1977). Over 200 species of bacterial, yeasts, and filamentous fungi have been shown to metabolize one or more hydrocarbon compounds, which range in complexity from methane to compounds o over 40 carbon atoms (ZoBell, 1973a).

Because marine bacteria are mainly psychrophilic (cold-adapted organisms that grow fairly rapid.y at temperatures near the freezing point), it is not surprising that microbial degradation of petroleum hydrocarbons can occur in cold regions. ZoBell (1973b) has demonstrated petroleum degradation at temperatures as low as -1.1°C. Kinney et al. (1969) found that biodegradation was more important than physical flushing in removing hydrocarbons from Cook Inlet. They estimated that the crude oil in Cook Inlet is complete.y biodegraded in one to two months. Karrick (1977 believes that microbial degradation is the most important process involved in weathering and eventual disappearance of petro.eum from the marine environment

Rates of microbia degradation of hydrocarbons in the marine environment depend on the chemical complexity of the oil, the characteristics of the microbial popu.ations, and environmental conditions; therefore,

it is difficult to predict the rate of microbial oil removal in the marine environment (National Academy of Sciences, 1975). Comparative estimates can be obtained, however, on the potential rates of microbial degradation in marine environments.

Measurements of the crude oil degradation potential (defined as the amount of $^{14}CO_2$ produced when a culture of microorganisms is inoculated with crude oil to which has been added a pure ^{14}C-hydrocarbon) were made from samples taken near Kodiak in November and April (Griffiths and Morita, 1978). The data were too limited to draw conclusions concerning spatial or temporal variability. The levels were similar to those obtained in Cook Inlet (although some areas of Cook Inlet have very high biodegradation potentials). There appeared to be no differences between the crude oil potential in the water and that in the sediments.

Data collected by Atlas (1978a) suggest that exposure to crude oil selects for and enriches hydrocarbon utilizers but at the same time reduces the species variation within a given microbial population. Griffiths and Morita (1979) found a reduced glucose and glutamate uptake when bacteria were exposed to crude oil (Table 5.5). While no changes in nitrogen fixation rates were observed during eight hours of exposure, nitrogen fixation appeared to be reduced after several months' exposure (Griffiths and Morita, in litt.).

These results have certain implications for oil and gas development. If hydrocarbon-degrading bacteria are selected for in chronically oiled areas, oil that enters the marine system will be more quickly degraded. However, the concomitant decrease in microbial diversity predicted by Atlas implies that the structure of bacterial populations might be altered, suggesting that some of the functions normally performed by the microbes might not be performed. It is not known, however, how an alteration in bacterial population would affect higher levels of the marine food web.

Table 5.5 The effects of crude oil on the uptake and respiration of glucose and glutamic acid by natural marine microbial populations found in water and sediment samples taken from the Lower Cook Inlet and the Beaufort Sea. The percent reduction is reported as the mean value for all observations (Griffiths and Morita, 1979).

Study Area	Date	GLUCOSE Percent Reduction	GLUCOSE Number of Observations	GLUTAMIC ACID Percent Reduction	GLUTAMIC ACID Number of Observations
WATER					
Beaufort	1/78	[c]45	8		
Beaufort	4/78	0	3	0	2
Beaufort	9/78	52	40		
Lower Cook	11/77	41	21		
Lower Cook	4/78	45	32	33	35
SEDIMENT					
Beaufort	9/77	[c]35	20	33	20
Beaufort	4/78	24*	5	7*	5
Beaufort	9/78	32?:	30		
Beaufort	1/79	12*	6		
Lower Cook	4/78	14+	26	18*	7

[c]These values are for average percent reduction in respiration only.

*These difference were not significant at the 0.05 level.

In the Beaufort Sea studies, Prudhoe Bay crude oil was used and in the Lower Cook Inlet study, Lower Cook Inlet crude oil was used.

5.3 PLANKTON

5.3.1 Introduction

The organic matter produced by phytoplankton through photosynthesis is an essential component of the food web in marine waters. The rate of phytoplankton productivity fluctuates seasonally according to changes in various physical, chemical, and biological parameters.

In the higher latitudes the greatest productivity occurs during the spring and summer. The increased light and stability in the water column stimulate the onset of the spring bloom. Lack of light is the major factor limiting productivity in the higher latitudes during the winter.

The water column is stabilized by the formation of the thermocline (a region of the water column characterized by a rapid temperature change). The presence of a thermocline reduces turbulence, which carries the plant cells into deeper waters and effectively decreases algal productivity. The same turbulence in winter is important in bringing nutrient-rich deeper waters to the surface where they are available to the phytoplankton during the spring bloom.

The lack of nutrients is probably the major cause of slowed phytoplankton growth after the spring bloom. Because the water column is stratified, nutrients are not regenerated in the surface waters as quickly as they are utilized by the phytoplankton. Usually nitrates are the limiting nutrient, but phosphate or silicate may also be important.

Soon after phytoplankton populations begin to increase, zooplankton populations, which feed on phytoplankton, also begin to increase. The increased grazing pressure also limits phytoplankton growth.

5.3.2 Phytoplankton

Presently there are few data on the distribution of phytoplankton in Kodiak waters. In a compilation of phytoplankton data for the entire Gulf of Alaska, the only data for the Kodiak area are a few samples collected during the summer in offshore waters (Anderson et al., 1977). The paucity of data is unfortunate in light of the high productivity of the Kodiak shelf.

Data on primary productivity are too sparse to infer seasonal patterns of spatial variability Larrance et al. 1977 found concentrations of chlorophyll at a maximum in July near the mouth of Cook Inlet. At Station 10, about 100 km northeast of Afognak Island, the maximum value occurred in early May, possibly indicating a shelf bloom of phytoplankton. The chlorophyll concentration at Station 11, 200 km east of Afognak Island, did not change markedly during the sampling period of April to August. The highest primary productivity values (5-10 $mC/m^2/day$) in this study were recorded at Station 11 in May 1976.

Anderson et al. (1977) described phytoplankton trends from data collected from the neritic and oceanic zones of the Gulf of Alaska. Similar trends probably occur in the Kodiak area. These authors found a marked seasonal variation in levels of chlorophyll a in the surface layers of neritic areas, i.e., areas shoreward of 200 m depth. Spring averages were generally higher than summer averages. Similar trends were observed in chlorophyll a levels in the euphotic zone

In surface waters and at depths down to 25 m primary productivity peaked in summer in oceanic zones, but it peaked in spring in neritic zones, and remained higher throughout the umm than in oceanic zones (Anderson et al., 1977). Below 25 m productivity is low in spring in neritic zones and in um in oceanic zones Productivity below 50 m was negligible in both zones because of the low light intensity.

Surface levels of nutrients (phosphate, nitrate, silicate) also vary seasonally (Anderson et al., 1977). They peak during winter and then steadily decrease until umm An increase between summer and fall has been attributed to regeneration and mixing. Average nitrate concentrations approach zero in neritic areas in summer but remain well above those necessary for phytoplankton growth in oceanic areas. The difference has been attributed to the shorter growth period in ic areas and to the lower biomass of oceanic phytoplankton resulting from grazing (cf. Anderson et al., 1977). Surface concentrations of phosphate and silicate are similar, both seasonally and geographically to those of nitrate. Average phosphate concentrations do not drop as low as nitrate concentrations in neritic areas, suggesting that nitrate is probably a limiting nutrient in those areas.

Little information is available on the seasonal or geographic variations in phytoplankton itin of Kodiak waters Larrance et al. (1977) found that the microflagellates, which are members of the Chrysophytes and Cryptophytes, are numerically dominant in the oceanic areas of the Gulf of Alaska, while larger diatoms, such as Thalassiosira sp. and Chaetoceros sp., are dominant in the neritic areas. Anderson et al. (1977) did not distinguish between oceanic and neritic species because of the limited number of neritic stations sampled. For the most part, however, the subarctic phytoplankton communities are widely distributed. The species distributions could not be correlated with biological differences among subarctic water, mixed water, Alaska gyre water, and Alaskan stream water. Table 5.6 shows rankings for the most abundant phytoplankton of the Gulf of Alaska based on 121 ship of opportunity samples.

Effects of petroleum on phytoplankton

Petroleum in the marine environment may inhibit the growth of phytoplankton. Laboratory studies have shown that the toxicity of petroleum hydrocarbons to phytoplankton varies with species, environmental ditions, and the type and concentration of oil (Anderson et al., 974; Pulich et al., 1974; Mironov, 1970) At low levels, however, oil has been shown to stimulate phytoplankton growth (Dunstan et al., 1975). Anderson et al. (1974) showed that crude oils with a high percentage of aromatic hydrocarbons are the most toxic. Other studies, however, have shown that aliphatic hydrocarbons inhibit phytoplankton photosynthesis more than do aromatics (Parker, 1974).

Because of their drifting habit and rapid generation time, coastal or open water populations of phytoplankton are unlikely to be chronically polluted by petroleum. Nearly forty years of petroleum operations off the Louisiana coast have had no detectable effect on the phytoplankton of that region (Fucik, 1974). This may not be true, however, of enclosed basins or bays where exchanges of bay water with open ocean water are limited and where phytoplankton are restricted to the bays. Hydrocarbon levels in the Bedford Basin, Nova Scotia, were calculated to be sufficient to depress photosynthetic activity by a few percent (Gordon and Prouse, 1973). Decreases in phytoplankton productivity from chronic oil pollution have also been reported from the Caspian Sea (Clark, 1971)

Major oil spills, for the most part, have affected the phytoplankton only minimally. After the Torrey Canyon spill, all stations sampled except one had healthy phytoplankton populations. At the exceptional station algae of the family Prasinophyceae showed shrinking of the cell contents from the cell wall. Diatoms and dinoflagellates seemed unaffected, however (Smith, 1968). Studies after the Santa Barbara oil spill in 1969 failed to show contamination of phytoplankton by the oil (Oguri and Kanter, 1971).

Table 5.6 Rankings of the most abundant phytoplankton species in the Gulf of Alaska. Compilations were made from 121 ship of opportunity samples (modified from Anderson et al., 1977).

	RELATIVE RANK				
	Occurrences	Mean No. cells/1	Max. % of total cells	Mean carbon/1	Max. % of total carbon
Diatoms					
Thalassiosira lineata	1	---	---	---	---
Nitzschia sp. (*Pseudonitzschia* group)	2	4	---	---	---
Nitzschia pseudonana	3	1	---	1	---
Denticula seminae	4	2	5	3	---
Corethron hystrix	---	5	1	5	2
Rhizosolenia alata f. *inermis*	---	3	2	4	4
Asteromphalus spp.	---	---	4	---	---
Ethmodiscus rex	---	---	3	---	3
Dinoflagellates					
Ceratium pentagonum	---	---	---	---	5
Gyrodinium spp.	5	---	---	---	1
Coccolithophorids					
Cyclococcolithus sp.'B.'*	---	---	---	2	---

* *Cyclococcolithus* sp. 'B.' resembles *Cyclococcolithus fragilis*.

5.3.3 Zooplankton

Zooplankton are the most important consumers of phytoplankton. In turn, the zooplankton are consumed by organisms at higher trophic levels. In spite of their importance in the food web, however, little is known about zooplankton numbers or distributions on the Kodiak shelf.

The NORPAC Atlas (1960) shows that off Kodiak Island zooplankton biomass values (presumably settled volume) were about 200 $cm^3/1000\ m^3$. North of Afognak Island 400 $cm^3/1000\ m^3$ were reported. These data are for summer only and are based on very few samples.

Damkaer (1977) found (320 km east of Afognak Island) that zooplankton volume varied from about 1 to 10 ml/m^3 in the upper 25 m with maximum values in late May and early July. For the entire water column (1400 m deep) zooplankton volume estimates varied from 750 ml/m^2 in early April to 1260 ml/m^2 in early July. Since these samples were taken from deep oceanic waters these data may not be representative of the nearshore waters of the lease area.

Copepods were the most abundant holoplankters in the nearshore zone off Kodiak (Dunn et al., 1979a). Cnidarians, pteropods, amphipods, chaetognaths, larvaceans, and euphausiids were also important (present at $\geq$ 70 percent of the stations). Siphonophores, heteropods, mysids, and thaliaceans were present at less than 5 percent of the stations. Zooplankton were more abundant on the shelf during the fall than in the spring.

Euphausiids are an important food source of fish, birds, and marine mammals. Dunn et al. (1979a) found that euphausiids spawn from early March until early fall. They are found throughout the Kodiak shelf area.

Effects of petroleum on zooplankton

Holoplankton populations show large seasonal fluctuations; they have generation times of weeks or months. Thus it is likely that effects of oil spills on open-water populations would be negligible or short-lived. Studies of the effects of oil on zooplankton lend support to this hypothesis. Zooplankton were found to have ingested small particles of oil after the *Arrow* spill in Chedabucto Bay, Nova Scotia. As much as 10 percent of the oil in the water column was found in zooplankton feces (Conover, 1971). No permanent effect on zooplankton was observed after either the *Arrow* or the *Torrey Canyon* spill (Smith 1968), but an entirely different outcome is possible in chronically polluted basins or enclosed bays where the organisms would be continuously exposed to the hydrocarbons.

5.4 BENTHIC INVERTEBRATES

5.4.1 Introduction

Continental shelf and slope waters surrounding the Kodiak archipelago are biologically very productive. Large populations of commercially harvested species of crabs, shrimp, and fishes use these waters as principal spawning, rearing, and foraging grounds. In addition, large populations of noncommercial, yet ecologically important, benthic invertebrates are found throughout the region. Benthic invertebrates play a key role in the trophic structure of the Kodiak marine environment. If invertebrate populations are adversely affected by petroleum development or natural phenomena, populations of many marine fish, birds, and mammals will also be affected.

Major fishing grounds for crabs and shrimp are located in Kodiak waters; small quantities of scallops and clams are also harvested. Total value of the shellfish catch to the fishermen in 1978 was $38.6 million (Fig. 5.1). Nearly 21 percent of the entire Alaskan shellfish catch was taken within the Kodiak Management Area (Fig. 5.2). Most of the Kodiak OCS lease tracts are located within this zone.

The oil industry and Bureau of Land Management have designated 1.3 million hectares of offshore tracts to the east of Afognak, Kodiak, and Trinity Islands to be leased for OCS development in December 1980 (Lease Sale #46). These tracts are located in 30-250 m of water. The possibility of conflicts between exploration, refining, and transportation of oil and gas and the fishing industry will have to be faced by developers, resource managers, and Kodiak citizens (see Chapter 7 for further explanation).

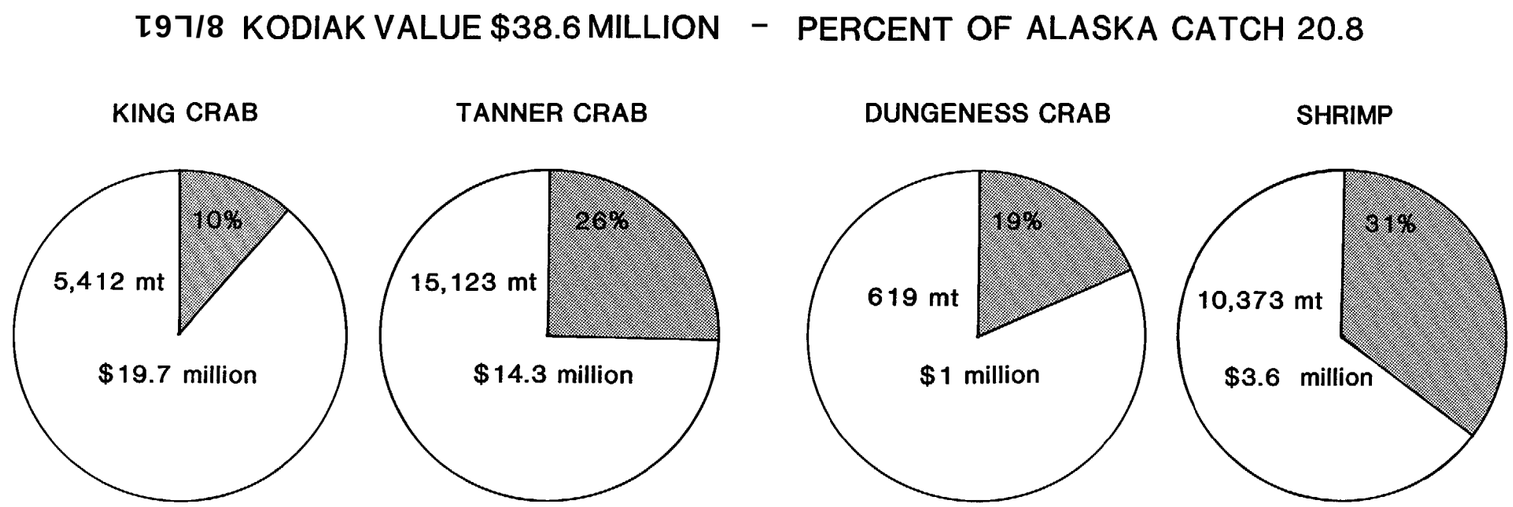


Figure 5.1 Commercial catch of crabs and shrimp in ADF&G Kodiak management district in 1978, compared to total Alaskan catch. The Kodiak catch is given in metric tons (mt). Values are based on the average price paid to the fishermen (ADF&G, 1979a).

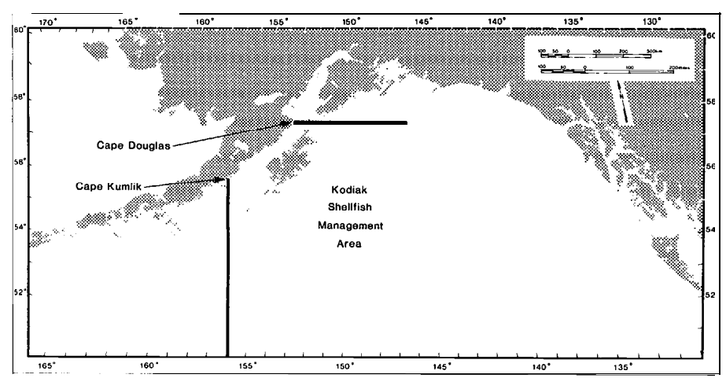


Figure 5.2 Kodiak shellfish management area (ADF&G, 1979a).

A thorough understanding of the invertebrate populations is a prerequisite to assessing the consequences of oil and gas development on the Kodiak shelf. Knowledge of the life histories, seasonal distributions, population dynamics, and feeding relationships of invertebrates will allow researchers to determine the vulnerability and sensitivity of species to environmental disturbances. It can also be used by resource managers in decision-making and in reducing conflicts among users of the various resources. Where to build an LNG plant, or how to route tanker traffic so as to minimize disturbance of commercial crab and shrimp populations near Kodiak are examples of the kinds of decisions which will have to be made.

This chapter provides an overview of commercially important benthic invertebrate populations in the Kodiak area and briefly describes their value as a fishery. Non-commercial, ecologically important species are also discussed.

5.4.2 Commercially important species

Information concerning the distribution and abundance, population dynamics, and trophies of benthic invertebrates is compiled by the Alaska Department of Fish and Game (ADF&G), International Pacific Halibut Commission (IPHC), National Marine Fisheries Service (NMFS), International North Pacific Fisheries Commission (INPFC), North Pacific Fisheries Management Council (NPFMC), and OCSEAP-supported personnel. Common benthic invertebrates in the Kodiak area that are of commercial value are listed in Table 5.7.

King crab

King crabs (*Paralithodes camtschatica*, *P. platypus*, and *P. brevipes*) are found in the North Pacific Ocean, Bering Sea, and Okhotsk Sea (Marukawa in Bright, 1967). In the vicinity of Kodiak, *P. camtschatica* is distributed from the sublittoral zone (Powell and Nickerson, 1965; Feder et al., 1979) to water depths of about 275-350 m (Bright, 1967; ADF&G, 1976). The fishery typically takes adult crabs in 36-200 m of water (AEIDC, 1974). Juvenile crabs are usually found at shallower depths than adults (Fig. 5.3).

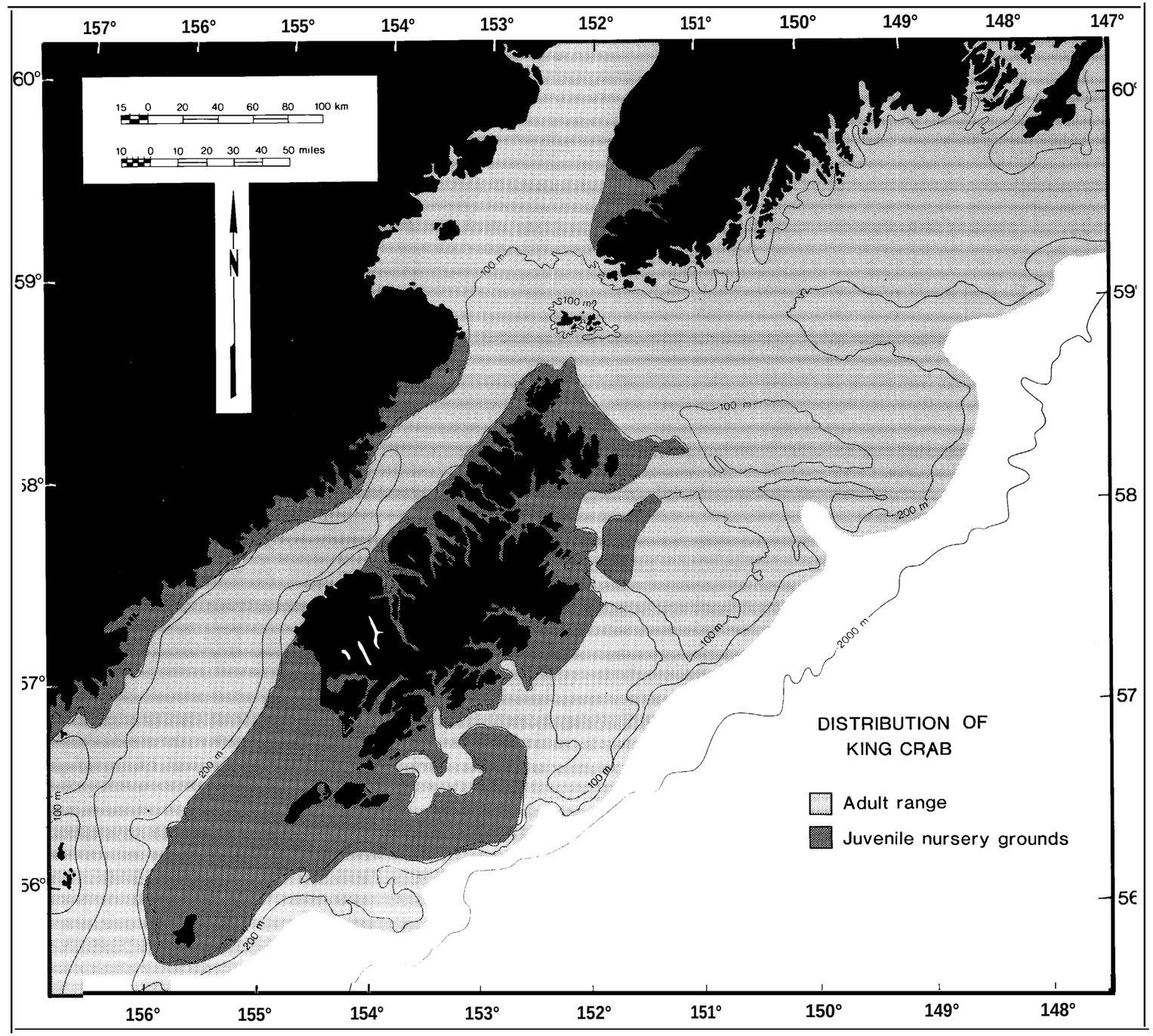


Figure 5.3 King crab distribution in the Kodiak region (Feder et al., 1979; Blackburn, 1979a; Ronholt et al., 1978; ADF&G, 1976, 1979a).

Table 5.7 Commercially important invertebrates of the Kodiak Area.

Common Name	Scientific Name
Red king crab	Paralithodes camtschatica
Tanner (snow) crab	Chionoecetes bairdi
Dungeness crab	Cancer magister
Pink shrimp	Pandalus borealis
Humpy shrimp	Pandalus goniurus
Spot shrimp	Pandalus platyceros
Coonstripe shrimp	Pandalus hypsinotus
Sidestripe shrimp	Pandalopsis dispar
Razor clam	Siliqua patula
Weathervane scallop	Patinopecten caurinus

Adult king crabs migrate annually from deep water to shallower areas along the Kodiak coast and onto offshore banks such as Portlock and Marmot Flats to breed (Powell, 1964; McMullen, 1967). During migration females and males school separately. Females precede males to the breeding grounds by a month or so, and have been observed on these grounds as early as January (Fig. 5.4; Powell et al., 1974). While migrating shoreward, king crabs probably follow the submarine valleys on the shelf which usually lead them to embayments (Powell, 1964; Powell and Reynolds, 1965). King crabs may travel as far as 100-115 km to reach their breeding grounds (ADF&G, 1976).

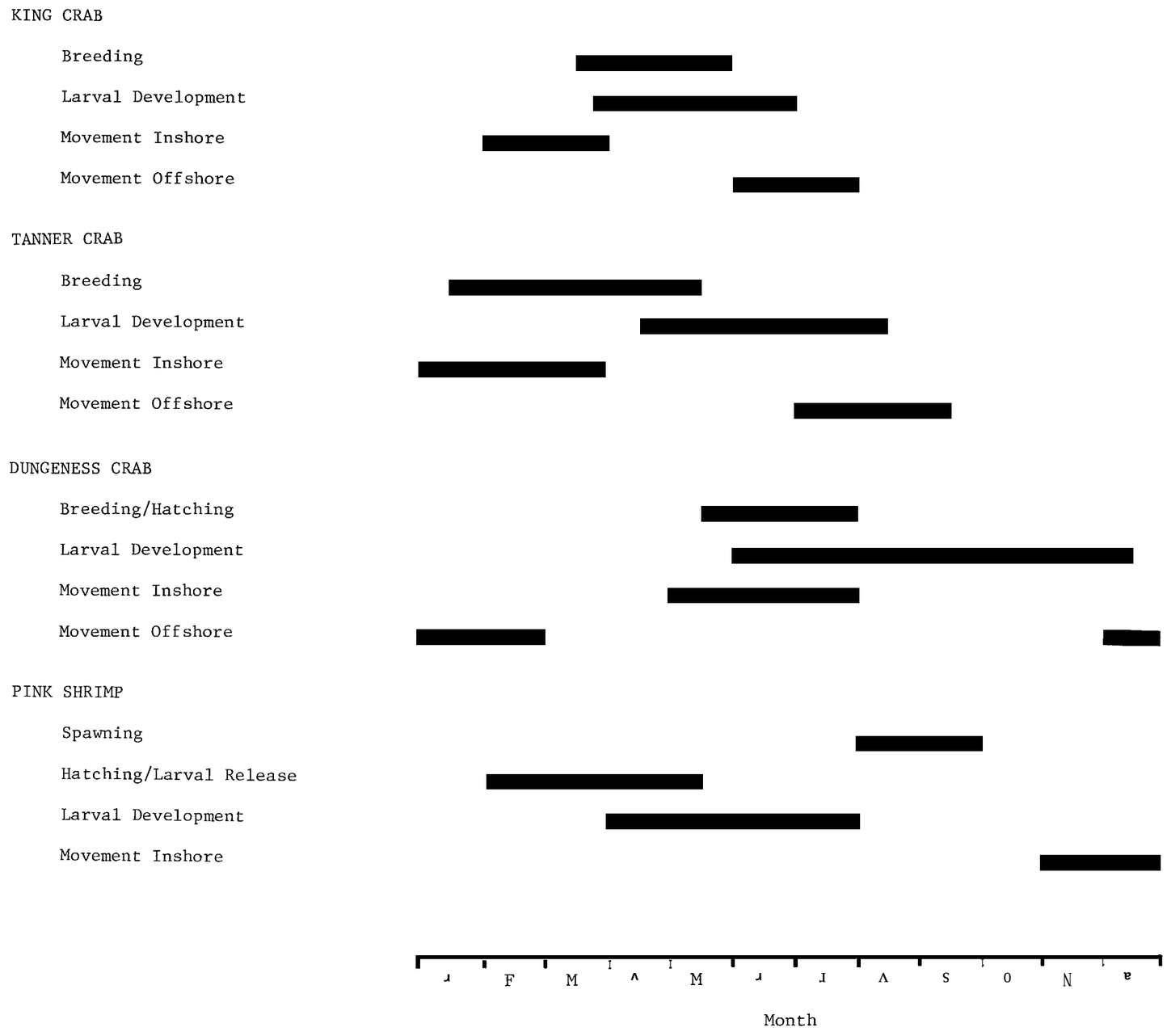


Figure 5.4 Generalized life history tables for commercially important crabs and shrimp in Kodiak area (ADF&G, 1976; Buck et al., 1975; Bright, 1967; Eldridge, 1972a, b; Fox, 1972; Hoopes, 1973; Mayer, 1972).

Female crabs must molt before mating, but males need not. Males generally molt annually, but old males (> 8 years old) shed their exoskeletons only once every two or three years. Molting takes place on the breeding grounds from February through May; younger adults molt earlier in the season than older crabs. Males molt earlier than females of the same size (Gray and Powell, 1966).

Copulation occurs shortly after the female molts. If it does not take place within several days, fertilization will not occur (Kurata, 1960). Older males may play a more significant role than younger males in reproductive success of the stock because they are able to mate throughout the entire season, while young males are hampered by the stress of ecdysis 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 producing 400,000 eggs (Eldridge, 1972a). Ovigerous females and adult male king crabs apparently feed heavily in coastal bays of Kodiak after mating before returning to deep waters (Feder et al., 1979).

Free-swimming zoea larvae are released the next season as females return to their breeding grounds. Zoea larvae molt through four instars, then metamorphose into a glaucothoe benthic larval phase. Glaucothoe larvae molt into a juvenile stage that resembles the adult (Buck et al., 1975).

Juveniles live solitary, secretive lives on rocky substrates until they are a year old, or about 15 mm in length. They usually inhabit intertidal areas, often associated with algae, molluscs, and echinoids (Bright, 1967). At one to two years of age, they begin to move about actively and aggregate, forming dense pods. These usually contain up to several thousand individuals (Powell and Nickerson, 1965; Bright, 1967), although an immense pod of perhaps 500,000 crabs was observed in Chiniak Bay in April, 1962 (Powell and Nickerson, 1965). Older juveniles (> 60 mm carapace length) again disperse, and, like adults, move offshore to feed. in summer and fall, returning to shallower waters in spring. King crabs do not reach maturity until their seventh or eighth year (Powell, 1967). Most studies have shown that king crabs segregate by sex and age class on their offshore feeding grounds (literature cited in Pereyra et al., 1976).

The growth of king crabs, as measured by frequency of molt and increase in size, is affected primarily by the abundance of food (Bright, 1967) and by temperature (Kurata, 1960). Crabs molt up to 11 times during their first year. In the next two years they grow to about 60 mm carapace length (CL). After three years, both sexes usually molt annually. Males increase about 16 mm in carapace length per annum, whereas females grow more slowly. Males grow to a maximum size of 200 mm CL, females to 160 mm CL (Weber, 1967). King crabs probably live for about 14 years (Powell, 1967).

The abundance of king crab has been estimated from catches taken during exploratory trawl surveys (Ronholt et al., 1978; ADF&G, unpub. data). In 1973-75, 22,000 mt of crabs were estimated to be on the Kodiak Shelf and in Shelikof Strait. The estimate for 1961 was 2.7 times as great for the same sampling area (Ronholt et al., 1978). Intensive fishing for the species probably was the main cause of the decline.

The ADF&G closely monitors the commercial catch of king crab. The fishery for king crab in the Kodiak area began in the late 1940's. In the early 1960's, the harvest increased significantly, peaking in the 1965-66 fishing season (Fig. 5.5). Since then there has been a major decline in the commercial catch, even

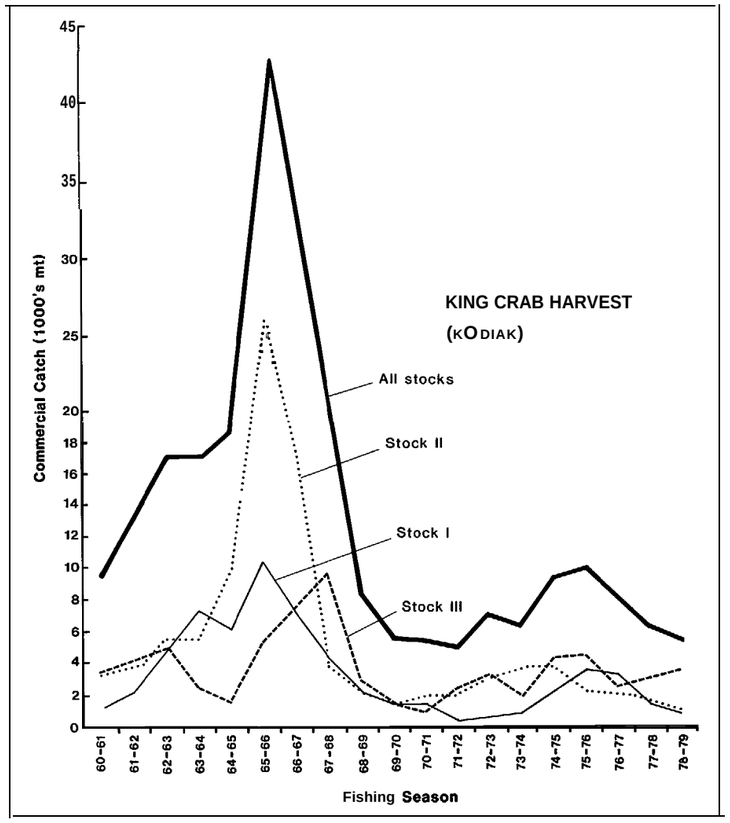


Figure 5.5 Annual commercial catch of king crab by stock in Kodiak management district 'for 1960-79. Catch reported in metric tons (ret) (ADF&G, 1979a).

though the fishing effort has remained high (Fig. 5.6). Key fishing areas for the 1969-75 period are shown in Fig 5.7, but smaller amounts of crabs also were taken throughout the region (ADF&G, 979a

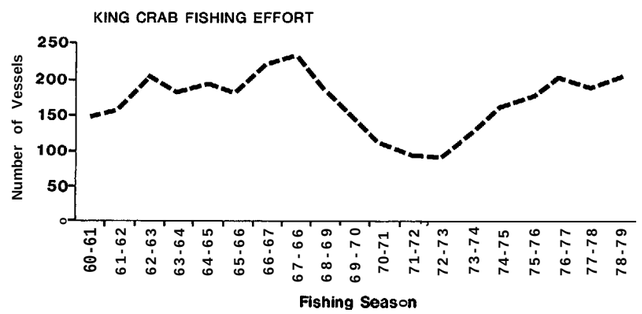


Figure 5.6 Fishing effort for king crab in Kodiak management district, 1960-79 (ADF&G, 1979a).

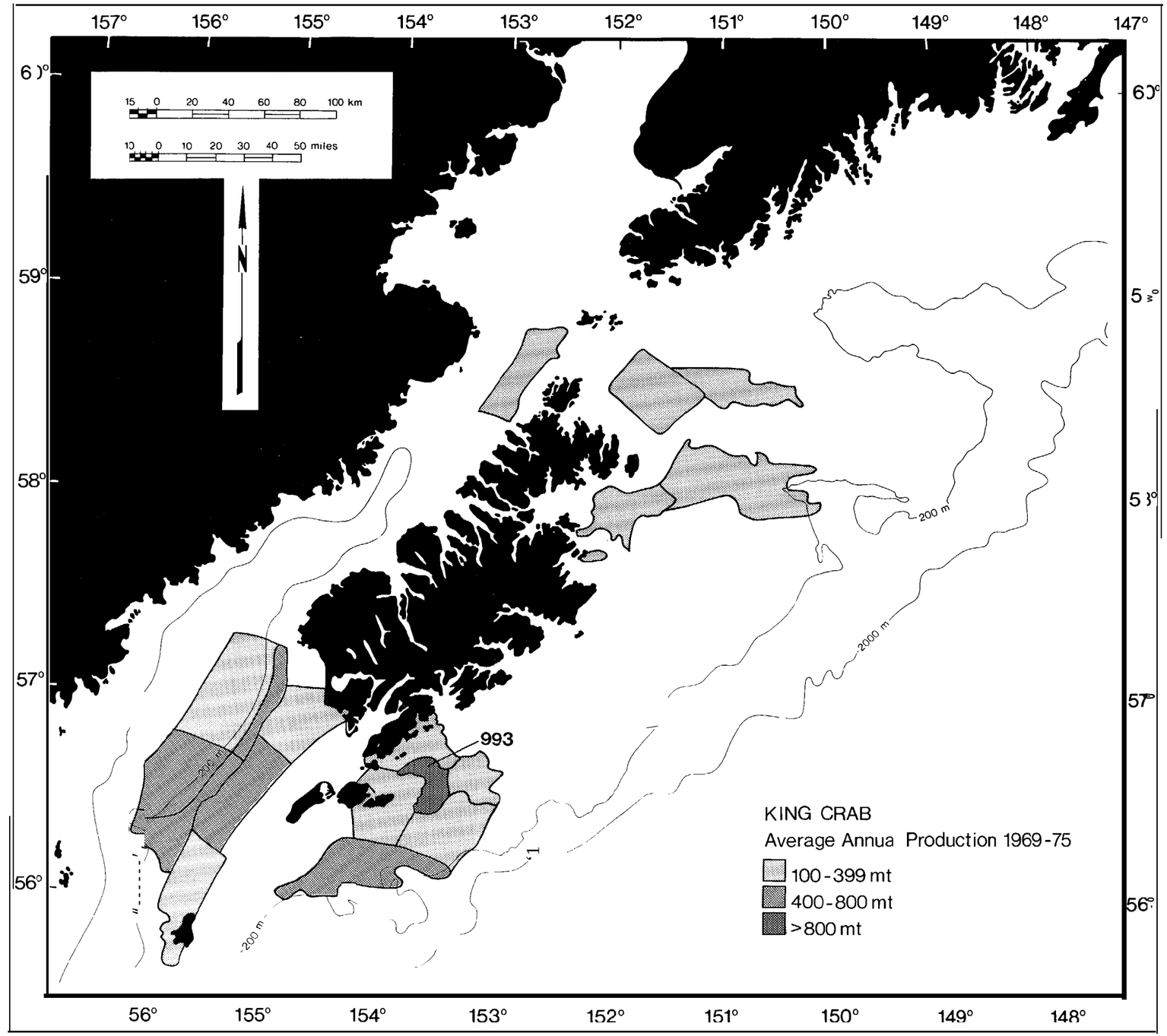


Figure 5.7 Areas of high commercial catches of king crab by U.S. fishermen, 1969-75. King crab were harvested in smaller amounts throughout the region (Ronholt et al., 1978).

From tag return data, the king crab population of the Kodiak management district has been separated into six large stocks (Fig. 5.8; Powell and Reynolds, 1965). Within each stock are found segregated groups called schools. The three stocks historically most important to the Kodiak fishery are located northeast (I), southeast (II), and southwest (III) of Kodiak. Important schools within these three districts are illustrated in Fig. 5.9.

The 1978-79 fishing season extended from September 10 through January 15. Total catch was 5121.4 mt, down 10 percent from the previous season, even though the number of vessels (194) fishing for king crab increased. Eighty-six percent of the catch was taken during the "seven-inch" season (Sept. 10 to Nov. 30). The distribution of catches among districts and schools for the 1978-79 season is given in Table 5.8. The total harvest of crabs was 98 percent of the maximum harvest guidelines in the southwest district, 62 percent in the southeast district, and 48 percent in the northeast (ADF&G, 1979a).

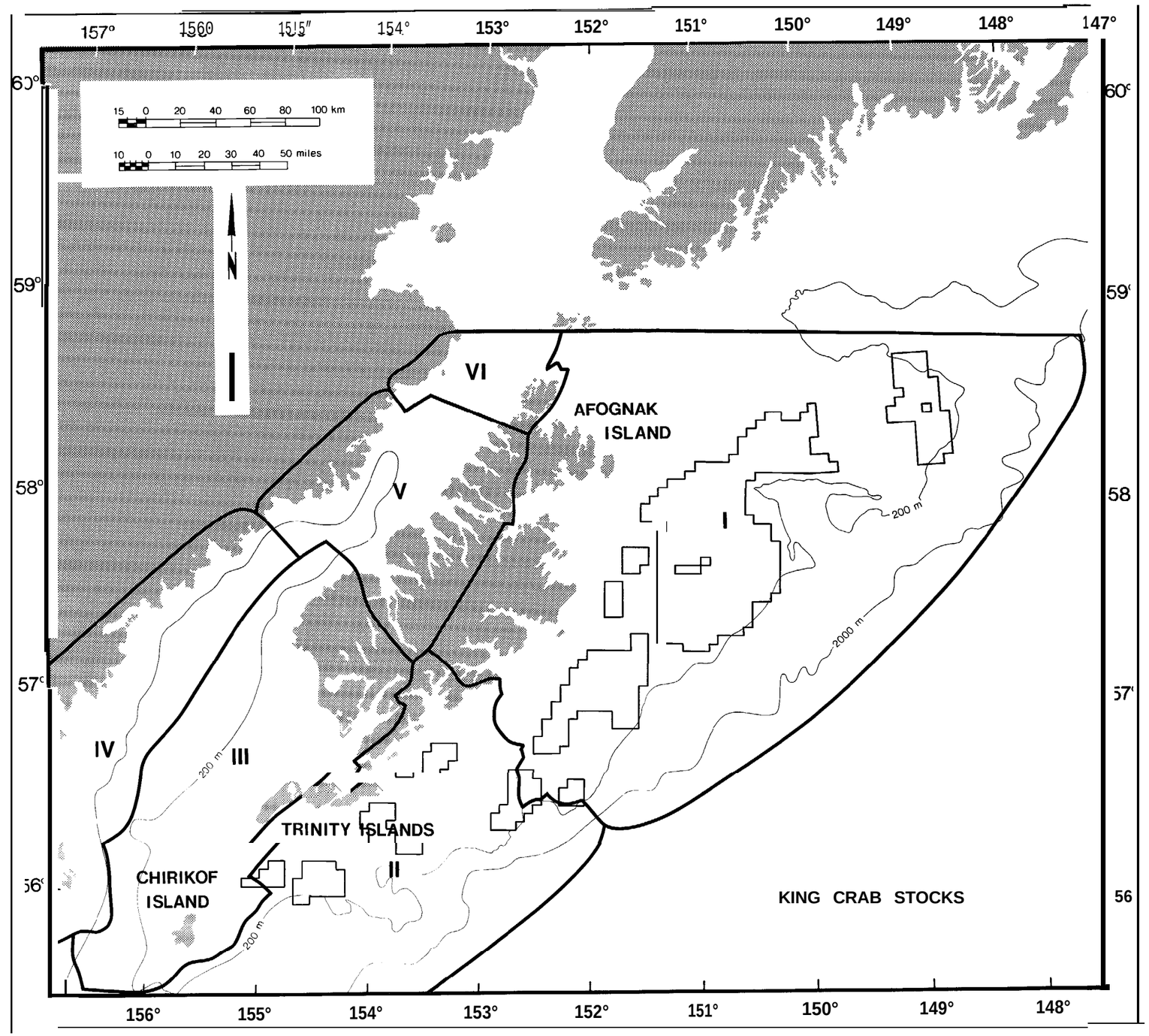


Figure 5.8 Major stocks of king crab in the Kodiak management district (ADF&G, 1976).

Table 5.8 King crab commercial catch, 1978, by district and crab school. Percent of catch that has entered the fishery for the first time (recruits) is given. Number in parentheses corresponds to area designation in Fig. 5.4 (ADF&G, 1979a).

	Catch	
Northeast District (Stock I)	metric tons	percent recruits
Portlock (6)	208.4	18
Marmot Bay (5)	18.7	53
Marmot Gulley (10)	97.1	3·
Marmot Gulley 12)	89.2	25
Chiniak Bay (9)	9.7	57
Chiniak Gulley 14)	137.9	30
(18)	206.2	47
Kiliuda Bay 13)	≈··.2	86
TOTAL	794.4 (15.5% Kodiak catch)	
Southeast District (Stock II)		
Sitkalidak (17)	7	-
Horse's Head (20)	299.5	3
Trin.ty Islands (22)	2s··.2	17
East Chirikof (24)	375.6	26
TOTAL	912.0 (17.8% Kodiak catch)	
Southwest District (Stock III)		
Alitak Bay (21)	205.6	75
West Chirikof (26)	53 .8	14
Compass Rose (30)	1,623.9	38
Ikolik-Alitak (34)	992.5	56
TOTAL	3,353.8 (65.5% Kodiak catch)	
Shelikof Strait (Stock IV)		
TOTAL	61.2 (1.2% Kodiak catch)	

Recruitment is a process in which individuals become available to the fishery It may be achieved by into a region fished or by growth (Ricker, 975). A recruit is defined here as an .ndividual that has attained a size or age that .s exploitable for the

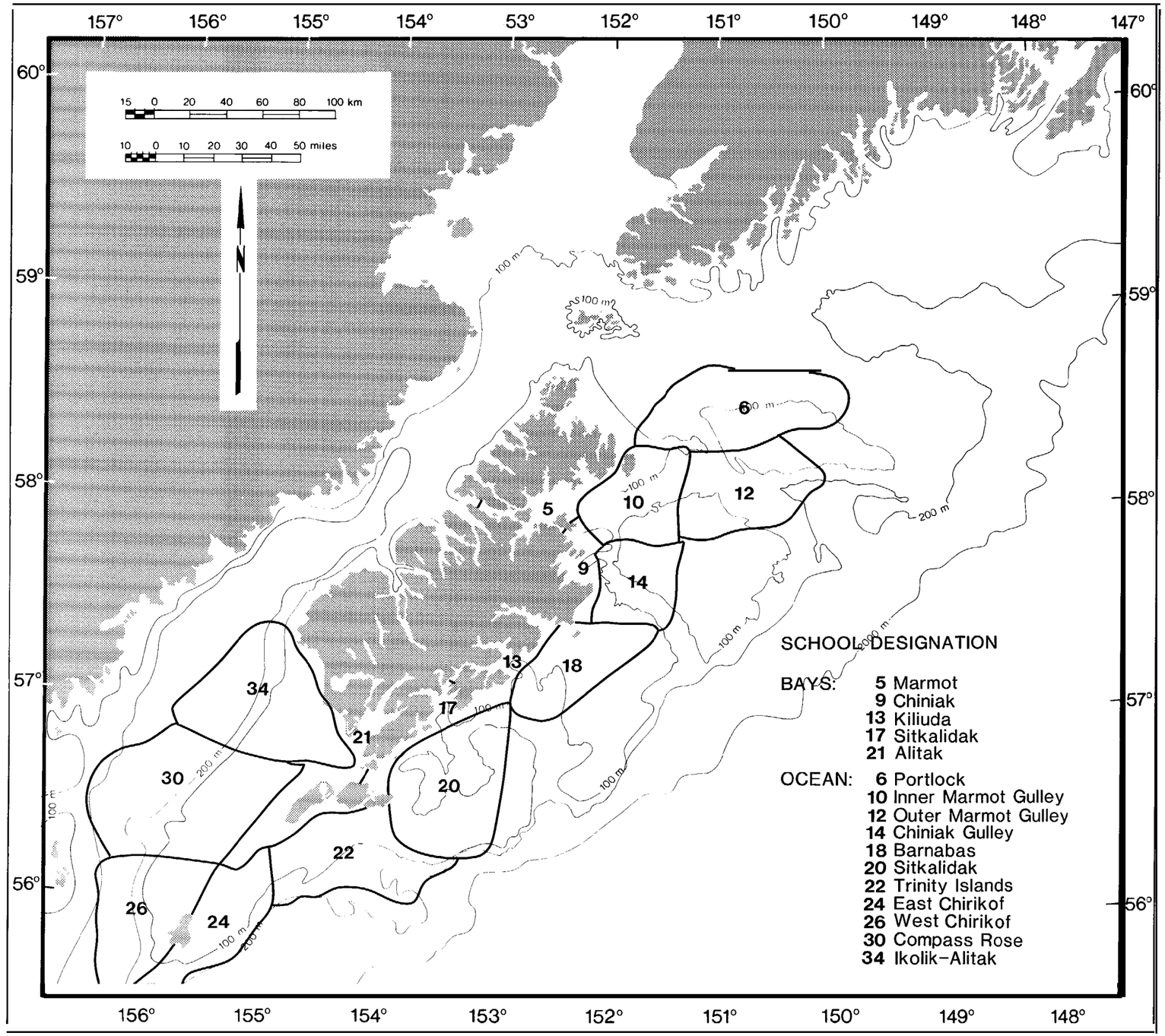


Figure 5.9 King crab schools which are most heavily exploited by the fishery in the Kodiak management district (ADF&G, 1979a).

first time during that fishing season. For instance, male king crabs that molt and become larger than 178 mm CL are recruits of that year. Percent recruitment is often used as one index of viability of a stock. A large proportion of recruits in the catch usually indicates a strong year-class and several years of relatively successful fishing thereafter. Stocks of king crabs appear healthiest in the southwest district, according to the percentage of recruits in the catch (Table 5. 8). This figure was 51 percent in the southwest, 26 percent in the southeast, and 38 percent in the northeast (ADF&G, 1979a).

King crab stock assessments have been conducted by the Kodiak office of the Alaska Department of Fish and Game for the past eight years. Unfortunately, funding of research was cut back severely in 1978-79, and only the southwest and southeast districts could be studied in detail. The relative abundance of crab size-classes in these areas suggests that recruitment will be very good in the 1979-80 and 1980-81 seasons. Harvest guidelines for the 1979-80 season range from 9,500 to 14,100 mt with a probable catch of 11,800 mt or 2.3 times that taken in 1978-79. Predictions for the 1981-82 and 1982-83 seasons, though, are for only "fair" catches (ADF&G, 1979a).

Tanner crab

Three species of Tanner crabs occur in Alaska: Chionoecetes bairdi, C. opilio, and C. angulatus, with C. bairdi the species common in the Gulf of Alaska (Bright, 1967). Tanner crabs are probably the most widely distributed invertebrate of commercial importance in the Gulf (Feder and Jewett, 1978a; Ronholt et al., 1978). Tanner crabs occur from the shallow littoral zone (B. Donaldson, ADF&G, Kodiak, pers. comm.) to depths of 475 m (Fig. 5.10); greatest concentrations are found in water deeper than 100 m (Bright, 1967; Eldridge, 1972b; ADF&G, 1976; Feder and Jewett, 1978a; Ronholt et al., 1978).

In early spring adult Tanner crabs move into shallower depths to spawn (Bright, 1967; AEIDC, 1974; ADF&G, 1975; NPFMC, 1978). The timing of these movements in the Kodiak area is shown in Fig. 5.4. Tanner crabs move onto the inner Aleutian shelf to breed from January through May (AEIDC, 1974). The species migrates into Cook Inlet from March through September, with the peak of spawning occurring from May to August (Bright, 1967) . Tanner crabs spawn in the Copper River delta in April and May (Hilsinger, 1976). In the fall, after breeding, crabs move back into deeper water. Tagging studies have shown that, except for spawning migrations, male Tanner crabs do not wander over great distances (Watson, 1970).

Females are mature when they have completed their puberty molt, and mating commences shortly thereafter while their shells are still soft. Males breed in a hard-shelled condition. Successful mating between two hard-shelled adults occurs in this species (Hilsinger, 1976; NPFMC , 1978) but is less common. Mature male Tanner crabs, like other male decapods, are probably attracted to females by chemical odors released by the females (Kittredge and Takahashi, 1972).

After egg extrusion and fertilization, females carry their egg masses for about eleven months. Gravid females brood an average of 30,000-80,000 eggs (Eldridge, 1972b; ADF&G, 1975), although egg masses of up to 318,000 ova have been recorded (Hilsinger, 1976). In the Copper River area about 80 percent of the eggs are produced by females 90-109 mm in carapace width (CW) (Hilsinger, 1976).

It is suspected that females control hatching times, as larval release appears to coincide with phytoplankton blooms (ADF&G, 1975). Bright (1967) found that captive Tanner crab larvae develop in 12-14 days. Ambient temperatures and food availability most assuredly influence the rate of development and larvae might take much longer to mature into juveniles in the field. Larvae molt through two zoeal stages, a megalops form, and finally metamorphose into juveniles (Bright, 1967; Buck et al., 1975). Juvenile Tanner crabs, which resemble adults, are bottom-dwellers.

The frequency of molting and growth in juveniles is inversely proportional to age. A growth model for the species is presented in the Tanner crab fisheries management plan (NPFMC, 1978). Males and females have similar growth rates until maturity. Females do not molt after their puberty (maturity) molt, whereas males continue to molt annually. Older males, however, molt only once every two or three years (Bright, 1967; Pereyra et al., 1976). Female size at 50 percent maturity is 80 mm CW (Hilsinger, 1976) . Males may attain a maximum size of 185 mm CW, females 125 mm. Tanner crabs are thought to have a lifespan of 12-17 years (Pereyra et al., 1976).

Information on natural mortality in Alaskan Tamer crab stocks is summarized by Pereyra et al. (1976) . Disease, parasites, and predation are the main causes of death.

Tanner crabs have been harvested commercially in the Gulf of Alaska since 1951, but the domestic fishery started on a large scale only in 1968 (Ronholt et al., 1978). The commercial catch and effort in the Kodiak region are shown in Fig. 5.11. As the fishery for king crab in Kodiak decreased during the 1970's, that of Tanner crab expanded (ADF&G, 1979a). Improved processing techniques and higher prices for Tanner crab ($0.40/lb. in 1978) have also stimulated this fishery in Kodiak.

Figure 5.10 Tanner crab distribution in the Kodiak region (Feder, 1977c; Feder et al., 1979; Blackburn, 1979a; ADF&G, 1976, 1979a; Donaldson et al., 1979).

It has not yet been determined whether there are distinct biological stocks of Tanner crabs near Kodiak (Donaldson et al., 1979). While management of the fishery is still in its early phases, the North Pacific

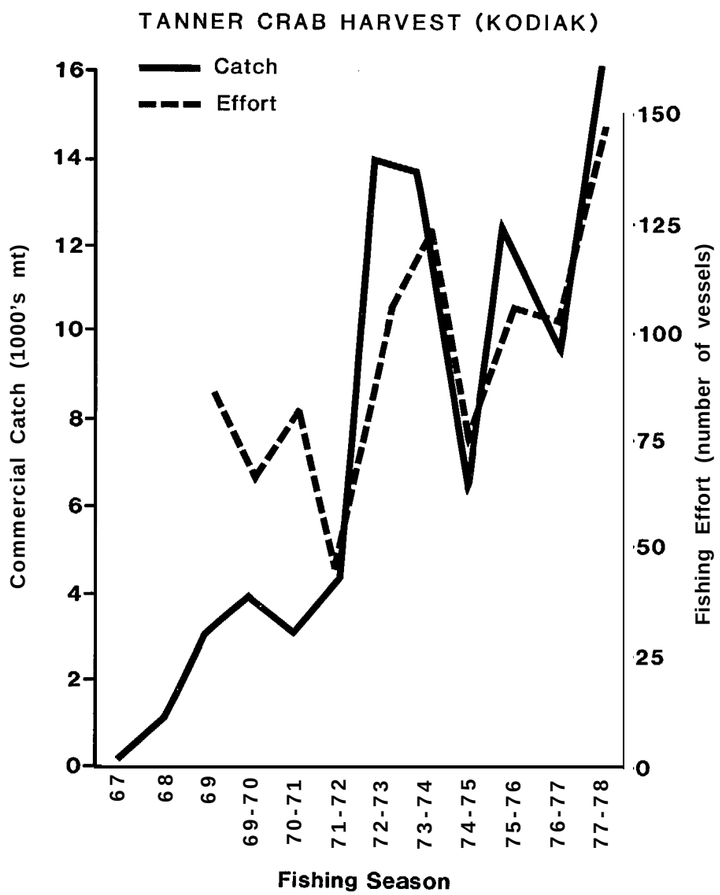
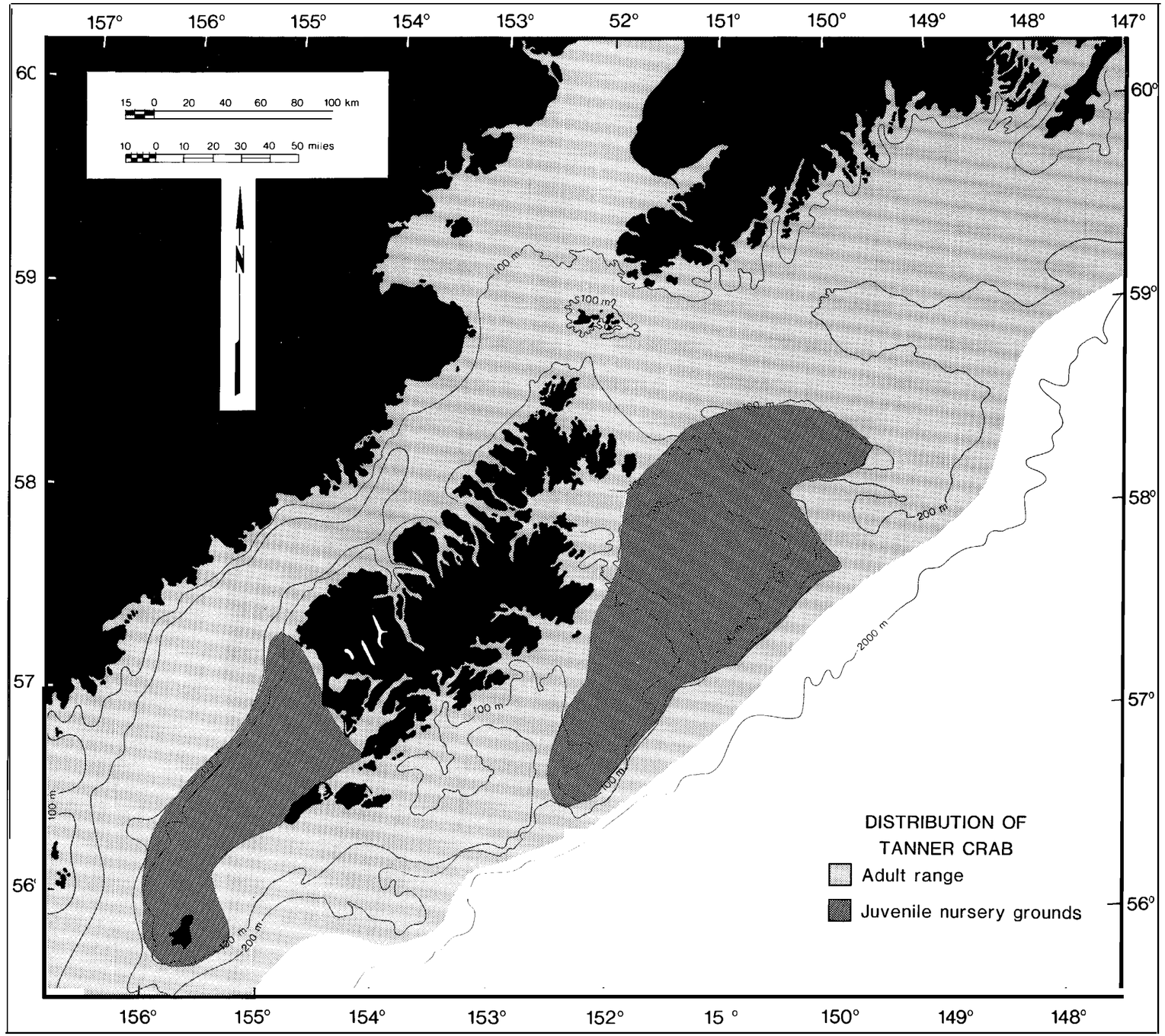


Figure 5.11 Annual commercial catch and fishing effort for Tanner crab in the Kodiak management district, 1967-78 (ADF&G, 1979a).



Fisheries Management Council has prepared a fisheries management plan for Tanner crab. In this plan they specify an Acceptable Biological Catch (ABC) of 9,100-15,910 mt of Tanner crabs for the Kodiak region (ADF&G, 1979a). The 1977-78 harvest of 15,813 mt (ADF&G, 1979a) approached the upper limit of the ABC (Table 5.9).

Key areas for Tanner crab fishing during the past decade are shown in Fig. 5.12 and Table 5.9. The most productive regions are to the south of Kodiak Island, but catches vary from year to year in each area.

The Tanner crab fishing season in 1978 ran from January 5 to May 15. Most crabs were caught between February 16 and April 15.

Table 5.9 Percent Tanner crab catch by ADF&G fishing area and season. Total Kodiak catch given in metric tons (ret) (ADF&G, 1979a).

Fishing Area	Fishing Season 72-73	73-74	74-75	75-76	76-77	77-78
Northeast	14.7	20.6	20.3	14.8	13.6	11.7
East	17.4	18.8	17.8	18.4	14.8	11.7
Southeast	5.4	6.3	4.6	21.4	28.5	15.7
Southwest	30.1	24.1	28.9	19.6	8.6	26.5
N. Mainland	22.4	23.5	25.9	16.7	16.6	20.4
S. Mainland	0.4	0.2	0.1	t	t	t
West	9.4	5.8	1.3	15.9	17.5	13.8
Total Catch (ret)	13,925	13,527	6,191	12,400	9,399	15,096

t = catch less than 0.05 percent

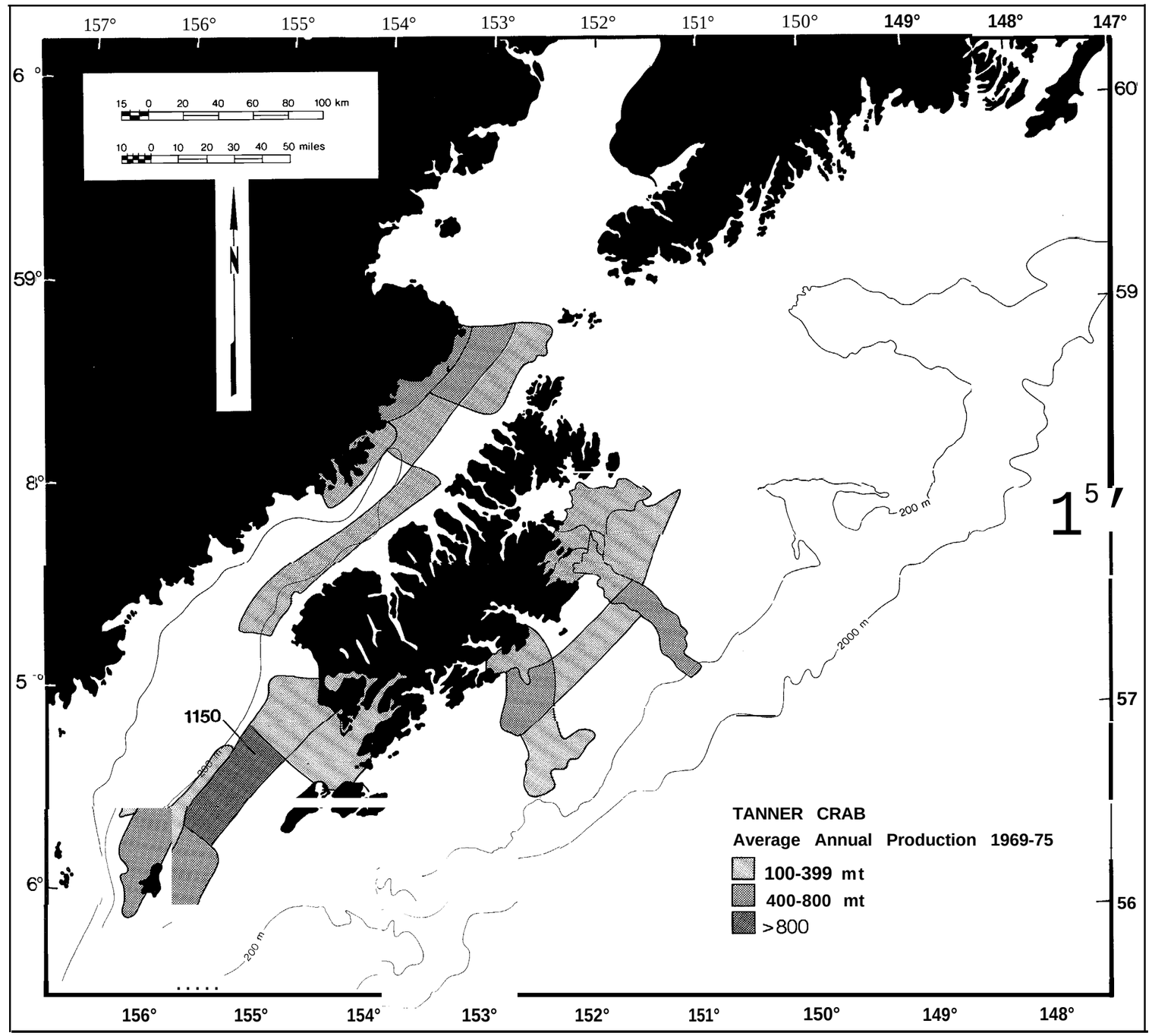


Figure 5.12 Areas of high commercial catches of Tanner crab by U.S. fishermen, 1969-75. Tanner crabs were harvested in lesser amounts throughout the region (Ronholt et al., 1978).

Dungeness crab

Dungeness crabs are distributed in coastal waters along the Pacific coast of North America from ≥aja California to Amchitka Island in the Aleutian chain (McKay 1943, Hoopes, 973). In the Kodiak area, they occur in bays, estuaries, and the open shelf along the entire coast from the .ntertidal zone to 90 ∞ water (Hoopes, .973; ADF&G, 1975; et al.. 1975). Areas ∘f major concentrations ∘f the species are shown in Fig. 5.13. Adult crabs move into the deepest part of their range in winter, apparently avoiding the low temperatures and sal.nities found in the nearshore zone Adults move inshore in spring with the onset ∘f the reproductive period (Mayer, 1972; Hoopes, 973). Dungeness crabs are found on most substrates but prefer sandy or bottoms (ADF&G, .975 . Juvenile crabs inhabit .ntertidal and subtidal waters. They typically hide among protective strands ∘f algae ≥nd eelgrass, or lie buried in the sand (McKay, 1943; Butler, 196∞ . Planktonic larvae are found in epipelagic waters in late spring (Mayer, 972 .

The life cycle ∘f Dungeness crab has been um marized by Mayer .1972), 197≥ , ADF&G .975). Ξuck et al. 1975), and Fig. 5.4. Females spawn in early spring and summer in shallow water. They produce as many as 1.5 million eggs and carry them for seven to ten months before releasing p.anktonic .arvae Larvae molt through si× ≥∘eal stages in three to four months, then into a megalops stage Megalops larvae molt into benthic-dwelling juveniles, which resemble adults. Dungeness crabs mature in about three years Males and females have approximately 140 mm and 1∞∞ mm CW respec-

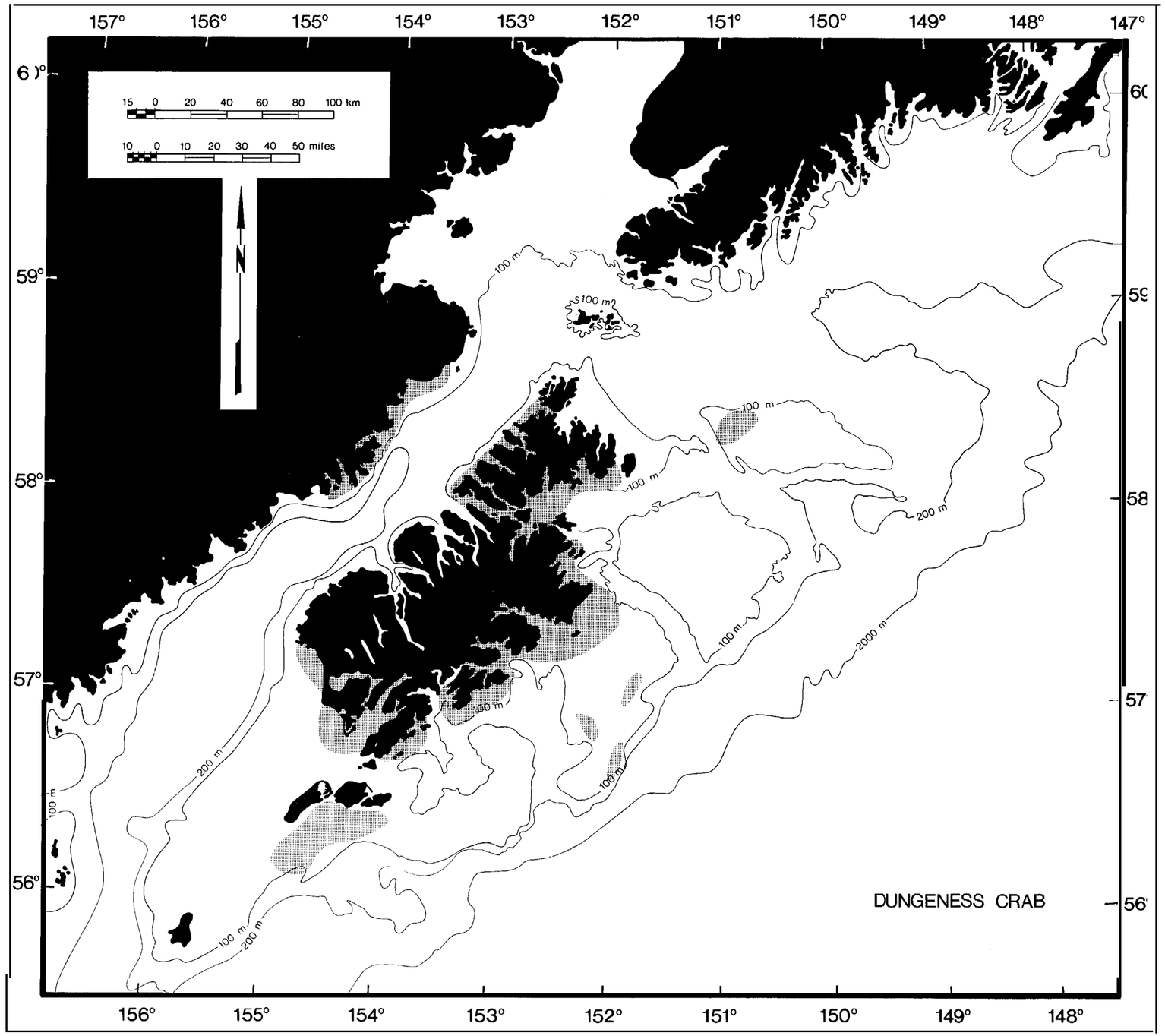


Figure 5.13 Dungeness crab distribution in Kodiak region, excluding areas in Lower Cook Inlet and adjacent to the Kenai Peninsula (modified from Murturgo, 1975).

tively at maturity. Growth is more rapid in Dungeness crabs than in king and Tanner crabs. Male Dungeness crabs may reach 200 mm CW in eight years, while females attain 150 mm CW. Data on natural mortality are lacking, but these crabs presumably face natural hazards similar to those of king and Tanner crabs.

The abundance of Dungeness crab in the Kodiak area is unknown (ADF&G, 1976). Some estimates for populations in the early 1960's are given by Ronholt et al. (1978), but they are probably low because of limited sampling inshore. Extrapolation of catch levels to biomass estimates is more difficult for this species of crab than for king or Tanner crab because the fishing effort for Dungeness is related to the fishing and markets for king and Tanner crab. For example, a decline in the Dungeness crab catch may be a result of large catches of king and Tanner crab earlier in the year rather than the reflection of a decline in Dungeness crab standing stock. Because fishermen try to optimize effort, however, the areas where high catches occur probably coincide with the location of dense populations of harvestable crabs. Key fishing areas during 1969-75 are mapped in Fig. 5.14.

The fishery for Dungeness crab started in Alaska in 1913 (Hoopes, 1973) and in the Kodiak management district in 1962 (ADF&G, 1979a). It is primarily a domestic fishery in which crabs are caught with pots fished in 7-50 m of water (Mayer, 1972). The Kodiak fishery extends from May 1 to December 31, with most crabs taken from June through September. In 1978, 58 percent of the catch was harvested in July and August (ADF&G, 1979a).

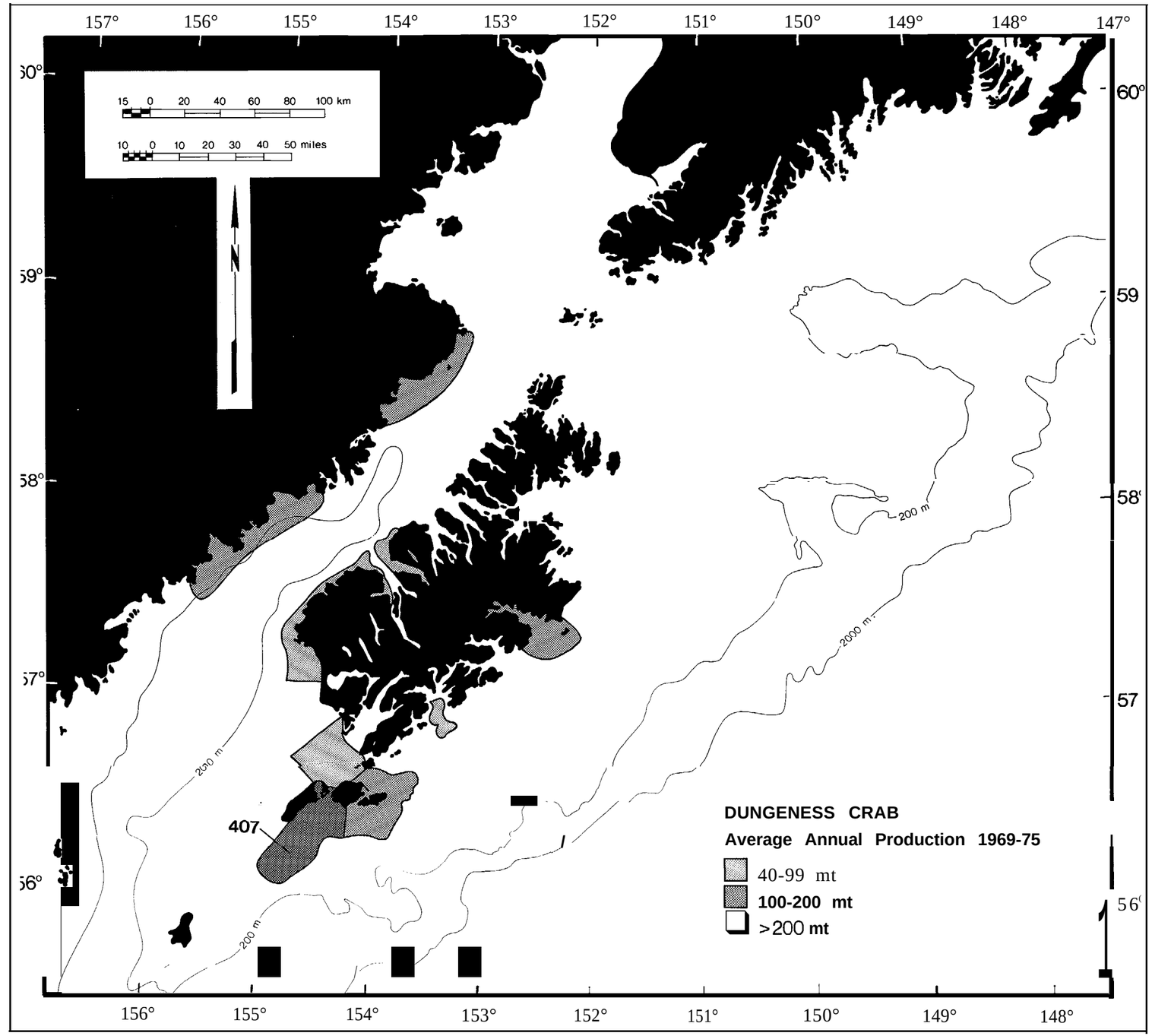


Figure 5.14 Areas of high commercial catches of Dungeness crab by U.S. fishermen, 1969-75. Dungeness crab were harvested in lesser amounts on the inner continental shelf throughout the region (Ronholt et al., 1978).

The catch and effort data for Dungeness crab in the Kodiak management district for 962 through 1978 re presented in Fig. 5.15 The reduced catches and ishery effort in the early 1970's were, in part, a

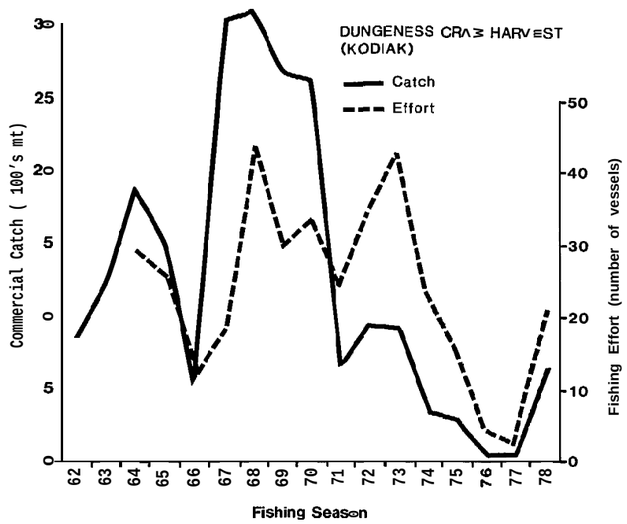


Figure 5.15 Annual commercial catch and fishing effort for Dungeness crab in the Kodiak management district, 1962-78 (ADF&G, 1979a).

result of the rap.d expansion of the Tanner crab fishery (Figs 5.10 and 5.11). In 1978 the price per pound that fishermen received for Dungeness crab increased from $0 30 in 1977 to $0 75. and catches were notably higher than in the previous several years (ADF&G, 1979a)

The Westward Regional office (Kodiak) of ADF&G monitors the catch and effort within subsections of the management district (Fig. 5.16). In the past severa

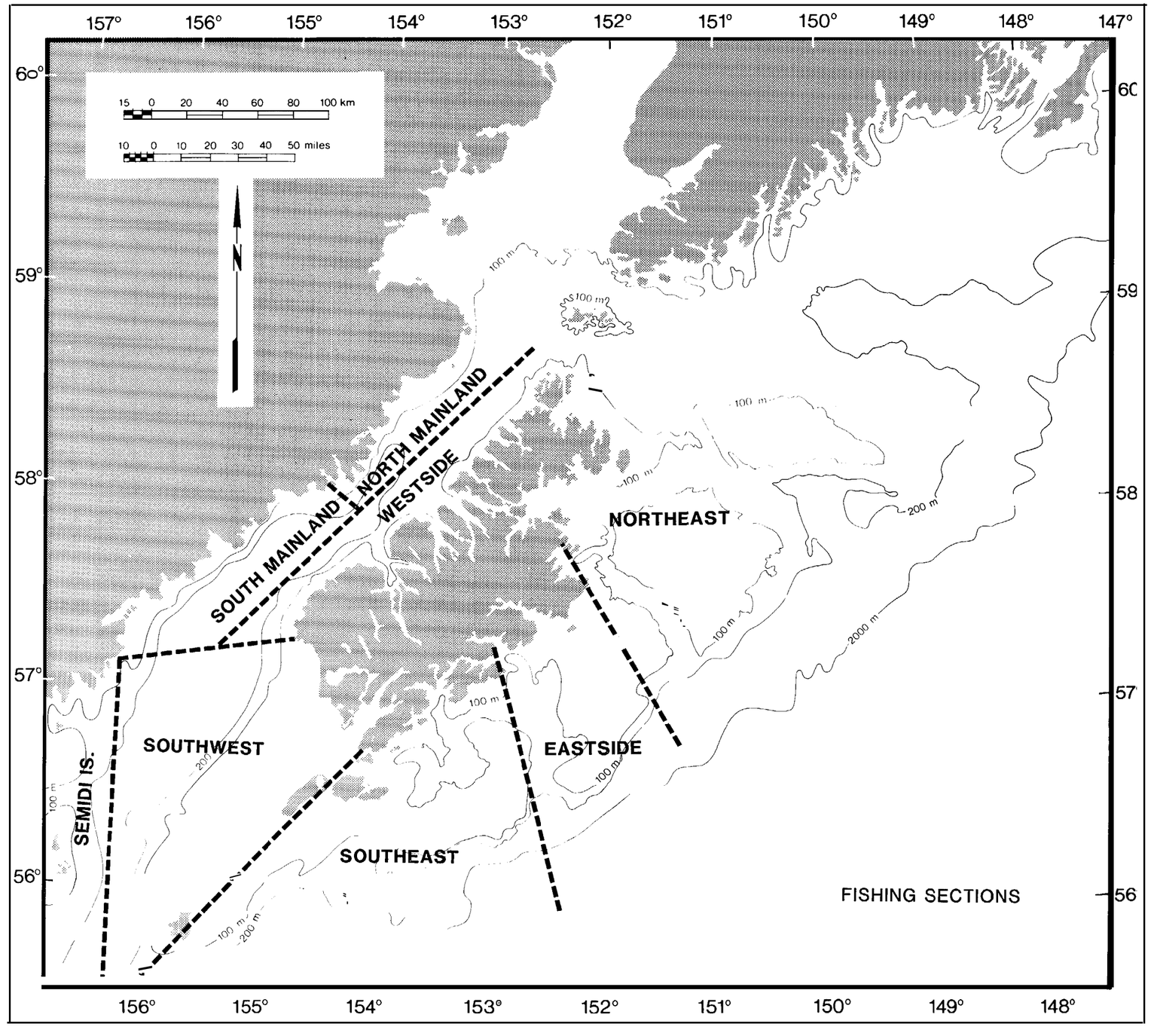


Figure 5.16 ADF&G fishery management areas for Dungeness crab.

years, fishing has been conducted close to ports in the Eastside and Westside districts. With the increased economic stimulus in 1978, the fishing fleet also worked the historically productive areas in the south (Table 5.10).

Table 5.10 Dungeness crab commercial catch and effort, by fishing section, Kodiak management district, 1978 season. Crab weight given in metric tons (ret). Percent of total Kodiak catch for each fishing section shown in parentheses (ADF&G, 1979a).

	Catch			Effort		
Fishing Section	mt (%)	no. crabs	average crab/pot	no. vessels	no. landings	no. pot lifts
Northeast	16.1 (2.6)	16,863	5	5	35	3,290
Eastside	191.2(30.9)	197,389	5	14	90	36,407
Southern*	111.3(18.0)	111,371	12	3	14	8,571
N. Mainland	8.1 (1.3)	8,479	8	22	4	1,030
S. Mainland	166.5(26.9)	164,923	7	2	22	21,086
Westside	126.0(20.3)	119,332	5	4	20	23,249
Total	619.2	618,357	6	30	185	93,633

*Data for Southeast and Southwest sections combined.

The stock of Dungeness crabs in the Kodiak area is apparently healthy. Recruits accounted for 69 percent of the catch in 1978 for the entire Kodiak district (ADF&G, 1979a). The average number of crabs caught per pot in areas little fished over the past several years (Southern districts) was much higher than the rates for the more intensively fished Eastside and Westside districts (Table 5.10). The age composition of population, determined by mark-recapture methods, confirms a healthy stock (ADF&G, 1979a). The ADF&G predicts a commercial harvest of 900-1,800 mt in 1979, if markets remain profitable (ADF&G, 1979a).

Pandalid shrimp

Fourteen species of pandalid shrimp occur in the Gulf of Alaska (Fox, 1972). Species common in Kodiak waters are listed in Table 5.7. Pink shrimp is the predominant form caught in trawl surveys (Feder and Jewett, 1977; 1978a; Blackburn, 1979a; Ronholt et al., 1978) and accounts for more than 95 percent of the commercial catch in Kodiak (Buck et al., 1975). Small quantities of bumpy shrimp are caught by the fishery in Alitak Bay (ADF&G, 1979a); coonstripe and sidestripe shrimp are taken incidentally to the harvest of pink shrimp. spot shrimp, the largest pandalid in the region, is harvested in rocky inshore areas by a small pot fishery (B. Donaldson, ADF&G, Kodiak, pers. comm.).

Adult pandalid shrimp inhabit waters from the intertidal zone to beyond the continental shelf. The distribution of shrimp in the Kodiak area is mapped from data of Murturgo (1975), Buck et al. (1975), and Blackburn (1979a) (Fig. 5. 17). Pink shrimp prefer depths of 75-180 m (Fox, 1972; AEIDC, 1974) and concentrate within 40 miles of the coast in submarine ravines on muddy bottom (Ivanov, 1969). The preference for a green mud habitat by both pink and ocean shrimp (Pandalus jordani) has been correlated with the high organic content of these clayey substrates (Fox, 1972). Substrates with a high organic content also support large numbers of infauna such as polychaetes and clams which pink shrimp eat (Feder, pers. comm.). Pink shrimp also avoid water warmer than 8 C and concentrate between the 3.5 and 4.2 C isotherms (Ivanov, 1964). Fox (1972) describes the depth range for other pandalids in the north Pacific. The typical capture depths and preferred substrates of the commercially sought pandalids in Kodiak are reviewed by Buck et al. (1975) and Ronholt et al. (1978).

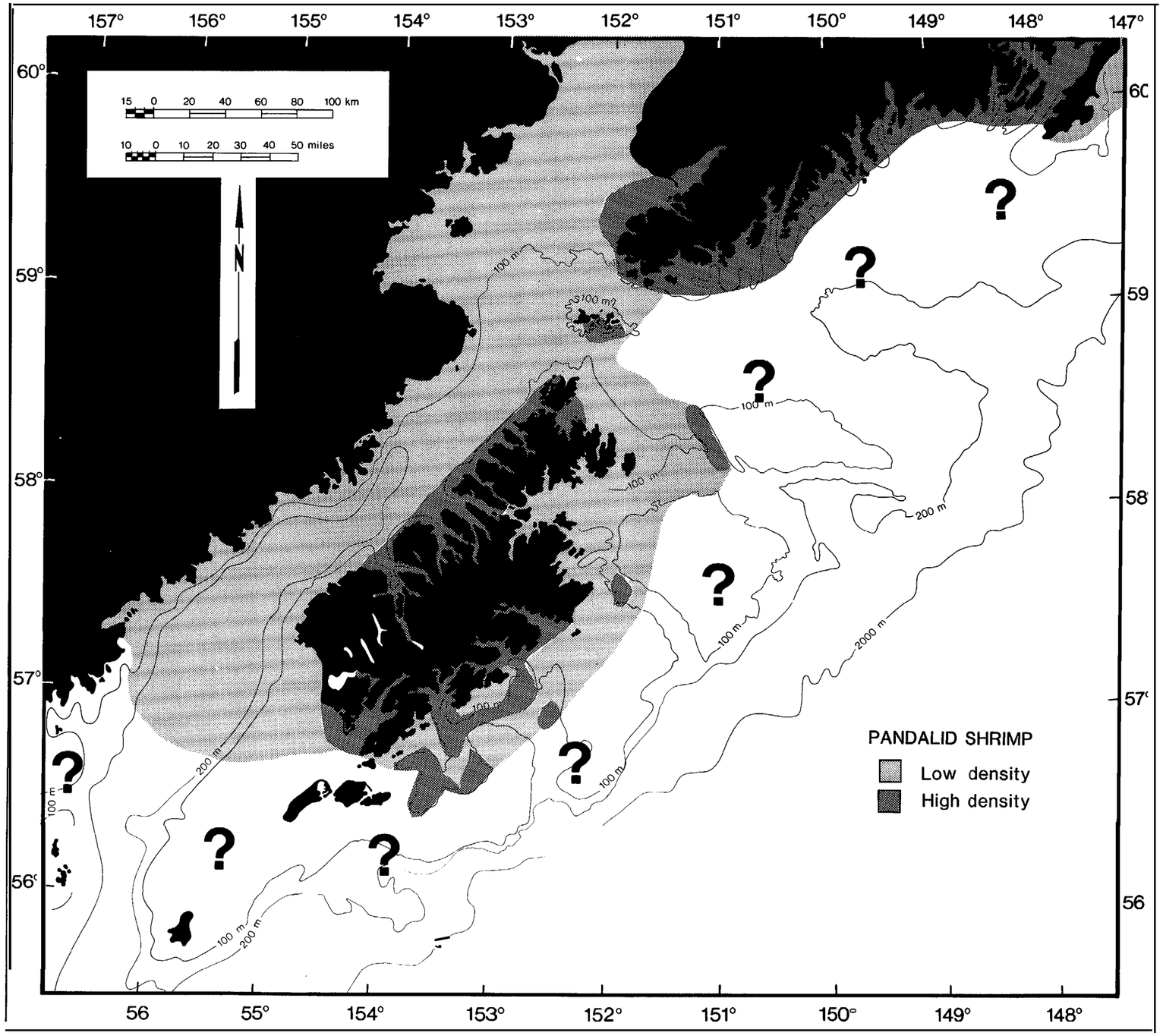
Adult shrimp migrate seasonally. In August and September shrimp move into shallow bays and adjacent to islands to spawn (Ivanov, 1969; Buck et al., 1975). Spawning sites around Kodiak have not been located, but they are probably widespread. After mating the female extrudes eggs, remaining ovigerous for five to six months (Fig. 5.4). Pandalids are less fecund than crabs; they produce only 900 to 3,000 eggs per brood (Fox, 1972). Free-swimming nauplii are released in February and March. Within two and a half months these mature into a juvenile form that is benthopelagic. Juvenile shrimp are found at shallower depths than adults (Buck et al., 1975).

Pandalid shrimp, with the possible exception of humpies and coonstripes, are protandric hermaphrodites. They initially develop as males, mature in two years, breed as males through their third or fourth year, then transform into females and continue to breed as females until six years of age (Fox, 1972; Buck et al., 1975).

Information on growth and natural mortality in Kodiak shrimp stocks is lacking. Predation by fishes is significant, however (Section 5.6).

The shrimp fishery in Alaska has existed at least since 1918, with its center in southeastern Alaska until the 1950's (Wiese, 1971; Fox, 1972). A Kodiak fishery developed in 1958 and was a major industry in the late 1960's and early 1970's (ADF&G, 1979a). At present, however, the Kodiak stocks appear to be in a major decline (ADF&G, 1979a). The 1960-78 catch and effort record for the management district is shown in Fig. 5.18.

Figure 5.17 Pandalid shrimp distribution in the Kodiak region (Murturgo, 1975; Buck et al., 1975; ADF&G 1976, 1979a; Feder, 1977b; Feder et al., 1979; Blackburn, 1979a).



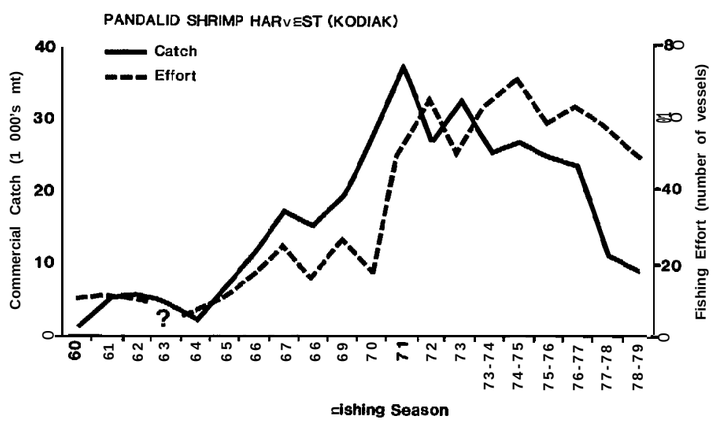


Figure 5.18 Annual commercial catch and fishing effort for pandalid shrimp, predominantly pink shrimp, in the Kodiak management district, 1960-79 (ADF&G, 1979a).

Management efforts have increased in the past several years as stocks continued to decline. The Kodiak management district has been divided into fishing sections and subsections (Fig. 5.19). Quotas were set up in 1972. In 1973 a harvest season (May 1 to February 28) was established that halted fishing during the time of larval release. Seasons are closed early if quotas in sections are met. Thus, the harvest season varies from year to year according to stock abundance. Most sections remain open for fishing only two to three months each year (ADF&G, 1979a).

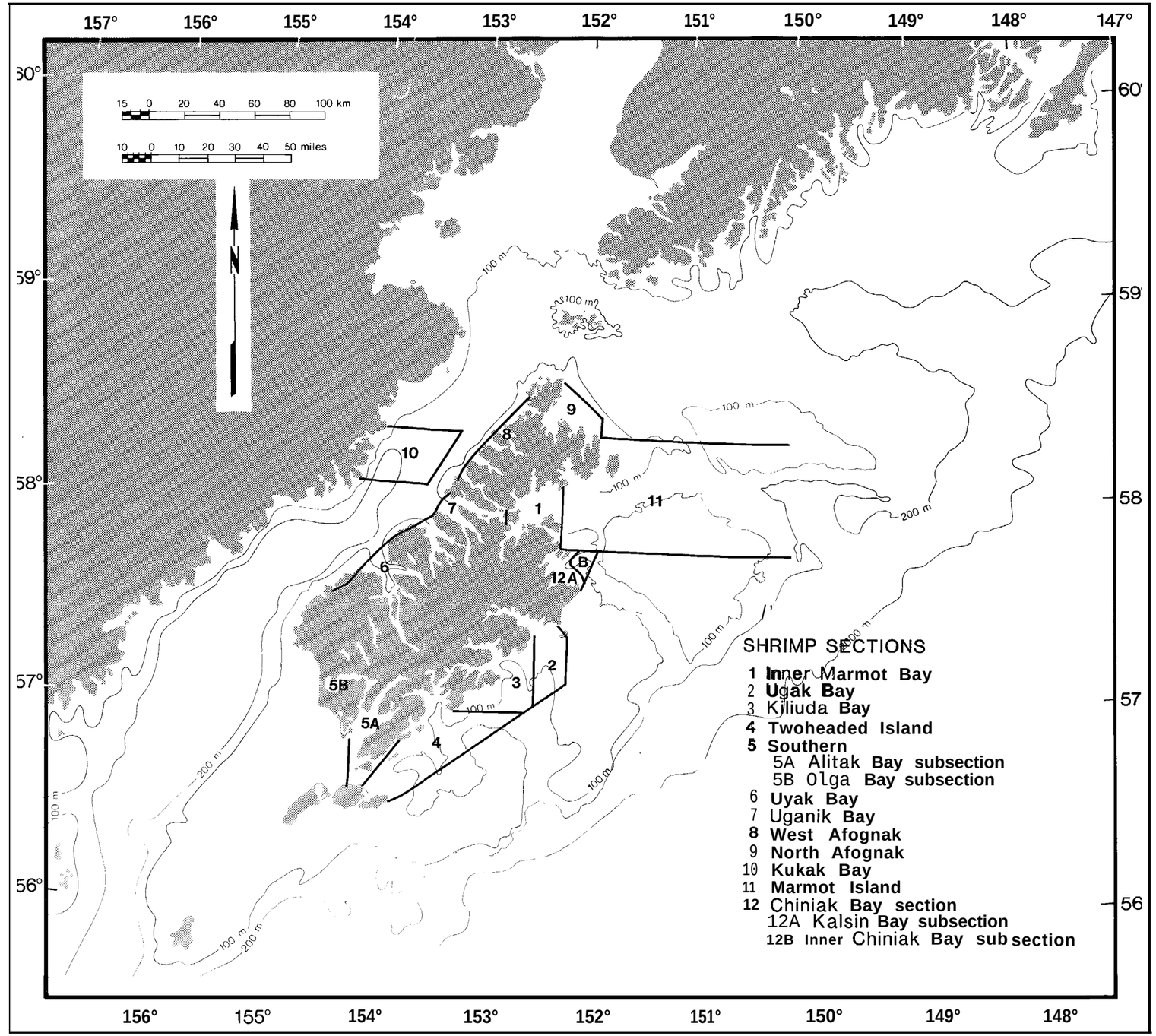


Figure 5.19 Management areas for shrimp in Kodiak district (ADF&G, 1979a).

The 1978 shrimp harvest in Kodiak was the poorest in over a decade, even though fishing effort remained strong (Fig. 5.18). There was a 22-percent decline from the 1977-78 catch. Large quantities of shrimp have been caught in past years from Marmot Island, Two Headed Island, Kiliuda Bay, and the Southern districts. Virtually no shrimp were harvested in these Northeast and Eastside areas in 1978-79 (Fig. 5.20). Alitak Bay was one of the few areas around the archipelago that continued to have large populations of shrimp. Because of reduced catches in previously productive areas, the shrimp fleet exploited several new locations. Two areas were productive: Wide and Puale Bays on the Alaska Peninsula across the Shelikof Strait from Kodiak. In Puale Bay, 2,292 mt of shrimp were harvested in 1978-79; 2,071 mt were taken in Wide Bay. This combined catch represented 46 percent of the seasonal catch for the Kodiak management district. Catch quotas had not been established in these two new areas and 95 percent of the seasonal catch there was taken from August 6 to September 16 (ADF&G, 1979a). This finding not only indicates the high efficiency of the fleet but also suggests that stocks were rapidly depleted by the intense fishing effort.

Harvest projections for shrimp in 1979-80 remain poor. The ADF&G has set guidelines of 3,636-10,455 mt and estimates a probable harvest of 4,545 mt, only half the 1978-79 shrimp catch in the management district. The projected catch in 1979-80 is only 12 percent of the peak harvest, in 1971 (Fig. 5.18).

The reasons for the sharp decline in shrimp populations around Kodiak are not well understood. The following causes have been suggested: (1) larval survival and recruitment were severely affected by harsh winters in 1970-71: stocks have not recovered those losses; (2) changing environment around Kodiak; (3) poor fishery management; (4) increased incidence of diseased egg masses; and (5) synergistic effects of these factors (ADF&G, 1979a). Whatever the causes, the shrimp populations of Kodiak are in a precarious state. Abundance levels may already be below the reproductive capacities of species to maintain their populations.

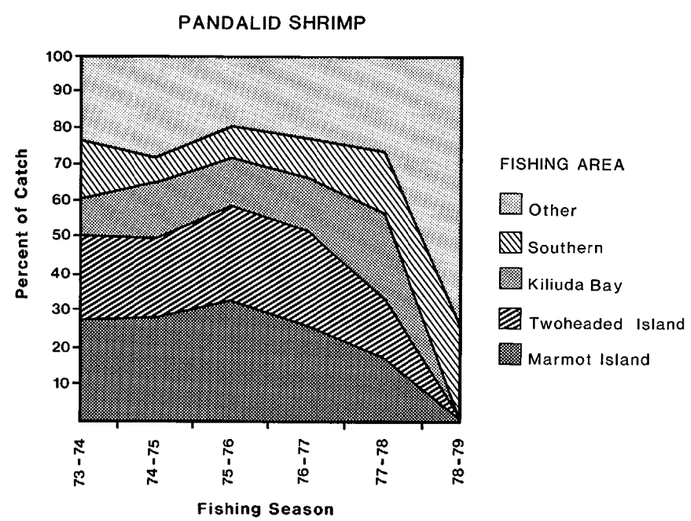


Figure 5.20 Percent composition of shrimp catch, by fishing area and season (data from ADF&G, 1979a).

Clams and scallops

The razor clam is the primary mollusc harvested in Kodiak. In the past, weathervane scallops were the main species commercially sought.

Razor clams accounted for the largest percentage of the biomass of both total fauna and bivalve molluscs on the intertidal sandy beaches along the Alaska Peninsula and Kodiak coasts (Kaiser and Konigsberg, 1977). They are found in highest concentrations along exposed beaches, rather than protected ones (Paul and Feder, 1976). The principal harvest areas near Kodiak have been on the Alaska Peninsula in Kukak Bay, Hallo Bay, Big River, and Swikshak Beach (ADF&G, 1979a). Commercial quantities of clams are also taken in Cook Inlet and on beaches near Cordova in Prince William Sound (Paul and Feder, 1976).

The razor clam fishery is slowly recovering from the 1964 earthquake that destroyed many of the populations and their habitat. Between 1970 and 1974, 45 to 90 mt of the species were harvested per year, but from 1975 to 1978 harvests have been almost nil. The 1978 harvest was 0.6 mt, worth $1,000, and accounting for 2 percent of the Alaskan catch (ADF&G, 1979a).

Razor clams spawn in summer, requiring specific water temperatures for incubation and fertilization (Nosho, 1972; Nickerson, 1975). Prolific egg producers (6-10 million), razor clams also have high larval and juvenile mortality. Juveniles settle into the top few centimeters of windswept beaches and are subjected to frequent heavy surf (Kaiser and Konigsberg, 1977). Razor clams burrow actively as juveniles and may also move inshore, offshore, and along the coast. By their third year they are more stationary, remaining so for the rest of their lives. Maturity is at 4.5-5.5 years and a length of 115 mm. They may live more than 15 years (Nosho, 1972).

Scallop beds are generally restricted to 55-130 m water depths, 30-70 km offshore, and to substrates that are a mixture of sand, gravel, and mud (Hennick, 1970, 1973; ADF&G, 1975). The Marmot and Portlock Banks support the major concentrations of scallops in the Kodiak area (Fig. 5.21). Large beds of weathervane scallops are also located from Cape Fairweather to Cape St. Elias, with small concentrations found east of Montague Island.

The weathervane scallop spawns in June and July, releasing gametes into the water column. Fertilization depends on local water movements. After brief egg and planktonic larval stages, juvenile scallops settle, preferably on mud, clay, sand, or gravel (Eldridge, 1972c). Scallops mature in three years, when they are 80-125 mm (measured from the umbo to the outer shell margin). As scallops grow, they add additional bands of shell (about one per annum) (Hennick, 1970). Scallops may live for more than 15 years. Some specimens measure 225 mm or more in size (Hennick, 1970).

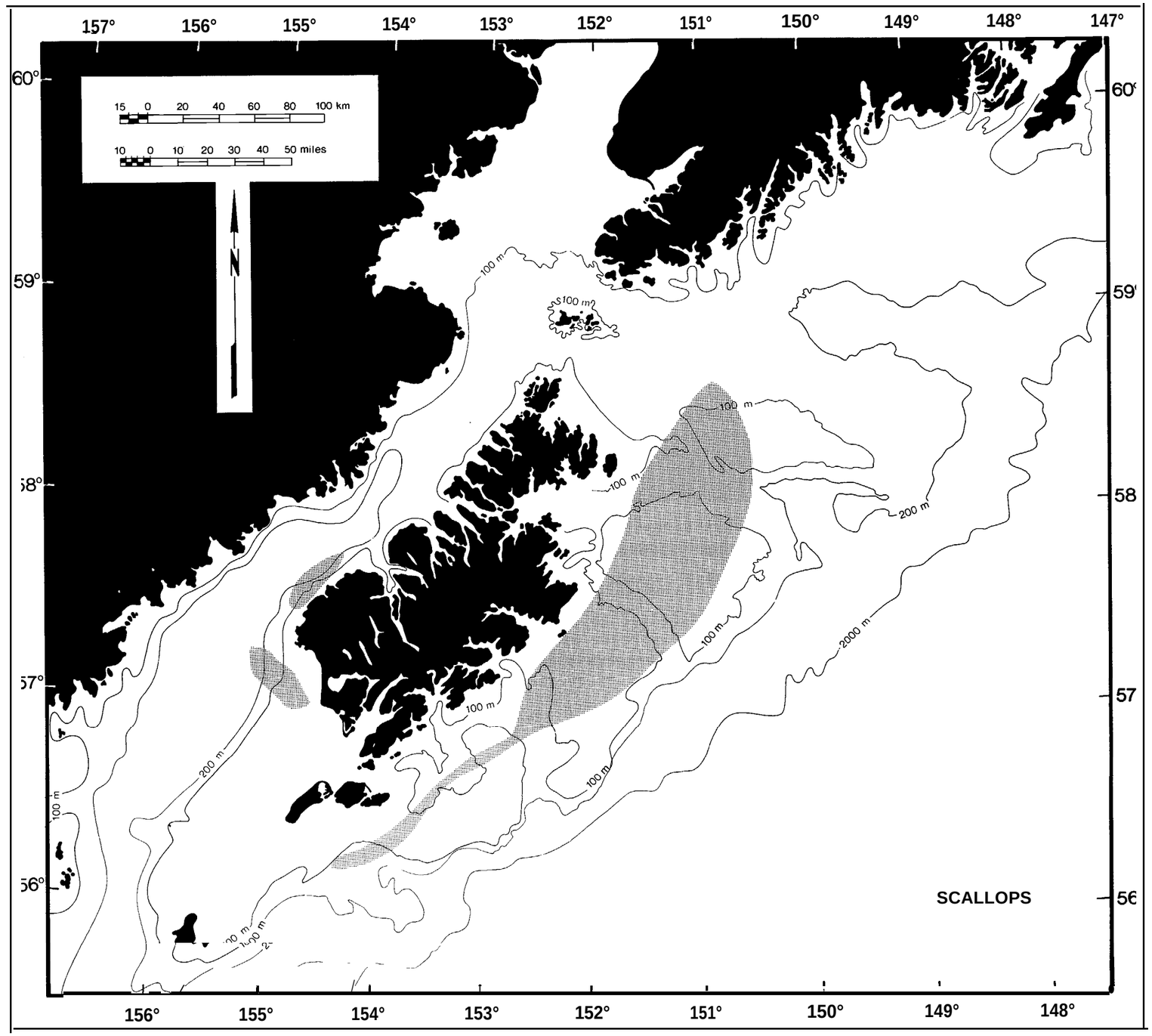


Figure 5.21 Distribution of scallops near Kodiak archipelago (modified from Murturgo, 1975).

Areas of historically high commercial scallop catches are illustrated in Fig. 5.22. The total catch for the area east of Kodiak Island was 1,667 mt or 51 percent of the gulf-wide harvest in 1969-75 (Ronholt et al., 1978). The 1974 catch of 67 mt was worth $200 thousand, down sharply from catches in the early 1970's (ADF&G, 1976). No scallop catch was reported in the Kodiak management district in 1978 (ADF&G, 1979a).

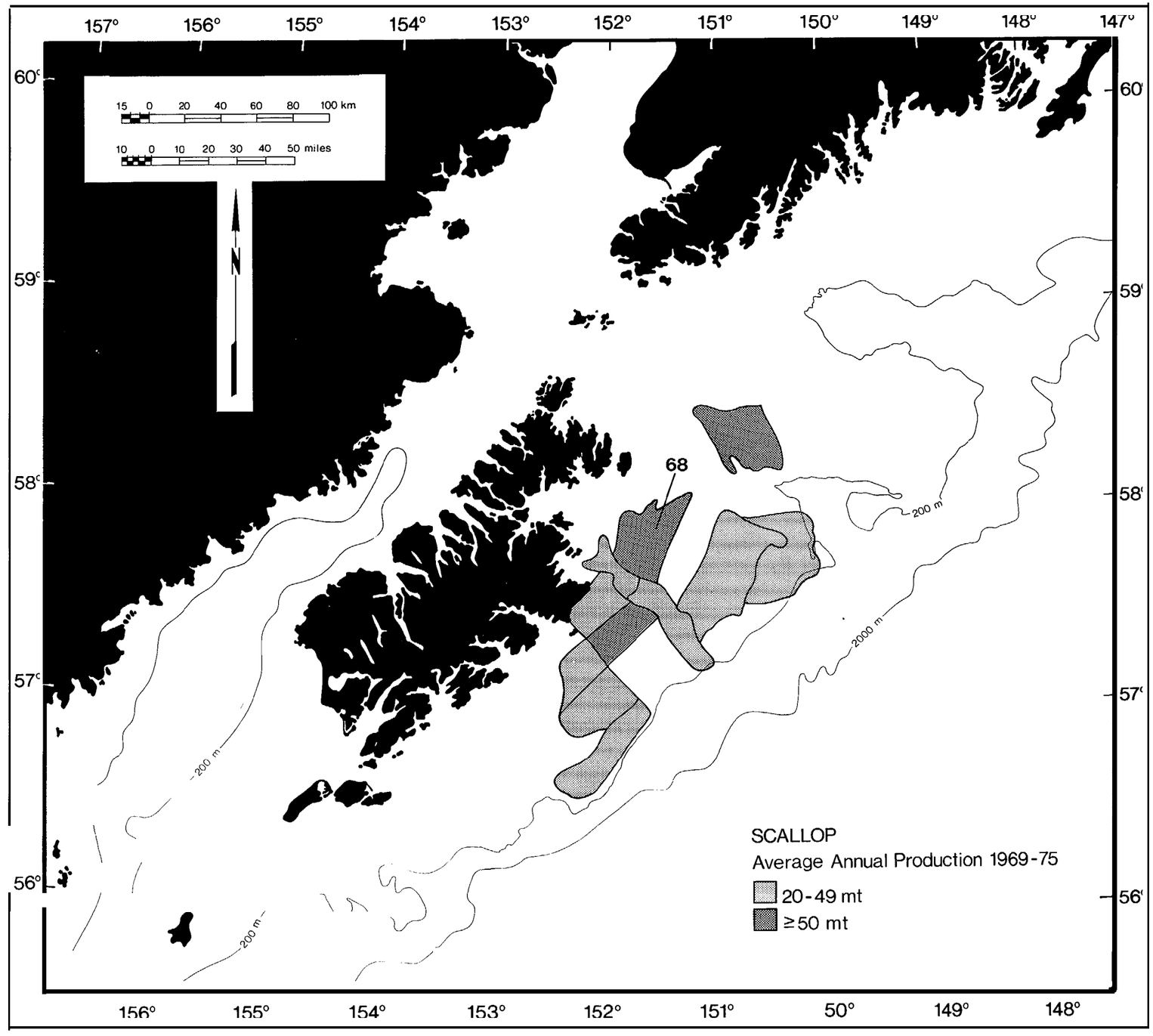


Figure 5.22 Areas of high commercial catches of scallops by U.S. fishermen, 1969-75 (Ronholt et al., 1978).

5.4.3 Non-commercial benthic invertebrates

Benthic invertebrates which are not harvested commercially are, however, of great importance in the marine ecosystem surrounding the Kodiak archipelago. Their biomass is substantial, they are an integral part of marine food webs, and many are sensitive or vulnerable to hydrocarbons and heavy metals. Thus they are important organisms to study with respect to OCS development.

Shevtsov (1964a, 1964b) and Semenov (1964) reported the distributions of invertebrates from the Gulf of Alaska. In a more comprehensive study, Semenov (1965) described marine benthic assemblages or communities (biocenoses in the Russian literature). He showed the relationship between water depth, substrate type, and prevalent mode of feeding among benthos. The biomass densities of the benthos in the Gulf of Alaska, grouped by feeding mode and substrate type, are shown in Table 5.11. Non-mobile filter feeders (e.g., barnacles, mussels) were found in greatest concentrations among rocky substrates. They were common at moderate water depths (45-90 m) and most abundant in between submarine canyons and on banks such as Albatross Bank. The strong currents in these areas prohibit sediments from accumulating, thus maintaining a rocky or gravelly habitat which provides attachment sites for these animals. Mobile filter-feeders (e.g., scallops) were found on sand and gravel substrates and were common between 50 and 150 m water depths, especially on coarser sediments such as those found on the Portlock Banks. Browsers (e.g., ophiuroids, hermit crabs) were found at about the same water depths as mobile filter-feeders; they were abundant around Chirikof and the Trinity Islands and were associated with all substrate types. Non-selective feeders (e.g., sipunculid worms) were typically found in 100-244 m of water. These were common west of Kodiak in the entrance to the Shelikof Strait (Fig. 5.23). They prefer substrates with a relatively high organic content. Carnivores typically were found in rocky environments.

Table 5.11 Relationship between the distribution of trophic groups of benthos and types of bottom sediments (Semenov, 1965).

Substrate	No. of Stations		Filter feeders		Detritus feeders		Carnivores	Total biomass
			nonmobile	mobile	browsers	nonselective		
			g/m²	g/m²	g/m²	g/m²		g/m²
Mud	12	0.80	0.66	1.27	11.16	41.90	8.15	63.14
Sandy mud	10	0.50	0.19	2.65	11.51	39.54	4.03	57.92
Muddy sand	11	0.51	12.88	1.08	15.55	5.75	4.54	39.80
Sand	9	0.39	0.64	19.13	20.26	0.51	7.17	47.71
Mud with admixture of pebbles & gravel	7		7.09	7.09	15.05	5.71	6.66	41.60
Sandy mud, gravel, pebbles	6		32.36	4.62	17.99	*13.53*	1.88	*70.38*
Muddy sand, gravel, pebbles	20		62.69	18.76	22.27	*4.16*	12.35	120.23
Pebbles, gravel, sand, stones, shells	14		15.82	9.55	12.22	1.35	11.00	49.94
Rocks	3		470.30	4.78	11.90	0.04	30.27	517.29

Benthic invertebrates (all types) were found in greatest concentrations on the continental shelf in the western Gulf; here the average biomass was 180 g/m². In the northern and eastern Gulf of Alaska, biomasses of 64 and 23 g/m² of benthic invertebrates were reported, respectively.

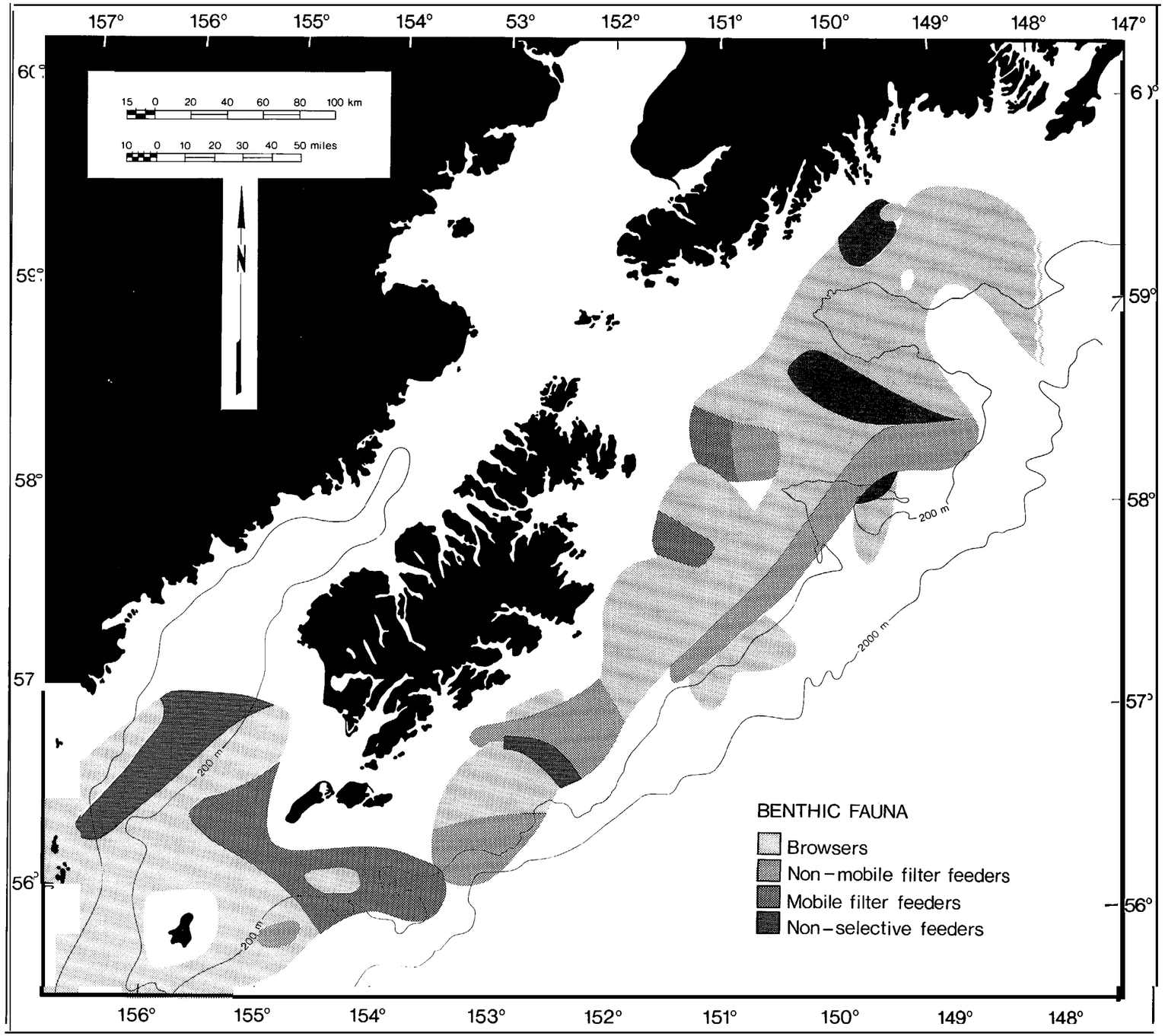


Figure 5.23 Distribution of benthic invertebrate feeding types (Shevtsov, 1964a; Semenov, 1965).

More recently a team of researchers from the University of Alaska and the NMFS has studied the benthic invertebrates of the Alaskan Continental Shelf and Slope. The distribution and abundance of epifauna and infauna and their trophic relationships are discussed by Feder (1977a, 1977b, 1977c); Feder, Hoberg, and Jewett (1979); Feder and Jewett (1978a, 1978b, 1979a, 1979b); Feder and Matheke (1979); Feder, et al. (1976a); Feder et al. (1976b); Feder and Paul (1979); Paul and Feder (1976); Paul, Feder, and Jewett (1979); Ronholt et al. (1978).

Feder and Jewett (1979b) surveyed the epibenthic fauna of Alitak and Ugak Bays (Fig. 5.24) with otter trawl gear in June, July, and August, 1976 and March, 1977. Twelve phyla, 23 classes, 66 families, 79 genera, and 106 species were identified. A list of common epibenthic organisms found in Kodiak bays is shown in Table 5.12. Arthropoda (Crustacea) were predominant in number of individuals and biomass;

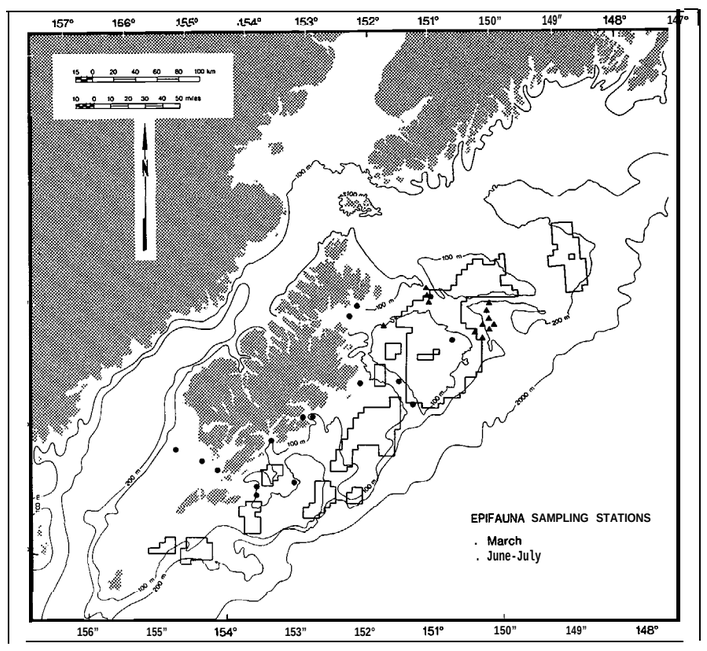


Figure 5.24 Epifauna sampling stations 1976-79 (Feder and Jewett, 1979b; Feder et al., 1979).

Table 5.12 Common epibenthic organisms of Alitak, Ugak, Izhut, and Kiliuda Bays that are not commercially harvested (Feder and Jewett, 1979b; Feder et. al., 1979) .

Scientific Name	Common Name
Cnidaria	
Metridium senile	sea anemone
Mollusca	
Mytilus edulis	blue mussel
Clinocardium ciliatum	Iceland cockle
Macoma spp.	clam
Nucula tenuis	clam
Nuculana fossa	clam
Axinopsida serricata	clam
Fusitriton oregonensis	Oregon triton
Nucella lamellosa	frilled dogwinkle
Arthropoda	
Balanus crenatus	barnacle
Balanus rostratus	barnacle
Eualus biunguis	shrimp
Crangon dalli	sand shrimp
Crangon communis	gray shrimp
Agris lax	rock shrimp
Agris dentala	rock shrimp
Pagurus ochotensis	hermit crab
Pagurus capillatus	hermit crab
Oregonia gracilis	decorator crab
Hyas lyrata	lyre crab
Cancer oregonensis	cancer crab
Echinodermata	
Evasterias echinosoma	sea star
Stylasterias forreri	sea star
Pycnopodia helianthoides	sunflower star
Echinarachnius parma	sand dollar
Strongylocentrotus droebachiensis	green urchin
Stronglyocentrotus purpuratus	purple urchin
Ophiura sarsi	brittle star

Porifera, Cnidaria, Annelida, Mollusca, and Echinodermata accounted for only 2 percent of the observed biomass (Table 5.13). Commercially important king crab, Tanner crab, and pink shrimp were the organisms taken most commonly from these bays. The biomass was greatest in both bays in March. The lowest biomass occured in August in Alitak Bay and in June in Ugak Bay. The average epifaunal biomass during all sampling months was 4.7 g wet wt/m^2.

Table 5.13 Number, weight., and density of major epifaunal invertebrate phyla of Alitak and Ugak Bays, June, July, August 1976 and March 1977 (Feder and Jewett, 1979b).

	Number of organisms		Weight (kg)		Percent of total weight		Biomass density (g/m^2)	
	Alitak	Ugak	Alitak	Ugak	Alitak	Ugak	Alitak	Ugak
Porifera	649	1037	44	89	0.38	1.25	0.02	0.04
Cnidaria	71	275	12	45	0.10	0.63	0.01	0.02
Mollusca	276	570	17	6	0.14	0.09	0.01	a
Arthropoda	294718	162337	11587	6S20	99.10	95.85	5.94	3.39
Echinodermata	77	577	23	137	0.19	1.93	0.01	0.07
TOTAL	295791	164796	11683	7097	99.91	99.75	5.99	3.52

* average biomass <0 .01g/m^2

Epifauna were sampled with try net and otter trawl gear in Izhut and Kiliuda Bays from April to November *1978* and on the Kodiak Shelf in March, June, and July 1978. Monthly average biomass estimates for each area are given in Table 5.14 (Feder et al., 1979). They are

Table 5.14 Densities of epibenthic organisms by weight, for inshore and offshore stations sampled in 1978 (Feder et al., 1979).

Location	Mean Biomass (g/m^2)						
Inshore	Mar.	Apr.	May	June	July	Aug.	Nov.
Izhut Bay		1.56	1.63	5.27	2.26	3.72	1.76
Kiliuda Bay		2.04		2.80	2.06	5.58	4.89
Offshore							
Portlock Bank	0.47	-					
Kodiak Shelf				3.94*	-		

*biomass is average for June and July sampling.

similar in magnitude to the estimates reported for Alitak and Ugak Bays (Feder and Jewett, 1979b, Table 5.13). Both of these studies, however, indicate much less dense concentrations of benthic invertebrates than those reported by Semenov (1965; Table 5.11). One explanation is that the Russian samples were collected with grab samplers, which presumably captured infauna as well as epifauna whereas samples taken with otter trawl gear contained few infauna. Most of the epifauna taken in the four bays were carnivorous crabs, shrimp, and echinoids. When the biomass densities of these forms are compared with those reported by Semenov (1965), the disparity in biomass values decreases. In general, biomass densities are less than 10 g/m^2 (Tables 5.12-14). Since rocky offshore areas were not sampled by Feder et al. (1979), comparison with Semenov's (1965) data for rocky areas is not possible.

The composition of the epifauna, by phylum, in Izhut and Kiliuda Bays in 1978 is shown in Table 5.15. Populations in Kiliuda Bay are similar to those in Alitak and Ugak Bays (Table 5.13). Commercially valuable populations of king crab, Tanner crab, and pink shrimp account for most of the trawled biomass. In Izhut Bay a large percentage of the epibenthic biomass in all months was composed of the sunflower starfish. Average biomass estimates for this echinoid ranged from 15 to 61 percent of the epibenthic catch. Other noncommercial species (i.e., sponges, anemones, and starfish) were also consistently found in catches although in much smaller amounts. Of the commercially sought species, only Tanner crab was taken in large amounts throughout the year in Izhut Bay. Pink shrimp did comprise 45 and 23 percent of the biomass in August and May, respectively. King crabs were virtually absent from the samples taken in Izhut Bay (Feder et al., 1979).

Table 5.15 Percent biomass composition of epibenthic organisms trawled in Izhut and Kiliuda Bays, 1978 (Feder et al., 1979).

Phylum	Apr	May	Jun	Jul	Aug	Nov
Izhut Bay						
Porifera	21.9	0	0	0.3	0	t
Cnidaria	7.5	2.3	0.3	2.8	t	2.2
Mollusca	2.1	2.9	0.1	4.6	2.1	0.2
Arthropoda	5.8	44.0	83.4	58.7	64.7	56.9
Echinodermata	61.7	50.8	15.6	33.3	33.0	40.5
Other	1.0	0	0.6	0.3	0.2	0.4
Kiliuda Bay						
Porifera	0.1	-	0	t	0	t
Cnidaria	0	-	0	13.9	t	0.9
Mollusca	6.9	-	0	3.6	2.4	2.8
Arthropoda	90.6	-	100.0	81.9	97.0	96.1
Echinodermata	2.4	-	0	t	0	0
Other	0.2	-	0	0.6	0.6	0.2

In addition to sampling epifauna in selected bays of Kodiak, Feder et al. (1979) conducted preliminary sampling on the Kodiak Shelf (June and July) east of the Archipelago and in the vicinity of the Portlock Bank (March) (Fig. 5.24). Sea stars and sea urchins were the major epibenthic forms, in terms of biomass, near Portlock Bank with king and Tanner crabs of secondary importance. King and Tanner crabs were the principal species collected on the Kodiak Shelf in June and July (Table 5.16), however.

Table 5.16 Percent biomass composition of the leading epibenthic species, 1978 (Feder et al., 1979).

Phylum	% Biomass of All Phyla	Predominant Taxa	% Biomass of Phylum	% Biomass of All Phyla
Portlock Bank: March				
Echinodermata	47.1	Dipsacaster borealis	60.1	24.7
		Strongylocentrotus spp.	24.8	10.7
		Diplopteraster multipes	5.4	2.2
			90.3	37.1
Arthropoda	30.8	Chionoecetes bairdi	79.9	24.6
		Paralithodes camtschatica	16.2	5.0
			96.1	29.6
Mollusca	28.0	Fusitriton oregonensis	51.7	14.5
		Neptunea lyrata	24.8	6.9
		Octopus sp.	15.6	4.7
			92.1	25.8
	99.9			
Kodiak Shelf: June-July				
Arthropoda	80.5	Paralithodes camtschatica	50.9	41.0
		Chionoecetes bairdi	42.4	34.1
		Pandalus borealis	5.2	4.2
			98.5	79.3
Cnidaria	8.8	Ptilosarcus gurneyi	40.4	3.6
		Metridium spp.	28.6	2.5
		Actiniidae	26.0	2.3
			95.0	8.4
Echinodermata	7.9	Echinarachnius parma	47.1	3.7
		Holothuroidea	41.2	3.3
			88.3	7.0
	97.2			

The sampling of benthic invertebrates around Kodiak to date provides some information on the types of large forms present and on their seasonal distribution and abundance. This information, combined with the data from fish studies, is a starting point for describing the marine communities on the Kodiak shelf. The largest gap in our knowledge of the Kodiak marine benthos is the lack of information on infaunal populations. It is apparent from trophic analysis (reported in detail later) that the large crab and shrimp populations of Kodiak waters prey heavily on the infauna and small epifauna. To comprehend the interactions among the various populations and to

predict the effects of OCS development on them, more extensive sampling is needed. Epibenthic surveys should be extended to other areas; a more complete seasonal record is required, and sampling of the smaller-sized species must be performed.

5.4.4 Feeding relationships

Predator-prey interactions are identified and community dynamics predicted, at least in part, by examining the stomach or gut contents of the species in question. Food webs from these analyses indicate the major dependencies among infauna, epifauna, pelagic invertebrates, fish, marine birds, and mammals. These graphical models show pathways energy transfer within the ecosystem. Together with information on uptake rates, physiological tolerances, deputation abilities, and vulnerability to contaminants, food webs can be used to predict the fate and effects of particular pollutants on marine communities.

Trophic relationships of several dominant epibenthic invertebrates occurring in Kodiak (Feder and Jewett, 1979b; Feder et. al., 1979), Lower Cook Inlet (Feder, 1977a; Feder and Jewett, 1978b; Feder and Paul, 1979; Paul et al., 1979), the northeast Gulf of Alaska (Feder and Matheke, 1979), and the Bering Sea (Feder, 1977a) have been examined. A generalized food web containing the principal prey and predators of common invertebrates and fishes of the Kodiak nearshore region is presented in Fig. 5.25 (Feder and Jewett, 1979b). Although the prey species have been identified, their relative importance in the diets of predators is not yet known. The degree to which infauna are consumed is also unknown. Many infauna are soft-bodied forms that cannot be identified in the gut of crabs, shrimp, echinoderms, and fishes.

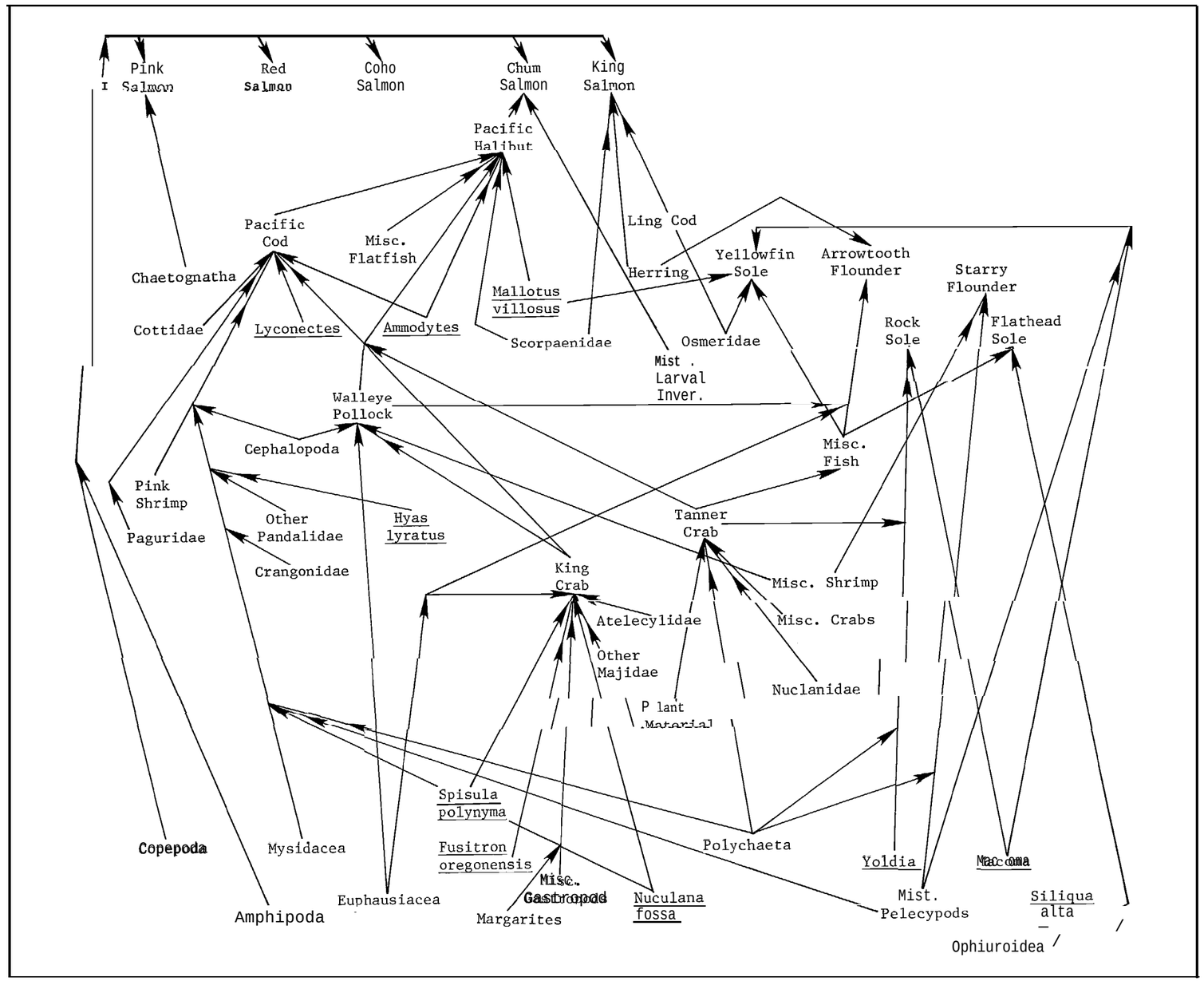


Figure 5.25 Generalized food web based on stomach analysis of epifauna taken in Alitak and Ugak bays and inshore waters around Kodiak Island, Alaska (Feder and Jewett, 1979b).

Feeding relationships of dominant benthic epifauna are discussed below. They are based on stomach content analyses of specimens taken from the western Gulf of Alaska or from the adjacent waters of the Bering Sea.

Larval king crabs consume planktonic diatoms, barnacle larvae (Buck et al., 1975), and probably a variety of copepods, hyperid amphipods, and fish larvae. Larval development coincides with nearshore plankton blooms in Kachemak Bay (Bright, 1967) and probably in Kodiak as well. Juvenile king crabs are omnivores that eat algae, coelenterates, polychaetes, clams, octopi, crabs, other crustaceans, echinoderms, and fish (Bright, 1967; Pereyra et al.,1976; IPHC, 1978).

Adult king crabs are, by and large, top carnivores in the nearshore marine environment around Kodiak. A proposed food web with king crab as the apex predator is shown in Fig. 5.26. King crabs were recently collected in Izhut, Anton Larsen, Chiniak, and Kiliuda Bays and the Kodiak Shelf (Fig. 5.27). Gut contents

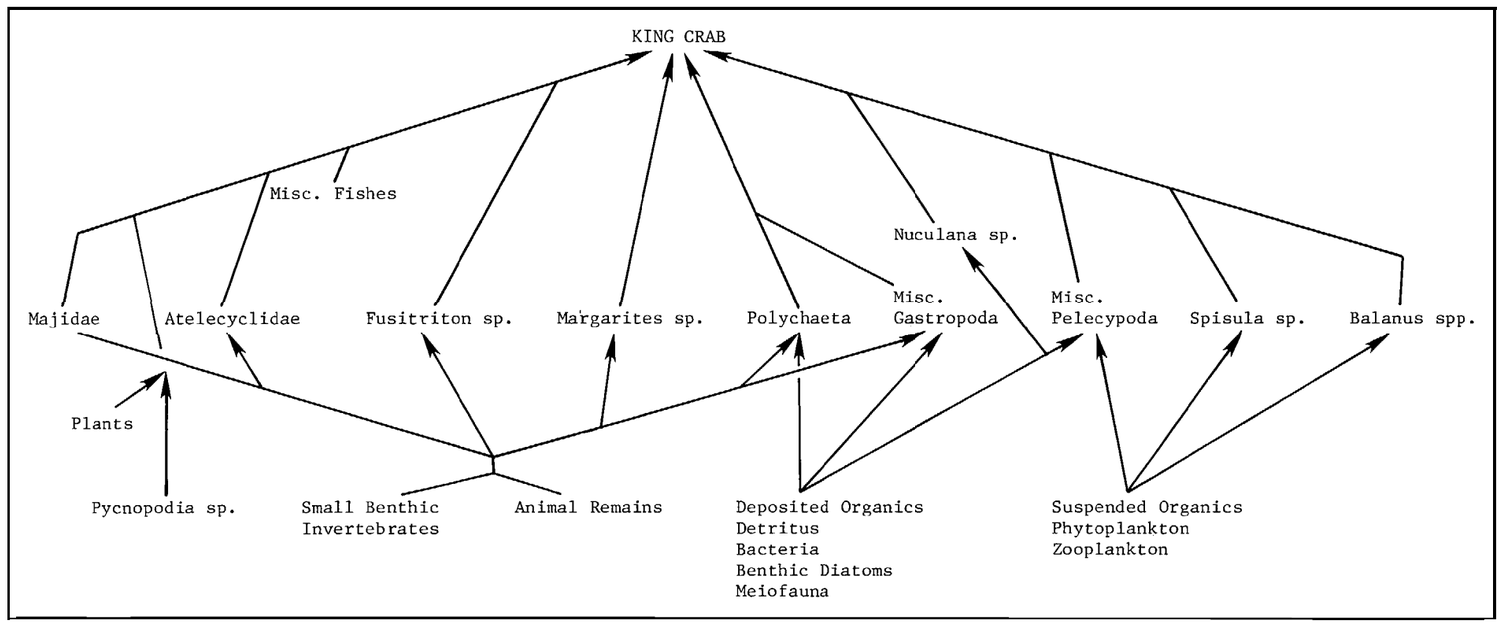


Figure 5.26 Food web for king crab in Alitak and Ugak bays and inshore waters of Kodiak Island, Alaska (Feder and Jewett, 1979b).

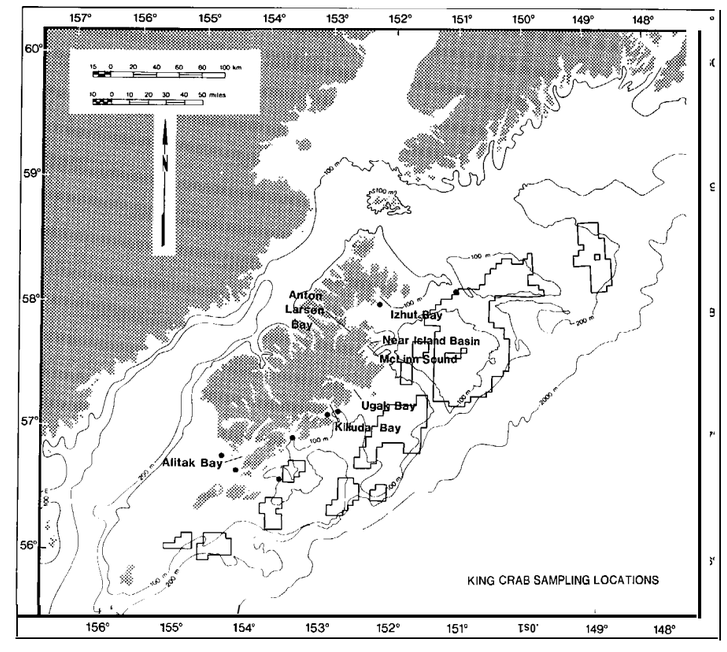


Figure 5.27 Sampling stations for king crabs, 1979 (Feder et al., 1979).

were examined, and the principal prey are shown in Fig. 5.28 and Table 5.17. Clams and barnacles appear to be of chief importance to the nearshore populations of king crabs in Kodiak Island bays, whereas fish were most frequently observed in the crab specimens collected from Izhut Bay on Afognak Island. Feder et al. (1979) believe that the king crabs fed opportunistically on fish that were wounded or killed by surface-feeding shearwaters, Black-legged Kittiwakes, and northern sea lions and sank to the bottom of the bay. The birds and sea lions were foraging in schooling Pacific sand lance and capelin. Offshore populations of king crabs fed primarily on clams and cockles (Feder et. al., 1979). In their discussions of the diets of king crab, Feder et al. cite other studies that show that pelecypods and gastropod molluscs are the most frequently observed prey, although the species of molluscs making up the diet commonly vary among regions. Prey taken by king crabs also varies with the crab molt cycle. Hard-shelled crabs in the Okhotsk Sea fed on *Siliqua media*, a razor clam, but recently molted king crabs with soft shells consumed large numbers of young *Tellina* clam, a species with a very thin shell (Kulichkova in l?eder et al, 1979). The apparent preference for barnacles in the diets of recently mated (and soft-shelled) king crabs may also indicate a temporal change in preferred prey.

King crabs as adults have few predators. Pacific cod and Pacific halibut are known predators (Buck et al., 1975; Pereyra et. al., 1976; IPHC, 1978), and other gadids, scorpaenids, and elasmobranchs are suspected. Adult crabs are most susceptible to predation just after molting, when their shells are still soft.

Larval Tanner crabs feed on various plankton

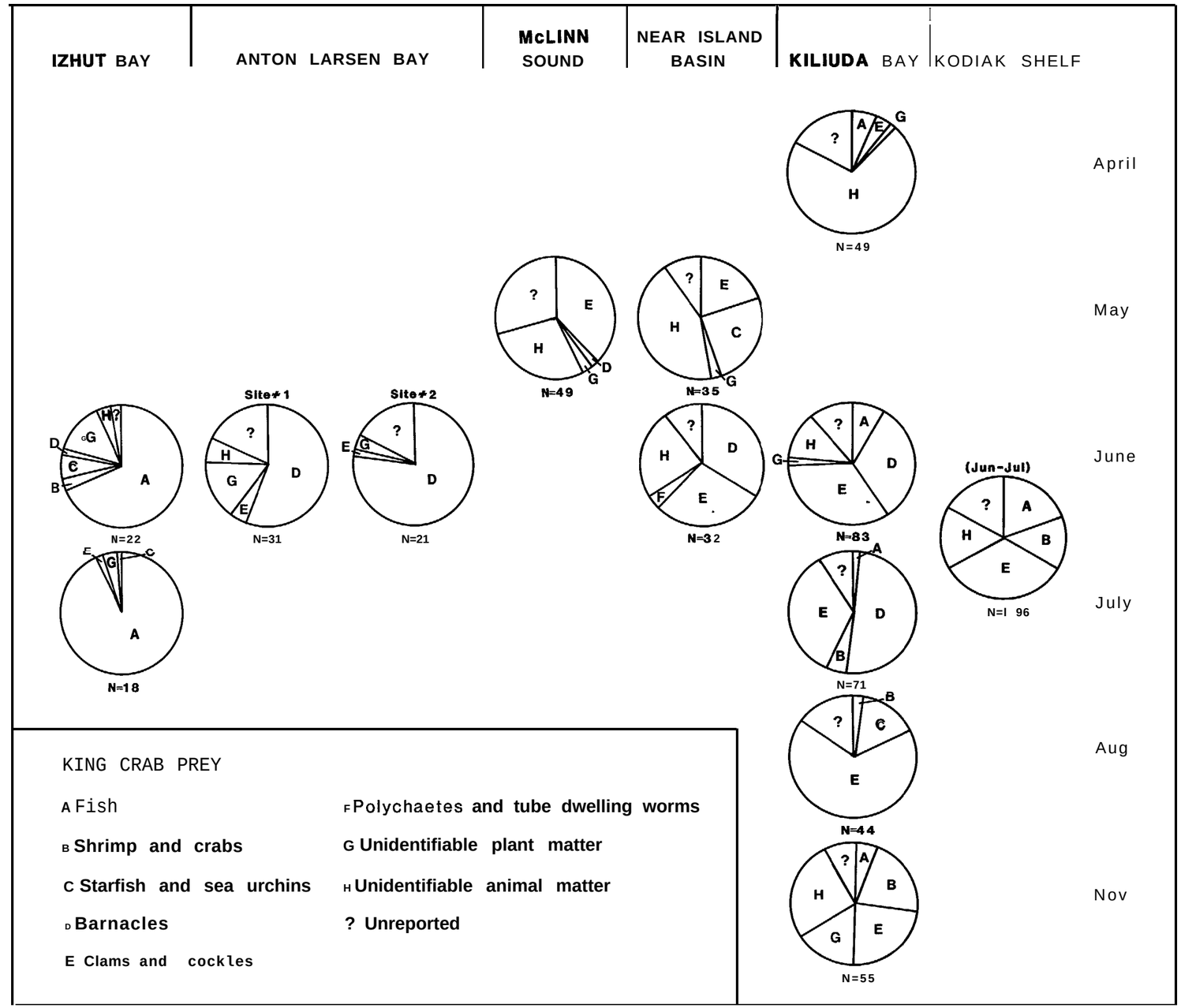


Figure 5.28 Principal prey of king crabs based on stomach content analysis of crabs taken in Kodiak bays and continental shelf, 1979 (Feder et al., 1979).

Table 5.17. Percent frequency of occurrence of prey organisms in king crab stomachs collected in the Kodiak area, 1978. Number of stomachs given in parentheses (Feder et al., 1979).

Location	Plant	Hydroids	Annelids	Nuculana spp.	Clinocardium spp.	Axinopsida spp.	Nucula tenuis	Macoma spp.	Mya spp.	Protothaca staminea	Gastropod	Balanus spp.	Decapods	Echinoids	Fishes
Izhut Bay															
Jun (22)	32				14								23	5	55
Jul (18)	28			11	11	6									78
Anton Larsen Bay															
Jun #1 (31)	71	52	16		3			16		10	10	39+			
Jun #2 (21		76						14		24		48+			
Near Island Basin															
May (35)	66		37+					29	9		14	23		14	
Jun (32			50+					31	19	38		63			
McLinn Island															
May (49)	69							41		18	29	27	40		
Kiliuda Bay															
Apr (49)	8			4	6		4						8		2
Jun (83)	30		22	42	11		23	28				35	40		7
Jul (71				63	31		39	38				27+	27		8
Aug (44)				23			20	41					11	2	
Nov (55)	47					24		44			13		24		7
Kodiak Shelf															
Jun-Jul (196)				57	26		56						27+		29

(Bright, 1967) although the exact composition of their diet has not yet been reported. Diatoms, algae, and hydroida have been found in the gut of juvenile Tanner crabs (Bright 1967); detritus is also consumed (ADF&G, 1975). It is likely that juvenile Tanner crabs feed on a wide variety of prey as young king crabs do; however, this has not yet been documented.

Feeding habits of adult male Tanner crabs from Alitak and Ugak Bays have been studied by Feder and Jewett (1979b). A preliminary food web with this crab as the apex predator is shown in Fig. 5.29. Pelecypods, caridean shrimp, and polychaetes occurred most frequently in Tanner crab stomachs (Feder and Jewett, 1979b). Only 70 crabs were examined in this study. Thus the findings, though accurate, are based on limited data. According to Feder et al. (1979), a more complete description of Tanner crab feeding habits is forthcoming shortly. The diet of Tanner crab populations in Cook Inlet is more fully known. Analysis of more than 700 crabs showed that clams (particularly Macoma sp.), pagurid hermit crabs, and barnacles are the chief prey. Crangonid shrimp, polychaetes, amphipods, and ophiuroids are of secondary importance. In all, prey from four phyla and 17 genera were identified from Tanner crab stomachs. The species appears to be an opportunistic consumer, feeding on whatever prey is abundantly available (Paul et al., 1979).

Amphipods prey on Tanner crab eggs (Hilsinger, 1976). A variety of fish eat Tanner crab juveniles. Octopi, gadids, liparids, and the yellowfin sole take adult crabs (Pereyra et al., 1976; Feder and Jewett 1979b).

Dungeness crabs feed on shrimp, crabs, barnacles, bivalves and polychaetes (Hoopes, 1973). Clams seem to be the preferred prey (Mayer, 1972) Predators of Dungeness crab larvae include herring, salmon, and smelt. Adult crabs are eaten by Pacific halibut, gadids, sculpins, and rockfishes (Mayer, 1972). To date, no detailed analysis of the trophic relationships of this species in Kodiak waters has been reported.

Pandalid shrimp larvae feed on zooplankton, selecting brachyuran crab larvae (AEIDC, 1974; Pereyra et al., 1976). Juvenile shrimp are opportunistic scavengers. Adults are carnivorous benthic feeders whose main prey consists of polychaetes and crustaceans (AEIDC, 1974). Predators of shrimp are numerous and include other marine invertebrates, birds, and mammals. A detailed analysis of the trophics of pink shrimp in Kodiak waters is forthcoming (Feder et al., 1979).

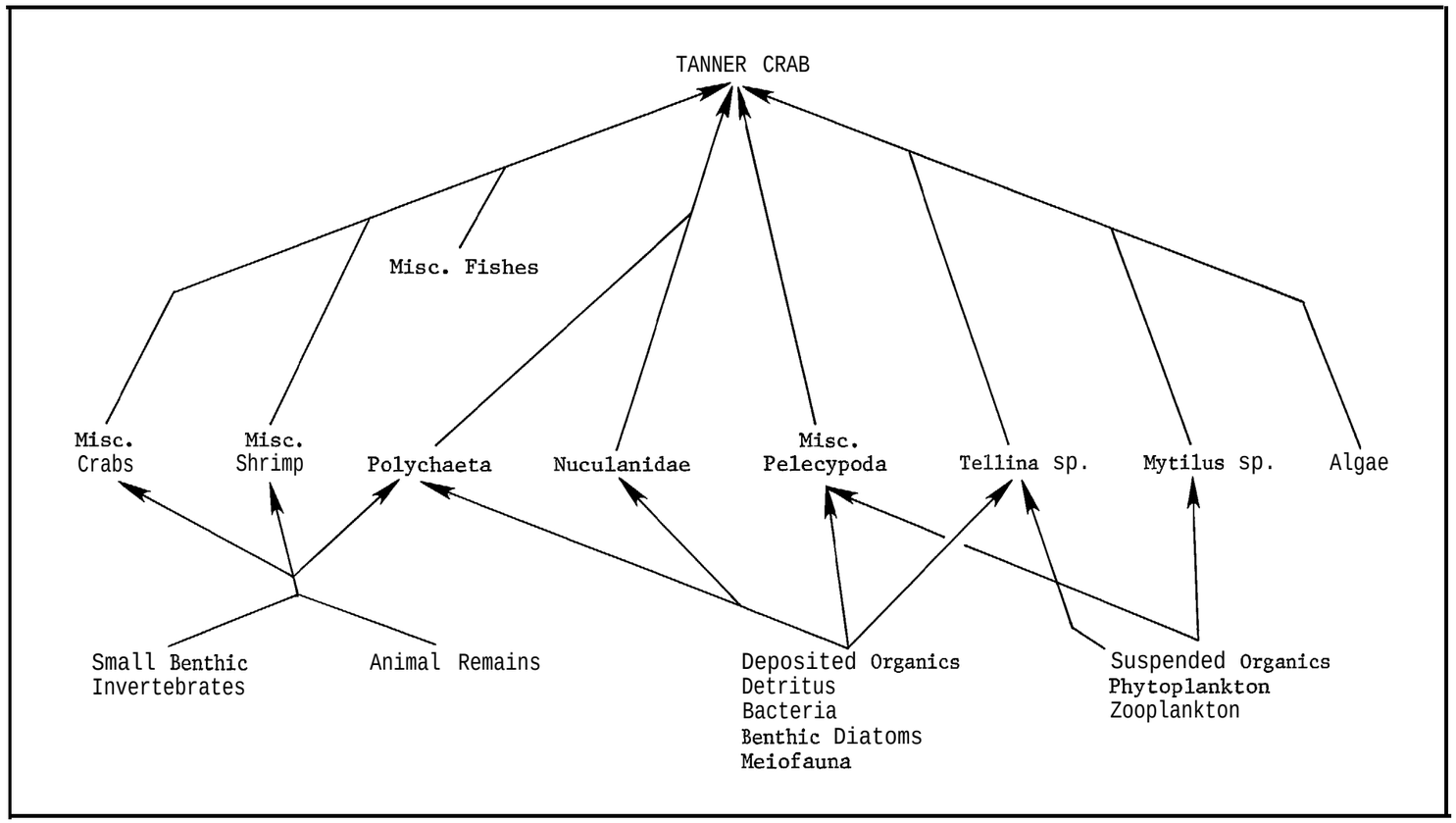


Figure 5.29 Food web for Tanner crab in Alitak and Ugak bays, and other inshore waters of Kodiak Island (Feder and Jewett, 1979b).

Scallops and clams are filter-feeders, utilizing phytoplankton, zooplankton, and resuspended detritus as primary food sources. They are thus important links between benthic microfauna and macrofauna populations. Since scallops and clams are long-lived in northern waters (Robertson, 1979) and can store heavy metals in their tissues (Malins, 1977), they may be good indicators of man's impact on the Alaskan marine ecosystem.

The feeding habits of echinoderms are not well known. Sunflower starfish, the dominant echinoderm found in trawl samples taken from Izhut Bay, fed on small gastropod and clams. This starfish probably competes with king and Tanner crab for food (Feder et. al., 1979). Intertidal populations of sunflower starfish in Prince William Sound appear to select Mytilus edulis, the blue mussel, other molluscs, and small gastropod (Paul and Feder, 1975). Farther south off the U.S. coast, starfish prey heavily on bivalve molluscs and barnacles (Paine 1969). Sea urchins are herbivores. They feed on kelp in the Aleutians (Estes, Smith, and Palmisano, 1978) and the North Atlantic (Mann and Breen, 1972).

5.4.5 Effects of OCS Development

Potential effects of OCS development on the marine benthic invertebrate populations around Kodiak are unknown. Information on life histories, population dynamics, and trophic relationships is available for only a few of the large, commercially important crabs, shrimp, and molluscs. The lack of comprehensive data on the distribution and abundance of infauna and small epifauna on the Kodiak shelf does not permit the prediction of the effects of toxicants, effluents, and building activities related to OCS development on benthic communities. Long-term studies of natural fluctuations in populations have not been done; therefore, it is impossible at this time to differentiate between natural variations in population characteristics and those caused by industrial activity.

Laboratory research has been conducted on the effects of hydrocarbons on biochemical, physiological, and behavioral responses of Alaskan marine species. Tanner crabs in a post-molt phase autotomized their legs after exposure to Prudhoe Bay crude oil (Karinen and Rice, 1974). Molting and survival of larval king crab and coonstripe shrimp were adversely affected after exposure to 0.8-0.9 ppm concentrations of the water-soluble fraction (WSF) of Cook Inlet crude oil (Mecklenburg, et al., 1976). When king crabs were exposed for three days to WSF (concentrations unreported) of Cook Inlet crude oil, there was extensive vacuolization in the gill cytoplasm and

disruption of the cell surfaces. Presumably, respiratory activity was impaired (Smith, 1976) and this may have been the immediate cause for the decreased larval survivorship reported by Wells and Sprague (1976) and Mecklenberg et al. (1976). Smith (1976) also reported that the WSF of oil was ingested and incorporated into the hepatopancreas, the main digestive organ of the king crab. The effects of this action are not known. Water-soluble fractions of oil are known to affect adversely respiration in certain shrimp species (F. G. Johnson, 1977); spot shrimp may be narcotized and eventually die (Sanborn and Malins, 1977). In other static bioassay research, the sensitivities of 39 Alaskan marine species to Cook Inlet crude oil were examined by Rice et al. (1979a). Pandalid and crangonid shrimp, king crab, and the littleneck clam, Protothaca staminea, showed high sensitivity to the oil (refer to Table 5E.18 and accompanying text for further discussion). Similar reactions may occur in individuals in the natural environment; however, further testing in situ is necessary for confirmation of the laboratory results.

Several aspects of the life histories of crabs make them particularly sensitive to exposure to oil, gas, waste water effluents, and heavy metals. During their spawning season, males are attracted to mature females by chemical substances released by the females. The extreme sensitivity of male decapods to the specific character and concentration of these pheromones is well documented (for example, McLeese, 1970; Kittredge et al., 1971; Atema and Gagosian, 1973; Eales, 1974). If a contaminant interferes with either the production of the signal or its reception, then the reproductive behavior, and hence species viability, may be drastically affected. Minute quantities of crude oil have been shown to affect feeding behavior (another chemosensory response) in American lobsters. These animals are attracted to and consume food contaminated with oil derivatives (Atema and Stein, 1974). The same behavioral response may occur in king, Tanner, or Dungeness crab.

OCS development in the Kodiak lease area increases the likelihood of industrial contaminants being released into the sea or being carried downstream from their source and dissolving or settling to the substrate. The severity of the effect on the benthic ecosystem depends on the nature of the contaminant, the amount released, the chemical reaction of the pollutant to seawater, the timing of the release, weather conditions, and a host of other factors. The most likely type of contamination during the construction and exploration phases of OCS development would be localized, chronic, low-level pollution around oil platforms. Construction wastes and drilling muds would settle to the substrate and smother some species, particularly sessile forms. Some deposit-feeding infauna and epifauna would probably ingest these wastes with as yet undetermined effects. The species composition in the vicinity of the platforms would probably change. Using in situ methods, Atlas et al. (1978) showed that, following a 60-day exposure to crude oils, amphipods were much less abundant in contaminated sediments while some polychaetes were attracted to the area.

In an oil well blowout or tanker accident, large quantities of hazardous material could drift to the substrate over a large area, be carried downstream, and settle out in the biologically productive troughs that transect the Kodiak shelf. The pollutant would likely admix with the fine-grained sediments in the troughs (see Chapter 3) and remain there for tens of years as the Katmai ash has done after the 1912 eruption of Mount Katmai (Wright, 1970; Bouma and Hampton 1976 and 1978, Hampton et al. 1979a). The chemical activity of the pollutant will vary with physical location, temperature, depth, and the nature of the sediment. Thus, its effects on the biota are difficult to predict. Deposit-feeding infauna and epifauna probably would ingest some of the contaminants and transfer them to detritus-based food chains. As previously discussed, such commercially valuable species as king crab, Tanner crab, and pink shrimp seem to prefer these troughs as habitat (Ivanov, 1964; Powell, 1964; Feder et al., 1979). King and Tanner crabs are known to feed extensively on deposit-feeding clams (Feder and Jewett 1979b; Feder et al., 1979). Thus a large oil spill in the Kodiak area would probably have both direct and indirect deleterious effects on local crab and shrimp populations.

The effects of OCS development on nearshore benthos would probably be more severe and apparent than those on offshore populations. If crude or refined petroleum products were released inshore, some soluble or insoluble mixture of hydrocarbons would be borne by currents into coastal embayments. The pollutants would probably become stranded on shore, adhere to rooted vegetation or algae, and settle out onto the substrate. The resident biota would thus be chronically contaminated by varying concentrations and forms of hydrocarbons.

OCS development on the Kodiak Shelf will result in an increase in industrial activity in and around the city of Kodiak and the bays on the east side of the Island. Tanker docks, water and sewage treatment plants, and housing will all be built. If gas or oil is discovered, LNG facilities or oil refineries may also be required. Water quality in the littoral and sublittoral zone is almost certain to decline, and the biota will have to adapt to altered environmental conditions. It is too early to predict what changes will occur.

5.5 INTERTIDAL AND SHALLOW SUBTIDAL ZONES

5.5.1 Introduction

The intertidal zone is the area between the highest and lowest tides of the year. The boundaries of this area are inexact and highly modified by local physiography and exposure to wind and waves. The intertidal is notable for the often abrupt vertical stratification (zonation) of biota produced by the interplay of tides, waves, desiccating wind and insolation, and biologic interactions. The diverse communities living in this complex environment may be particularly vulnerable to the effects of petroleum development associated with stranding of floating oil, shore construction, and dredging.

The shallow subtidal, as defined here, includes the algal (seaweed) beds often continuous with those of the rocky intertidal and extending offshore to depths of 20 m. Many seaweed and invertebrate species occur in both zones but usually predominate in one or the other. A prominent feature of the shallow subtidal is the forest canopy effect produced by such large kelps as Nereocystis luetkeana.

The intertidal and shallow subtidal zones of the Kodiak Island area are highly productive. Although world-wide plankton productivity is believed to be greater than that of marine kelps and seaweeds (Ryther, 1969), the productivity density of coastal areas such as those of Kodiak Island is higher than that of open waters. In an area of Nova Scotia with a high coastline-to-water ratio, macrophyte production was estimated to be three times as much as phytoplankton (Mann, 1972a). In the Kodiak Island area, seaweeds form a lush band from the 20-m isobath to mean high water in the rocky intertidal. The complex bay and headland geography of the Kodiak area results in more than 3,900 km of shoreline, although the length of the main archipelago is only 280 km.

Sand and gravel beaches, though not as stable or obviously lush as the rocky intertidal, nonetheless harbor significant infaunal communities. Some species, such as the ubiquitous razor clam, Siliqua patula, are of some commercial importance but are mostly taken for individual use.

The rocky intertidal of the Kodiak area had been little studied before the OCSEAP investigations (e.g., Rigg, 1915; Nickerson, 1975; Nybakken, 1969; Weinmann, 1969; see Feder and Mueller, 1972, for a review of the Gulf of Alaska literature in general). More recent work in the Gulf has been reported by Calvin and Ellis (1978) and Rosenthal and Lees (1977). The descriptions reported here are based on field studies conducted by personnel of the Auke Bay Laboratory, National Marine Fisheries Service (Zimmerman et al., 1978) and the Alaska Department of Fish and Game (Kaiser and Konigsberg, 1977). Study site locations are shown in Fig. 5.30.

Substrate type is critical in determining intertidal community composition. Table 5.18 shows the relative apportionment of substrate categories among various Alaskan areas. The Kodiak area can be seen to have a high proportion of bedrock and boulder substrates, which support rich macrophyte and invertebrate communities. Only the Aleutian chain is similar in this regard. This means that the Kodiak area may be especially vulnerable to oil spills because of its preponderance of epilithic biota (oil spill vulnerability indices have been derived for Kodiak Coastal subenvironments by Hayes and Ruby (1979)). Most communities of this type are concentrated on the seaward side of the archipelago (Table 5.19).

Table 5.18 Distribution (percent) of intertidal coastline among substrate categories for various Alaskan coastal areas (Zimmerman et al., 1977).

	Region				
Substrate	Kodiak Island	Aleutian Islands	St. George Basin	Bristol Basin	Norton Sound
Bedrock	48.1	56.0	8.0	7.0	11.0
Boulder	12.4	30.0	16.0	7.0	18.0
Gravel	31.5	6.0	16.0	12.0	24.0
Sand	7.8	7.0	36.0	32.0	16.0
Mud	0.2	0	24.0	43.0	26.0

Table 5.19 Number of kilometers and percent of major substrate types in the Kodiak Island area (Zimmerman et al., 1978).

	Region					
Substrate	Kodiak and Af ognak Islands	Barren Islands	Trinity Islands	Chirikof Island	Total km	Percent
Bedrock	1,775	90.0	15.3	26.5	1,907	48.1
Boulder	479	2.4	5.6	3.2	490	12.4
Gravel	1,191	2.4	55.0	0	1,248	31.5
Sand	127	6.4	151.0	23.3	308	7.8
Mud	9	0	0	0	9	0.2
Total km	3,581	101.2	226.9	53.0	3,962	100.0

5.5.2 Vertical zonation in the Kodiak area

Rocky intertidal communities mm ly exhibit distinct vertical zonation over a relatively short height interval as a result of differing periods of exposure by the tides to the atmosphere.

Biotic conditions such as competition for space and light, predation, and grazing also play a role in establishing intertidal zones. The average length of exposure tends to set the upper bounds of many intertidal species, while biotic interactions are often responsible for the lower limits. Many species are not at all limited in the lower direction, but flourish in the shallow subtidal as well. The zonational structure of the Kodiak Island area is similar not only to that of other subarctic areas of Alaska but even to that of other northern temperate locales. Many species occur from the Bering Sea to Baja California in Mexico.

According to Zimmerman et al. (1978), the Stephenson model with three main compartments bes describes zonation in the Kodiak area (Stephenson and Stephenson, 1972). The major zones are the supralittoral or splash zone, the littoral or true intertidal zone, and the subtidal Within these major zones subzones can often be delineated (Table 5.20). Zones are usually defined by the presence and/or abundance of conspicuous indicator species. For example, in the

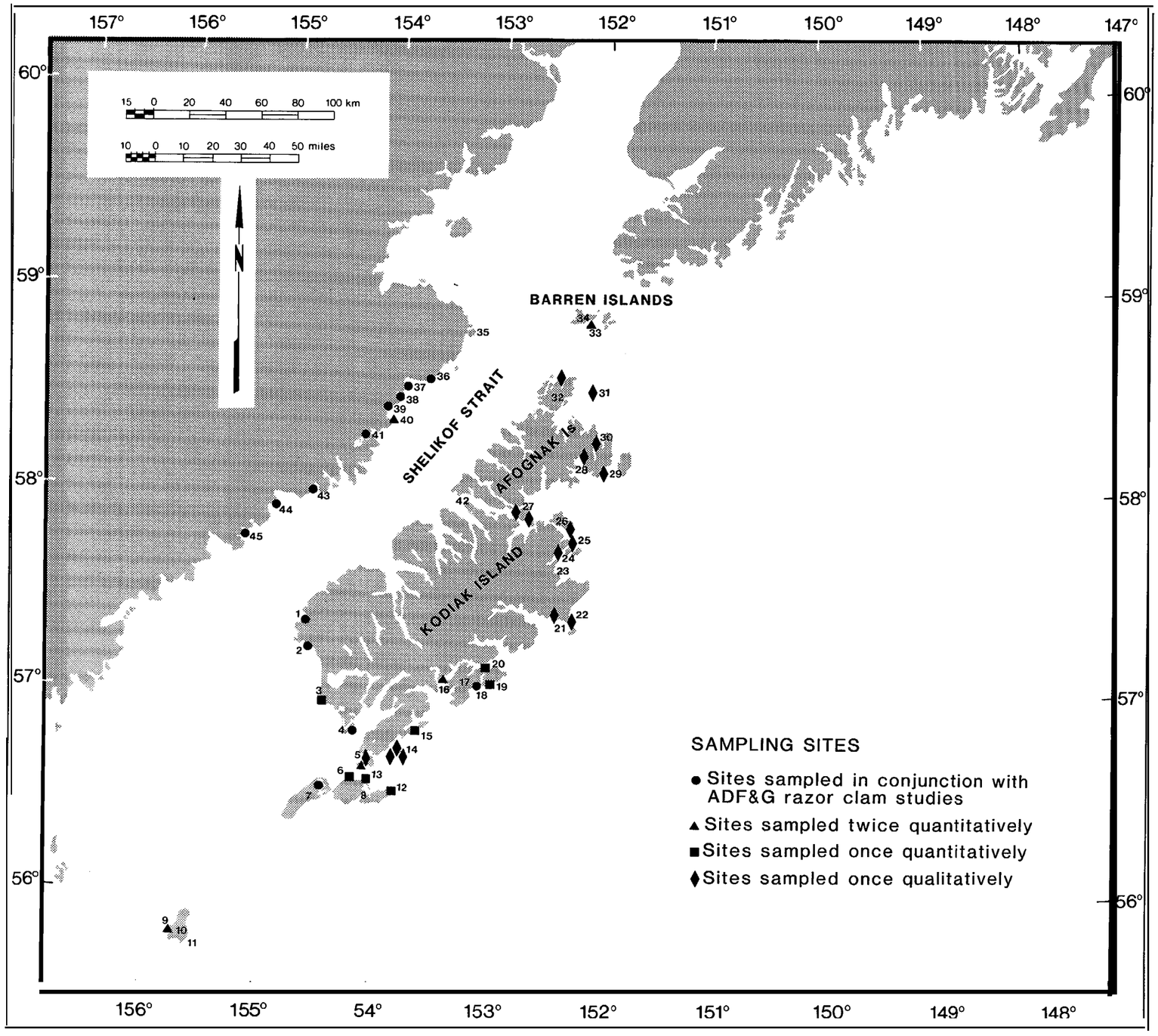


Figure 5.30 Intertidal sites sampled in the Kodiak area, 1975-76 (Zimmerman et al., 1978).

Table 5.20 Generalized zonation of rocky intertidal areas of the Kodiak Island area (Zimmerman et al., 1978).

Zone	Approximate Tidal Range	Biological Name	Characteristic Organisms
ZONE 1: Supralittoral fringe	Highest reach of spray to mean higher high water	Porphyra-Prasiola zone = Littorina zone (Stephenson and Stephenson, 1972, p. 20) = Littorina-Verrucaria zone (Lewis, 1964, p. 82)	Prasiola meridionalis, Porphyra sp., Littorina sitkana
ZONE 2: Littoral zone	Mean higher high water to low water of spring tides		
Subzone 2A		Barnacle-Endocladia zone = barnacle zone (Nybakken, 1969, p. 75) = upper barnacle zone (Lewis, 1964)	Littorina sitkana, Chthamalus dalli, Balanus glandula, Acmaea digitalis, diatom colonies, Collisella pelta, Endocladia muricata, sterile Fucus distichus
Subzone 2B		Fucus zone = Fucus zone Nybakken, 1969, p. 123) = Fucus zone (Stephenson and Stephenson, 1972) = Balanus, Patella, Fucus zone (Lewis, 1964, p. 82) = upper mid-littoral zone (Kozloff, 1973, p. 124)	Fertile Fucus distichus, Mytilus edulis, Nucella lima, N. lamellosa, Odonthalia floccosa
Subzone 2C		Rhodymenia zone = red algae belt (Lewis, 1964, p. 82) = Rhodyphyceae zone (Lewis, 1964, p. 78)	Rhodymenia palmata, Ulva-Monostroma, Balanus cariosus, Cumaria pseudocurata
Subzone 2D		Alaria zone = Alaria zone (Weinmann, 1969, p. 29)	Alaria spp., Lithothamnion sp., Ptilota filicina, Crisis. Halichondria panicea, Katharina tunicata
ZONE 3: Infralittoral fringe	Low waters of spring tides to true subtidal (below lowest low water)	Laminaria zone	Laminaria longipes, Laminaria dentigera, Lithothamnion sp., Corallina sp., Acmaea mitra

Kodiak Island area, the mussel Mytilus edulis is often found in a dense band on large rocks in protected areas. Similarly, the rockweed Fucus distichus is found nearly everywhere in the upper intertidal, while one or more species of the brown kelp Alaria are common in the lower intertidal. In the lower intertidal and shallow subtidal the growth of organisms, especially seaweeds, is more lush than in the higher zones (Fig. 5.31).

The following discussion indicates the dominant and conspicuous rocky intertidal organisms common to the Kodiak Archipelago and outlines their zonal significance. Tidal heights are relative to MLLW (mean lower low water).

The rocks of the splash zone (+3 to 5 m) are frequently bare except for a thin veneer of bluegreen algae and small populations of snails (e.g., Littorina sitkana) or amphipods. The green alga Prasiola meridionalis is the highest-occurring seaweed, growing principally in the splash zone where seabirds have deposited guano. The leafy red alga Porphyra is also found in the splash zone, though it is more common in the mid-intertidal.

The dominant seaweed in the true littoral zone (MLLW to +3 m) is the brown alga Fucus distichus. Within this area four subzones may be distinguished. The uppermost (+2 to 3 m) is characterized by patchy growths of sterile Fucus, tufts of the red alga Endocladia muricata, and clusters of small barnacles (Chthamalus dalli and Balanus glandula). Other inhabitants are the limpets Collisella digitalis (the highest-occurring limpet) and C. pelts. Much of the upper littoral consists of bare rock.

The mid-littoral subzone is covered by tides twice a day. Algal and invertebrate cover is almost complete. The principal component of the mid-littoral is

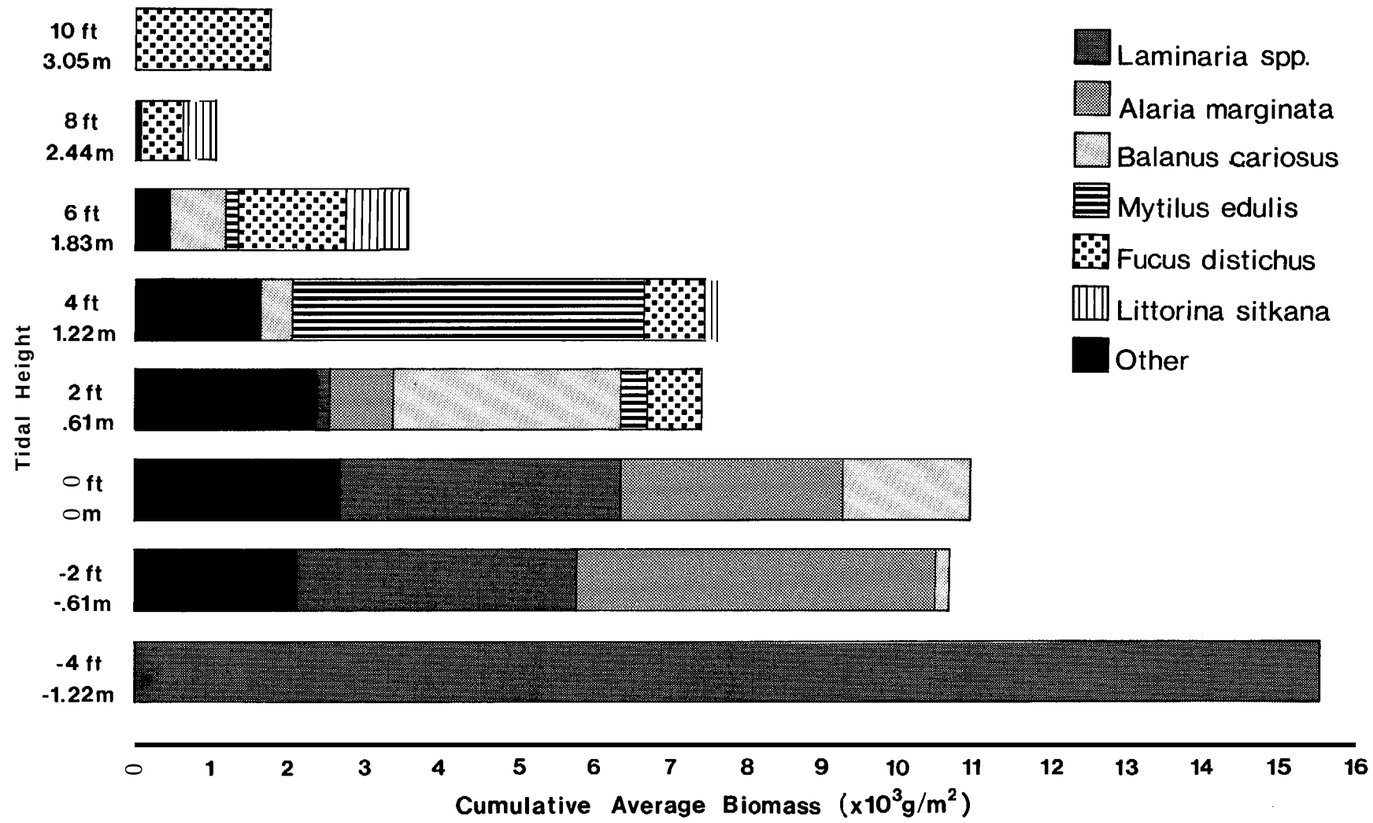


Figure 5.31 Relationship between average biomass of predominant intertidal species as related to tidal height. The re ative contribution of each species to the average biomass is also shown (data from Zimmerman et al., 1978).

Fucus Although Fucus may be abundant throughout the littora zone, making designation of this subzone somewhat arbitrary, it is in this height interval that the rockweed is dominant. That is, above the mid-littoral Fucus are not we l developed and canopy-forming, while below it they are being replaced by red algae. Other constituents of the mid-littoral include the sac-like red alga Halosaccion glandiforme, the red alga Odonthalia/Rhodomela and the polysiphonous red alga Pterosiphonia. Odonthalia floccosa and Rhodomela larix, which are sometimes difficu t to separate in the field--hence their combination into one taxon--occur only in flat, surf-swept beaches, where they may form dense, narrow bands at the lower margin of the Fucus fertile zone.

The mussel Mytilus edulis occurs as a local mid-littoral dominant in protected waters or on the protected sides of large hummocks. It is an important space competitor that provides secondary interstitial space and substrate for many small invertebrates. The barnacle Balanus cariosus may occur throughout the littoral zone, but is most abundant in the mid-ittoral It is a significant space titor and provides habitat for worms and other sma l invertebrates. Two predatory snails of this subzone, Nucella lima and N. lamellosa, feed on mussels and barnacles by drilling through their shells. N. lima is the most frequently observed throughout the Kodiak Island area, but N. lamellosa may be locally abundant in protected waters.

Below the mid-littoral is a dense band of red algae named the Rhodymenia subzone for its principal component Rhodymenia (=Palmaria) palmata. While this subzone is a prominent feature of the Gulf of Alaska above 55° N. it is absent at lower atitudes in the north Pacific. These red seaweeds may be scattered or dense; at their heaviest densities they may exc ude all barnacles, littorines, whelks, and limpets. Several other species have their upper distributional imits in the Rhodymenia subzone. The ephemeral green a gae Monostroma and Ulva may be common, especially if Rhodymenia is not prominent. They are rapidly colonizing, leafy seaweeds, often indicative of mechanica disturbance. They sometimes grow epiphytically on old growths of Rhodymenia. Am the numerous chitons whose distributions begin in the Rhodymenia subzone are the leather chiton Katharina tunicata, mm at most studied sites, the mossy chiton Mopalia muscosa and the lined chiton Tonicella lineata. The last two usually occur lower in the intertidal than Katharina. Chitons are grazing herbivores and are preyed upon by birds and sea stars. The limpet Notoacmea scutum, the six-rayed sea star Lepasterias hexactis, and the small sea cucumber Cucumeria pseudocurata are also often found in the Rhodymenia subzone, though their intertidal distribution extends above and below it.

Sea stars are predatory animals which belong to a small group of organisms called ecological dominants. The term "ecological' dominant" means that their influence on community structure is greater than would be suggested by their abundance. The sea star Pisaster ochraceus, which occurs in the north Pacific and southern California as well as in the Gulf of Alaska, has been shown to be instrumental in maintaining community diversity by facultative choice of prey (Paine, 1966) and to regulate the lower limit of distribution of the mussel Mytilus californianus (Pianka, 1978). Some algae exhibit similarly disproportionate ecological roles by competition for space and light or by provision of a protective canopy beneath which flourishes an understory community. The brown kelp, Hedophyllum sessile, which has been recorded at Sundstrom Island in the Kodiak Archipelago, forms a significant canopy in the lower intertidal of exposed areas of the Pacific Northwest (Dayton, 1975).

The strongest break in floral distribution usually occurs at MLLW, above which relatively small foliose red and brown algae dominate and below which the large-bladed brown kelps take over. The break is not complete in the Kodiak Island area, however, and zonal "transgressions" are frequent. Along the coast of North America the flowering surf grass, Phyllospadix, is often taken as an indicator of MLLW (Ricketts and Calvin, 1968). In the Kodiak Island area as elsewhere, however, Phyllospadix is also found at the edges of tide pools and in standing-water areas of flat bedrock shores higher in the intertidal. Organisms below MLLW are exposed only during minus tides, which occur about half the days of the year. Exposure to air is brief and often mitigated by splash and spray.

The lowest subzone of the littoral is termed the Alaria subzone (MLLW to lowest spring tides) for its domination by this long-bladed brown kelp genus. The most common species is A. marginata, but A. nana, A. tenuifolia, and A. fistulosa (normally a subtidal form) are also found occasionally. Feathery, fern-like Ptilota spp. and Neoptilota asplenoides, red algae, are abundant in this subzone at some sites. Prominent invertebrates include the highly colored sponge, Halichondria panicea, and the bright red sea star, Henricia leviuscula; both are common in the Kodiak Island area. Two other residents of this and lower zones are the encrusting ectoprocts (bryozoans or moss animals), Crisis and Filicrisia. Encrusting sponges and ectoprocts serve as food for Henricia (Mauzey et al., 1968).

The true subtidal zone, or sub-littoral fringe, has its upper boundary at the lowest spring tides. The large brown kelp, Laminaria, begins dominance in the shoreward extreme of this zone. The most common species in the Kodiak Island area is L. dentigera. Red, calcified coralline algae are also abundant in this zone. These include erect, articulated species such as Bossiella or Corallina and encrusting forms such as Lithothamnion. The corallines and other species also occur in tide pools throughout the littoral and on exposed rocks around MLLW, but not in such abundance. The limpet, Acmaea mitra, is found only at lower subtidal elevations and in large tide pools. Large, predatory sea stars and other invertebrates are also important.

The zone model proposed here consists of a composite of components found at various study sites. Wave exposure, slope, and substrate all play a part in determining community structure, and these differ from site to site. For example, many areas are essentially flat or uneven in slope, so that distance from the water line may be more important than actual height. Moreover, the vertical extent of the intertidal may be quite limited so that intertidal variation is subtle and poorly defined. Nevertheless, the model is useful as a predictor of the probable constituents of a partitular biotic assemblage.

The essential characteristics of rocky intertidal study sites are given in station models in Fig. 5.32.

SPECIES KEY

A-Alaria sp.
AS-Acmaea scutum

BB-Balanus balanoides
BC-Balanus cariosus
BG-Balanus glandula
BSP-Balanus sp.
CO-Coralline algae
CP-Collisella pelta
CU-Cucumaria sp.

E-Endocladia muricata
EI-Enteromorpha intestinalis
EV-Evasterias
F-Fucus distichus

G-Gigartina sp.
HC-Halosaccion glandiforme
HP-Halichondria panicea

HS-Hedophyllum sessile

KT-Katharina tunicata
L-Laminaria sp.
LS-Littorina sitkana

ME-Mytilus edulis
N-Nereocystis luetkeana
NL-Nucella lamellosa
OF-Odonthalia floccosa
PO-Pisaster ochraceus
POR-Porphyra sp.
PR-Prasiola meridionalis
PY-Phyllospadix

RH-Rhodymenia palmata
RX-Rhodomela larix

USP-Ulva sp.

ZONES

Supralittoral fringe
Subzone A
Subzone B
Subzone C
Subzone D
Littoral zone
Infralittoral fringe

RELATIVE BIOTIC COVER

Zero to sparse cover
Intermediate cover
Dense cover

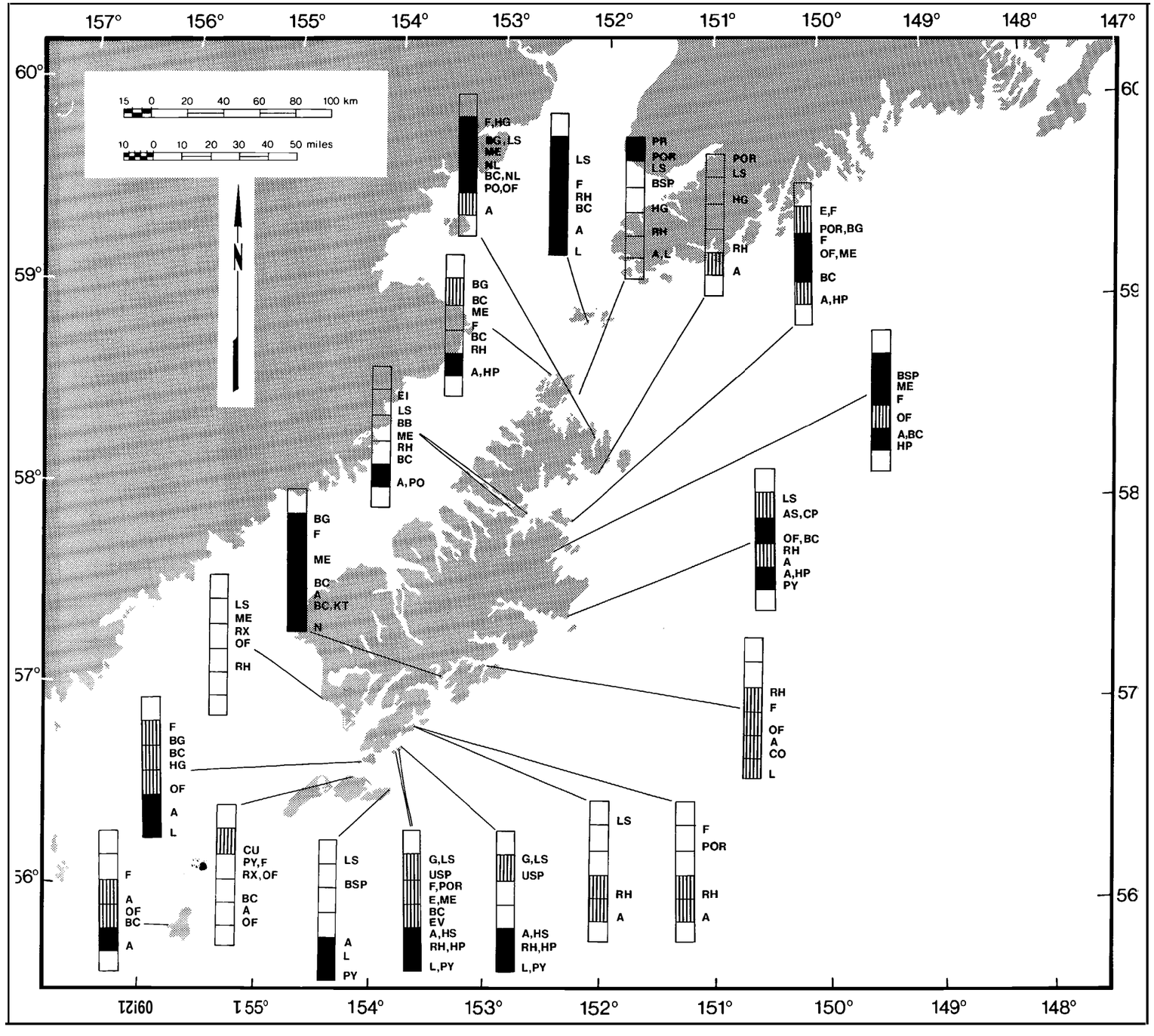


Figure 5.32 Relative biotic cover at intertidal sampling sites (Zimmerman et al., 1978).

5.5.3 Shallow subtidal

Quantitative estimates of subtidal brown seaweed cover and biomass were made along 30-m diver transects at nine sites in the Kodiak Island area (Calvin and Ellis, 1976). Floating kelps (*Alaria fistulosa*, *Nereocystis luetkeana*) were not counted, though rough estimates of their abundance were made. The distribution and relative abundance of floating kelp beds in the Kodiak Archipelago are shown in Fig. 5.33. While these estimates hold for the period of study, values today may be very different, since kelp beds are known to exhibit radical growth and regression under the influence of storms, high water temperature, low nutrient concentration, and grazing.

Six species of the Laminariaceae were found in the quadrats in addition to some species of *Alaria*: *Laminaria dentigera*, *L. yezoensis*, *L. longipes*, *L. groenlandica*, *Pleurophycus gardneri*, and *Agarum cribrosum*. On the exposed outer coast *L. dentigera* was the numerical and biomass dominant (26-90 percent and 57-91 percent of the outer coast samples, respectively). At Cape Barnabas the site sampled under a heavy *Nereocystis* canopy was exceptional, with *Pleurophycus* comprising 50 percent of the individuals and 94 percent of the biomass. *Agarum* was dominant (49 percent of the individuals and 37 percent of the biomass) at the protected estuarine site of Ugak Bay.

Except for the site at Ugak Bay, where the substrate was unsuitable for kelp, the average combined weights (per m^2) of all species of kelp were similar among sites. Individual quadrats, however, showed a substantial range (Table 5.21). The quadrat at Bumble Bay with the heaviest kelp stand (35.0 kg/m^2) contained only *L. dentigera*.

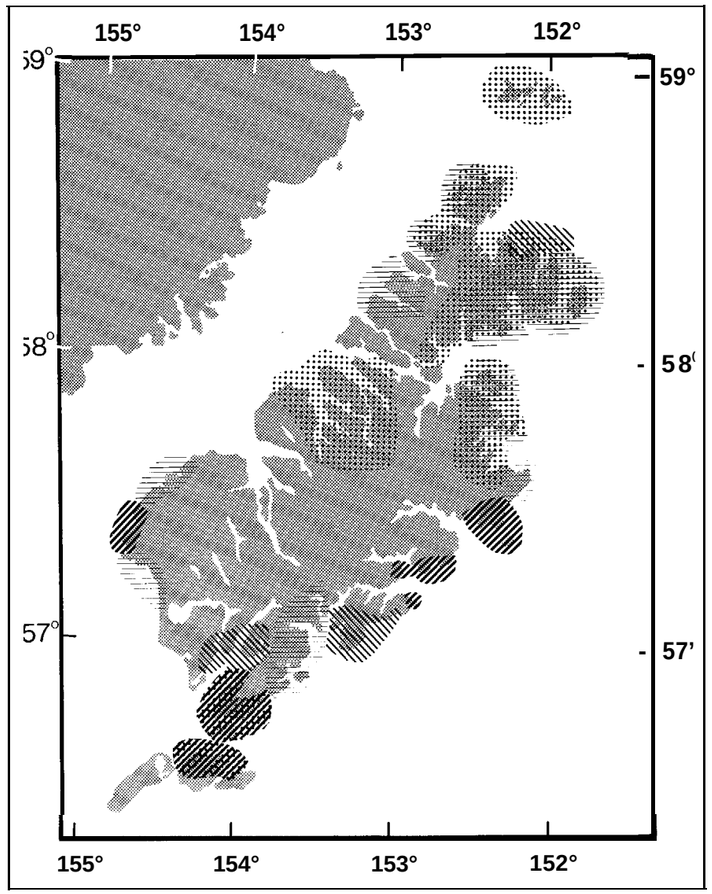


Figure 5.33 The location of kelp beds on Kodiak Island and areas for which 50 percent or more of the rocky intertidal is covered with biota (Zimmerman et al., 1977).

Table 5.21 Weights of Laminariaceae in quadrat samples in May 1976 at these areas of S. Kodiak Island (Calvin and Ellis, 1976).

Area	Number of Site	Weight (kg/m^2) Mean	Weight (kg/m^2) Range
Outer Coast	6	12.3	2.4 to 35.0
Semi-Protected (Sitkalidak Strait)	2	15.4	6.8 to 28.8
Protected (Ugak Bay)	1	4.8	2.0 to 11.2

5.5.4 Seasonal variation

Since few sites were sampled more than once in the Kodiak Island area and these instances did not involve sampling the same transect on return visits, no valid seasonal data were acquired. Inferences of seasonal differences must therefore be drawn from studies of adjacent Gulf of Alaska areas (e.g., Lees, 1977; O'Clair et al., 1978) with similar climatic regimes.

The severity of the subarctic winter in the Kodiak Island area is greatly mitigated by the maritime influence of the surrounding waters. Since icing conditions probably occur only in the most protected heads of fiords, many species can overwinter as adults in the intertidal zone. Summer (June through August) is the period of greatest biological activity. Subtidal kelp samples in late May showed new growth with developing reproductive sori and old growth with degenerating sori, suggesting the onset of a reproductive period (Calvin and Ellis, 1976). Seasonal sampling at specific intertidal heights at Gull Island and Seldovia Point in Kachemak Bay, Lower Cook Inlet, revealed cover and biomass minima for some abundant dominants in the period October through May, especially in the mid- to upper intertidal. A rockweed Fucus distichus exhibits this pattern at Gull Island, with cover and biomass being greatest in late summer and least in the winter. The trend is less distinct for F. distichus at Seldovia Point, where biomass and, to a lesser degree, cover remain relatively constant throughout the year. Alaria crispa at Gull Island is similar in its pattern to F. distichus, with cover and biomass maxima occurring in early summer. The biomass of Spongomorpha spp., Monostroma spp., Odonthalia floccosa, and Rhodomela larix is greater in the summer and decreases during the fall. In fact, the total biomass of Gull Island and Seldovia Point is greatest for all tidal heights during the summer, decreases during the fall, and is at a minimum in winter.

No general pattern of seasonal cover or biomass is evident among the dominant species (i.e., Agarum cribrosum and Laminaria groenlandica) in the lower intertidal and shallow subtidal zones.

5.5.5 Environmental control of community structure

A primary objective of intertidal sampling has been to describe the community composition and abundance throughout the Kodiak Island area before petroleum development.

It is clearly impossible to survey all sites adequately for this purpose, although extensive, low-resolution aerial surveys were made by Sears and Zimmerman (1977). It is therefore desirable to correlate biotic variability with physical variables and/or experimentally document the controlling and interactive forces operating at representative study sites to extrapolate to unstudied locales. The limited field sampling program conducted during the OCSEAP study was inadequate; the sampling effort varied among stations, and intertidal height intervals were not sampled uniformly. However, the cursory site descriptions do permit some tentative observations.

Bedrock (exposed reef) and large-boulder substrates appear to promote the development of taxonomically rich communities with large biomass (Table 5.22). The site at Cape Sitkinak, which is exposed to extremes of wind and waves, is excluded from this discussion because the abundant kelp stands visible under shallow standing water on the survey date were not sampled.

The site ranked highest in average biomass, Three Saints Bay, also had a rich community whose diversity was largely attributable to a high number of invertebrate taxa. This site harbored unusually dense populations of Porphyra, Mytilus, and heavy-walled Balanus cariosus. A second, more protected area surveyed at Three Saints Bay was found to have fewer Alaria, B. cariosus, and Katharina than the partially protected area but more encrusting corallines and Tonicella. The

Table 5.22 Relationship between species diversity (counts of taxa), biomass, and intertidal site characteristics (Zimmerman et al., 1978).

Study Site	Wave Exposure	Profile	Substrate	Number of Taxa: Plants	Invertebrates	Total	Biomass* (kg/m^2)
Sundstrom Island	full	sloped	bedrock	58	138	196	6.1
Sud Island	full	sloped	large boulders	68	130	198	3.0
Chirikof Island	full	flat	bedrock	65	106	171	3.4
Cape Sitkinak	full	flat	bedrock	21	31	52	0.93
Dolina Point	full	flat	small boulders	29	37	66	1.7
Low Cape	full	flat	small boulders	14	45	59	0.47
Three Saints Bay	partial	sloped	bedrock	41	114	155	19.1
Cape Kaguyak	partial	sloped	large boulders	23	47	70	3.1
Lagoon Point	partial	sloped	small boulders	35	71	106	7.3

* Wet weight of 16 plant and invertebrate species.

upper zone at this second area was characterized by unusually high densities of B. glandula, Chthamalus dalli, and littorine snails. The branched Odonthalia/Rhodomela taxon was also abundant here in contrast to the partially protected area.

The high wave exposure/small boulder sites at Dolina Point and Low Cape yielded low numbers of taxa and low biomass. The exposed, flat shoreline was strewn with small boulders and cobbles which were frequently disturbed by waves. Biotic cover was so sparse at Dolina Point that extra large sampling quadrats were used. At Low Cape, 10 of 11 quadrats sampled contained Mytilus edulis, but these were small, suggesting recent settlement. At both sites the most developed assemblages were found in stable areas of immovable boulders.

Three transects differing in substrate stability were surveyed at Lagoon Point, and the biotic assemblages reflected this difference. The large-boulder

transect revealed the highest species diversity and cover. The intermediate transect had less cover except for Rhodymenia, and the upper third of the transect was barren except for some scattered, leafy Porphyra. The third transect had only small boulders and a corresponding decrease in invertebrate species and overall biotic abundance. The relatively high species count at Lagoon Point may be an artifact of the extended sampling there.

As sites were unbalanced with respect to the various physical characteristics, no further correlation is possible. It is interesting, however, that the three richest sites were all small islands (Sundstrom, Sud, and Chirikof).

5.5.6 Beaches

Beaches composed of unconsolidated sedimentary substrates create a far different set of environmental conditions from those commonly found in the rocky intertidal zone. Habitat extremes range from the quiet, burrow-ridden mudflats of protected tidal backwaters to the constant churning of sand and gravel on unprotected beaches, and the communities they support are naturally quite different. Of the 30 beaches in the Kodiak area with known populations of the commercially important razor clam, Siliqua patula (Fig. 5.34), 12 were systematically sampled by Kaiser and Koenigsberg (1977).

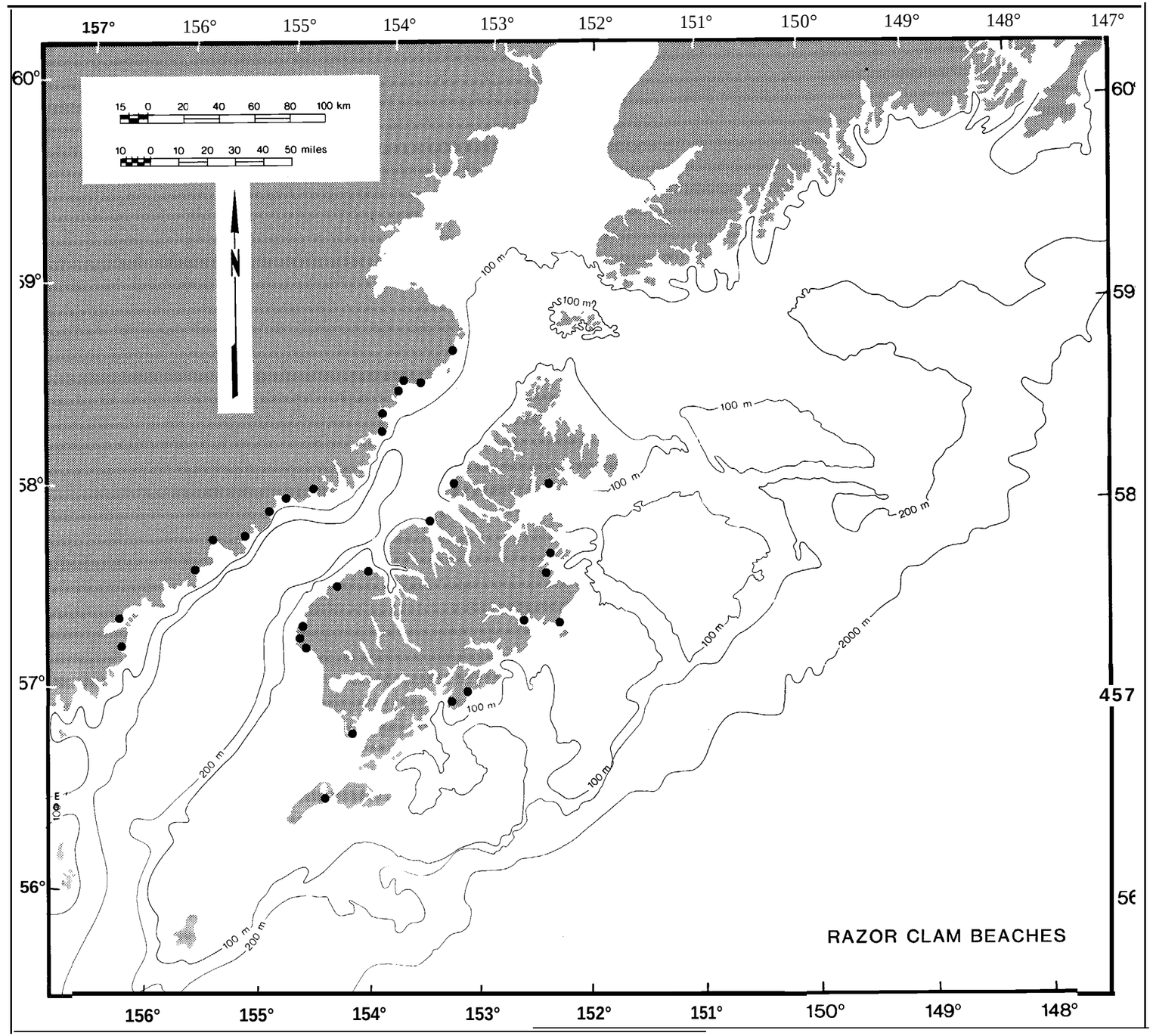


Figure 5.34 Beaches with known populations of Pacific razor clams. Asterisk denotes those beaches surveyed during the 1976 field season (Kaiser and Koenigsberg, 1977).

The collections produced a number of species of bivalves (clams) polychaete worms, and nemertean or ribbon The ta c compos tion of the beach samples is shown in Table 5.23. The razor clam was the mos abundant clam; Scolelepis squamatus was the most mm polychaete. The low abundance of ribbon worms probably reflects their natural fragility and the size of the sampling mesh

Table 5.23 Intertidal sandy beach fauna: Taxonomic composition of twelve samples from Kodiak Island and adjacent Alaskan Peninsula (Kaiser and Konigsberg, 1977).

Species	Number
Mollusca	
Bivalves (Clams)	
Siliqua patula	1280
Macoma lama	257
Spisula polynyma	116
Siliqua alta	63
Clinocardium nuttallii	30
Macoma balthica	30
Mya arenaria	20
Tellina lutea alternidenta	20
Macoma voldiformis	8
Macoma nasuta	3
Macoma loveni	2
Macoma calcarea	2
Protothaca staminea	1
Tellina nucleodes	1
Tresus capax	1
Annelida	
Polychaeta (Segmented worms)	
Scolelepis squamatus	2905
Nephtys caeca	254
Nephtys californiensis	155
Haploscoloplos elongatus	181
Ophelia assimilis	165
Eteone longa	18
Glycinde picta	14
Anaitides groenlandica	10
Nephtys ciliata	3
Cistenides brevicoma	4
Nemertea (Ribbon worms)	
Cerebratulus californiensis	13
Other Nemerteans	14

Because of sampling bias toward the razor clam habitat, the results are not representative of all Kodiak beaches. Very gravelly beaches probably harbor a depauperate infauna compared to that of flat, fine-grained beaches. Table 5.24 shows the relationship between sediment size and taxonomic diversity in the razor clam habitats and demonstrates some of the physical requirements of Siliqua. Halibut Bay had the

Table 5.24 Sediment characteristics, taxonomic diversity richness (counts), and density of Siliqua patula in the Kodiak area (Kaiser and Konigsberg, 1977).

Site	Tide Level Stations Surveyed	Mean Grain Size	No. S.patula sample	Number of Taxa Bivalves	Polychaetes
Tanner Head	7	0.26	24	5	3
Halibut Bay	10	0.21	268	7	8
Swikshak	6	0.22	121	6	7
Vi lage	5	0.28	208	3	8
Big River	5	0.25	211	6	6
Hallo Bay	8	0.39	63	10	7
Kukak Bay	10	0.25	105	9	8
Bumble Bay	6	0.60	4	1	3
Tugidak	5	0.23	23	1	5
Dakavak	7	0.27	50	1	8
Kashvik	7	0.40	117	4	7
Alinchak	4	0.33	85	3	3

finest mean grain size (though not too fine; see Nickerson's 1975 discussion on inhibiting effects of silt on settling Siliqua veliger larvae) and also the highest yield of razor clams. The lowest density was at the beach with the coarsest sand sampled, Bumble Bay (Fig. 5.35) The close geographic proximity of these two beaches suggests that sediment characteristics are important in controlling infaunal populations and associations

The cumulative intertidal distributions of the most dense infaunal organisms from the twelve beach surveys are given in Fig. 5.36. The polychaete Scolelepis showed the broadest range. Although Siliqua is found primarily in the intertidal, it has been recovered by dredge at a depth of 55 m (Nickerson, 1975).

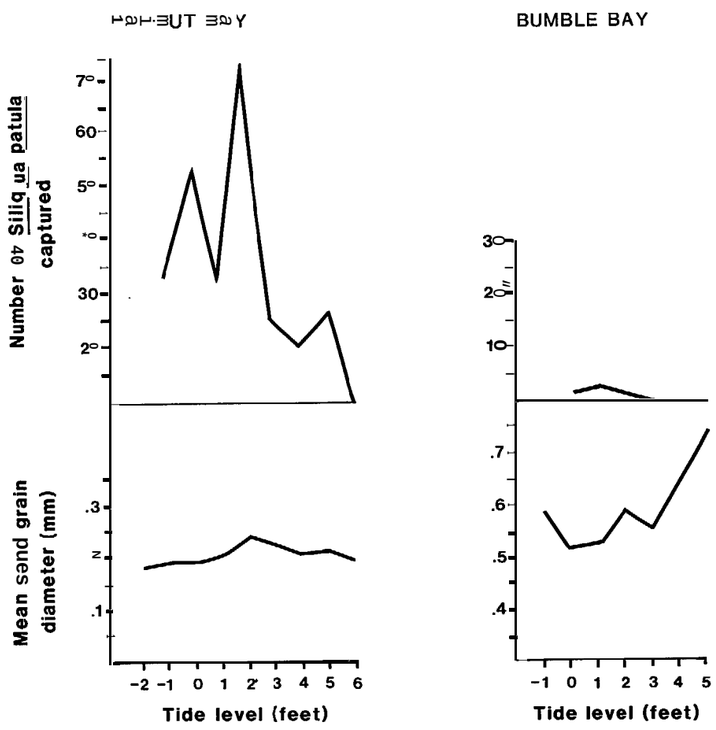


Figure 5.35 Intertidal distribution of the razor clam Siliqua patula and mean sediment grain size at two Kodiak Island beaches (after Kaiser and Konigsberg, 1977).

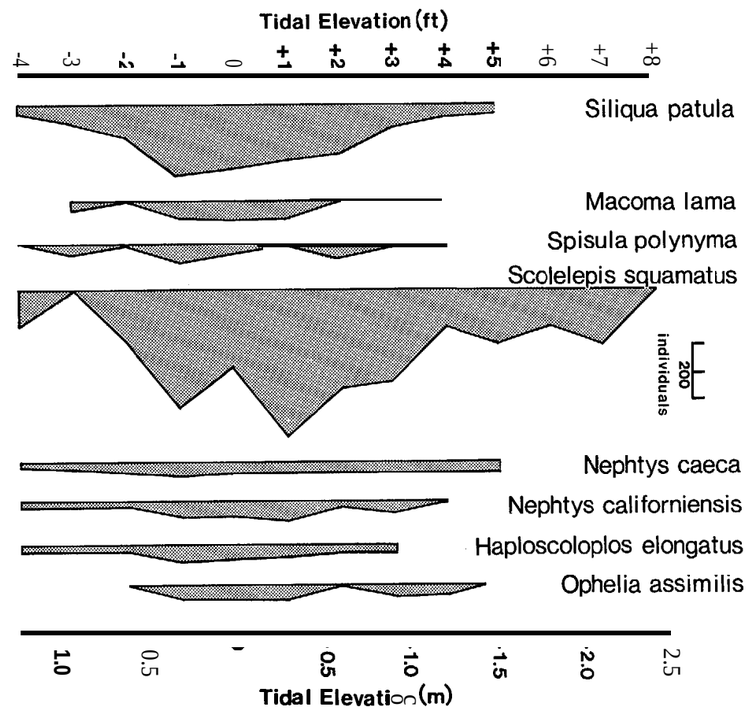


Figure 5.36 Vertical distribution of abundant sandy beach invertebrates sampled at twelve sites on Kodiak Island and adjacent Alaska Peninsula (Kaiser and Konigsberg, 1977).

5.5.7 Vulnerability of the Kodiak Island intertidal zone to potential oil spills

An oil spill vulnerability index (OSVI) based on substrate type has been developed for the Kodiak Archipelago by Hayes and Ruby (1979; see Section 2.5.2). The index predicts the residence time of oil on a particular type of coastline. Kodiak is a moderate-to-high-risk area, 71.2 percent of the coastline having indices from 6 to 8, with a predicted spill longevity of from one to eight years. The rest of the coast is a relatively low-risk area (indices 1 and 2)

Site-specific information for the Kodiak Archipelago suggests greater vulnerability than is depicted by the Hayes and Ruby model. First, because of long periods (especially in summer) of low wind and wave energy, the exposed rocky headlands and eroding wave-cut platforms (ideally cleansed by wave action) may increase the index value from 1 and 2 to 6 and 7 Second, the many fiords on the island will act as oil traps, causing the oil to move into rather than out of the most vulnerable areas located deep in fiords and embayments.

The Hayes and Ruby model concerns expected residence time in various physical environments. Biological sensitivities to oil are far more difficult to model and essentially impossible to predict, despite the efforts of a number of post-spill studies. Among the factors that must be considered in attempting to resolve this uncertainty are: type and amount of petroleum spilled, slick structure, oil weathering stage, season, weather, tides, life history stage of impinged species, community composition, and local

substrate and beach morpho.ogy. Thus far, each spil incident has resulted in the elucidation of a new environmental response scenario and has raised more questions than it has answered (Clark and Fin.ey, 1977). It seems also clear from the results of these studies (e.g , Sanborn, 1977; Thomas. 1978; Southward and Southward, 1978; Hampson and Moul, 1978; Clark et al., 1978; Notini, 1978) that while some dramatic effects may be evident, the intertidal is far too spatia ly variable to attribute subt.e changes to the action of spilled oil on the basis of post-spill studies. These subtle changes may ultimately prove more important than the more obvious short-term manifestations. An obvious problem has been the difficulty in selecting study areas that serve as true controls with which to compare affected areas.

We may, however, make some general predictions, in part based on the previously cited studies and in part based on speculation. The most obv.ous is that the more lex mm ties will tend to be more disrupted than w l those simp.er ones subject to chronic natural disturbance. This disrupt.on may take the form of selective declines (or sometimes long-term enhancement of various popu.ations. At one extreme, the barren site at Cape Sitkinak would probab.y not be material.y affected at the macrobiotic level. Natural disturbance communities tend to be populated by opportunistic ephemerals such as the sea lettuce Ulva. These species are frequently the first to recover or recolonize following petroleum insult.

The mechanical effect of waves is important in determ.ning the outcome of oil spills in the intertidal. Wave energy (combined with tides) can result in the stranding of oil in the splash zone, but can also accelerate the natural clearing of rocky intertidal areas. Thus, it is expected that exposed coasts wou.d tend to recover faster than protected areas, although the latter may not be as susceptible to impingement in the first place.

Substrate is also important, although one cannot make a blanket prediction comparing impacts at rocky versus sedimentary habitats. High energy, coarse-grained beaches should be cleansed during times of erosion, but may accumulate buried oil strata if oil comes ashore during the accretion part of the sand transport cycle. These may later be uncovered with renewed o.l release to the environment. Oil may percolate rapidly in gravelly substrates, but lie on the surface in a weathered, asphaltene pavement on flat, fine-grained or muddy protected beaches. Where oil is not persistent at the surface of sediments, the effect on mobile, frequently reco.nizing sandy-beach infauna shou.d be transient. In contrast, the structurally stable rocky intertidal communities may be subject to greater impact because of the inability of species to escape the mechanical or toxic effects of oil. In the rocky intertidal, she.led organisms such as barnacles, limpets, and mussels may survive short-term insult by simply c.osing up while the slick is ashore If thick stranding does not occur, they may escape altogether. Heavy or protracted exposure to oil, however, can produce massive kills of both algae and invertebrates. Algae may become b.eached over time despite their mucilaginous coating that tends to prevent direct adhesion of oil. Invertebrate may be accompanied by a.gal increases in response to reduced grazing pressure from limpets and chitons Conversely, some grazers (e g Littorina show long-term growth enhancement because of increased ephemeral a gal cover during the recovery phase. These algae take advantage of space created by the death and removal of large grazers and large, canopy-forming seaweeds.

A very important factor affecting vulnerability is the timing of a spill relative to species-specific patterns of recruitment. Larval and molting stages of many organisms are known to be highly sensitive to toxic components of petroleum. If not killed outright, these stages may otherwise be adversely affected, such as by inhibit.on of settling response By the same token, random spatial patterns of larva recruitment may cause selective increases of a given species at some, but not all, affected or unaffected areas This "noise" tends to obscure the differences due to oil impingement

The time of detrimental effects has been highly varied, ranging from a few days in cases of lightly oiled sandy beaches or wave-swept rocky coasts to many years in heavily oi.ed protected areas It is likely that within any area of diverse habitat such as Kodiak Island, the entire range of previously observed effects is possible.

5.6 FISH

5.6.1 Introduction

Continental shelf and slope waters surrounding the Kodiak archipelago are some of the most biologically productive areas in the Gulf of Alaska. Large populations of salmon, herring, smelt, halibut, pollock, other groundfish, crabs, and shrimp use these waters as their principal spawning, rearing, and foraging grounds. Coastal fiords and embayments are the nursery areas for many key pelagic (e.g., salmon, herring, capelin) and demersal (e.g., halibut, pollock, cod) fishes that, as adults, are far-ranging. Migratory routes of economically important stocks from other Alaskan regions (e.g., Bristol Bay sockeye salmon, Unimak Pacific ocean perch, southeastern Alaskan Pacific halibut) lie along the outer continental shelf to the east of the Kodiak Island group.

Major fishing grounds for salmon, halibut, crab, and shrimp are located in Kodiak waters. The total value of the catch to fishermen in 1978 was $86.7 million (ADF&G, Kodiak office, pers. comm.). The only population center of any size, the port of Kodiak, ranks second in the nation in the value of fishery products landed.

The oil industry and Bureau of Land Management have designated 1.3 million hectares of offshore tracts to the east of Afognak, Kodiak, and Trinity Islands to be leased for OCS development in December 1980 (Lease Sale #46). These tracts are located in 30 to 250 m of water. Potential conflicts between exploration, refining, and transportation of oil and gas and the fishing industry are major issues that developers, resource managers, and the Kodiak populace must face.

A thorough understanding of the fish populations is required to assess the consequences of development on the Kodiak Shelf. Knowledge of the life histories, seasonal distributions, population dynamics, and feeding relationships of fishes will allow researchers to predict the vulnerability and sensitivity of species to environmental disturbances. It can also be used by resource managers in decision-making and in minimizing resource conflicts. Where to build an LNG plant, or how to route tanker traffic so as to minimize disturbance of commercial fish populations near Kodiak are examples of the kinds of decisions which will have to be made.

This chapter provides an overview of fish populations in the Kodiak area and briefly describes the extent and value of the commercial fisheries. Information on fishes of commercial value or of potential commercial value, as well as ecologically important species, is emphasized.

5.6.2 Distribution, abundance, and population dynamics

Submarine topography, circulation patterns, seasonal changes in temperature and salinity, location of preferred habitats and prey, and fishing effort are some of the major conditions that influence the distribution and abundance of fish populations. Marine habitats surrounding the Kodiak Island group are diverse. The nearshore marine environment is characterized by numerous reefs, skerries, terraces, and in places, luxuriant algal growth. Water depths are generally less than 60 m. Inlets and fiords are common, providing relatively protected deep-water (up to 200 m) habitats for marine life. The offshore continental shelf is a broad plateau with several large banks (e.g., Marmot Flats, Albatross, and Portlock Banks) rising above it. Additionally, several major submarine canyons, such as the Chiniak and Kiliuda Troughs, transect the shelf (see Fig. 2.19). Beyond the shelf the seafloor slopes down steeply into the Aleutian trench. The irregularities of topography and water depths, and consequently of substrate types and associated benthos, within relatively short distances provide many potential niches for marine fishes. (For a more detailed discussion of the physical marine environment seaward of the Kodiak archipelago and seasonal density distributions of plankton and benthos, see Chapters 2, 3, 5.3, and 5.4.)

The preferred habitats of many marine fishes found in Kodiak waters vary with life stage and season. For instance, maturing salmonids feed in oceanic, epipelagic habitats hundreds of kilometers away from Kodiak, yet these anadromous fishes are abundant as adults in coastal waters from June through September each year, staging for their spawning runs (ADF&G, 1976). Salmon smelts emigrate in spring and summer from freshwater streams and lakes into estuaries, where they remain for several months before migrating to the open ocean (Buck et al., 1975; Gosho, 1977). Many fishes that as adults occur in deeper water on. the continental shelf and slope inhabit the littoral and sublittoral areas of the Kodiak Island group as juveniles (Harris and Hartt, 1977; Rogers and Rogers, 1978; Rogers et al., 1979; Hunter, 1979). Populations of many fishes (e.g., . . Pacific halibut, cod, walleye pollock) range into shallower depths in summer than in winter (Hughes, 1974; Ronholt et al., 1978; IPHC, 1978). Although larval fishes have only limited control over their movements, there is a pronounced seasonality in their appearance in Kodiak waters (Dunn and Naplin, 1974; Dunn et al., 1979a).

The distribution of fish populations is constantly changing. Their typical distribution patterns and

level of abundance can be estimated from long-term observations, but populations should be monitored regularly to determine shifts in their composition and patterns of movement. Some fish populations, like those of walleye pollock, are expanding rapidly in the Gulf of Alaska, while others, such as those of Pacific ocean perch, are apparently declining (Ronholt et al., 1978). Knowledge of natural long-term changes in fish populations is necessary to differentiate them from human effects such as OCS development.

Sampling procedures

Information on the distribution, abundance and population dynamics of fishes in the Gulf of Alaska has been collected by OCSEAP scientific teams, the Bureau of Commercial Fisheries (BCF), National Marine Fisheries Service (NMFS), Alaska Department of Fish and Game (ADF&G), International Pacific Halibut Commission (IPHC), International North Pacific Fisheries Commission (INPFC), North Pacific Fisheries Management Council (NPFMC), and various university personnel.

Survey methods have included exploratory trawl sampling, egg and larval surveys, mark and recapture studies, aerial surveys, catch and escapement counts, and monitoring catch and effort data of the commercial fisheries. Each of these methods has advantages and disadvantages; each is best suited for a particular type of fish or life stage. For instance, benthopelagic fishes like Pacific ocean perch are not as easily sampled by otter trawl as many pleuronectids, nor are fishes that occur in rocky areas. Thus, estimates of these less accessible populations based solely on otter trawl collections do not yield a true picture of the populations. Gear selectivity is discussed in depth by Gulland (1969), Ricker (1975), Steele (1977), and Smith and Richardson (1977).

Because sampling effort, location, and season have varied among surveys, it has often been difficult to compare the data on a year-to-year or area basis. As scientific sampling has usually taken place from April through October, there is little information on the behavior and movements of fish in winter.

Additional problems arise in analyzing commercial catch statistics. Productive areas and marketable species are sought within limited fishing seasons. Extrapolating the seasonal distribution and abundance from these data is obviously risky. Other constraints in interpreting survey data will be discussed later.

Salmonids

Salmon and trout are seasonally distributed throughout Kodiak offshore waters, coastal embayments, and freshwater watersheds. These habitats are used by one or more life stages of salmonids (Table 5.25). The principal species occurring in and near the Lease Area are: pink (*Oncorhynchus gorbuscha*), sockeye (*O. nerka*), chum (*O. keta*), coho (*O. kisutch*), and chinook salmon (*O. tshawytscha*), rainbow or steelhead trout (*Salmo gairdneri*), and Dolly Varden char (*Salvelinus malma*) (Buck et al., 1975; Stern et al., 1976).

Table 5.25 Life history data for five species of Pacific salmon (adapted from Burner, 1964; Bailey, 1969; Merrell, 1970; Hartman, 1971).*

	Species				
Characteristics	Pink	Sockeye	Chum	Coho	Chinook
Freshwater habitat	Short streams	Short streams and lakes	Short and long streams	Short streams and lakes	Large rivers
Length of time young stay in fresh water	one day or less	1 to 4 years	Less than 1 month	1 to 2 years	3 to 12 months
Length of ocean life	1-1/3 years	½ to 4 years	½ to 4 years	1 to 2 years	1 to 5 years
Year of life at maturity (years)	2	3 to 7	2 to 5	2 to 4	2 to 8
Average length at maturity (cm)	50.8	63.5	63.5	61	91.4
Average weight at maturity (kg)	1.8	2.7	4.1	4.5	10
Range of weight at maturity (kg)	0.9 to 4.1	0.7 to 4.5	1.7 to 20.4	1.7 to 13.6	1.1 to 56.8
Principal spawning months	Jul-Sep	Jun-Sep	Sep-Oct	Sep-Dec	Aug-Sep
Fecundity (number of eggs)	2,000	4,000	3,000	3,500	5,000

*Exceptions to these general descriptions occur frequently.

In general, maturing salmon are found in oceanic, epipelagic waters far from Alaskan coasts (Godfrey et al., 1975; French et al., 1976; Neave et al., 1976). Royce et al. (1968) report that pink, sockeye, and chum salmon are widely dispersed in the Gulf of Alaska south to 41*N latitude in winter and 48*N latitude in summer. Stocks originating in Asia, Alaska, Canada, Washington, and Oregon are all found in this broad region, and cohorts move across the Kodiak continental shelf when returning to their sites of origin (Foerster, 1968; Royce et al., 1968; Stern et al., 1976). Many coho and chinook salmon inhabit more coastal regions during their entire oceanic phase. Steelhead trout and Dolly Varden char are common inshore along the Kodiak archipelago (Buck et al., 1975; ADF&G, 1976; Stern et al., 1976).

Following an oceanic phase of variable duration (Table 5.25) in which salmon feed abundantly and reach maximum size, maturing cohorts return to coastal waters and search the shorelines for environmental clues (Hasler, 1966) that will lead them to their natal streams, lakes, and estuaries, where they spawn. Maturing salmon usually enter Kodiak waters from the northeast; however, routes are not fixed, and considerable wandering may occur before fish enter their spawning waters (Fig. 5.37). Wandering has been observed in sockeye tagged on the northwest coast of Kodiak Island. Salmon tagged in this area were recovered in Alitak Bay, Chignik Bay on the southern Alaska Peninsula, Bristol Bay, and Cook Inlet.

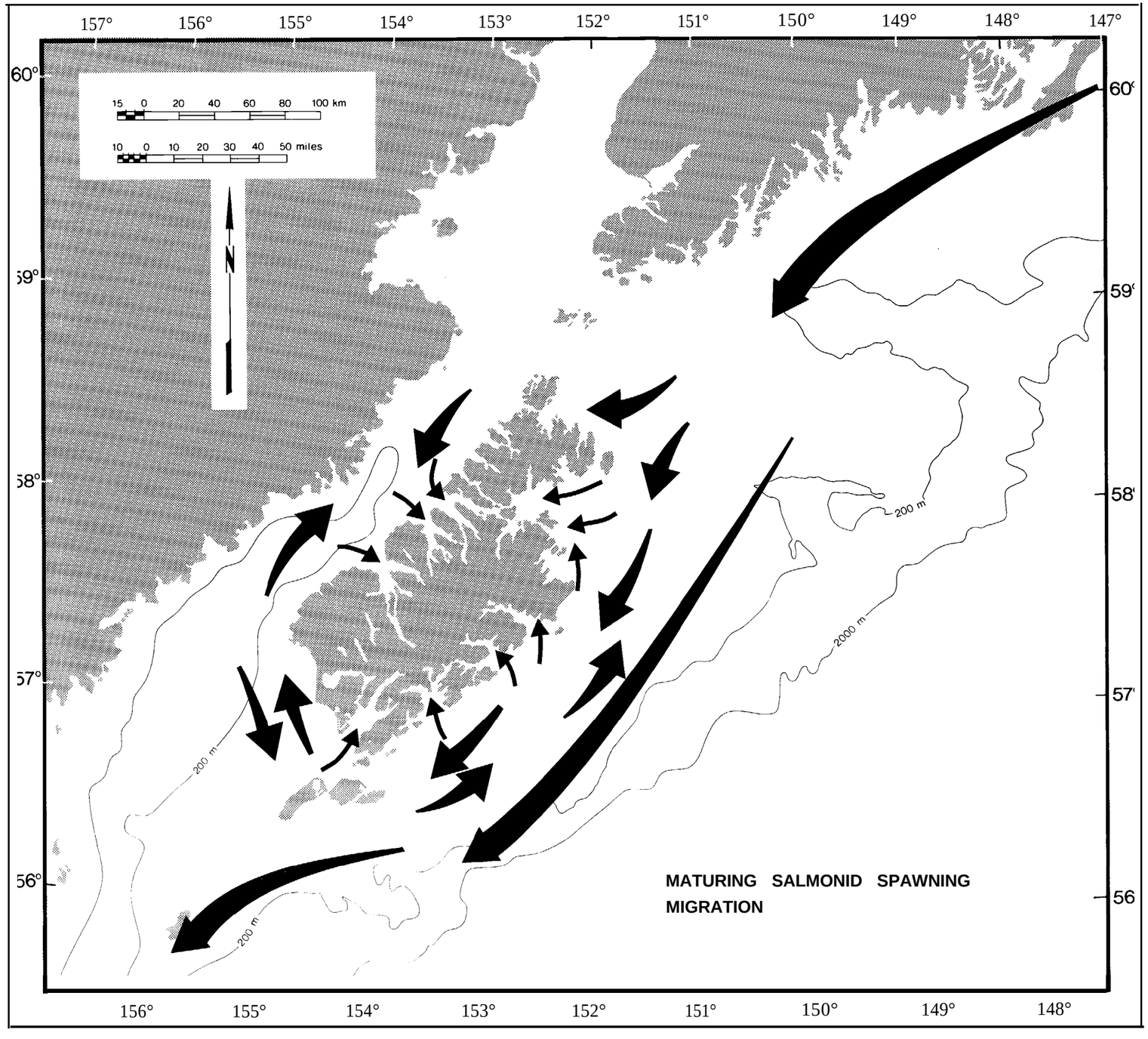


Figure 5.37 Generalized migratory pathways of maturing Pacific salmon approaching the Kodiak archipelago.

Arrival time at the spawning streams is nearly the same from year to year (Royce et al., 1968; Buck et al., 1975; Stern et al., 1976). The spawning season for five salmon species returning to Kodiak is given in Fig. 5.38. Commercial fishing for each species takes place during their respective spawning seasons. The timing of spawning runs varies slightly from area to area around Kodiak (ADF&G, Kodiak office, pers. comm.).

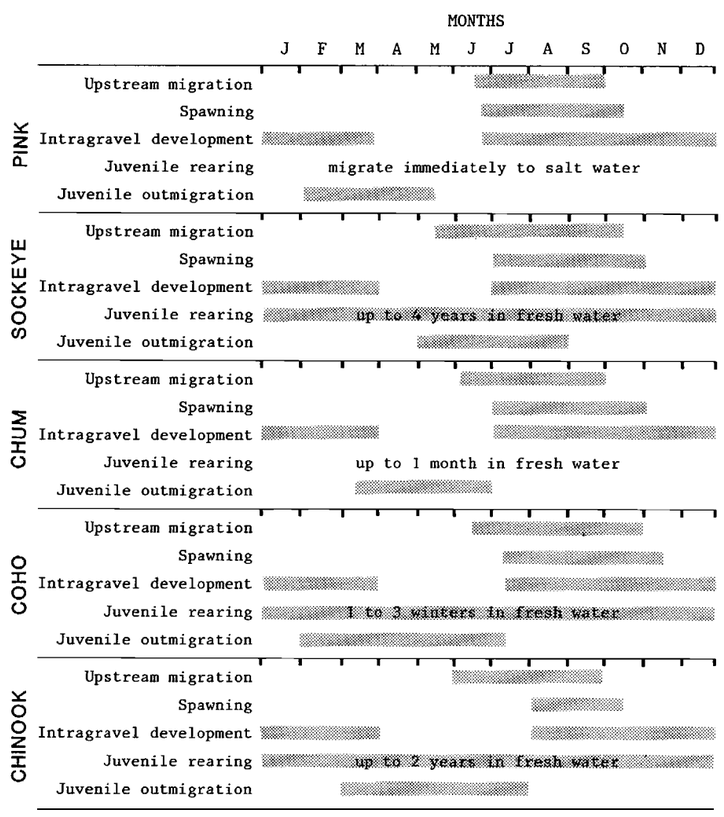


Figure 5.38 Time table of Pacific salmon life histories (Buck et al., 1975).

Pink salmon

Pink salmon are abundant in the Kodiak area, spawning in 240 streams as well as in intertidal areas (ADF&G, 1976). Streams that sustain large spawning runs of pink salmon are shown in Fig. 5.39. Pinks account for about 80 percent of the total salmon catch in the region each year (Fig. 5.40). Largest catches are regularly recorded from ADF&G Management Districts 258, 257, and 252 (Fig. 5.41), which include the southeast coast of Kodiak Island, Alitak Bay, and Uganik Bay (Buck et al., 1975; Stern 1976). Peak spawning runs, as measured by catch and escapement counts, occur from mid-July through mid-August. Pink salmon migrate on an odd/even-year basis, which has resulted in the evolution of two distinct genetic races (ADF&G, 1976). For the entire Kodiak region, the even-year pink salmon stocks consistently produce larger return populations (Fig. 5.40), but this trend is not true for each individual district. A record 15 million pink salmon were caught in the Kodiak region in 1978. The escapement estimate (those fish that avoid being caught and are able to spawn) of 4 million fish was also a record, and very large catches (ADF&G, Kodiak Office, pers. comm.) are forecast for 1980. Further aspects of spawning, fry development, and smolt migration into salt water are given in Table 5.25 and Fig. 5.37.

Between 1925 and 1972 an estimated average of 274 million juvenile pink salmon entered the Kodiak marine waters annually; in peak years estimates ranged to 719 million fry (Stern, 1976). These estimates were based on the number of females spawning (calculated by assuming escapement equal to 30 percent of the total run and an even sex ratio), average fecundity (Table 5.25), and a 10-percent survivorship from the egg phase. In 1978, an escapement of 4 million spawners was estimated (21 percent of the total run), and about 400 million fingerlings were produced. Stern (1976) may have slightly overestimated historical production values.

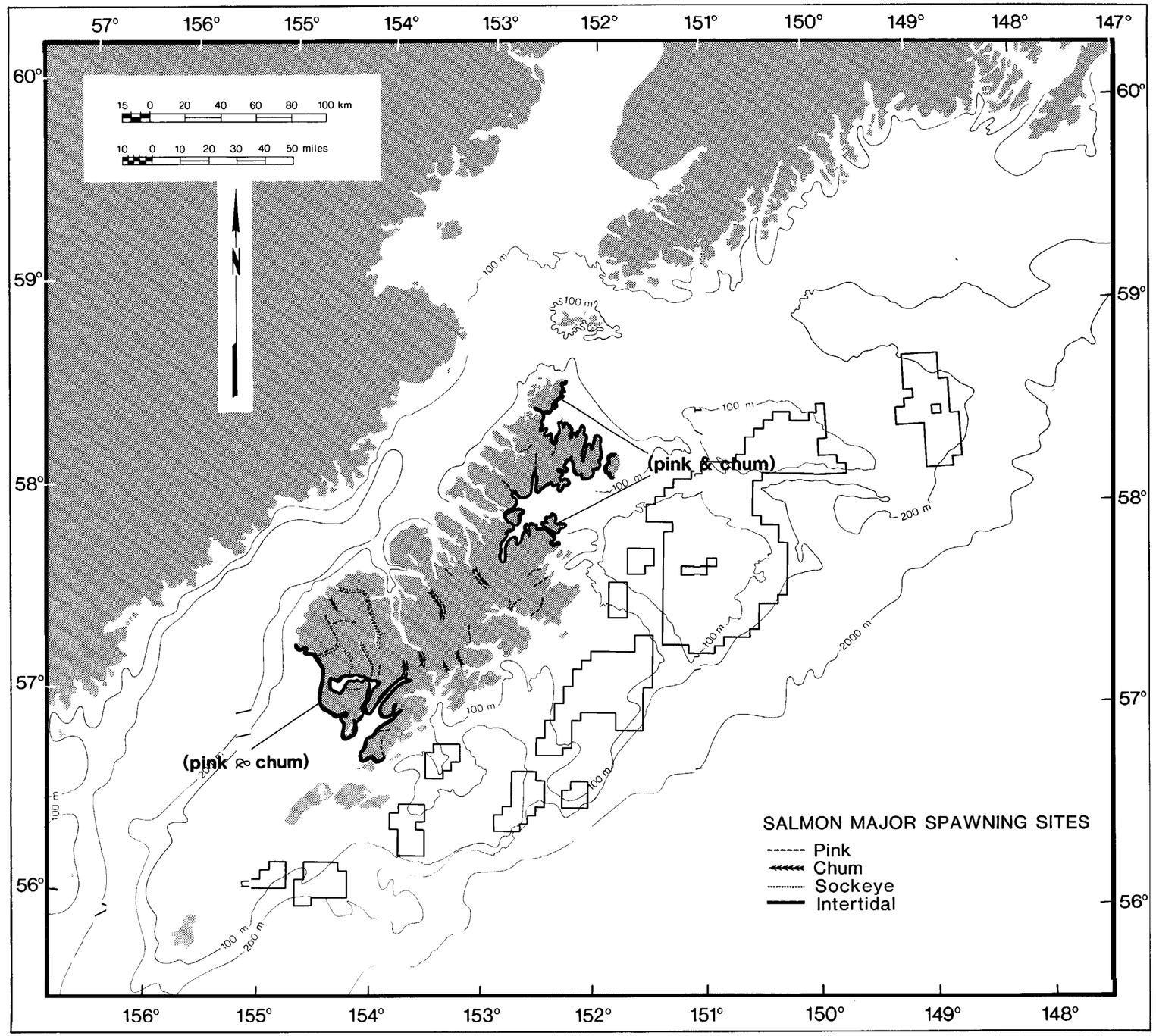


Figure 5.39 Spawning locations of Pacific salmon on the Kodiak archipelago (Buck et al., 1975; ADF&G, 1976).

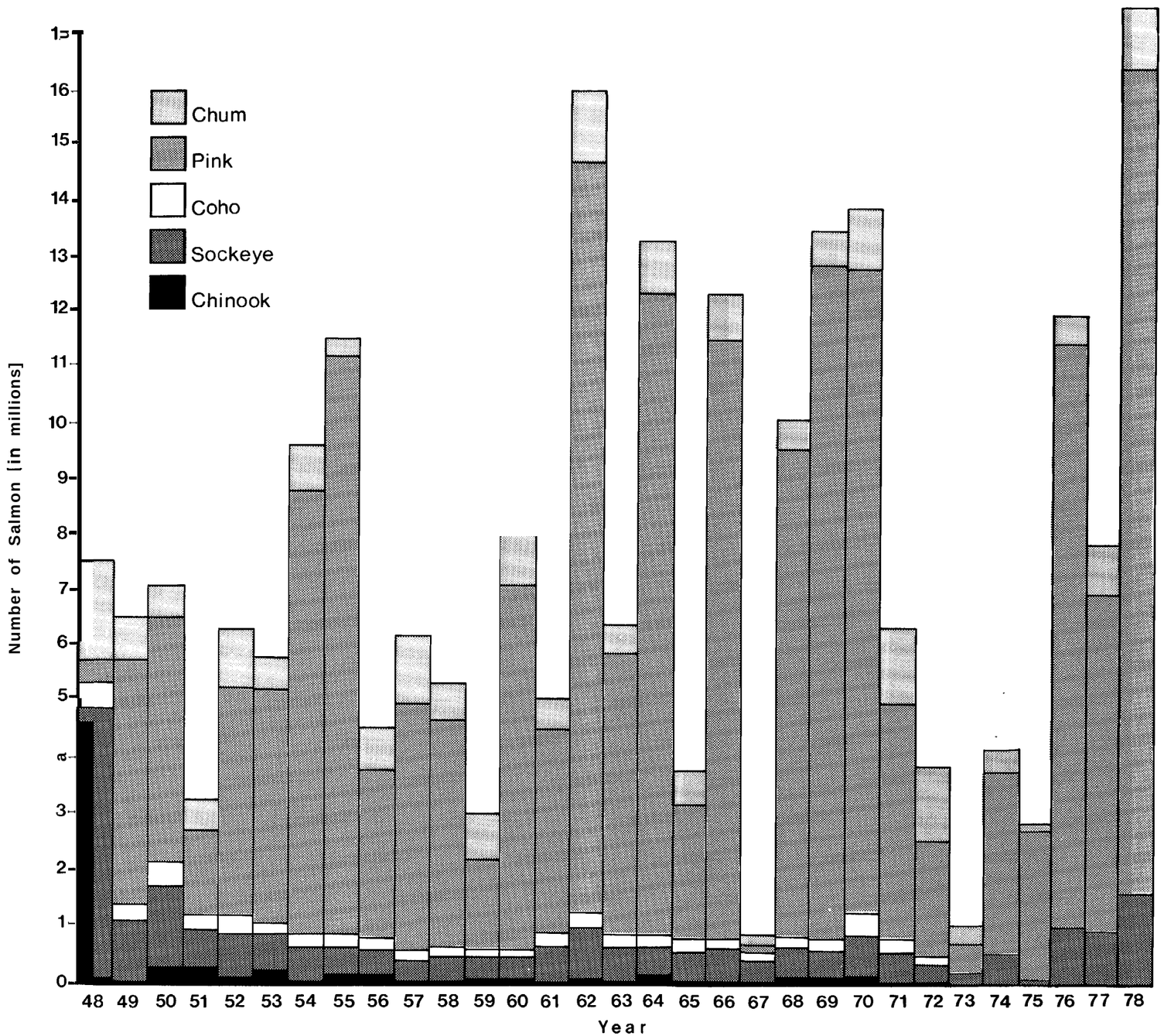


Figure 5.40 Commercial catch of Pacific salmon, by species, for the Kodiak region from 1948-78. Small catches of coho and chinook are not shown for 1973-78 period (Lechner et al., 1972; ADF&G, 1979b).

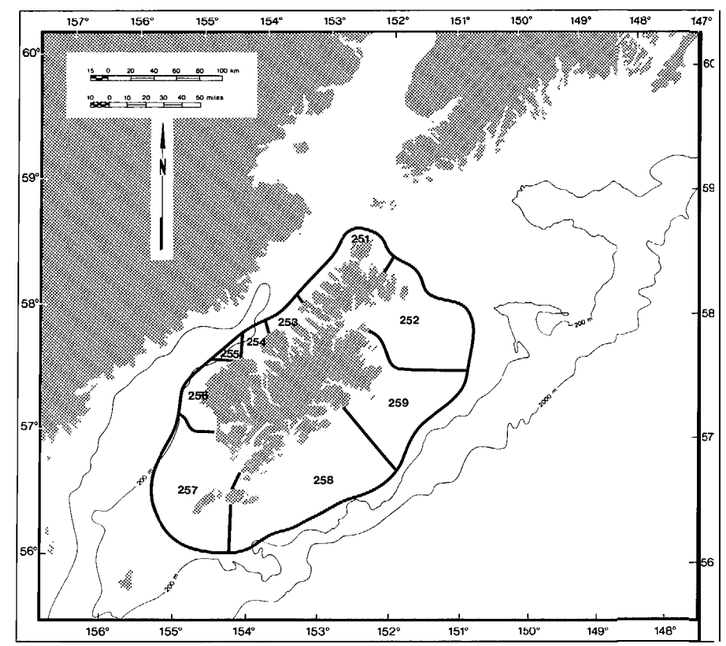


Figure 5.41 ADF&G Pacific salmon management districts, Kodiak region.

The principal juvenile salmonid outmigration route follows the periphery of the northern Gulf of Alaska and then turns southwest past Kodiak Island (Royce et al., 1968) (Fig. 5.42). Juvenile pink salmon enter the ocean from streams and estuaries during July, August, and September (Fig. 5.38). They do not scatter randomly but migrate in a narrow band (about 30 km in width) along the coast. Other salmonid migrants travel a route similar to that followed by juvenile pink salmon (Royce et al., 1968). The migration includes not only locally spawned fish but also some spawned in streams hundreds of miles to the northeast (Stern, 1976). The migration in the Kodiak area continues into October and November, then juvenile pinks leave the coastal zone, and move south into the open ocean (Royce et al., 1968).

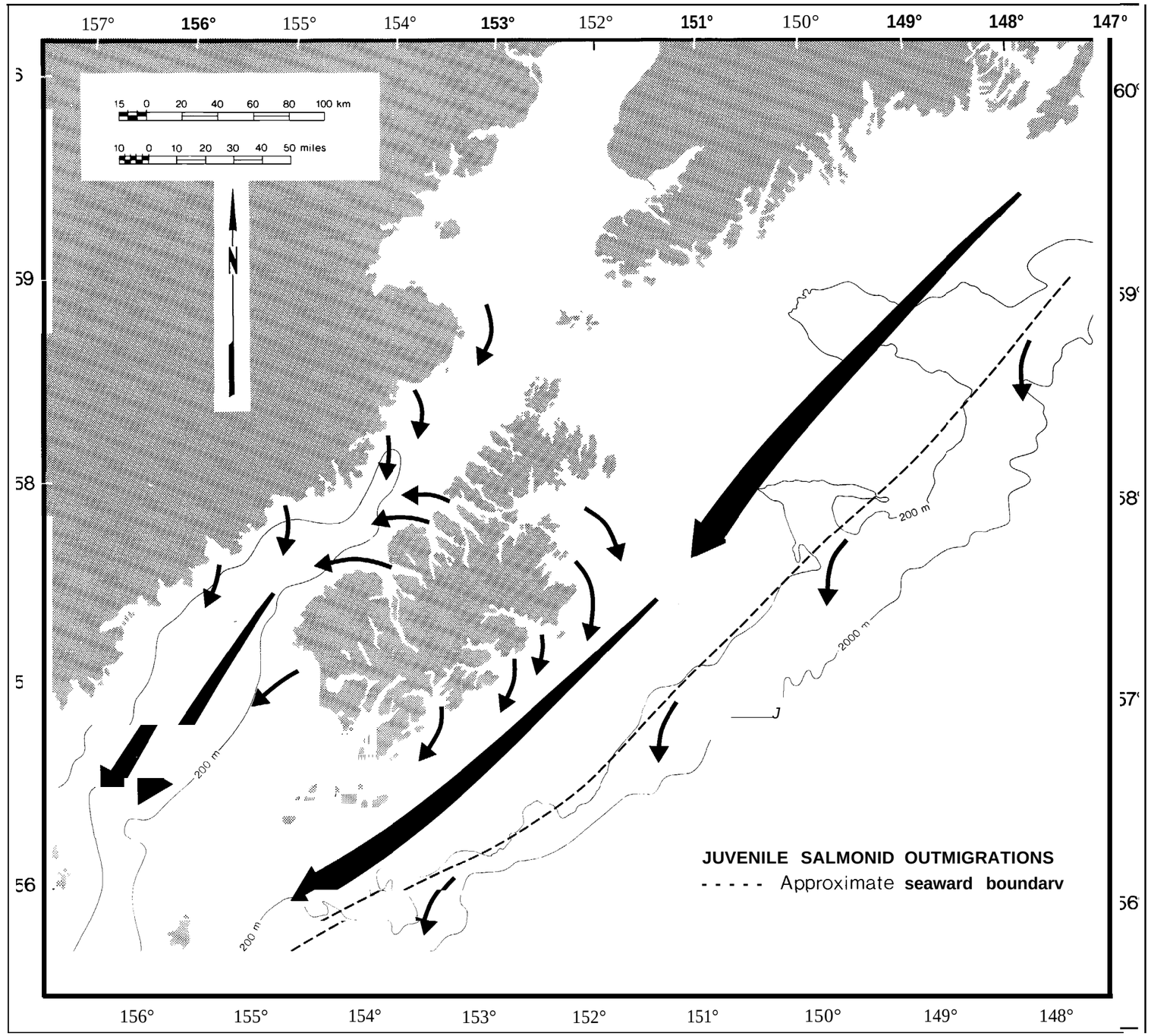


Figure 5.42 Generalized migratory pathways of juvenile Pacific salmon leaving the nearshore zones in the vicinity of Kodiak.

Sockeye salmon

Sockeye rank second to pink salmon in importance to the Kodiak fishery. The 30-year record of catches is shown in Fig. 5.40. In 1978 the total catch of 1,072,000 fish was worth $5.47 million (ADF&G, Kodiak Office, pers. comm.). It was the first time in 30 years that the catch of sockeyes exceeded one million fish. The average annual catch for the 1948 through 1978 period was 495,000 fish. About 60 percent of the sockeyes are taken incidental to the pink salmon fishery in July and August. Sockeyes are caught primarily in ADF&G's management districts 255 and 256 (Fig. 5.40) on the southwest side of Kodiak, en route to their primary spawning sites in the Karluk, Red, and Frazer river systems (Fig. 5.41). Several minor spawning areas on the archipelago include Uganik, Afognak, and Paul Lakes, and Saltery Cove (ADF&G, 1979b). Sockeye salmon typically select spawning sites close to lakes. The free-swimming fry move into these and remain for one or more years. Preferred spawning habitats are streams flowing into lakes, the upper sections of large outlet rivers, and along the shores of lakes (Foerster, 1968). Sockeye are generally the earliest salmon to spawn in Kodiak (Fig. 5.38) and are the primary species commercially sought in June. In 1978 peak catches took place in the third week of June (ADF&G, 1979b).

Juvenile sockeye migrate into salt water somewhat later in the year than other salmon (Fig. 5.38). Stern (1976) estimated that an average annual population of 15 million smolts enter the sea with peak production three times as great. The 1978 outmigration was estimated at 40 million smelts, based on Stern's assumptions of sex ratio, escapement, fecundity, and smolt survivorship.

Chum salmon

Chum salmon are the only other salmon of commercial importance in the region. Historical catch statistics are given in Fig. 5.40. In 1978, 814,000 chum were caught, considerably above the average since 1934 of 624,000. The total catch was worth $2.6 million to the fishermen (ADF&G, Kodiak Office, pers. comm.). Largest catches of chum salmon have been taken within Management Districts 253, 254, and 258 (Buck et al., 1975) (Fig. 5.41). Many of the prime spawning sites for chum are similar to those for pink salmon (Fig. 5.39), and the two species are the only salmon that spawn in intertidal waters to any extent. The chum salmon run in Kodiak generally occurs between late July and late October (Fig. 5.38), with peak catches in early August (Stern, 1976; ADF&G, 1979b). Chum smolt begin to enter salt water in mid-March (Fig. 5.38); juveniles inhabit coastal nursery grounds for three to four months prior to offshore migrations. Stern (1976) estimates that an average of 40 million fingerlings enter the sea each year; the young-of-the-year class was estimated at 64.3 million fish in 1978 (ADF&G, 1979b).

Coho and chinook salmon

Coho and chinook salmon have relatively small spawning populations in the Kodiak region. In 1978 fewer than 50,000 coho valued at $273,000 were harvested (ADF&G, Kodiak Office, pers. comm.). Coho spawn in streams concentrated in the northeast and southwest corners of Kodiak Island (Buck et al., 1975). Typical spawning times are given in Fig. 5.38 and Table 5.25. Because of their late arrival, commercial interest in this species is low. They are usually taken incidentally to the pink and chum salmon. Fifty percent of the coho caught in 1978 were taken in the Afognak region in September. Only 3,228 chinook salmon were harvested in 1978; however, this was the highest catch in 33 years (ADF&G, 1979b). Maturing chinook salmon begin to enter the nearshore zone during early June, and the migration continues into autumn. In the Kodiak Archipelago populations have spawned historically in the Karluk and Red River systems, while introduced populations have used the Dog Salmon River/Fraser Lake system (ADF&G, 1976). Additional features of the life histories of both species are given in Fig. 5.38, Table 5.25, and Stern (1976).

Dolly Varden char and steelhead trout

Historical data on catch statistics and apparent abundance of Dolly Varden char and steelhead trout in the Kodiak region are lacking (Stern, 1976). During the spring and summer char are commonly caught by sport fishermen in areas adjacent to Kodiak City, Pasagshak, Womens, Middle, Kalsin, Monashka, and Anton Larsen Bays. They are typically found within 100 m of shore (D. Rogers, Univ. Washington, FRI, pers. comm.) and are extensively distributed throughout the Kodiak Island group. Char probably spawn in every stream in the region (J. Blackburn, ADF&G, Kodiak, pers. comm.). Spawning occurs in autumn along the British Columbia coastline (Hart, 1973), and probably takes place a month or two earlier in Kodiak.

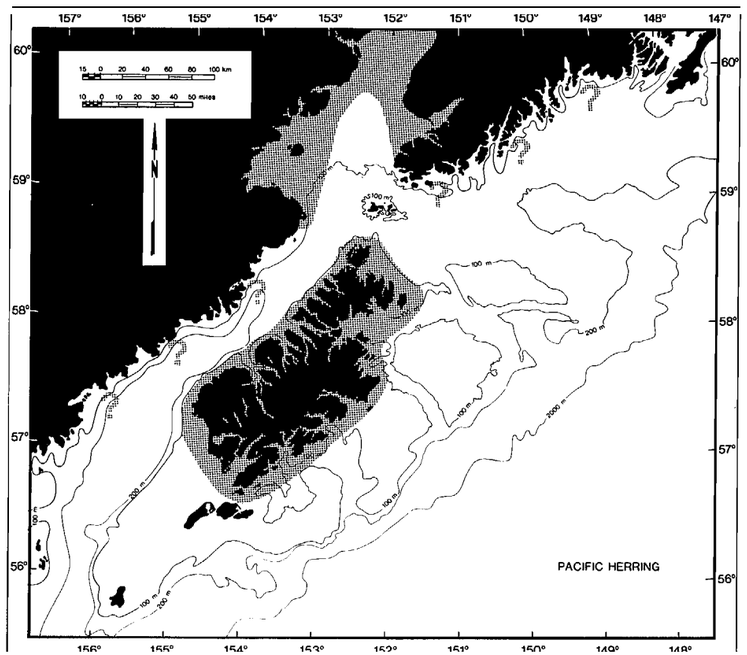
Steelhead trout return from extensive oceanic migration in the north Pacific to spawn in streams along the Kodiak archipelago (Hart, 1973). Maturing and adult steelheads are taken by commercial fishermen from June through August in offshore waters near Kodiak (Stern, 1976). These fish have spent one to five years at sea (Hart, 1973), prior to these spawning migrations. Although not well documented, steelheads are thought to spawn in numerous streams on the archipelago. These spawning fish are sought by sport fishermen. The Karluk River and its tributaries are important sites for this fishing (L. Jarvela, OCSEAP, Juneau, pers. comm.).

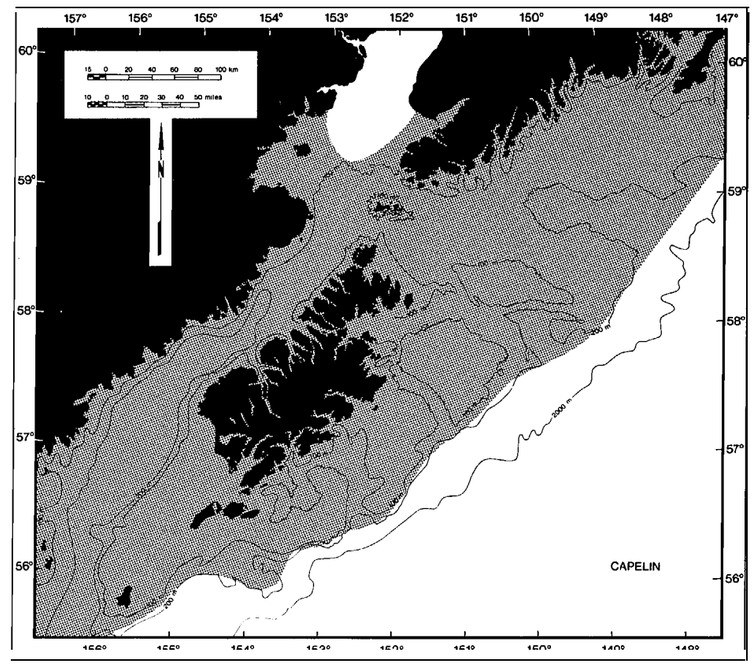
Non-salmonid pelagic species

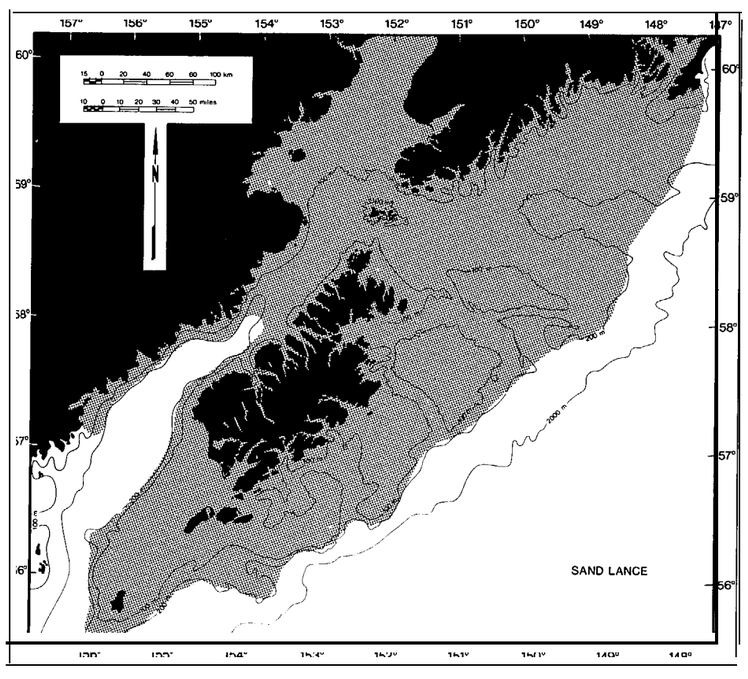
Information on the distribution and abundance of non-salmonid pelagic fishes near Kodiak is for the most part limited to data on species commercially sought, or on those prominent as incidental catches of U.S. and foreign commercial fishing fleets. A synoptic review of the existing literature on the distribution, abundance, life histories, and fisheries of 34 common pelagic fishes (15 families) is given by Macy et al. (1978). These pelagic species generally live near the water surface, often feeding or migrating over long distances. The forms which occur in dense schools are most easily caught, and thus are most intensively fished. These pelagic species provide valuable forage for many commercially and ecologically important fishes, birds, and mammals.

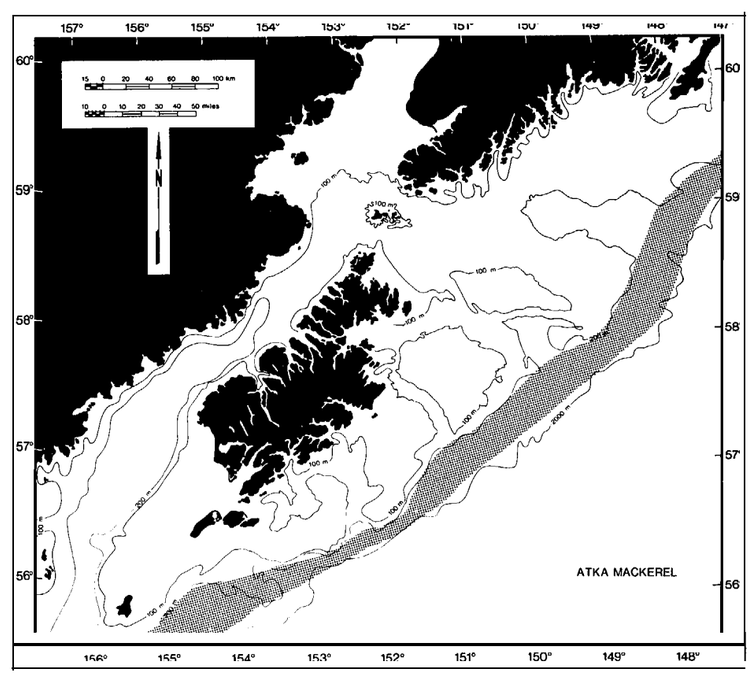
Distributions of several dominant pelagic fishes are shown in Fig 5.43. These are generalized data based on commercial fisheries statistics and experimental survey catches. The offshore seasonal movements of these fishes are poorly understood. Some species like capelin (Mallotus villosus) are suspected of seasonal migrations across the Kodiak shelf to specific spawning sites along the coast because the species behaves in this manner in the North Atlantic and Barents Sea (Jangaard, 1974).

Figure 5.43 Distribution of Pacific herring, capelin, Pacific sand lance, and Atka mackerel in the Kodiak region (Macy et al., 1978; J. Blackburn, ADF&G, Kodiak office, pers. comm.).









Pacific herring

Unlike those of most pelagic fishes, the life history and seasonal movements of Pacific herring (Clupea harengus pallasi) in Kodiak coastal waters have been fairly well documented. Knowledge of the species can be attributed, in part, to the existence of a fishery in the Kodiak area since 1912 (ADF&G, 1976). Between 1934 and 1950 the average annual catch was 34,440 metric tons, with a range of 15,280-109,925 mt; there was no harvest in 1949 (ADF&G, 1979b). In the past twenty years the catch has drastically declined (Fig. 5.44), but in 1964 increased effort in the fishery coincided with the advent of the Japanese market for sac roe (ADF&G, 1976). Thus, most of the current fishing effort coincides with the spawning season of the Pacific herring. The ex-vessel value of the catch in 1978 was $100,000 (ADF&G, Kodiak office, pers. comm.).

In the Kodiak area spawning occurs primarily from May through mid-June (Rounsefell, 1930; ADF&G, 1976). In the Prince William Sound/Copper River Delta vicinity, herring spawn from early March to early June (Reid, 1972). Peak spawning times vary somewhat from year to year, and populations do not necessarily return to the same area in successive years to spawn. Water temperatures may play an important role in the exact timing and location of spawning (ADF&G, 1976).

On the east side of the island preferred spawning substrates are found in the Chiniak Bay and Old Harbor areas (Fig. 5.44). Most large bays along the west and east sides of Kodiak and Afognak Islands are spawning areas for herring and consequently are considered good fishing grounds (Buck et al., 1975).

Gravid females extrude their eggs onto algae, submerged tree branches, and other stabilized substrates along shallow, rocky shores (Reid, 1972). Attendant

males release milt at the same time. Spawning herring can be so dense that they appear to generate milky plumes when viewed during aerial overflights.

Most schools of mature herring disappear after spawning and swim into deeper, offshore water to feed (Taylor, 1964) then move into shallower waters in autumn, where they overwinter. Large concentrations of Pacific herring have been noted in recent years on the west side of Kodiak Island in Uyak, Uganik, and Viekoda Bays.

Larval and juvenile herring use bays in Kodiak as nursery grounds, feeding extensively on calanoid copepods (Harris and Hartt, 1977). By late fall young herring move into deeper, offshore waters (Reid, 1972). Whether herring follow migratory routes or merely show general inshore-offshore movements has not yet been ascertained (Macy et al., 1978).

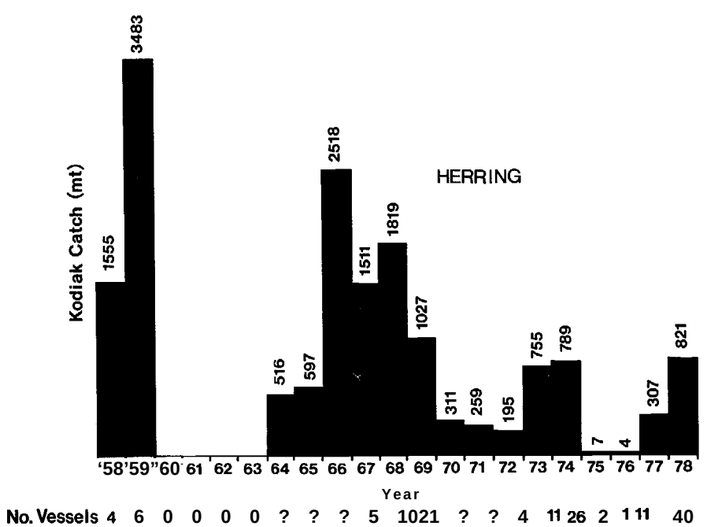
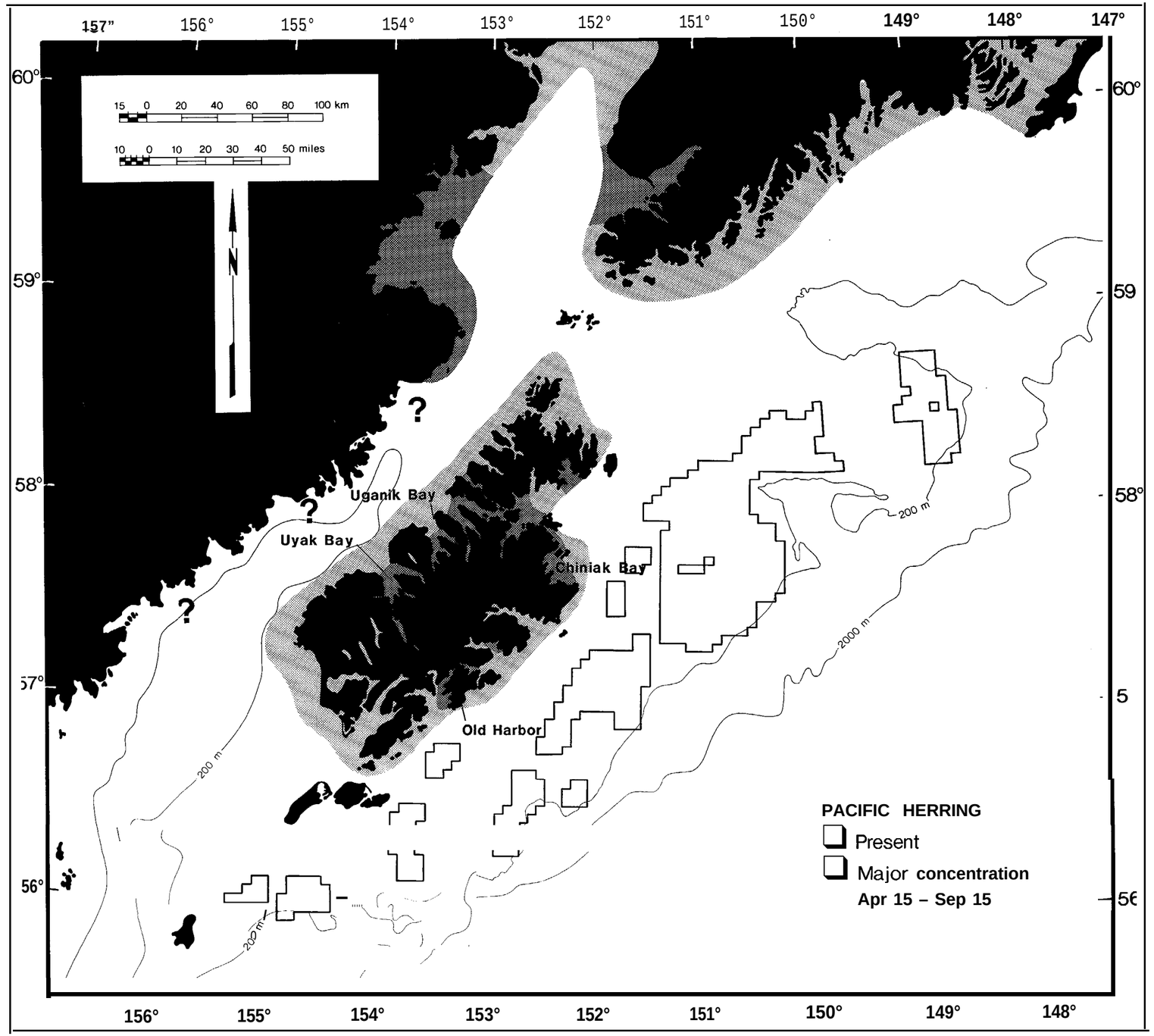


Figure 5.44 Pacific herring catch and effort data for the Kodiak area, 1958-78 with locations of major fishing effort (Lechner et al., 1972; ADF&G, 1979b).



Capelin

Capelin are abundant in Kodiak waters and a principal prey of many fishes (Harris and Hartt, 1977; Rogers and Rogers, 1978; Rogers et al., 1979), marine birds (Sanger et al., 1978), and pinnipeds (Calkins and Pitcher, 1978; Pitcher and Calkins, 1978). Young-of-the-year and juvenile capelin were the predominant pelagic fish captured in Kaiugnak, Alitak, and Ugak Bays in May-September 1976 at surface and midwater depths (Harris and Hartt, 1977). Smelt larvae, probably capelin, were clearly preponderant in ichthyoplankton hauls taken from Izhut, Kalsin-Chiniak, Kiliuda, and Kaiugnak bays during the summer of 1978 (Rogers et al., 1979).

Capelin spawn along exposed pebbly beaches (Hart, 1973) which have rather narrowly defined habitat characteristics. Water temperatures, substrate grain size, tidal stage, and ambient light conditions all affect spawning (Jangaard, 1974). Suitable spawning sites are found along small sections of beaches in most bays on the east side of Kodiak Island. The only extensive sandy beaches are located west of Alitak Bay on the southwest side of the island. Approximately 50 percent of the Trinity Islands shoreline is suitable for capelin spawning, and capelin apparently spawn here in large numbers (Fig 5.45). Spawning probably occurs along Kodiak shores in May and June (J. Blackburn, ADF&G, Kodiak Office, pers. comm.). It occurs in September and October in the Strait of Georgia, British

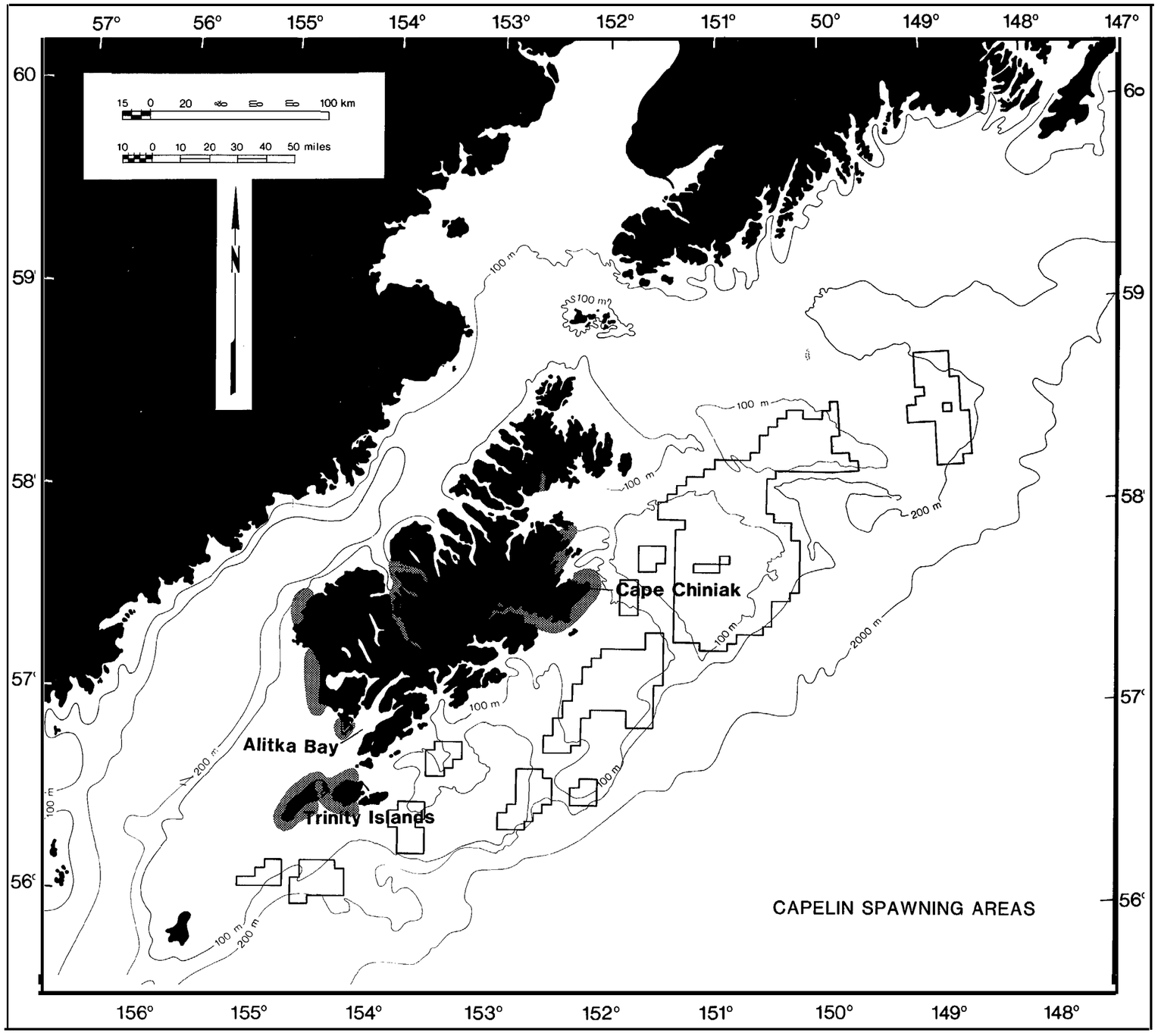


Figure 5.45 Principal spawning areas for capelin along the shores of the Kodiak archipelago (ADF&G, 1976; J. Blackburn, ADF&G, Kodiak office, pers. comm.).

Columbia (Hart, 1973) and in June through July in the Bering Sea (Musienko, 1970). Spawning populations are composed mainly of individuals of ages III and IV. Most fish die after spawning. Demersal eggs attach to beach substrates and hatch in 15-30 days at 5-10°C. (Jangaard, 1974).

Capelin larvae are epipelagic and were concentrated over North and Middle Albatross Banks and the Chiniak Trough in fall 1977, suggesting major spawning grounds shoreward of these areas. They were caught in greatest numbers in the Kiliuda Trough and 20-50 km northeast of the Trinity Islands during spring 1978 cruises (Dunn et al., 1979a). It is not clear where these larvae were spawned. In the fall survey the areas sampled were to the east of Kodiak and Afognak Islands. Spring sampling was more extensive and included tows both north and south of the archipelago (Fig. 5 .46). No hauls were made to the west of the islands, in the Shelikof Strait, in either of the surveys. Smelt larvae (probably capelin) were the most prevalent species caught in Izhut, Chiniak, Kiliuda, and Kaiugnak Bays during ichthyoplankton surveys conducted in 1978-79. However, they were collected only during June through August (Rogers et al., 1979). These data also confirm that the spawning season is in late spring and early summer in Kodiak waters.

Apart from these recent surveys and anecdotal data, little information is available on the seasonal movements of capelin in the region. Considering the apparent importance of the species, more investigations are necessary to further describe its seasonal distribution, abundance, life history, and trophic relationships.

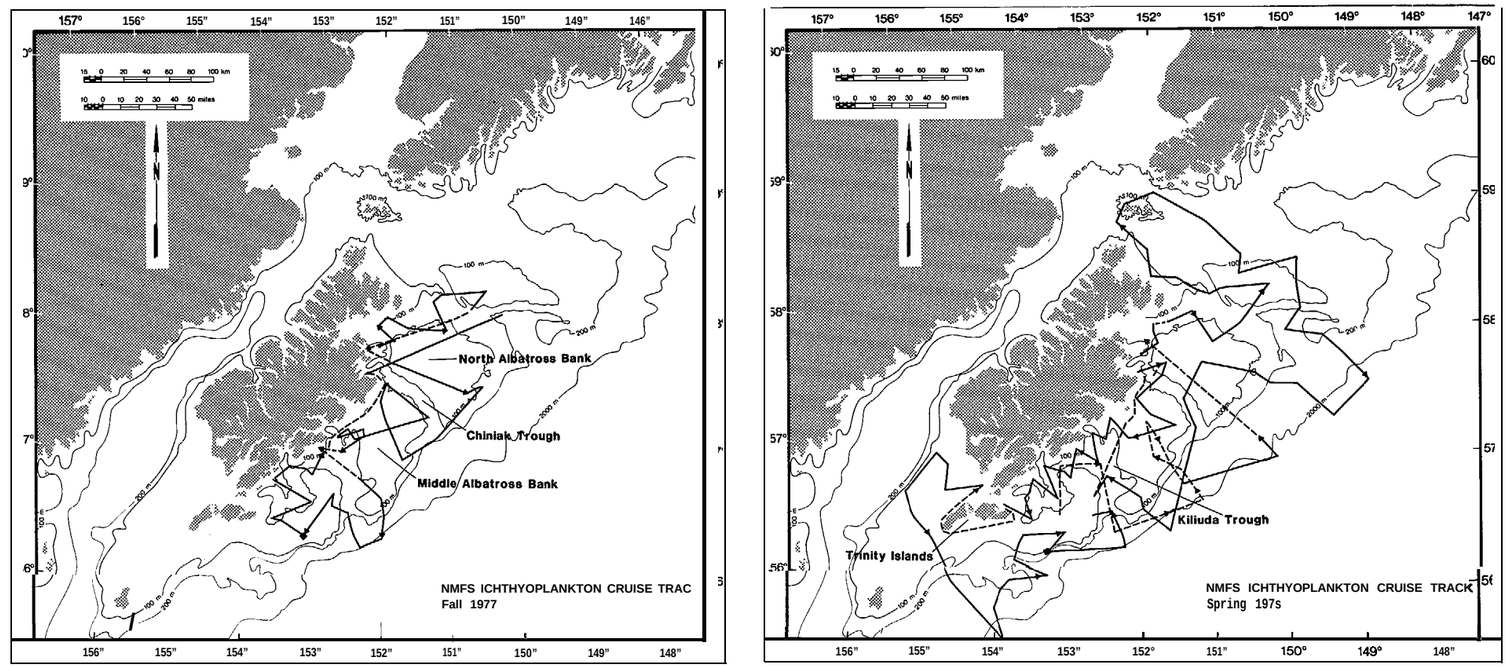


Figure 5.46 NMFS ichthyoplankton survey cruise track, fall 1977 and spring 1978 (Dunn et al. , 1979) .

Pacific sand lance

Pacific sand lance (Ammodytes hexapterus) probably occur throughout the continental shelf region from near shore to the edge of the shelf (Fig. 5.43). As adults they are more abundant near shore (Macy et al. , 1978). According to Trumble (1973), sand lance spawn in winter at depths of 25-100 m in areas of strong currents. Eggs are demersal and are buried in the sand. Larvae are epipelagic and disperse farther offshore with age. Large concentrations of larval sand lance were found over the Portlock and Albatross Banks (Favorite et al. , 1975) . Juvenile sand lance are benthopelagic, inhabiting sandy substrates (Macy et al., 1978) but rising in the water column to feed (Harris and Hartt, 1977) . Juvenile sand lance are found at shallower depths than adults, and both life stages move into deeper water in the fall and winter (Andriyashev in Harris and Hartt, 1977). Pacific sand lance are an important prey of many other fish (see Fish Trophies section) . They are common in both pelagic and benthic fish assemblages and are important in energy transfer between systems.

Atka mackerel

Atka mackere _____ mm _____ monopterygius) are widely distributed in epipelagic waters of the north Pacific Ocean and Bering Sea. Seaward of Kodiak they are taken most frequently along the continental shelf break (Fig. 5.43). Adults migrate annually to inshore spawning grounds. Optimal spawning conditions occur in the straits between islands, where swift currents prevail. Rocky substrates at depths of 10-17 m and temperatures from 5 to 8°C are preferred. Exact spawning sites near Kodiak have not been determined, but large concentrations of adult Atka mackerel have been noted inshore, along the south coast of the Aleutian chain from May through October (see Macy et al., 1978, for review). Larvae were collected over the Kiliuda Trough in fall surveys, and in the Albatross Banks region in spring (Dunn et al., 1979a), but s.tes of their origin are unknown. In recent years this hexagrammid has been a major target of Soviet fisheries (Ronholt et al , 1978). It is not harvested by domestic fishing fleets operating out of Kodiak. The total foreign catch in 1978 was 18,800 mt or 97 percent of the estimated optimum yield (M. Alton, NMFS, Seattle, pers. comm.)

Other important pelagic fishes, in terms of apparent abundance and trophic relationships, are Pacific sandfish (Trichodon trichodon) (Harris and Hartt, 1977), prowfish Zaprora silenus) (Macy et al., 1978), and several smelts (Osmeridae) (Hart, 1973). Brief descriptions of their distribution, population dynamics, and feeding habits have been summarized by Macy et al. (1978).

Demersal fishes

Demersal (bottom-dwelling) fishes are often referred to simply as groundfish, especially when discussed in relation to the commercial fishery. OCSEAP studies, however, usually refer to them as flatfish (Pleuronectiformes), rockfish (Scorpaenidae), roundfish (all other Osteichthyes), and elasmobranchs (Chondrichthyes) (Ronholt et al., 1978). In this review the last classification is used. To date, 138 species representing 26 families of demersal fishes have been captured in the Gulf of laska. The most diverse families are Hexagrammidae (30 spp.), Cottidae (24 spp.), and Pleuronectidae (16 spp.) (Quast and Hall, 1972). Abundance is not necessarily related to diversity, however. Common demersal fishes in Kodiak are listed in Table 5.26. All of them probably have preferred habitats and depth ranges throughout the region, and a particular species may be considered "common" in only part of its total range (e.g., sablefish, rock sole).

Resource surveys have been conducted periodically by federal and state agencies in waters surrounding the Kodiak archipelago to determine the species composition, distribution, and relative abundance of demersal fish populations. The most extensive survey of demersal fishes in recent years was done by the NMFS (1973 through 1976). They collected samples from 96 stations in the Kodiak-Shelikof-Chirikof area. Fish were taken with otter trawl gear from water depths down to 400 m. (Ronholt et al., 1978). The NMFS sampling occurred from May through October; distribution patterns may differ in winter. Hughes (1974) has shown this to be

Table 5.26 Common demersal fishes in the Kodiak region (Buck et al., 1975; ADF&G, 1976; Harris and Hartt, 1977; Ronholt et al., 1978; Rogers et al., 1979; Hunter, 1979).

Flatfish
*Pacific halibut (Hippoglossus stenolepis)
Rock sole (Lepidopsetta bilineata)
Yellowfin sole (Limanda aspera)
Flathead sole (Hippoglossoides elassodon)
Starry flounder (Apltichthys stellatus)
Butter sole (Isopsetta isolepis)
Sand sole (Psettichthys melanostictus)
*Arrowtooth flounder (Atheresthes stomias)
Rex sole (Glyptocephalus zachirus)
Roundfish
*Walleye pollock (Theragra chalcogramma)
*Pacific cod (Gadus macrocephalus)
Pacific tomcod (Microgadus proximus)
Alaska eelpout (Bothrocara pusillum)
*Sablefish (Anoplopoma fimbria)
Kelp greenling (Hexagrammos decagrammus)
Rock greenling (H. lagocephalus)
Masked greenling (H. octogrammos)
Whitespotted greenling (H. stelleri)
Lingcod (Ophidon elongatus)
Yellow Irish lord (Hemilepidotus jordani)
Red Irish lord (H. hemilepidotus)
Great sculpin (Myoxocephalus polyacanthocephalus)
Tubenose poacher (Pallasina barbata)
Sturgeon poacher (Agonus acipenserinus)
Alaskan ronquil (Bathymaster caeruleofasciatus)
Searcher (B. signatus)
Snake prickleback (Lumpenus sagitta)
Crescent gunnel (Pholis laeta)
Rockfish
*Pacific ocean perch (Sebastes alutus)
Black rockfish (S. melanops)
Tiger rockfish (S. nigrocinctus)
Elasmobranchs
Big skate (Raja binoculata)
Blake skate (R. kincaidi)
Starry skate (R. stellulata)
Spiny dogfish (Squalus acanthias)

*Species of major importance to fishing industry.

true for fish populations sampled in this vicinity in 1961. No single survey can provide sufficient data to describe the distribution of fish populations thoroughly; their movements are too dynamic. The work of Ronholt et al. (1978) is the most comprehensive to date, however. Additionally, their comparisons of survey data from the 1960's and the 1970's provide some insight into long-term fluctuations of standing stocks of demersal fishes.

Roundfish, particularly walleye pollock, and a number of flatfish are abundant throughout the Kodiak region; rockfish are less frequently caught. The density distributions of these three classes of fish, based on the NMFS survey, are shown in Figs. 5.47-5.49. Elasmobranchs were infrequently caught on the continental slope east of Kodiak and in the Chirikof-Shelikof Trough. Overall, largest populations of demersal fish appear to be located southeast and southwest of Kodiak.

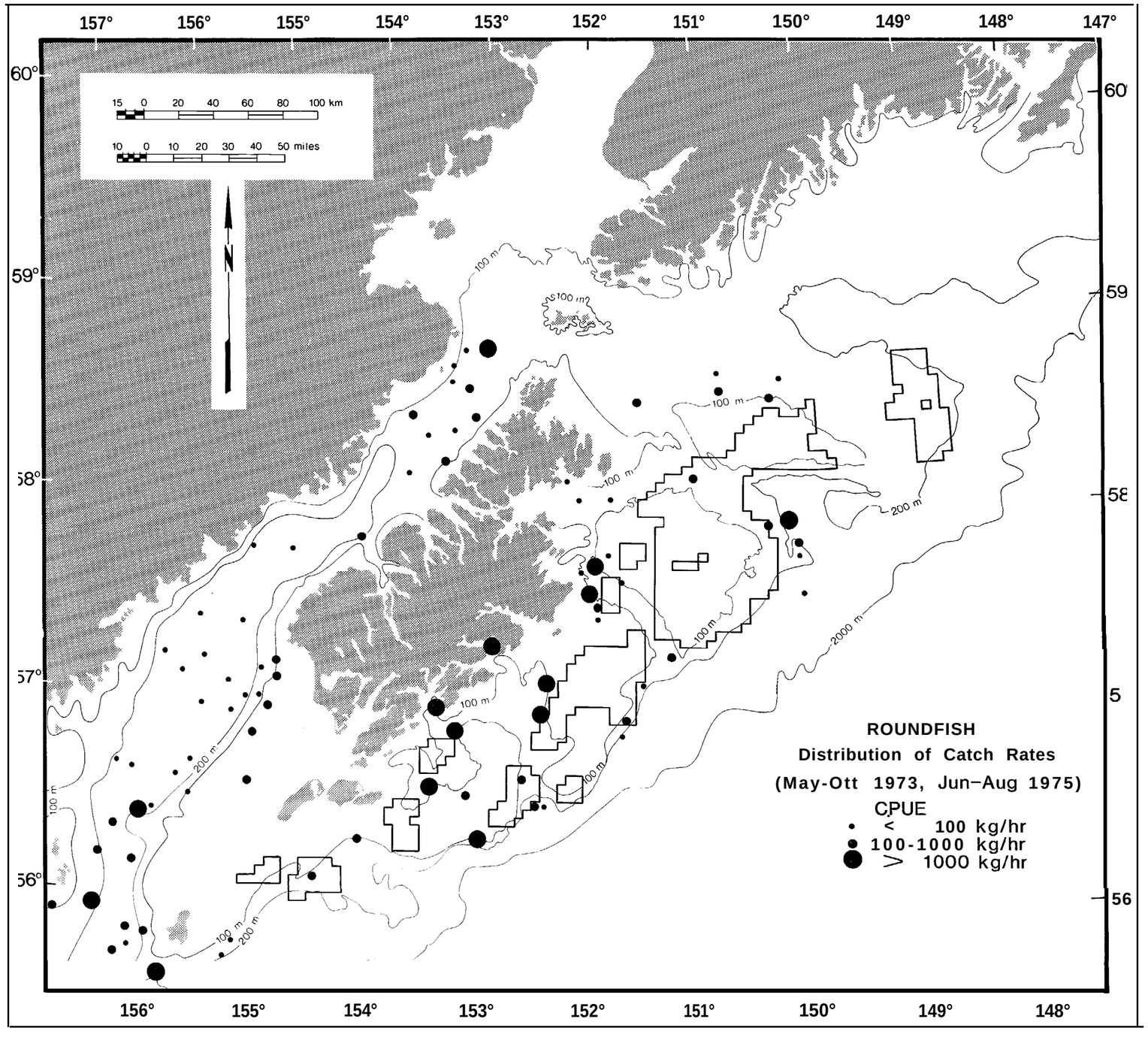


Figure 5.47 Distribution of standardized catch rates (CPUE) of roundfish, based on NMFS survey data (Ronholt et al., 1978).

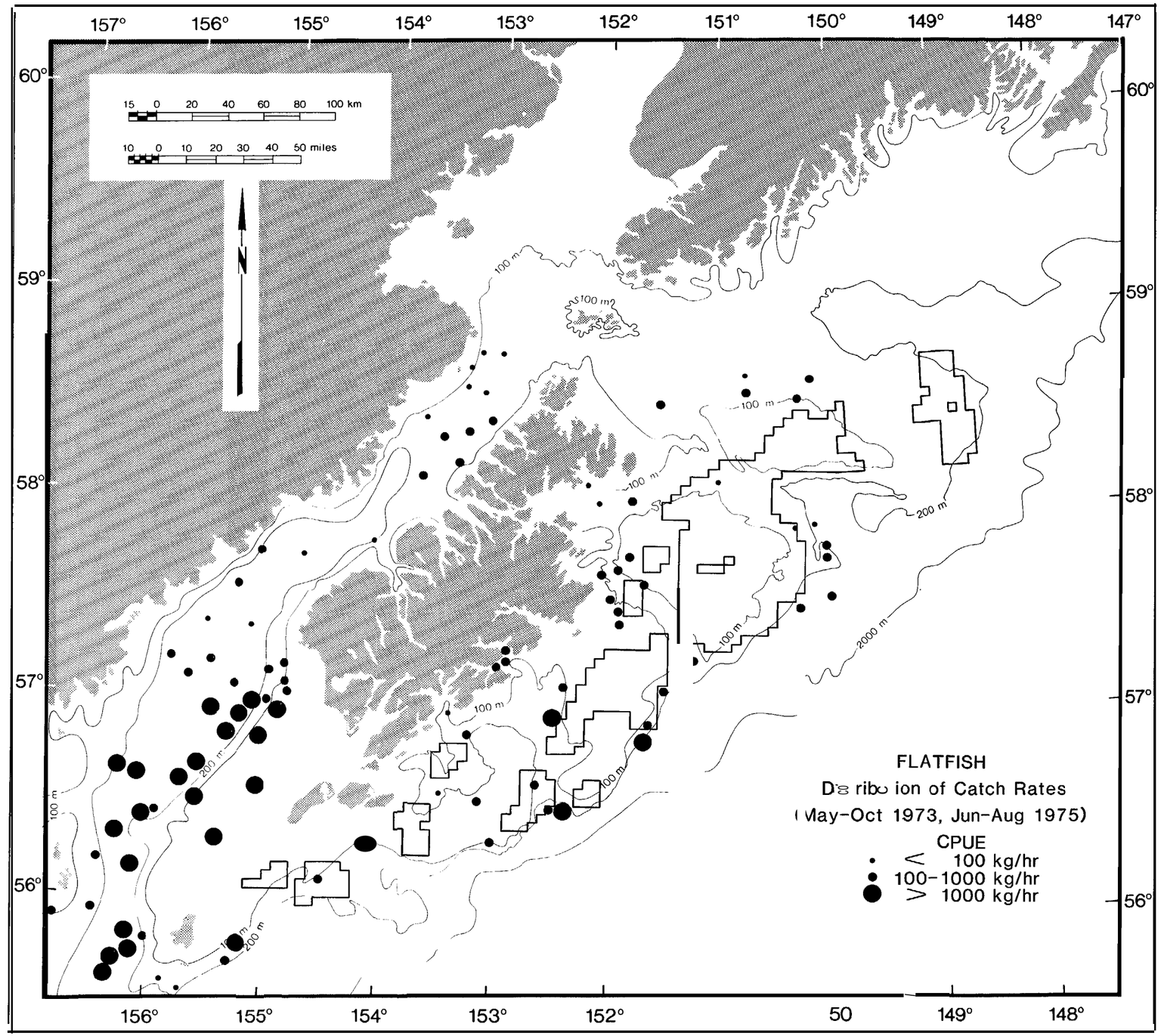


Figure 5.48 Distribution of standardized catch rates (CPUE) of flatfish, based on NMFS survey data (Ronholt et al., 1978).

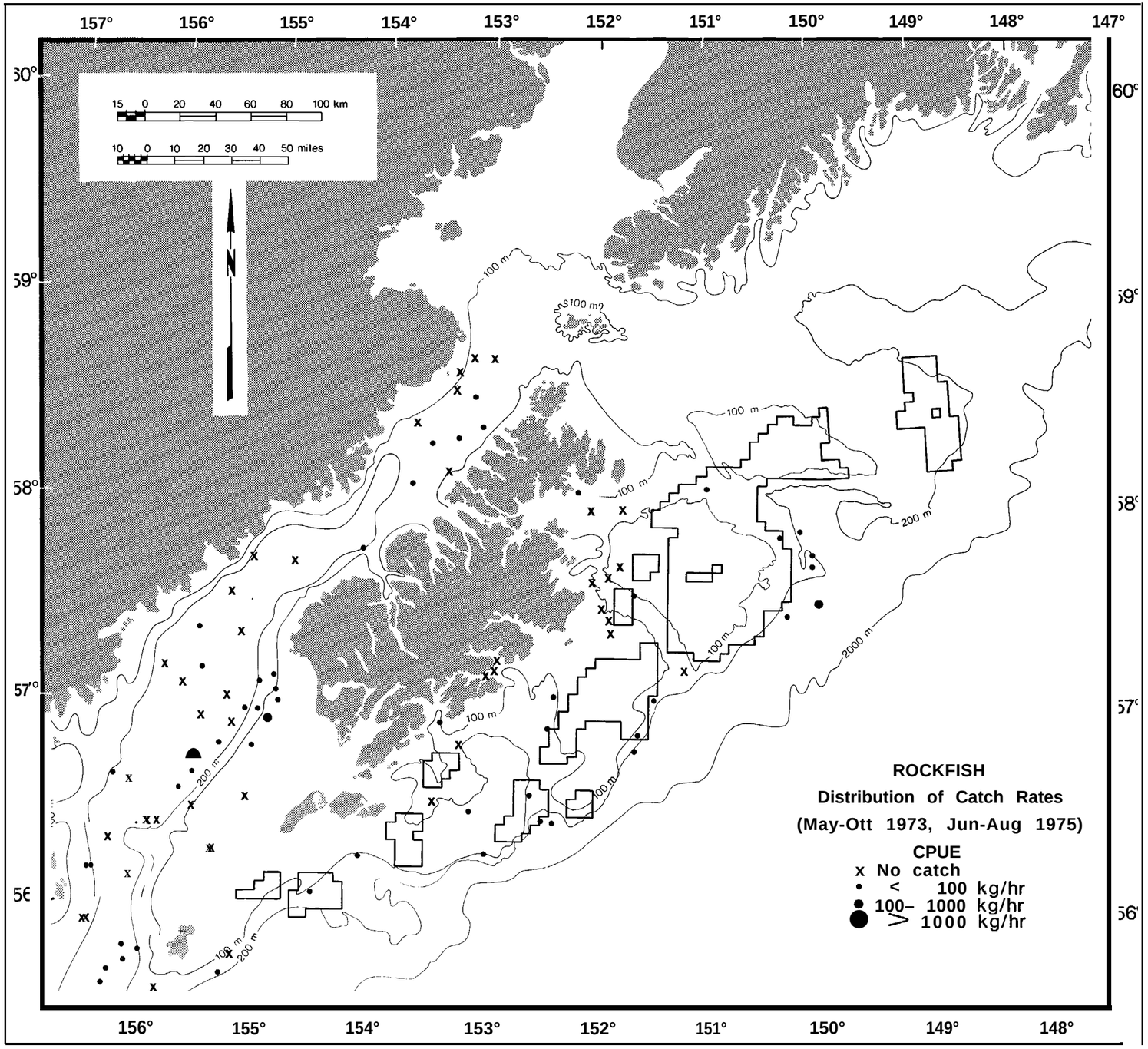


Figure 5. 49 Distribution of standardized catch rates (CPUE) of rockfish, based on NMFS survey data (Ronholt et al., 1978).

The average catch rates (CPUE), number of stations sampled, and estimated abundance of demersal fishes caught in four statistical areas (Fig. 5.50) are given in Tables 5.27-5.30. For comparison, data collected during the 1961-62 IPHC resource survey are also presented. The highest catch rates of roundfish, flat-

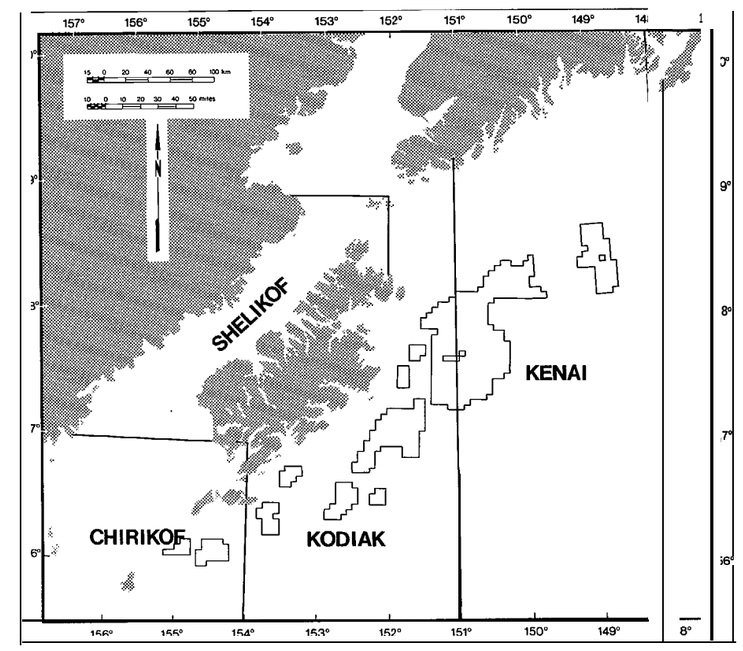


Figure 5.50 Statistical areas near Kodiak considered in the demersal fish resource surveys (Ronholt, et al., 1978) .

Table 5.27 Average catch rates and estimated abundance of roundfish (Ronholt et al., 1978).

Statistical Area	Depth Zones (m) 1-100 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled	101-200 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled	201-400 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled
May - Oct 1961									
Kenai	-	-	(0)	321.6	112,000.0	(8)	54.0	7,345.9	(1)
Kodiak	130.[illegible]	35,779.6	(24)	155.1	30,563.0	(42)	23.7	673.2	(2)
Shelikof	112.[illegible]	7,059.3	(1)	88.1	8,212.3	(28)	32.9	3,461.6	(44)
Chirikof	57.[illegible]	16,550.6	(26)	212.4	43,368.0	(28)	59.8	7,456.8	(33)
Sept - Nov 1961									
Kenai				Not Data					
Kodiak	122.[illegible]	33,365.0	(7)	276.6	54,507.2	(22)	41.1	1,169.6	(2)
Shelikof	-	-	(0)	46.0	4,288.8	(13)	78.3	8,229.5	(28)
Chirikof	36.7	10,614.6	(10)	186.2	38,010.9	(11)	163.0	20,336.1	(12)
June - Aug 1962									
Kenai	96.7	10,089.4	(3)	9[illegible].5	31,858.7	[illegible]	39.8	5,4[illegible]2.8	(31)
Kodiak				No Data					
Shelikof				No Data					
Chirikof				No Data					
Sept - Nov 1962									
Kenai	-	-	(0)	43.9	15,283.6	(19)	[illegible]65.3	8,882.0	2
Kodiak				No Data					
Shelikof				No Data					
Chirikof				No Data					
May - Oct 1973-75									
Kenai	-	-	(0)	313.7	76,182.1	(25)	76.3	7,656.1	(8
Kodiak	450.0	64,448.0	(6)	1,088.2	134,313.0	(15)	624.5	34,820.5	(10
Shelikof	75.9	491.8	(3)	261.7	10,679.8	(9)	79.4	8,275.7	(7
Chirikof	83.5	9,981.6	(8)	1,270.2	205,001.0	(19)	89.7	12,019.4	(19

Table 5.28 Average catch rates and estimated abundance of flatfish (Ronholt et al., 1978).

Statistical Area	Depth Zones (m) 1-100 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled	101-200 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled	201-400 x̄ CPUE (kg/hr)	Estimated Abundance (mt)	# Stations Trawled
May - Oct 1961									
Kenai	-	-	(0)	143.4	43,931.8	(8)	215.7	29,352.8	(1
Kodiak	270.9	74,059.0	(24)	250.3	49,325.4	(42)	176.8	5,029.1	(2
Shelikof	108.0	6,785.6	(1)	178.5	16,631.6	(28)	199.1	20,931.8	(44
Chirikof	149.5	43,303.4	(26)	163.4	33,368.3	(28)	488.2	60,919.7	(33
Sept - Nov 1961									
Kenai				No Data					
Kodiak	172.5	47,172.4	(7	253.7	49,997.6	(22)	38.3	[illegible],090.7	2
Shelikof	-	-	(0	207.9	19,373.1	(13)	227.7	2[illegible]38.1	(28
Chirikof	142.5	41,282.6	10	344.2	70,266.2	(11)	264.7	3[illegible]34.5	(12
June - Aug 1962									
Kenai	155.3	[illegible].2[illegible]4	(3)	16[illegible].5	59,024.0	61	184.9	25,169.8	3
Kodiak				No Data					
Shelikof				No Data					
Chirikof				No Data					
Sept - Nov 19[illegible]2									
Kenai		-	[illegible]	89.1	3,036.[illegible]	(19)	44.7	19,686.2	(12)
Kodiak				No Data					
Shelikof				No Data					
Chirikof				No Data					
May - Oct 1973-75									
Kenai		-	(0	249.2	60,516.5	(25)	130.7	13,111.3	(8
Kodiak	482.6	69,107.7	(6	297.2	36,682.9	(15)	757.2	42,220.4	(10
Shelikof	85.1	551.3	(3	221.2	9,028.2	(9)	135.9	14,167.0	(7
Chirikof	73.4	8,774.2	(8	93.5	15,090.5	19)	251.8	33,741.6	(19

Table 5.29 Average catch rates and estimated abundance of rockfish (Ronholt et al. ,1978).

Statistical Area	1-100 x̄ CPUE (kg/hr)	1-100 Estimated Abundance (ret)	1-100 # Stations Trawled	101-200 x̄ CPUE (kg/hr)	101-200 Estimated Abundance (ret)	101-200 # Stations Trawled	201-400 x̄ CPUE (kg/hr)	201-400 Estimated Abundance (ret)	201-400 # Stations Trawled
May - Ott 1961									
Kenai			(0)	81.8	28,239.0	(8)	33.1	4,506.3	(1)
Kodiak	5.4	1,463.4	(24)	25.6	5,045.5	(42)	4.0	112.9	(2)
Shelikof	0	0	(1)	2.6	239.5	(28)	10.9	1,141.1	(44)
Chirikof	<0.1	1.9	(26)	135.4	27,635.4	(28)	83.8	10,463.1	(33)
Sept - Ott 1961									
Kenai					No Data				
Kodiak	0.1	40.7	(7)	16.5	3,254.7	(22)	3.2	89.7	(2)
Shelikof			(0)	4.2	396.0	(13)	22.6	2,374.3	(28)
Chirikof	0	0	(10)	32.0	6,518.5	(11)	71.1	8,868.0	(12)
June - Aug 1962									
Kenai	1.0	105.2	(3)	34.4	11,997.5	(61)	76.6	10,422.7	(31)
Kodiak					No Data				
Shelikof					No Data				
Chirikof					No Data				
Sept - Nov 1962									
Kenai			(0)	32.9	11,488.0	(19)	80.6	10,966.1	(12)
Kodiak					No Data				
Shelikof					No Data				
Chirikof					No Data				
May - Ott 1973-75									
Kenai			(0)	11.8	2,862.4	(25)	3.1	312.9	(8)
Kodiak	0.2	21.7	(6)	2.6	320.2	(15)	108.8	6,066.1	(10)
Shelikof	0	0	(3)	2.5	102.8	(9)	1.0	108.1	(7)
Chirikof	<0.1	4.1	(8)	24.1	3,897.1	(19)	2.6	345.5	(19)

Table 5.30 Average catch rates and estimated abundance of elasmobranchs (Ronholt et al., 1978).

Statistical Area	1-100 x̄ CPUE (kg/hr)	1-100 Estimated Abundance (ret)	1-100 # Stations Trawled	101-200 x̄ CPUE (kg/hr)	101-200 Estimated Abundance (ret)	101-200 # Stations Trawled	201-400 x̄ CPUE (kg/hr)	201-400 Estimated Abundance (ret)	201-400 # Stations Trawled
May - Ott 1961									
Kenai			(0)	26.7	9,291.3	(8)	40.8	5,555.7	(1)
Kodiak	1.5	423.1	(24)	6.6	1,298.4	(42)	0.1	1.4	(2)
Shelikof	3.6	228.1	(1)	9.4	879.0	(28)	5.2	542.9	(44)
Chirikof	0.2	43.8	(26)	2.7	550.1	(28)	23.9	2,984.9	(33)
Sept - Ott 1961									
Kenai					No Data				
Kodiak	6.7	1,827.9	(7)	0.8	150.5	(22)	4.1	117.2	(2)
Shelikof			(0)	14.1	1,310.6	(13)	5.2	543.1	(28)
Chirikof	2.4	698.9	(10)	0.4	89.6	(11)	7.5	933.1	(12)
June - Aug 1962									
Kenai	0	0	(3)	10.2	3,551.4	(61)	12.4	1,681,7	(31)
Kodiak					No Data				
Shelikof					No Data				
Chirikof					No Data				
Sept - Nov 1962									
Kenai			(0)	6.2	2,170.7	(19)	9.9	1,345.6	(12)
Kodiak					No Data				
Shelikof					No Data				
Chirikof					No Data				
May - Ott 1973-75									
Kenai			(0)	1.2	290.8	(25)	3.2	324.3	(8)
Kodiak	0	0	(6)	1.5	179.2	(15)	0.2	8.6	(10)
Shelikof	1.2	7.8	(3)	0.5	20.6	(9)	6.7	702.5	(7)
Chirikof	0	0	(8)	1.7	269.7	(19)	7.8	1,049.3	(19)

fish, and rockfish were trawled during the NMFS survey in the Kodiak statistical area. About 58 percent of the roundfish in Kodiak were caught at depths of 101-200 m. Relatively high concentrations were in the Kiliuda and Chiniak Troughs (Fig. 5.47). Highest concentrations of flatfish occurred in 0-100 m of water in Kodiak, but in deeper zones elsewhere (Table 5.28). Flatfish were prevalent in the seaward entrance of the Chirikof-Shelikof Trough (Fig. 5.48). Rockfish were abundant along the continental slopes (201-400 m) east of Kodiak (Fig. 5.49). The importance of the four statistical areas around Kodiak relative to the entire Gulf of Alaska catch is indicated in Tables 5.31 and 5.32.

Table 5.31 Percentage of total Gulf of Alaska fish population (estimated biomass) occurring in four statistical districts near Kodiak (0-400 m), based on 1973-75 data (Ronholt et al., 1978).

	PERCENT OF GULF OF ALASKA ESTIMATED BIOMASS				
	Statistical Area				
Fish Group	Kenai	Kodiak	Shelikof	Chirikof	Σ
Roundfish	8.9	24.7	2.1	24.0	59.7
Flatfish	12.5	25.1	4.0	9.8	51.4
Rockfish	11.2	22.2	0.7	14.7	48.6
Elasmobranchs	2.2	0.7	2.6	4.7	10.2

Table 5.32 Estimated biomass during the 1960 and 1970 resource assessment surveys in the Gulf of Alaska (Ronholt et al., 1978).

Region	1960		1970	
	mt/km^2	Rank	mt/km^2	Rank
Fairweather	20.4	1	5.4	8
Yakutat	9.0	5	7.5	5
Prince William	2.5	9	7.8	4
Kena i	9.2	4	6.7	6
Kodiak	9.7	3	18.6	1
Shelikof	6.3	7	5.7	7
Chirikof	11.4	2	9.5	4
Shumagin	5.8	8	---	---
Sanak	6.7	6	18.4	z
Total	8.9		10.9	

Comparisons between the catches recorded during the IPHC and NMFS trawls are shown in Tables 5.33 and 5.34. According to Ronholt et al. (1978), the only significant change in abundance occurred for elasmobranchs in the Kenai area. Some catch rates for fish groups in specific area/depth zones were remarkably dissimilar when the decade comparisons were made, however (Table 5.24). Although not statistically significant, the following trends were evident: (1) a marked increase in roundfish, flatfish, and rockfish stocks on the Kodiak/upper slope zone, and (2) moderate increases in roundfish and flatfish stocks on the continental shelf east of Kodiak (Ronholt et al., 1978).

Table 5.33 Comparison of mean (geometric) catch rates (CPUE) of fish groups caught during two resource surveys conducted around the Kodiak archipelago (Ronholt et al., 1978).

	IPHC (1961-1963) x CPUE (kg/hr)		NMFS (1973-76) x CPUE (kg/hr)
		Flatfish	
Kenai	118.21		103.96
Kodiak	134.76		363.40
Shelikof		No data	
Chirikof	158.14		68.60
		Roundfish	
Kenai	55.82		112.43
Kodiak	76.40		233.18
Shelikof		No data	
Chirikof	59.47		125.10
		Rockfish	
Kenai	21.12		4.40
Kodiak	2.46		1.53
Shelikof		No data	
Chirikof	4.66		2.23
		Elasmobranchs	
Kenai	19.91		1.73*
Kodiak	1.52		1.11
Shelikof		No data	
Chirikof	2.49		1.46

* Significant decrease in population

Table 5.34 Ratio of IPHC to NMFS geometric mean CPUE index (from Ronholt et al., 1978).

	Depth Zones (m) 1-100	101-200	201-400
		Flatfish	
Kenai		1.23	0.40
Kodiak	2.86	2.07	4.92
Shelikof		No Data	
Chirikof	0.46	0.35	0.55
		Roundfish	
Kenai		3.01	0.80
Kodiak	2.12	4.27	13.71
Shelikof		No data	
Chirikof	1.47	3.32	1.63
		Rockfish	
Kenai		0.28	0.06
Kodiak		0.51	24.83
Shelikof		No data	
Chirikof		0.05	0.19
		Elasmobranchs	
Kenai		0.10	0.06
Kodiak		0.65	
Shelikof		No data	
Chirikof		0.66	0.30

Pacific halibut

Pacific halibut (Hippoglossus stenolepis) have been the primary target species of a commercial fishery in the North Pacific since 1888, and they have been taken in the Kodiak region since 1922 (IPHC, 1978). Although their stocks have been stressed by fishing for decades, the fishery remains viable and is of chief concern to the populace of several Alaskan communities, most notably Kodiak City (IPHC, 1977).

Halibut occur on or near the continental shelf along the entire southern coast of Alaska south to California and northward into the Bering Sea. Preferred water depths vary with season and age. During the NMFS survey, the species comprised about 5-10 percent of the flatfish catch in the Kodiak vicinity (Ronholt et al., 1978). Halibut are usually found in 30-275 m of water, although the setline fishery has recovered fish from 1,100 m (Fig. 5.51; Bell and St. Pierre, 1970; IPHC, 1978).

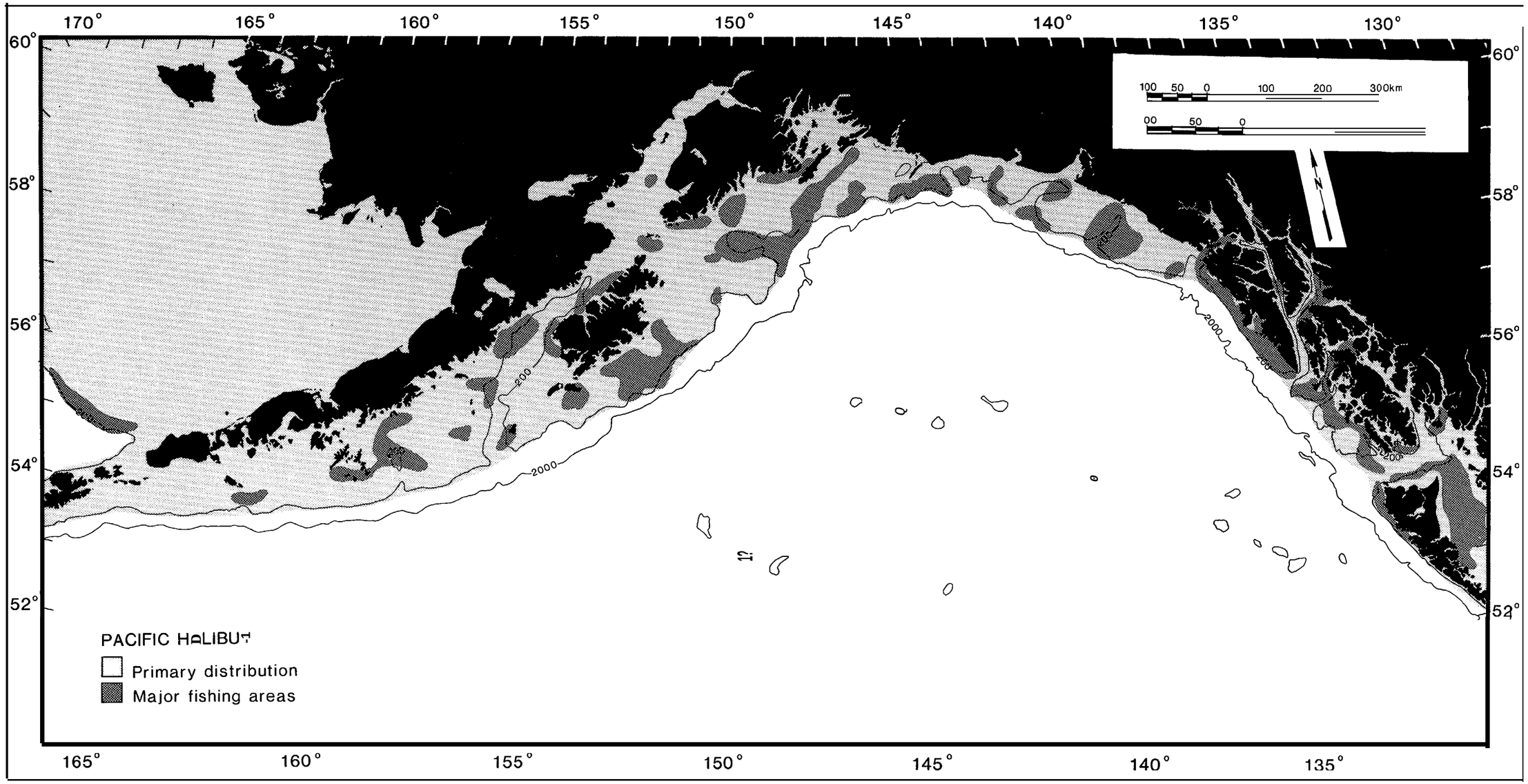


Figure 5.51 Distribution of Pacific halibut in the Gulf of Alaska with major fishing grounds highlighted (IPHC, 1978).

The seasonal movements, migratory routes, spawning, and early life history of Pacific halibut have been studied in detail since 1923, with the inception of the IPHC (Thompson and Herrington, 1930; Thompson and Van Cleve, 1936). Tagging studies indicate that adult halibut migrate annually from their shallow feeding grounds, such as the Portlock Banks, to deeper winter spawning grounds, then return to their summer grounds. Some adults emigrate long distances and do not return to the same grounds (Bell and St. Pierre, 1970; Skud, 1977; IPHC, 1978). Mechanisms that trigger these pioneer emigrations are unknown. Most tagged fish were recovered within 150 km of their initial release site (Table 5.35).

Halibut spawn from November to March at 180-450 m depths along the edge of the continental slope. Major spawning sites in Alaska are Yakutat, Cape Suckling-Yakataga ("W" grounds), and Portlock Banks (Fig. 5E.16); Cape Spencer, Cape St. Elias, Chirikof, and the Trinity Island "outside" grounds are other known spawning areas (Skud, 1977; IPHC, 1978; E. Best, IPHC, pers. comm.). Eggs have been collected throughout the entire region, and spawning is likely to occur at suitable depths all along the slope.

Halibut eggs have been recovered from 40-935 m of water, with highest densities at depths of 100-200 m near the edge of the continental slope, between yakutat and Portlock Banks (Thompson and Van Cleve, 1936). Currents in the Gulf of Alaska carry the eggs and larvae northward and westward for six to seven months. Larval buoyancy is such that at first they passively drift in water deeper than 200 m, then rise slowly toward the surface (Thompson and Van Cleve, 1935; Skud, 1977; IPHC, 1978). Favorite et al. (1977) have concluded that eggs released along the southeastern coast of Alaska would be transported to the northern Gulf of Alaska and advected shoreward at speeds of 5-10 cm/see, equivalent to 4-8 km/day, or 700-1400 km over a six-month larval period.

Juvenile halibut settle out of the plankton in May and June and are found in shallow bays along the coast of Alaska including the Aleutian Islands, where water depths are less than 100 m (Thompson and Van Cleve, 1936). Halibut one to three years old are more likely to be found farther inshore than older prerecruits four to eight years old according to IPHC (Best, 1974) and NMFS (Ronholt et al., 1978) trawl survey data from stations sampled throughout the Gulf of Alaska. Important halibut nursery grounds near the Kodiak OCS lease areas are Alitak Bay, the shallow shelf region surrounding the Trinity Islands, Cape Chiniak, and Portlock Bank, but these areas are by no means inclusive (Best, 1974). A reexamination of the IPHC data base indicates that movements of juvenile halibut may be quite extensive (Skud, 1977).

Skud (1977) hypothesizes that juvenile halibut display compensatory emigration movements which counteract the westward drift of eggs and larvae. From age and size data taken during IPHC trawl surveys (IPHC, 1966) it has been demonstrated that the mean age of juvenile halibut is progressively older from west to east. The three-year-olds were dominant at Unimak and

Table 5.35 Release and recovery location of tagged adult Pacific halibut, 1925-76 (adapted from Skud, 1977).

		Recoveries by Region							
Release Region	Number Released	Bering Sea	Shumagin	Chirikof	Kodiak	Yakutat	SE Alaska	BC	Total
Bering Sea	20,435	756	21	69	125	116	83	53	1,223
Shumagin	5,992	0	202	104	35	20	24	11	396
Chirikof	9,193	0	37	473	91	20	17	10	648
Kodiak	16,501	0	17	119	1,294	40	36	25	1,531
Yakutat	11,431	0	31	122	428	1078	62	52	1,773
SE Alaska	9,729	0	0	0	1	4	1945	85	2,035
British Columbia and South	59,642	0	1	0	7	39	194	17,288	17,529
TOTAL	132,642	756	309	887	1,981	1,317	2361	17,524	25,135

Chirikof, four-year-olds at Chiniak, five-year-olds at Cape St. Elias, and five- and six-year-olds in British Columbia (Best, 1968, 974). In addition, of the juvenile halibut tagged west of Cape Spencer (Area 3 . 3 percent of the recoveries were taken in British Columbia. These findings led Skud (1977) to suggest that, contrary to earlier findings (Thompson and Herrington, 1930), there is extensive intermingling of halibut stocks north and south of Cape Spencer. Furthermore, it is the juvenile fish, not the adults, that are primarily responsible for maintaining the population distributions.

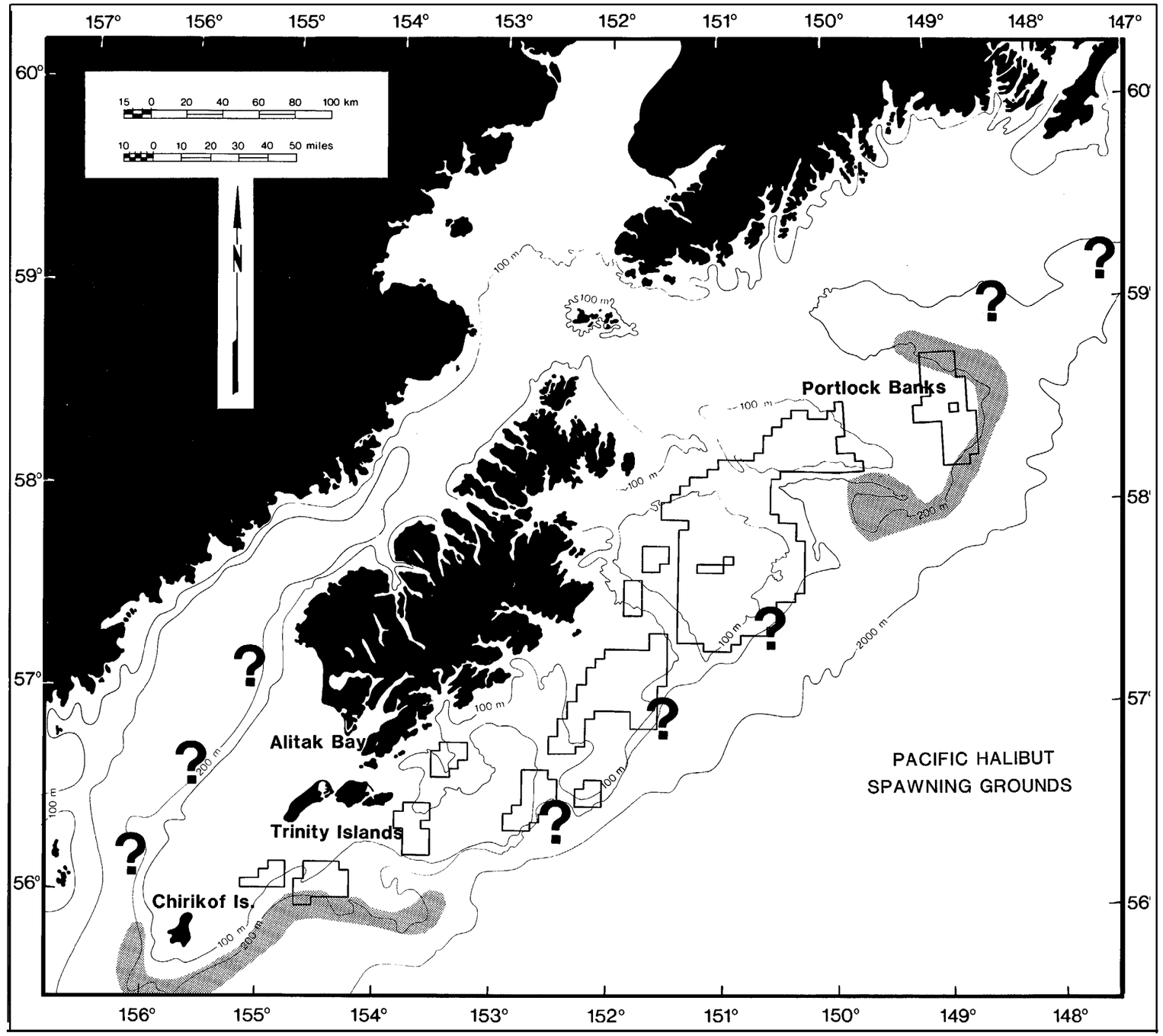
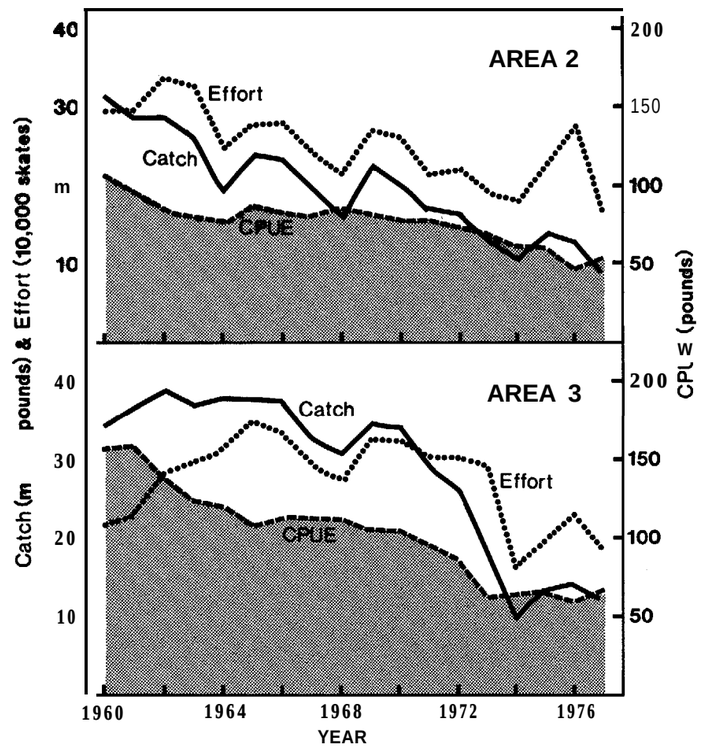


Figure 5.52 Two known spawning grounds of Pacific halibut on the Kodiak outer continental shelf (Skud, 1977; IPHC, 1978; E. Best, IPHC, pers. comm.).

Abundance estimates of Pacific halibut are inferred from catch and age data using a cohort analysis technique. Abundance of adults has declined sharply in IPHC'S regulatory Areas 2 and 3, from about 10 million fish per area in the 1950's to 5 million fish per area in the 1970's. One index of abundance, catch per unit effort (CPUE), is shown for halibut (1960-77) in Fig. 5.53. The IPHC uses the abundance of three-year-old halibut as an indicator of juvenile stocks. After increasing during the 1930's, abundance peaked in the 1940's at more than 10 million fish in both Areas 2 and 3. Stock estimates declined to about five million fish in the late 1940's. Occasional strong year-classes appeared in the 1950's and 1960's, but the trend in abundance has declined in the Gulf of Alaska through 1976 (IPHC, 1977), with a slight increase in 1977 (Skud, 1978). The most recent reports still estimate juvenile stocks in the Gulf at less than three million fish (IPHC, 1977).



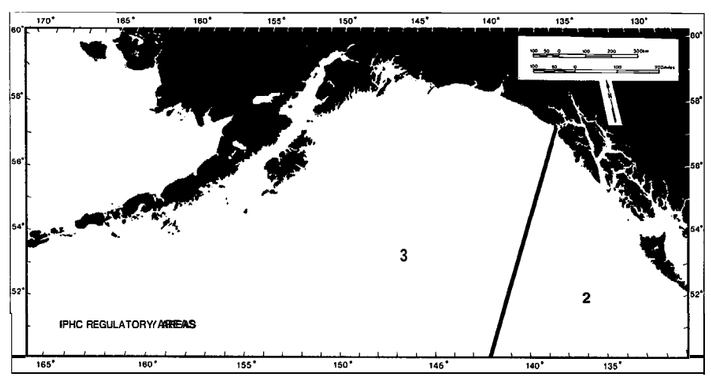


Figure 5.53 Catch statistics of Pacific halibut based on U.S. and Canadian setline fishing in the IPHC Regulatory Areas 2 and 3, 1960-77 (IPHC, 1977; IPHC, 1978).

Arrowtooth flounder

Arrowtooth flounder (turbot) (Atheresthes stomias) is another commercially important flatfish. It was the most abundant flatfish species caught in the Gulf of Alaska during the 1973-76 NMFS survey. This species is widely distributed throughout the region. Arrowtooth flounder comprised 52 and 53 percent of the flatfish catch in the Kenai and Chirikof districts, respectively; they were less common in the Kodiak (10 per cent) and Shelikof areas (14 per cent) (Ronholt et al., 1978). Highest concentrations of turbot were found between 201 and 400 m water depths (Hughes, 1974; Ronholt et al., 1978), but they also occur at even greater depths (Hart, 1973). Larvae have been recorded from the surface down to 200 m (Hart, 1973). Juveniles probably occur in shallower water than adults, as they do in the Bering Sea (Shuntov, 1970). Large catches of arrowtooth flounder were taken from 1973 to 1975 in the Chirikof-Shelikof Trough (Ronholt et al., 1978). These flounders probably inhabit deeper waters in winter than summer (Shuntov, 1970). Other than some data from the commercial fishery, which will be discussed later, little is known about the life history of this species in Kodiak waters. In the Bering Sea it spawns from December to February (Shuntov, 1970), but exact spawning grounds have not been determined (Pereyra et al., 1976).

Other flatfishes (flathead sole, rex sole, rock sole, and Dover sole) were caught regularly from 1973 to 1976. Details of their distribution and relative abundance are reported by Ronholt et al. (1978). Feeding relationships of these species are discussed below.

Walleye pollock

Walleye pollock (Theragra chalcogramma) .s perhaps the most important roundfish, commercially and ecologically, in the entire Gulf of Alaska They were found at 90 of 96 stations around Kodiak in the 973-75 survey (Ronholt et al., 1978) (Fig. 5.54) and at 8 percent of the stations in the northeast Gulf of Alaska in 1975 (Ronholt et al., 1976). Pollock appear to be replacing Pacific ocean perch as the ecological dominant fish of the Amchitka region (Simenstad et al., 1977). In general, walleye pollock inhabit the outer continental shelf region and the troughs around Kodiak. Preferred depths appear to be between 100 and 200 m (Ronholt et al., 1978), although mm fishermen working in the Shelikof Strait report taking large catches from depths as great as 300 m (J. Blackburn, ADF&G, Kodiak office, pers mm.). Juvenile pollock inhabit more tal waters and are routinely taken in the bays and fiords of the Kodiak Archipelago (Rogers et al., 1978; Feder et a ., .979).

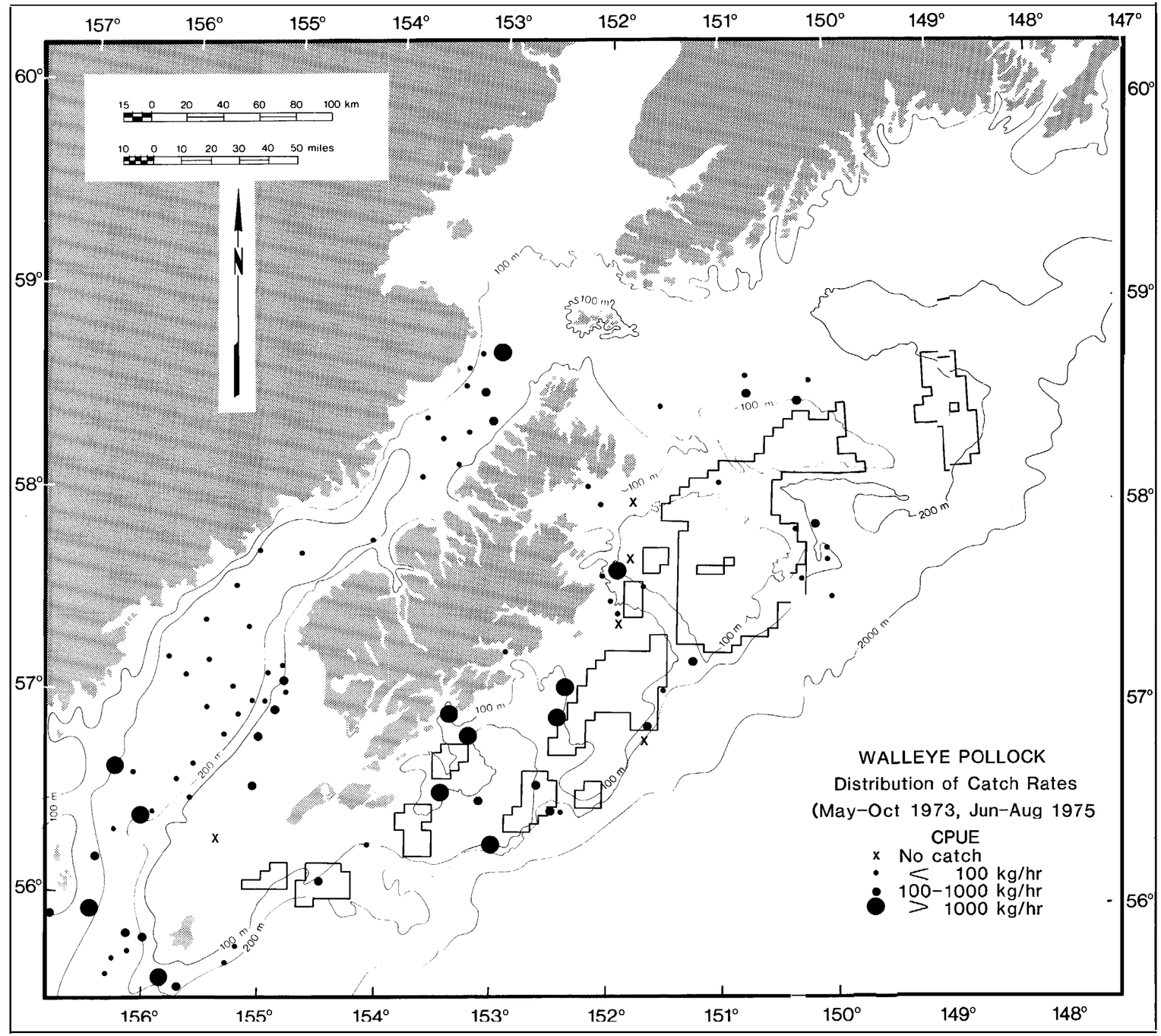


Figure 5.54 Distribution of standardized catch rates (CPUE) of walleye pollock, based on NMFS survey data (Ronholt et al., 1978).

Walleye pollock are extremely abundant in the Kodiak region. In sampling conducted in April and May 1972 by NWAFC in waters contiguous to Kodiak Island, walleye pollock eggs accounted for 97.2 percent of the fish eggs captured; they were most abundant just west of Kodiak (Dunn and Naplin, 1974). Pollock were also the predominant larvae, constituting 62 percent of the total catch. The highest density occurred southwest of the Trinity Islands. In 1973-75, 441,000 mt of the species were estimated to inhabit the four statistical areas (Fig. 5.50) at depths of 0-400 m. This estimate equaled 43.3 percent of the entire biomass of all fishes and invertebrates combined. Pollock accounted for 90 percent of the roundfish catch in Chirikof, 72 percent in Shelikof, 67 percent in Kodiak, and 79 percent in Kenai (Ronholt et al., 1978). During the past several years trawl fishermen working in the Shelikof Strait from Malina Bay south to Chirikof Island have often reported catches of up to 1.8 mt/hr composed of 80 percent pollock, 7 to 8 percent Pacific cod, and 2 to 3 percent sablefish (J. Blackburn, ADF&G, Kodiak office, pers. comm.).

Walleye pollock were far less abundant in the early 1960's. For instance, in the May-October 1961 period an estimated biomass of 32,640 mt of pollock inhabited the four statistical areas in 0-400 m of water (Ronholt et al., 1978), or only about 7 percent of the 1973-75 estimates. To the east of Kodiak, including the proposed lease areas, stocks increased 30-fold from the early 1960's to mid-1970's. Within the next decade a domestic fishery for pollock in this area is likely.

Some life history data on pollock in the Gulf of Alaska are provided by Hart (1973) and Hughes and Hirschhorn (1979). Prime spawning periods are noted as March and April for stocks throughout the Gulf of Alaska (Hughes and Hirschhorn, 1979). Pollock probably spawn in the Kodiak region during April and May (J. Dunn, NMFS, Seattle, pers. comm.). Females with ripening ovaries have been observed in the Shelikof Strait during February-April (J. Blackburn, ADF&G, Kodiak, pers. comm.). These times are similar to those reported for the stock of walleye pollock in the eastern Bering Sea (Smith, 1979).

Size at 50 percent maturity of Gulf of Alaska pollock stocks is 29-32 cm fork length (FL) for males and 30-35 cm FL for females. By age three both sexes are fully mature (Hughes and Hirschhorn, 1979). Smith (1979) presents data that indicate that pollock reach maturity slightly older in the Bering Sea.

There are insufficient data to map pollock spawning grounds near Kodiak. However, high concentrations of eggs were taken with bongo nets and neuston gear in March and April of 1978 in the Chirikof-Shelikof Trough northwest of the Trinity Islands, south and east of the Trinity Islands, and in the Kiliuda Trough east of Sitkalidak Island (Dunn et al., 1979a). These findings suggest that pollock may be spawning in the Kiliuda Trough and along the shelf break in the Chirikof-Shelikof Trough. High concentrations of larvae were observed in summer tows (1978) east of Trinity Island and near the slope of the Chirikof-Shelikof Trough, supporting this hypothesis (J. Dunn, NMFS, Seattle, pers. comm.). Pollock spawn in the southeast Bering Sea along the edge of the continental shelf at midwater depths (Smith, 1979), an environment similar to that associated with the troughs near the Kodiak archipelago.

Pac fic cod

Pacific cod (Gadus macrocephalus) is the second most abundant roundfish in the Kodiak waters. It is distributed from inshore embayments (Harris and Hartt, .977; Rogers et al., .979) to the continental slope (Hart. 1973). Around the Kodiak rchipelago it is usually caught in water less than 100 m deep (Ronholt et al., 1978 . The distribution of cod catch rates during the NMFS 1973-75 survey is plotted in Figure 5.55 At that time an estimated 67,700 mt of Pacific cod were available to trawling in the four statistica areas, or about 12 percent of the roundfish for this region. During May-October 1961, an estimated 117,006 mt of cod inhabited the region, mainly in the Kenai/outer continenta shelf zone (Ronholt et al., 1978).

Little information on the life history and seasonal movements of Pacific cod in Kodiak waters is available. In the northeast Pacific they are bel eved to migrate to deeper waters (unspecified depths) in autumn, spawn in winter, and return to sha lower areas in spring (Hart, .973). Along the British Columbia coast, cod seem to shift their distribution but remain within the 6-9°C sotherms They move to offshore banks (90-145 m in winter and return to 30-75 m water depths n spring and umm (Ketchen, .961). (Ketchen also provides growth and mortality data for Pacific cod in Canadian waters.

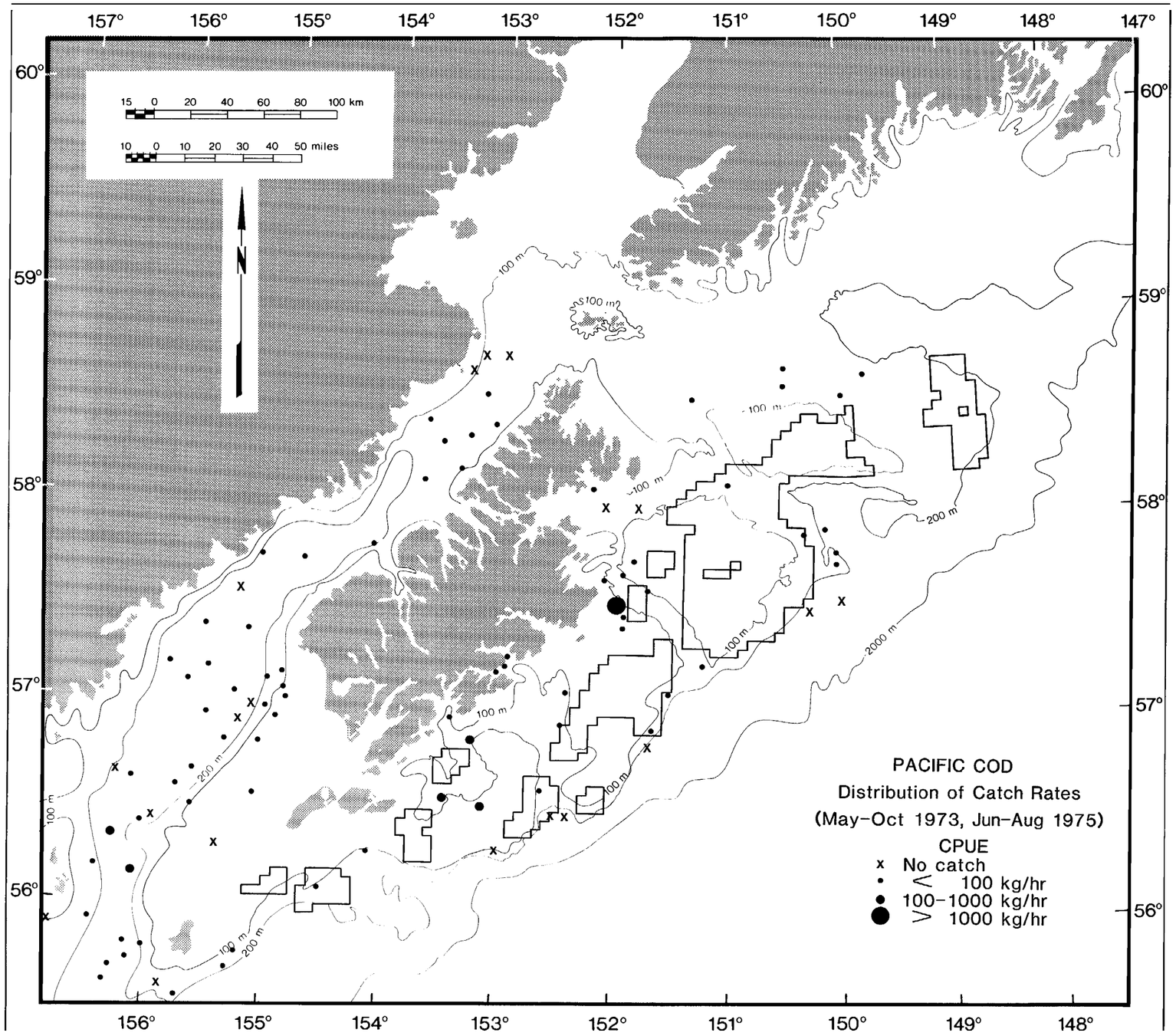
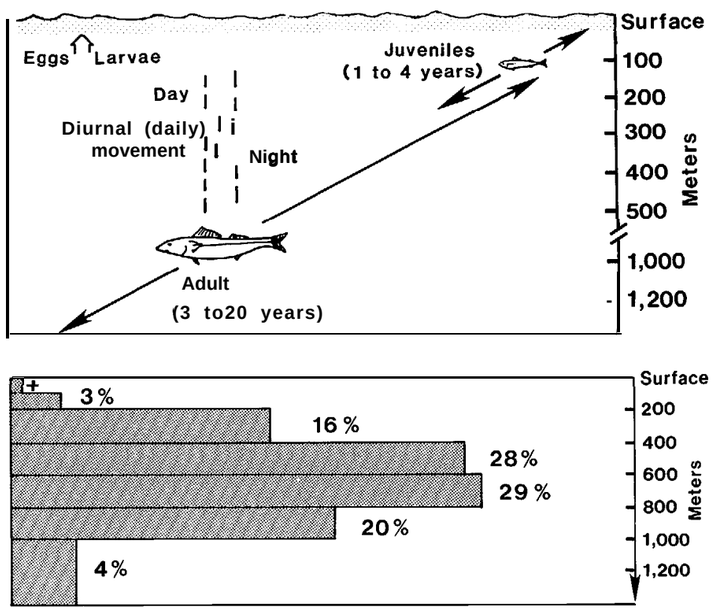


Figure 5.55 Distribution of standardized catch rates (CPUE) of Pacific cod, based on NMFS survey data (Ronholt et al., 1978).

Sablefish

Sablefish (blackcod) (Anoplopoma fimbria) is another commercially important roundfish. It is common along the continental slope from the Queen Charlotte Islands to the Shumagins, where about 67 percent of the north Pacific stocks occur (Low et al., 1976). Its distribution near Kodiak is shown in Figure 5.56. The species was only occasionally caught by NMFS crews in 1973-75 (Ronholt et al., 1978), but they were sampling in shallower areas than the preferred habitats of the species. Sablefish comprised 68 to 100 percent of the roundfish catch in the northeast Pacific at depths greater than 200 m in an earlier survey (Alverson et al., 1964). At those depths it ranked second to flounders in relative abundance in the demersal fish community (Low et al., 1976).



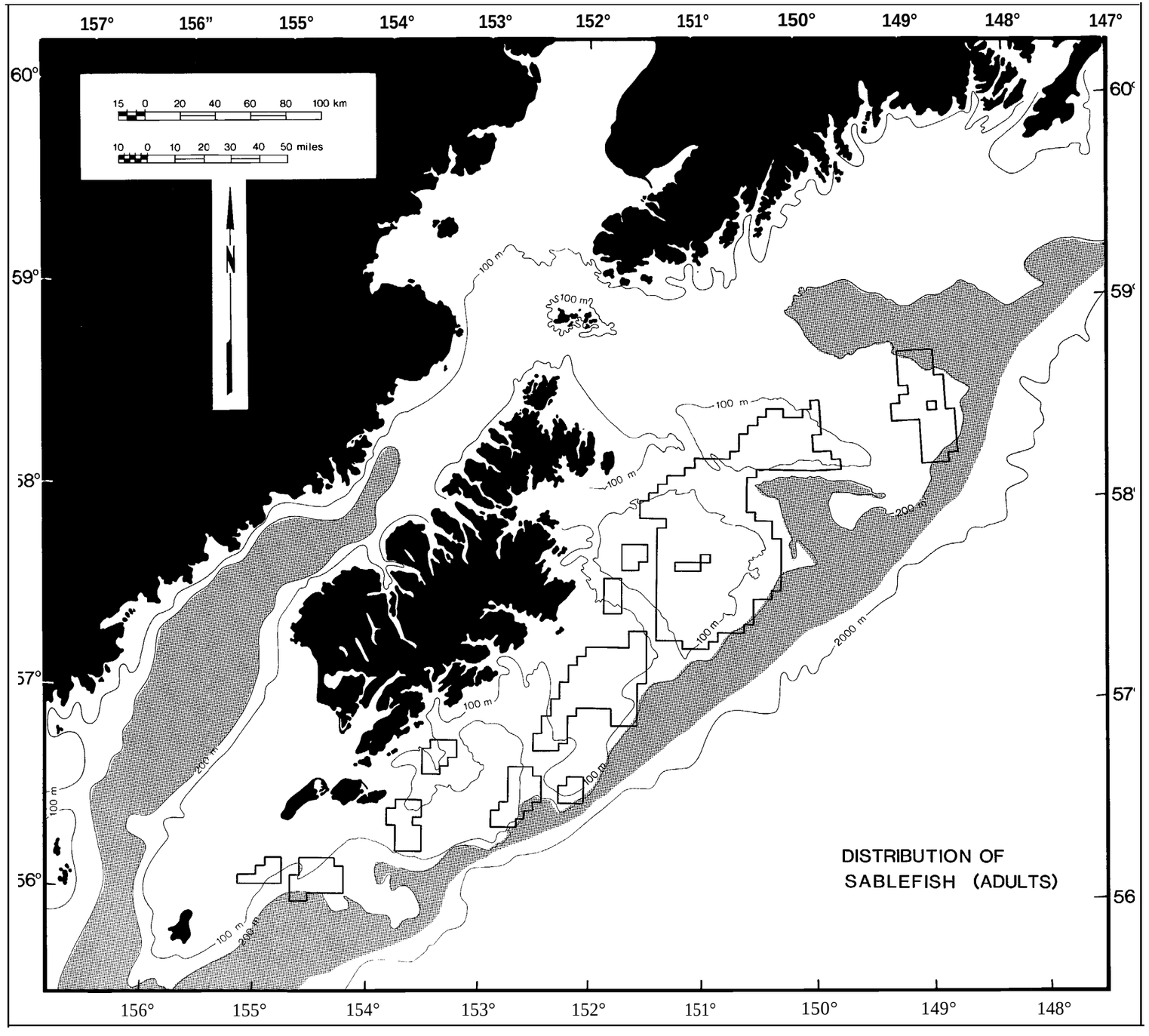


Figure 5.56 Distribution of sablefish (adult) in the Kodiak area (based on data in Low et al., 1976; Ronholt et al., 1978).

It is evident from tagging studies that large-scale migrations of sablefish occur. Bering Sea stocks apparently intermingle with those as far south as California (Low et al., 1976).

Maturity is attained at five to seven years of age. Spawning takes place during winter at depths of 250-750 m (Thompson, 1941). There is no evidence of a spawning migration; sablefish in spawning condition are found throughout the range of the species (Low et al., 1976). Buoyant eggs rise to the surface, and in the Kodiak area a high percentage drift over the shelf, where they develop into larvae. Further aspects of sablefish biology are discussed by Shubnikov (1963), Kulikov (1965), Hart (1973), and Low et al. (1976).

Pacific ocean perch

Pacific ocean perch (Sebastes alutus) is the primary rockfish commercially sought in the Kodiak region at this time. Its range extends from southern California north into the Gulf of Alaska and westward along the Aleutian chain. Populations also occur in the Bering Sea along the shelf break and as far west as Kamchatka (Major and Shippen, 1970). From Unimak Island to Prince William Sound, Pacific ocean perch populations are centered in 100-800 m of water (Lyubimova, 1963). The distribution of this rockfish near Kodiak is shown in Fig. 5.57.

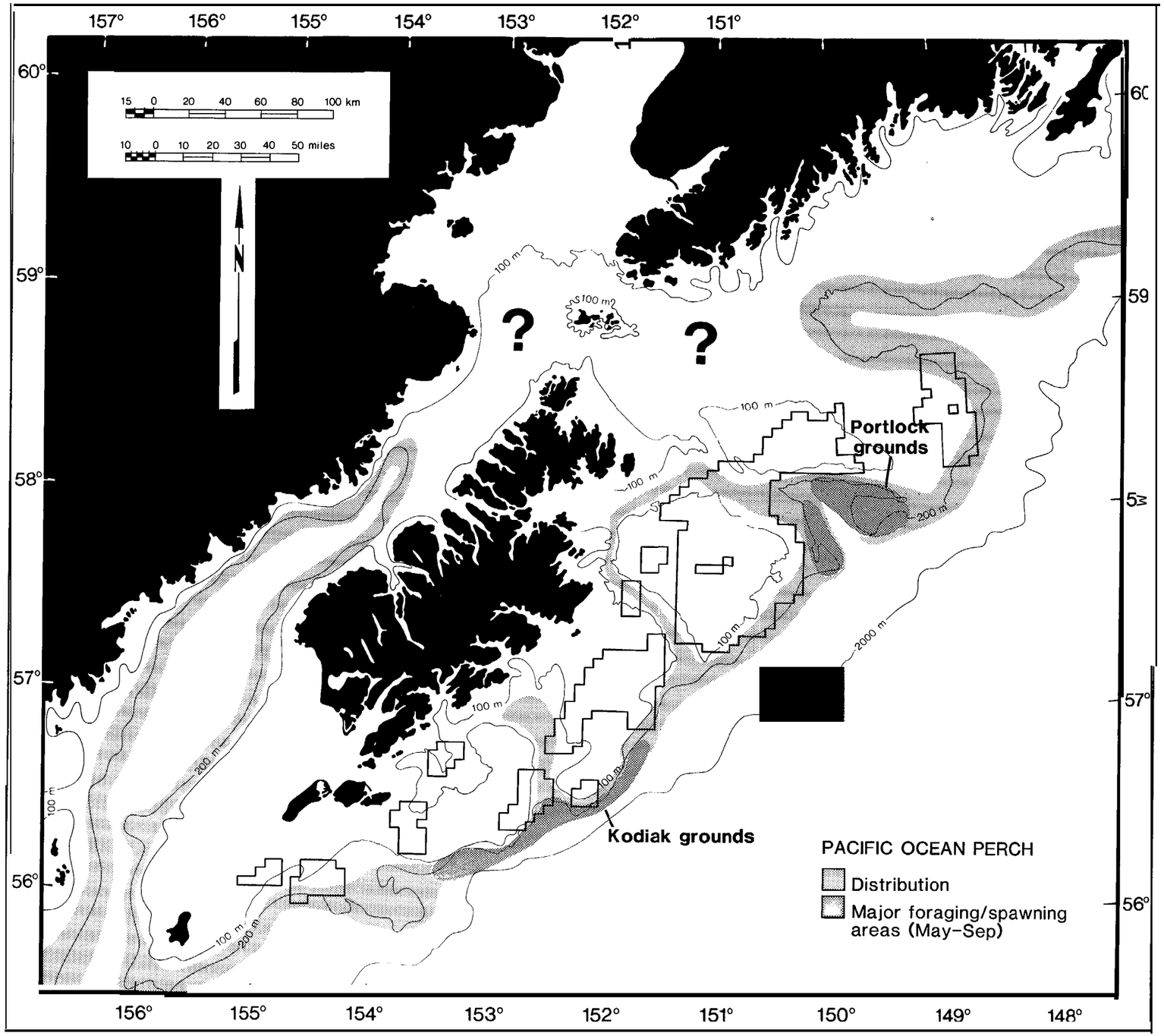


Figure 5.57 Distribution of Pacific ocean perch in the Kodiak area (Lyubimova, 1963; Lisovenko, 1964; Ronholt et al, 1978).

Pacific ocean perch migrate seasonally. Major concentrations of perch forage south of Unimak Pass from May through September. The Portlock Banks, Kodiak (Fig. 5.57), and Shumagin grounds are of secondary importance to feeding rockfish. Dense schools composed of both sexes consume vast quantities of pelagic euphausiicls and calanoid copepods. Fish are typically observed in 100-150-m water depths at this time. In September feeding ceases and mating is believed to occur on the feeding grounds (Lyubimova, 1963). After mating, females migrate to the northeast areas of the Gulf and are found widely dispersed "from October through April. Males remain in their primary foraging grounds; small schools are sharply localized at 250-450-m depths from November through March (Lyubimova, 1963). The species is viviparous and the times of fry emergence at different latitudes are given by Major and Shippen (1970). Fry emergence around Kodiak begins in April (Lyubimova, 1963). After spawning, females return to their foraging grounds, and dense aggregates of heterosexual schools form again.

The distribution of Pacific ocean perch larvae in the Gulf of Alaska has been studied by Lisovenko (1964). However, as taxonomic identification of scorpaenid larvae is very difficult, Lisovenko assumed all rockfish larvae he collected were Sebastes alutus. Major and Shippen (1970) point out the difficulties in ascertaining life histories when larval identification is in doubt. Alverson and Westrheim (1961) deduced that young juvenile Pacific ocean perch inhabit surface waters during daylight hours; they probably are demersal at night. Older juvenile fish prefer waters 125-150 m deep until they mature (Paraketsov in Major and Shippen, 1970).

The abundance of Pacific ocean perch is difficult to ascertain because of their benthopelagic habits. They are much less easily caught by trawling gear than many other demersal species. Hence, estimates of their abundance are likely to be low (Ronholt et al., 1978). In 1961, 75,141 mt were thought to be present in the four statistical areas around Kodiak, with 91 percent of the biomass located in the Kenai and Chirikof areas. By 1973-75, however, the estimate was only 5,278 mt (Ronholt et al., 1978). This sharp decline in abundance probably resulted, at least in part, from heavy fishing pressure by Soviet and Japanese fleets in the intervening years (Major and Shippen, 1970).

Extent of demersal fishery

Except for Pacific halibut and a few pollock and cod, domestic fishermen are not fishing for demersal fishes near Kodiak to any extent. This is not true, however, of foreign fishing fleets.

Japanese and Soviet fleets catch most of the fish taken by foreign nationals; Poland, the Republic of Korea, and Taiwan also fish in the northeast Gulf of Alaska (Ronholt et al., 1978). Ninety percent of the Japanese catch in Alaskan waters consists of three species: Pacific ocean perch, sablefish, and walleye pollock. Pacific ocean perch and walleye pollock are caught mostly by trawling; sablefish are harvested by long-lining (Ronholt et al., 1978). The total Japanese fisheries catch for 1969-74, broken down by species and areas, is presented in Table 5.36. Japanese fishing productivity for 1964-74 is illustrated geographically in Fig. 5.58.

Table 5.36 Total Japanese trawl and longline catch of fishes harvested in the Kodiak Lease Area and vicinity, 1969-74. Data are reported in metric tons (Ronholt et al., 1978).

	Statistical Areas					
Species	Kenai	Kodiak	Shelikof	Chirikof	Total	Percent Gulf of Alaska (catch)
Pacific ocean perch	33,800	19,700	0	28,600	82,100	44
Sablefish	17,100	10,900	10	10,700	38,710	34
Walleye pollock	10,000	21,200	0	12,700	43,900	70
Arrowtooth flounder	3,200	1,800	0	3,200	8,200	58
Miscellaneous fishes[a]	6,100	4,700	0	5,000	15,800	7
TOTAL	70,200	58,300	10	60,200	188,700	45
Percent of Gulf of Alaska[b] (catch)	17	14	<1	14		

[a] Miscellaneous fishes are mainly Pacific cod, flatfishes, rock fishes and elasmobranchs.
[b] The reported Japanese catch for the entire Gulf of Alaska was 419,000 mt.

The Soviets have fished in the Gulf of Alaska since 1960. By 1963 they had established a year-round fishery in the gulf. A complete catch record for the 1960's is not available. Pacific ocean perch was the main species sought. Soviet fishing increased in the 1970's, and since 1973 a more complete record of Soviet catch statistics has become available. In 1973-75, walleye pollock, Atka mackerel, and Pacific ocean perch were the principal species caught by the Soviet fishing fleet. Soviet fishermen landed 34,000 mt of Atka mackerel and 60,300 mt of walleye pollock in this period, or about 41 percent of the total Soviet catch in the gulf (Ronholt et al., 1978).

Other foreign fleets began fishing in the Kodiak

area within the last decade, but catch and effort have not been well documented (Ronholt et al., 1978). The overall foreign groundfish catch in the Kodiak region was 100,305 mt in 1978 (Table 5.37), up from previous years (Ronholt et al., 1978), but still only 60 percent of the estimated optimum yield (OY). This suggests that the groundfish stocks as a whole are not overfished, and more could be harvested without impairing the resource. Atka mackerel stocks, however, appear to be fully exploited. Flounders, cod, pollock, and Pacific ocean perch stocks could withstand heavier fishing pressure without stressing their reproductive capacities (M. Alton, NMFS, Seattle, pers. comm.). The conclusion that perch are underutilized (Table 5.37) differs from the earlier findings of Ronholt et al. (1978). Optimum yield values are based on factors in

Table 5.37 Total foreign and domestic groundfish catch (in mt) in the "Chirikof-Kodiak" INPFC areas of 1978 by species and groups related to optimum yield (OY) (M. Alton, NMFS, Seattle, unpub. data).

Species or Group	Foreign Catch	Domestic Catch*	Total Foreign & Domestic	Optimum Yield	% of OY**
Pollock	61,499	514	62,013	95,200	65
Atka mackerel	18,806	---	18,806	19,400	97
Flounders	6,284	81	6,365	14,700	43
Pacific cod	5,584	631	6,215	19,400	32
Sablefish	3,088	1	3,089	3,800	8
Pacific ocean perch	2,023	---	2,023	7,900	26
Other rockfish	581	1	582	800	73
Other fish	2,440	113	2,553	8,600	30
Total	100,305	1,341	101,646	169,800	60

*Includes Kodiak westward, but most of catch in Kodiak to Shumagin area.

**Optimum yield is the amount of fish that can be continuously harvested from a stock under current environmental conditions, ± an amount considered for the purposes of promoting economic, social, or ecological objectives as established by law and public participation processes (for a legal definition see PL 94-265).

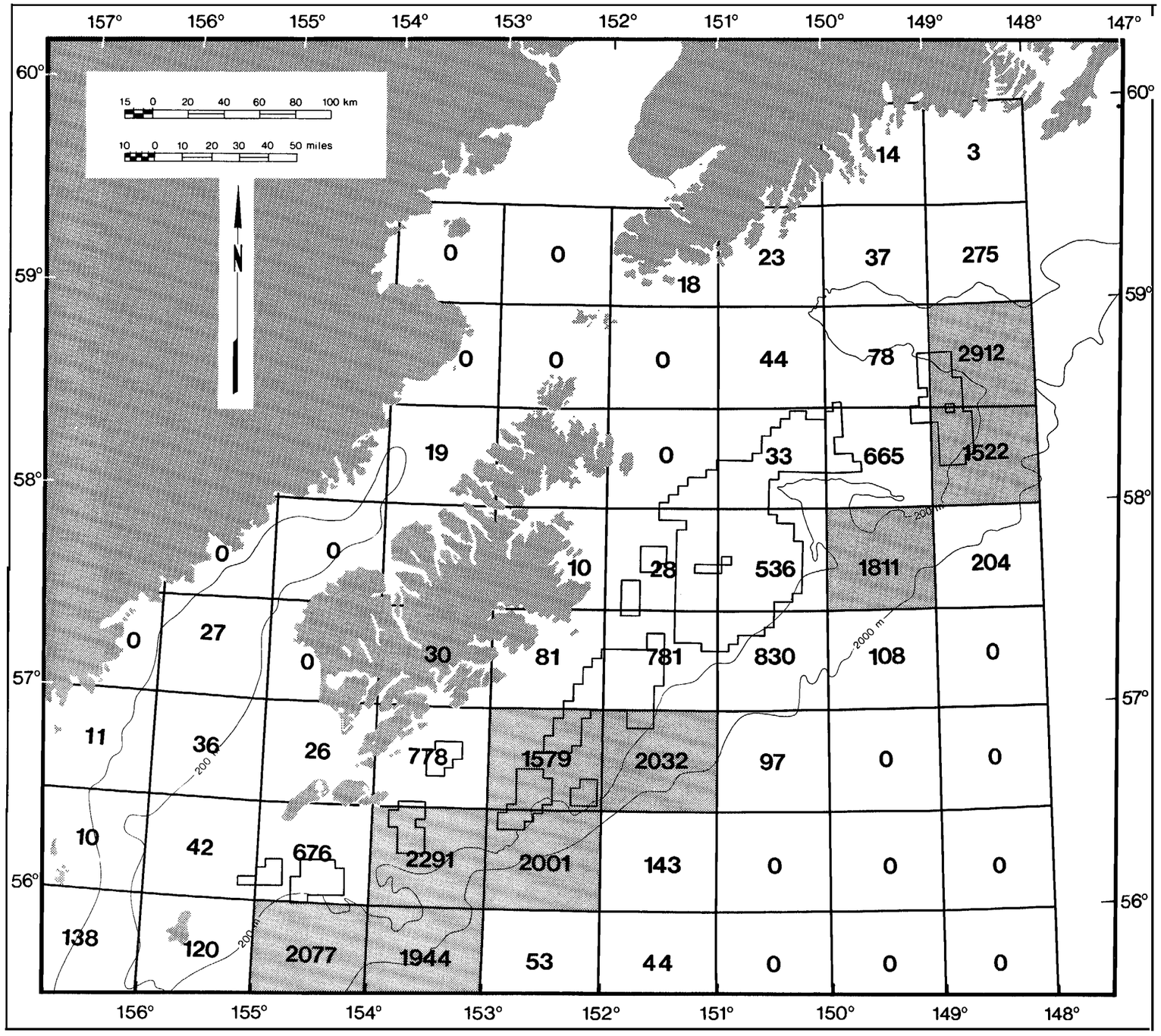


Figure 5.58 Distribution of mean annual demersal fish catch by Japanese trawl and longline fisheries, 1964-74 (Ronholt et al., 1978). Units are metric tons.

addition to biological ones; however, relying on them alone for making decisions on fishery management without frequent stock reassessments is unwise.

With the passage of the "Fishery Conservation and Management Act of 1976," which became effective 1 March 1977, the United States extended its jurisdiction over the fisheries resources to the 200-mile seaward limit. The Act was designed to establish a regulatory program to regulate all fisheries in the conservation zone. Domestic and foreign fish quotas, time-area closures, minimum size limits, and gear restrictions have been, or are being, formulated for the demersal fishes of the Gulf of Alaska. Foreign nations are permitted to fish in the Conservation Zone under bilateral treaty agreements with the U.S. However, the domestic fisheries are given primary consideration in these agreements. The long-term effect of this action will be to restrict foreign fisheries and to increase domestic efforts and catches within the U.S. Fisheries Management Zone (J. H. Branson, North Pacific Fisheries Management Council, pers. Comm.). The implications of this change in fisheries resource utilization are still unclear, but domestic fisheries and foreign policy may be appreciably altered.

5.6.3 Feeding relationships and marine fish communities

Knowledge of predator-prey relationships is important in assessing the effects of OCS development on faunal populations. Data on seasonal variations in distribution and abundance of organisms alone are insufficient. Predator-prey relationships can be ascertained and food web models constructed by analyzing the gut contents of organisms and, when possible, by watching them eat. Marine food web models show major dependencies among infauna, epifauna, pelagic fishes and invertebrates, birds, and mammals. They increase our understanding of energy flow through the ecosystem and help elucidate community structure and function. They may thus be used to predict the transfer and accumulation of industrial contaminants in a community of marine animals.

All life stages of the fishes of the Kodiak region thrive on a rich complement of zooplankton, benthic and pelagic organisms, and other fishes. The trophic relationships are complex and may vary with life stage, season, location, and physiological condition of the predator and prey. Generalizations are difficult, and predicting the fate and effect of pollutants in marine food webs is fraught with uncertainties at present. Nonetheless, some typical feeding strategies and common energy pathways may be mentioned.

It is suspected that many fishes time their production of eggs so that larvae will coincide with zooplankton blooms, thereby utilizing available food resources optimally and increasing their survival. Spring runoff from Kodiak Island probably increases the nutrients in the nearshore waters, triggering the onset of phytoplankton blooms similar to those in temperate estuarine systems (Pratt, 1965). Zooplankon populations, in turn, increase as they graze on the abundant diatom populations (Martin, 1965). Zooplankters such as calanoid and harpacticoid copepods, hyperid amphipods, and euphausiids are the principal prey of numerous juvenile fishes inhabiting the coastal waters of the Gulf of Alaska. (Simenstad, et al., 1977; Rogers and Rogers, 1978; Rogers et al., 1979; Smith et al., 1978). Some common fishes (e.g., capelin, yellowfin sole, and ronquils) of Kodiak waters have larval populations that peak in late spring and early summer (Harris and Hartt, 1977; Rogers et al. 1979), a time coinciding with the spring bloom of phytoplankton and subsequent succession of zooplankton populations.

Juvenile fish tend to change their diet as they grow. The variety of prey taken increases with age which probably reflects a more mature mouth and digestive tract. Older juvenile fish are also more adept at capturing a variety of prey. As an example of expanding diets with age, the prey of fingerling pink salmon during their first summer in the marine environment is shown in Table 5.38. Most of the prey of young walleye pollock are benthic: polychaetes, majid crabs, and amphipods in the northern Gulf of Alaska. Older pollock take more pelagic prey (Fig. 5.59), especially euphausiids (*Euphausia* spp., *Thysanoessa* spp.) and teleost fishes such as Pacific sand lance (Smith et

Table 5.38 Major prey of age 0.1 pink salmon in nearshore waters of the Kodiak archipelago. Size of prey spectra reported as number of taxa (data from Rogers and Rogers, 1978; Rogers et al., 1979).

	Average Percent			
	Number		Weight	
Dominant Prey	April (N=22)	May (N=220)	June (N=371)	July (N=119)
Copepods				
Harpacticoid	91	172	44	44
Calanoid	3	4	45	8
Amphipods				
Gammarid	6	23	6	9
Euphausiids	o	0	14	1
Cumacea	o	4	4	17
No. Taxa	3	12	21	26
Mean Fish Length (mm)	?	?	49	68

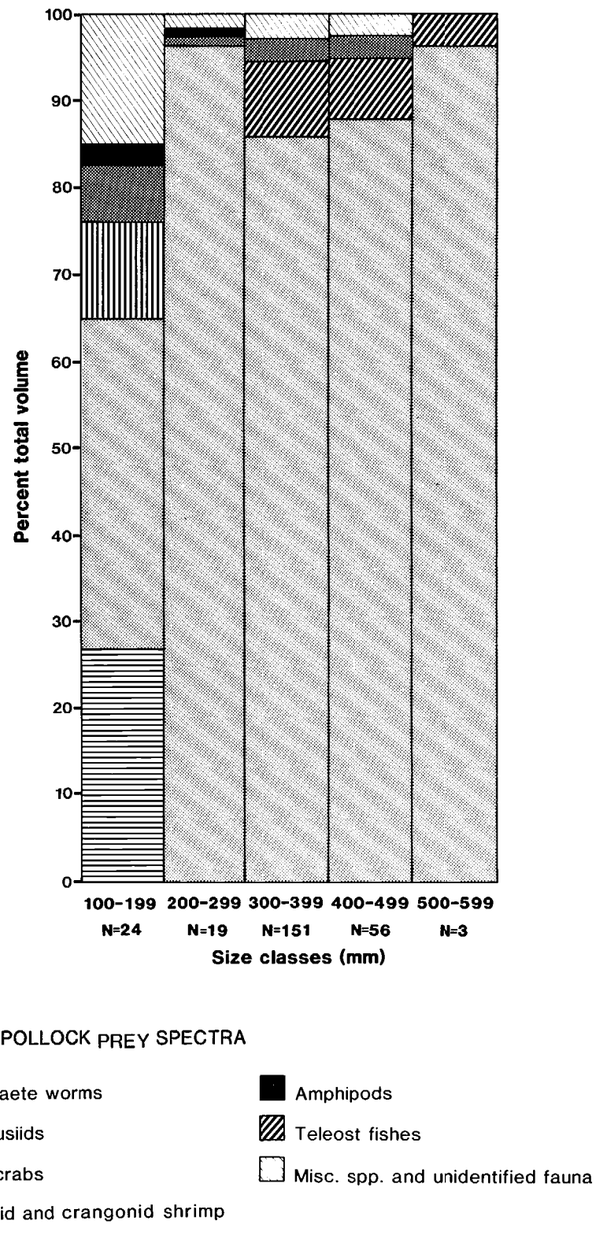


Figure 5.59 Diet composition of walleye pollock taken in the northern Gulf of Alaska, by fish size class. "N" indicates the number of stomachs analyzed (data from Smith et al., 1978).

al., 1978), Pacific herring (Hart, 1973), and juvenile salmonids (Armstrong and Winslow, 1968). Mysids, sand lance, and rock sole are the principal prey of adult populations of pollock near Amchitka (Simenstad et al., 1977). Diets of some common juvenile and adult fishes in Kodiak waters are compared in Figs. 5.60 and 5.61.

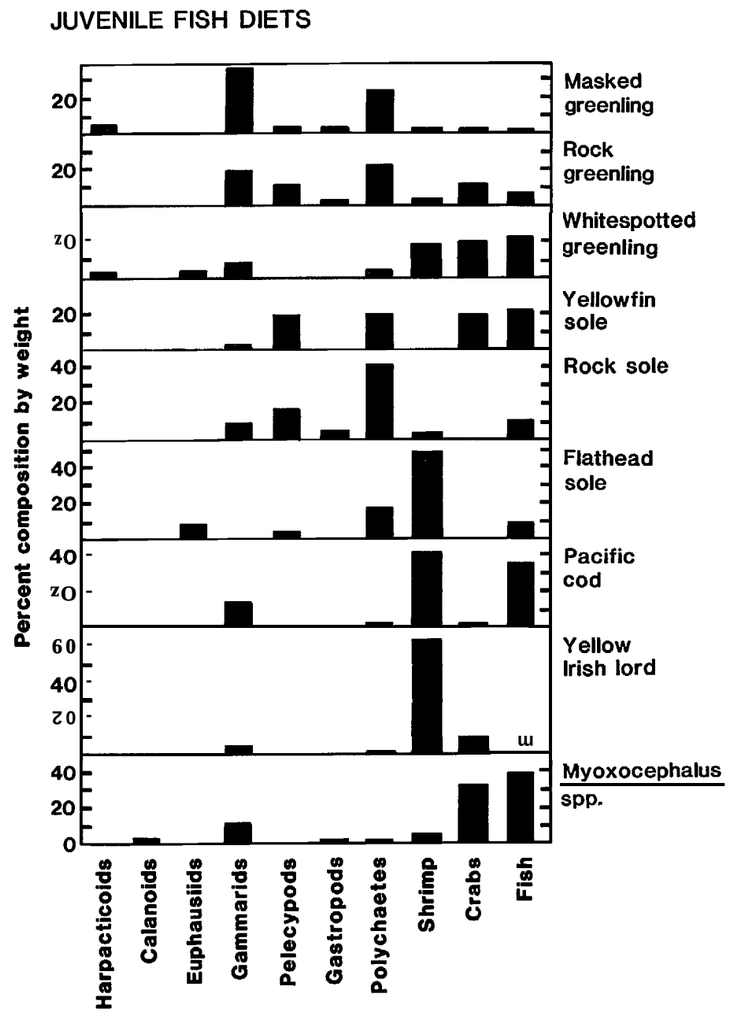


Figure 5.60 Percent composition by weight of major food items in the stomachs of juvenile fishes taken from Kodiak nearshore waters (modified from Rogers et al., 1979).

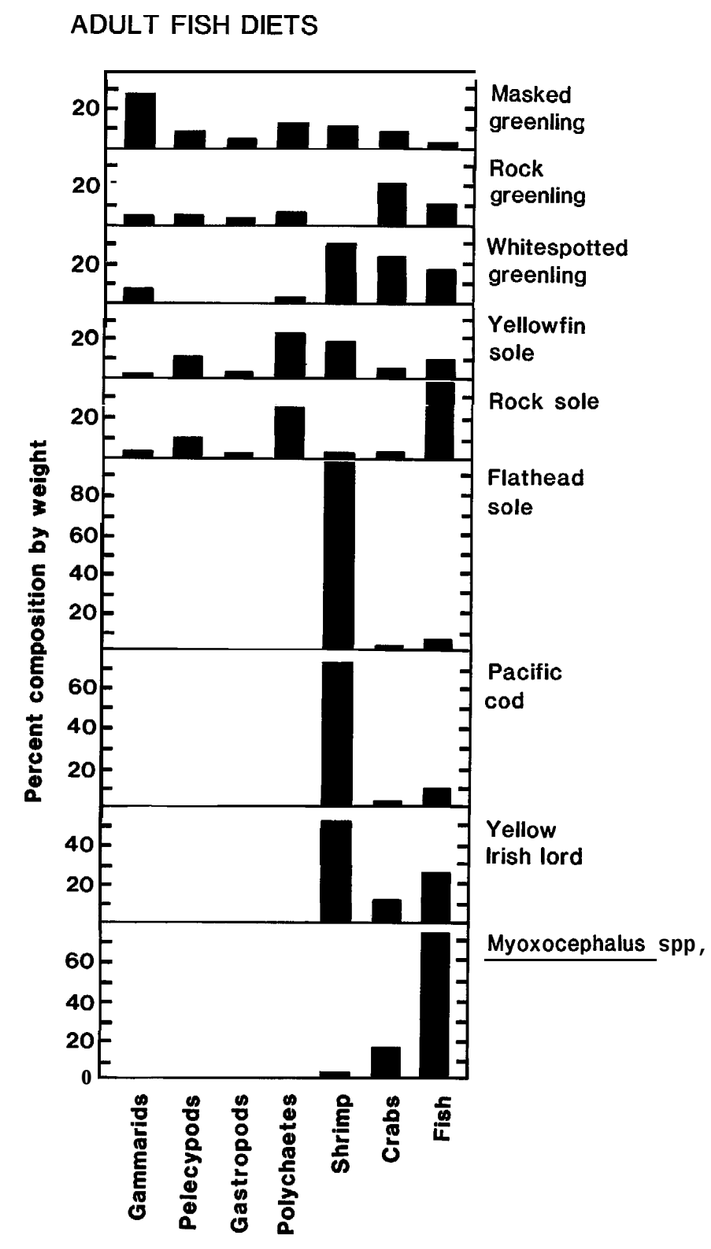


Figure 5.61 Percent composition by weight of major food items in the stomachs of adult fishes taken from Kodiak nearshore waters (modified from Rogers et al., 1979).

Geographic location and depth play a large role in determining the availability of prey. Physiographic features, currents, proximity to river drainages, seismic activity, and prevailing storm tracks all affect the distribution of offshore sediments (see Chapter 3), which, in turn, affects the distribution of benthic fauna (Thorson, 1957; Rhoades, 1974; see Benthos section for further discussion). Dover sole feed on crustaceans and molluscs in water depths of about 100 m off the coast of Oregon, but take polychaetes at greater (100-150 m) depths (Pearcy and Hancock, 1978). This modification in diet corresponds to changes in prey availability (Bertrand, 1971) and substrate type (Pearcy, 1978). In the northern Gulf of Alaska, Dover sole fed almost exclusively on terebellid polychaetes in 0-200 m, onuphid polychaetes, amphipods, and pelecypods at 201-300 m, and onuphid polychaetes and ophiuroids at 301-600 m (Smith et al., 1978). Unfortunately, the corresponding distributions of benthic invertebrates were not reported; thus prey availability could not be determined from this study. Bottom sediments, however, have been mapped (Carlson et al., 1977) and vary considerably with depth, suggesting corresponding changes in the distribution of benthic fauna. Pacific cod take a wide variety of prey on the Kodiak shelf; juvenile Tanner crab, Chionoecetes bairdi, is taken most frequently (Jewett, 1978). Inshore populations of cod in Izhut and Kiliuda Bays feed mostly on pink shrimp, Pandalus borealis, however (Feder et al., 1979).

Though some fishes have been shown to alter their diets considerably with life stage, season, geography, depth, and prey availability, other species tend to feed on specific classes of prey. For instance, DeGroot (1971) presents evidence that pleuronectids (flatfishes) specialize in feeding on either fish, crustaceans, or a combination of polychaetes and molluscs. In addition, all flounders are known to take an array of incidental prey. Flatfish such as Pacific halibut and arrowtooth flounder that prey on fish and pelagic macroinvertebrates have large symmetrical jaws and sharp dentition suited for grasping mobile organisms, whereas flounders such as rex and rock soles, which feed on polychaetes, molluscs, and amphipods, have asymmetrical, small mouths and an alimentary tract adapted to digest benthic organisms. A species is limited by its morphology in the type of prey it can ingest, but it may take a variety of taxa within that type. Arrowtooth flounder fed on walleye pollock and Pacific sand lance on the Kodiak shelf (Feder et al., 1979) but on capelin near Kayak Island and on Pacific herring at other sites in the northern Gulf of Alaska (Smith et al., 1978). Rex sole preyed on onuphid polychaetes in the northern Gulf of Alaska (Smith et al., 1978), but mostly on other families of polychaetes and gammarid amphipods off the coast of Oregon (Pearcy and Hancock, 1978). Mysids are of primary importance in the diet of walleye pollock in the Aleutians (Simenstad et al. 1977), while euphausiids are their principal prey in the Gulf of Alaska (Smith et al. 1978). The fact that arrowtooth flounder and walleye pollock populations are increasing in the Gulf of Alaska (Ronholt et al., 1978) may be related to their opportunistic food habits.

Co-existing species, especially those that are closely related taxonomically, often appear to partition the food resources, thereby reducing competitive interactions. Yellowfin, rock, and sand sole and starry flounder are common flatfishes in the Kodiak region (Harris and Hartt, 1977; Hunter, 1979) which have quite different diets. These are graphically displayed according to a measure of relative importance, IRI (Pinkas et al., 1971), in Fig. 5.62. Percent frequency of occurrence, the proportion of stomachs examined that contain a specific prey item, is plotted on the horizontal axis. Percent total by number of each prey is shown on the positive vertical axis; percent total by weight is drawn on the negative vertical axis. The relative sizes of the areas in the figure indicate the importance of the prey to the consumer. Clams are the chief prey of yellowfin sole, whereas polychaetes are important to rock sole (Harris and Hartt, 1977). A detailed analysis of food resource partitioning of other pleuronectids from the Kodiak shelf is presented by Hunter (1979). Partitioning of food resources for hexagrammids (greenings) in nearshore waters of Kodiak has also been studied (Rogers et al., 1979).

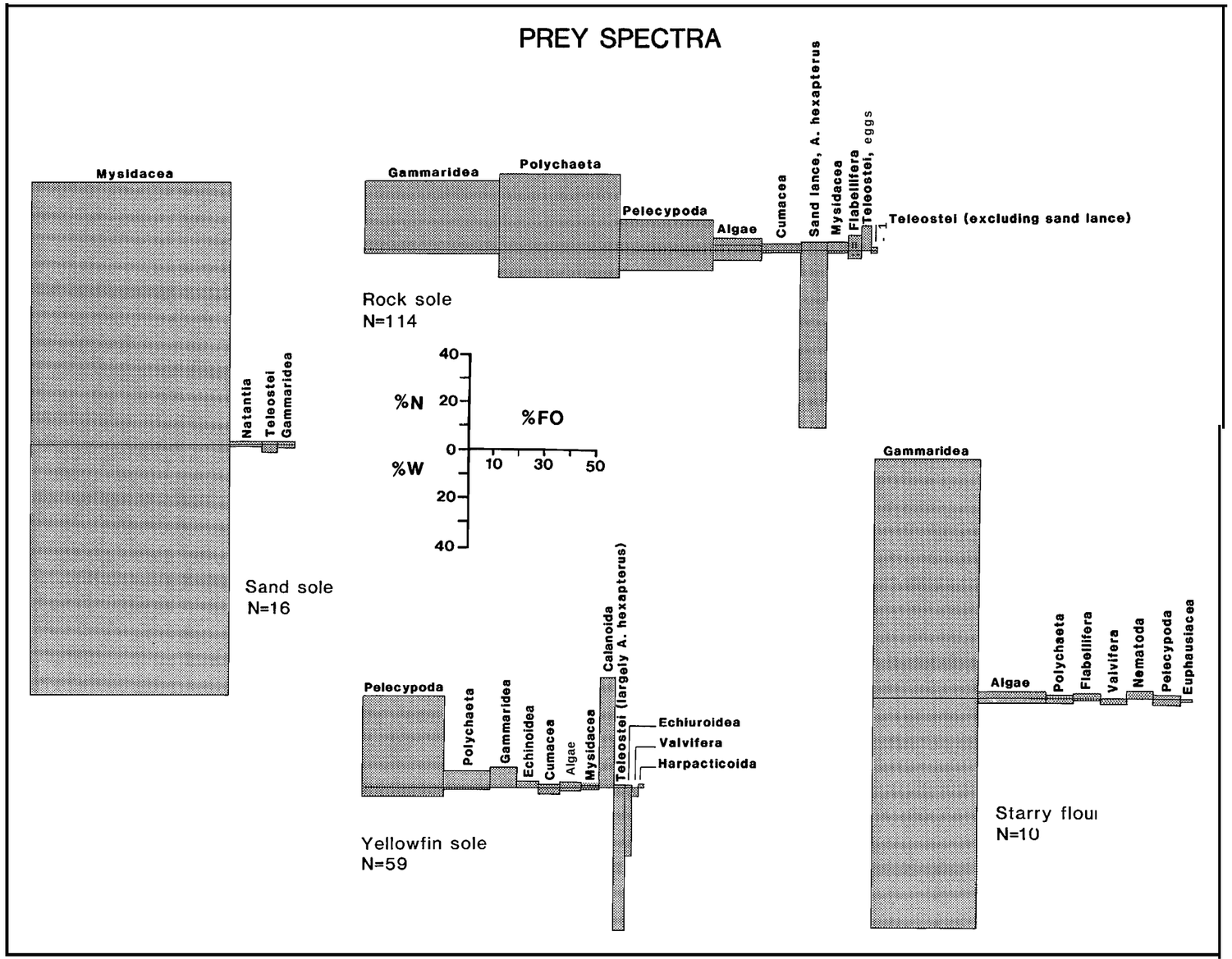


Figure 5.62 Prey spectra of four common flatfishes of the Kodiak region (Harris and Hartt, 1977). Diet composition is reported as Index of Relative Importance (IRI). See text for explanation of scales.

Table 5.39 Principal prey of common fishes in the Kodiak region.

PREDATOR		PREY: Phytoplankton, Algae	Sponges (PORIFERA)	Corals, hydroids (CNIDARIA)	Polychaetes (ANNELIDS)	Chitons	Gastropods	Pelecypods	Cephalopods	Ostracods (ARTHROPODS)	Calanoids (Copepods)	Harpacticoids (Copepods)	Barnacle larvae	Mysids	Cumaceans	Isopods	Amphipods	Euphausiids	Pandalids (Shrimp)	Crangonids (Shrimp)	Larvae (Shrimp)	King & hermit (Crabs)	Tanner (Crabs)	Larvae (Crabs)	Insects	Ophiuroids (ECHINODERMS)	Echinoids (ECHINODERMS)	Eggs (Fish)	Larvae (Fish)	Clupeidae	Salmonidae	Osmeridae	Gadidae	Zoarcidae	Trichodontidae	Bathymasteridae	Stichaeidae	Pholidae	Ammodytidae	Scorpaenidae	Anoplopomatidae	Hexagrammidae	Cottidae	Agonidae	Pleuronectidae	Miscellaneous
Clupeidae	Pacific herring	E	.	.		.			.	.	A	E A	E E	.	.			E	.	.	E	.	.	E	.	.	.	E	E	.	.		.	.	.	.	.		.	.	.		.	.	.	B
Salmonidae	*Pink salmon (juvenile)	A	.	.		.	AB		.	B	AB	AB	B	B	AB			B	.	.	.	B	.	A	AB	.	.	A	A	.	.	A	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Chum salmon (juvenile)	.	.	.		.	A		.	B	AB	AB	AB	A	AB	B	AB	AB	.	.	B		A	A	A B	.	.	A	B	B	B	.		.	.	.	.	B		.	.	.	B	.	.	B
	Sockeye salmon	.	.	.		.	J		J	J	J	J	J	.	J		J	J	.	.	.	.	.	J	J	.	.	.	.	.	.	J	.	.	.	.	.	.		.	.	.		.	.	J
	Coho salmon (juvenile)	.	.	.	B	.			.	.	.	.	.	.	A		A	S .	.	.	.	B	.	AS	AB	.	.	.	.	.	.		.	.	.	.	.	.		.	.	.		.	.	AB
	Chinook salmon	.	.	.		.			.	I	H	H	H	.	.		H	HI	I	.	.	.	.	HI	.	.	.	.	.	.	.		.	.	.	.	.	.		.	.	.		.	.	H
	Do 11 y Va rden	A	.	.	A	.			.	.	.	.	.	A	.		A	.	.	.	.	.	.		A	.	.	A	.	.	.		.	.	.	.	.	.	A	.	.	.		.	.	A
Osmeridae	Capelin	.	.	.	A	.			.	.	ABC	A	.	C	.		AC	C	.	B	A	.	.	B	.	.	.		A	.	.		.	.	.	.	.	.		.	.	.		.	.	.
Gadidae	*Pacific cod	AB	B	D	ABD	.	BD	BD	D	B	B	A B	B	ABD	A	B	ABD	BD	BD	BD	.	BD	AD	.	.	D	D	.	.	BD	B	BD	D	D	D	B	D	.	BD	D	.	D	BD	D	BD	A
	*Walleye pollock	.	.	.	BC	.	c	c	C	.	B	C .	.	B	B		BC	BC	BCK	BC	B	B	BC	B	.	.	.		B	.	.		.	.	.	.	.	.	B	.	.	.		.	.	C
Stichaeidae	Snake prickleback	A	.	A	AB	.	B	AB	.	B	B	AB	B	A	AB		AB	B	B	.	.		B	.	.	B	B	AD.		.	.		.	.	.	.	.	.		.	.	.		.	.	.
Trichodontidae	Pacific sandfish (juvenile)	.	.	.	.	.			.	.	.	.	.	A	.		A B	B	AB	.	A	B	A	B	.	.	.		A	B	.		.	.	.	.	.	.	B	.	.	.		.	.	B
Ammodytidae	Pacific sand lance	.	.	A	.	.	AB	AB	.	B	AB	AR	AB	AB	B		A B	B	.	.	B	A	.	B	A	.	.		A R	.	.		.	.	.	.	.	.		.	.	.		.	.	.
Scorpaenidae	Pacific ocean perch	.	.	.	.	.			.	.	FG	.	.	F	.		F	FG	G	.	G	.	.	G	.	.	.	.	.	.	.		.	.	.	.	.	.		.	.	.		.	.	.
Anoplopomat idae	Sablefish	.	.	.	.	.			.	.	.		.	.				BK	B	.	.	.	.	B	.	.	.	.	.	B	.	B	.	.	.	.	.	.	K	.	.	.		.	.	B
Hexagrammidae	Kelp greenling	B	.	.	B	.	B	B	.	.	.	.	.		B	B		B	.	.	.	B	B	.	.	.	.	.	.	.	.		.	.	.	.	.	.		.	.	.		.	.	B
	*Rock greenl ing	B	B	B	B	B	B	B	B	.	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B		B	B	B	.	.		.	.	.	.	.	B		.	.	B	B	.	.	.
	*Masked greenling	AB	.	B	AB	AB	B	AB	B	B	B	A B	B	B	AB	AB	AB	AS	B	B	AB	B	B	AB	AB	B	B	A	B B	.	.		.	.	.	.	.	.		.	.	B	B	.	B	A
	*White spotted greenling	AB	.	.	AB	B	AB	AB	B	B	AB	AB	B	B	B	B	B	AB	B	B	B	B	B	B	B	.		B	B	.	.		.	.	.	.	B	.	B	B	.	B	B	.	B	.
Cottidae	*Yellow Irish lord	B	B	.	B	K	BK	BK	BK	.	B	B	B	B	.	B	BK	BK	BK	BK	.	BK	BK	B	.	B	K		B	B	.		.	K	.	.	BK	.		.	B	.	B	.	.	K
	Red Irish lord	B	.	.		B	B	B	B	.	.	.	B	.	.		.	.	.	.	.		B	.	.	.	.		.		.		.	.	.	.	.	.		.	.	.		.	.	B
	* Great sculpin	B	.	B	AB	.		BK	K	.	B	AB	B	B	B	B	A	.	ABK	BK	.	B	ABK	A	B	.		.		B	B	BK	BK	K	.	.	K	.	AB	A	B	.	B	K	ABK	ABK
Pleuronectidae	Arrowtooth flounder	.	.	.		c			C	C	.	.	.	.	.		c	.	c	c	.		c	.	.	c	.	.	.	C	C	c	CK	C	.	.	C	.	K	.	.	.	c	.	c	CK
	Rex sole	.	.	.	c	.		c	.	.	c	.	.		c		c	c	c	c	.	c	.	.		c	.	.	.	.	.	.	.	c	.	.	.	.		.	.	.		.	.	
	*Flathead sole	.	.	.	BK	.	c	BCK	C	.	B	B	.	B	B	B	BK	BC	BK	BK	BK	BCK	.	B	.	BCK	.		B	K	.	B	.	K	.	.	B	B	B	.	.	B	B	.	B	C
	Pacific halibut	.	.	.	.	.	B	BL	L	.	.		.	B	.				B	B		BL	BL	.	.	.		.	.	BL	.		L	.	.	.	.	.	BL	L	BL	.	L	.	L	B
	*Rock sole	A B	K	B	ABK	B	B	ABK	B	B	B	B B	K	AB	AB	B	AB	BK	K	B	BK	B	B	B	B	BK	BK	AB	B	B	.	B	.	.	.	.	BK	B	A B	K	.	B	B	B	B	A R
	*Yellowfin sole	A	B	B	AB	.	B	AB	.	.	AB	AB	B	B	AB	B	AB	B	B	B		B	B	.	B	B	A	B B	B	.	.	B	.	.	.	.	B	.	AB	.	.	.	B	.	B	.
	Dover sole			.	c	.	c	c	c	.	.	.	.		c		c	c	c	.	.	.	c	.	.	cc	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		.		c
	$, Starry flounder		A	.		A			A	.	.		.	.	.		A	A	A	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		.	.	.
	*Sand sole			.	.	.		.	.	.		.	.	A	.		A	.	A	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.			.	.		.		A

A - Harris and Hartt, 1977
B - Rogers et al. , 1979
C - Smith et al. , 1978
D - Jewett, 1978
E - Macy et al. , 1978
F - Lyubimova, 1965
G - Major and Shippen, 1970
H - Hart, 1973
I - Major et al. , 1978
J - Foerster, 1968
K - Feder et al. , 1979
L - IPHC, 1978

* Dominant prey shown in Figs. 5.59 thru 5.62 and Table 5.38

An overview of prey consumed by fishes mm to the northern Gu.f of Alaska with emphasis on predation in the Kodia area is shown in Table 5.39. The principal prey of additional fishes, which are mm to several bays of Kodiak and Afognak islands (Alitak, Ugak, Kaiugnak, Izhut, Kalsin, and Kiliuda) from Apri through September are shown in Tab.e 5.40

Pacific halibut, although not studied .n detail in the aforementioned fish food surveys, is of major mm cial importance to the Kodiak groundfish fishery Adult Pacific halibut consume mostly fishes (other flatfishes, walleye pollock, Pacific cod, rockfishes, and Pacific sand lance), squid, octopi, and .arge such as king and Tanner crabs (Simenstad et al., 1977; Smith et al., 1978; PHC 1978). Juvenile halibut are also piscivorous, but tend to take a greater proportion of crustaceans. Cook Inlet populations feed mainly on shrimp (PC data in Smith et al., 1978).

Table 5.40 Dominant prey items (ranked) in stomachs of some common fishes in Kodiak bays, Summer 1976-1978 (Harris and Hartt, 1977; Rogers et al., 1979).

Prey	Predator						
	Chum salmon (juv.)	Coho salmon (juv.)	Dolly Varden	Capelin	Snake prickleback	Pacific Sandfish (juv.)(ad.)	Pacific Sand lance (juv.)(ad.)
Polychaetes					3		
Calanoids		2					1 1
Harpacticoids	1	2			2		
Mysids	3						
Gammarids	2	1	1		1		
Euphausiids						2	
Shrimps						3	
Crab larvae						1	2
Fish larvae						2	
Fish			2				

The fishes of the Kodiak shelf can be grouped into assemblages (Table 5.41) on the basis of distribution and feeding relationships; they occur primarily in the following habitats:

(1) epipelagic: 0-100 m deep
(2) offshore/demersal: > 30 miles from shore > 100 m deep
(3) coastal/demersal: < 30 miles from shore, including embayments; 25 m deep
(4) littoral-sublittoral/demersal: tidally influenced nearshore zones, substrate generally < 25 m deep
(5) littoral-sublittoral/pelagic: nearshore water column, general.y < 25 m deep.

Our knowledge of the seasonal movements and biological requirements (such as food and shelter of fishes in the Kodiak area is incomplete. For example, extensive work on pelagic fis fauna has not yet been done and the life histories of many of the noncommercial, yet numerically abundant, species are rly known. Therefore, to describe these assemblages as true mm .ties (Whittaker, .970 may be premature. Perhaps it is best to consider them as most likely interacting fish fauna in a given area. Further work is .ary to e.ucidate these relationships

Knowledge of marine communities can be used to predict which species are most likely to be harmed by OCS development on the Kodiak shelf. By knowing the source, composition, and of contaminants together with the physical of the area, trajectory models can be constructed (see Physical

Table 5.41 Marine fish assemblages in the Kodiak region

Epipelagic	
Pacific herring	Capelin
Salmon (maturing)	Pacific sandfish
Mainly: Pink	Pacific sand lance (juv.)
Chum	Atka mackerel
Sockeye	
Littoral/Pelagic	
Pacific herring (seasonal)	Dolly Varden
Salmon (juv.)	Capelin (juv., seasonal)
Mainly: Pink	Pacific sand lance (ad.)
Chum	Larvae: many species
Sockeye	
Littoral-Sublittoral/Demersal	
Snake prickleback	Crescent gunnel
Pacific sandfish (juv.)	Snailfish
Greenlings (ad. and juv.)	Juveniles:
Kelp greenling	Flounders
Rock greenling	Rockfish
Musked greenling	Sculpins
Whitespotted greenling	Codfishes
Coastal/Demersal	
Pacific sand lance (juv.)	Red Irish lord
Pacific cod (juv.)	Other sculpin
Pacific halibut (juv.)	Poaches
Yellowfin sole	Rock greenling
Rock sole	Kelp greenling
Dover sole	Whitespotted greenling
Great sculpin	Masked greenling
Yellow Irish lord	
Offshore/Demersal	
Walleye pollock	Sablefish
Pacific cod	Pacific halibut
Pacific sand lance (ad.)	Arrowtooth flounder
Eelpouts	Rex sole
Searchers (ronquils)	Flathead sole
Shortspine thornyhead	

Oceanography chapter), and predictions can be made regarding which organisms will come into contact with the pollutant. Once a heavy metal, petroleum derivative, or synthetic chemical has been taken up by a species, further predictions concerning the fate of the pollutant through the marine food chain can be made. For instance, a lightweight hydrocarbon spilled from an oil tanker, pipeline, or well head would probably remain in surface water and be advected shoreward and to the southwest along the Kodiak shelf (see Chapter 2). Epipelagic fishes, many of which have dense schooling habits (e.g., Pacific sand lance, Atka mackerel) could be directly fouled by the oil-laden water. Struhsaker (1977) showed that exposing Pacific herring to one fraction of petroleum (benzene) induced premature spawning, impaired ovarian and larval development, and reduced survivorship of adult fish. Groundfish such as Pacific halibut, rock sole, and Pacific cod prey on a variety of clupeids, including Pacific herring (IPHC, 1978; Rogers et al., 1979, Table 5.39). Pollutants ingested or adhering to herring may accumulate in these fishes and eventually be incorporated into benthic food chains. Even if epipelagic fishes do not come into immediate contact with the discharged pollutants, their principal prey (copepods, mysids, euphausiids, crustacean and fish larvae) may. Prey populations may die, or they may accumulate and concentrate pollutants that will eventually be incorporated into epipelagic food chains.

OCS development on the Kodiak shelf will result in increased onshore development along the east side of the archipelago. Kodiak harbor in Chiniak Bay will have increased ship traffic; the city will have additional pressure on its sewage and water treatment facilities; a coastal LNG facility may be built, and the overall risk of environmental impairment increases.

Recent studies have shown that nearshore, estuarine waters are used as spawning grounds for such commercially important species as salmonids, herring (Buck et al., 1975), and king crab (Feder et al., 1979; Guy Powell, pers. comm.). They are also important nursery areas for most larval and juvenile fishes (Harris and Hartt, 1977; Rogers et al., 1979). Chronic, low-level exposure of young fish to pollutants could affect their physiology and behavior, impeding growth and decreasing survivorship (Patten, 1977). Furthermore, heavier-grade oils may sink, become incorporated into the littoral sediments, be consumed by deposit-feeding invertebrates (such as polychaetes), and enter the benthic food chains (Feder and Jewett, 1977; Feder et al., 1979). As few in situ studies on the fate and effects of industrial pollutants in Alaskan marine ecosystems have been made, much of this discussion awaits verification.

5.7 BIRDS

5.7.1 Introduction

Marine ecosystems support distinctive communities of birds, whose composition, distribution, breeding season, and movements are determined mainly by the spatial and temporal distribution of the food supply. Generally, higher concentrations of birds are found in neritic waters (those over the continental shelf) than in oceanic waters (those seaward of the shelf). Primary productivity and zooplankton concentrations are usually higher in neritic waters because of the influx of nutrients from land drainage, vertical mixing over the shelf, and local upwellings close to shore. Oceanic birds generally feed on the surface or a short distance under water. Crustaceans, squid, and in tropical areas, flying fish, are their major prey. Many birds in neritic waters and in regions of upwellings, however, feed on fish, which they catch by diving. Many birds are attracted to convergent fronts or rips (boundaries between unlike water masses) where prey are concentrated for feeding. In areas where upwellings bring nutrient-rich waters to the surface, successive blooms of phytoplankton, herbivorous zooplankton, and carnivorous zooplankton occur. Since currents continuously carry water away from the center of upwelling, however, these members of the food chain are displaced away from the upwelling. Birds which specialize on zooplankton and micronekton thus find food most abundant at some distance from the center of upwelling. Small fish which eat mainly phytoplankton are also found near upwelling areas, and birds which prey on these fish often are found nearby.

Upwellings are not regularly found in the waters near Kodiak. There is, however, frequent mixing in the water column over the banks which brings nutrients to the surface. Seasonal changes in plankton growth are not yet well documented. Over the shelf a spring increase in zooplankton is thought to occur. In deep waters, away from the shelf, the zooplankton breed independently of the increase in phytoplankton biomass, and, by grazing, prevent a preliminary phytoplankton bloom. Euphausiids swarm to the surface while spawning and thus provide a food source independent of upwelling.

The distribution of suitable breeding areas and the seasonal variation in the food supply are probably the major selective forces on the breeding biology of marine birds. The distribution of islands and other safe nesting places may either restrict birds to only a

small fraction of the total available feeding area or require them to spend much time flying to and from more distant feeding grounds. The timing of egglaying is closely governed by seasonal availability ia the food supply.

General information on the breeding phenologies of Alaskan marine and coastal birds has long been available (Gabrielson and Lincoln, 1959). As one proceeds northward from the equator, the length of the breeding season of birds becomes shorter. The reproductive period of more northern populations of a species is usually compressed and may be several weeks shorter than that of more southern lations. Superimposed oa this geographic trend are local year-to-year fluctuations in weather and in food supply. An unseasonab y late spring may delay the start of breeding, while a poor food supply may lead to increased mortality of young or may even prevent breeding altogether. Natura populations can compensate for these year-to-year uncertainties. In late seasons the breeding effort at a colony is usually more highly synchronized and compressed into a shorter period; when conditions are favorable. individual pairs and the population as a whole produce greater numbers of more vigorous young, thus offsetting poor years.

True marine species tend to have low fecundity but high survivorship (Ashmole, 1971); a pair may thus enjoy many breeding seasons, and the success or failure of a particular season is not so critical for individual fitness or maintenance of a population as it is for shorter-lived species. On the other hand, such populations increase very slowly, and recovery of the breeding population from significant mortality may take many generations.

Birds are believed to be important members of mar ne ecosystems, but quantification of their role in such systems has hardly begun. In terms of numbers and the amount of food they consume, they must play an important role, at least locally. Wiens and Scott (1975) estimated that four species feeding in the neritic zone along the Oregon coast consumed 22 percent of the annual production of pelagic fish Marine birds may contribute to the stability of the ecosystem by foraging on prey species that are temporarily abundant (Wiens et al., 1978b). The approximately 420,000 birds breeding at Cape Thompson consumed an estimated 13,100 metric tons of food during a four-month breeding period (Swartz, 1966). The 1,200,000 breeding birds in the Kodiak area must therefore consume about 36,000 metric tons of food during the breeding season, or over 50 percent of the weight taken annually by the shellfish and finfish fisheries (see Sections 5.4 and 5.5

The estimated total energy flow through pelagic bird populations in the Kodiak area was greatest (24,300 kcal/km^2/day) during August and September (Table 5.42) but varied with season (Fig. 5.63) because of the movements of the species (Wiens et al., 1978a). Shearwaters accounted for up to 92 percent of the total energy demand of the community.

Table 5.42 Estimated energy demands (kcal/km^2) of bird populations in the Kodiak area. Values in italics are percentages of the total energy flow for a lease area at that time (Wiens et al., 1978a).

Species	April	May	June	Aug-Sept	Oct
Northern Fulmar	8 *2*	13 *t**	212 *7*	168 *1*	252 *7*
Sooty Shearwater	–	2,030 *32*	859 *28*	22,220 *91*	6 *t*
Short-tailed Shearwater	11 *3*	34 *1*	1,780 *58*	348 *1*	1,910 *55*
Fork-tailed Storm-Petrel	--	86 *1*	71 *2*	358 *1*	62 *2*
Herring Gull	21 *6*	12 *t*		6 *t*	--
Gulls	193 *54*	101 *2*	20 *1*	27 *t*	--
Black-legged Kittiwake	--	2,030 *32*	51 *2*	230 *1*	--
Arctic Tern	--	45 *1*	23 *1*	--	--
Common Murre	112 *32*	126 *2*	6 *t*	57 *t*	12 *t*
Tufted Puffin	11 *3*	1,900 *30*	24 *1*	934 *4*	612 *18*
Horned Puffin	--	--	11 *t*	15 *t*	610 *18*
TOTAL	335	6,380	3,060	24,300	3,460

t = trace

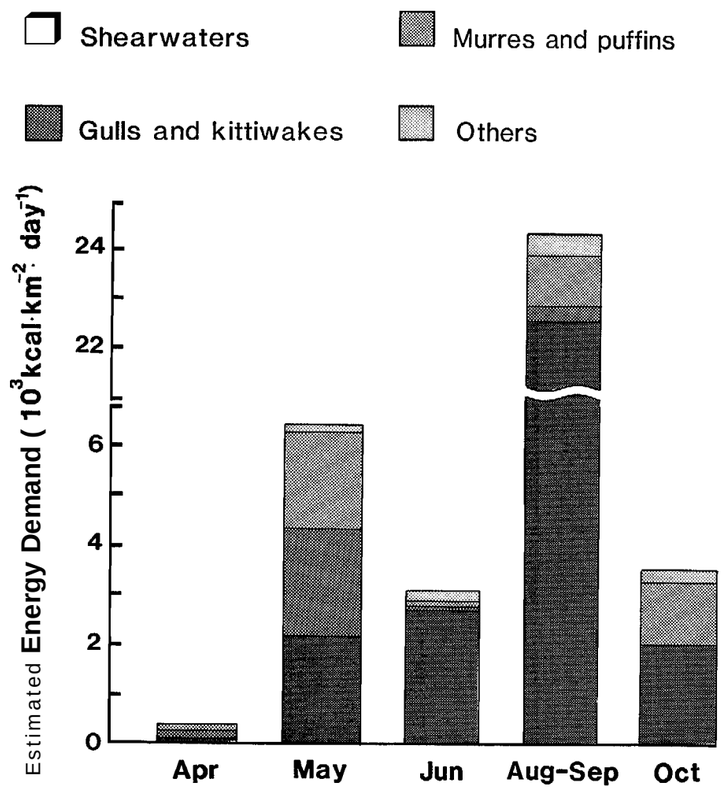


Figure 5.63 Temporal apportionment of total energy demand among the species groups recorded during transect censuses in the Kodiak area (Wiens et al.,1978).

The role of marine birds in recycling nutrients is not yet well understood. While Pomeroy (1970) believes that birds and mammals are unimportant in the cycles of essential elements in marine systems, Tuck (1960) points out that seabird excrement is rich in nitrates and phosphates. He describes the murky, excrement-laden water which flows continuously from murre colonies and which may discolor the surrounding waters for many square miles. Unlike the 100,000 tons of guano which accumulate annually on the sites of Peruvian seabird colonies, the excrement of Arctic seabirds is continuously washed into the sea and becomes available to marine nutrient cycles.

Birds in the Subarctic Pacific Region consume an estimated 0.5 to 1.1 million metric tons of food and return from 110,000 to 220,000 metric tons of feces to the sea each year (Sanger, 1972). High nutrient levels and high densities of certain species of algae and fishes have been found in waters adjacent to seal and seabird colonies along the California coast (Morejohn, 1971).

Seabirds may play a vital role in Alaskan marine ecosystems by recycling nutrients during seasons when oceanic circulation does not supply nutrients to photosynthetic strata, thus "smoothing out" the seasonal distribution of primary production (Weller and Norton, 1977). Manuring by seabirds and seals is an important agency for the addition of nitrogen and phosphorus to island soils (Smith, 1978; 1979).

5.7.2 Marine birds of Alaska

The marine birds of Alaska can be placed in three categories:

1. Those that spend most of their life on marine waters and obtain their food from the sea while flying, swimming, or diving; these include members of the Procellariiformes, Pelecaniformes, and Charadriiformes.
2. Those that occupy freshwater habitats while breeding but feed in marine waters at other times; these include members of the Gaviiformes, Podicipediformes, Ciconiiformes, Anseriformes, Gruiformes, Charadriiformes, and Coraciiformes.
3. Terrestrial birds which forage on the coast; these include members of the Falconiformes and Passeriformes.

The first category consists of the true seabirds and includes the most abundant marine birds found in Alaska in the summer.

Members of the Procellariiformes are known as tubenoses because all members of the family have tubular nostrils. Other characteristics of the order are a deeply grooved, hooked bill, webbed feet, thick plumage, and a peculiar musky odor. All members are totally marine, feeding alone or in groups dispersed over open water according to the distribution of their food. They normally come ashore only to breed. They have a long breeding cycle, a low reproductive rate (clutch size is one.), a long period of immaturity> and a long life expectancy (Bourne, 1964). Members of three of the four families in the order are found in Alaskan waters.

Three species of the Diomedeidae (albatrosses) have been recorded in Alaskan waters (Gabrielson and Lincoln, 1959; Kessel and Gibson, 1979). None of them breeds in Alaska. The Short-tailed Albatross (Diomedea albatrus), which breeds in Japan, may once have been common in Alaska, but the present world population is probably less than 200 pairs. Individuals are occasionally seen off the Aleutian Islands (AOU, 1975). The Black-footed Albatross (D. nigripes) and the Laysan Albatross (D. immutabilis) both breed mainly on the Leeward Chain of the Hawaiian Islands (Palmer, 1962). Both species are common in Alaskan waters, the Black-footed being more frequent in the Gulf of Alaska, while Laysan are probably more numerous in the Bering Sea and near the Aleutian Islands.

Albatrosses are among the largest seabirds. They have exceptional powers of gliding flight. The Laysan Albatross feeds mainly on squid, while the Black-footed is a feeding generalist, taking dead or living fishes, squid, crustaceans, and other animals (Ainley and Sanger, 1979).

Nine species of the Procellariidae (petrels and shearwaters) have been recorded from Alaskan waters. Five are rare or casual in the Alaskan region; a sixth, the Scaled Petrel (Pterodroma inexpectata), is uncommon in Alaskan water (Gabrielson and Lincoln, 1959; Kessel and Gibson, 1979). The Sooty (Puffinus griseus) and the Short-tailed (P. tenuirostris) Shearwaters are the most abundant summer pelagic birds in Alaskan waters. Both species breed in the Southern Hemisphere and spend the austral winter on waters in the Northern Hemisphere. The Northern Fulmar (Fulmarus glacialis) is the only Alaskan breeding species.

Typical petrels are of medium to large size. Most species nest in burrows. They have a rapid and gliding flight, usually close to the surface of the water. Many species feed on the surface, but the Sooty and Short-tailed Shearwaters are wing-propelled divers (Storer, 197), feeding by what Ashmole (1971) calls pursuit plunging (Fig. 5.64). Fulmars are scavengers (Ainley and Sanger, 1979); the more specialized diets of the Alaskan shearwaters are discussed later.

Two species of the Hydrobatidae (storm-petrels), the Fork-tailed (Oceanodroma furcata) and the Leach's (O. leucorhoa) Storm-Petrels, occur in Alaska as breeding species. They breed in crevices and burrows, usually in colonies. They spend the winter on the open ocean; the wintering grounds of the Alaskan species are not fully known. When feeding, they flutter characteristically over the water, often striking the surface with their feet; the feeding method is known as pattering (Fig. 5 64). They eat a variety of prey and are the smallest members of the generalist groups of tubenoses (Ainley and Sanger, 1979).

The only family in the Pelecaniformes which is found in Alaska is the Phalacrocoracidae (cormorants). It is represented by four species: the Double-crested (Phalacrocorax auritus), Brandt s (P. penicillatus), Pelagic (P. pelagicus), and Red-faced (P. urile) Cormorants. The Brandt s Cormorant is rare and very local in Alaska, known only from a few sight records and a small colony in Prince William Sound (Kessel and Gibson, 1979); the other three species are common along the coast. The Double-crested Cormorant breeds throughout most of North America in freshwater and marine habitats. The Pelagic and Red-faced are common coastal species throughout most of the North Pacific. Most species are colonial, breeding on ledges or rocky islands along marine coasts (Thomson, 964). Although

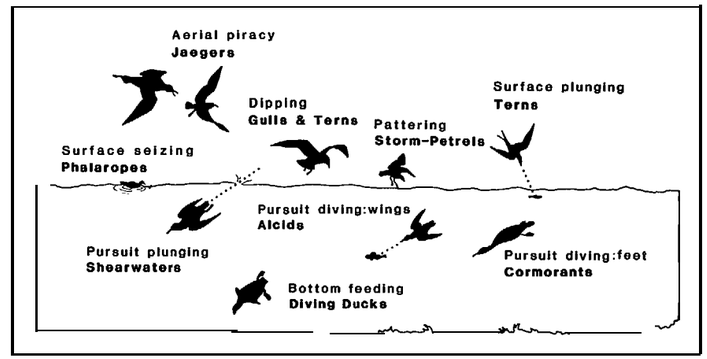


Figure 5.64 Seabird feeding methods (modified from Ashmole, 1971).

the young have functional nostrils, those of adults are almost completely closed, and the birds must breathe through their mouths. Their plumage is easily wetted in contrast to that of most other marine birds. Cormorants enter the water only to feed. They feed by pursuit diving (Fig. 5.64), using their feet for propulsion. They eat mainly fish.

The Charadriiformes are a diverse group of birds represented in Alaska by the Scolopacidae (sandpipers and their allies), Phalaropodidae (phalaropes), Charadriidae (plovers), the Haematopodidae (oystercatchers), the Stercorariidae (skuas and jaegers), the Laridae (gulls and terns), and the Alcidae (auks). The phylogenetic relationships among these birds have recently been analyzed by Strauch (1978). Some or all members of these families spend most of their lives on marine waters. For the present discussion, all members of the Scolopacidae, Phalaropodidae, Charadriidae, and Haematopodidae, which in North America are commonly called shorebirds, will be classified in the second group mentioned above: those birds that breed near fresh water but otherwise feed on salt water. The last three families will be discussed here even though not all of their members are true seabirds.

Four species of Stercorariidae are known from Alaska. The South Polar Skua, Catharacta maccormicki, is very rare visitor to the North Pacific (Kessel and Gibson, 1979). The Pomarine (Stercorarius pomarinus), Parasitic (S. parasiticus), and Long-tailed (S. longicaudus) Jaegers are common breeding birds on the arctic tundra. Their ecology in northern Alaska has recently been described (Maher 1974). Skuas and jaegers are similar to gulls but have raptor-like habits and hooked bills. During the winter they are independent of land; they take food from the surface of the water while in flight (Wynne-Edwards, 1964). On their breeding grounds, they eat mostly rodents and birds (Maher, 1974). Near the colonies of other species they prey on the eggs and young of these birds, and they chase and harass other birds until they drop or disgorge their prey (Fig. 5.64). Off the breeding grounds and at sea, they are opportunistic, taking a variety of prey (Maher, 1974; Ainley and Sanger, 1979). They are mm spring and fall migrators off Alaska

Seventeen species of gulls and five species of terns have been recorded from Alaska (Kessel and Gibson, 1979), but only three species of gulls, the Glaucous-winged (Larus glaucescens) and Mew (L. canus) Gulls and the Black-l Kittiwake (Rissa tridactyla), and two species of terns, the Arctic (Sterna paradisaea) and Aleutian (S. aleutica) terns, are to be considered here by virtue of their numbers or their breeding distribution in the Gulf of Alaska marine habitat. A few other species, especially the Herring Gull (L. argentatus), may prove to be important winter residents in the Gulf. Of these, only the Black-legged Kittiwake, and perhaps the Arctic Tern, are true seabirds. The other species are essentially coastal. However, small numbers of Glaucous-winged and Herring Gulls occur regularly on Gulf of Alaska pelagic

waters (Sanger, 1973). Gulls and terns are cosmopolitan in distribution and are among the most familiar marine birds. Gulls are larger and heavier, with stouter bills and shorter tails, while terns are small and slim, with narrow, pointed bills and long tails. Both are strong fliers; terns appear lighter and more buoyant. Gulls often soar whereas terns frequently hover. Both gulls and terns are gregarious and nest in large colonies, although isolated pairs and small groups of breeders are common in the Kodiak region. Kittiwakes are unique among gulls in nesting on the faces of cliffs; their breeding biology exhibits many adaptations to this habitat (Cullen, 1957). Both gulls and terns feed by dipping (Fig. 5.64) and shallow pursuit plunging; in flight they pick prey from just at or slightly below the water surface (Ashmole, 1971). Gulls also frequently feed while walking in shallow water or on land and by pecking at prey while sitting on the water. They seldom dive. Terns, on the other hand, feed mostly by surface plunging (Fig. 5.64). They do not pursue prey underwater, but rather rely on the force of the plunge to carry them deep enough to capture prey. Gulls are omnivorous. The large gulls have become serious pests to other avian species and aircraft in many areas because human garbage offers a plentiful winter food supply. Kittiwakes and terns eat mostly fish.

Sixteen species of the Alcidae have been recorded in Alaska. Fourteen of them are breeding species on the Gulf of Alaska. Alcids are the northern ecological equivalents of penguins (Spheniscidae) and diving petrels (Pelecanoididae). Most species breed in the north Pacific (Udvardy, 1963). Alcids are compact and streamlined and have short, narrow wings and webbed feet. The various species have specialized nesting habitats. Some use rock ledges, while others prefer crevices in rock; some excavate burrows in soil, while others nest directly on the ground. Alcids always nest within flying distance of the ocean. Most species are colonial nesters.

Alcids are wing-propelled diving birds. They feed by pursuit diving (Fig. 5.64); they dive from the surface and actively pursue prey underwater. Some species feed on the bottom.

The alcids which breed in the Gulf of Alaska can be placed in four groups (Bédard, 1969). The first group consists of the large, fish-eating species: the Common (Uris aalge) and Thick-billed (U. lomvia) Murres, and the Pigeon Guillemot (Cepphus columba). Murres nest in dense colonies on cliffs while guillemots nest in more dispersed colonies or as isolated pairs in natural crevices, usually in rock.

The second group consists of the small, fish-eating species: the Marbled (Brachyramphus marmoratus), Kittlitz's (B. brevirostris), and Ancient (Synthliboramphus antiquus) Murrelets. The species of Brachyramphus nest in a variety of habitats including mountains above timberline on the bare ground and in trees. Although both species are common or abundant, few nests have ever been found. The Ancient Murrelet is nocturnal, and the young leave the burrow within two days of hatching.

The third group consists of the small, plankton-eating species: Cassin's (Ptychoramphus aleuticus), Parakeet (Cyclorrhynchus psittacula), Crested (Aethia cristatella), Least (A. pusilla), and Whiskered (A. pygmaea) Auklets. Cassin's Auklet nests in burrows, but the others nest in natural cavities and crevices.

The fourth group consists of the puffins, which eat mainly fish and squid: the Rhinoceros Auklet (Cerorhinca monocerata), and the Horned (Fratercula corniculata) and Tufted (Lunda cirrhata) Puffins. Although called an auklet, the Rhinoceros Auklet is structurally and behaviorally a puffin. Puffins are colonial and nest in burrows or crevices. The Rhinoceros Auklet enters and leaves its burrow only at night, while the other two species are active throughout the day.

The second category of Alaskan marine birds, those that occupy freshwater habitats during the breeding season but feed in marine waters at other times, can be subdivided into four groups:

1. Those that spend all or most of the nonbreeding season on coastal waters. These include members of the Gaviidae (loons), the Podicipedidae (grebes), the Anseridae (waterfowl), and the Phalaropodidae (phalaropes).
2. Those that feed mainly by wading. These include members of the Ardeidae (herons) and the Gruidae (cranes). Herons and cranes are rare on Kodiak and will not be considered further. This group also includes the Scolopacidae (sandpipers and allies), the Charadriidae (plovers), and the Haematopodidae (oystercatchers).
3. The Belted Kingfisher (Megaceryle alcyon), a member of the Alcedinidae. This fish-eating species is common throughout much of Alaska including marine coasts where it feeds on fish and possibly intertidal invertebrates. It is only peripherally a member of the marine ecosystem and will not be considered further.

Four species of loons and two species of grebes are found regularly in the Gulf of Alaska. They nest on inland waters and spend their winters in ice-free regions, mostly on marine coasts. An unknown fraction of Alaskan populations leaves the state for the winter. Loons and grebes are highly adapted for an aquatic existence and are almost helpless on land. They seldom fly except in migration; they dive when disturbed by predators or man. They are fish-eating, foot-propelled diving birds.

Three species of swans, seven species of geese, fifteen species of dabbling ducks, seven species of diving ducks, twelve species of sea ducks, one species of stiff-tailed duck, and four species of mergansers are known from Alaska. Almost all the waterfowl species make use of coastal environments, especially during migration and in winter. Swans, geese (with the exception of the Brant, Branta bernicla, and the Emperor Goose, Philacte canagica), and dabbling and stiff-tailed ducks make extensive use of coastal wetlands, estuaries, and bays. These often roost on open water but seldom feed there. On the other hand the Brant, the Emperor Goose, diving/sea ducks, and mergansers rely extensively on marine waters during the winter. The distribution of Brant during the nonbreeding season is highly correlated with the distribution of eelgrass (Zostera marina), its major food at that season (Bellrose, 1976). The majority of the Alaskan breeding population of Brant winters south of the state (Palmer, 1976). Up to 20 percent of the Alaskan breeding population of Emperor Geese may winter in Kodiak coastal waters (Palmer, 1976). They feed on eelgrass and a variety of algae and intertidal invertebrates (Bellrose, 1976: Palmer, 1976; Eisenhauer and Kirkpatrick, 1977).

One species of diving duck, eleven species of sea ducks, and two species of mergansers are common or abundant wintering species on Kodiak waters. One of the sea ducks, the Common Eider, Somateria mollissima, is also a common coastal breeding species. Common Eiders incubate their eggs without feeding, and mother and ducklings enter the sea soon after the young hatch. Diving ducks eat a considerable amount of plant material inland during the breeding season, but all of the ducks mentioned here rely on animal food during the winter. Diving and sea ducks feed on the bottom (Fig. 5.64), where they eat a variety of invertebrates. These species undergo an annual simultaneous molt of the wing feathers that leaves them flightless for three to five weeks (Weller, 1976). Details of the diet of Kodiak area ducks are discussed later.

The large numbers of breeding or staging shorebirds that are found in other areas of Alaska do not occur on the Kodiak Archipelago, possibly because of its mostly rocky coastline and location west of the major shorebird migratory pathways (see Gill et al., 1979). Probably the most important species are the Black Oystercatcher (Haematopus bachmani), which is a common permanent resident of rocky coasts on the Gulf of Alaska, the Rock Sandpiper (Calidris ptilocnemis), which commonly winters on Kodiak's rocky shores, and the Northern (Phalaropus lobatus) and Red (P. fulicarius) Phalaropes, which are found during migration in large flocks in Kodiak waters. Oystercatchers feed in rocky habitats on molluscs, mainly mussels (Mytilus) and limpets (Acmaea), which they stab or jab off rocks (Hartwick, 1976). Rock Sandpipers frequently feed on wave-washed rocks. Their diet is poorly known but probably consists of small gastropods and crustaceans. The two common Alaskan phalaropes spend most of their migration and winter on open water. Red Phalaropes tend to stay further offshore than do Northern Phalaropes. They feed by surface seizing (Fig. 5.64) of small invertebrates.

The third category of birds which use Alaskan marine habitats, the terrestrial birds which forage on the coast, includes raptors and songbirds.

The most important raptors along the Kodiak coast are the Bald Eagle, Haliaeetus leucocephalus, and the Peregrine Falcon, Falco peregrinus. These species are of special concern because their populations in other areas of North America are endangered. The coastal population along the Gulf of Alaska, however, appears not to have suffered the losses observed elsewhere (Hamerstrom et al., 1975; Cade, 1975). Along the Gulf of Alaska Bald Eagles nest in trees, on cliffs, and occasionally on the ground (Gabrielson and Lincoln, 1959; Troyer and Hensel, 1965). Bald Eagles eat a variety of food, including birds, fish, and carrion. During the salmon spawning season, they join with gulls, Ravens (Corvus corax), and bears in feeding on the remains of spawned-out salmon (Gabrielson and Lincoln, 1959). Peregrine Falcons usually nest on high and inaccessible ledges. They feed mainly on birds (White et al., 1973; Ainley and Sanger, 1979), which they capture on the wing. They have been observed feeding on storm-petrels far at sea (Craddock and Carlson, 1970).

Several species of passerine birds feed on beaches and in the intertidal zone. Most conspicuous of these are the Raven and the Northwestern Crow (C. caurinus), both of which feed on invertebrates and carrion. Ravens also prey on eggs and young at seabird colonies. Winter Wrens (Troglodytes troglodytes) in Alaska west of Prince William Sound are found only along marine coasts. They build their nests in crevices and crannies in cliffs and talus slopes along the shore. They forage on the beach and eat amphipods (beach fleas), insects, and other small invertebrates. Water Pipits (Anthus spinoletta) and Song Sparrows (Melospiza melodia) also forage frequently in intertidal areas.

5.7.3 Distribution and habitat usage by Kodiak birds

Pelagic distribution

Information on the distribution of marine birds on the waters in the Kodiak area is available from a series of aerial and shipboard transects for the Gulf of Alaska (Lensink and Bartonek, 1976; Lensink et al., 1976; Gould, 1977; Harrison, 1977; Wiens et al., 1978b) and a more intensive survey along the south and east coast of Kodiak during 1977 (Gould et al., 1978).

The results of the general Gulf of Alaska surveys are shown according to season for all birds in Fig. 5.65 and by month for several bird groups in Table 5.43. While coverage is spatially and temporally spotty, it appears that areas with bird densities of at least 50 birds/km^2 can be found in the Kodiak area throughout the year. These data show that no area stands out as being consistently more important to birds than any other area. Shearwaters are clearly the most abundant birds from May through September (Table 5.43). In October, shearwaters and Northern Fulmars were the most abundant species. In January and March, alcids, mainly murres, were most abundant.

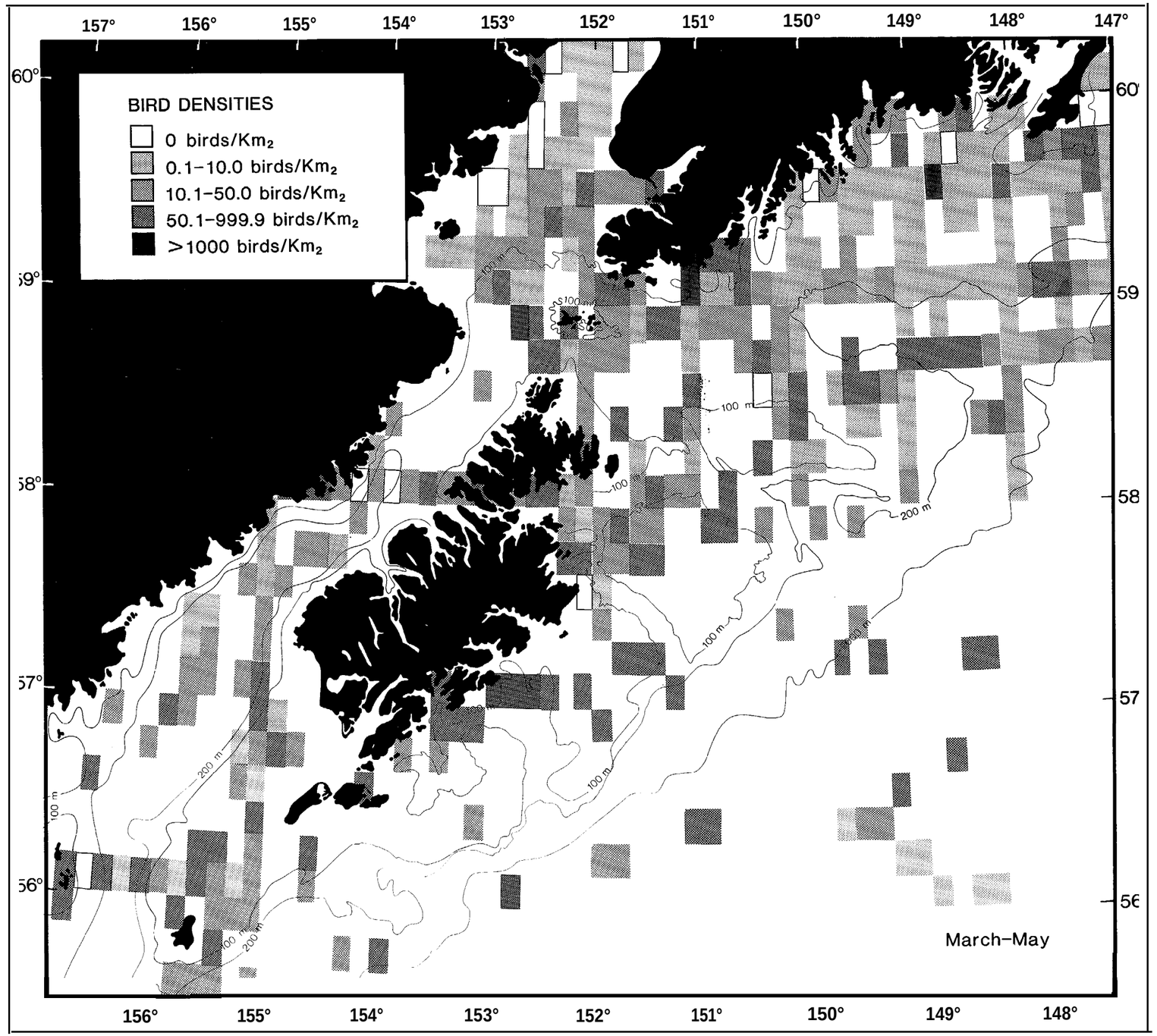
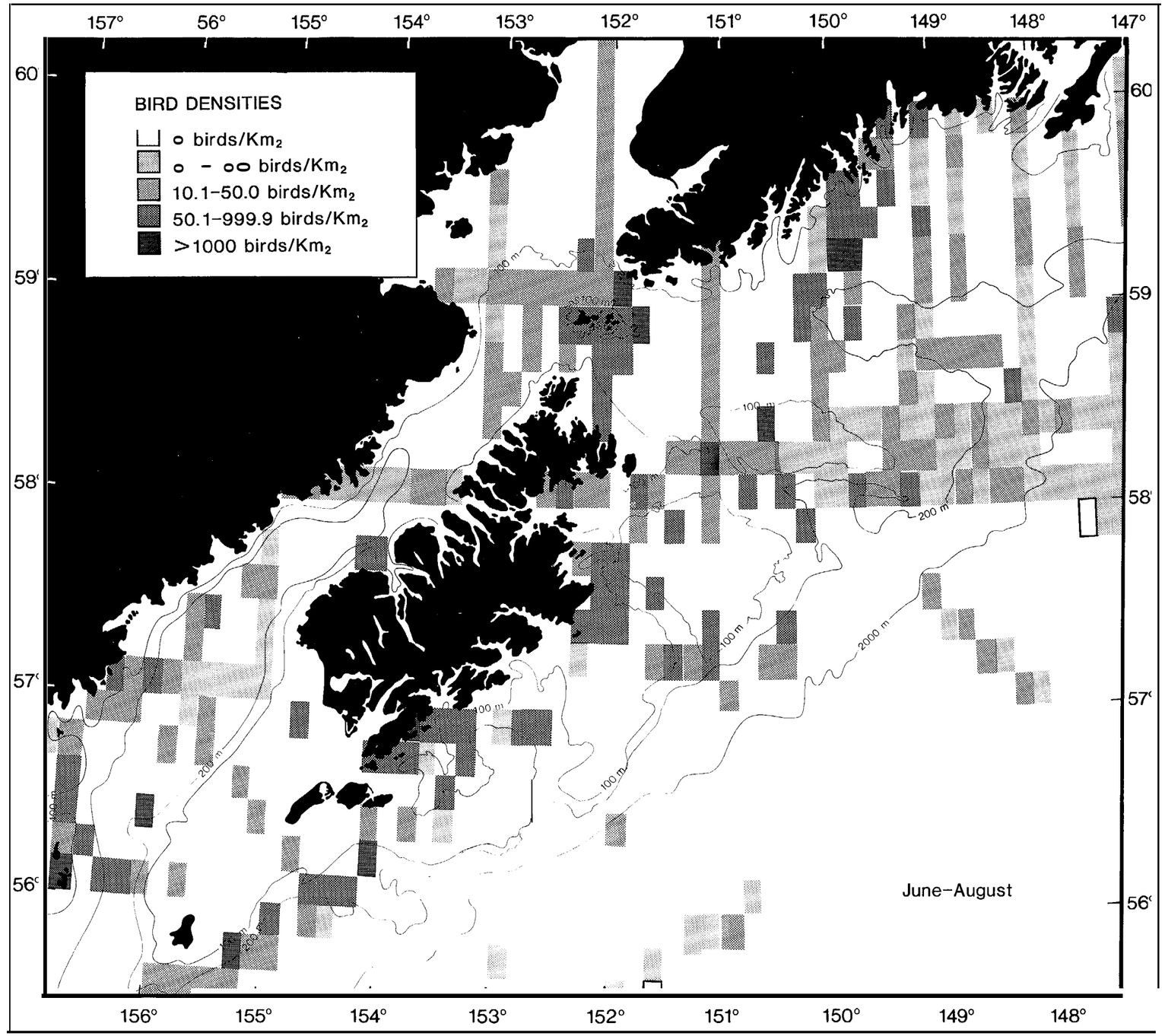


Figure 5.65 Seasonal distribution of pelagic birds from a combination of shipboard and aerial survey data from 1975 to 1977. See text for data sources.



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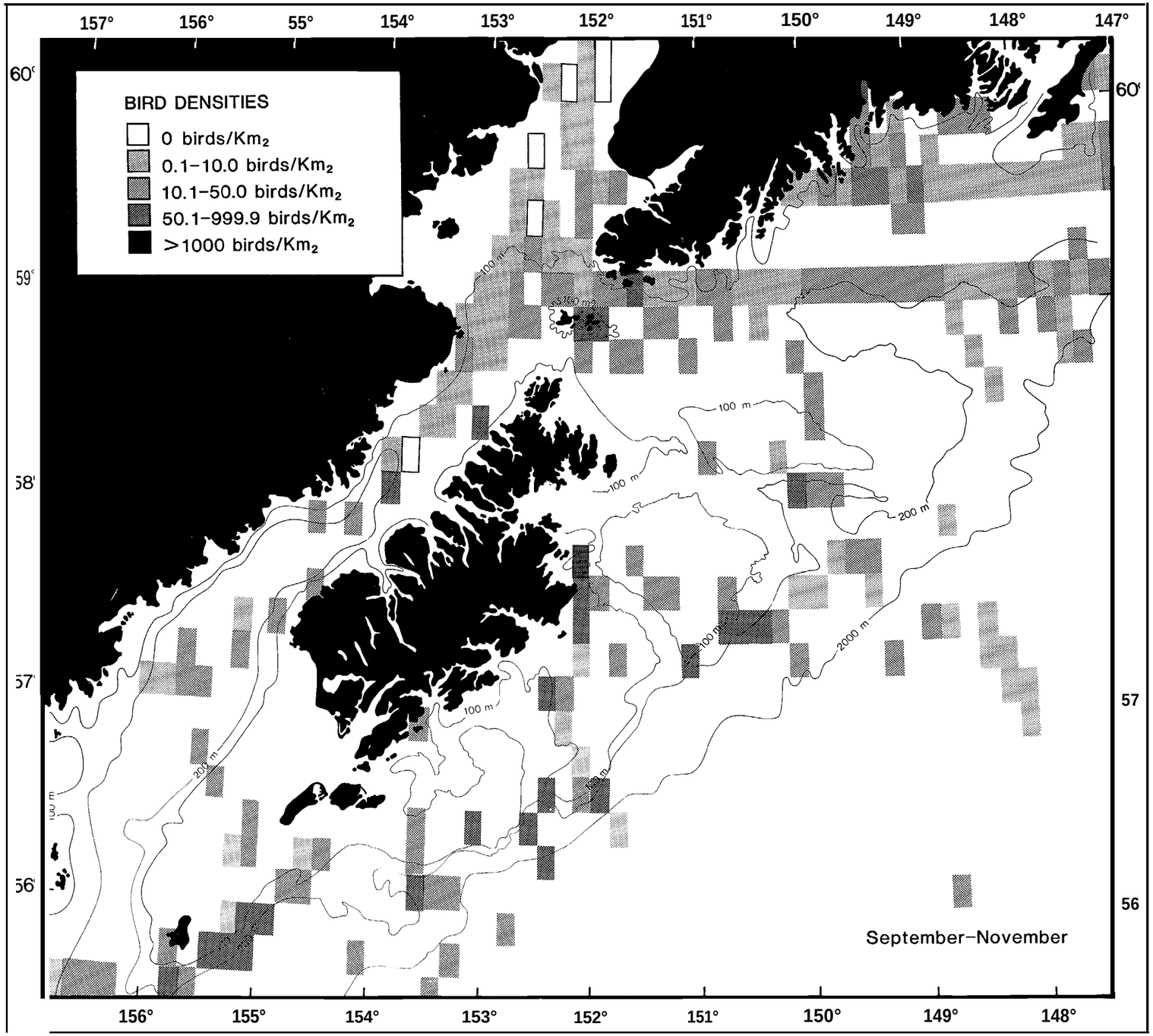

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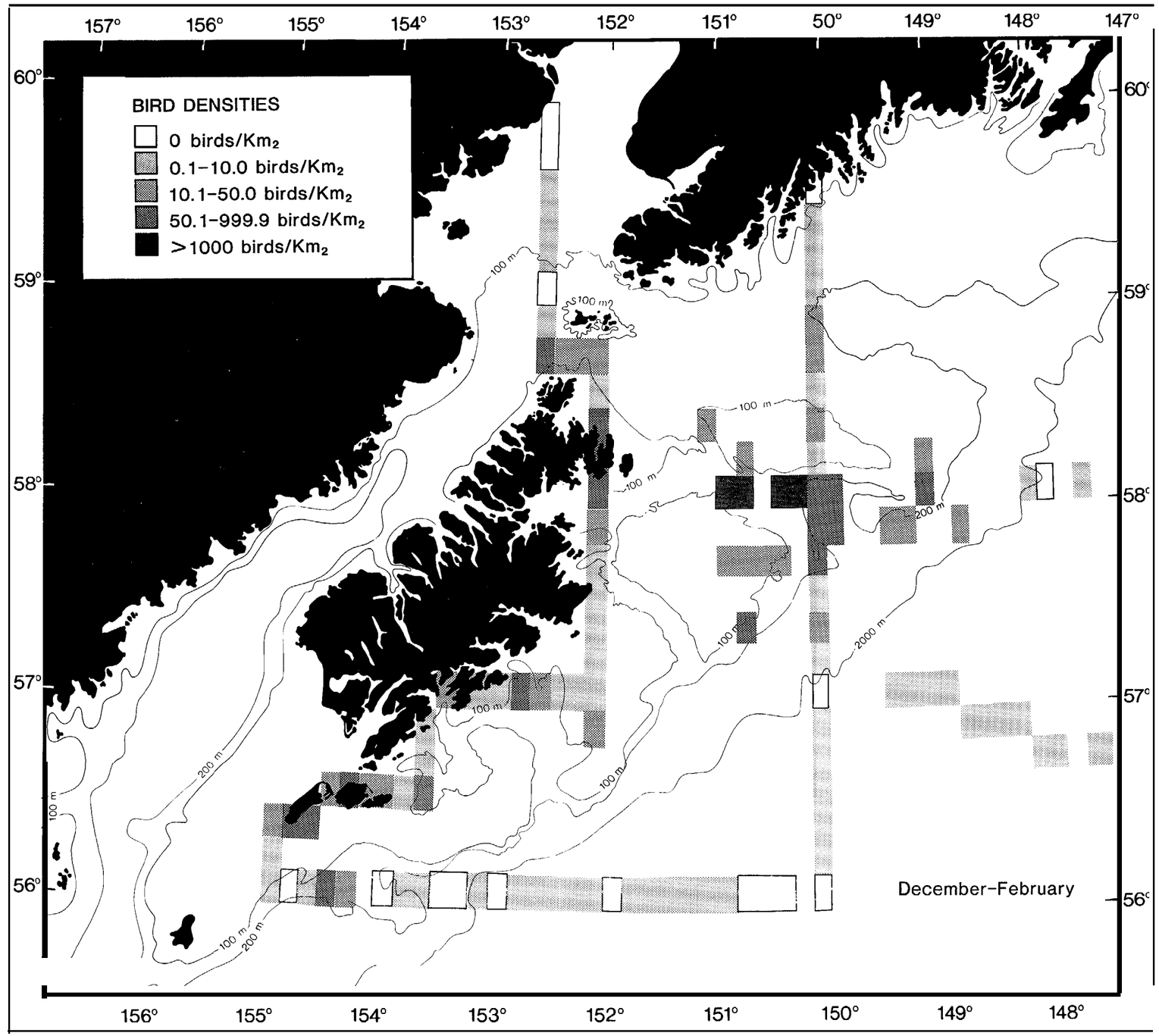


Figure 5.65 continued

Table 5.43 Relative abundance of marine birds from combined shipboard and aerial pelagic transects, 1975-1977 (data from several sources, see text).

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ott	Nov
Loon	t	0	0	0	0	0	t	0	0	t	t
Albatross	0	0	+	0	+	t	+	t	+	+	+
Northern Fulmar	+	+	+	+	+	++	+	+	+	++	++
Shearwater	t	0	+	+	++++	++++	+++	+++	+++	+1-	+
Storm-Petrel	0	+	+	+	+	+	+	+	+	+	+
Unidentified tubenose	0	0	0	+	0	+	+	0	0	+	0
Cormorant	t	+	+	0	+	+	+	t	t	+	0
Dabbling duck	0	0	0	0	0	0	0	0	t	0	0
Diving duck	+	0	+	0	+	0	0	0	0	+	t
Bald Eagle	t	0	0	0	0	0	0	0	0	0	0
Phalarope	0	0	0	0	+	+	+	0	0	t	0
Other shorebird	0	0	0	+	1-	0	0	t	t	0	+
Skua/jaeger	0	0	0	0	+	+	+	t	t	+	+
Glaucous-winged Gull	+	+	+	+	+	+	+	t	t	+	+
Black-legged Kittiwake	+	+	+	+	++	+	+	+	t	+	+
Other gull	+	+	+	+	+	+	+	+	t	0	+
Tern	0	0	0	+	+	+	+	+	+	0	0
Murre	++	+	++	+	++	+	+	+	+	+	+
Guillemot	++	0	0	0	+	+	+	t	0	0	t
Murrelet/auklet	t	0	+	0	+	+	+	+	+	+	+
Puffin	+	+	+	t	+	+	++	+	+	+	+
Unidentified alcid	+	+	+	0	+	+	+	+	+	+	+
Passerine bird	0	0	0	+	+	0	0	0	0	t	0
Unidentified bird	t	0	+	+	+	+	0	+	0	0	+

0 = no birds, t = <1 bird/km^2, + = 1-9 birds/km^2, ++ = 10-29 birds/km^2, +++ = 30-99 birds/km^2, ++++ = 100 + birds/km^2.

Maps are not yet available for the data from the intensive survey around Kodiak. Table 5.44 summarizes the seasonal occurrence and abundance of 88 species of marine birds for this area (Sanger et al., 1979). Many of these species are found in the area throughout the year and over both shallow and deep waters. Some are more restricted in their spatial or temporal distribution. Albatrosses, Pink-footed (Puffinus creatopus), Flesh-footed (P. carneipes), and New Zealand (P. bulleri) Shearwaters, Scaled Petrel, Leach's Storm-Petrel, and Red-legged Kittiwakes (Rissa brevirostris) are rare in Kodiak waters and were found only over shelf and oceanic waters. Dabbling and diving ducks were found mainly on bays and estuarine waters. There were no records for any of the shearwaters or petrels (except the Northern Fulmar) storm-petrels, phalaropes, jaegers, or terns in the winter. Cormorants were found only on bays and estuarine waters during the winter.

Table 5.44 Seasonal occurrence and abundance (order of magnitude)[a] of marine birds over Kodiak Island waters (Sanger, Gould, Baird, and Krasnow, 1979).

Family	Species	Bay and estuarine waters				Shelf and oceanic waters[b]			
		Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Gaviidae	Common Loon	1[c]	?	?	1	1	1	1	-
	Yellow-billed Loon	-	-	-	-	1	-	1	-
	Arctic Loon	1	-	?	1	-	-	1	
	Red-throated Loon	1	1	1	1	-	-	-	
Podicipedidae	Red-necked Grebe	1	-	-	1	-	-	-	
	Horned Grebe	-	-	?	2	1	-	-	
Diomedeidae	Black-footed Albatross	-	-	-	-	2	3	2	
	Laysan Albatross	-	-	-	-	2	2	2	
Procellariidae	Northern Fulmar	2	2	2	-	4	4	4	4
	Pink-footed Shearwater	-	-	-	-	1	-	-	
	Flesh-footed Shearwater	-	-	-	-	1	1	-	
	New Zealand Shearwater	-	-	-	-	1	1	-	-
	Sooty Shearwater	2	3	3	-	5	5	5	
	Short-tailed Shearwater	2	3	3	-	6	5	5	-
	Manx Shearwater	-	1	-	-	-	1	-	
Hydrobatidae	Scaled Petrel	-	-	-	-	2	3	3	
	Fork-tailed Storm-Petrel	-	2	2	-	4	4	4	
	Leach's Storm-Petrel	-	-	-	-	3	3	3	-
Phalacrocoracidae	Double-crested Cormorant	2	1	1	2	1	1	?	
	Pelagic Cormorant	2	2	2	3	1	1	1	
	Red-faced Cormorant	2	2	2	3	1	1	1	
Anatidae	Whistling Swan	1	-	-	1	-	-	-	
	Canada Goose	?	-	1	-	1	1	-	
	White-fronted Goose	1	-	1	-	-	-	-	
	Black Brant	2	-	-	-	4	-	-	
	Emperor Goose	2	-	-	2	-	-	-	
	Mallard	3	-	-	3	1	-	-	
	Gadwall	2	-	-	2	-	-	-	
	Pintail	3	1	1	2	-	-	1	
	Green-winged Teal	1	1	1	2	-	-	-	
	Blue-winged Teal	1	1	-	-	-	-	-	
Anatidae	American Wigeon	2	?	?	2	-	-	-	—
	European Wigeon	1	-	1	-	-	-	-	
	Northern Shoveler	1	-	1	1	-	-	1	
	Redhead	-	-	-	1	-	-	-	
	Canvasback	1	-	?	1	-	-	-	
	Ring-necked Duck	1	-	-	1	-	-	-	
	Tufted Duck	-	-	-	?	-	-	-	
	Greater Scaup	2	?	?	2	-	-	-	
	Lesser Scaup	1	-	-	1	-	-	-	
	Common Goldeneye	3	?	2	2	-	-	1	
	Barrow's Goldeneye	1	?	?	1	-	-	-	
	Bufflehead	1	-	2	2	-	-	-	
	Oldsquaw	3	-	-	4	2	-	-	2
Anatidae	Harlequin Duck	2	2	2	2	1	1	1	-
	Steller's Eider	2	-	2	3	1	-	-	1
	Common Eider	2	2	2	3	2	-	-	1
	King Eider	2	-	-	3	1	-	-	1
	Spectacled Eider	-	-	-	1	-	-	-	-
	White-winged Scoter	3	1	2	3	1	2	1	-
	Surf Scoter	2	1	1	2	-	-	1	1
	Common Scoter	3	1	1	3	1	1	-	1
	Smew	1	-	-	?	-	-	-	-
	Common Merganser	1	?	?	1	-	1	-	
	Red-breasted Merganser	1	1	1	1	-	1	-	
Phalaropodidae	Red Phalarope	1	-	-	-	1	1	1	
	Northern Phalarope	1	1	1	-	3	3	3	
Stercorariidae	Pomarine Jaeger	2	2	2	-	3	3	3	
	Parasitic Jaeger	2	2	2	-	2	2	2	
	Long-tailed Jaeger	1	1	?	-	1	1	-	
	Skua	-	1	-	-	1	1	-	-
Laridae	Glaucous Gull	1	1	1	1	1	1	-	1
	Glaucous-winged Gull	3	3	3	3	3	3	3	3
	Slaty-backed Gull	-	-	1	-	-	-	-	1
	Herring Gull	1	1	1	1	1	1	1	1
	Thayer's Gull	-	-	-	?	-	-	1	-
	Ring-billed Gull	-	-	-	-	1	-	-	
	Franklin's Gull	-	-	-	-	-	1	-	
	Bonaparte's Gull	-	1	-	-	-	-	-	
	Mew Gull	3	3	3	3	1	1	1	
	Sabine's Gull	-	1	?	-	-	1	1	
	Black-legged Kittiwake	4	4	4	2	4	4	4	5
	Red-legged Kittiwake	-	-	-	-	1	1	1	1
	Arctic Tern	3	3	3	-	3	3	3	-
	Aleutian Tern	2	2	-	-	2	2	-	-
Alcidae	Common Murre	3	3	3	4	4	4	4	5
	Thick-billed Murre	1	1	1	1	1	1	1	1
	Pigeon Guillemot	3	3	3	3	3	3	3	-
	Marbled Murrelet	3	3	3	3	4	4	4	
	Kittlitz's Murrelet	1	1	1	-	1	1	1	
	Ancient Murrelet	1	1	1	1	2	3	-	
	Cassin's Auklet	3	2	2	?	3	4	4	?
	Parakeet Auklet	-	1	-	-	3	2	2	
	Crested Auklet	-	-	3	4	2	1	2	3
	Least Auklet	-	-	-	?	1	1	-	?
	Rhinoceros Auklet	-	2	2	?	2	2	2	2
	Horned Puffin	3	3	3	1	3	3	4	1
	Tufted Puffin	4	4	4	1	5	4	5	5

[a]Magnitude of abundance based on a bay area of 2,857 km^2 and a shelf/oceanic area of 58,825 km^2

[b]Winter surveys of the shelf/oceanic area are few and in most cases the data are not as reliable as those for other areas and seasons.

[c]1 = probably less than 100; 2 = hundreds; 3 = thousands; 5 = hundreds of thousands; 6 = probably 1,000,000 or more

Monthly estimates of densities from the south and east coasts of Kodiak from both aerial and shipboard surveys are shown in Fig. 5.66. Aerial surveys were made from March through June. They show a peak density in May and a falling off in June. The shipboard surveys were carried out from late May through mid-September. They show an increase in densities in the bays in July, a peak in August, and a falling-off in September. On the shelf, they show an increase in densities from May through July, high levels maintained into August, and a gradual falling off in September. The overall densities reported from aerial surveys were higher in May, but lower in June than those reported for shelf waters from shipboard surveys. The aerial surveys show a sudden increase in shearwaters in Kodiak waters in May (Fig. 5.66). In spring the numbers of murres in deep waters decrease while those in shallow waters remain stable (Fig. 5.66). This may indicate

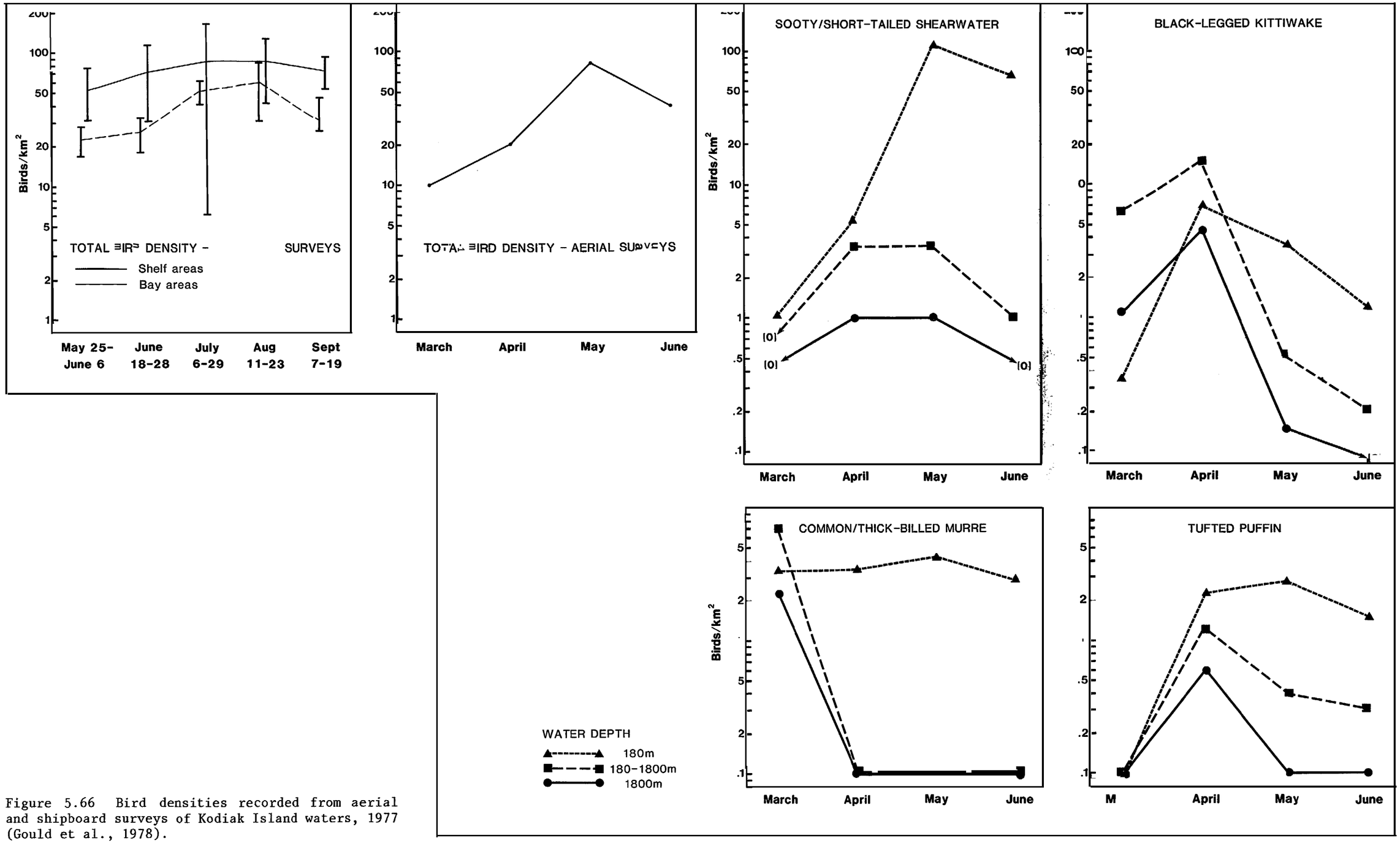


Figure 5.66 Bird densities recorded from aerial and shipboard surveys of Kodiak Island waters, 1977 (Gould et al., 1978).

that many of the murres which winter in the Kodiak area come from other breeding areas. The pattern shown in tufted puffin s ghtings is more complex. Between March and April there is a large increase in puffin numbers in all Kodiak waters, indicating that birds which winter in other areas are moving into the area. Between April and May puffins move into shallower waters though there may also be movement of some birds from Kodiak. The increase in bird densities found in bays in August may be attributed to the fledging of the year's young.

Gould et al. (1978) found no differences in density between bank and trough areas of the continental shelf, but rather an indication that the areas over the steep slopes occurring between them are mportant feeding habitat for birds The distribution of large bird flocks (Gould, U S Fish and Wildlife Service, Anchorage, pers. mm supports this suggestion (Fig 5.67).

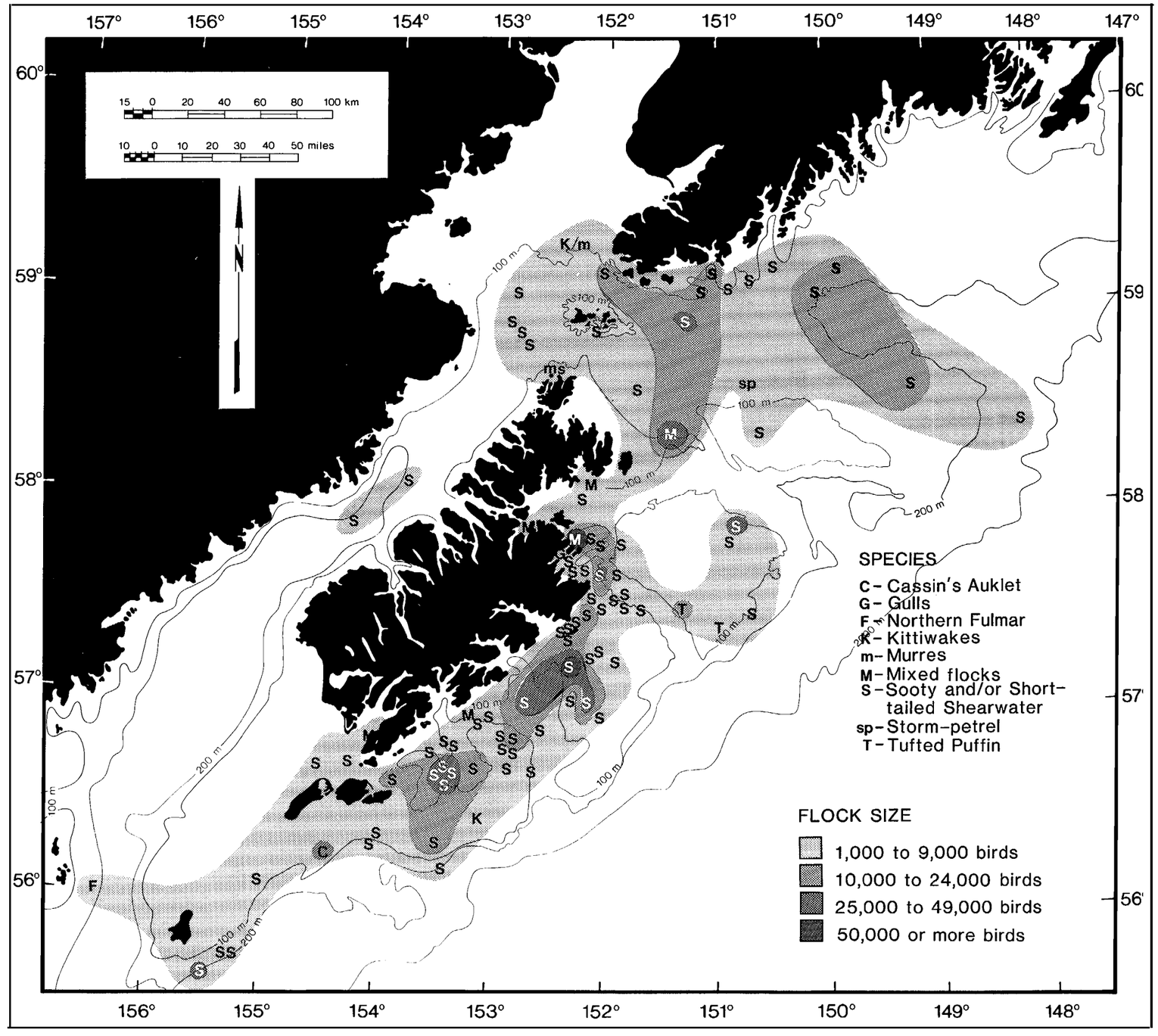


Figure 5.67 Distribution of large bird flocks in Kodiak waters (Gould, USFWS, pers. comm.).

The summer Kodiak shelf marine bird population is estimated at two million birds (Gould et al., 1978; Sanger et al., 1979). Shearwaters comprise about 84 percent of total numbers and 83 percent of the biomass of this population (Table 5.45). The three dominant breeding species (kittiwakes, murres, and puffins) thus comprise less than 20 percent of the numbers or biomass of the Kodiak spring-summer bird community.

The paucity of winter data remains a serious deficiency in our knowledge of the distribution and abundance of Gulf of Alaska birds ; surveys by BLM/USFWS in the winter of 1979-80 have not yet been analyzed.

Table 5.45 Estimated sizes and biomass levels of pelagic marine bird populations off eastern Kodiak Island[a], 26 May -19 September 1977 (Sanger et al., 1979) .

Species	$\bar{X}$ Sp wt. , g.[b]	Numbers[c] 1,000's of birds	Numbers[c] % of Total	Biomass[d] Metric Tons	Biomass[d] % of Total
Sooty Shearwaters	935	615	28.0	575	34.8
Short-tailed Shearwater	645	1,235	56.3	795	48.2
Black-legged Kittiwake	440	75	3.4	35	2.1
Common Murre	1,060	105	4.8	110	6.7
Tufted Puffin	815	165	7.5	135	8.2
		2,195		1,650	

[a]The area considered includes 2,885 km^2 of bays and fjords, from Point Banks on Shuyak I., south to the Aliulik Peninsula, plus 30,464 km^2 of shelf waters due east and south of this area, offshore to the 200 m curve, or longitude 150°W., whichever is closer to shore (total area = 33,348 km)

[b]$\bar{X}$ weights of birds sampled

[c]Average densities (birds /km^2) in study area during 1,232 10-minute transect counts x 33, 346 km^2

[d]Numbers x X weight of species

Coastal distribution

The surveys of Kodiak birds reported above include considerable information on the occurrence of birds on Kodiak bays and estuaries (see Table 5.44) during the spring and summer. Information on the winter use of Kodiak coastal marine habitats has been reported by Arneson (1977), Dick (1979), and Sanger et al. (1979). Arneson (pers. comm.) summarized the seasonal status of

Table 5.46 Relative abundance of intertidal and inshore. birds of the Kodiak Archipelago by region and seasol (Arneson, pers. comm.; Dick, 1979).

Family	Species	Geographic Region 1 Afognak W	1 s	1 F	2 Shuyak W	2 S	2 F	3 Chiniak W	3 S	3 F	4 South W	4 S	4 F	5 East W	5 S	5 F
Gaviidae	Common Loon	U	c	c	U	c	c	U	c	c	U	c	c	U	c	c
	Yellow-billed Loon	u			u			U	?	O	? U			u		
	Arctic Loon	U	c	u	U	c	u	U	c	u	U	c	u	U	c	U
	Red-throated Loon	U	u	u	U	u	c	U	u	c	u			U	u	c
Podicipedidae	Red-necked Grebe		R		U	U	R	U	U	R	U	U	R	U	U	RU
	Horned Grebe		R		C	U	R	U	C	U	R	U	U	R	U	RU
Phalacrocoracidae	Double-crested Cormorant	C	c	c	C	c	c	C	c	u	c	C	c	c	C	c
	Pelagic Cormorant	A	A	A	A	C	c	c	A	A	A	C	c	c	C	c
	Red- faced Cormorant	U	c	c	U	c	c	U	c	c	c	U	c	c	U	c
Ardeidae	Great Blue Heron	R						R								
Anatidae	Whistling Swan		R	R	R	U	u	R	U	U	U	u	u	RU		U
	Trumpeter Swan	R				R			R			R			R	
	Canada Goose		R	R		u	u	O	u	o	u	c	c		U	U
	Black Brant		U	U		c	U	?	C	O	U	C	U		C	U
	Emperor Goose	u			u			C	u	o	o	c		c		
	White-fronted Goose		R	R		u	u	O	u	o	u	U	U		U	U
	Snow Goose		R	R		R	R	O	R	O	R	R	R		R	R
	Mallard	C	C	U	C	C	u	c	C	u	c	C	u	c	C	u
	Gadwall	U	U	u	U	U	u	U	u	?	u	U	u	U	U	u
	Pintail		RC		c	R	A	R	A	C	A	R		RA		A
	Green-winged Teal	U	c	U	C	U	c	u	c	U	C	U	C	U	c	u
	Blue-winged Teal	o			O	R		O	R			O		O		
	European Wigeon	R	R		R	R	R	R	R	O	R	R	R	RR		R
	American WigeOn	U		U	U	c	u	c	U	c	u	c	U	c	u	c
	Northern Shoveler	U	U			U	U		C		u		U	U		
	Ring-necked Duck							R								
	Canvasbacks							R						R		
	Greater Scaup	u			c			A	C	U	C	u		c		
	Lesser Scaup	R						R								
	Common Goldeneye	A	C	R	C	C	R	A	C	R	C	C	R	A	C	R
	Barrow's Goldeneye	c	U	R	U	C	U	R	U	C	U	R	U	C	U	R
	Bufflehead	C	u	u	U	u	u	C	u	u	C	u	u	C	U	U
	Oldsquaw	A	C	O	C	c	o	A	C	O	C	A	O	C	A	O
	Harlequin Duck	C	c	u	C	c	u	A	C	U	C	C	U	C	A	C
	Steller's Eider	C	C	R	U	U	R	U	A	C	R	A	C	R	U	C
	Common Eider	C	c	c	U	u	u	C	c	c	C	c	c	C	C	C
	King Eider	C	C	R	U	u	R	U	C	C	R	c	R	U	C	R
	Spectacle Eider							R								
	White-winged Scoter	C	C	R	C	A	R	C	A	R	C	A	R	C	A	Rc
	Surf Scoter	C	C	R	C	C	R	C	C	R	C	C	R	C	C	R
	Black Scoter	C	C	R	C	C	R	A	C	R	C	C	R	A	C	Rc
	Sinew							R								
	Common Merganser	U	U	R	U	U	R	C	C	R	C	C	R	C	C	Rc
	Red-breasted Merganser	C	c	c	U	u	u	C	C	C	C	C	C	C	C	C
Accipitridae	Bald Eagle	C	c	u	c	c	c	u	c	c	c	U	C	C	U	C
	Golden Eagle							R								
	Marsh Hawk	O		U	U			R		U	U			U		
Falconidae	Peregrine Falcon	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	Gryfalcon							R					R			
Gruidae	Sandhi 11 Crane	O	R	O	R		R	R		R	R		R	R		R
Rallidae	American Coot				R											
Haematopodidae	Black Oystercatcher	C	c	c	C	c	c	C	c	c	U	U	U	C	C	C
Charadriidae	Semipalmated Plover	0		U	U	c	c	O	c	c	O		c		c	c
	American Golden Plover	O	U	O	R	U	O	R	O	U	O	R	O	U	O	R
	Black-bellied Plover	O	u	o	U	o	u	O	U	O	U	O	U	O	U	O
Scolopacidae	Surfbird	U	u	o	U	c	o	u	U	c	o	U	?	O	U	C
	Ruddy Turna tone	O	u	o	U	o	u	O	u	o	u	O	U	O	U	O
	Black Turnstone	U	u	u	U	u	u	U	c	u	u	U	u	u	U	u
	Common Snipe	R	C	C	R	C	C	R	C	C	C	R	C	C	R	Cc
	Whimbrel	O	R	O	R	O	R	O	U	O	R	O	R	O	R	O
	Bristle- thighed Curlew	O	R	O		O	R	O		R	O		O	R	O	
	Spotted Sandpiper	O	R	U	R	O	R	U	R	O	R	U	R	O	R	U
	Wandering Tattler	O	u	?	u	O	u	?	u	O	c	?	u	O	u	?
	Greater Yellowlegs	O	u	u	u	O	c	c	c	O	c	c	c		O	c
	Lesser Yellowlegs	O	R		u	O	R		u	O	R	?	U	O	R	U

Family	Species	Geographic Region 1 Afognak W	1 S	1 F	2 Shuyak W	2 S	2 F	3 Chiniak W	3 S	3 F	4 South W	4 S	4 F	5 East W	5 S	5 F
Scolopacidae	Rock Sandpiper	C	u	u	C	u	u	A	U	?	U	U	u	C	u	u
	Sharp-tailed Sandpiper	O	O	O	?	O	O	R	U	O	O	R	O	O	O	R
	Pectoral Sandpiper	O	?	O	?	O	u	o	O	u	o	U	O	U	O	U
	Baird's Sandpiper	O	R	O	R	O	R	O	R	O	R	O	R	O	R	O
	Least Sandpiper	O	c	c	c	O	c	c	c	O	C	A	?C	O	c	c
	Dunlin	R	U		u	R	U		u	R	U		u	R	U	
	Sanderling	O	R	O	O	O	R		o	O	R	O	O	O	R	
	Semipalmated sandpiper	O	R	O	R	O	R	O	R	O	R	O	R	OR		R
	Western Sandpiper	O	u	o	u	O	c	o	c	O	c	o	c	O	c	o
	Short-hi lled Dowitcher	O	u	u	u	O	u	u	u	o	u	u	u	O	u	u
	Long-billed Dowitcher	o	R	O	H	O	R	O	R	O	R	O	R	O	R	OR
	Bar-tailed Godwit	O	R	O	O	O	R	O	R	O	R	O	R	O	R	O
	Marbled Godwit	O	R	O	O	O	R	O	O	O	R	O	O	O	R	O
Phalaropodidae	Red Phalarope	O	u	o	u	O	u	o	u	O	u	o	u	O	U	O
	Northern Phalarope	O	u	u	u	O	c	c	c	O	c	c	c	O	U	U
Stercorariidae	Pomarine Jaeger	O	u	o	u	O	u	o	u	O	u	o	u	O	u	o
	Parasitic Jaeger	O	C	?	C	O	C	?	C	O	C	?	C	O	C	C
	Long-tailed Jaeger	O	U	?	U	O	U	?	U	O	U	?	U	O	U	U
	Skua								R							
Laridae	Glaucous Gull	U	R	O	R	U	R	O	R	U	R	O	R	U	R	O
	Glaucous-winged Gull	AA			AA	AA		AA		AA	AA		AA	AA		AA
	Herring gull	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	Thayer's Gull	R			R			R			?			R		
	Ring-billed Gull								R							
	Mew Gull	C	c	c	C	C	C	U	c	c	U	U	U	C	c	c
	Bonaparte's Gull	O	u	u	O	u	u	O	u	u	O	U	U	O	U	U
	Black- legged Kittiwake	U	C	A	C	U	C	A	C	C	C	A	C	U	C	A
	Red-legged Kittiwake													R		
	Sabine's Gull	O	u	o	u	O	u	o	u	O	u	o	u	O	U	O
	Arctic Tern	O	c	c	c	O	c	c	c	OA		AA		OA		AA
	Aleutian Tern	O	u	u	u	O	u	u	u	O	u	u	u	0	7	? ?
Alcidae	Common Murre	C	c	c	c	C	u	u	u	C	c	c	c	U	U	U
	Thick-billed Murre	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	Pigeon Guillemot	AA			AA	U	u	u	u	C	c	C	C	U	U	U
	Marbled Murrelet	C	c	c	c	U	u	u	u	C	C	C	C	U	U	U
	Kittlitz's Murrelet	?	U	u	u	?	U	u	u	?	U	u	u	?	U	u
	Ancient Murrelet	R	U	U	U	R	U	U	U	U	u	u	u	R	U	U
	Cassin's Auklet	O	u	u	u	O	u	u	u	O	u	u	u	O	u	u
	Parakeet Auklet	U	u	c	u	U	u	u	u	U	u	u	u	U	U	U
	Crested Auklet	C	u	u	u	C	u	u	u	U	U	U	U	U	U	U
	Least Auklet	?		0		?		0		?				?	O	
	Rhinoceros Auklet	?	R	R	R	?	R	R	R	?	R	R	R	?	R	R
	Horned Puffin	R	C	C	C	R	C	C	C	R	C	C	C	R	C	C
	Tufted Puffin	R	A	A	A	RA		AA		RA		AA		R	C	C
Alcedinidae	Belted Kingfisher	C	c	c	c	C	c	c	c	C	c	c	c	U	U	U
Corvidae	Black-billed Magpie	c	c	c	Cc		ccc	C	c	c	c	U	U	U	C	C
	Common Raven	c	c	c	Cc		ccc	C	c	c	c	U	u	u	C	C
	Northwestern Crow	A	A	A	AA		AA	AA		AA	AC		CCC	AA		AA
Troglodytidae	Winter Wren	c	c	c	C	c	c	c	C	c	c	?	?		C	c
Turdidae	Varied Thrush	u						u								
Motacillidae	Water Pipit	O	c	o	C	O	c	o	C	O	c	o	C	O	C	O
Fringillidae	Savannah Sparrow	O	C	A	C	O	C	A	C	O	C	A	C	O	C	AC
	Fox Spa rrow	R	C	A	C	R	C	A	C	R	C	A	C	R	C	AC
	Song Sparrow	C	c	c	C	C	c	c	C	c	c	c	C	c	c	c
	Lapland Longspur	O	R	R	R	O	R	R	R	O	R	R	R	O	R	R
	Snow Bunting	C	u	o	u	C	u	o	u	C	u	o	u	C	U	O

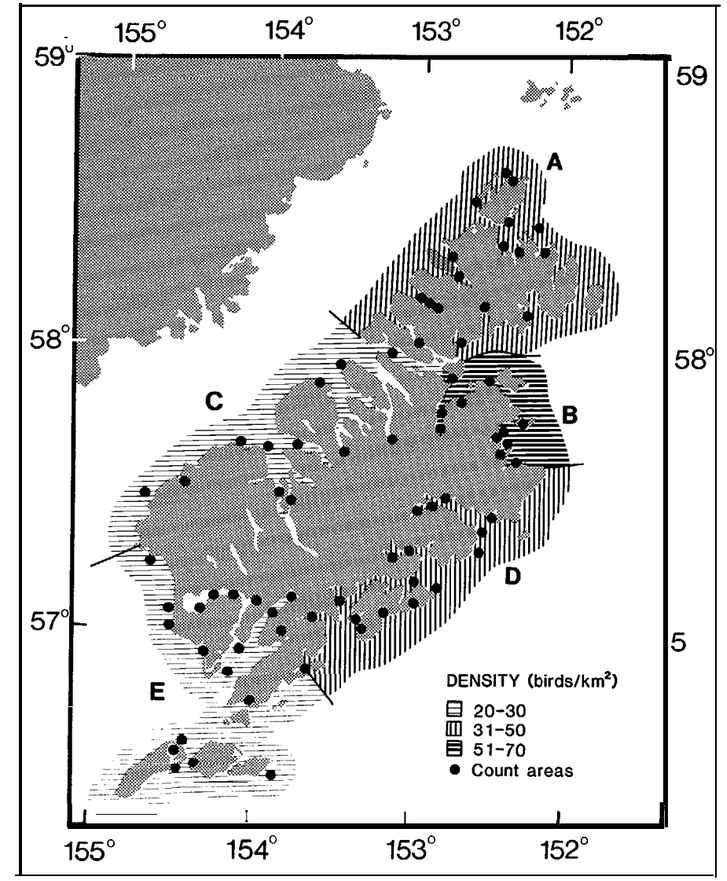
W = winter (Nov-Mar)
S = spring (Apr-Mav)
s . summer (June-July)
F = fall (Aug-Ott)

A = abundant
C = common
U . uncommon
R = rare
0 = absent
? = uncertain
blank = unknown

1 = Afognak-Shuyak: Dolphin Point to Raspberry Cape
2 = NW side: Raspberry Cape to C. Ikalik
3 = Chiniak: Dolphin Point to Cape Chiniak
4 = South side: Cape Ikalik to Cape Kaguyak (+ Trinities)
5 = SE side: Cape Chiniak to Cape Kaguyak

about 120 species in Kodiak intertidal and inshore areas (Table 5.46). In an aerial survey of Kodiak coastal birds during February and March 1976, Arneson (1977) found the highest densities of birds on the north and east coasts of the archipelago (Fig. 5.68). Ducks, especially sea ducks, were the most abundant birds. Highest densities were observed on Chiniak and Kizhuyak Bays. Counts of waterfowl in nearshore and estuarine areas conducted by Kodiak National Wildlife Refuge personnel in the period December through April are shown in Table 5.47. Since these data were collected by several observers, using different methods, and covering different areas, and since they were probably gathered under different weather conditions, they should be compared with caution. Overall, they indicate that in December and April 70 to 80 percent of all the waterfowl counted were dabbling ducks, while in January through March about 65 percent of all waterfowl counted were sea ducks.

Figure 5.68 Winter densities of Kodiak coastal birds (Arneson, ADF&G., pers. comm.).



Group of birds	A	B	C	D	E	Average
	Densities (birds/km^2)					
Loons	T*	T	T	T	T	T
Grebes	T	0	0	T	T	T
Cormorants	2	2	T	1	T	1
Swans and Geese	0	0	0	T	T	T
Dabbling Ducks	3	2	8	4	1	4
Diving Ducks	14	9	2	4	2	5
Sea Ducks	13	44	12	23	12	20
Mergansers	T	T	T	T	T	T
Raptors	T	T	T	T	T	T
Shorebirds	2	2	T	2	1	2
Gulls and Jaegers	1	4	1	1	3	2
Alcids	1	2	3	9	T	3
Corvids	2	T	T	1	T	1
other Passerines	T	0	0	0	T	T
other birds	T	0	T	T	T	T
Total Densities	40	67	28	48	20	39

* T = less than 1 bird/km^2

Table 5.47 Waterfowl counts from nearshore and estuarine areas of Kodiak Island (Sanger et al., 1979).

	Date (Mo/Yr)												
	12/66	12/72	01/66	01/72	01/73	02/66	02/72	02/75	03/66	03/77	0.$/66	04/69	04/76
Area	NW	Misc.	NE	NE	All	NW	SW	All	NW	All	NW	All	Chiniak
Miles	?	?	?	?	682	112	?	596	?	872	112	?	?
Platform	Plane	Plane	Plane	Plane	Ship	Plane	Plane	Ship	Plane	Plane	Plane	Plane	Plane
SPECIES													
Unidentified swan	42										34		+*
Emperor Goose		110		98	621		90	52		113		150	200
White-fronted Goose													+
Black Brant													200+
Mallard	1412	3298	2448	1089	700	1140	447	2556	1576	3512	4533	2864	+
Gadwall					30			75		12	2562		
Pintail		882	2		200			4				75	4500
Green-winged Teal		109								1			+
American Wigeon		371								90	550	60	200+
Northern Shoveler													12
Unidentified scaup			150		80	8		15	10	700	100		+
Common Goldeneye					146								+
Barrow's Goldeneye					24			30					+
Unidentified goldeneye	553		613	212	1142	323	86	1205	1001	5202	1772		
Bufflehead	100		99		36	62		27	30	403			+
Oldsquaw			158	8101	7863	126	1400	9410	213	1875	200		+
Harlequin	522			370	691	33		675	70	1109	8		+
Steller's Eider			200		340		10	1176		677			+
Common Eider					4512			58		108			+
King Eider								4654					
Unidentified eider		86			69			1745					
White-winged Scoter					3059			2073		1764			+
Surf Scoter					1194			327		167			+
Common Scoter					2154			1402		1691			+
Unidentified scoter		343	330	344	3192	176	65	984	282	5987	140		
Common Merganser					21			21		13			+
Red-breasted Merganser					13			34		10			+
Unidentified merganser			24		39			27		21	120		

*+ = present

Summaries of Arneson's (1977) surveys are shown in Figs 5.69 and 5.70. Figure 5.69 shows the kinds of birds found in each habitat type, whereas Fig. 5.70 shows the types of habitats each kind of bird uses. Most kinds of birds show habitat specificity. One type of bird accounted for over 50 percent of the usage of a type of habitat for 17 out of the 20 habitats. One type of habitat accounted for over 50 percent of the usages of a type of bird for 11 out of 15 types of birds. Overall, about 78 percent of the birds were found in bay water, and 4 to 5 percent were found on exposed inshore waters and lagoon waters. The remaining habitats held 2 percent or less of all the birds observed. Sea ducks accounted for 51 percent of all birds, and dabbling ducks, diving ducks, and alcids accounted for 9 to 13 percent. The remaining kinds of birds accounted for 5 percent or less of all the birds observed. Unfortunately, the relative availability of the habitat types has not been reported.

Current evidence from several sources thus indicates that during the winter, coastal Kodiak supports large populations of sea ducks.

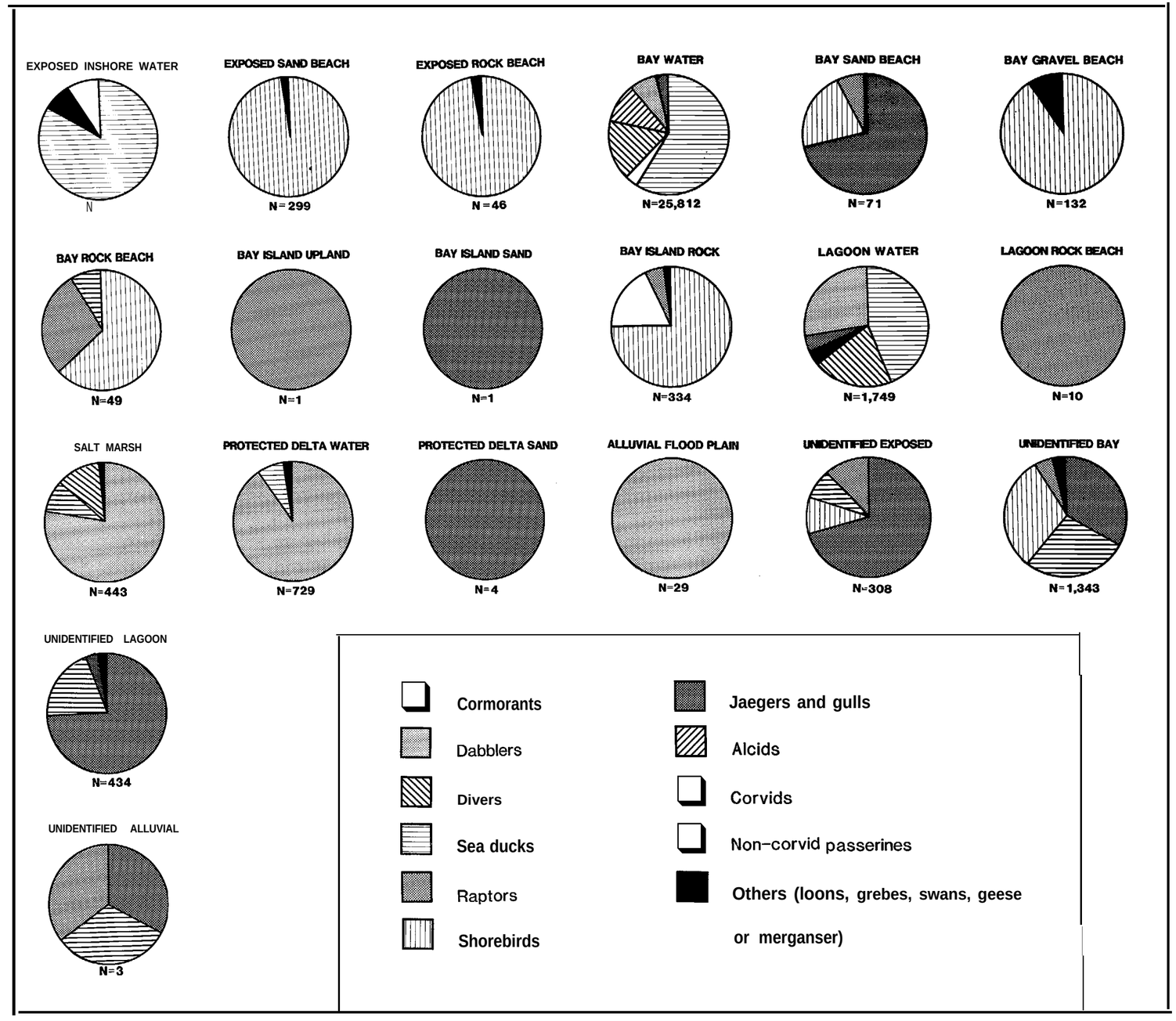


Figure 5.69 Distribution of birds among Kodiak coastal habitats, winter 1977 (Arneson, ADF&G, pers. comm.).

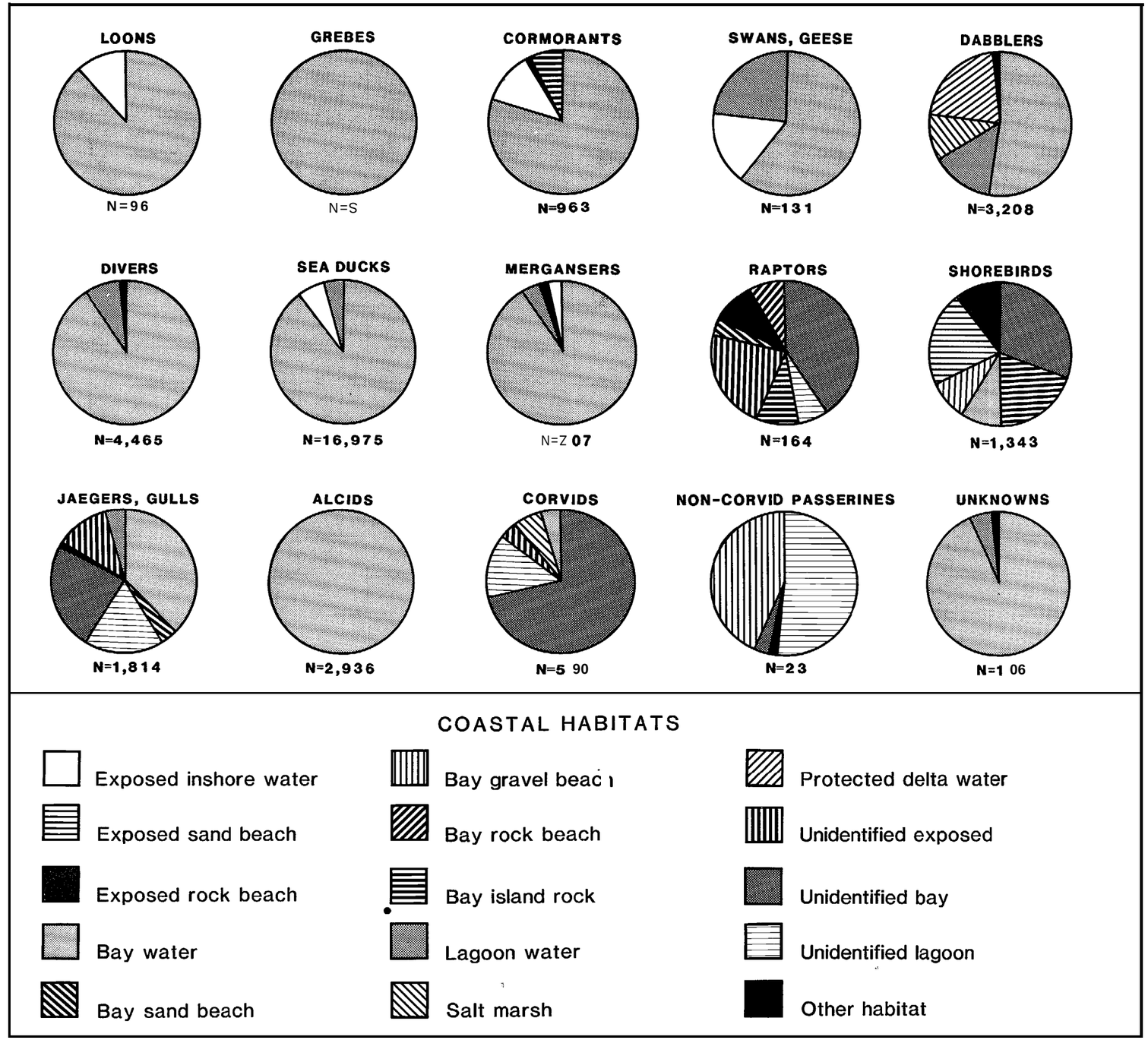


Figure 5.70 Types of Kodiak coastal habitats used by various kinds of birds, winter 1977 (Arneson, ADF&G, pers. comm.).

Kodiak bird colonies

Approximately 1.2 million birds nest in the colonies of the Kodiak area (Table 5.48; Sowls et al., 1978). Of these, about 650,000 (56 percent) nest on the Barren Islands, 380,000 (32 percent) on the Kodiak Archipelago, and 140,000 (12 percent) on the north shore of Shelikof Strait. The most abundant species are the Fork-tailed Storm-Petrel (26 percent), Black-legged Kittiwake (12 percent), and Tufted Puffin (37 percent). Murres, of which about 99 percent are Common Murres, represent 16 percent of the total number of birds. The distribution of these colonies is shown in Fig. 5.71. The distribution of the colonies of 12 species of marine birds in the Gulf of Alaska is shown in Fig. 5.72.

Of the species surveyed, about 50 percent or more of the Gulf of Alaska populations of Fork-tailed Storm-Petrel, Mew Gull, Arctic Tern, Aleutian Tern, and Common Murre breed in the Kodiak area. One of the two known major colonies of Fork-tailed Storm-Petrel in the gulf is located on the Barren Islands (Fig. 5.72a). However, since the species is active at its colonies only at night, and nests in talus, many colonies probably remain undetected. Most of the larger colonies of Mew Gulls in the Gulf are on Kodiak (Fig. 5.72e.). The centers of abundance for breeding Arctic Terns in the Gulf are on Kodiak and in Prince William Sound (Fig. 5.72g). Known breeding colonies of Aleutian Terns are found in the Gulf only on Dry and Icy Bays and the Kodiak Archipelago (Fig. 5.72h). The major colonies of Common Murres on the Gulf are found on the Shumagin Islands, Mitrofania Island, Semidi Island, north shore of Shelikof Strait, Barren Islands, on Chisik Island in Cook Inlet, and on Barwell Island just off Resurrection Peninsula (Fig. 5.72i).

Table 5.48 Estimates of breeding populations at Kodiak area bird colonies (Sowls et al., 1978).

Species	REGION* A	B	C	D	E	F	G	Total	Total GOA
Northern Fulmar	20							**20**	474,560
Fork-tailed Storm-Petrel	300,000				X**			**300,000**	607,000
Leach's Storm-Petrel					X			**x**	889,400
Double-crested Cormorant	**X**	163		42		7	30	**242**	2,942
Pelagic Cormorant	**X**	1,350	366	1,955		369	x	**4,040**	15,389
Red-faced Cormorant	**40**	663	110	985		1,573	935	**4,306**	19,878
Cormorant (sp.)	**1,450**	2,291	427	591	677	2,716	5,505	**13,657**	
Harlequin Duck	P***	194	37			25	13	**269**	1,141
Common Eider		78		46			x	**124**	1,143
Bald Eagle	17	4	6		6	19	3	**55**	205
Peregrine Falcon	2				2			**4**	30
Black Oystercatcher	P	312	93	45	19	2	6	**477**	1,202
Glaucous-winged Gull	5,170	9,324	13,390	4,114	4,570	2,855	8,350	**47,773**	171,485
Mew Gull		430	345	452	220	50		**1,497**	3,121
Black-legged Kittiwake	***33,800***	4,951	**9,500**	27,547	3,080	62,202	1,750	**142,830**	944,570
Arctic Tern		441	80	709	1,760	2>830		**5,820**	**10,776**
Aleutian Tern		40		388	50	300		**778**	1,128
Common Murre	91,000	240		1,780	x		x	**93,030**	201,702
Thick-billed Murre	x	300					x	**300**	1.547
Murre (sp.)						510	92,800	**93,310**	
Pigeon Guillemot	194	***903***	156	512	42	307	137	**2,251**	26,999
Ancient Murrelet	302							**302**	105,802
Parakeet Auklet	910	***479***		60		150		**1,599**	88,673
Rhinoceros Auklet	1,000							**1,000**	112,588
Horned Puffin	12,700	496	650	737	2	850	6,657	**22,093**	594,359
Tufted Puffin	204,600	15,750	32,502	91,462	31,350	36,333	23,092	**435,089**	1,222,224
Totals	651,219	38,413	***57,662***	131,425	41,778	111,098	139,278	1,170,866	5,497,864

*A = Barren Islands; B = Afognak-Shuyak: Dolphin Point to Raspberry Cape; C = NW Kodiak: Raspberry Cape to Ayakulik; D = Chiniak: Dolphin Point to Cape Chiniak; E = S Kodiak: Ayakulik to Cape Kaguyak, including the Trinity Islands; F = SE Kodiak: Cape Chiniak to Cape Kaguyak; G = North shore of Shelikof Strait.

**X = Present; ***P = Probably present

More than 25 percent of the Gulf's breeding populations of Pelagic Cormorants, Bald Eagles, Black Oystercatchers, Glaucous-winged Gulls and Tufted Puffins are found in the Kodiak area. Since Bald Eagles and Black Oystercatchers do not nest in colonies and are difficult to detect by the methods used by Sowls et al. (1978), the results reported may not reflect their actual distribution and abundance. Pelagic Cormorants (Fig. 5.72b), Glaucous-winged Gulls (Fig. 5.72d), and Tufted Puffins (Fig. 5.721) are widely distributed throughout the Gulf of Alaska.

Black-legged Kittiwakes are among the dominant breeding species of the Kodiak area. Though their colonies on the Shumagin Islands are numerous, those on the Semidi Islands and Middleton Island are equally or more numerous.

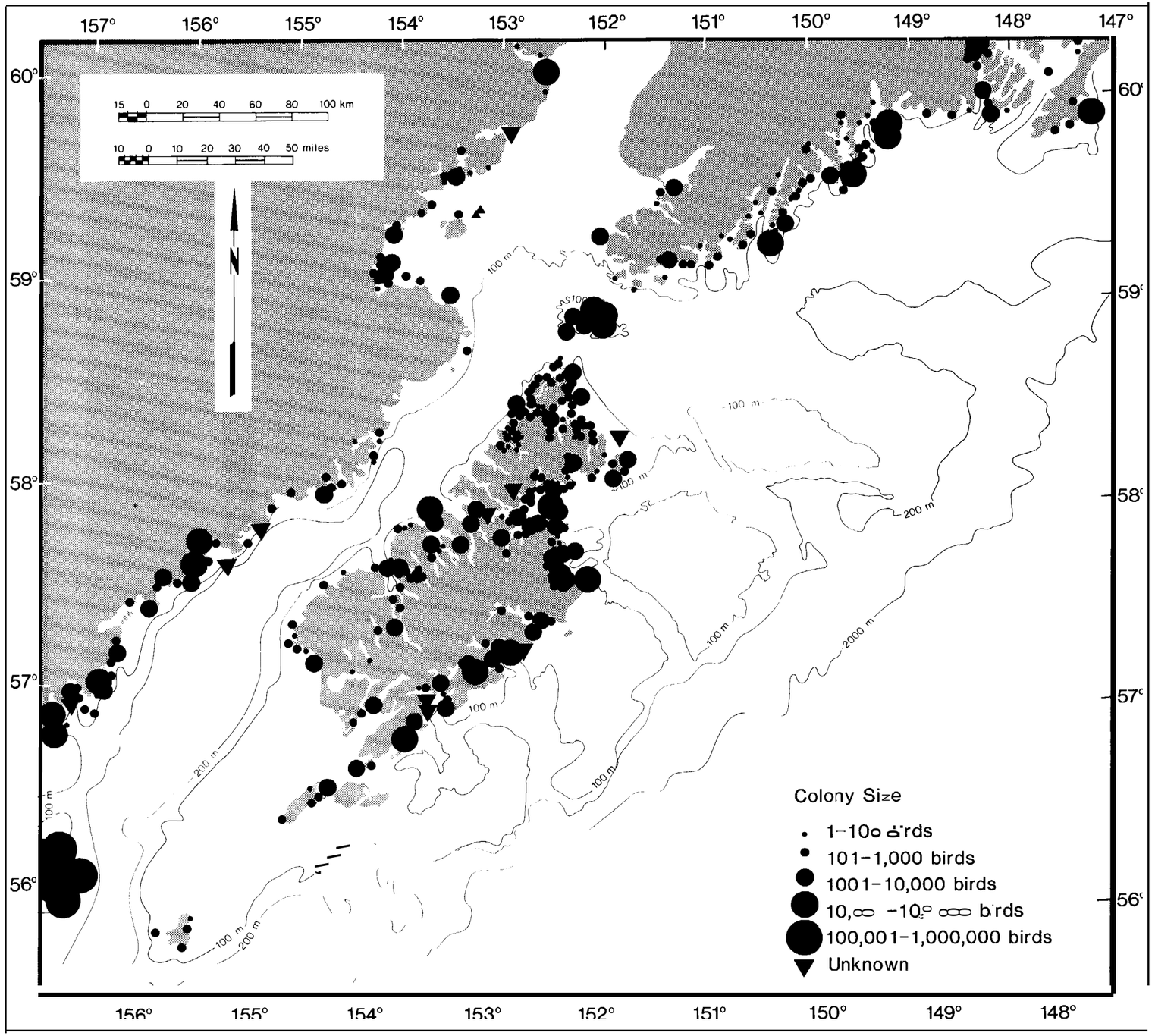


Figure 5.71 Distribution of bird colonies in the Kodiak area (Sowls et al., 1978).

Figure 5.72a-l Gulf of Alaska distributions of colonies of representative species of marine birds (Sowls et al., 1978).

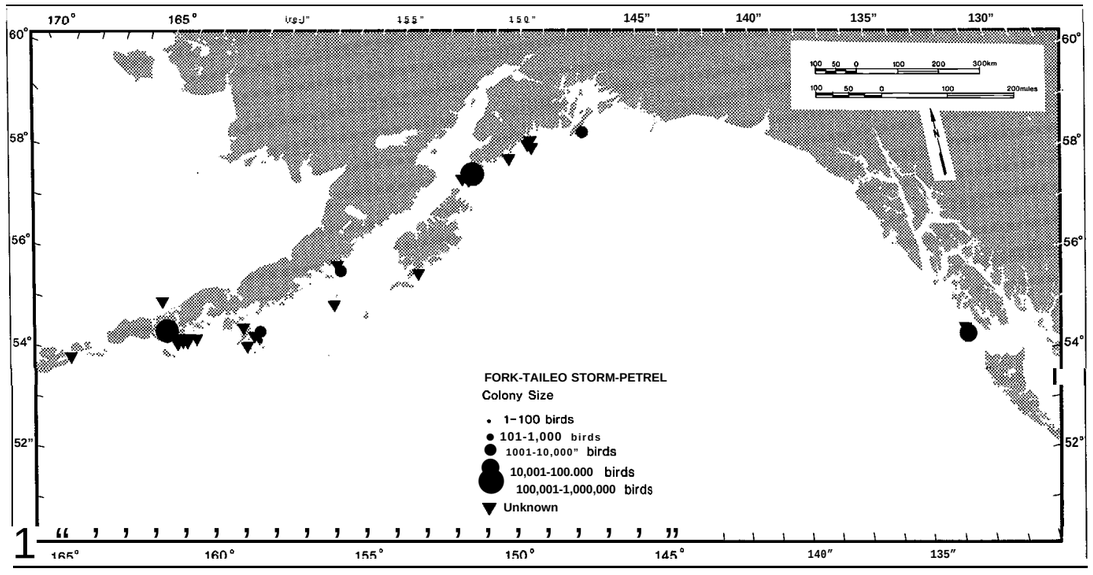


Figure 5.72a Fork-tailed Storm-Petrel

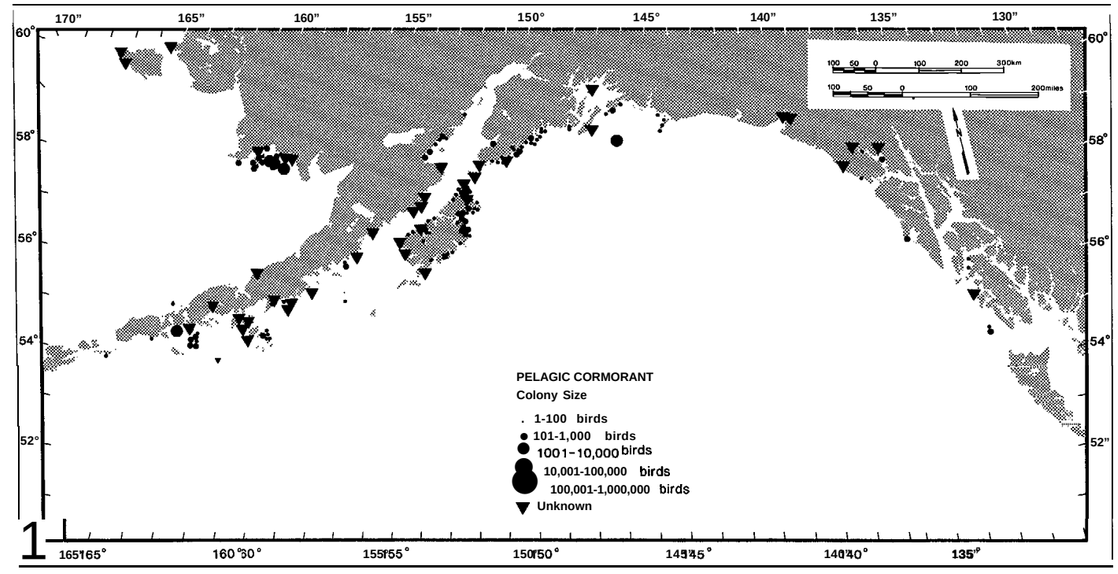


Figure 5.72b Pelagic Cormorant

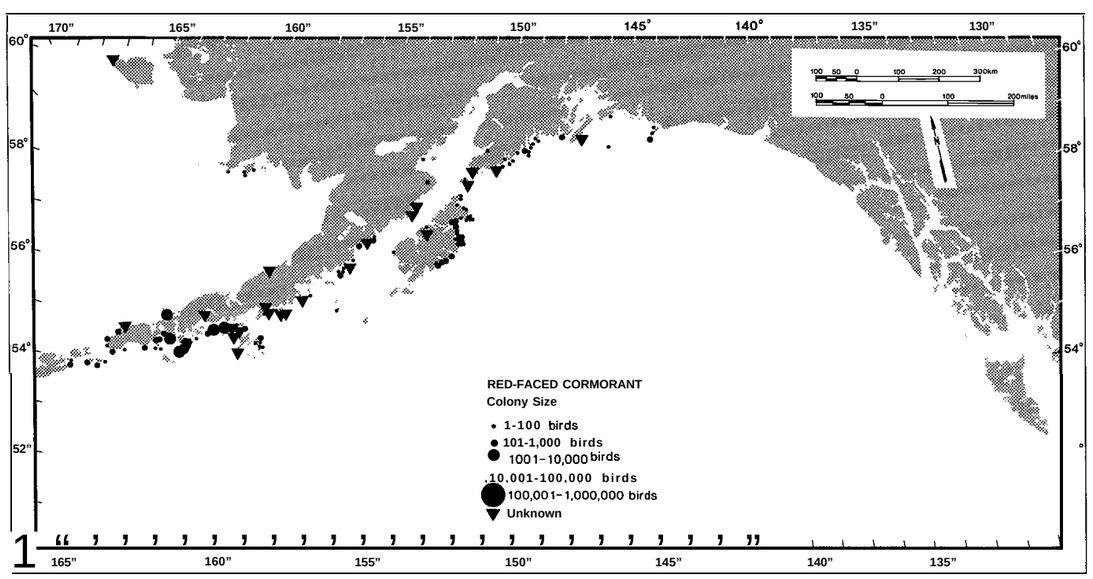


Figure 5.72c Red-faced Cormorant

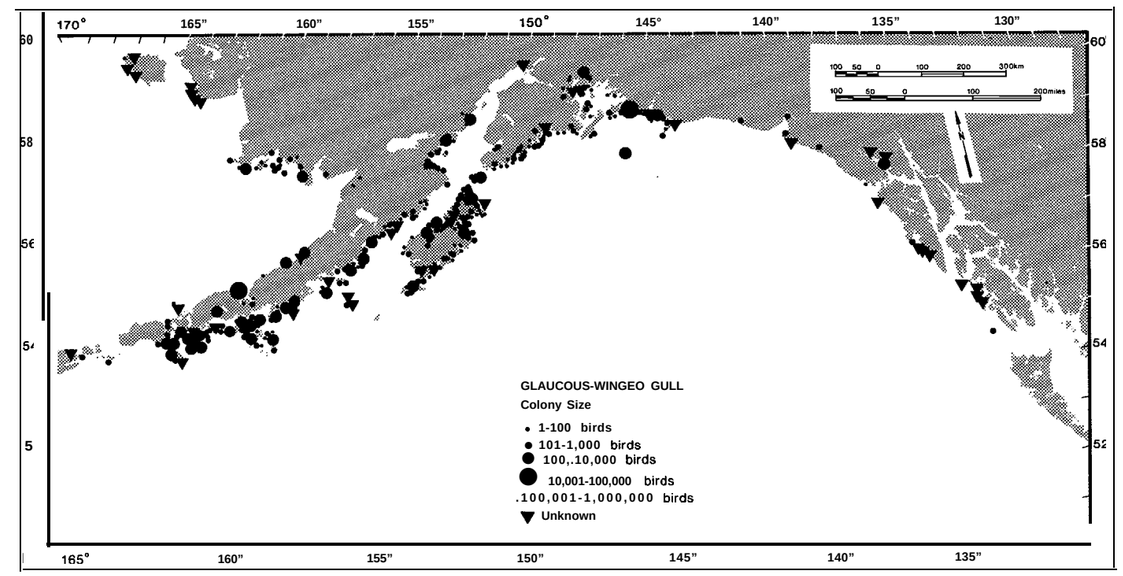


Figure 5.72d Glaucous-winged Gull

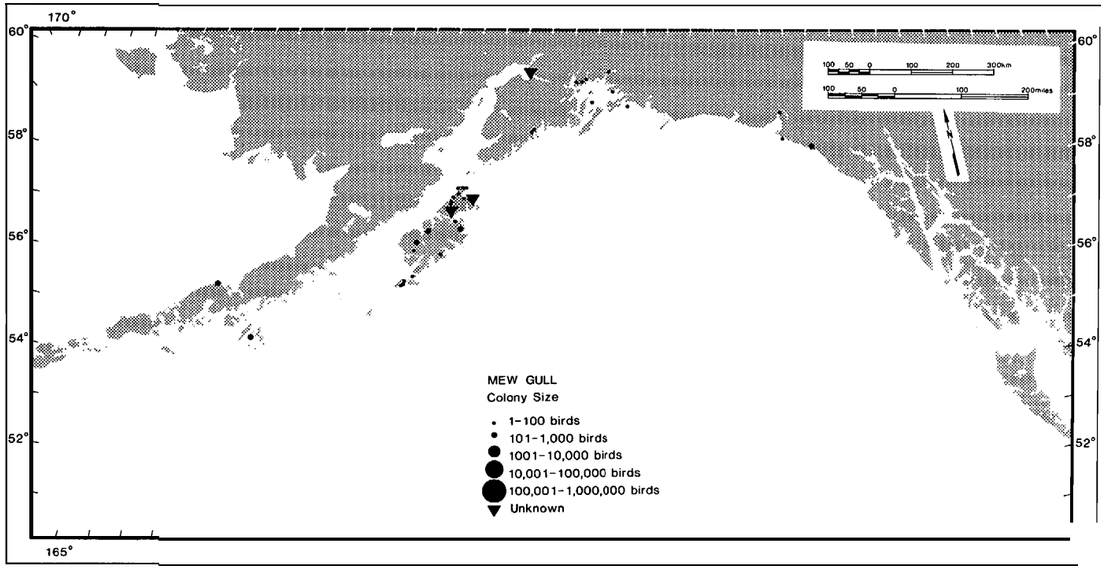


Figure 5.72e Mew Gull

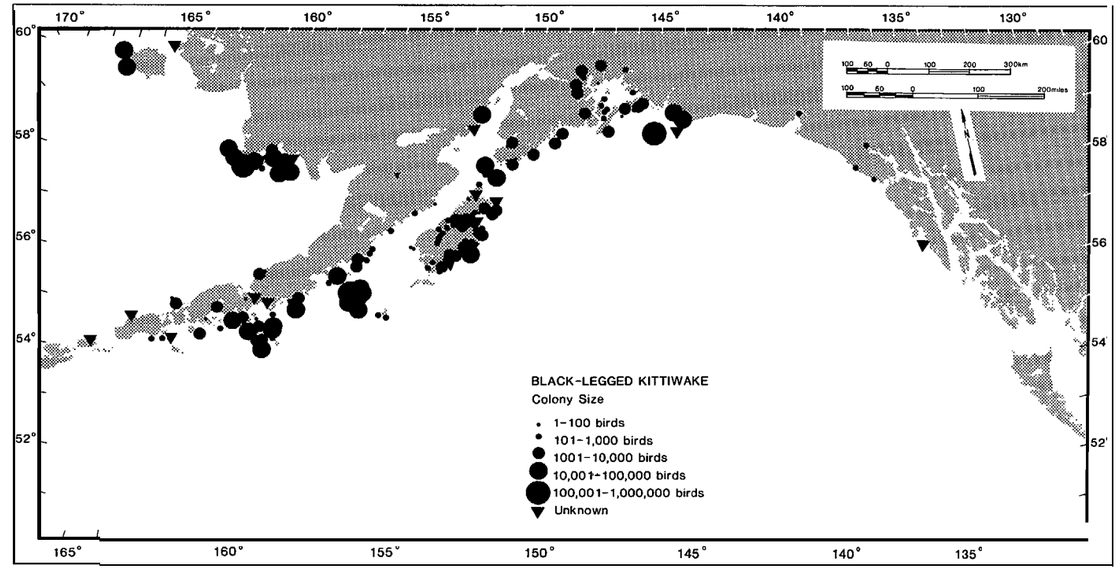


Figure 5.72f Black-legged Kittiwake

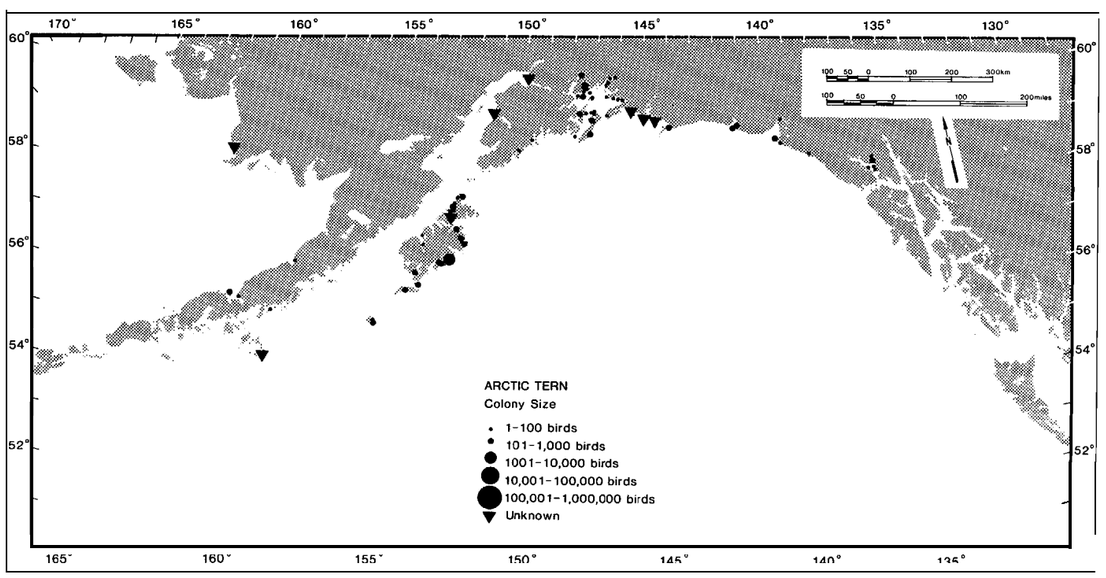


Figure 5.72g Arctic Tern

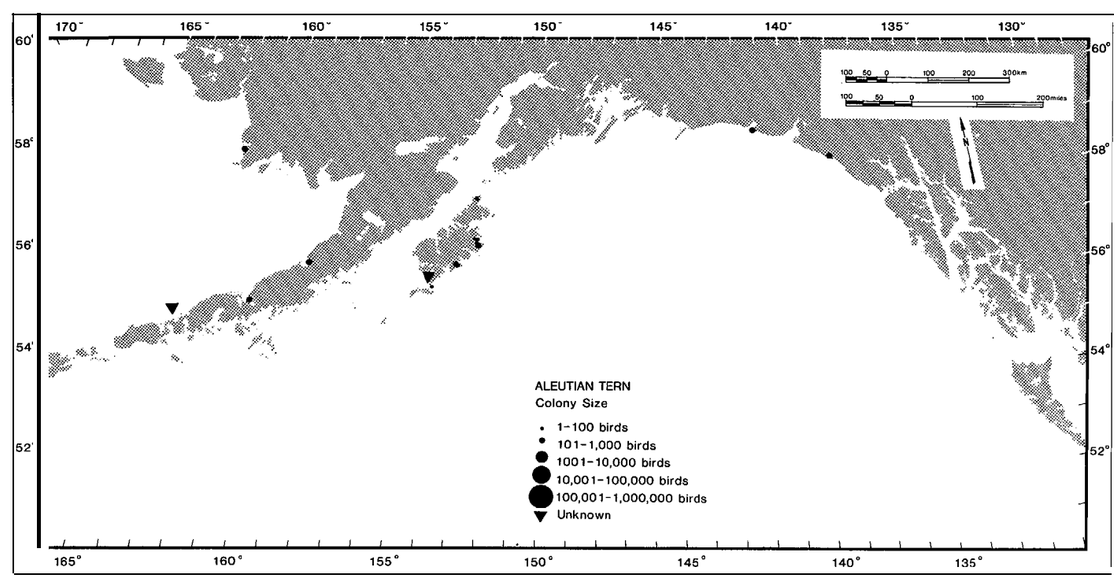


Figure 5.72h Aleutian Tern

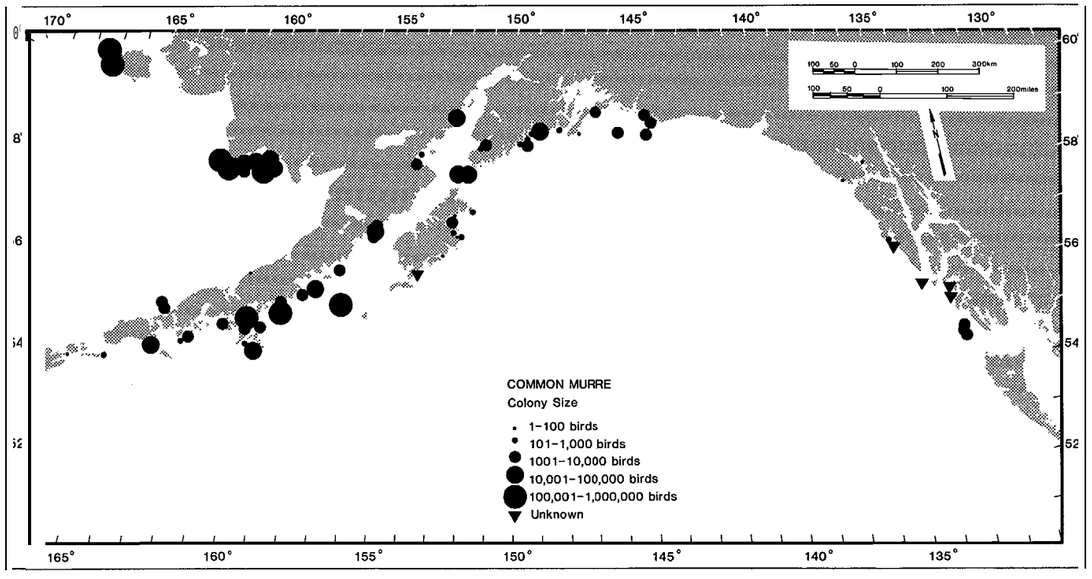


Figure 5.72i Common Murre

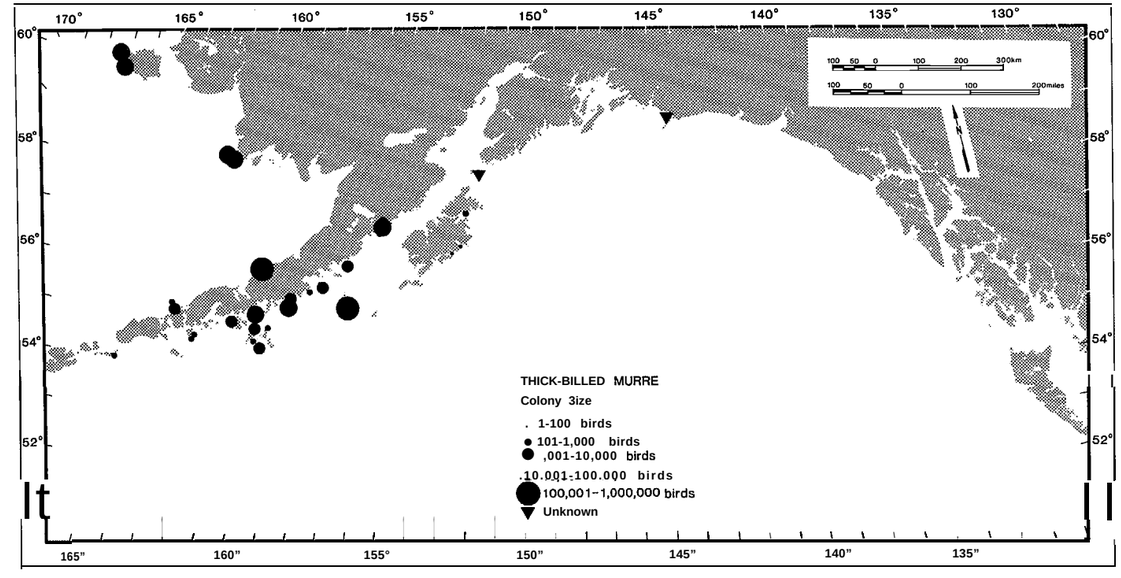


Figure 5.72j Thick-billed Murre

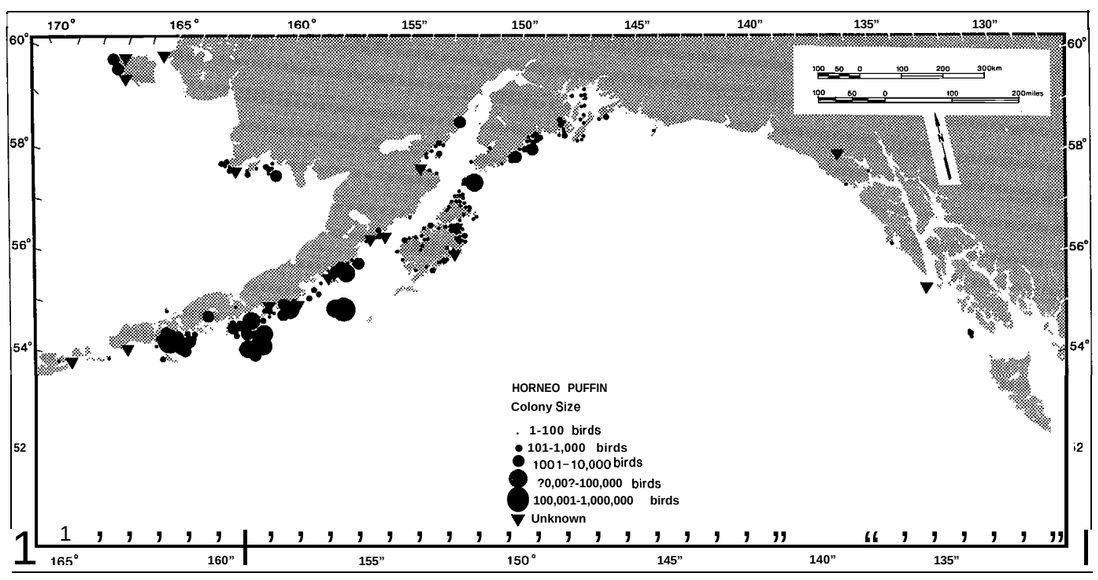


Figure 5.72k Horned Puffin

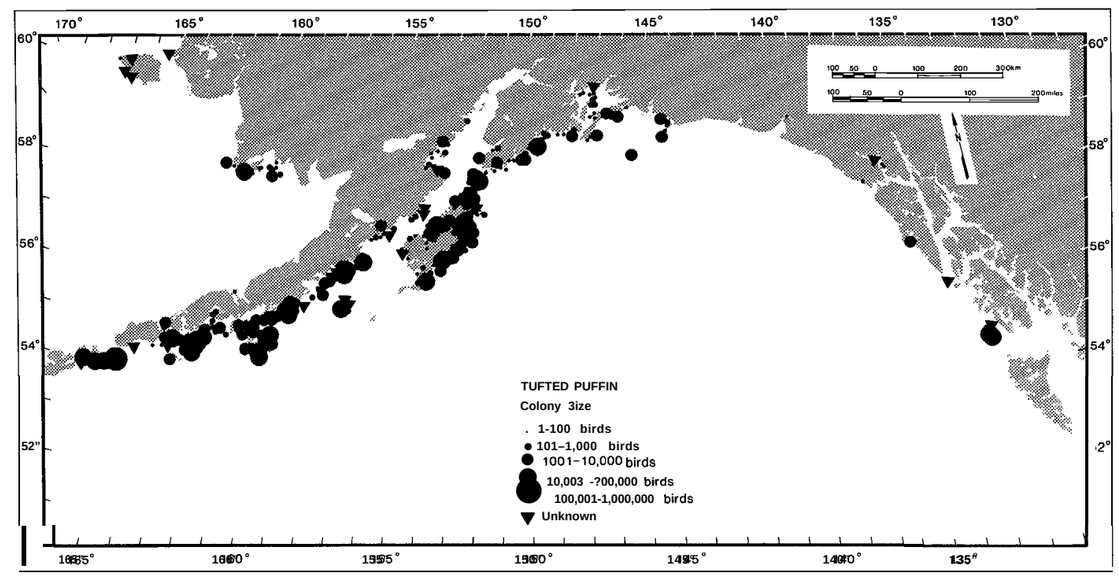


Figure 5.721 Tufted Puffin

The distribution of Bald Eagle nests on the Kodiak National Wildlife Refuge (Fig. 5.73) was surveyed in 1963 (Troyer and Hensel, 1965). One hundred fifty-eight active nests were located by aerial observations. The results of a ground search in a small area of high nesting density indicated that about 20 percent of the active nests were missed in the aerial survey. From these results it was estimated that there were 190 active nests in 1963. Most of the nests were in cottonwood trees (Populus trichocarpa), below 60 m above sea level, and near the coastline.

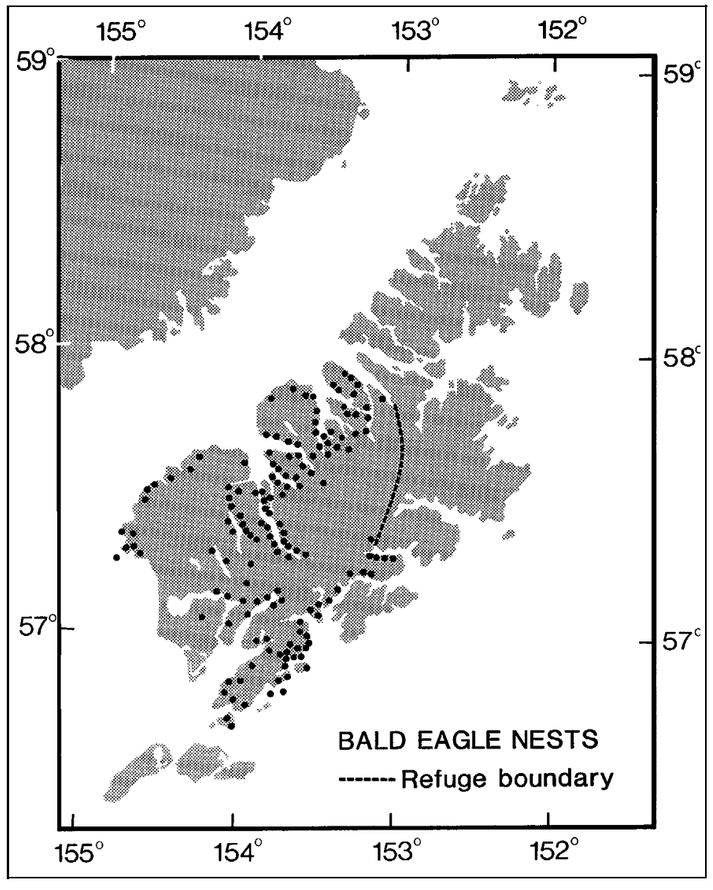


Figure 5.73 Distribution of Bald Eagle nests on Kodiak National Wildlife Refuge (Troyer and Hensel, 1965).

In May, 246 eagles were found and in July and August, 372 eagles were found along salmon streams. These results are 25 to 100 percent greater than those reported by Sowls et al. (1978) (Table 5.48), but probably better reflect current Kodiak populations since the observation of Sowls et al. (1978) were collected incidentally to surveys of colonial birds.

Endangered species

The endangered Aleutian Canada Goose (Branta canadensis leucopareia) is not known to occur in the Gulf of Alaska (Paul Springer, U.S. Fish & Wildlife Service, Aleutian Canada Goose Recovery Team, pers comm.). The only known breeding ground is Buldir Island at the western end of the Aleutian Chain (Woolington et al., 1979). A small flock of Canada Geese has been found on the Semidi Islands each summer since 1977 (S. Hatch, University of California, pers comm.). At least three pairs bred in 1979. Sufficient information to determine the subspecies of these birds is not yet available, but they are known to have several of the characteristics of leucopareia. Current evidence indicates that in fall the geese breeding on Buldir migrate east along the Aleutians to about Unimak, and then fly across the Pacific to California (Fig. 5.74). In the spring they move north along the Oregon and [illegible] coasts before making a direct flight to the Aleutians. Recently a flock of about 80 Aleutian Canada Geese suspected to represent an unknown breeding flock was found staging on the Oregon coast (P. Springer, pers. comm.). Most of the birds on Buldir have been marked with leg bands or neck collars; none of the birds in this Oregon flock were marked. On the basis of current knowledge, it appears unlikely that development in the Kodiak area would present a hazard to the preservation of this goose. On the other hand, current knowledge is too incomplete to be certain that the Aleutian Canada Goose does not occur in the Kodiak area.

Three subspecies of the Peregrine Falcon (Falco peregrinus) breed in Alaska. Pealei is a dark-plumaged race which is resident along the southern coast of Alaska and on the Aleutian Islands. Its populations are not considered to be threatened. The two endangered light-plumaged subspecies (anatum, tundrius) breed in the interior and in northern Alaska. Both races are highly migratory and winter from the southern United States to southern South America. The birds can be found throughout North America during migration.

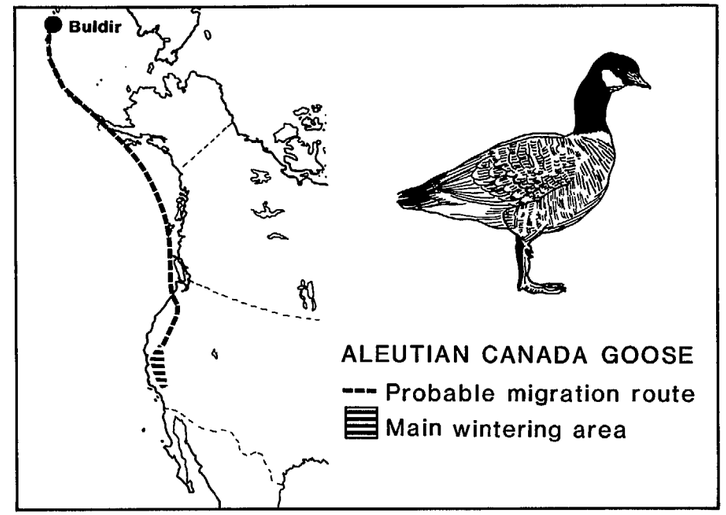


Figure 5.74. Distribution of the Aleutian Canada Goose (after Palmer, 1976). Only known breeding location is Buldir Island but there is evidence that it may also breed elsewhere (see text for details).

The current status of North American Peregrine Falcon populations has been reviewed in Schaeffer and Ehlers (1978) .

A total of five light-plumaged Peregrine Falcons have been observed wintering on Kodiak Island between 1973 and 1979. It was originally believed that these birds were members of the endangered subspecies, but they are now thought to be representatives of the light-colored "Queen Charlotte" subgroup of pealei (R. A. Macintosh, National Marine Fisheries, Kodiak, pers. Comm.). Individuals of the endangered races regularly occur along the southern Alaska coast, including Kodiak Island, during migration (Gabrielson and Lincoln, 1959) . It is unlikely, however, that petroleum development in the Kodiak area would influence the maintenance or recovery of endangered populations.

5.7.4 Population dynamics

The population dynamics of a species comprise the birth and death statistics for the population. For birds these include the number of eggs laid per clutch, the frequency at which clutches are laid, the survivorship of eggs and young, the age of first reproduction, and the subsequent survival of adults throughout their lifetime (Ricklefs, 1973),

Current evidence is consistent with the theory that the clutch and brood size of seabirds correspond to the most young the parents can adequately feed (Lack, 1968; Ricklefs, 1973; Nelson, 1978). Species which feed offshore, such as tubenoses, murres, auklets, and puffins, have a clutch of one, while species which feed inshore, such as cormorants, gulls, terns, guillemots, and murrelets, have clutches of two to four (Lack, 1968; Ashmole, 1971); thus clutch size is negatively correlated with the distance adults travel to obtain food. In Alaska the breeding season is so short that marine birds can rear only one brood per season. Many species will, however, lay a second clutch if the first is lost early in the season.

The breeding phenologies recorded for nine species of marine birds breeding on Chiniak Bay (Nysewander and Hoberg, 1978; Nysewander and Barbour, 1979) and Sitkalidak Strait (Baird and Moe, 1978; Baird and Hatch, 1979), Kodiak Island, in 1977 and 1978 are shown in Fig. 5.75 and those for ten species breeding on the Barren Islands (Manuwal and Boersma, 1978; Manuwal, 1979) in 1976 through 1978 are shown in Fig. 5.76. For the three study sites egglaying typically occurs from mid-May through mid-July, hatching from mid-June through mid-August, and fledging from mid-July through mid-September. The initiation and ending of these activities have varied by two to three weeks during the few seasons in which data were gathered. Thus breeding activity at these colonies can be expected to occur from early May through late September. In addition to nesting, many of these species make preliminary visits to participate in courtship at or near the colonies a month or more before actual nesting begins. Colonial species thus are vulnerable to disturbances and pollution near the colonies for at least the period April through September.

Two patterns of the relative mortalities of eggs and nestlings are found in marine birds. In tubenoses, cormorants, and alcids egg mortalities are usually higher than nestling mortalities, whereas in gulls and terns nestling mortalities are generally higher " (Ricklefs, 1969). Eggs are lost primarily by being rolled out of the nest by the parents, overheated in

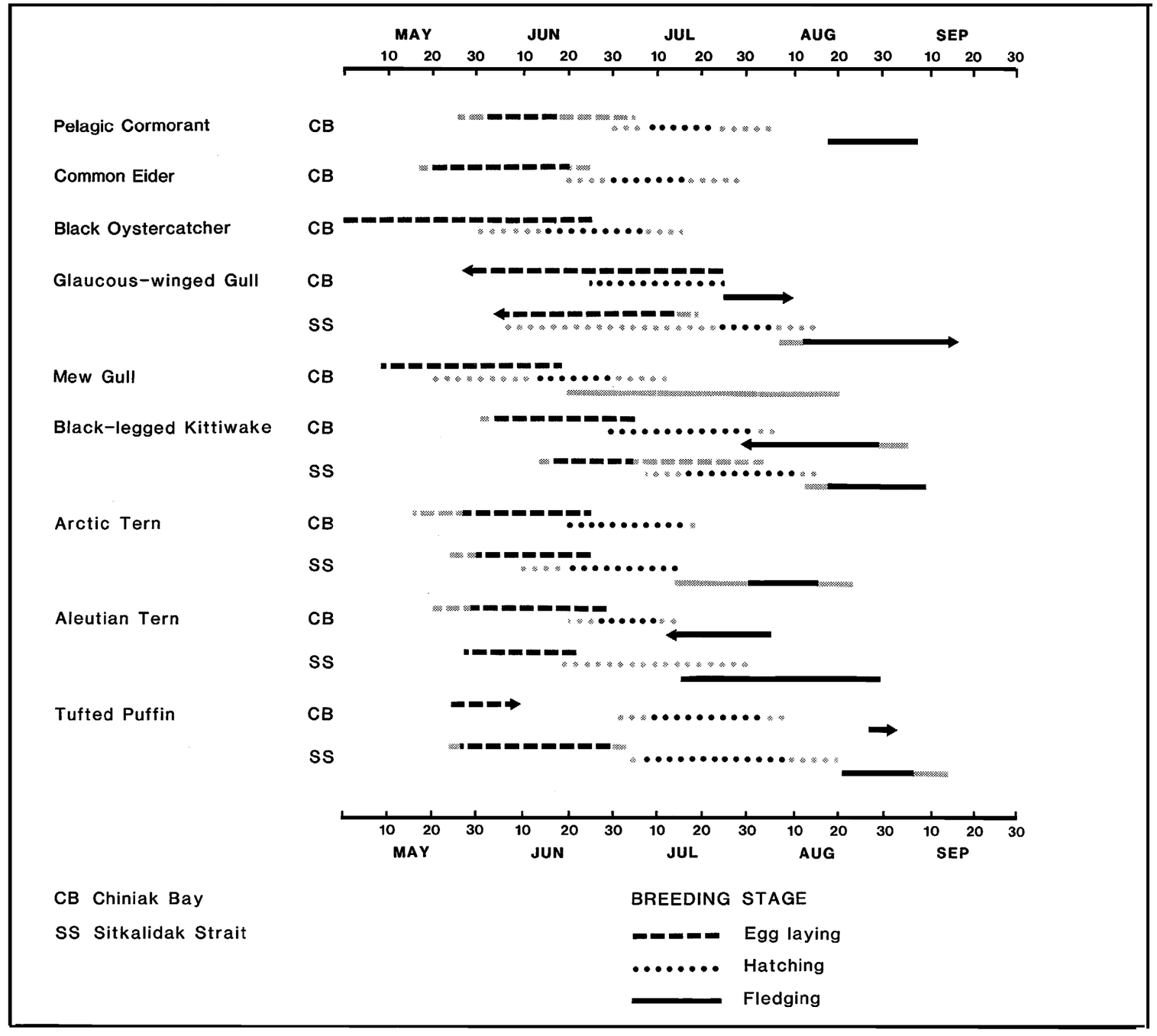


Figure 5.75 Breeding phenologies for nine species of marine birds breeding on Kodiak Island (Baird and Moe, 1978; Nysewander and Hoberg, 1978; Baird and Hatch, 1979, Nysewander and Barbour, 1979). Light symbols represent the year-to-year variation in the start and/or end of the different breeding stages. Solid symbols represent the periods used in two or more study seasons. Arrows indicate that stage extended beyond observation period.

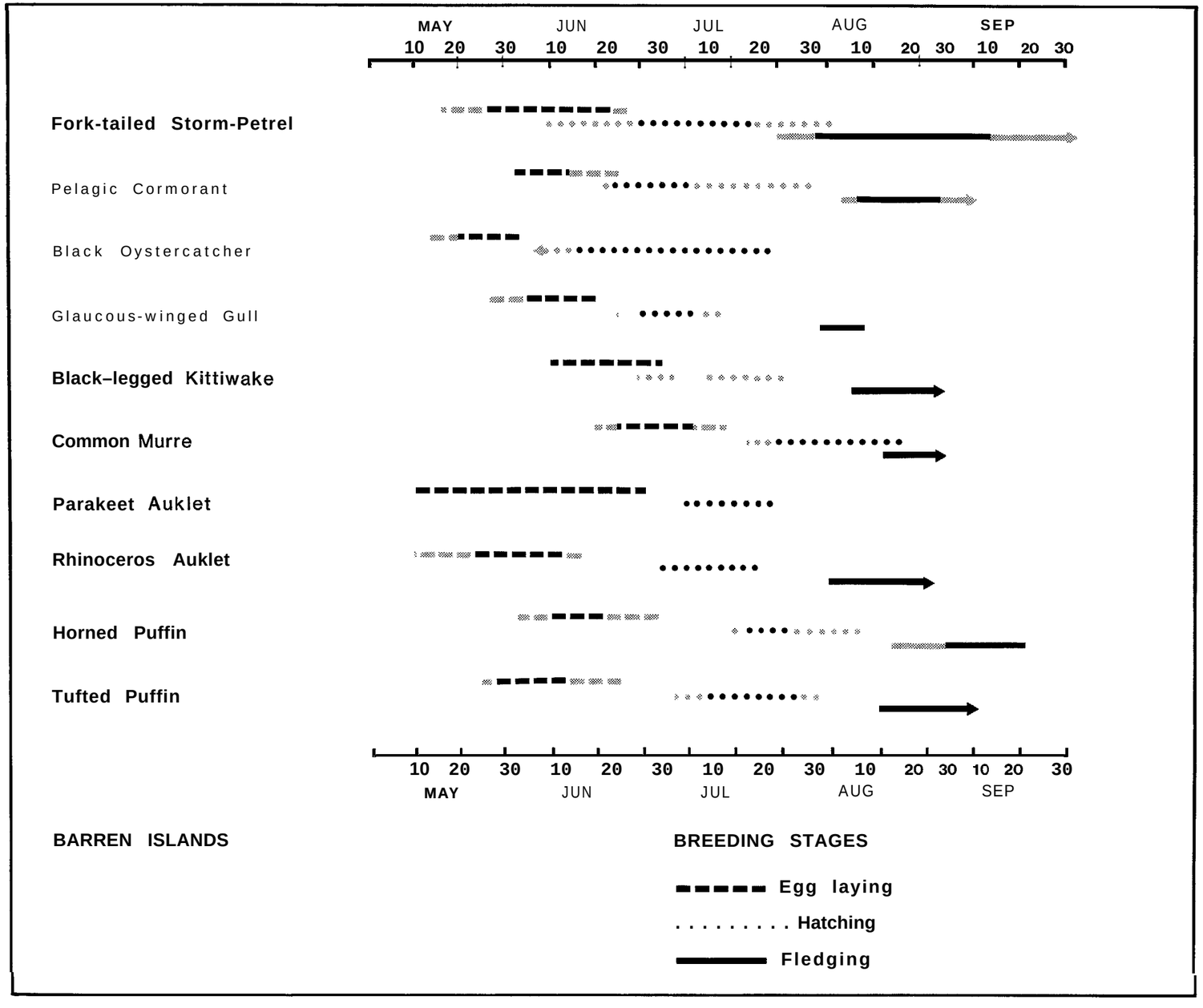


Figure 5.76 Breeding phenologies **for ten species of marine birds breeding on the Barren Islands** (Manuwal **and Boersma,** 1978; Manuwal, 1979). **Light symbols represent the year-to-year variation in the start and/ or end of the different breeding stages. Solid symbols represent the periods used** in two or more Study seasons. Arrows indicate that stage extended beyond observation period.

the sun, or destroyed by predators. Chicks are frequently lost to predators, starvation, extreme weather conditions, and by falling off ledges. Information for several species has been summarized and discussed by Ricklefs (1969). He reports a range of breeding success (young fledged per egg laid) of 0.04 to 0.62 (average 0.32); tropical species had less success than northern species.

The reproductive success of nine species of marine birds breeding on Chiniak Bay (Nysewander and Hoberg, 1978; Baird and Hatch 1979), Kodiak Island, in 1977 and 1978 is shown in Table 5.49 and that for seven species breeding on the Barren Islands (Manuwal and Boersma, 1978; Manuwal, 1979) 1976 through 1978 is shown in Table 5.50. On Kodiak breeding success for all species and seasons averaged 0.48 and on the Barren Island 0.45. These values are somewhat higher than Ricklefs (1969) reports for a similar group of northern species. The productivity (young produced per pair, including pairs which started to nest but failed before any eggs were produced) of a species varied from year to year. On both Kodiak and the Barren Islands cormorants and gulls had the largest year-to-year differences while storm-petrels, oystercatchers, and puffins had the smallest year-to-year differences.

Table 5.49 Reproductive success of Kodiak marine birds (see text for sources).

Species	Location[a]	Year	Total nests	Nests with eggs	Clutch size	Hatching[b] success	Fledging[c] success	Breeding[d] success	Productivity[e]
Pelagic Cormorant	CB	1977	26	25	3.52	0.69	0.62	0.42	1.42
Pelagic Cormorant	CB	1978	28	21	2.17	0.35	0.44	0.15	0.25
Red-faced Cormorant	CB	1977	77	57	?	?	?	?	1.91
Red-faced Cormorant	CB	1978	78	30	?	?	?	?	1.33
Common Eider	CB	1977	?	19	4.55	0.68	1.00	0.68	2.95
Common Eider	CB	1978	?	20	4.55	0.36	1.00	0.36	1.65
Black Oystercatcher	CB	1977	10-12	5	2.40	0.83	1.00	0.83	0.83-1.00
Black Oystercatcher	CB	1978	14	12	2.08	0.52	1.00	0.52	0.93
Glaucous-winged Gull	CB	1977	40	33	2.64	0.90	0.62	0.55	1.20
Glaucous-winged Gull	CB	1978	38	35	2.49	0.60	0.60	0.36	0.82
Glaucous-winged Gull	SS	1977	84	54	2.48	0.75	0.89	0.67	1.07
Glaucous-winged Gull	SS	1978	117	53	2.28	0.48	0.74	0.36	0.38
Mew Gull	CB	1977	66	60	2.63	0.84	0.30-0.50	0.2-0.42	0.60-1.00
Mew Gull	CB	1978	40	40	2.51	0.86	0.21-0.32	0.1-0.28	0.45-0.70
Black-legged Kittiwake	CB	1977	210	177	1.91	0.85	0.90	0.76	1.46
Black-legged Kittiwake	CB	1978	259	171	1.72	0.70	0.96	0.68	0.77
Black-legged Kittiwake	CB	1977	136	114	1.68	0.74	0.76	0.57	0.74
Black-legged Kittiwake	SS	1978	121	65	1.28	0.36	0.71	0.26	0.16
Arctic Tern	CB	1977	?	96	2.21	0.85	?	.	?
Arctic Tern	CB	1978	?	67	1.91	0.53	?	?	?
Arctic Tern	SS	1977	?	44	2.05	0.82	0.20-0.66	0.17-0.54	0.34-1.11
Aleutian Tern	CB	1977	?	45	1.89	0.88	?	?	?
Aleutian Tern	CB	1978	?	121	1.78	0.16	?	?	?
Aleutian Tern	SS	1977	?	37	1.60	0.81	0.17-0.54	0.14-0.44	0.22-0.70
Tufted Puffin	CB	1977	30	25	1.00	0.88	0.91	0.80	0.67
Tufted Puffin	CB	1978	51	46	1.00	0.84	0.89	0.76	0.69
Tufted Puffin	SS	1977	93	67	1.00	0.61	0.85	0.52	0.38
Tufted Puffin	SS	1978	103	69	1.00	0.52	0.89	0.46	0.31

[a]Locations: CB = Chiniak Bay, SS = Sitkalidak Strait; [b]Hatching success = Eggs hatched/eggs laid; [c]Fledging success = chicks fledged/eggs hatched; [d]Breeding success = Chicks fledged/eggs laid; [e]Productivity = young produced/pair, includes pairs which started to nest but failed before any eggs were produced.

The productivity for all study locations of Pelagic Cormorants was about 90 percent in 1977 and 30 percent in 1978 of that reported from a two-year study in British Columbia (Drent et al., 1964). For Glaucous-winged Gull the productivity in 1977 was about 125 percent and in 1978 about 55 percent of that reported by Drent et al. (1964) for a four-year period in British Columbia. For Black-legged Kittiwakes the productivity reported for 1977 was about 75 percent and for 1978 about 40 percent of that reported by Coulson and White (1958) for a rapidly growing population in Britain.

About one-third of the eggs and young produced in the Kodiak region were lost during the nesting cycle. Often the cause of mortality was unknown; an egg or nestling merely disappeared. On the Kodiak Island study sites the eggs of gulls and terns were regularly collected for food by natives. The predation of the eggs and chicks of other species by gulls appears to be lower on Kodiak than it is in the Aleutian region. Thus the apparent depression of gull populations by native egging may be beneficial to other birds. Bald Eagles appear to prey regularly on colonies near their nests (Nysewander and Hoberg, 1978). River otters (Lutra canadensis) are locally destructive of eggs and young (Manuwal and Boersma, 1978, Manuwal, 1979) but are not a major cause of mortality. Storms and continued bad weather were obs to cause significant

mortality to the chicks of Fork-tailed Storm-Petrels, Pelagic Cormorants, Mew Gulls, Black-legged Kittiwakes, terns, and puffins.

Human activity in and near colonies often frightens away adult birds, exposing eggs and young to predation. A common theme in the reports of workers on bird colonies in the Gulf of Alaska is the high incidence of nest abandonment by puffins because of human disturbance. Birkhead (1977a) observed that regular visits to measure chicks of the Common Murre greatly increased mortality. While the restricted activities of OCSEAP investigators appear to have had little effect on these populations, sustained human activity in or near marine bird colonies will wreak havoc among them.

The postfledging survival of marine birds is difficult to measure, especially since the onset of sexual maturity is usually delayed. Several species of gulls, terns, and alcids continue to feed young after they leave the breeding colonies (Ashmole, 1971). Survival rates of young birds have been found to be low during their first winters but they increase to adult rates by the time they reach maturity (Ashmole, 1971; Ricklefs, 1973). The age of sexual maturity may be as late as nine to twelve years in large seabirds. The age at onset of reproduction is correlated with the annual survival rate of adults. Delayed reproduction thus has the effect of restricting the recruitment of young into the breeding population to a rate which corresponds to adult losses (Lack, 1966; 1968).

Once marine birds reach the age of reproduction, they have high survival rates, typically 93 to 97 percent for tubenoses, 80 to 85 percent for cormorants, and 81 to 96 percent for gulls, terns, and alcids.

Table 5.50 Reproductive success of Barren Islands marine birds (see text for sources).

Species	Year	Total nests	Nests with eggs	Clutch size	Hatching[a] success	Fledging[b] success	Breeding[c] success	Productivity[d]
Fork-tailed Storm-Petrel	1977	?	100	1.00	0.84	0.69	0.58	0.58
Fork-tailed Storm-Petrel	1978	100	85	1.00	0.73	0.94	0.68	0.58
Pelagic Cormorant	1977	63	63	2.84	0.64	0.89	0.57	1.62
Pelagic Cormorant	1978	67	61	3.64	0.29	0.66	0.19	0.64
Black Oystercatcher	1977	?	12	3.00	0.92	1.00	0.92	2.76
Glaucous-winged Gull	1977	?	44	2.45	?	?	0.55[e]	1.35
Glaucous-winged Gull	1978	?	25	2.52	0.35	0.18	0.06	0.16
Black-legged Kittiwake	1977	49	49	1.76	0.83	0.62	0.51	0.90
Black-legged Kittiwake	1978	52	46	1.41	0.28	0.39	0.11	0.13
Horned Puffin	1976	?	14	1.00	0.79	0.36	0.28	0.28
Horned Puffin	1977	2	14	1.00	0.93	0.69	0.64	0.64
Horned Puffin	1978	18	18	1.00	0.88	0.75	0.66	0.66
Tufted Puffin	1976	?	40	1.00	0.40	0.68	0.32	0.32
Tufted Puffin	1977	?	56	1.00	0.$0	0.78	0.39	0.39
Tufted Puffin	1978	?	25	1.00	0.84	0.79	0.68	0.47[f]

[a]Hatching success = eggs hatched/eggs laid; [b]Fledging success = chicks fledged/eggs hatched; [c]Breeding success = chicks fledged/eggs laid; [d]Productivity = young produced/pair, includes pairs which started to next but failed before any eggs were produced; [e]Indirect estimate (see Manuwal and Boersma, 1978); [f]Estimate from undisturbed study plot (Manuwal, 1979).

The growth potential of populations

Bird populations appear to maintain themselves near some 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 has been developed from observations and experiments on many species (Lack, 1954; Hutchinson, 1978). The relative importance of the many factors which regulate populations, however, is still hotly debated. Sma11 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 example 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 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 time at which it faces the greatest probability of extinction by random accident. The balance between the capacity for population increase and population density, which can ordinarily carry a population through most of its difficulties, may be completely 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 young fledge, no information has been gathered on post-fledging mortality. Recruitment also depends on the emigration and immigration rates of the young. There is considerable information on seabirds which indicates that some colonies do not produce enough young to maintain their numbers while others produce surpluses. The maintenance of a population of a species over a large area thus may depend on the success 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) 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 Kodiak area, though details may be somewhat 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 sub-adult 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 contrast the relative importance of breeding and non-breeding birds to the maintenance of the population. There may not be any real situation in which only these age-classes would be killed. Scenario three could represent the effect of oil spills early in the breeding season when only the adults were present at a colony. Scenario four could represent the effect of oil spills during the period when adults accompany chicks at sea. Scenario five could represent the effect of oil spills during the winter when all age groups may occur together.

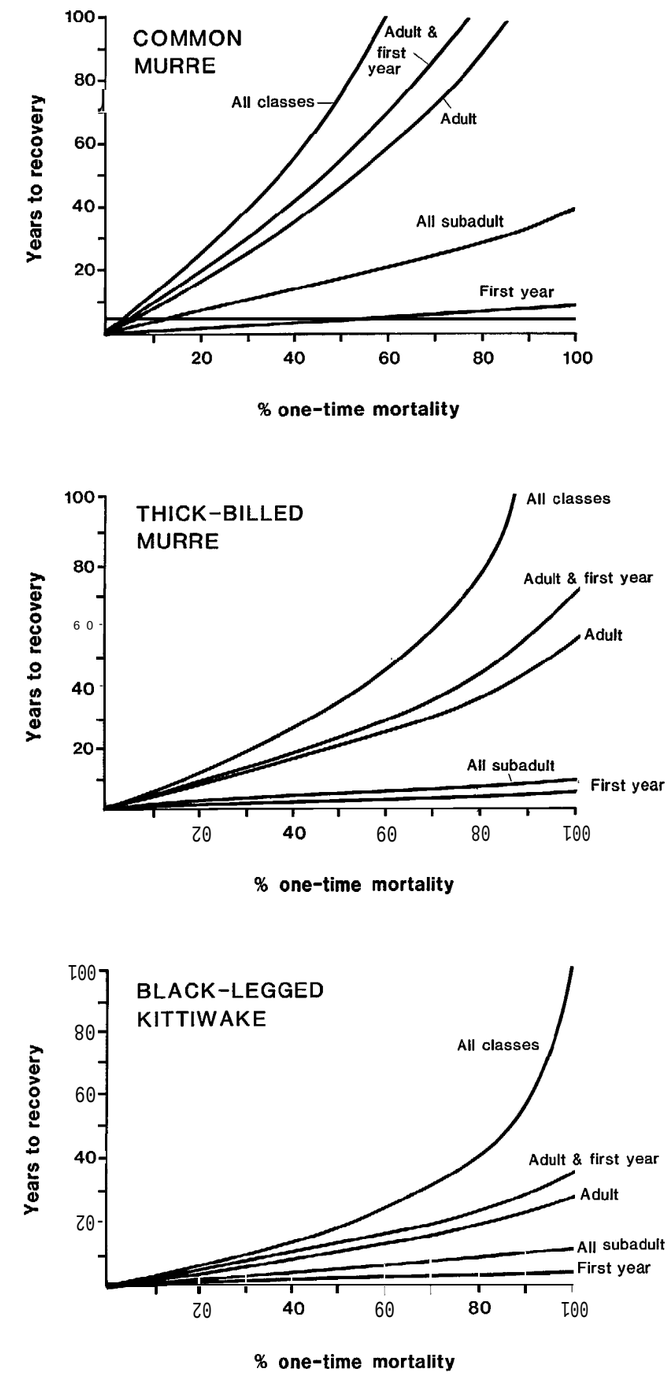


Figure 5.77 Time to recovery as a function of one-time mortality of various age-class combinations of Common Murres, Thick-billed Murres, and Black-legged Kittiwakes (Wiens et al., 1979).

The time to recover (defined as the time for population to attain its original size) from a one-time imposed mortality for the five scenarios is shown in Fig. 5.77. 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 which causes the death of 50 percent of the population is more than twice that from an event which causes the death of 25 percent of the population. Second, the death of adults affects the time of recovery more than that of any other age-class. Mortality of as many as all of the sub-adults has only about one-third the effect of mortality of the adults.

It is predicted that a Common Murre population would take about 50 years to recover from a catastrophe that killed 50 percent of the adults, a Thick-billed Murre population about 20 years, and a Black-legged Kittiwake population about 10 years. These differences are due to the differences in estimates of the fecundity or survival of the species. Thick-billed Murres had a higher fecundity rate than Common Murres, and Black-legged Kittiwakes 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 Common Murres a one-percent decrease in annual adult survival is predicted to cause a fourfold increase in recovery time, whereas a one-percent increase would cause only a 1.7-fold decrease in recovery time (Fig. 5.78). This outcome suggests that the population could not recover if annual adult survival decreased more than 1.3 percent. The model does not, however, include any density-dependent components which could influence fecundity and survival rates and thus decrease recovery times.

The model predicts that the effects of long-term chronic sources of mortality could cause more damage to

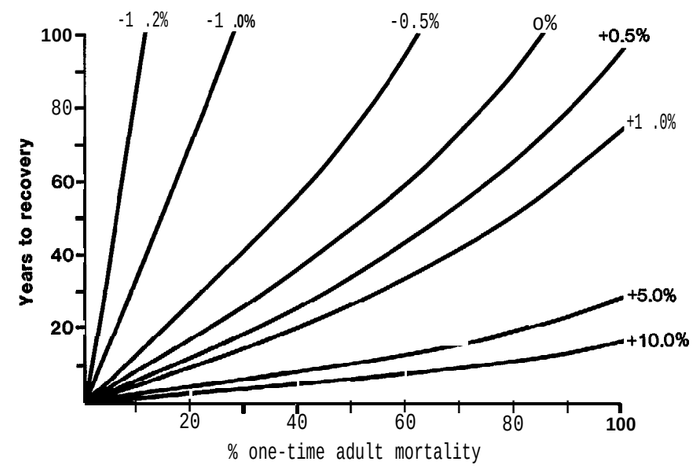


Figure 5.78 Time to recovery as a function of one-time adult mortality at different levels of change in the mean adult annual survival rate of Common Murres (Wiens et al., 1979).

a population than a short-term catastrophe. While 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 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 Fulmars 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 from 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.

5.7.5 Trophies

An understanding of the feeding ecology and diet of marine and coastal birds gives insight into the roles that various species play in local ecosystems. To identify their roles in food webs and in 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 populations, 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.

Diet of adults

Information on the diets of Kodiak marine birds comes from surveys which covered large areas of the Gulf of Alaska during 1969-76 (Sanger and Baird, 1977), open-water habitats near Kodiak in summer 1977 (Sanger et al., 1978), and Chiniak, Izhut, and Kiliuda Bays in winter, spring, and summer 1978 (Krasnow, et al., 1979).

Figure 5.79 displays composite diets of five species of marine birds from near Kodiak Island in summer 1977 (Sanger et al., 1978), and Fig. 5.80 shows similar but less detailed information for three other species from the Gulf of Alaska (Sanger and Baird, 1977). On the basis of percent volume and frequency of occurrence, fish, especially capelin, were the major prey of six species. Euphausiids were the principal prey of Short-tailed Shearwaters, and squid were the most important for Thick-billed Murres. While fish support most of the species, because Short-tailed Shearwaters are so numerous, euphausiids may support greater numbers of individuals (Sanger et al., 1978). In contrast to these results, Wehle (1976) found that Horned and Tufted Puffins ate mostly squid around Buldir Island in the western Aleutians.

The diets shown in Fig. 5.79 are composites of five sampling periods. The variation in diet for these sampling periods (from the end of May to mid-September, (1977) is shown in Fig. 5.81. Because of the small sample sizes and the large proportion of unidentified fish, there is little basis for identifying seasonal trends in the diets of these bird species. For the shearwater species, however, it does appear that the proportion of fish in the diets increases through July and August.

Data on the prey of Kodiak marine birds are available from Chiniak Bay in the winter and from Izhut and Kiliuda Bays in the spring and summer (Krasnow, et al., 1979). Oldsquaws and Black Scoters were studied only in the winter; Common Murres and Marbled Murrelets were studied in winter, spring, and summer; while Sooty and Short-tailed Shearwaters, Black-legged Kittiwakes, Pigeon Guillemots, and Tufted Puffins were studied only in the spring and summer.

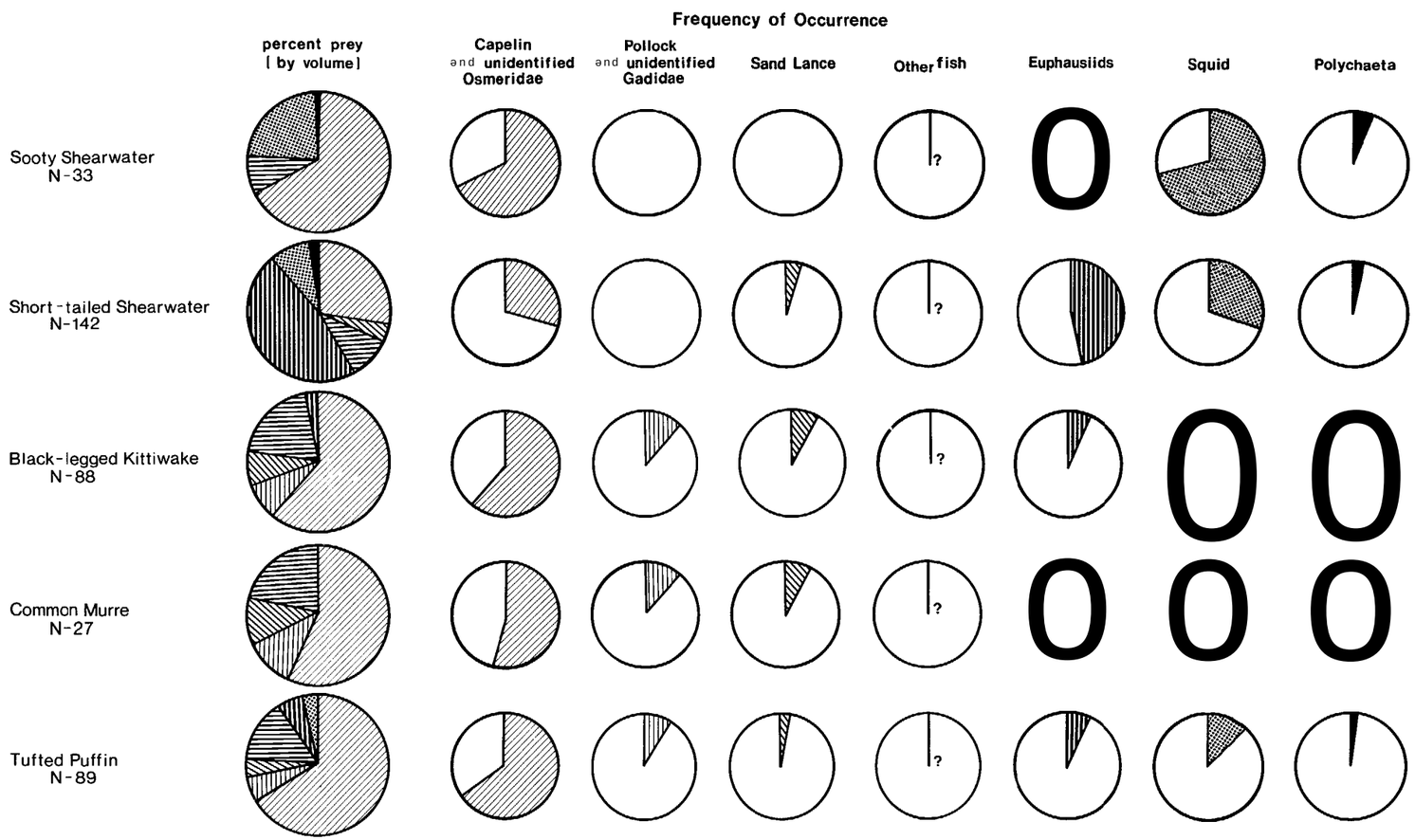


Figure 5.79 Diet of five species of marine birds, Kodiak area, summer 1977 (Sanger et al., 1978).

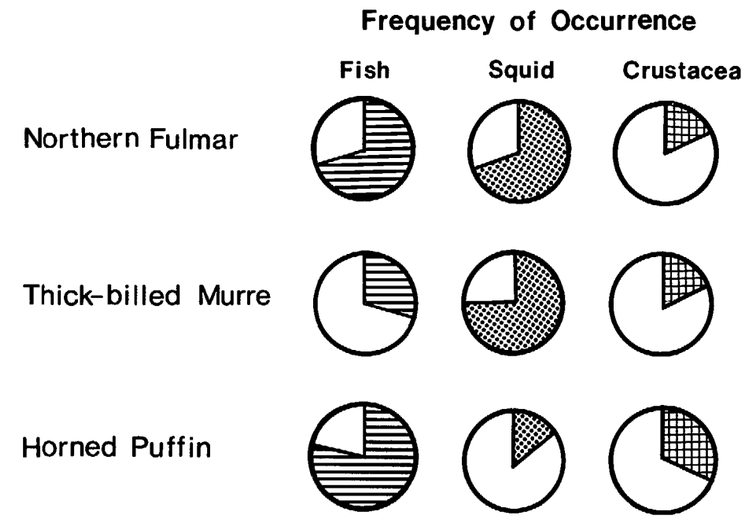
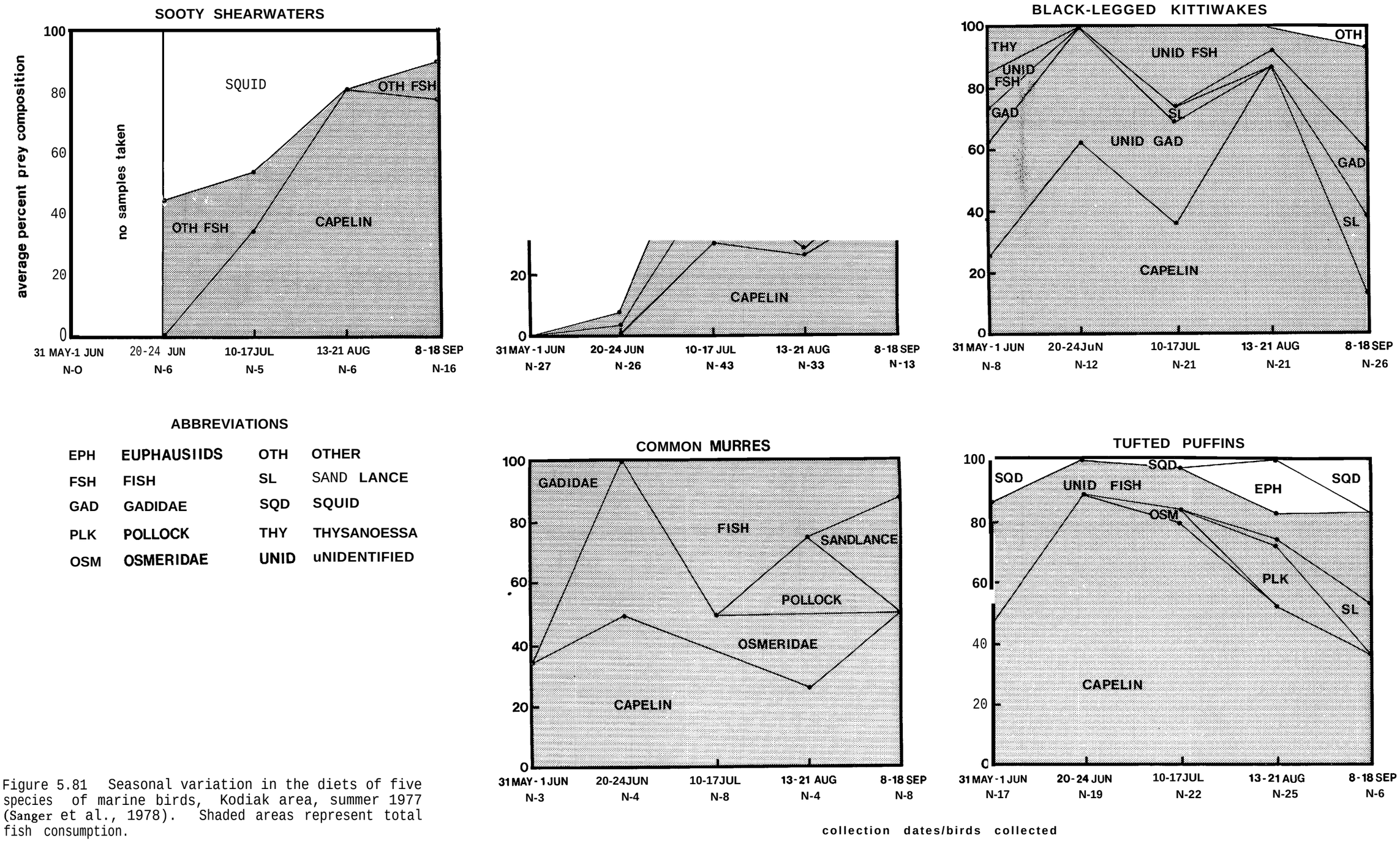


Figure 5.80 Diet of three species of marine birds, Gulf of Alaska, 1969 through 1976 (Sanger and Baird, 1977).



ABBREVIATIONS

EPH	EUPHAUSIIDS	OTH	OTHER
FSH	FISH	SL	SAND LANCE
GAD	GADIDAE	SQD	SQUID
PLK	POLLOCK	THY	THYSANOESSA
OSM	OSMERIDAE	UNID	uNIDENTIFIED

Figure 5.81 Seasonal variation in the diets of five species of marine birds, Kodiak area, summer 1977 (Sanger et al., 1978). Shaded areas represent total fish consumption.

The two ducks fed mostly on sessile or slow-moving invertebrates; Black Scoters preferred blue mussels, whereas Oldsquaws ate a variety of bottom-dwelling forms (Fig. 5.82). In both seasons, Common Murres ate mostly fish. In winter walleye pollock was the principal prey, while in spring and summer walleye pollock, capelin, Pacific sandfish, and Pacific sand lance were all important. One bird, however, had eaten only euphausiids. Marbled Murrelets ate crustaceans (mostly mysids) and fish in all seasons, with a shift from mostly mysids in the winter to mostly fish in the spring and summer. Short-tailed Shearwaters ate mostly euphausiids, while fish were the major prey of all of the other species studied only in the spring and summer.

Although sample sizes are small, there are clear trends in the utilization of the three major prey (euphausiids, capelin, and Pacific sand lance). Euphausiids were taken only in April through June, indicating that they were available only during that period. Capelin generally constituted a greater proportion of the volume of prey consumed in early summer, while Pacific sand lance were more important in July and August. The extent to which this pattern is determined by seasonal migrations of these organisms is unknown.

A comparison of the 1977 and 1978 summer data indicates an increased use of Pacific sand lance in 1978. The percentage volume of capelin consumed was about the same in both years, but there were shifts in its importance to individual species between the years. Comparisons between these two years are preliminary because the results were analyzed differently. The 1977 data are currently being reanalyzed (Krasnow et al., 1979).

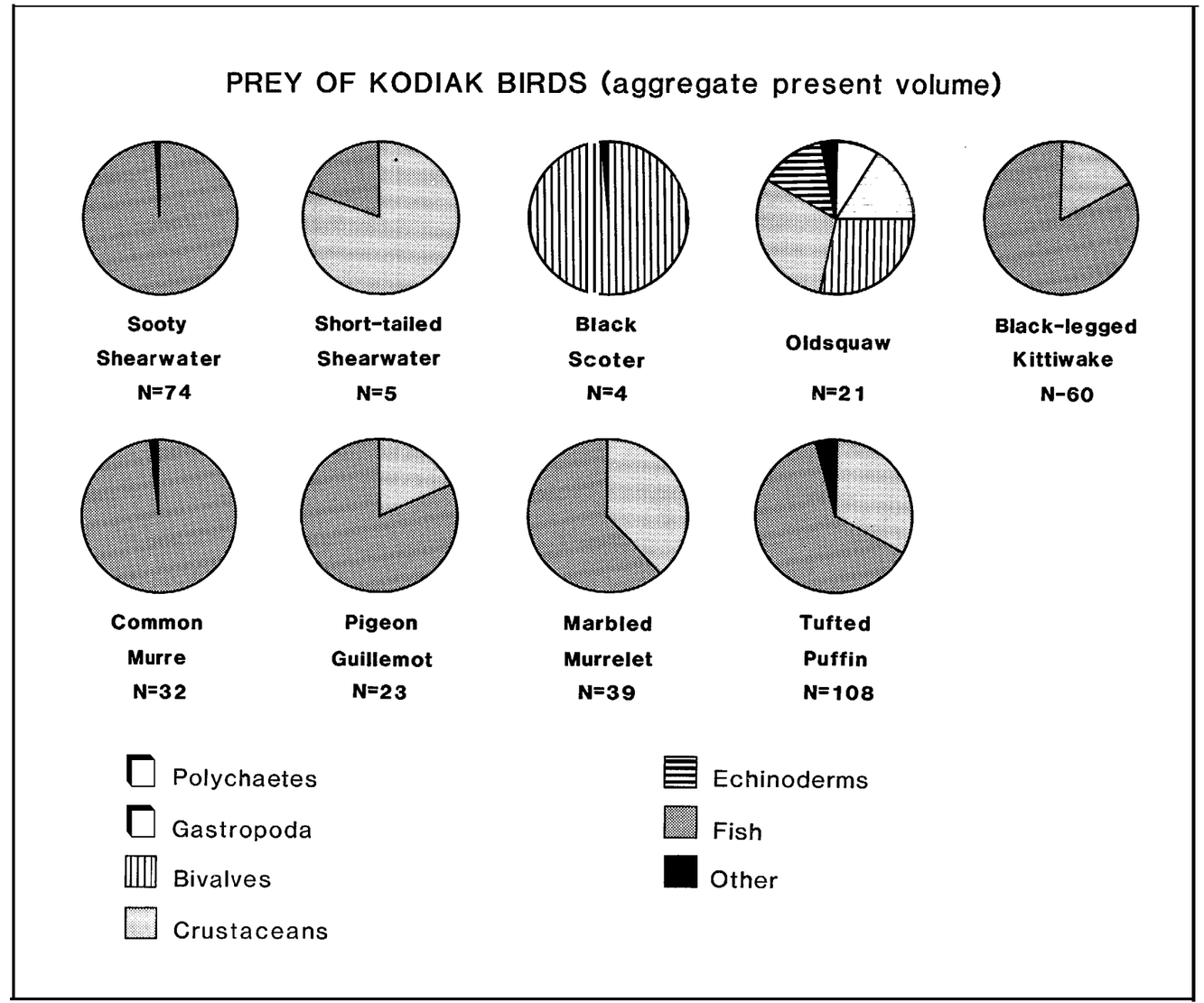


Figure 5.82 Diets of marine birds from Chiniak Bay, February 1978 and Izhut and Kiliuda Bays, spring and summer 1978 (Krasnow et al., 1979).

Diet of young

The diets of the chicks of five species of marine birds from Sitkalidak Strait, Kodiak Island, and the Barren Islands are shown in Fig. 5.83. Food samples were obtained by collecting material regurgitated by chicks and food samples left in burrows by adults when their chicks were prevented, by taping their beaks shut, from eating, and by capturing feeding adults (Baird and Moe, 1978; Baird and Hatch, 1979; Manuwal and Boersma, 1978; Manuwal, 1979). Capelin and Pacific sand lance were heavily utilized as food by all species. The use of capelin decreased and that of Pacific sand lance increased in 1978 compared to 1977. The heavy use of capelin, a species rich in oil, parallels the preference for oil-rich sprats (Sprattus sprattus) by common puffins (Fratercula arctica) as food for their young (Harris and Hislop, 1978). Harris and Hislop (1978) reckon that puffins obtain the best return for effort expended by feeding their young a few large, oil-rich species. They also report that young puffins are easy to raise in the laboratory when fed exclusively on sprats, but all die if fed exclusively on whiting (Merlangus merlangus), a fish with a higher protein but lower fat content. The productivity of Glaucous-winged Gulls and Black-legged Kittiwakes at these colonies was lower in 1978 than in 1977, while that of the two puffin species was essentially the same (Tables 5.49 and 5 .50). It is suspected that dietary differences between the two years are directly related to the differences in gull productivity. Since gulls feed on or near the surface while puffins dive for their food, the dietary difference observed among gulls and puffins in 1978 may reflect an absence of capelin in surface waters in 1978 (P. Baird, USFWS, Anchorage, pers. comm.). Studies on the nutritive value and behavior of the various prey would give insight into how changes in prey populations might affect marine bird breeding populations.

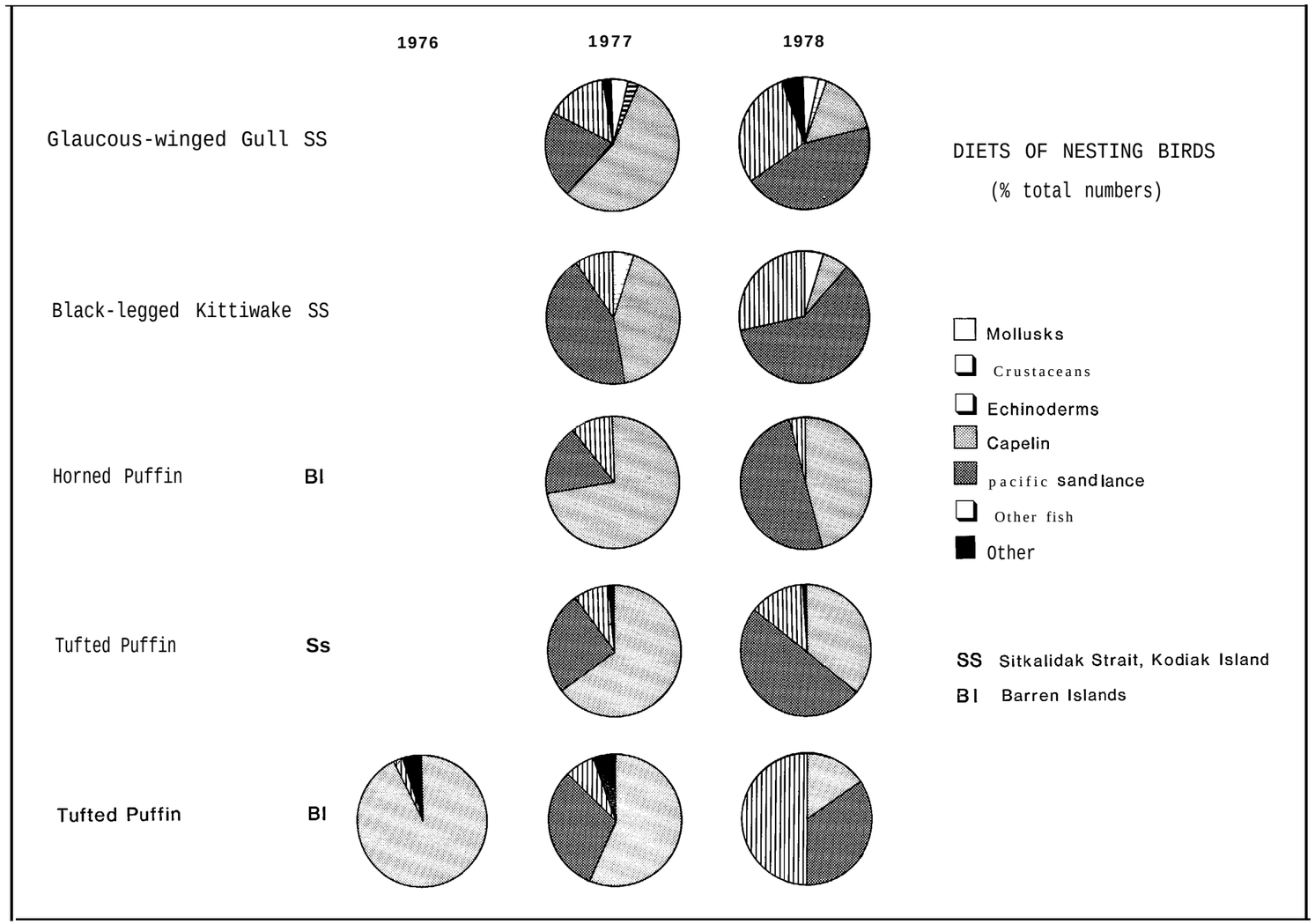


Figure 5.83 Diets of the chicks of five species of marine birds from Sitkalidak Strait, Kodiak Island, and the Barren Islands (see text for sources).

Feeding areas

The principal foraging areas for birds breeding in the Chiniak/Marmot Bay and Sitkalidak Strait areas are shewn in Fig. 5.84 (Baird, Gould, and Sanger, U.S. Fish and Wildlife Service, Anchorage, pers. comm.). Information on foraging areas is also available for the Semidi Islands (Leschner and Burrell, 1977) and Ugaiushak Island (Wehle et al., 1977).

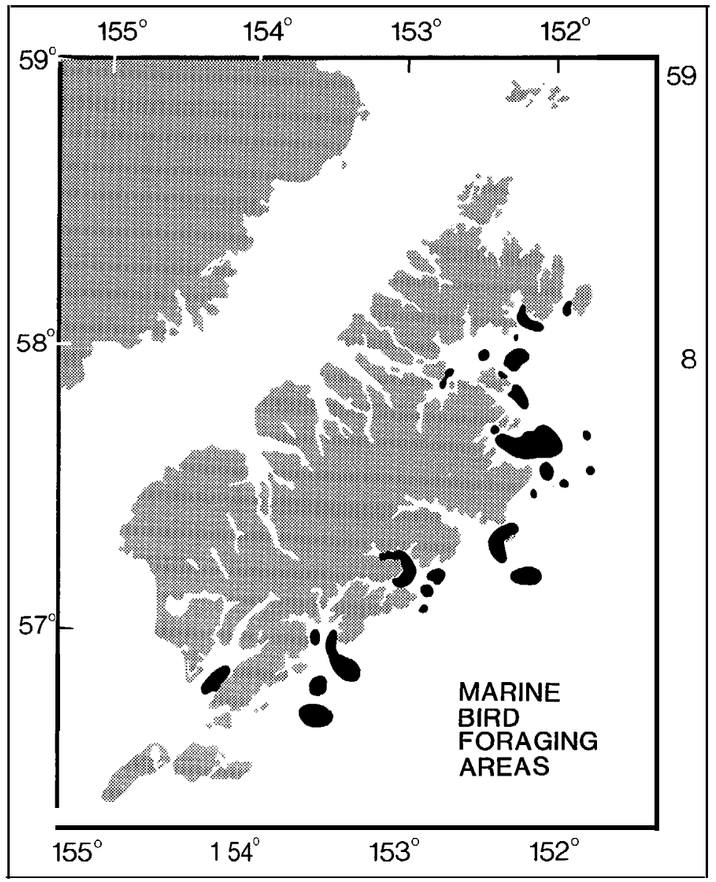


Figure 5.84 Principal foraging areas for birds breeding in the Chiniak/Marmot Bay areas and the Sitkalidak Strait area (Baird, Gould, and Sanger, U.S. Fish and Wildlife Service, Anchorage, pers. comm.).

Pigeon Guillemots fed within several hundred meters of shore at both locations; the species is well known as a littoral feeder (Bédard, 1976). Cormorants fed primarily within 2 km of shore, Horned Puffins concentrated within 3 km of shore (Ugaiushak), Black-legged Kittiwakes near shore and out of sight of land (Ugaiushak); murres fed more than 0.5 km from shore (Ugaiushak), Parakeet Auklets occasionally fed in riptides near islands, but usually over 1 km offshore (Semidis); Tufted Puffins were rarely seen feeding near land (Semidis), while Rhinoceros Auklets were never observed feeding near land (Semidis). Wehle (1976) reported that around Buldir Island Horned Puffins fed in shallower waters, usually within 1 km of the island, while Tufted Puffins fed in deeper water up to at least 15 km from land.

Wiens et al. (1978b) found that in Alaska waters most feeding flocks of marine birds occur within 5 km of land, usually in areas of greatest coastline complexity. Baird and Moe (1978) reported that in Sitkalidak Strait feeding flocks usually formed along convergence currents, especially in areas where there was a rapid change in bottom topography (Fig. 5F.22). Bédard (1976) suggests that coastline and slope configuration, water circulation, and seasonal and local characteristics (tidal rips, fronts, etc.) may be more important than simple distance from land in determining the feeding locations of marine birds. Hunt (1978) reported that foraging birds were concentrated within ten nautical miles around the Pribilof Islands and in the vicinity of the 100-meter shelf break.

Formation of flocks

Wiens et al. (1978b) studied the formation of feeding flocks in pelagic areas near Kodiak Island. They found that Black-legged Kittiwakes initiated 84 percent of the mixed feeding flocks they observed to form (Table 5.51). They concluded that other species rely on kittiwakes to locate food. Their observations of the responses of cormorants and Horned Puffins to foraging kittiwakes (Table 5.52) support this conclusion. They also present evidence that puffins have

Table 5.51 Species roles in mixed species feeding flock formation (Wiens et al., 1978b).

Species	Number of flocks in which species occurred (N = 112)	Number of flocks species initiated	Percent of flocks initated
Sooty Shearwater	3	1	33
Short-tailed Shearwater	27	9	33
Cormorants	31	2	6
Glaucous-winged Gull	23	2	9
Black-legged Kittiwake	101	85	84
Horned Puffin	52	7	14
Northern sea lion	4	4	100
Harbor seal	2	2	100

Table 5.52 Species' responses (%) to behavioral cues of Black-legged Kittiwakes in feeding flock formation (Wiens et al., 1978b).

		Kittiwake behavior	
Species	Response	Plunge & leave (N=54)	Plunge & circle (N=26)
Black-legged Kittiwake	Positive	94	100
	Negative	6	0
Horned Puffin	Positive	0	73
	Negative	100	27
Cormorants	Positive	2	88
	Negative	98	12

difficulty in locating schooling fish and suffer impaired breeding success when kittiwakes are scarce. It thus appears that a decrease in kittiwake populations caused by petroleum development activities at their nesting cliffs could have detrimental effects for other species.

Baird and Moe (1978) suggest that Arctic terns initiate feeding flocks in Sitkalidak Strait, but they do not present sufficient evidence to establish the role of each bird species in flock organization.

Both research teams cited above observed the occasional participation of mammals in these mixed feeding flocks. Wiens et al. (1978b) found that, in the formations observed, northern sea lions and harbor seals initiated all of the mixed feeding flocks in which they occurred (Table 5.51).

5.7.6 Effects of pollution

Two kinds of hazards to bird populations in the Kodiak 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 from 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 to occur, 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).

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. German 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 uncle r laboratory conditions tolerated the chronic administration of oil-contaminated food well. 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 matchability 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 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 seems to indicate 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 before they could be eaten, a food source for the birds would have been lost. This could have serious implications 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 be in the form of drilling rigs in foraging areas or in 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. Repeated disturbance to a seabird colony can cause long-term reduction in productivity (Birkhead, 1977a). 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.

Perhaps the greatest potential risk to Kodiak colonial marine birds as a result of human disturbance is predation by gulls. Gull population numbers, especially around the North Atlantic, have skyrocketed since the turn of the century as human activities have provided them with abundant winter food supplies. The increase in gull populations has usually led to greatly increased predation on other colonial-nesting birds. Indeed, Nettleship (1972) found significantly greater chick mortality for Common Puffin colonies where gull populations were high. If the disposal of human refuse is not carefully controlled in areas where oil development takes place, gull populations will soar at the expense of the populations of other species. Furthermore, gull/aircraft collisions are a serious problem worldwide, and increased Alaskan gull populations would intensify the probability of such collisions.

Bird populations in the Kodiak 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 Kodiak 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, owing to the short food chains and lack of alternative food sources. An expected result would be lowering of 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 5.53 shows OVI's for water birds of the Kodiak area. They are arranged according to ranges of OVI. According to King and Sanger (1979), an OVI of 1-20 indicates species with low vulnerabilities; damage or future costs would not be expected. An OVI of 21-40 indicates species for which there is low concern. An OVI of 41-60 indicates species for which it would not be considered catastrophic if some birds were adversely affected. These species should, however, be monitored to be sure that their status is not adversely affected. An OVI of 61-80 or 81-100 indicates species where concern is high. Comparing this table with King and

Sanger's Tables 4 and 5, which illustrate OVI's for 109 species of birds of Southeast Alaska and 123 species of birds of the Aleutian Islands, respectively, shows that there are more species in Kodiak with a higher OVI than there are in either of the areas shown by King and Sanger. This indicates that the birds of the Kodiak area, as a whole, are more vulnerable to oil development than are those of Southeast Alaska or of the Aleutian Islands.

Another hazard to birds living in the Kodiak area relates to the physical environment. An oil spill in cold regions "could have greater adverse consequences than an equivalent spill at lower latitudes" (Norton, 1977). Degradation of spilled oil by microbes would take place slowly because of lower temperatures than in temperate regions (Atlas, 1978b). Natural oxidation would also be slower. Bird species which feed in large flocks are numerous. Large populations could thus be eliminated by a single spill. Finally, cleanup and containment might be slow and difficult because of the lack of manpower and technology (Norton, 1977) and because of the storms which are so common in the Kodiak area in winter.

Table 5.53 Oil vulnerability indices of Kodiak marine birds.

OVI 1-20		OVI 21-40		OVI 41-60		OVI 61-80		OVI 81-100	
Flesh-footed Shearwater	1	Canada Goose	34	Common Loon	47	Yellow-billed Loon	65	Pigeon Guillemot	82
New Zealand Shearwater	1	White-fronted Goose	36	Arctic Loon	58	Fork-tailed Storm-Petrel	67	Marbled Murrelet	84
Manx Shearwater	1	Mallard	36	Red-throated Loon	49	Leach's Storm-Petrel	63	Kittlitz's Murrelet	88
Scaled Petrel	1	Gadwall	38	Red-necked Grebe	44	Pelagic Cormorant	63		
Blue-winged Teal	1	Green-winged Teal	34	Horned Grebe	48	Red-faced Cormorant	63		
European Wigeon	1	American Wigeon	36	Black-footed Albatross	50	Black Brant	70		
Ring-necked Duck	1	Northern Shoveler	34	Laysan Albatross	52	Emperor Goose	70		
Tufted Duck	1	Long-tailed Jaeger	39	Northern Fulmar	57	Oldsquaw	66		
Sinew	1	Herring Gull	38	Pink-footed Shearwater	47	Steller's Eider	12		
Skua	1	Ring-billed Gull	36	Sooty Shearwater	51	Common Eider	68		
Slaty-backed Gull	1	Bonaparte's Gull	40	Short-tailed Shearwater	53	King Eider	70		
Franklin's Gull	1	Arctic Tern	32	Doubled-crested Cormorant	52	Spectacle Eider	78		
				Whistling Swan	50	White-winged Scoter	72		
				Redhead	52	Surf Scoter	72		
				Canvasback	52	Common Scoter	72		
				Greated Scaup	52	Northern Phalarope	62		
				Lesser Scaup	50	Common Murre	70		
				Common Goldeneye	48	Thick-billed Murre	70		
				Barrow's Goldeneye	56	Ancient Murrelet	74		
				Bufflehead	52	Parakeet Auklet	80		
				Harlequin Duck	60	Crested Auklet	76		
				Common Merganser	56	Least Auklet	80		
				Red-breasted Merganser	56	Rhinoceros Auklet	74		
				Red Phalarope	58	Horned Puffin	72		
				Pomarine Jaeger	41	Tufted Puffin	72		
				Parasitic Jaeger	43				
				Glaucous Gull	45				
				Glaucous-winged Gull	56				
				Thayer's Gull	42				
				Mew Gull	44				
				Sabine's Gull	44				
				Black-legged Kittiwake	43				
				Red-legged Kittiwake	49				
				Aleutian Tern	53				
TOTALS	12		433		1,666		1,761		254

5.8 MAMMALS

5.8 1 Introduction

Four distinct types of mammals inhabit the marine environment in the Gulf of Alaska: the cetaceans, which include the whales, dolphins, and porpoises; the pinnipeds, which include the seals, fur seals, sea lions, and the walrus (*Odobenus rosmarus*); the sea otter (*Enhydra lutris*); and several land mammal species which frequent the beaches, littoral zone, and occasionally shallow marine water, principally to feed. The last category includes bears, foxes, the river otter (*Lutra canadensis*), and deer. All of these species have been exploited by man. Native peoples and others have used them as sources of food, pelts, and other by-products; several species have been hunted for sport and some have been widely killed as pests.

The Marine Mammal Protection Act of 1972 (PL-92-522) fully protects most marine mammal species from any exploitation except: (1) harvest for subsistence or cultural use by native peoples; (2) scientific studies by permit; (3) incidental take by fisheries under permits; (4) northern fur seal management; (5) capture for public display by permit; and (6) return of management to states complying with federal regulations. The State of Alaska has attempted to regain management authority for nine species since passage of the act, but has been unsuccessful, except for walrus. After litigation on regulation of subsistence harvests, walrus management was given back to the federal government. As a result, virtually all marine mammal management is under federal statute (MMPA, Endangered Species Act of 1973 (16 U.S.C. 1531-1543; 87 Stat. 884)) or international treaty (Convention on Conservation of North Pacific Fur Seals). Most populations of the large cetacean species have been so depleted that they have been designated as endangered or threatened under the Endangered Species Act of 1973 and by the International Whaling Commission. Northern fur seals are harvested by the U.S. under the CNPFS (Convention on Conservation of North Pacific Fur Seals), signed by Japan, the USSR, Canada, and the U.S. The most significant law for planning OCS development is the Marine Mammal Protection Act, which requires that marine mammal

> stocks should not be permitted to diminish beyond the point at which they cease to be a significant functioning element in the ecosystem of which they are a part, and, consistent with this major objective, they should not be permitted to diminish below their optimum sustainable population.

Furthermore, it is required that such stocks

> should be protected and encouraged to develop to the greatest extent feasible commensurate with sound policies of resource management and that the primary objective of their management should be to maintain the health and stability of the marine ecosystem.

Considerable knowledge of the biology of Alaskan marine mammals and of the marine ecosystems in which they live is necessary to design a plan for the development of Alaska's petroleum resources which meets the letter and spirit of this act. OCSEAP research on marine mammals has focused on obtaining such knowledge.

Relatively little is known of most marine mammal species. Even enumeration of the population can be difficult. As a result most studies being conducted are basic, emphasizing descriptive natural history. Comprehensive data may never be available even for a single tract. As a result, data collected from other areas may have to suffice for a specific tract until comparable site-specific data are developed or there is good reason to doubt their applicability. Further, the highly migratory nature of most marine mammals may require lease decisions including an examination of the status of the entire species although the site in question may only be of seasonal importance.

Marine mammals are all modified for living in the sea and share many characteristics. These species spend much of their time in cold waters and most have a variety of adaptations to maintain body temperature, such as thick layers of subcutaneous fat and countercurrent heat exchangers in the circulation to extremities. Some species also have heavy pelage. The species which rely almost exclusively on their fur for insulation, such as the northern fur seal (*Callorhinus ursinus*) and the sea otter, are particularly vulnerable to oil, since even a small amount of it fouling their pelage destroys their insulation. All Alaskan marine mammals are carnivores and are frequently at the highest trophic level in their food webs. Because of this they may be vulnerable to significant changes in the abundance and quality of organisms lower in the web.

Current knowledge of the marine mammals which occur in the Kodiak area is discussed below in an order emphasizing their dependency on the sea. The discussion starts with the cetaceans, which spend their entire lives in the water, and ends with species which venture into marine environments only occasionally.

5.8.2 Cetaceans

Of all mammals, cetaceans are most highly adapted to aquatic life. Their bodies are streamlined and fusiform (cigar-shaped), some have a dorsal fin, the forelimbs (flippers) are paddle-shaped, the hind limbs are vestigial and not visible externally, and the tail has developed into a horizontally flattened fluke. They are nearly hairless, lack sebaceous glands, and are insulated by thick blubber. Their skulls are highly modified through the migration of the external nares (nostrils) to the top of the head. The baleen whales are the largest living (or fossil) animals known. Among the cetaceans are the fastest animals in the sea; dolphins have been observed to maintain speeds of about 32 km/hr for up to 25 minutes (Johannessen and Harder, 1960) and a blue whale (Balaenoptera musculus) was observed swimming for 10 minutes at 37 km/hr (Gawn, 1948). Like all other mammals, cetaceans must breathe air, but unlike most other mammals, they are able to alternate between periods of eupnea (normal breathing) and long periods of apnea (cessation of breathing). Small cetaceans may surface to breathe several times a minute, but some whales can remain submerged for over one hour. Fin whales (B. physalus) have been recorded diving to depths of 500 m, and there is a record of a sperm whale (Physeter macrocephalus) becoming entangled in a cable at 1,134 m. The latter have been tracked on sonar to nearly 1,828 m and by hydrophore to 2,427 m. Inferential evidence suggests diving capability in excess of 3,150 m and there is speculation they have no depth limit. The physiological and morphological adaptations of cetaceans to deep and prolonged dives are discussed by Slijper (1962), Elsner (1969), Kooyman and Andersen (1969), and Lenfant (1969).

Baleen whales (Mysticeti)

Baleen whales differ from other cetaceans in several ways but particularly in their dentition (Vaughan, 1972; Nishiwaki, 1972). Although baleen whales develop teeth in the fetal stage, these never erupt; after birth a series of baleen plates develops from the palatine ridges. All baleen whales are filter-feeders; they allow food-rich water to pass into the mouth and through the baleen plates. The fringed medial surface of baleen overlaps with adjacent baleen fringes to form a sieve-like filter. The food strained from the water by the baleen is gathered by the tongue and swallowed.

Distribution

Seven of the nine known species of baleen whales are known to occur in the Gulf of Alaska: gray whale (Eschrichtius robustus), minke whale (Balaenoptera acutorostrata), sei whale (B. borealis), fin whale (B. physalus), blue whale (B. musculus), humpback whale (Megaptera novaeangliae), and right whale (Balaena glacialis). All of these except the minke whale have been designated as endangered or threatened. Bryde's whale (Balaenoptera edeni), which occurs in the temperate North Pacific, and the bowhead whale (Balaena mysticetus), which is found in arctic waters, could stray into the gulf, although this seems unlikely and there are no records of its occurrence.

It has long been known that the entire eastern Pacific population of gray whales migrates annually from wintering grounds along the southwestern coast of North America to summering grounds in the Bering Sea and Arctic Ocean. They perform the longest known mammalian migration, traveling from 10,000 to 22,000 km round trip (Vaughan, 1972). The details of routes taken between the Gulf of Alaska and the Bering Sea, however, have been the subject of considerable debate (Gilmore, 1978). Recent work (Braham, 1977; Braham et al., 1977; Hall, 1979) indicates that the route shown in Fig. 5.85 is probably the one taken by this species. The species closely follows the coastline during both north- and southbound migrations in the Gulf of Alaska; in some areas during good weather about 70 percent are found within 700 m of the shore during the autumn southbound migration (Rugh and Braham, 1978).

Whaling records show that the area southwest of Kodiak was once an important area for sei, fin, and blue whales (Nishiwaki, 1966). Recent sightings of minke, sei, fin, and humpback whales have been made

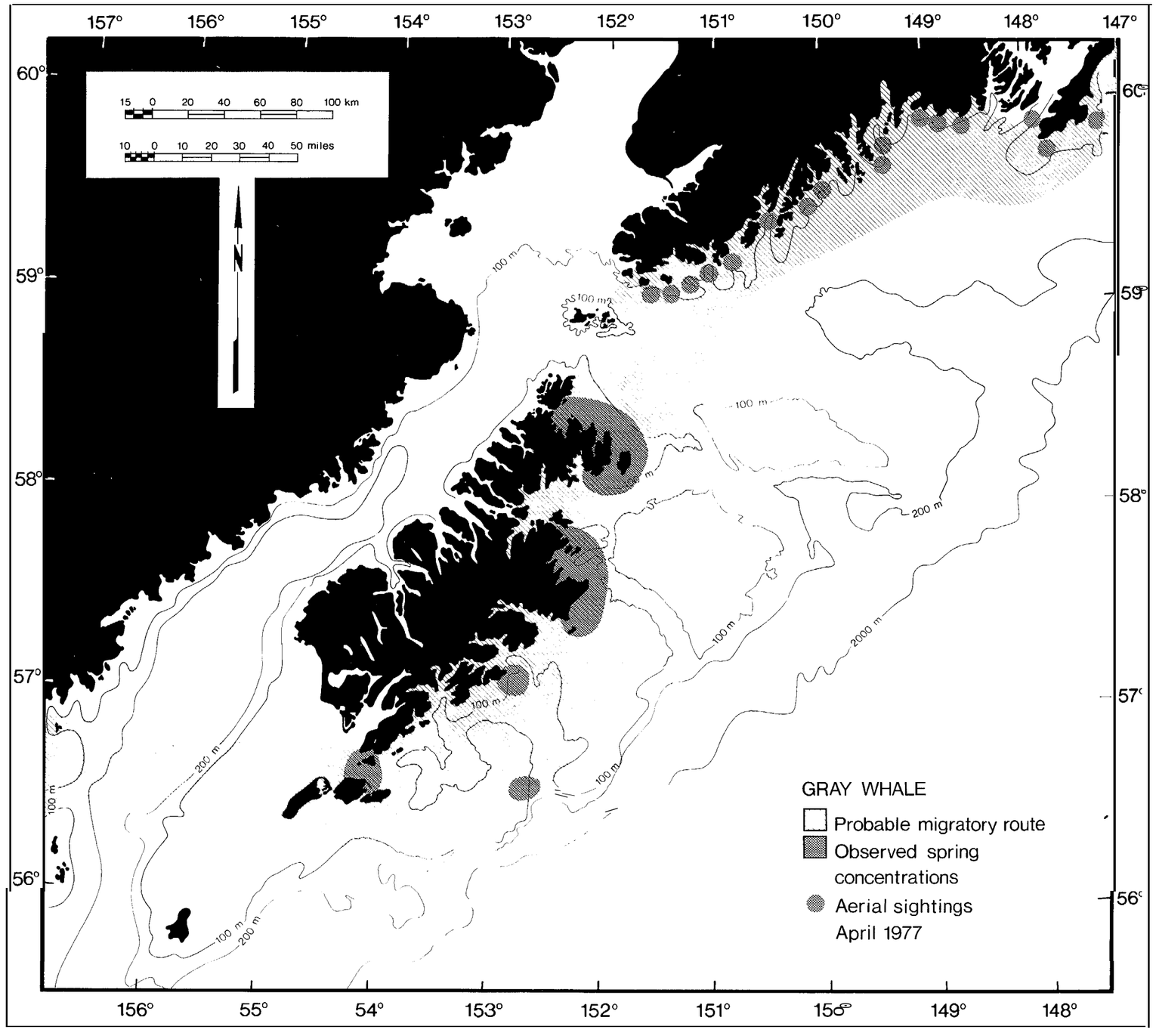


Figure 5.85 Probable migratory route of the gray whale (Braham, National Marine Mammal Laboratory, unpublished data; Hall, 1979).

near Prince William Sound and in the region south of Montague Island (Fiscus et al., 1976). The distribution of sightings of minke, sei, blue, and humpback whales near Kodiak (Fiscus et al , 976) for all seasons from 958 through 976 is shown in Fig. 5.86. The seasonal distribution of sightings of the fin whale throughout the Gulf of Alaska (Braham, National Marine Mammal Laboratory, NOAA, unpub data is shown in Fig. 5.87. These sightings demonstrate that during the spring fin whales are distributed throughout the Gulf of Alaska, perhaps indicating migration into the gulf. There are no recent reports of sightings of right whales in the gulf. The distributions shown in Figs. 5.86 and 5.87 are concentrated near or within the shelf

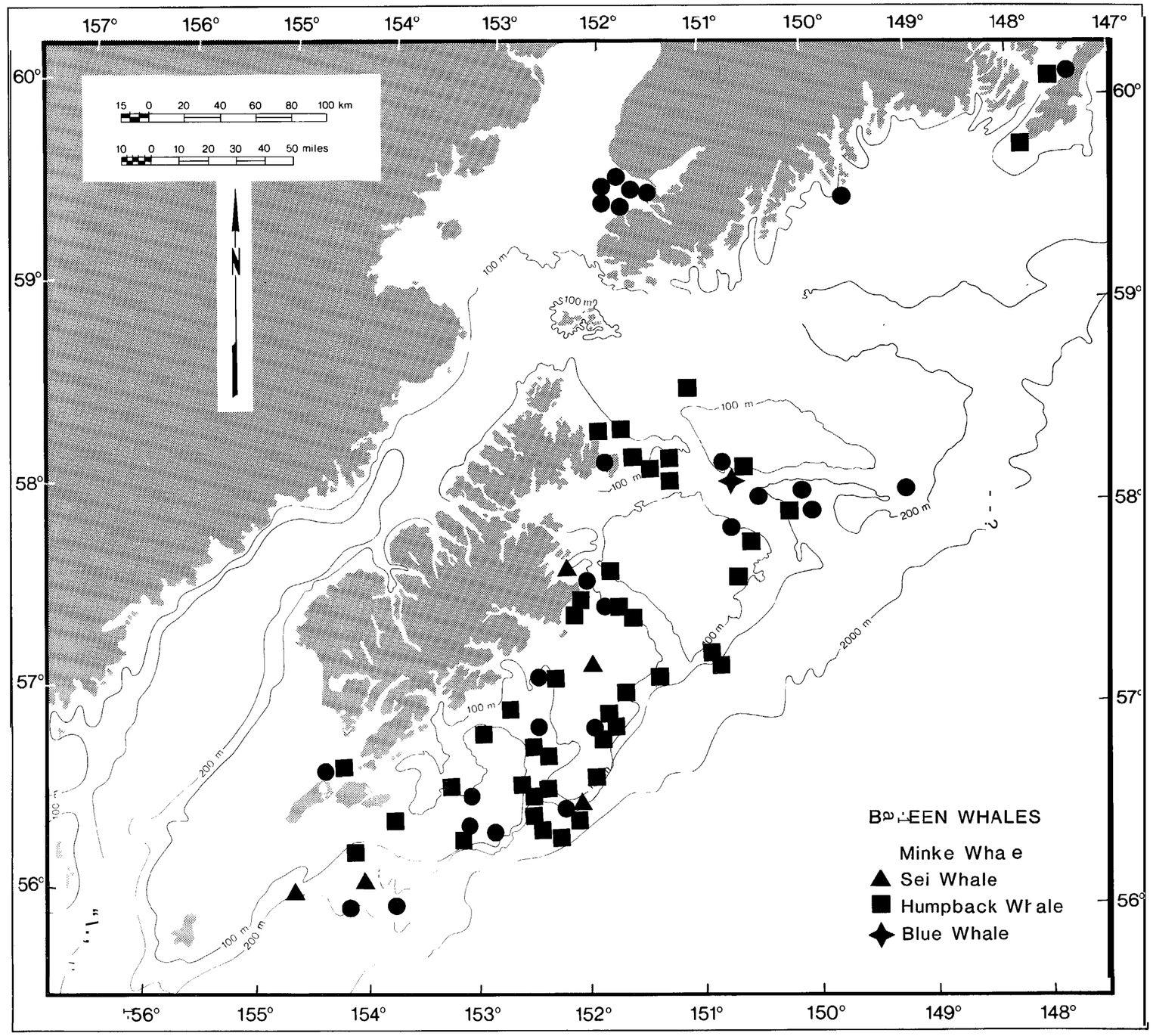
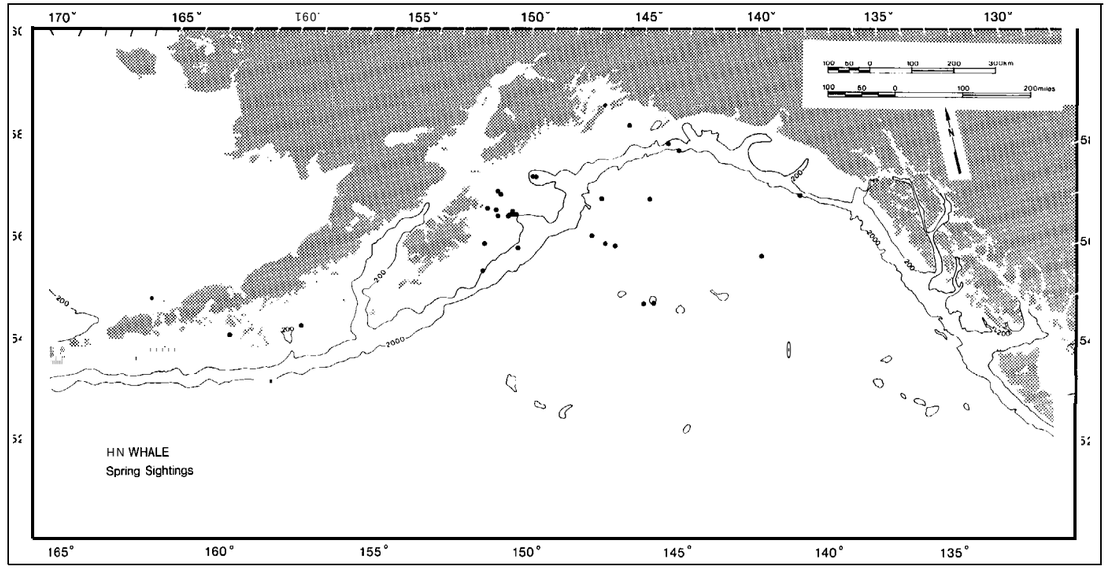
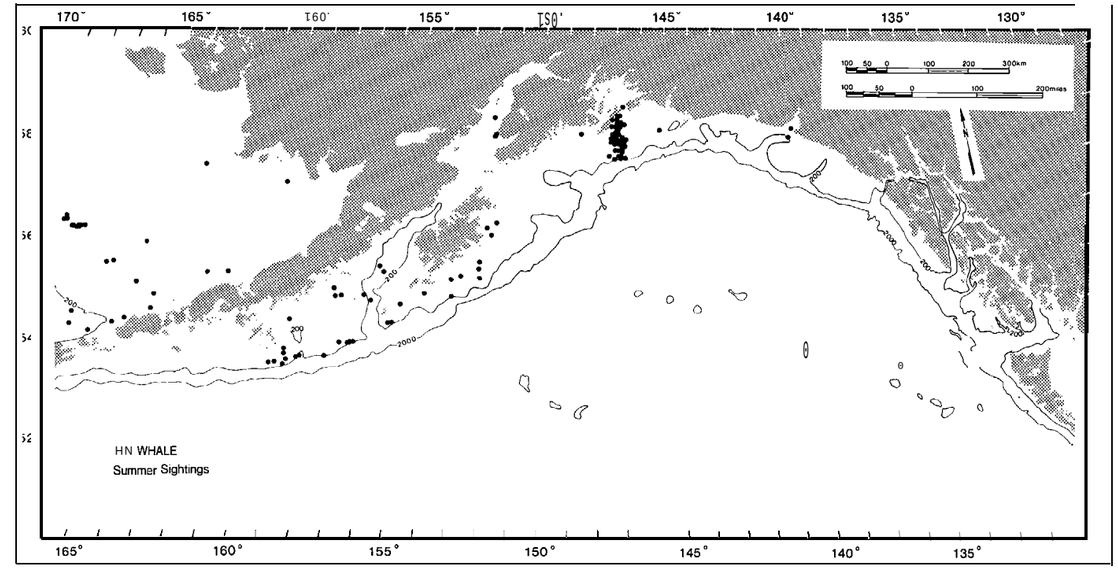


Figure 5.86 Distribution of sightings of four species of baleen whales for all seasons from 1958 through 1976 (Fiscus et al., 1976).





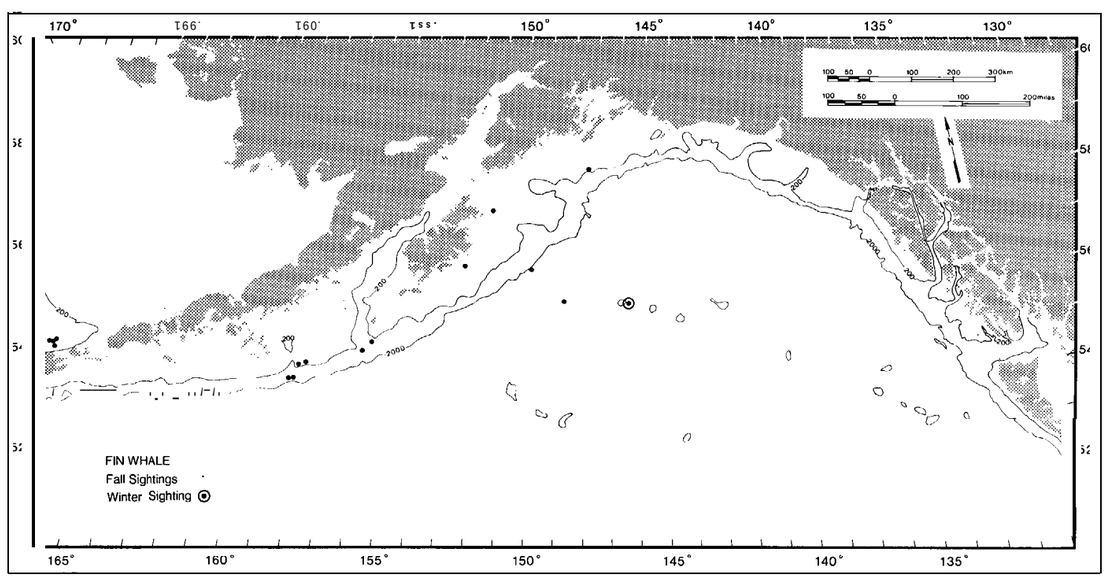


Figure 5.87 Seasonal distribution of fin whale, 1958 through 1977 (Braham, National Marine Mammal Laboratory, unpublished data).

break and indicate that baleen whales have been sighted most frequently in waters less than 2,000 m deep. Unfortunately, sampling throughout the gulf was not uniform. Sightings of humpback whales within the 2,000 m depth contour adjacent to the entire southeastern shore of Kodiak Island are frequent (Fiscus et al., 1976). Nasu (1974) suggests that in summer baleen whales prefer areas where coastal and oceanic waters mix. The general migratory hypothesis is that most baleen whales migrate to polar waters in summer months to feed and to more temperate waters in winter to breed and calve. Humpback whales in Alaska have been identified from photographs by distinctive coloration (and other features) off Hawaii and the Revillagigedo Islands (20°S) south of Baja, Mexico (Darling, unpub. data).

Population dynamics

At least four different aspects of the natural history of whales must be known to understand their population dynamics and to make predictions of how the population might respond to environmental perturbations. These are the immature mortality rate, the age of first reproduction, the fecundity of the females, and the adult mortality rate (Eberhardt, 1977). This information is extremely difficult to gather, as it may necessitate collecting whales to determine age, structure of the population, and reproductive status of individuals. Even population estimates for cetaceans are difficult due to the short period of time they spend at the surface, especially if their populations are small and/or widely distributed. Reproductive rates are usually low for large, long-lived animals. The gestation period for most baleen whales is about 10 to 12 months, and females probably breed only once every two years (Nishiwaki, 1972; Vaughan, 1972) but may breed as infrequently as every four years as suspected for southern right whales (Payne, unpub. data). Whether females breed the year after an early termination of pregnancy or loss of a calf soon after birth is not known.

The large species of baleen whales have been over-exploited, and their populations have declined to such an extent that most are now recognized as endangered (Nishiwaki, 1972; Scheffer, 1972; Rice, 1974). Recent estimates of North Pacific stocks are gray whales: 15,000 (Rugh and Braham, 1978); minke: 10,000 (Nishiwaki, 1972); sei: 28,000 (Rice, 1974); fin: 17,000 (Tillman, 1975); blue: 1,500 (Tillman, 1975); humpback: 850 (MMPA, 1978); and right: 200 (Tillman, 1975). Only the gray whale population, which was almost exterminated early in the century, has recovered significantly under protection.

Trophies

Most baleen whales eat mainly large quantities of planktonic species (amphipods, copepods, and euphausiids), although gray whales feed almost exclusively on benthic amphipods, and small fishes can be regionally important to humpbacks (Pike, 1962; Nemoto, 1970; Nishiwaki, 1972; Table 5.54, Fig. 5.88). Baleen whales exhibit two typical pelagic feeding patterns: swallowing, in which large patches of clumped prey are swallowed at one time, and skimming, in which dispersed prey are caught by swimming with the mouth open for extended periods (Mitchell, 1978; Pivorunas, 1979). Gray and sei whales apparently use both methods; minke, fin, blue, and humpback whales are swallowers, and

Table 5.54 Principal food types and feeding strata of baleen whales (Pike, 1962; Nemoto, 1970; Nishiwaki, 1972).

Species	Principal food types	Feeding strata
Gray Whale	amphipods	Coastal-benthic
Minke Whale	fish euphausiids copepods	Surface-photic zone
Sei Whale	copepods	Surface-photic zone
Fin Whale	euphausiids copepods fish	Surface-photic zone
Blue Whale	euphausiids	Mid-water
Humpback Whale	euphausiids fish	Surface-photic zone
Right Whale	copepods euphausiids	Surface-photic zone

right whales are skimmers. Swallowers rely on heavy patches of prey, such as euphausiids and gregarious fish, while the skimmers feed on more sparse plankton patches. Humpbacks are known to concentrate fishes by the use of exhaled air underwater to form a "bubble-net." Skimmers may be more vulnerable to the presence of oil, whether benthic or pelagic, since they must process large volumes of water per volume of food ingested.

Information on the carrying capacity of the Gulf of Alaska for cetaceans is lacking. Generally, the larger species of whales feed heavily for four or more months in arctic and subarctic regions where food supplies are abundant during long polar summer days, then migrate to subtropical regions to breed and calve during winter, where they appear to fast (Brodie, 1975). During the feeding season they build up large quantities of fat, which are then metabolized during the winter fasts. Crude estimates of dietary needs (Brodie, 1975) and current cetacean populations in the North Pacific (Scheffer, 1972; Fiscus et al., 1976) indicate that baleen whales there consume about 50,000 metric tons of food per day. These species thus rely on a seasonal superabundance of food and are vulnerable to its reduction or contamination.

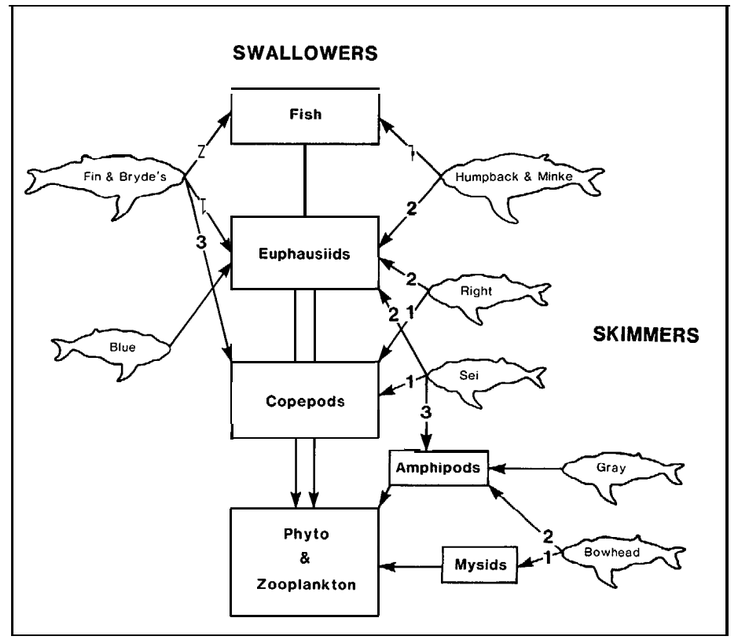


Figure 5.88 Generalized food web showing predation by swallowing and skimming baleen whales on main food sources. "Skimmers" strain a long column of water with their mouth continuously open, whereas "swallowers" gulp a mouthful at a time, then close the mouth, squeeze the water out, and retain the food (modified from Mitchell, 1978).

Toothed whales, dolphins, and porpoises (Odontoceti)

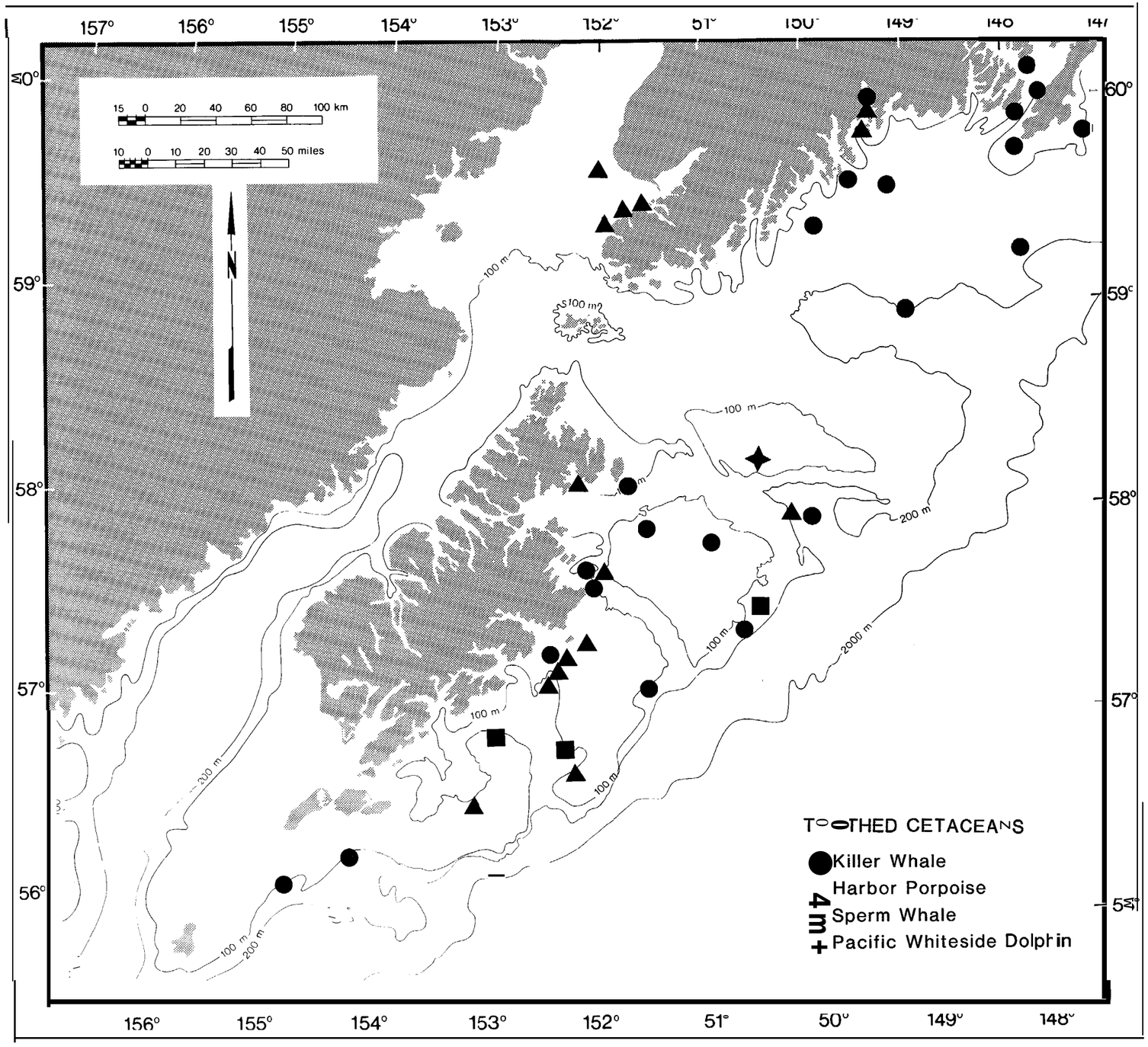
Odontoceti are distinguished by their teeth. Unlike most other mammals, they have permanent dentition at birth. They are the most important cetaceans in terms of abundance, diversity, and widespread distribution.

Distribution

The Odontoceti include about 74 recent species. Of these, about six occur regularly or frequently in the Gulf of Alaska: Pacific whitesided dolphin (Lagenorhynchus obliquidens), killer whale (Orcinus orca), harbor porpoise (Phocoena phocoena), Dall porpoise (Phocoenoides dalli), beluga (Delphinapterus leucas), and sperm whale. The sperm whale has been designated an endangered species. Fiscus et al. (1976) list six more species which are of casual or hypothetical occurrence in the gulf. It is likely that other Pacific species will occasionally enter gulf waters.

The area southwest of Kodiak was once an important area for sperm whales. The distribution of sightings of Pacific whitesided dolphin, killer whale, harbor porpoise, and sperm whale near Kodiak (Fiscus et al., 1976; Mercer et al., 1977) for all seasons 1958 through 1976 is shown in Fig. 5.89. The distribution of these sightings, like those of baleen whales, indicates that these species may prefer areas within the shelf break.

The beluga is a summer resident in Lower Cook Inlet and a year-round resident in the Bering Sea. The Lower Cook population is considered by Sergeant and Brodie (1969) to be geographically isolated and therefore it may be genetically distinct from the Bering Sea population. The wintering grounds of the Cook Inlet population are unknown. Harrison and Hall (1978) made only two sightings of belugas near Kodiak (one in March

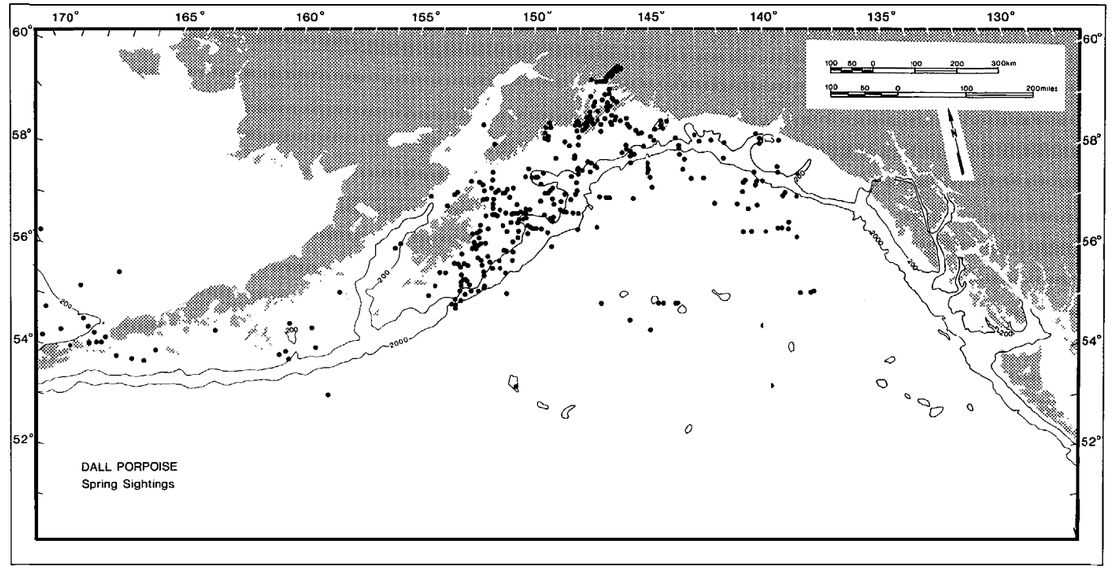


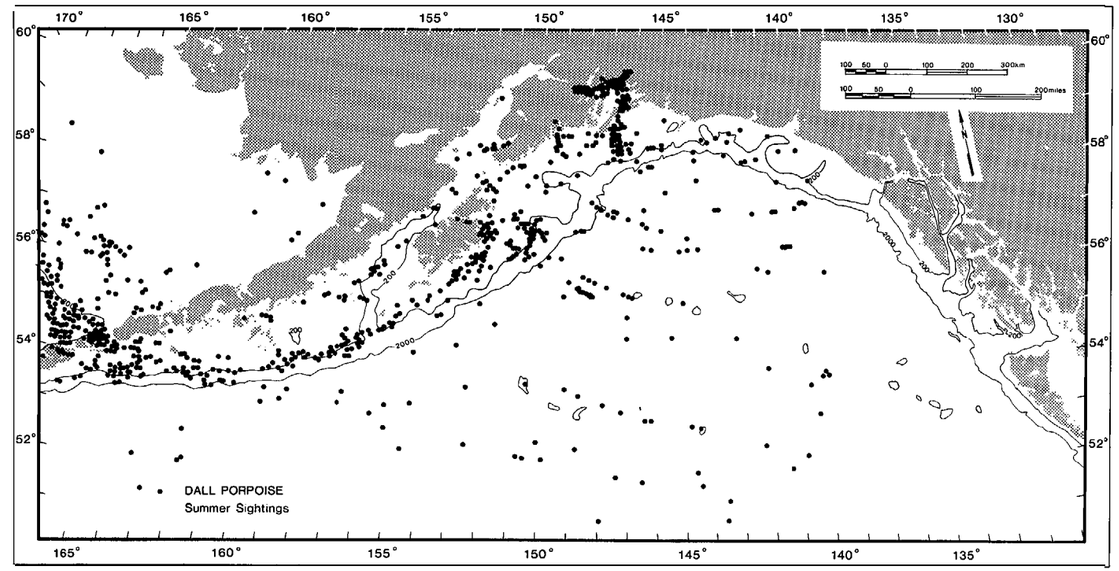
and two in July) in the course of 40,000 km of aerial surveys in the gulf.

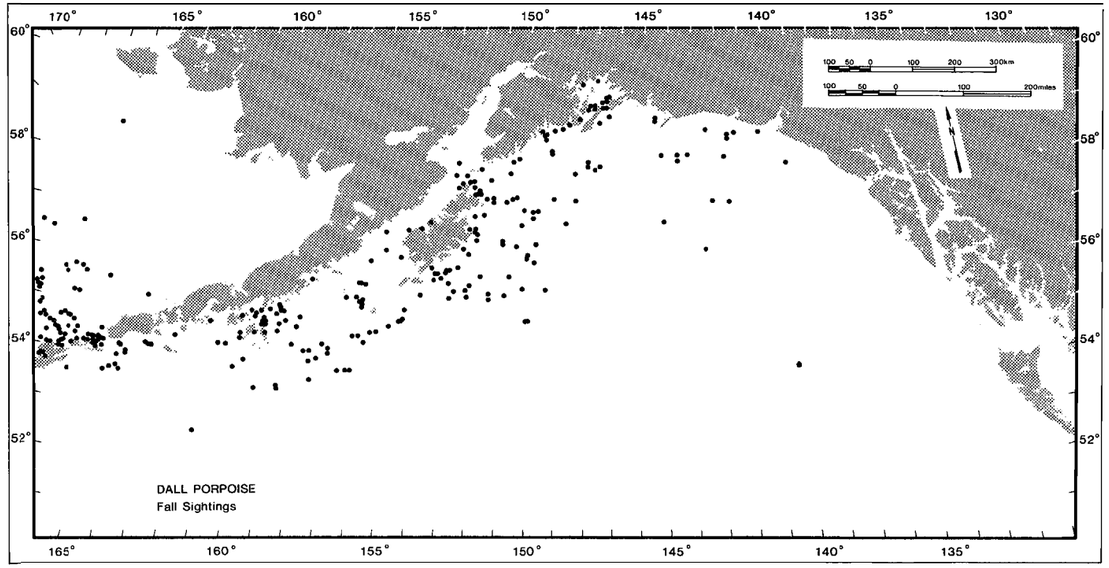
Although the Pacific whitesided dolphin is rarely sighted in the gulf, a school of over 500 was seen just outside Montague Strait in October 1976 (Hall and Tillman, 1977). This species is thought to occur in tion with warm surface temperatures; it not seen in the gulf in 1977 when surface temperatures were cooler than in 1976

In general, relatively little is known about the movements and abundance of the small cetaceans because they are difficult to study and of little commercial value Scheffer, 1972). Of the smaller cetaceans, only the harbor porpoise and the Dall porpoise are considered mm The harbor porpoise is a rather shy species which appears to prefer quiet bays and never plays at the bows of ships (Scheffer, 1972). Its status in the Kodiak area is unknown The Dall porpoise, on the other hand, feeds in large groups and often plays at the bows of ships (Scheffer, 1972) As would be expected, it is frequently reported from shipboard urveys. The seasona distribution of sightings of Dal porpoise is shown in Fig. 5.90. These sightings show that Dall porpoise are ubiquitous throughout the Gulf of Alaska in all seasons, with an

Figure 5.89 Distribution of sightings of four species of toothed cetaceans for all seasons from 1958 through 1976 (Fiscus et al., 1976; Mercer et al., 1977).







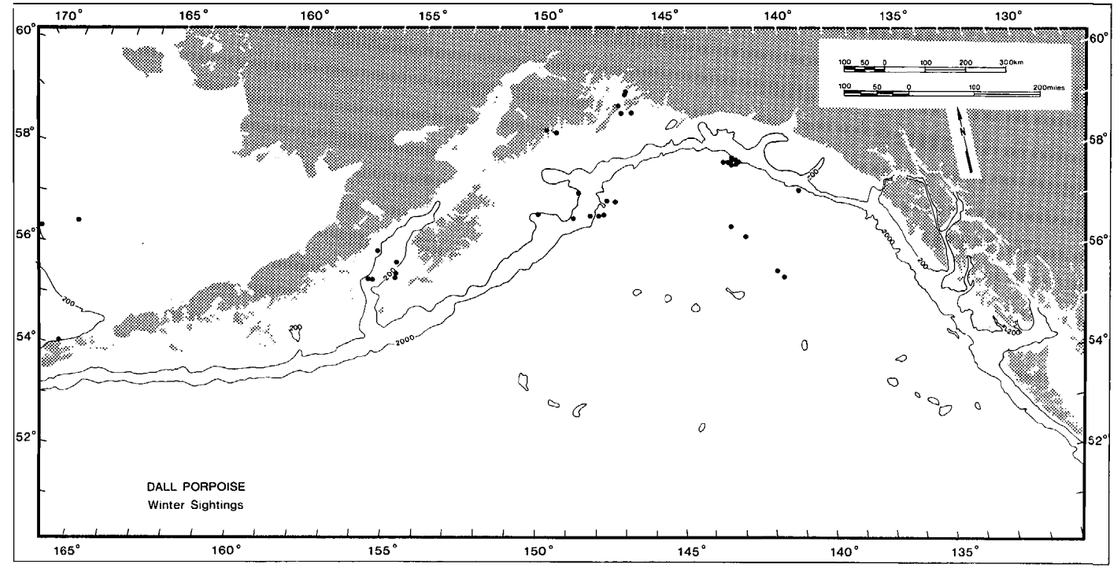


Figure 5.90 Seasonal distribution of Dall porpoise, 1958 through 1977 (Braham, National Marine Mammal Laboratory, unpublished data).

apparent concentration from Kodiak waters to Prince William Sound in the spring. The frequency of occurrence of the species in the Gulf of Alaska appears to be strongly influenced by water temperature (Fig. 5.91) (Braham and Mercer, 1978). Dan porpoises are believed to be migratory, but the details of their seasonal movements are unknown. Because of the relatively large incidental take of Dan porpoises by Japanese high sea gillnetters harvesting salmon, studies are being conducted by the National Marine Fisheries Service to learn more about this species.

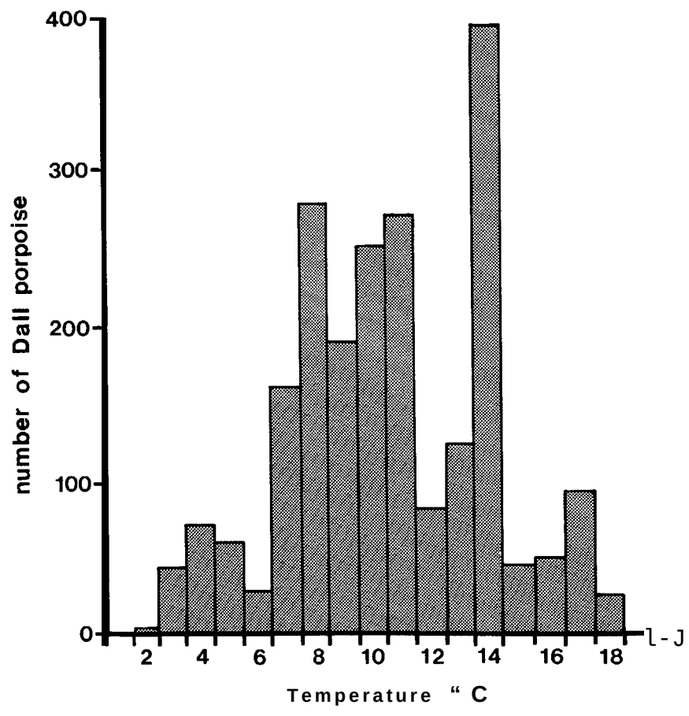


Figure 5.91 Abundance of Dan porpoise as a function of sea surface temperature (Braham and Mercer, 1978).

Population Dynamics

The gestation period for the smaller toothed whales, dolphins, and porpoises ranges from about 8 to 14 months and females produce one young every one to four years (Vaughan, 1972). For the sperm whale the gestation period is about 15 months, and a female bears one young every four or five years; sperm whale calves may nurse for two years before weaning (Rice, 1978).

There are few data on which to base population estimates for the toothed cetaceans in the Gulf of Alaska. Those of Scheffer (1972) appear to be educated guesses. Fiscus et al. (1976) suggest that Scheffer's estimate of a population of 1,000 harbor porpoise for the northwestern Gulf of Alaska is too low to account for the number of sightings of the species. ADF&G (1973) estimates that the beluga population of Cook Inlet is about 500. Tillman (1975) estimates the North Pacific stock of sperm whales to be about 200,000. The Japanese high sea gillnet salmon fishery is reported to kill more than 10,000 Dan porpoises annually (Mizue and Yoshida, 1965; Mizue et al., 1966). Fiscus et al. (1976) believe that this kill rate has "only indirect" effect on the gulf population, as it is thought not to migrate routinely as far west as 175° W, the fisheries' eastern limit.

Trophies

Toothed cetaceans in the Gulf of Alaska eat mainly fish, cephalopods, and, in the case of killer whales, some other marine mammals (Table 5.55).

Table 5.55 Principal food types and feeding strata of toothed cetaceans (Pike, 1962; Nemoto, 1970; Nishiwaki, 1972) .

Species	Principal food types	Feeding strata
Killer whale	fish cetaceans pinnipeds	Surface-photic zone
Harbor porpoise	fish	Surface-photic zone
Dan porpoise	fish cephalopods	Surface-photic zone
Beluga	fish	Benthic-ocean floor Surface-photic zone
Sperm whale	cephalopods fish	Benthic-ocean floor Mid-water

Effects of oil and gas development on cetaceans

Because of their size, the expense of capture and maintenance, and legal concerns, only limited experimentation has been carried out on the effects of human activities on cetaceans. At present most predictions of the possible effects that OCS development might have on cetaceans are based on fixed observations and are often extrapolated from what is known about other mamma 1s. Work has recently begun to investigate the direct effects of oil on cetaceans. Additional work on the possible effects of noise and baleen fouling by oil has also been initiated.

Cetaceans produce a wide variety of sounds which have been shown or hypothesized to be important in their communication and navigation (Caldwell and Caldwell, 1972; Thompson et al., 1979). Background noise from human activities might cause social disruption or echo-confusion.

The effects of oil on cetaceans are unknown. There appear to be no documented cases of cetacean mortalities directly attributable to oil. Brownell (1971) was unable to find any evidence that petroleum caused the deaths of 11 cetaceans found stranded on California beaches after the Santa Barbara Channel oil spill. Possible effects of oil on cetaceans can be inferred from current knowledge of these animals. Tinyakov et al. (1973) and Dargoltz et al. (1978) report that the cetacean epidermis has high metabolic activity. Since the outermost layer is unkeratinized (Ling, 1974), oil contacting the skin surface might affect ionic regulation and water balance. Heavy oils might clog baleen plates, while light oils might damage their structural integrity. Studies currently in progress may contribute more information in the near future. The effects of ingested or inhaled oil are unknown. Carpenter et al. (1978) report that prolonged inhalation of hydrocarbons by rats caused central nervous system disturbance, bronchopneumonia, and death.

5.8.3 Pinnipeds

Pinniped morphology and behavior are modified for an amphibious marine life. All species use the land (or ice) to breed, give birth, or molt, to varying degrees. The harbor seal (*Phoca vitulina*) may spend time on land daily, while the northern fur seal may spend from six to eight months at sea. Pinnipeds appear awkward on land, but some can move quickly and many species haul out only near the water's edge, perhaps to reduce the risk from land-based predators. Perhaps in response to land-based predators and human harassment, many rookeries and haulouts are on islands. The northern fur seal is believed to have the longest migratory path of all pinnipeds and may cover 10,000 km a year. Scheffer (1958) estimated the top swimming speed of a northern (Steller) sea lion (*Eumetopias jubatus*) to be 29 km/hr. The body is enveloped in a thick layer of fat, which provides insulation and an energy reserve during lactation and fasting. They have large eyes, which may be an adaptation for feeding at night and in deep or murky waters. Pinnipeds have slit-like nostrils, which are closed except when voluntarily opened to breathe. The Weddell, an Antarctic species, can dive to depths of at least 600 m or stay submerged over 45 minutes on a single breath (Kooyman and Andersen, 1969). Dives of up to 20 minutes have been reported for several species, including the harbor seal (Scheffer and Slipp, 1944; Backhouse, 1954). Among their adaptations to prolonged dives are slowing of the heart rate, reduced blood flow to the limb muscles thus conserving the available oxygen in the blood primarily for the heart and brain, a high tolerance to CO_2 in the tissues, large amounts of oxygen-storing myoglobin in the muscles, and a more pronounced capability for anaerobic (oxygen-less) metabolism than terrestrial mammals.

Members of two pinniped families occur regularly in the Gulf of Alaska. The family Otariidae, the eared seals, includes the northern (Steller) sea lion and the northern fur seal which are found year round and the California sea lion (*Zalophus californianus*), which is seen occasionally during winter. The family Phocidae, true or earless seals, is represented year round by the land-breeding harbor seal (*P. v. richardsi*) and the occasional northern elephant seal (*Mirounga angustirostris*).

Otariids swim primarily with their foreflippers and rotate their hind flippers beneath their bodies for quadripedal locomotion on land. They are also characterized by small external ears and heavy pelage (especially the fur seals). They are gregarious throughout the year and gather in large breeding rookeries. Typically the mature males are much larger than the mature females. All species are polygynous, with males fighting for breeding territories or access to estrous females. Pups may be suckled for over eight months in some species.

Phocids swim primarily with their hind flippers and as a result cannot rotate them forward to be used on land. Instead these animals rhythmically undulate the torso forward or pull themselves forward using

their foreflippers. Phocids lack external ears, and they have a relatively short pelage. There are both monogamous and polygynous species in the family. Pups usually wean within six weeks (Pitcher and Calkins, 1979) .

Distribution

The northern sea lion is distinctive in its use of a few specific locations along the coast as breeding and pupping rookeries and hauling grounds. In late May the adults gather on the breeding rookeries, where dominant bulls fight for territories. Females arrive and pupping, followed by mating, takes place on these territories. The bulls usually desert their territories by early July toward the end of the breeding season. Mature males unable to obtain territories on the rookeries and females without pups gather on hauling grounds, where mating sometimes takes place (Calkins et al., 1975).

Northern sea lion haulout areas and rookeries occur throughout the Kodiak area (Fig. 5.92) (Calkins and Pitcher, 1977, 1978). The population size is probably in excess of 30,000 (Table 5.56). Available data do not indicate that the 40-50 percent population decline of the species over the last 10 years identified in the Eastern Aleutian Islands (Braham et al., 1977) is also occurring in the Kodiak Area. Major

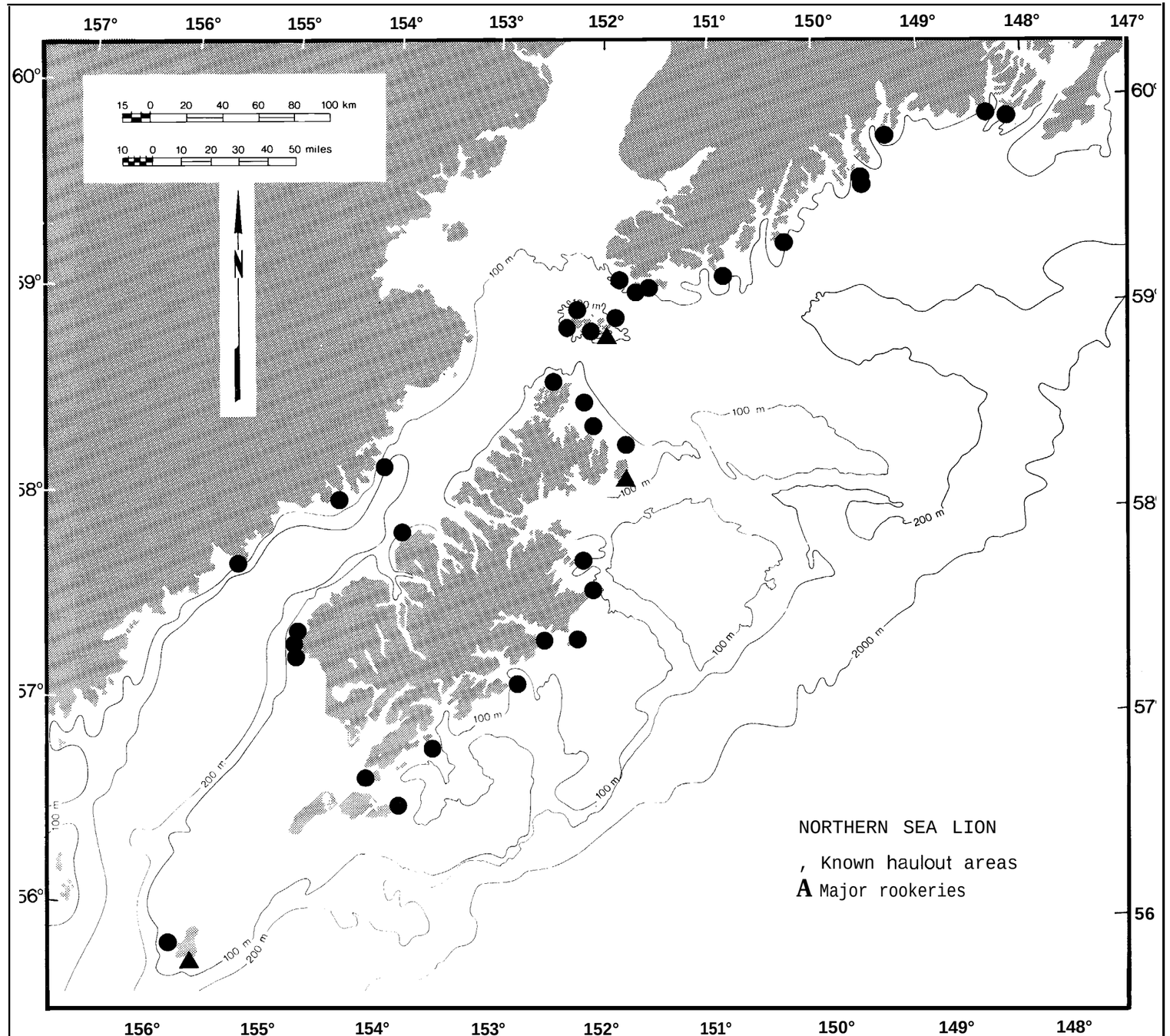


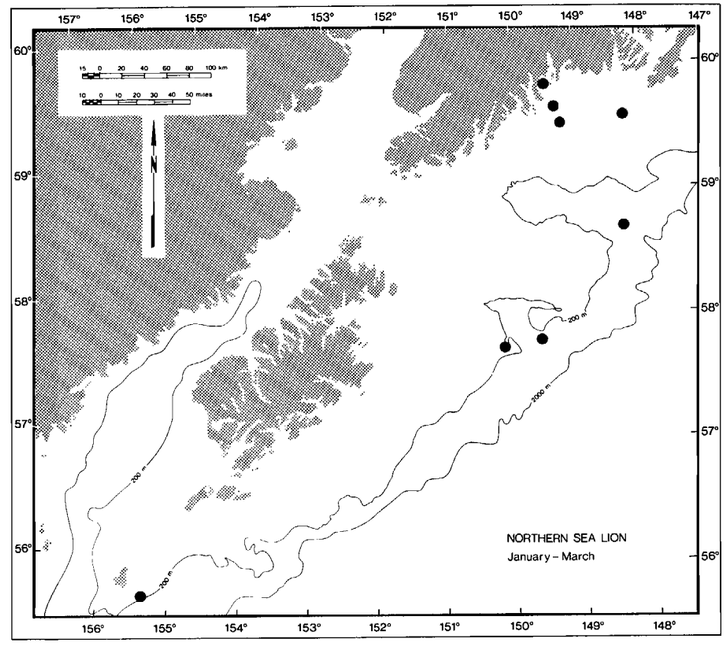
Figure 5.92 Distribution of northern (Steller) sea lion haulout areas and rookeries (Calkins and Pitcher, 1977; 1978).

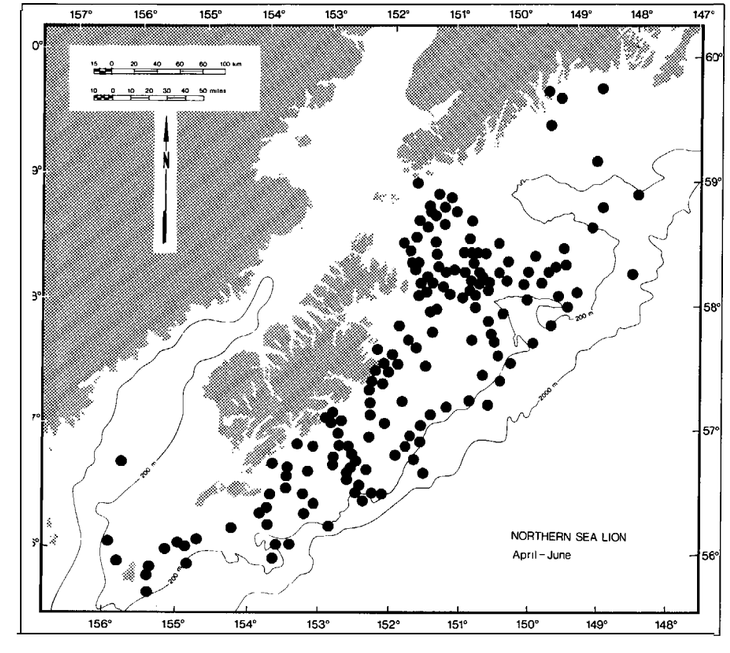
Table 5.56 Population estimates of northern (Steller) sea lions (Calkins and Pitcher, 1977; 1978).

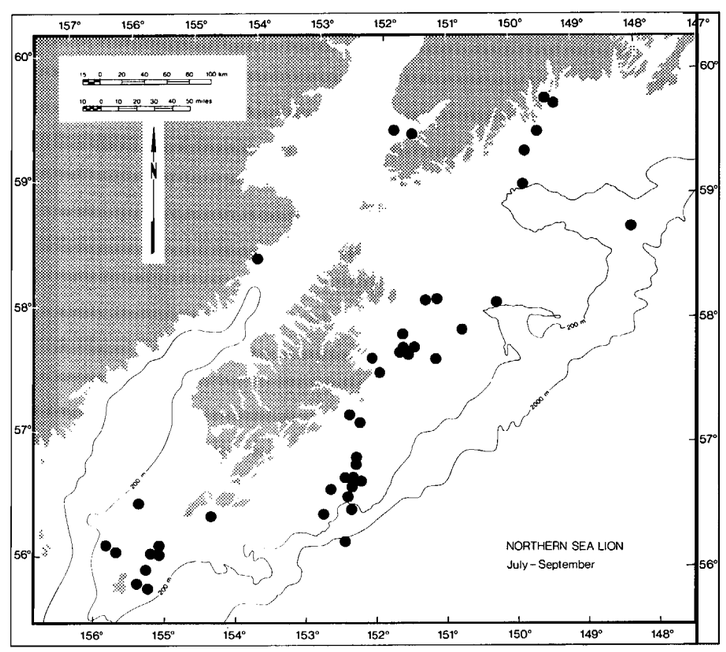
Location	1957 Mar	1957 Jun	1975 Oct	1976 Mar	1976 Jun	1976 Oct	1977 Mar
Barren Islands	585	12797	7547	388	8100	-	-
Latax Rocks	-	3334	466	322	1164	1	-
Sea Otter Island	-	-	398	51	541	227	-
Sea Lion Rocks	1600	302	121	127	432	21	-
Marmot Island	1425	4157	8256	3655	9862	7670	-
Long Island	-	-	0	62	0	-	-
Cape Chiniak	-	-	-	883	365	122	-
Gull Point	-	-	-	28	145	-	-
Cape Barnabas	540	1598	-	120	364	28	-
Twoheaded Island	2740	2810	-	1636	1615	1469	-
Cape Sitkinak	470	343	-	257	120	302	-
Chirikof Island	-	1742	-	3879	2391	5332	-
Nagai Rocks	-	-	-	1401	657	554	-
Cape Ikolik	-	-	-	425	385	1213	-
Cape Ugat	-	-	-	222	0	0	-
Cape Gull	-	-	-	0	207	-	-
Takli Island Rocks	-	-	-	1014	1877	700	413
Puale Bay	-	-	-	1014	1877	10000	14234+
TOTALS	7360	27083	16788	15484	30102	27639	14647+

rookeries are present on Sugarloaf (Barren Islands), Marmot, and Chirikof Islands (Fig. 5.92). In 1976 these three rookeries produced about 11,000 pups, or an estimated 9[illegible] percent of the Kodiak Area production and about 60 percent of the pup production of the entire Gulf of Alaska (Calkins and Pitcher, 1977).

The seasonal pelagic distribution of sea lions is shown in Fig. 5.93. These observations indicate that sea lions range out to the shelf throughout the year (Mercer et al., 1977).







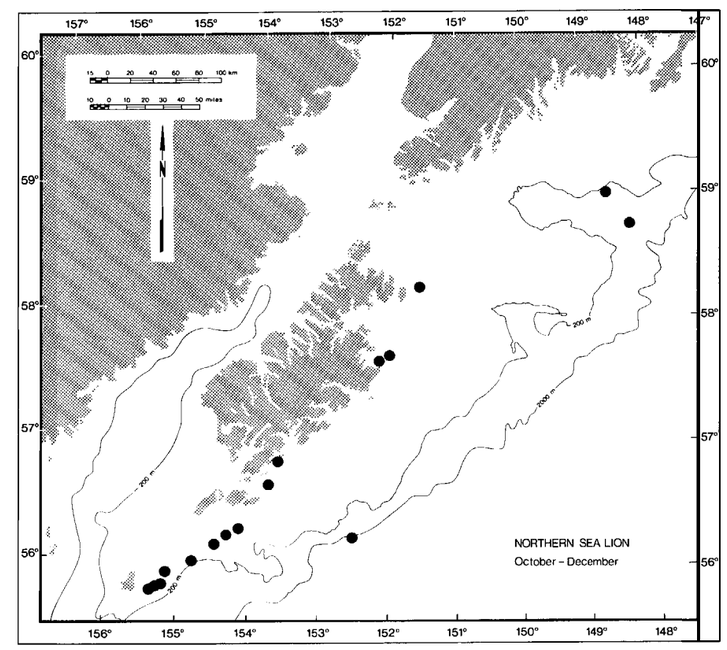


Figure 5.93 Marine sightings of northern (Steller) sea lion for various seasons (Mercer et al., 1977).

Considerable movement of sea lions in the Gulf of Alaska (Fig 5.94) has been detected by observing individuals branded on their natal rookeries (Calkins and Pitcher, 1979). Fig. 5.94 illustrates the extent of some of this movement. These movements appear to be a combination of dispersal of the young and seasonal movements. Calkins and Pitcher (1979) report that of 6,429 pups branded in 1975 and 1976 at Marmot Island (66 percent) and Sugarloaf Island (34 percent), only a few (less than 4 percent) were resighted in 1978 as two- or three-year-olds. Of those resighted at Sugarloaf, 53 percent were branded there as pups and the remainder were branded at Marmot Island. Sea lions have largely moved away from their rookeries of birth and have been sighted at haulouts from Chirikof and the Semidi Islands in the southwest to Cape St. Elias in the northeast. Studies at the latter site and Sugarloaf Island indicate differences in haulout patterns for branded sea lions. Branding studies such as these yield considerable information on the dispersal and seasonal movements of sea lions, which may be extremely important in estimating any long-term impact of spills or blowouts, should adverse effects to this species be found (Calkins and Pitcher, 1979).

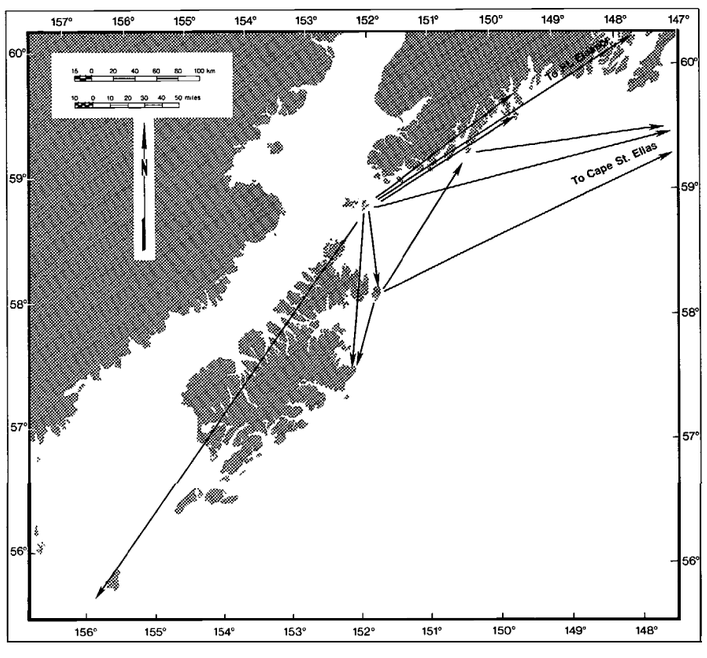


Figure 5.94 Movements of branded northern (Steller) sea lions (Calkins and Pitcher, 1977).

Northern fur seals occur throughout the Gulf of Alaska (Fiscus et al., 1976; Marine Mammal Division, 1978). During April through June they are most abundant along the continental shelf and on the banks off Kodiak Island, where large schools of capelin and Pacific sand lance are also found (Fig. 5.95). Almost all of the approximately 1,500,000 animals in the Pribilof Islands breeding population migrate through the Kodiak area (Baker et al., 1963). Southward migration begins in August with immature animals, and older animals continue through the area until the end of March. The northward migration to the Pribilof breeding grounds begins in March and continues through June. Peak populations are present in the gulf during June and are lowest from August through October. Calkins (ADF&G, pers. comm.) reports that six northern fur seals, including females up to six years old, spent two to three weeks on the Barren Islands during June and July 1978. The harvest of this species in the Pribilofs employs about 450 people. The cost of the harvest program, about $3.2 million annually, is slightly in excess of the value of the furs when sold (USDC, 1979).

The land-breeding harbor seal is the most abundant pinniped of coastal Alaska from Dixon Entrance to the Bering Sea. An ice-breeding harbor seal Phoca larga is found in the Bering Sea and Arctic waters. A common resident of coastal waters throughout the area, harbor seals are found at times in rivers and even some freshwater lakes. Haulout areas include offshore rocks, sandbars, and beaches of remote islands. Floating ice pans calved from glaciers, when available, are used for hauling out. During winter, ice shelves which form at the heads of bays are frequently used as hauling platforms.

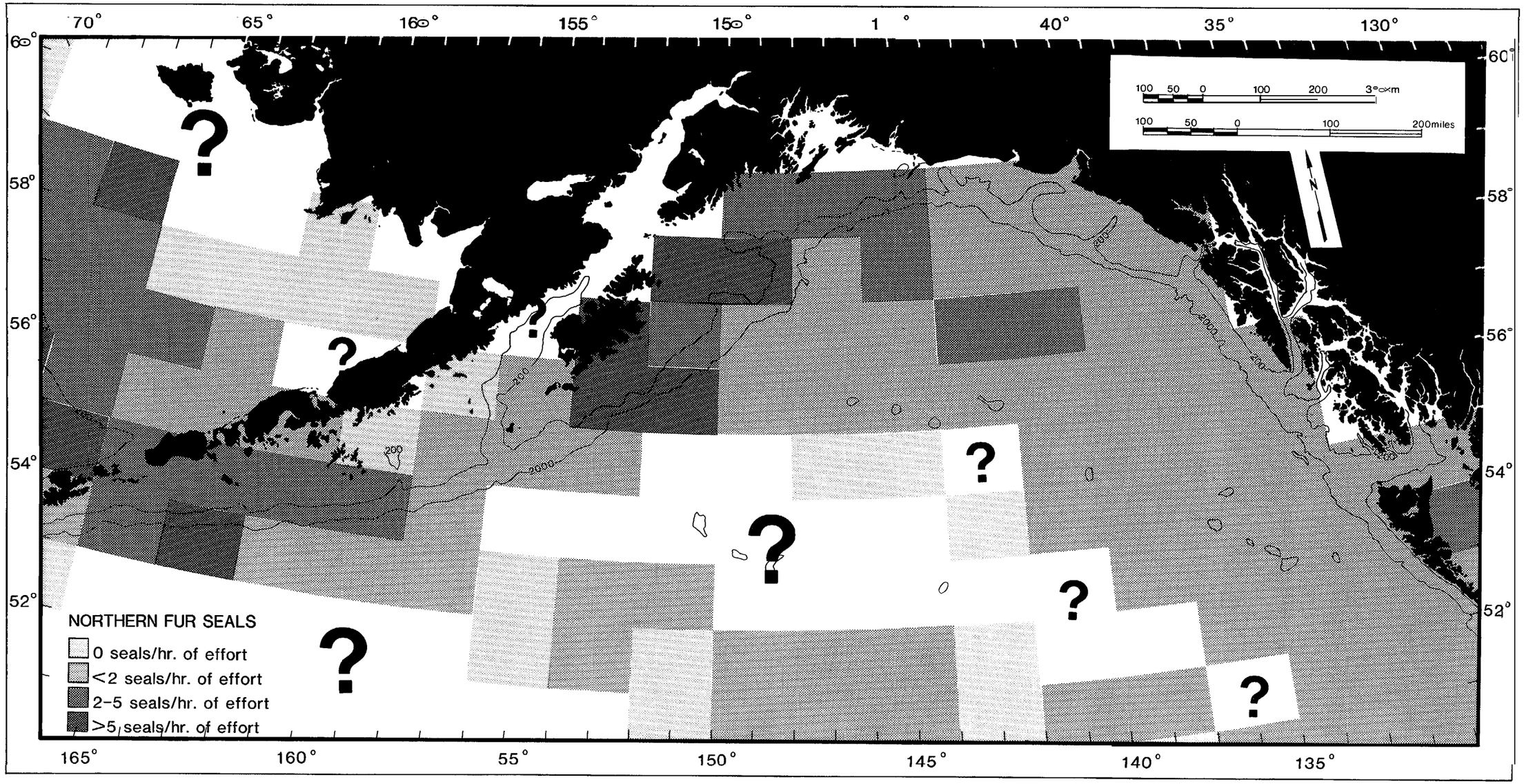


Figure 5.95 Sightings of northern fur seals in the Gulf of Alaska for 1958 through 1974 (Marine Mammal Division, 1978).

Harbor seals occur all along the shoreline of the Kodiak Archipelago (ADF&G, 1973; Pitcher and Calkins, 1977; Fig. 5.96). Although this species is not usually believed to congregate in dense colonies, many areas of high density (10 or more animals) are found in the Kodiak area (Table 5.57). The largest known concentration of harbor seals is found on Tugidak Island (13,000). Concentrations of 100 to 800 animals have been observed on Sitkinak Island, Geese Islands, Aiaktalik Island, Ugak Bay, and Ayakulik River. The pupp ing and molting seasons frequently produce the highest population counts, suggesting that the species needs to haul out at these times. If SO, it may be particularly sensitive to human disturbance during pupping and molt periods (B. W. Johnson, 1977).

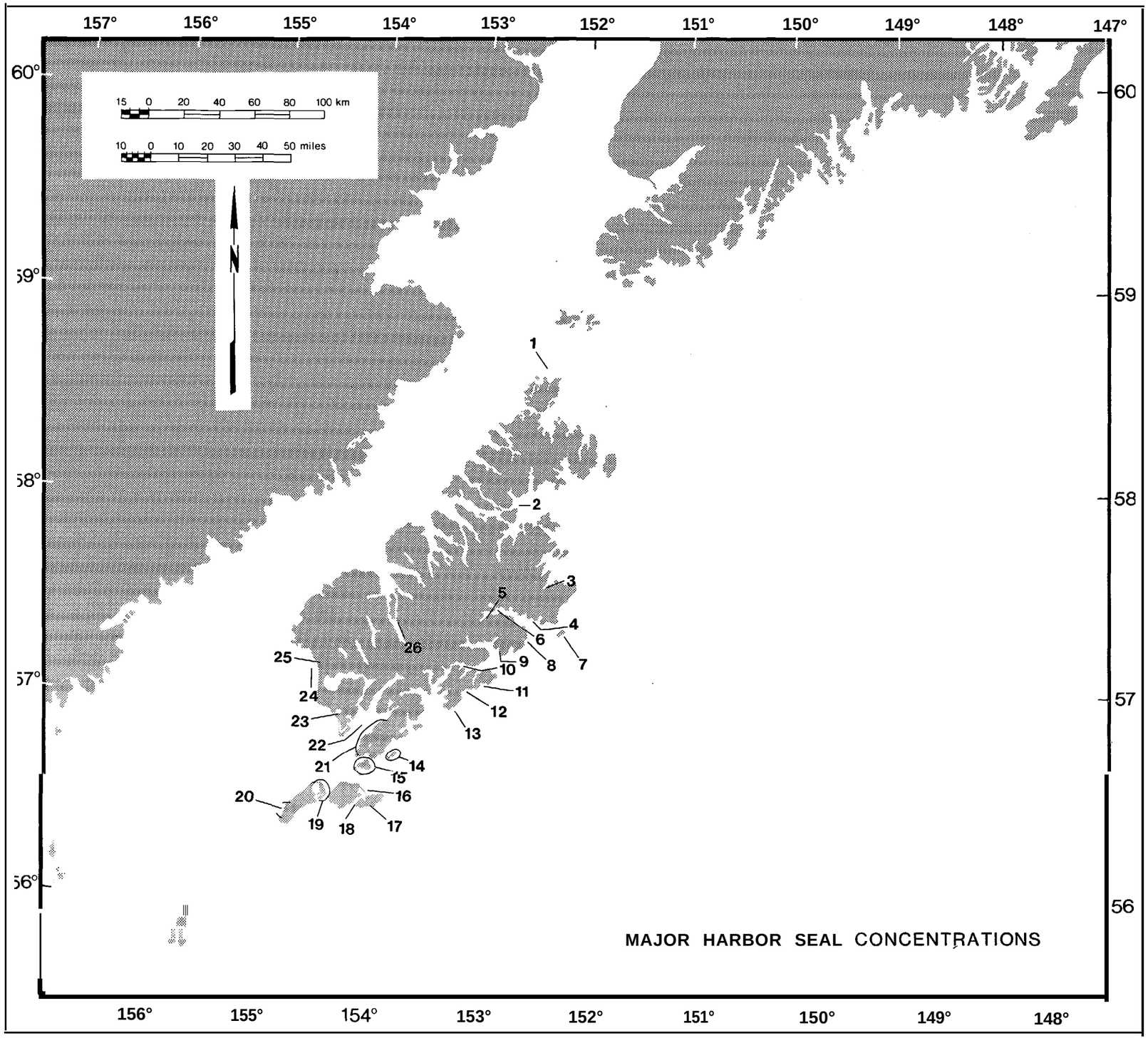


Figure 5.96 Locations of major (greater than 150 seals) harbor seal concentrations in the Kodiak Island/ Shelikof Strait area (Pitcher and Calkins, 1979). The number of seals observed at each numbered location is listed in Table 5.57.

Table 5.57 Observed harbor seal populations over 150 individuals (Pitcher and Calkins, 1979).

	Location	Number of Seals Observed
1*	Latax Rocks	175
2	Hog Island	160
3	Kalsin Bay	200
4-8	Ugak Bay and Islands	2,367+
9	NE Kiluda Bay	160
10-13	Sitkalidak Island area	248
14	Geese Islands	670
15	Aiaktalik Island	635
16-18	Sitkinak Island	1,450
19-20	Tugidak Island	13,960
21	Aliulik Peninsula	200
22	Middle Reef	150
23	Sukhoi Lagoon	350
24-25	Ayakulik River and Island	175
26	Alf Island	250

*Localities indicated by number on Fig. 5.96.

Pelagic sightings of harbor seals in April through October 1958 through 1976 (Fiscus et al., 1976) are shown in Fig. 5.97. These sightings indicate that harbor seals are usually found in waters less than 200 m deep during these months.

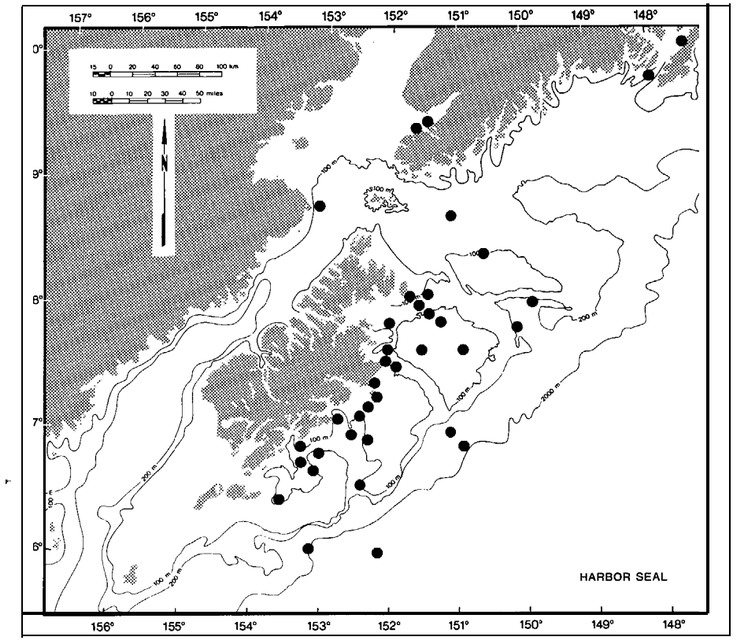


Figure 5.97 Distribution of marine sightings of harbor seals, 1958 through 1976 (Fiscus et al., 1976).

Population Dynamics

Northern sea lion females become sexually mature at three to six years of age and males at about four years of age, although males may have to be much older to successfully compete for breeding territories and access to estrous females. Eighty-one percent of all collected females were found to be pregnant (Calkins and Pitcher, 1978). Pupping takes place from late May to mid-July, with a peak early in June (Calkins and Pitcher, 1977, 1978).

This species is polygynous. Males control breeding territories. Most breeding by males occurs by territorial bulls with estrous females on their territories. Some males have semi-aquatic territories, which could result in an increased exposure to oil. Mortality of a significant percentage of the breeding male population, even though it represented only a small percentage of the total male population, could have long-term genetic effects on the population as reproduction would necessarily be carried out by less competitive males. Because males frequently fast during the breeding season, they may be more vulnerable to disease, pollution, or changes in prey abundance after the season than other age/sex classes. Data on the vulnerability of the breeding males to petroleum development activities are needed.

Braham et al., (1977) have documented a 40-50 percent decrease in the sea lion population of the eastern Aleutian Islands over the last 10 years, but have not identified a single cause. There is currently no evidence that a similar decline is taking place in the Kodiak area (Table 5.56).

The Alaskan northern fur seal population (about 1.5 million) is managed by harvesting subadult males to produce the maximum net productivity (largest harvestable numbers on a sustained basis; Scheffer, 1972). The population is therefore held below carrying capacity (maximal numbers). The sex ratio and age distribution of the population is also manipulated for maximum harvest (Marine Mammal Division, 1978). Most of the Pribilof population migrate through, or winter in, the Gulf of Alaska. Northern fur seal movements through the Gulf of Alaska are complex, with seasonal variations in number, age, and sex. During the winter adult males probably concentrate in the Gulf of Alaska, while adult females move farther south along the coast, reaching as far south as California (Fiscus et al., 1976). The movements of immature animals resemble those of adult females. By April the adult males start to move toward the breeding grounds as females become more numerous in the Gulf of Alaska. With the major

movement of adult females, the gulf population reaches a peak in May. By late June or early July the population in the gulf consists almost entirely of immatures. As the immatures also move toward the breeding grounds, the gulf population reaches its lowest numbers during August through October. Adult males would be most vulnerable to the effects of OCS development during spring, early summer, and early winter. Immatures might be exposed on a year-round basis to potential oil-related impacts, but less so during August through October.

Harbor seal females become sexually mature at four to five years of age, males at about seven years of age. About 91 percent of all collected females five years old or older were found to be pregnant. Pupping takes place from mid-May to late June, with a peak in mid-June. About 23 to 36 percent of females and 32 to 50 percent of males collected were immature (Pitcher and Calkins, 1978; 1979).

Trophies

Pinnipeds eat a variety of invertebrates and fish. Generally, sma11 schooling fish such as herring (Clupeidae) are swallowed whole uncle r water while larger prey are consumed at the surface, where they are reduced to small pieces by violent shaking (Spalding, 1964) .

In a large sampling effort, Calkins and Pitcher (1978) reported on the stomach contents of 193 northern sea lions collected in the Gulf of Alaska. They found that the species eats about 6 percent by volume invertebrates, 93.9 percent fish, and 0.1 percent mammals, with capelin and walleye pollock the most commonly eaten fishes. In the Kodiak area they report that, of total prey items, the species eats about 54 percent capelin and 25 percent walleye pollock (Table 5.58). The remains of a harbor seal were found in one of the 71 stomachs they examined from the Kodiak area. Spalding (1964) reports that sea lions feed mostly during darkness.

The diet of the northern fur seal in the Gulf of Alaska consists of about 32 percent cephalopods and 68 percent fish (North Pacific Fur Seal Commission, 1975), with Pacific sand lance (about 25 percent) and walleye pollock (18 percent) the most common fishes (Table 5.58). Combined data for western Alaska and the Gulf of Alaska indicate a diet of 25 percent invertebrates and 75 percent fish, with squid (26 percent) and walleye pollock (32 percent) the major prey (North Pacific Fur Seal Commission, 1975). During the winter fur seals feeding off the Washington and British Columbia coasts were found to eat 20 percent salmon (Oncorhynchus spp.), 18 percent each of Pacific herring (Clupea harengus pallasi) and northern anchovy (Engraulis mordax), 12 percent of each of rockfish (Sebastes spp.) and squid (Teuthoidea), and 6 percent capelin (North Pacific Fur Seal Commission, 1975). In general, fur seals collected over the continental shelf tend to feed on fishes, while those collected beyond the shelf feed mostly on squid. Like northern sea lions, this species feeds mainly at night (Spalding, 1964), but also during daylight.

Harbor seals feed during daylight, mostly in nearshore waters (Spalding, 1964). Their diet in the Gulf of Alaska is about 30 percent invertebrates and 70 percent fish (Pitcher and Calkins, 1978). In the Kodiak area octopus (Octopus sp.) (30 percent) and capelin (23 percent) were found to be the major prey (Table 5 .58).

Table 5.58 Identification of the prey from the stomachs of northern sea lions (N = 71), northern fur seals (N = 172), and harbor seals (N = 102).*

Prey species	Northern sea lion (percent total)	Northern fur seal (percent volume)	Harbor seal (percent total)
Invertebrates			
Gastropod			tr
Cephalopods	1.4	32.5	29.5
Crustaceans	0.4	tr	2.2
Unid. Invertebrate	0.1		tr
Fishes			
Skates	6.6		tr
Salmon	1.7	5.2	2.9
Herring		1.5	4.2
Capelin	54.0	12.3	21.2
Eulachon			4.6
Walleye pollock	24.8	18.0	5.8
Other gadids	8.1	3.7	tr
Eelpouts	0.1		tr
Rockfish			tr
Greenings			tr
Cottids	0.1		6.6
Pacific sandfish	-	0.1	tr
Ronquil			tr
Pacific sand lance	-	25.0	1.1
Pleuronectids	0.7		5.8
Unid. fish	0.3	1.4	0.5
Mamma 1s			
Harbor seal	1.7		

* Data on Northern Sea Lions and Harbor Seals are from animals collected in the Kodiak Area (Calkins and Pitcher, 1978; Pitcher and Calkins, 1979); data on Northern Fur Seals are from animals collected in the Gulf of Alaska (North Pacific Fur Seal Commission, 1975) .

Effects of development on pinniped activity near rookeries and haulout areas

Harbor seals and other pinnipeds are known to panic easily when disturbed by humans or low-flying aircraft (B.W. Johnson, 1977; Loughrey, 1959). Such disturbances could lead to separation of mothers and pups and accidental injury or death of pups in any species. When adults return to colonies after such panics there may be an unusually high level of territorial aggression, which is potentially injurious to pups and adults. Intentional repeated harassment in British Columbia was effective in causing abandonment of traditional northern sea lion rookeries (Bigg, pers. comm.).

Petroleum

Oiled and dead pinnipeds have been found after several oil spills, but in almost all cases investigators have been unable to directly attribute mortality to oil (Simpson and Gilmartin, 1970; Brownell and LeBoeuf, 1971; LeBoeuf, 1971; Spooner, 1967; Warner, 1969; Davis and Anderson, 1976).

Kooyman et al. (1976) and Kooyman et al., (1977) showed that oiling doubled the thermal conductance of the pelts of northern fur seals, increased the conductance somewhat in the pelt of a Weddell seal (Leptonychotes weddelli), but had no effect on the pelts of a California sea lion or a bearded seal (Erignathus barbatus). These results indicate that oiling would seriously reduce the insulative properties of northern fur seals' pelage, which could make them unable to endure prolonged immersion in cold water.

Geraci and Smith (1977) placed ringed seals (Pusa hispida) in oil-covered water and observed irritation and inflammation of the eyes within eight minutes. After 24 hours of exposure the seals' eyes had severe conjunctivitis, swollen nictitating membranes, and evidence of corneal erosions and ulcers. Twenty hours after the seals had been placed in clean sea water the eyes showed no signs of irritation. No other effects of oil immersion were observed in these seals.

Animals may ingest oil from a spill either directly or through feeding on contaminated prey. Moore and Dwyer (1974) have reported that ingested volatile petroleum fractions of low molecular weight can cause acute cytotoxic damage in many marine organisms. More subtle organ damage may result from repeated ingestion of less volatile fractions. Geraci and Smith (1976) found that ringed seals rapidly absorbed crude oil into body tissues and fluids, ultimately excreting them via the bile and urine. Harp seals fed 75 ml of crude oil showed evidence of tissue damage. These results suggest that accidental ingestion of oil may not be immediately harmful to phocids. The long-term effects of ingestion of oil-contaminated food have not yet been studied. Geraci and Smith (1977) reported "transient" kidney and liver lesions in ringed seals in oil-covered water. They attributed these to the inhalation of volatile hydrocarbons.

Pups may depend more on their pelage for heat conservation than adults because they have little blubber at birth and a poor surface-area-to-volume ratio. Some phocid pups have a thick lanugal coat and swim soon after birth. Otariid pups usually do not swim until several weeks after birth. Both may be adaptations for heat conservation until blubber layers are built up. If so, pup vulnerability to oil-induced hypothermia may be significantly greater than that of adults.

5.8.4 Sea otter

The sea otter is the only member of the family Mustelidae that is exclusively marine. There is apparently no record of wild sea otters entering fresh water (Kenyon, 1972). The species inhabits inshore waters rich in bottom fauna, usually along rocky coasts. This is the smallest of the marine mammals. The forepaws are adapted for grasping food and grooming, and are not usually used for swimming. The hindpaws are broadly flattened and adapted for the sea otter's unique habit of swimming on its back on the surface. The fur consists of a layer of guard hairs about 3.8 cm long and an underlayer of dense fur about 3.2 cm long. Sea otters have no blubber and rely on air trapped in the fur for insulation. Much time is spent grooming.

The species is unique in that it sleeps, eats, and carries and nurses its young while resting or swimming on its back on the surface. Its normal swimming speed on the surface is about 3 km/hr, and its escape speed under water has been estimated at about 10 km/hr (Kenyon, 1972). Otters can dive to about 60 m. Estes (1977) found that the mean diving time during feeding in water up to 9 m was about 45 seconds, and in water 9 to 27 m deep, about 84 seconds.

Distribution

High densities of sea otters are found on the Barren Islands, Shuyak-Afognak Islands, and the Trinity Islands and Chirikof Island areas (Schneider, 1976) (Fig. 5.98). The Barren Islands population is thought to be at the carrying capacity of the habitat. This population does not appear to be supplying animals to repopulate areas where the species occurred before being almost exterminated by commercial hunting (1742 to 1911). The Shuyak-Afognak population is now quite dense and appears to be supplying animals which are repopulating the former range of the species to the southwest. Sea otters have been sighted throughout the shallow waters southeast of Kodiak Island, but only two established breeding groups have been found: the Trinity Islands (the larger) and around Chirikof Island. Sea otter densities in these areas are believed to be well below the capacity of the habitat but numbers are increasing. Sea otters have been present in the Semidi Islands at least since 1957. The present population is small and does not occupy all available habitat.

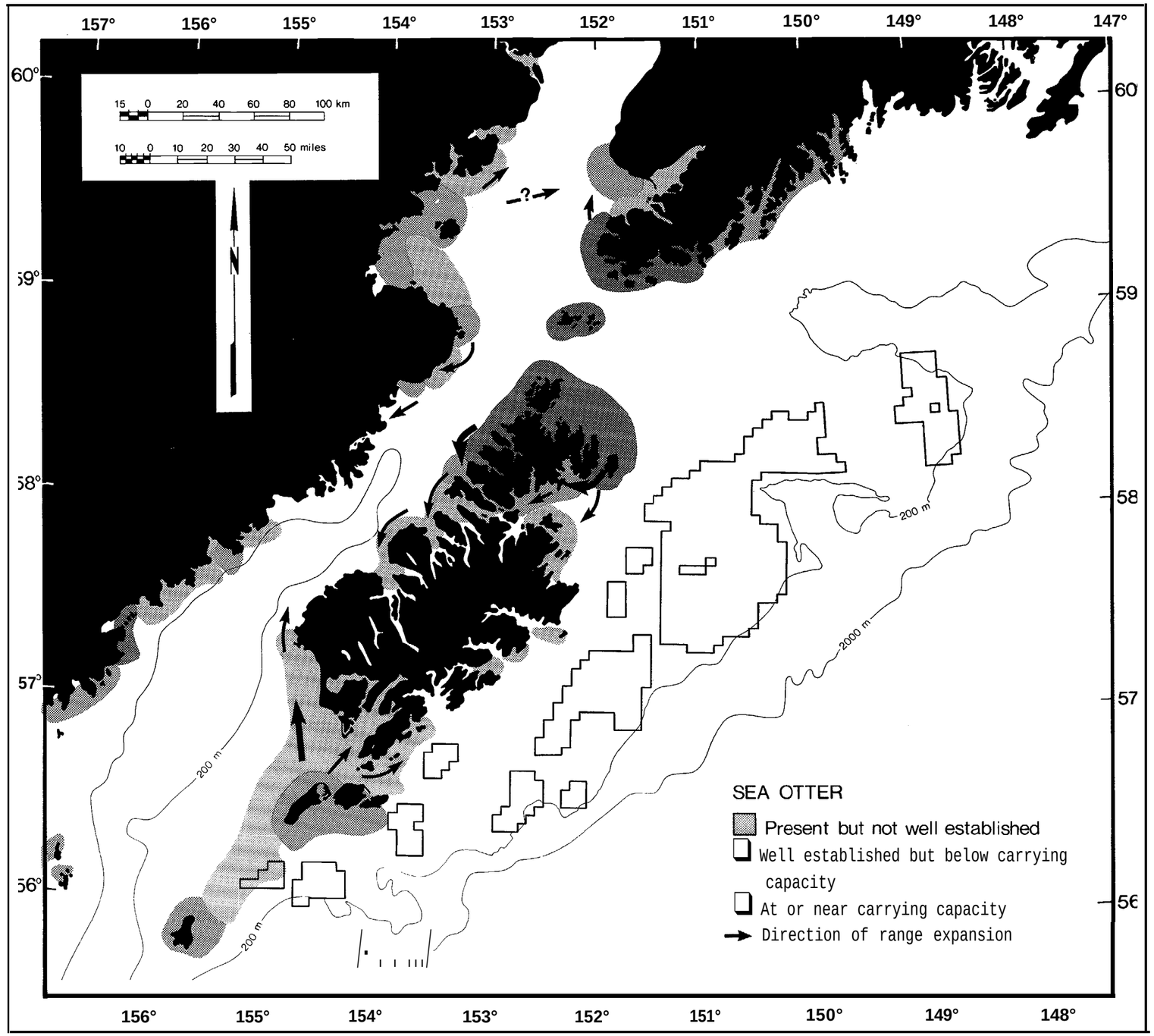


Figure 5.98 Distribution and range expansion patterns of sea otter populations around the Kodiak archipelago (Schneider, 1976; pers. comm.).

Population Dynamics

The Kodiak area population of sea otters was hunted to a very low level by the turn of the century. Under protection the species has recovered, and some areas may have reached carrying capacity. Animals from these areas are now reco onizing the former range of the species (Schneider, 1976). Moderate-to-high densities are ted to build up in Marmot and Chiniak Bays within the next 5 to 10 years. Eventually this population will probably merge with the Trinity Islands population. The Trinity Islands/Chirikof Island population is below the habitat's carrying capacity and is increasing in size. The population is expected to grow for many years and eventually repopulate the almost 10,000 km^2 of suitable sea otter habitat lying between Kodiak and Chirikof Islands (Schneider, 1976). Sea otters breed throughout the year, with a peak in breeding activity and births in the fall and winter.

Troph cs

Kenyon (1969) found that sea otter feeding habitat on Amchitka Island was limited to the intertidal and sublittoral regions within the 60-m depth contour. From the examination of 309 sea otter stomachs he found that about 98 percent of their diet consisted of molluscs, echinoderms, and fish (Table 5.59) The species has a relatively high metabolic rate for its size (Morrison et al., 1977), which is supported by a daily food consumption of from one-fifth to one-fourth of body weight. Estes and Palmisano (1974) estimated that sea otters eat about 35,000 $kg/km^2/yr$ of animal biomass on Amchitka. Sea otters thus are key members of nearshore marine communities and are important in determining community structure.

Table 5.59 Identification of prey from the stomachs of 309 sea otters from Amchitka Island (Kenyon, 1969).

Prey Item	% Volume	Minimum Frequency of Occurrence
Annelids	1	2
Crustaceans	<1	5
Molluscs	37	16
Echinoderms	11	58
Tunicates	<1	4
Fish	50	35

Role as a key species

Considerable evidence both from California (Estes and Palmisano 1974) and the Aleutian Islands (Palmisano and Estes, 1977; Simenstad et al., 1978), indicates that the sea otter is a key species in determining the structure of nearshore mm ties. Sea otters control herbivorous invertebrate populations and indirectly affect wave exposure and the composition of the rocky intertidal community (Fig. 5.99). In areas with dense sea otter populations, sea urchins, limpets, and chitons are reduced to sparse populations of small individua s; macroalgae flourish, providing food and shelter for a variety of organisms, especially crustaceans; wave exposure is reduced, si tation increases; and overall productivity is high. In contrast, similar areas with few or no sea otters have dense populations of large herbivores; macroa gae are severely overgrazed; bare rocky substrates are exposed to wave action; and overall productivity is low.

Effects of petroleum development

Sea otters are especially vulnerable to the effects of petroleum development in the region. Because they rely on their dense pelage for insulation, fouling of it by oil may cause severe thermal stress Laboratory studies show that oiling of sea otters has resulted in death and severe stress (Kooyman and Costa, 1979). These results have led to the prediction that mortality among oiled sea otters would be high. However, during the summ of 1979 several wild sea otters were oiled fitted with radio collars, and released in Prince William Sound (Costa and Kooyman, 1979). These animals were then tracked and observed for several weeks. During the course of the experiment there was

no known mortality nor evidence that the oiling affected the health of any of the otters. Sea otters have a basal metabolic rate about 2.5 times that of other mammals of their size. Captive animals support their metabolic rate by consumption of about 25 percent of their body weight daily. The species thus is also vulnerable to any reduction in its food supply.

The available evidence indicates that in mild weather sea otters can survive the effects of oiling for several weeks. In cold weather, however, mortality would probably be high. Long-term effects are not known, but could endanger some local populations and seriously retard the repopulation of former sea otter habitats (Costa and Kooyman, 1979).

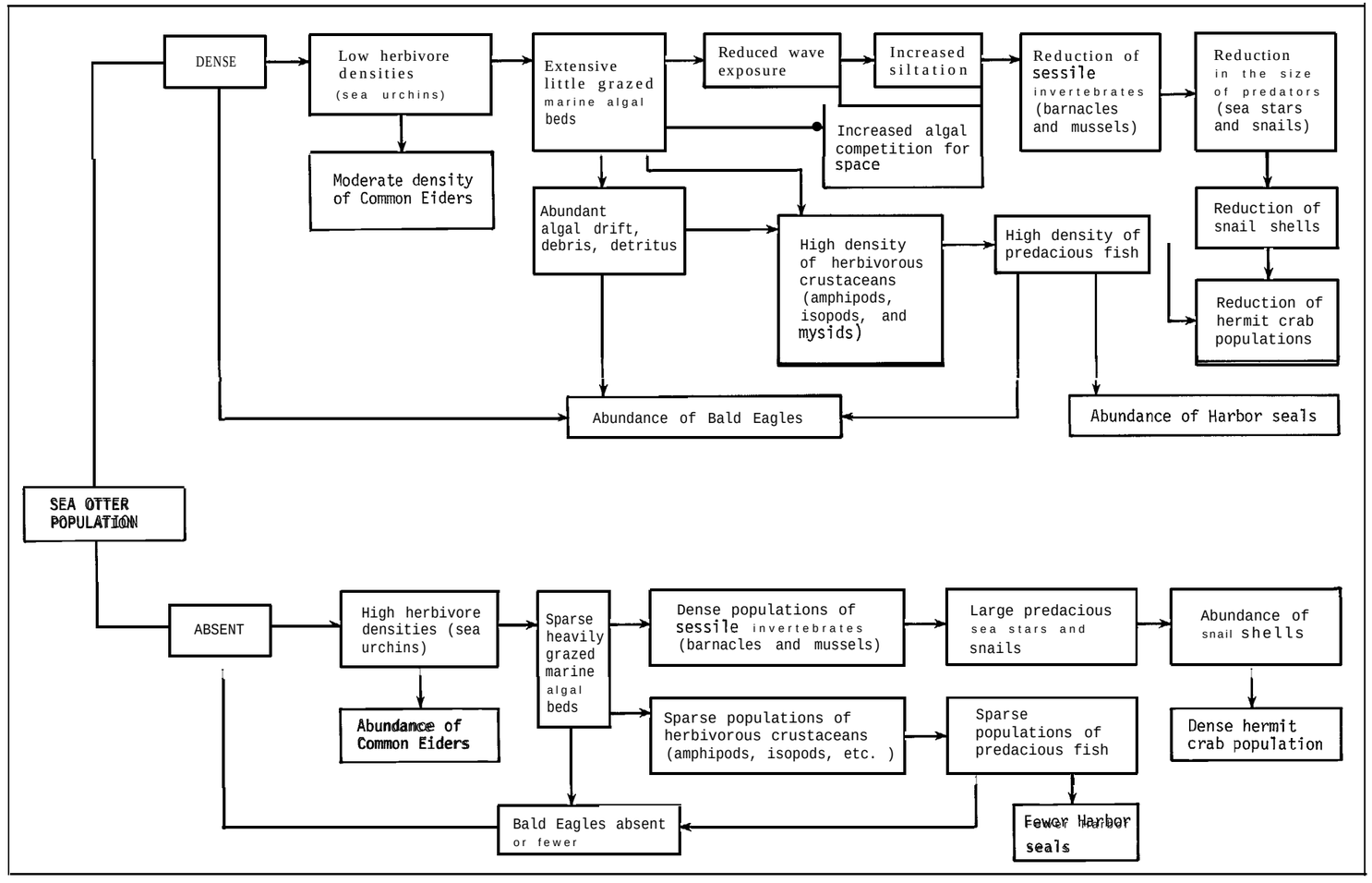


Figure 5.99 Diagram of interactions within nearshore communities with and without sea otter populations (Palmisano and Estes, 1977).

5.8.5 Terrestrial mammals

Kodiak and adjacent islands hold a population of 2,000-3,000 brown bears (Ursus arctos), which has changed little in recent times (ADF&G, 1973). Denning areas, where the bears winter, are found inland at higher elevations. In the spring the bears move to lower elevations, especially to coastal areas, to make use of limited herbaceous forage. From July through September, and on some streams until November, brown bears concentrate on all of the salmon streams in the area. This food resource is thought to be critical to the maintenance of this high-density population, especially for the segment of the population which enters winter dens late in the year (ADF&G, 1973).

The Sitka black-tailed deer (Odocoileus hemionus sitkensis) was introduced between 1923 and 1934 to Kodiak, where it has done well and is still increasing (ADF&G, 1973). During the winter these populations are forced into a narrow strip along the beach (Fig. 5.100), where forage is usually of poor quality. During these periods plant material (beach grass, sedges, and kelp) on beaches and in the intertidal zone may be the only available food. Contamination by oil of this limited food supply in winter would probably be fatal to a large proportion of these already-stressed populations.

Murie (1959) reports that river otters (Lutra canadensis) and red (Vulpes fulva) and Arctic foxes (Alopex lagopus) make heavy use of the coastal and marine environments. River otters are reported to frequent salt water and often swim to islands near the coast. River otters are also vulnerable to fouling of their pelage. Both species of foxes depend on a diet of beach fleas, clams, crabs, marine birds, and fish and other beach carrion.

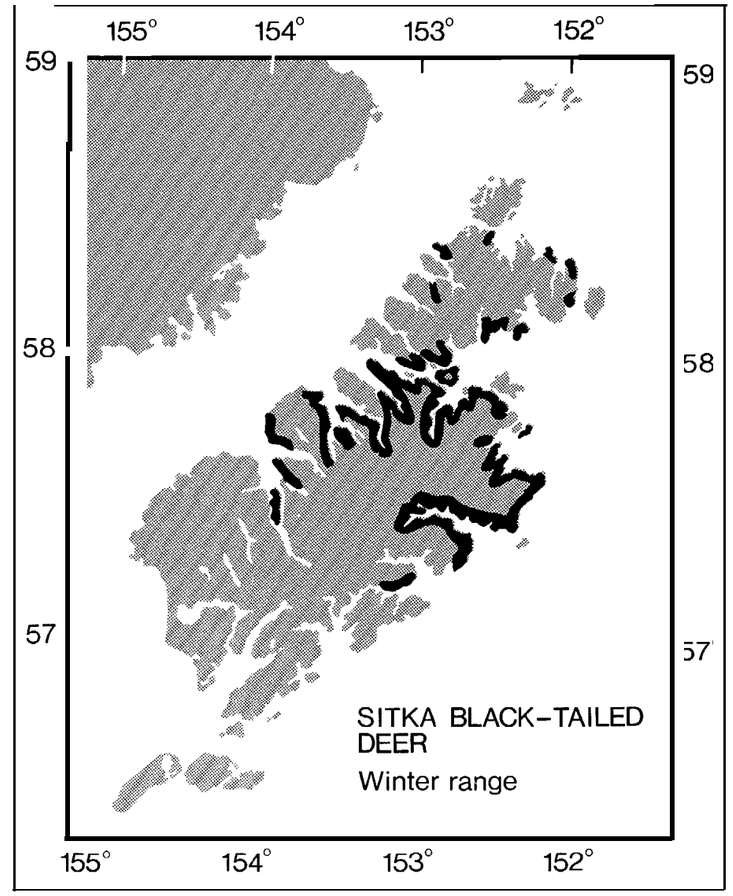
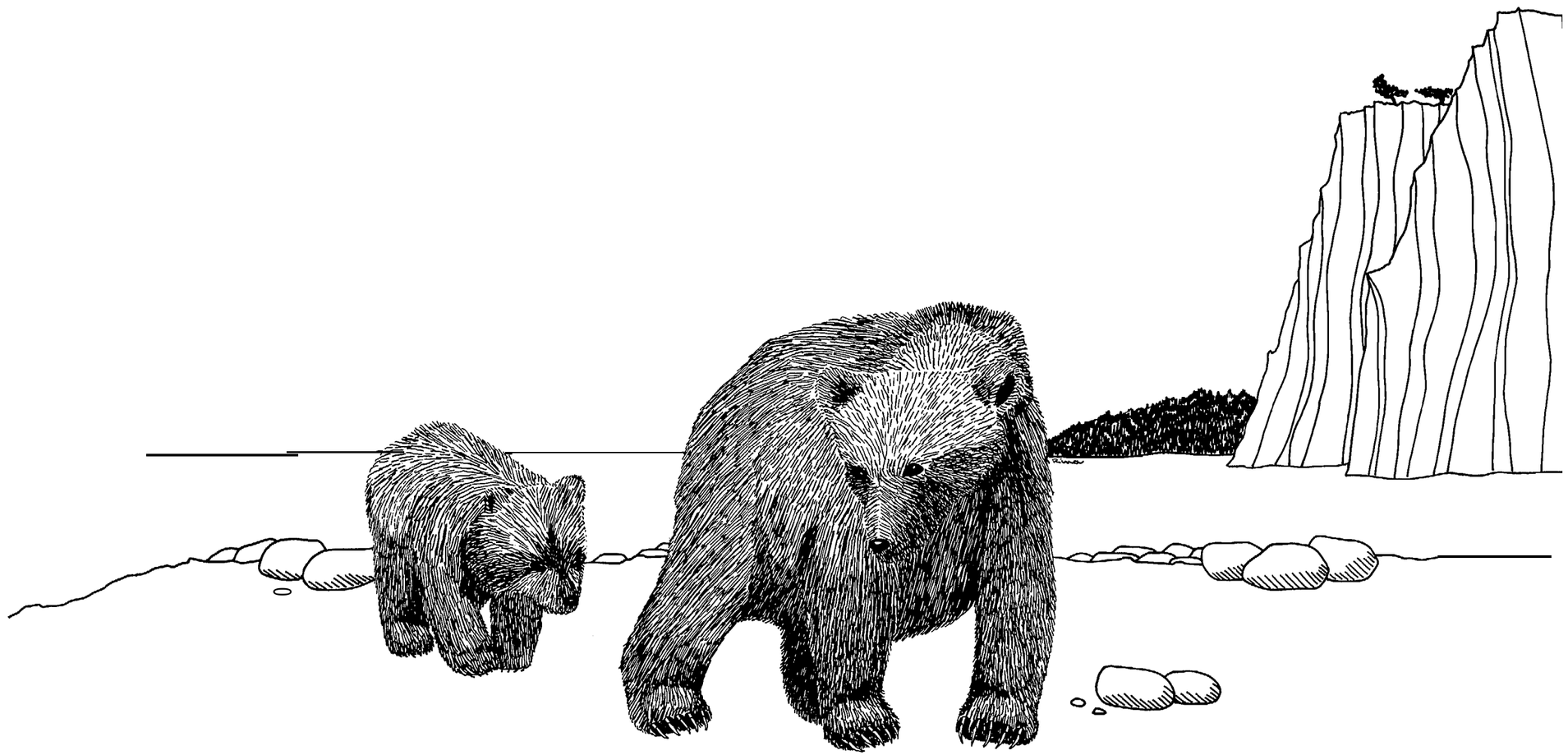


Figure 5.100 Winter coastal distribution of Sitka black-tailed deer (ADF&G, 1973).

6. Petroleum Industry Development



CHAPTER 6 PETROLEUM INDUSTRY DEVELOPMENT

M. J. Hameedi, OCSEAP

6.1 RELEVANCE

In order to achieve a reliable environmental assessment, we must attempt to predict the amounts and nature of petroleum resources and the magnitude of potential environmental disturbances and contaminant discharges, as well as to foresee what changes development activities themselves will bring. We need information about:

- the forms and relative amounts of petroleum hydrocarbons development is expected to produce (i.e., natural gas, gas condensate fluids, or crude oil)
- the number and locations of logistical support and supply bases
- the technology and facilities required for the extraction, processing, storage, and transportation of petroleum hydrocarbons
- the probable quantities and nature of regulated or accidental discharges of contaminants.

This information, combined with environmental data on the transport of pollutants, locations of sensitive habitats, and probable adverse effects of contaminants on biota, can be used to guide offshore petroleum development in such a way as to reduce to a minimum both conflicts among users of the resources and harmful effects on the environmental quality of the region. The analysis of combined data forms an integral part of the Environmental Impact Statement (EIS) prepared in anticipation of the lease sale. The Kodiak lease sale is scheduled for December 1980.

OCSEAP has identified three subtasks to obtain data and information on the probable sources, nature, and magnitude of environmental disturbances that might be associated with offshore petroleum development. These subtasks are:

1. Obtain and continually update estimates of the location, nature, and timing of platform, pipelines, and facility development in each lease area.
2. Estimate the quantity and physical and chemical nature of contaminants from each potential source based on projected design characteristics and operating methods, as well as on experience with petroleum development operations in other locations.
3. Estimate the nature and amount of possible environmental disturbance likely to accompany development.

The Bureau of Land Management and U.S. Geological Survey are the major sources of information on petroleum development offshore. Other sources are the U.S. Environmental Protection Agency, the Council on Environmental Quality, the U.S. Coast Guard, the State of Alaska, and the petroleum industry. But because there has been no petroleum exploration in this area, much of the information on which these tasks are based is preliminary, initial projections of sources and amounts of pollution and other environmental conditions are imprecise and largely speculative, and the prospects of the commercially attractive petroleum reserves are uncertain. More reliable estimates of development activities will become available as the size and types of petroleum resources become known after exploration. This account will be modified and updated as additional data become available.

6-Z DATA EVALUATION

Much of the information about development activities in this chapter is based on development scenarios included in the draft Environmental Impact Statement for Sale #46 and related studies conducted for the Bureau of Land Management (BLM, 1979b; BLM, 1979c; and USDI, 1980b). It is based on current estimates of mean resources and several production assumptions made in the draft EIS. For example, it was assumed that geological formations exist in this area favorable to the accumulation of petroleum hydrocarbons that can be recovered in commercial quantities, and that all production will consist of natural gas and gas condensate only. Data on different production alternatives and modifications of the proposed action are given in USDI (1980).

Current projections of the types and number of platforms, location of onshore facilities, and the timing of development activites are imprecise and largely speculative. They will be modified as exploration proceeds and development plans are submitted. A part of the account of environmental disturbances is based on data from other parts of the world where offshore petroleum production and associated activities have taken place, e.g., the North Sea. Such data may not be applicable to the Kodiak region.

The statements and data in this chapter are not intended to suggest a development scheme or a prediction of events in Kodiak. Any specific facility site mentioned represents only one plausible location within the wide range of alternatives that might be considered before final selection.

6.3 LOCATIONS, NATURE, AND TIMING OF THE DEVELOPMENT OF PLATFORM, PIPELINE, AND FACILITIES

The continental shelf east of the Kodiak Archipelago has been proposed for petroleum exploration and development. According to the current OCS leasing schedule, up to 564 tracts may be offered for sale in December 1980 (Sale #46). Geological and seismic data obtained by the U.S. Geological Survey indicate recoverable petroleum hydrocarbon resources in the western Gulf of Alaska. However, estimates of petroleum resources in the area are poorly defined and have changed significantly over the years. A large part of the resources is believed to be in the Albatross Basin. Much lesser quantities are expected in Tugidak and Portlock Basins.

Geologically, Albatross Basin is divided into several discontinuous arches or smaller basins. The western, shoreward side of the basin appears to be formed by a faulted and deformed zone that may be a major crustal boundary. This zone could serve either as a barrier or as a passageway to oil and gas migrating from the deeper sedimentary basin to the east (BLM 1979b) . The outcrops along the eastern coast of the Kodiak Archipelago are both marine and non-marine in character and overlie metamorphic rocks of pre-Tertiary age. This evidence suggests that the Sale #46 area is more likely to produce natural gas and gas condensate than crude oil. Natural gas consists principally of methane (as much as 90 percent by volume) and small amounts of ethane, propane, isobutane, and nonhydrocarbon gases such as carbon dioxide and hydrogen sulfide. Occasionally it contains small amounts of liquid hydrocarbons such as pentanes and hexanes. Gas condensate is a low-molecular-weight hydrocarbon mixture that is gaseous in the ground but condenses into liquid when produced (Hunt, 1979). It may include short-chained paraffins with five to ten carbon atoms (comparable to the gasoline fraction). Its extraction in liquid form may require some sort of chilling process.

Natural gas, specifically methane, is formed during diagenesis from microbial alteration of organic matter and during catagenesis and metamorphism by the thermal degradation of organic matter, The heavier hydrocarbons such as ethane, propane, and butane are formed principally after diagenic methane formation and before the peak catagenic generation of methane. This difference in the time of formation of hydrocarbons causes them to be distributed vertically in many basins. Thus dry gas is found on the stable shelf in the diagenic zone, heavier gas in the deeper catagenic zone, and dry gas in the deepest parts of the basin. This pattern occurs in many sedimentary basins throughout the world (Hunt, 1979), but it is not known if such a pattern also occurs off Kodiak. Further, the type of organic matter and the amount of source material determine the relative amounts of natural gas and gas condensate reserves: sapropilic marine material (spores and planktonic algae with high lipid content), besides generating ethane, propane, and butane, produces about "twice as much methane as humic material does. Humic material of continental origin generates mainly methane with only traces of higher hydrocarbons (Hunt, 1979).

Accurate information on this subject for the Kodiak region is not presently available to OCSEAP. The U.S. Geological Survey (USDI, 1980) estimates resources as of March 1979 as follows:

	Maximum	Mean	Minimum
Gas condensate, million barrels (MMbbl)	501	176	22
Natural gas, trillion cubic feet (tcf)	13.9	5.35	0.91

Proprietary data from three stratigraphic tests conducted along the central part of the Albatross Basin (probably in synclinal areas) between May and October 1977 suggest potential petroleum reserves in the area (BLM, 1979b).

Post-lease petroleum operations can be divided into four phases--exploration, development, production, and shutdown. Since tracts within a lease area vary in potential, these phases vary in duration from one tract to another, and often overlap. Other factors determining the timing and extent of activities during the various phases include market conditions, proximity of logistical support and shore facilities, environmental conditions, Federal, state, and local development policies, and the availability of suitable land for the construction of onshore service and supply bases. Should initial exploration efforts prove successful, follow-up sales in the vicinity may cause a consolidation of these activities and/or overlap of phases. When the supplies of extractable petroleum hydrocarbons are exhausted in the producing field, the production platforms are removed, and the associated equipment and structures are dismantled and carried away.

6.3.1 Exploration

Exploratory drilling usually starts within five to twelve months after a lease sale. In the northeastern Gulf of Alaska (NEGOA Sale #39) drilling of exploratory wells was begun on the most promising tracts within one year of the sale date. Exploration wells were usually 3,000-4,500 m deep. There are insufficient geological data to identify ranges of reservoir depths that may be encountered in the Kodiak region. In the draft Environmental Impact Statement for Sale #46, the average well depth of forty production wells is assumed to be 1,980 m (USDI, 1980b). Exploration drilling ordinarily takes about three months to complete under optimum conditions. Upon completion, whether a find has been made or not, the wells are plugged and the rig moved to another tract. Plugging a well does not always signify abandonment of the field; often where a strike is made near unleased tracts findings may be kept secret by the operators pending a sale of unleased tracts. If resources approximate the mean case, 24 exploration and delineation wells will probably be drilled in the Sale #46 area (USDI, 1980b).

If a discovery is made, additional wells are drilled nearby to determine the extent of the resource. Where the reservoir underlies tracts held by different companies, the leaseholders may choose to unitize the leases, that is, to agree who is to operate the block and how costs and profits are to be shared.

In the Sale #39 tracts, exploratory drilling was carried out by semisubmersible rigs such as the SEDCO 706 (Shell), Ocean Ranger (ARCO), Alaskan Star (Exxon), Ocean Bounty (Texaco), and Aleutian Key (Gulf). It is expected that semisubmersibles or possibly drillships will be used off Kodiak, although jack-up rigs may be used in water less than 50 m deep. Severe environmental conditions (including high waves, storms, and potential geological hazards) in the western gulf, have limited the use of other types of rigs in the area. A semisubmersible or drillship is much less vulnerable to geological hazards than a jack-up rig.

The requirements for shore facilities supporting petroleum exploration are varied. Often facility siting is the result of a compromise between technical criteria and environmental and socioeconomic suitability. Temporary service bases established for the exploration phase following Sale #39 were established at Yakutat, Seward, and Yakataga. Of these sites, only Seward is close enough to the proposed lease tracts of Sale #46 to serve as a service base. A new service base could be constructed in the Chiniak Bay area. Aircraft support could probably be supplied from airfields at Seward, Kodiak City, and Cape Chiniak. Several deep bays in the western gulf are potential sites for the construction of a new service base (Woodward-Clyde Consultants 1977, cited in BLM 1979b).

The Municipality of Kodiak, Coast Guard facilities, and a large seafood processing facility are located at Chiniak Bay. In order to make sites in this area acceptable for operations beyond the exploration phase, extensive dredging would be required. On the other hand, Kiliuda and Ugak Bays, although little developed, have deep water close to shore, ample turning space for tankers, and relatively flat land adjacent to the coastline (BLM, 1979b). Biological and other environmental considerations will undoubtedly influence the final selection process.

Ancillary support equipment during the exploratory stage will include supply boats to serve exploratory rigs and helicopters to transport personnel and some supplies. The extent to which these are required will depend on the number of exploratory rigs and their proximity to onshore service locations. In the Sale #39 area as many as 13 service vessels used the Seward service base during peak exploratory operations, with six in port at one time. This high level of activity is not expected in Kodiak; two rigs requiring four or five service vessels seem likely.

According to Kramer et al. (1978), typical supply vessels have a range of 300-500 km and are from 49 to 64 m long. Large helicopters are used wherever possible because they conserve fuel and work better in inclement weather. In Sale #39, one or two trips from Yakutat were made to each rig every day.

6.3.2 Development and production

Even if exploration is successful, petroleum production is not likely to begin until 1987. The development and construction of shore facilities and pipelines could be started in 1984. Definitive development scenarios, probable levels of industrial activities, and site-specific environmental data are not now available but will be before the approval of development plans. This account should, therefore, be read with reservations. It is based on the development of mean estimates of hydrocarbon resources. It also reflects the judgement that all production will consist of natural gas and gas condensate only. Different assumptions regarding future levels of exploration and development costs, operating expenses, the price and market for natural gas and gas liquids, taxation, and depreciation would determine the extent and timetable of industrial activities predicted for this area.

Assuming successful exploration, the following factors, in addition to those related to market potential and economics of investment, will affect decisions for development.

1. Potential reserves and delineation of field size. Estimates of resources in the Sale #46 area are small compared with the 19 trillion cubic feet of natural gas now used annually in the United States and 292 million barrels of oil produced annually from offshore U.S. wells. However, the use of natural gas and petroleum liquids in Alaska is expected to increase markedly. According to the data compiled by the Division of Minerals and Energy Management, State of Alaska, a 90-percent increase in natural gas consumption and a 130-percent increase in petroleum liquids consumption is possible by the year 2000 (The Anchorage Times, January 26, 1980).

2. Drilling depths. The time and effort required for drilling depend on geological formations, the number of wells to be drilled, and the depth of resources. The depth of the sedimentary basins in the Kodiak Tertiary Province is uncertain; deeper portions of basins may be as much as 6,000 m below the surface. According to the draft EIS (USDI, 1980b), 40 producing and service wells will have an average depth of 1,980 m. Continental Offshore Stratigraphic Test (C.O.S.T.) wells drilled in the mid-region of Albatross Basin were from 2,596 to 3,188 m deep (BLM, 1979b).

3. Water depth at the potential production field. Resource economics, technical considerations, and the time required for development of a particular field are greatly affected by the water depth. The minimum size of gas fields in Kodiak will probably be 0.5-1.75 trillion cubic feet depending on the total costs involved and the desired rate of return on the investment. From price structure and regulations specified by the National Gas Policy Act of 1978 one study calculated that no gas field regardless of size can earn a 15-percent return in 183 m (600 feet) of water with production limited to 24 wells producing 576 million cubic feet per day over a year (BLM, 1979b). The development of gas fields in deeper shelf areas may not be attractive to the petroleum industry.

4. Operating conditions. Only the most extreme weather and ocean conditions, such as storms or high sea states, hamper drilling, development, or production operations. Earthquakes and other geological hazards pose a much bigger problem. Offshore platform designs that might be used in this area take into account seismicity and different soil responses; some are specific to Alaskan conditions. Several recent papers on seismic design for offshore platforms, cited in a study sponsored by BLM (1979b), consider soil responses, soil-pile-structure systems, and responses of concrete platforms. Nonetheless, a serious seismic event could halt drilling and other operations and cause damage to pipelines and onshore facilities.

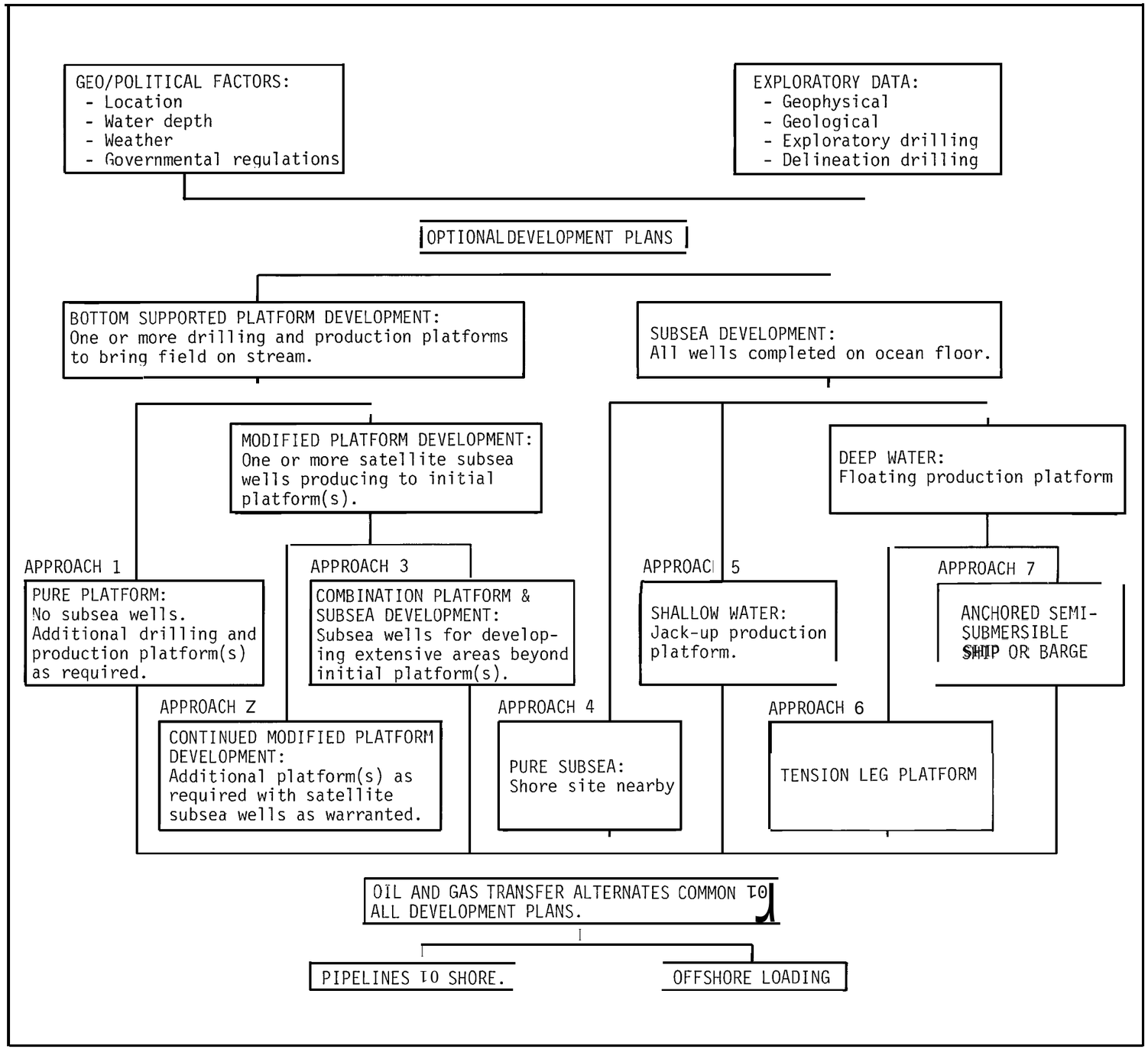
5. Environmental impacts. Operators will have to satisfy requirements of environmental safety and comply with operating orders and specific stipulations that will govern industrial activities. Some of these regulations may limit certain activities for a specific period. For example, aircraft operations might be curtailed or banned in the southern lease tracts during the harbor seal pupping season (mid-May to mid-July). Noise disturbance from low-flying aircraft is known to have caused significant pup mortality at Tugidak Island because of trampling by panicking adults and abandonment by mothers.

6. Economic criteria. Since field development after a discovery is guided principally by economics, market conditions, and government regulations, a decision criteria table is included here (Fig. 6.1). The economic criteria leading to field development show the relationship of exploratory data and environmental factors in the development of a hypothetical offshore petroleum resource. Such a relationship may be typical of the decision process used by lease holders to develop their tracts. An analysis of operating costs is not included here because it requires identification of technologies to develop, produce, process, store, and transport hydrocarbon resources. A standard resource economics model for the western Gulf of Alaska is described by Dames and Moore (BLM, 1979b).

Although it is too early to know the extent of OCS petroleum development activities in Kodiak, some projections can be made.

Platforms

By the year 1989, four steel-jacketed, bottom-founded production platforms may be installed. In this platform type, the steel latticework is lowered to the sea bottom and secured by piles driven 30-45 m into the seabed. Then the deck is set on the base by a derrick barge. The modules containing the production equipment, support facilities, crew accommodations, and a helicopter pad are also installed. Steel-jacket platforms have been used successfully elsewhere and may be



economically desirable in the Kodiak area. However, they have no storage capacity and installation in the seabed makes them vulnerable to geological hazards. At peak production, after 1989, some 40 production wells could be drilled from the four platforms (USDI, 1980b). The probable locations of these platforms cannot be predicted.

Although the use of steel-jacket platforms is assumed, newly designed platforms evolving from those proposed for use in the North Sea may have applications in the Kodiak area. Several "hybrid" platform designs combining facets of the steel-jacket, concrete gravity, and semisubmersible platforms are now available. Such designs have evolved to offset the increasing costs of "conventional" platforms with increasing water depth and at the same time to meet the need for platforms suitable for developing small-to-moderate-size offshore reserves (BLM, 1979b).

Figure 6.1 Economic criteria leading to field development (Reeds and Trammell, 1976).

Pipelines

According to the mean resource development scenario, natural gas and gas condensate would be separated at the well head and pumped to shore through two parallel 56 cm diameter pipelines. The route length from production platforms to Kiliuda Bay will probably be about 400 km (Fig. 6.2) All pipe, except for the final few kilometers, will probably be installed offshore by a lay or reel barge (USDI, 1980b).

Marine pipeline systems consist of a pressure source, gathering lines, transmission lines, and booster stations. Gathering lines bring petroleum hydrocarbons from the production platforms to the pipeline itself, which will probably terminate ashore in a cryogenic, air-cooled, liquefied natural gas (LNG) plant The design of the pipeline system will depend on field production rate, rate of arrival of carriers, location of production fields, and such physical factors as bottom profiles, benthic fauna, bottom currents, and seismicity.

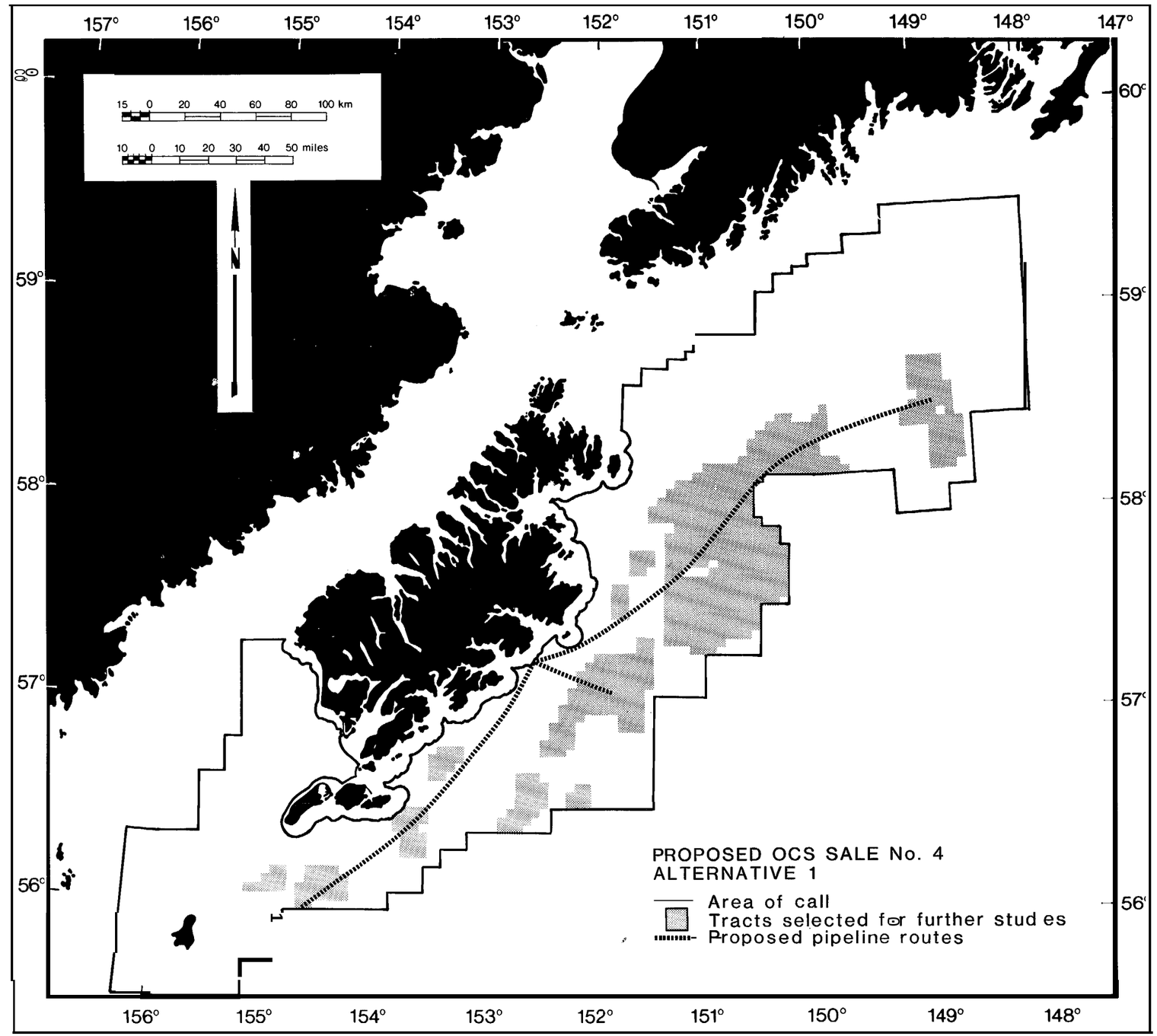


Figure 6.2 Possible marine pipeline routes for natural gas production (USDI, 1980b).

Lay or reel barges may be used to install the pipeline. Precoated sections of pipe are welded together, then lowered to the seafloor from the lay barge as it is winched forward on its spread of anchors. The pipe is then buried by a bury barge using high-pressure water jets to remove sediments under the pipe. Small gathering lines may be installed by reel barges. Pipe lowered from a reel barge is welded, tested, and coated onshore (Kramer et al., 1978). Modern lay barges have catamaran-shaped, semisubmersible hulls which provide greater stability than the older types; they can operate in rough seas (~6 m significant wave heights). It is estimated that under the conditions present in the western Gulf of Alaska, approximately 100-150 km of pipeline may be laid in one year with a single barge (J. P. Ray, Shell Oil Company, pers. comm.). Thus it is important that pipeline construction mesh with other development and production schedules.

Liquefied natural gas (LNG) plant

Economically recoverable natural gas and gas condensate are assumed to be present in the Sale #46 area. Current resource estimates reflect no production of crude oil (USDI, 1980b). Since there is no major local market, most of the gas and gas condensate found would be shipped to the west coast of the United States. Natural gas, principally methane, is liquefied by chilling it to -162°C in a liquefaction facility, the LNG plant. Hydrocarbons of higher molecular weight, such as propane and butane, can be liquefied under pressure at room temperature. Liquefaction reduces the natural gas to one six-hundredth of its original volume. The production of LNG can be reduced or halted to accommodate unexpected shipping delays. Thus a lower storage capacity is required for LNG facilities than for crude oil terminals (Kramer et al., 1978).

LNG plants require high capital expenditures, proximity to harbors suitable for LNG carriers, and access to fresh water and electrical power. Four basic elements constitute a LNG liquefaction facility: a liquefaction train, storage tanks, a marine loading facility, and support structures. Since the Kodiak LNG plant may be air-cooled, thermal effluents will not be produced. An LNG plant could be operational in Kodiak by 1987.

LNG storage tanks and loading

LNG is stored in insulated steel or concrete tanks designed to keep the natural gas liquefied. According to Kramer et al. (1978), industry now uses 9-percent nickel steel or aluminum tanks. The annular space between the inner and outer tanks is packed with insulation. The bottom of the tank is also insulated. A storage area is surrounded by a high concrete dike or other structures which can hold spilled LNG in case of tank failure. Only one jetty or berth will be required for loading. The LNG plant, storage tanks, and loading facility may be established on the southern side of Kiliuda Bay (USDI, 1980b). Kiliuda Bay has enough deep water and turning room for LNG carriers. Another suitable site is a headland east of Saltery Cove, on the north side of Ugak Bay.

LNG carriers

An LNG carrier, due to the light weight of its cargo, has a shallower draft than an oil tanker of comparable size. LNG carriers presently using Alaska facilities, Polar Star and Arctic Tokyo, are each about 244 m long and 34 m wide with a draft of 9.5 m and capacities of 72,000 m^3. Larger LNG carriers, as long as 320 m, are planned (Kramer et al., 1978).

The frequency of visits of LNG carriers to marine terminals depends on production rates and ship size. One ship visit every 8-10 days for the LNG plant is predicted for the Kodiak region based on the current loading frequency at the Phillips LNG plant in Kenai, Cook Inlet.

6.4 QUANTITIES AND PHYSICOCHEMICAL NATURE OF CONTAMINANTS ANTICIPATED FROM VARIOUS SOURCES

Several potential contaminants and hazards associated with petroleum exploration, development, and production activities can be identified for the Kodiak region. Their points of origin and relative magnitudes and the probability of the occurrence of pollution incidents cannot be specified at this time. The following account considers, in general terms, some of the sources of environmental disturbance and contamination.

6.4.1 Offshore platforms

Offshore platforms produce gaseous, liquid, and solid wastes. Discharges from drilling platforms are regulated by the U.S. Environmental Protection Agency (EPA) through National Pollution Discharges Elimination System (NPDES) permits and OCS operating orders and stipulations. Eight different types of discharges were produced by the exploratory drilling platform Ocean Bounty in the lower Cook Inlet:

1. treated effluent from the sewage treatment system,
2. brine from the domestic freshwater distillation unit,

3. seawater from the ballast system,

4. seawater and rainwater from the deck drains,

5. treated effluent from the hydrocarbon/water separator,

6. drill cuttings, mixed with seawater and drilling muds,

7. seawater, drilling mud, and cement from the drilling mud system, and

8. freshwater, water-soluble fractions of oil, and antifreeze from the blowout preventer.

These discharges could be expected from drilling rigs exploring the Kodiak region. Because of the small amounts and short duration, some of these sources may not have a significant adverse effect on the environment.

6.4.2 Drilling muds and fluids

Specially compounded 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. They may contain a variety of substances in a freshwater; saltwater, or oil base, including special clays and inorganic and organic compounds, some of which are toxic to biota.

A typical mud system on a drilling rig consists of a series of tanks which hold muds of different weights, a pump and associated plumbing, various mixers and screens, and a mudhose leading to the drill pipe (Fig. 6.3). The selected mud mixture is pumped into the drill bit, where it hydraulically assists in the removal of cuttings. The used drilling muds are returned to mud tanks. They can be recirculated into the drill hole after processing and treatment.

In the early stages of drilling, clays and seawater are the primary constituents of the drilling mud. At increasing depths other substances, including a

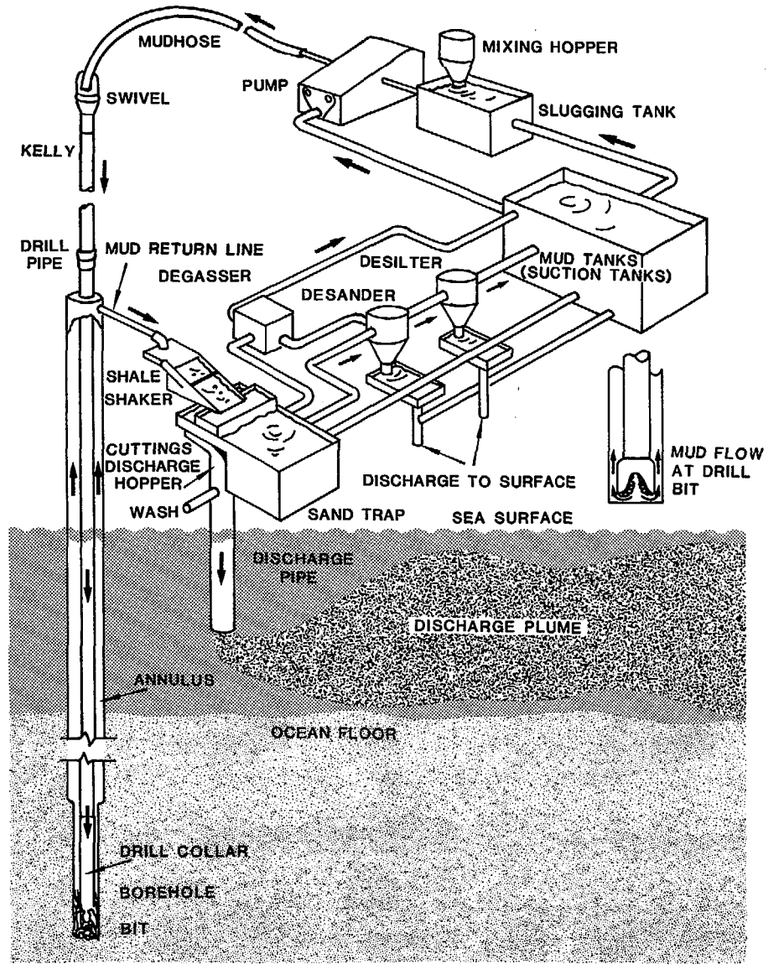


Figure 6.3 Schematic diagram of a drilling mud system and circulation path of the drilling fluid (Ray, 1979).

variety of chemical compounds, are added to control viscosity, filter loss, and cation contamination (Ray, 1979). Oil-based muds are seldom used in the exploratory phase offshore. In the development phase, they are used when a well must be deflected at a severe angle or when numerous wells are drilled from a single platform. Occasionally, abnormal formation pressures, exceptionally tight formations, or other problems require the use of oil-based or highly treated drilling muds.

At a given well about a dozen of the approximately 55 substances used to formulate the more than 500 commercial mud products are used in drilling (Ray, 1979). A particular makeup is determined by site-specific considerations and is usually proprietary in nature. Barite, caustic soda, bentonite clays, and lignosulfonates are the most commonly used components of water-based drilling muds; barite and bentonite contribute the bulk of the suspended solids content of muds (Table 6.1). Caustic soda and lignosulfonates are the most toxic components of muds (Dames and Moore, 1978).

Table 6.1 Some drilling mud constituents which are normally discharged into the sea (after USDI 1977).

Constituent Type/Use	Typical Substances
Weighting and gelling agents	Barite, siderite, attapulgite clay, bentonite clay
Thinning agents	Tannin, sodium acid pyrophosphate
pH control	Caustic soda, sodium bicarbonate
Dispersant and emulsifier	Ferrochrome lignosulfonate
Conditioner and texturizer	Organic polymer (starch, cellulose derivatives)
Flocculent	Gypsum, potassium chloride
Fluid loss agent	Carboxymethyl cellulose
Bactericide	Formaldehyde, pentachlorophenol
Defoamers and other specialty products	Proprietary

After use, drilling muds and fluids are separated, but substantial amounts of the muds could be discharged intermittently because of incomplete separation. Normal industry practice also involves routine discharges and periodic "dumps" if the mud formulation is changed or at the end of the operation. Assuming an average well depth of 1,980 m, 60 m^3 of drilling muds are expected to be discharged per well in the Kodiak area (USDI, 1980b).

6.4.3 Drill cuttings

Drill cuttings, consisting of chipped and pulverized sediment and rock, are usually dumped directly into the water near rigs and platforms. The amount of drill cuttings is related to the drilling depth. Drilling to an assumed average well depth of 1,980 m in Kodiak would produce 131 m^3 of cuttings per well (USDI, 1980b). Drill cuttings are heavier and coarser than drilling mud, and thus settle out faster. In the water column and on the seabed, these cuttings will disperse and be carried away. Local accumulation of large particles is usually not a major problem, but if several wells were drilled from a single platform large accumulations could result. For example, ten wells drilled from a single platform could yield 1,310 m^3 of cuttings. Under such circumstances, after determining the dispersion potential at selected sites, appropriate mitigating measures may be proposed. Such measures could include a specific stipulation requiring transportation of drill cuttings to disposal sites approved by the Environmental Protection Agency (USDI, 1980b).

6.4.4 Formation waters

Formation waters may be transported to shore for cleansing and eventually disposed of, reinjected into wells for pressure maintenance, or discharged into the sea. The amount of formation water extracted with natural gas or gas condensate is expected to be much lower than that extracted with crude oil. If only gas and gas condensate are produced the volume of produced formation water in Kodiak will be negligible (USDI, 1980b).

6.4.5 Dredging and burial of pipeline

The dredging and burial of pipeline cause local and probably temporary destruction of marine habitat, resuspension of sediment, and increased turbidity. It is estimated that pipeline burial would disturb approximately 1,859 m^3 of sediment per kilometer of pipe route. If 384 km of pipe were installed in Kodiak during the course of development, BLM estimates that 714,000 m^3 of sediment would be disturbed (USDI, 1980b). Some of the disturbed sediments would be resuspended and would resettle to the bottom, both locally and at a distance from the source.

The extent to which harbor dredging might be required is unknown.

6.4.6 Well blowouts and other accidents during drilling

The control of imminent blowouts can be accomplished by increasing the weight of mud and activating the blowout prevention equipment. If the control systems fail, hydrocarbons and/or other effluents will be released in large quantities into the environment. In a gas well blowout, escaping gas will either burn or disperse into the atmosphere. In calculating the probabilities of accidental blowouts and spills, it is assumed that realistic estimates of future accidents can be based on previous data, that accidents (and spills) occur independently of each other, and that the accident rate depends on the volume produced and transported (and indirectly on the duration of activities). Such statistics, largely based on data from the Gulf of Mexico, indicate that one blowout occurs for every 2,860 wells drilled (USDI, 1977). But the Kodiak lease area is a frontier area where no previous drilling has occurred, subsurface pressures are unknown, and the physical environment poses hazards to technology; hence the probability of a blowout may be higher than in an established field. BLM estimates that one blowout may occur in this area during the life of the field (USDI, 1977).

Accidents from platform collapses attributable to storms and earthquakes were included in a risk analysis for Sale #39 (USDI, 1976b). The predictions were based on the probabilities of platform collapse and well blowout, a safety factor of 1.5 or 2.0 in the platform design, and 96-percent reliability of the blowout protector valve. Table 6.2, extracted from data presented in the BLM analysis, presents selected probabilities. The information contained in this table can be illustrated by the following example: If a platform in the proposed area is designed with a margin of safety of 1.5 to withstand a 100-year storm and if the field life is 30 years, then the probability of a storm exceeding platform design specifications during the life of the field is 0.14 (1 chance in 7). If a subsurface valve system is installed with a reliability of 0.96, the probability of a blowout is 0.006 (1 chance in 167). For a valve reliability of 0.99, the probability of a blowout is 0.0014 (not included in the table). The table also shows that the likelihood of platform collapse increases linearly with the age of

Table 6.2 Estimates of platform collapse and well blowout assuming blowout preventer valve is 96 percent reliable (adapted from USDI, 1976b).

Event	Field life (years) 20	30	40
Severe s terms			
100-yr storm			
1.5 safety margin	0.09/0.0036	O. 14/0. 0056	0. 19/0.0076
2.0 safety margin	0.04/,0.0016	0.07/0.0028	0. 08/0. 0032
200-yr storm			
1.5 safety margin	0.05/0.002	0.07/0.0028	0.09/0.0036
2.0 safety margin	O .02/0. 0008	0.03/0.0012	0.04/0.0016
Earthquakes			
Richter 7.2			
1.5 safety margin	3.3/0.13	4.9/0.20	6.5/0.26
2.0 safety margin	2.8/0.11	4.2/0.168	5.6/0.22
Richter 8.6			
1.5 safety margin	0.33/0.013	0.49/0.02	0.65/0.026
2.0 safety margin	0.28/0.011	0.42/0.017	0.56/0.022

the field and decreases linearly with improved platform design. For example, a platform designed for a 100-year storm in a 20-year field will have the same likelihood of failure (0.09) as a platform designed for a 200-year storm in a 40-year field. Further, a platform is much more likely to collapse because of a major earthquake than because of a severe storm. For example, the likelihood for platform collapse from an earthquake of magnitude 8.6 is three to seven times higher than from a severe storm during the 20-year field life.

6.4.7 Waste discharge and accidents associated with liquefied natural gas (LNG)

A large amount of waste water is discharged into the marine environment from LNG plant operations. Phillips' LNG plant discharges about 189,000 m^3 of waste water annually into Cook Inlet (Kramer et al. , 1978) . The amount of discharge and separation of solids or toxic chemicals can be regulated to conform to water quality standards.

Because it is extremely cold, volatile, and flammable, LNG is potentially hazardous. A major spill at sea or in a harbor presents the greatest danger of serious fire and explosion (Kramer et al., 1978). Although LNG itself is not explosive, the greatest hazard of released LNG is the potential formation of a large, low-lying, flammable cloud. It is unlikely that such a vapor cloud could drift for a long time without encountering an ignition source. The smaller the populated area over which this cloud forms, the smaller the potential hazard. An accidental spill of 4,536 m^3 of LNG from the East Ohio Gas Company plant in Cleveland, Ohio, in 1944 resulted in the formation of a vapor cloud which flowed into the city streets and storm drain system. Upon ignition, the resulting fire and explosion killed 133 people, injured 300, and caused widespread property damage. The type of storage tanks and containment dike which were used in that plant are no longer permitted (SAI, 1976; Kramer et al., 1978) . Another hazard of LNG is that if spilled on water, it can explode without a source of ignition. This happened in 1973 at the Canvey Island LNG terminal at the mouth of the River Thames east of London. Whether such spills explode or not depends on the exact composition of LNG, the size of the spill, and the rate of evaporation (Davis, 1980).

The probability of a major accident involving LNG is extremely small. Possible causes of accidents include malfunction of the plant, transfer, and transportation systems, natural catastrophes (e.g., an earthquake), collision of ships, and aircraft hazards. The potential risks and probability of damage at the proposed Pacific Alaska LNG Company at Nikiski, Alaska, have been analyzed by SAI (1976).

6.4.8 Effluents and Emissions

Potential sources of low level, chronic contamination include support and supply bases, LNG carrier operations and routes, and increased automobile and aircraft traffic. The possible effects of such activities on surface and ground water (such as the introduction of inorganic plant nutrients, increased organic load, changes in the populations of microorganisms, incidence of disease) and the air quality have not yet been studied.

Water and air quality may deteriorate as a result of increased municipal sewage, increased utilization of ground water, and industrial activities, particularly during construction of shore facilities. The current industrial use of water in Kodiak is low and limited to fish processing. No additional large consumers can be supplied by the present water system, although slow development and foresight in planning could alleviate this problem. Little air pollution is predicted. If no petrochemical industry is located in Kodiak, the major sources of air pollution will be emissions from LNG carrier loading, accidental spills, and increased automobile traffic and residential fuel consumption. Air pollutants from these sources include suspended particulate, petrochemical oxidants and hydrocarbons, carbon monoxide, and nitrogen oxides. The amount and ultimate effect of emissions would depend on the size and complexity of operations, siting of facilities, local air circulation, other emissions in the area, and the level of emissions control and enforcement (Kramer et al., 1978).

Another potential problem is increased noise and air pollution from aircraft transporting materials and personnel between the coastal and offshore facilities.

6.5 NATURE AND AMOUNT OF ENVIRONMENTAL DISTURBANCE LIKELY TO ACCOMPANY DEVELOPMENT

In addition to pollution from accidental, uncontrolled spills or discharges, normal exploration, development, and production activities may remove or alter habitats, increase turbidity of the water, impair fishing, and affect aesthetic values. Site-specific information cannot be provided until there are discoveries and potential development sites have been identified. The following account outlines possible environmental disturbances.

6.5.1 Increased land use and loss of habitat

Space--water, land, and air--will be needed to explore, develop, produce, and transport hydrocarbon resources. According to a preliminary estimate furnished by BLM, 10 hectares of land might be required for each support/supply facility and about 80 hectares for an LNG terminal and related facilities (USDI, 1980b). In addition to land for support/supply bases and LNG facilities, other land requirements will increase as more people move into existing or new communities. This new population could affect land-use patterns, services and utilities, and subsistence/recreational use of coastal and marine resources. Some loss of habitat will result from emplacement of platforms and pipelines. More space will be needed for access to harbor frontage and marine facilities.

About a dozen harbor locations have been identified in the Kodiak region as possible sites for OCS-related onshore development. These sites were selected on the basis of information from the U.S. Geological Survey topographic maps and open-file reports, nautical charts, the Coastal Pilot, local comprehensive plans, and various agencies of the State of Alaska (Kramer et al., 1978). Some of these sites are located in Barling Bay, Kalsin Bay, Kizhuyak Bay, and Ugak Bay. An LNG plant could be established in Kiliuda Bay (USDI, 1980b). It is likely that most industry operations will be carried out from one or two onshore bases (J. P. Ray, Shell Oil Company, pers. comm.).

The ultimate selection of sites and transportation routes will be determined by the needs of industry, the policies and controls of local, state, and Federal governments, and an evaluation of environmental impacts. Sites will have to be evaluated in terms of resource requirements, conflicts of interest, effects on natural and socioeconomic environments, and geological and meteorological hazards. According to its resource management policies, the State of Alaska, in selecting 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).

6.5.2 Preemption of fishing areas

Commercial fisheries and seafood processing are important elements of the regional economy and lifestyle in Kodiak. Any significant harm to commercial fisheries would cause severe economic hardship to the community. Commercial fisheries could be hurt by preemption of fishing areas; loss of gear and buoys through entanglement with structures, vessels, and debris; contamination of fish or their prey; and competition for limited harbor facilities.

Major conflicts between the petroleum and fishing industries in the North Sea are related to accessibility of fishing areas and loss of fishing grounds (University of Aberdeen, 1978, cited in BLM, 1979b). If jack-up rigs are used in exploration one or two hectares of the seafloor will be needed for each structure. A semisubmersible rig, with its anchor system of 450 m radius, would occupy 130 hectares. Production platform and vessel activity could compete for sea lane space and preempt 50-200 hectares for 20-25 years. In view of the total area likely to be involved, such loss of fishing areas should not be a serious problem. On the positive side, platforms can help fishermen to navigate and can supply information on weather and sea conditions. The structures also provide substrate for marine organisms, including fish and their prey. There is, however, no evidence indicating increased biological productivity as a result of offshore petroleum structures.

6.5.3 Turbidity increase

Kodiak shelf waters are very clear, like deep oceanic areas. Several of the bays also have clear water; there are no major riverine sources of sediment, although a small amount of turbid water may enter the bays during spring and summer runoff. Typical concentrations of suspended matter in the oceans are less than 0.5 mg/l; in deltas and large river estuaries, concentrations exceeding 1 g/l are not unusual.

Turbidity will increase from disposal of drill muds and cuttings, resuspension of bottom sediments as a result of pipeline trenching and burial, and dredging to maintain navigation channels. The increased turbidity will probably not last long, but it may be deleterious where circulation and/or bottom currents do

not rapidly disperse suspended sediments and waste materials. Small particles can accumulate pollutants ranging from heavy metals to hydrocarbons, and thus introduce pollutants into marine food chains. Furthermore, abnormally high concentrations of suspended material could reduce the productivity of phytoplankton through reduced penetration of sunlight and adsorption of particles on phytoplankters. Major changes in sedimentation patterns can affect benthic assemblages. Any adverse effects are expected to be temporary. Drilling muds observed in the vicinity of a lower Cook Inlet Continental Shelf Stratigraphic Test (C.O.S.T.) well were quickly diluted; suspended portions of the effluent were reduced to 6 mg/l within 100 m of the drilling vessel (Dames and Moore, 1978). In this area currents are strong and ambient suspended sediment load is high, 2 to 20 mg/l. In regions of weak and inconsistent net currents such as on the Kodiak shelf banks, the dilution and dispersion of sediment plumes may be relatively slow.

6.5.4 Aesthetic considerations

The Kodiak Archipelago, with the exception of the City of Kodiak, is nearly or totally undeveloped, and in some places uninhabited by humans. Many islands have large and unique biological populations, coastal areas have biologically rich and diverse communities, and the numerous secluded fiords and bays are pastoral and serene. The placement of platforms and shore facilities, with the attendant human activities, could alter the environment, detracting from its aesthetic value. Drilling rigs, barges, flaring, work vessels, and storage and processing facilities will be highly visible. Small oil slicks from work vessels could be noticeable, particularly in confined areas. Pipeline burial and drilling will produce localized and temporary water turbidity. The magnitude of the effect can only be measured qualitatively from low to high depending upon the sensitivity of siting, structural design, and subsequent landscaping.

6.5.5 Increased human activities, vessels, and air traffic

Petroleum development in the Kodiak lease area will cause an increase in air and sea traffic, construction of buildings, and human population and activities. These events may be detrimental, beneficial, or have no effect on the regional biota. A knowledge of the behavior of species (including interactions, feeding and reproduction, and mortality rates) likely to be affected by petroleum development is essential.

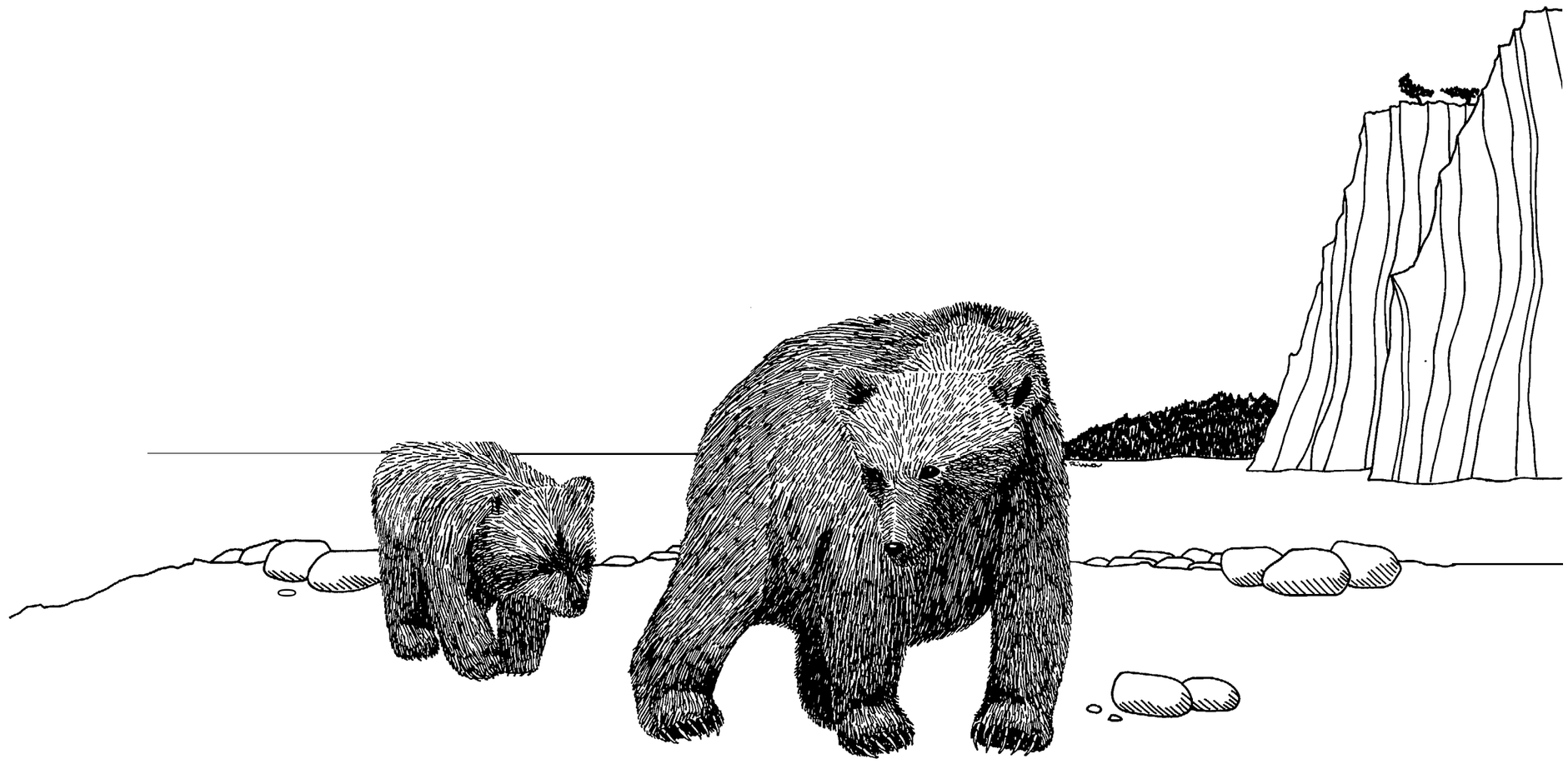
Human disturbance of birds could result from petroleum development activities such as increased traffic, construction of facilities near bird habitats, and the placement of offshore structures in foraging or migration areas. When adult seabirds are frightened off nests they leave their chicks vulnerable to predation. The loss of chicks and eggs from nests of cliff-nesting species during hurried departures by frightened adult birds has been observed in the Pribilof Islands and on Chisik Island.

Offshore petroleum development activities and the noise of increased sea traffic can cause marine mammals to abandon or curtail the use of hauling grounds, breeding rookeries, and foraging areas or alter their migratory routes. Observations of the reactions of marine mammals to human disturbance are summarized by BLM (USDI, 1980b). On Tugidak Island, panic in harbor seal populations caused by low-flying aircraft in early summer resulted in a stampede which caused about 20 percent of the pups to be crushed to death.

There is circumstantial evidence that low-frequency sound from large vessels interferes with communication of some of the baleen whales.

Shoreside and offshore structures, utility corridors, and the activities associated with them may repel or attract animals. Scavengers such as gulls and crows might benefit, but other birds, perhaps in migration, might be fatally attracted to lights. Animals may collide with or be entrapped by supply vessels or rig equipment. An increase in hunting and other recreational activities may disturb the populations of some species.

7. Kodiak Marine Environment and Planned Petroleum Development



CHAPTER 7 KODIAK MARINE ENVIRONMENT AND PLANNED PETROLEUM DEVELOPMENT

M. J. Hameedi, OCSEAP

7.1 INTRODUCTION

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. The Alaskan continental shelf, 74 percent of all U. S. continental shelf area, extending as far as 960 km off the coast in the southeastern Bering Sea, constitutes the nation's largest unexplored petroleum area. Consequently, Alaska has received special priority in the planning schedule for the Outer Continental Shelf (OCS) oil and gas development.

The Bureau of Land Management, Department of the Interior, as manager of the OCS Leasing Program, has implemented an environmental studies program. The principal objective of this program is to obtain and interpret information needed for the prediction, assessment, and management of impacts on the human, marine, and coastal environments which may be caused by OCS petroleum development (BLM, 1979a). Marine environmental studies are managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP), National Oceanic and Atmospheric Administration (NOAA). Results of these studies are provided to BLM before specific leasing decisions are made.

Several sedimentary basins in the Alaskan OCS region are scheduled to be leased for petroleum development. Lease sales were held in the northern Gulf of Alaska in April 1976 and in lower Cook Inlet in October 1977. Kodiak Sale #46 was initially planned for December 1976 in response to the accelerated leasing schedule of June 1975. The sale date was postponed to November 1977 and has now been rescheduled for December 1980.

In this chapter, an attempt is made to provide an overview of our knowledge of the Kodiak marine environment and discuss the implications of probable impacts of petroleum development. Much of the information is based on OCSEAP investigators' reports, development scenarios furnished by BLM, and discussions held at information synthesis workshops conducted in March 1977 and May 1979. Early funding was insufficient, sites were difficult of access, long periods of time were necessary for field sampling and analysis of fisheries data, and until recently some important sampling devices and techniques (e.g., ocean bottom seismographs) had not been invented; hence, studies of the area have been slow, and some results are not yet available. Some research projects are nearly finished and final reports are expected by the end of September 1980. Significant new findings will be reported to BLM before the decision to award leases is made. Additional, site-specific studies will be initiated after the lease sale, when plans for exploration and development have been made.

7.2 THE MARINE ENVIRONMENT

The Kodiak Archipelago extends from the Barren Islands to Chirikof Island in the western Gulf of Alaska. Sixteen major islands of the archipelago (Kodiak, Afognak, Sitkalidak, Sitkinak, Raspberry, Tugidak, Shuyak, Uganik, Chirikof, Marmot, Spruce, Whale, Amook, Ban, Ushagat, and Aiaktalik) cover approximately 12,750 km^2 of land area. Kodiak Island, the largest of the island group, has an area of 9,200 km^2. Most of the islands are mountainous; some peaks, such as Mt. Glottof (off Ugak Bay) and Konig Peak (west of Kiliuda Bay) exceed 1,300 m in elevation above sea level. Relief is usually about 300 m.

The geology of the western Gulf of Alaska is dominated by the interaction between the North American and Pacific Plates. The Kodiak region has been classified as an island arc collision coast where the relatively thin, but dense, oceanic crust is being thrust under a less dense continental crust at a fairly rapid rate. The two lithospheric plates converge at a rate of approximately 5 cm per year (Minster et al., 1974). The Alaskan Trench axis marks the initial downbending of the oceanic plate, and the active volcanic arc approximately traces its 100 km depth contour (Pulpan and Kienle, 1979b). The archipelago is composed of highly deformed and uplifted marine sedimentary, metamorphic, and volcanic rocks. Seven major lithologic units have been identified in the Kodiak region (Hayes and Ruby, 1979).

There is widespread evidence of tectonic activity, primarily uplift, in the form of wave-cut platforms as much as 300 m above the present sea level. Often these areas have terraces or stair steps, indicating relict still stands of the sea level. The physiography has been greatly modified by periods of glaciation (Hayes and Ruby, 1979).

Petroleum, which forms by decomposition and chemical alteration of organic matter under high temperature and pressure, is most often found in areas which were once covered by ancient seas. The Kodiak Tertiary Sedimentary Province, which extends across the continental shelf from Kodiak Island to the continental slope, is identified as a potential petroleum bearing area in the western Gulf of Alaska. This province is

bordered on the west by a complex fault zone; offshore the structure is less complex and culminates in an anticlinal arch at the edge of the continental shelf. The geometry of the anticline and the orientation of the sedimentary rocks are conducive to the formation of petroleum reservoirs and hence make this an attractive area for petroleum exploration (BLM, 1979b).

7.2.1 Physical characteristics

Meteorology and oceanic circulation in the Gulf of Alaska are dominated by the presence of the Aleutian low pressure system and the counterclockwise Alaska gyre. The Aleutian low pressure system, which is evident virtually the year round, increases in intensity from August until January as its center moves from the north Bering Sea southeastward to the Gulf of Alaska. In January, it shifts to the western Aleutian Islands. The system then progressively weakens and is least evident in July. The interaction between this system and the eastern Siberian and eastern Pacific high pressure systems determines the mesoscale wind patterns in the area (Favorite et al., 1974). The relative position and intensity of these systems dictate the presence of intense cyclonic winds over the gulf in January and moderate anticyclonic winds in July. In winter, the Aleutian low pressure system causes storms. A mid-latitude cyclone with resulting strong southeasterly winds over Albatross Bank was recorded in March 1978 (Reynolds et al., 1979). Such large-scale features and wind fields are not representative of local wind patterns, which are notably different both on the shore and over the shelf (Brewer et al., 1977). This variation is due to the near orthogonal position of major mountains on Kodiak Island relative to the orientation of the archipelago, and katabatic winds funneled by the mouths of fiords and estuaries. Orographic steerage of winds in the Kodiak region is effective for about 60-100 km (Reynolds et al., 1979). The passage of a single storm can cause substantial deviation from the mean wind pattern. On March 12, 1978, climatic mean winds from the northwest at Kodiak were distorted by the passage of an extratropical cyclonic storm which produced strong easterly and southwesterly winds. The resultant progressive vector diagram (PVD) yielded a vector mean wind of 1.4 m/see from the north (Reynolds et al., 1979). The climatic mean conditions for Kodiak and the adjoining marine area, compiled by Brewer et al. (1977), indicate that strong winds at Kodiak are primarily northwesterly and westerly, between four and six m/see from September to April; from May to August mean winds are weaker, three to four m/see, and variable in direction, but with a southeasterly and easterly sense. On the shelf and over offshore waters, mean winds are usually stronger and more variable.

The Alaska current, which flows in a counterclockwise direction in the Gulf of Alaska, is a major element of the subarctic North Pacific circulation. In the northwest Gulf of Alaska, it begins to assume the character of a western boundary current, becoming the narrower and higher speed Alaska Stream which flows southwestward off the Kodiak continental shelf at 50-100 cm/sec. The Alaska Stream is about 50 km wide. Its mean volume transport is about 12 million m^3/see, but higher (17 million m^3/see) and lower (8 million m^3/see) values have been recorded during OCSEAP studies in July 1976 and June 1978, respectively (Muench et al., 1979). Published information does not support the existence of any significant seasonal variation in volume transport as a result of seasonal variation in wind stress over the Gulf of Alaska, as both the observed maximum and minimum transport occurred in summer, a period of minimum wind stress curl. Royer (pers. comm.), however, has recently found evidence showing seasonal variation in volume transport in the Gulf of Alaska. It is speculated that since the planetary divergence becomes relatively small at high latitudes, mean transport response to the imposed wind stress curl is also small. The changes in volume transport are presumed to occur at the lateral boundaries rather than through deepening or shoaling of the stream (Muench et al., 1979).

Whereas there may not be a strong seasonal cycle in the volume transport of the Alaska Stream, there is evidence that currents over the continental shelf are stronger in fall and winter than in spring and summer, largely because of persistent wind direction and increased wind speed during the fall-winter period. Over the shelf, an additional influence of the trough-and-bank bathymetry characteristic of the Kodiak region results in an irregular flow regime and may lead to bathymetrically trapped "eddies" (Schumacher et al., 1979a). There is ample evidence that currents on the continental shelf, particularly over the banks, are characterized by weak mean flow (as much as an order of magnitude lower than those off the shelf), frequent reversals in direction, and strong tidal components (Muench et al., 1979).

The waters over the banks and troughs show differences in density profiles and the extent of vertical stratification. North Albatross, Middle Albatross, and Portlock Banks show little or no stratification most of the year. This condition probably results from a combination of winter thermohaline convection, tidal mixing, turbulence resulting from currents impinging on the banks, and effects of episodic meteorological

events (even in June and July, winds approaching and exceeding 10 m/sec are known to occur off Kodiak). Over the troughs, stratification is generally stronger, primarily caused by salinity. The occurrence of high-salinity water in troughs (salinity values greater than 33 ^{o}/oo have been observed in Kiliuda Trough) strongly suggests that the source of this water is the shelf-edge portion of the Alaska Stream. Current meter records also show flow events which might transport shelf-edge waters shoreward into Kiliuda Trough. The greater duration of such events in the upper water column suggests that initial forcing is applied at the surface by winds. Strong northeasterly winds would reverse the generally offshore flow. Sea level setup may establish a deep return flow, a feature observed in current meter records from Kiliuda Trough during winter (Muench and Schumacher, KSM, 1979). These data show a pronounced but weak flow (5-10 cm/sec) into the trough along the northeastern side of the trough and seaward flow on its southern side. Flow at the head of the trough was relatively strong (20 cm/sec) and southwesterly. Current meter moorings on Middle Albatross Bank showed a typically onshore current of the order of 10 cm/sec, but with considerable offshore and alongshore components. A generally onshore flow is also inferred from drift card and sea-bed drifter release and recovery data in Chiniak and Kiliuda Troughs and Kaiugnak Bay (Dunn et al., 1979b). It can be surmised that deep, shelf-edge water episodically flows shoreward in the troughs. This influx accounts for the observed high-salinity bottom water in the troughs and probably contributes oceanic materials and biota to the shelf and the bays.

The general circulation pattern that emerges as a result of OCSEAP studies strongly suggests that currents seaward of the shelf edge are characterized by strong mean flow, weak low frequency, and moderate tidal components. This implies a rapid transport of contaminants released or trapped in this area in the direction of the mean flow. On the other hand, currents over the shelf, particularly over the banks, are characterized by weak mean flow (as much as an order of magnitude lower than those on the shelf) and weak low frequency components, but a strong tidal component. This implies that, on the shelf, contaminants will remain for a longer period of time but their concentration will be readily reduced through tidal mixing. Tidal variance in currents over the banks is expected to be higher than in the troughs. Under certain conditions, contaminants released on the outer shelf could be expected to impinge upon shorelines and bays, particularly those at the heads of troughs. However, the contaminant dispersion and trajectories will always be greatly influenced by prevalent wind conditions and the occurrence of episodic events. For example, spilled oil on the North Albatross Bank would be pushed offshore into the Alaska Stream by strong southwesterly winds and advected out of the area, or, if the prevailing winds were strong and northeasterly, it would be advected into Chiniak Bay. A review of historic records of offshore winds shows that either of these wind types (as well as any other) can occur in the Kodiak region in a given period (Brower et al., 1977).

The influence of shelf topography on water mixing and circulation is also reflected in the distribution of sediment types and amounts on the banks and in the troughs. Much of Portlock and Albatross Banks is covered with a thin veneer of coarse-grained sediment, generally sparse in clay sizes and in some places containing abundant shells. The veneer is absent over large areas, exposing semi-lithified to lithified siltstones, silty sandstones, and pebbly mudstones. Coarse debris covered with fine-grained sediment can be found in shallow depressions on the banks. Chiniak and Kiliuda Troughs, on the other hand, contain surficial layers of fine-grained sediments up to 20 m thick, with surface sediments composed almost entirely of ash from the 1912 eruption of Katmai volcano. These troughs appear to be quiet areas of sedimentation, receiving fine-grained material winnowed from adjacent banks. They are likely to act as storage sites of pollutants that reach the sea floor of the Kodiak Shelf (Hampton and Bouma, 1979; Hampton, KSM, 1979).

Stevenson Trough, which may connect with the tidally dominant Cook Inlet, contains relatively well-sorted sand that has been molded into seaward-facing sand waves. Apparently, a high-energy bottom current regime in Stevenson Trough transports sediment seaward past the shelf toward the sea floor. Pollutants carried into this trough can be expected to experience a similar fate. The presence of such a flow regime has not been verified by actual current measurements; it is probably dominated by storm-related events as observed in the Bering Sea during summer 1978 (Schumacher et al., 1979b).

The coastline of the Kodiak Archipelago is characterized by the presence of a large number of fiords, especially in the northern region. These fiords were formed during the Pleistocene by valley glaciers, which deepened and widened the pre-existing river valleys. Kodiak fiord circulation, unlike that of typical fiords, is generally not restricted; either there are no moraine deposits or they lie submerged deep enough to permit free water exchange with the adjoining open water (Hayes and Ruby, 1979). Olga Bay, which is not a fiord, is connected to the open water by a narrow, shallow passage and probably has reduced water exchange and flushing of the basin. Water circulation in fiords

and bays is dominated by freshwater runoff, tidal currents, and winds. Tidal motion also introduces a large amount of turbulence which leads to effective mixing of the inflowing and outflowing water. Typically winds in fiords are locally generated and flow downslope from the mountains toward the mouth of the fiord.

The wave energy in different parts of the archipelago varies greatly because of the variable fetch and the orientation of shoreline with respect to incoming waves, which are predominantly westerly and northwesterly (Hayes and Ruby, 1979).

No site-specific studies on coastal or fiord oceanography have been conducted as part of OCSEAP. However, the coastal geomorphology of the region, nearshore oceanographic features, and sedimentology have been described by Hayes and Ruby (1979). They concluded that the Kodiak Archipelago represents extremely diverse subenvironments which are predominantly erosional in character. Sheer exposed rock scarps or exposed rock scarps with wave-cut platforms constitute about 25 percent of the coastline, protected rocky headlands about 34 percent. Sand and gravel beaches (22 percent) and gravel beaches (15 percent) lie along predominantly erosional shorelines cut into bedrock or semiconsolidated tills. Of the depositional shorelines, sheltered tidal flats and marshes represent only about 3 percent of the total coastline. Short stretches of fine-sand beaches and exposed tidal flats represent less than 1 percent of the shoreline.

The index of coastal vulnerability to oil spills (Hayes and Ruby, 1979), is based on the potential longevity of spilled oil in each subenvironment. Longevity is primarily a function of the intensity of the coastal processes, sediment grain size distribution, and transport trend. Sometimes biological features, e.g., the presence of a kelp bed, and sensitivity were also considered. The index ranges from 1 to 10 in order of increasing vulnerability of the environment and duration of oil retention. Nearly 70 percent of the Kodiak coastline falls in categories 6-8, having a spill longevity of one to eight years. Most of the remaining coastline falls in low vulnerability classes 1-2, having spill longevity of the order of a few days. However, because of the complexity and spatial irregularity of coastline characteristics (for example, a low-risk scarp may lie seaward of a large embayment with high-risk gravel beaches), the entire archipelago is considered a high-risk area. Furthermore, during periods of low wind and wave action, particularly in summer, many areas of low vulnerability would become high-risk areas.

7.2.2 Biological characteristics

The Kodiak shelf and overlying waters are highly productive and maintain diverse and abundant fauna and flora. The utilization of living marine resources is, and has been for centuries, of central importance to the existence and way of life of the people in this region. For decades, salmon, crab, shrimp, halibut, clams, and oysters have been exploited commercially or for subsistence and sport fishing. The importance of commercial fishing to the regional economy is illustrated by the annual value of the Kodiak area catch to fishermen, estimated at $90 million in 1978. Commercial fishing and fish processing industries are the most important part of the Kodiak economy, accounting for 36 percent of the total payroll for non-agricultural industries and involving about 40 percent of the non-agricultural work force (1977 statistics, Alaska Department of Labor).

The shelf areas are heavily utilized for feeding by spring and summer resident populations of birds, such as Black-legged Kittiwake and Tufted Puffin, winter residents, such as Mallard, Oldsquaw, and Steller's Eider, and transient populations of Short-tailed and Sooty Shearwaters. Shearwaters dominate the spring-summer pelagic bird community, comprising about 84 percent of the estimated total numbers and 83 percent of the biomass. More than 1.8 million shearwaters were estimated to be over the shelf east of the Kodiak Archipelago between May and September 1977. These birds feed in open shelf waters on pelagic organisms and obviously are important, though transient, consumers of the shelf productivity (Sanger et al., 1979).

Marine mammals are abundant throughout the area and extensively utilize the habitats and resources for feeding and breeding activities. Northern (Steller) sea lions, harbor seals, and sea otters are the most evident and possibly dominant marine mammals. Several species of cetaceans, including some listed as endangered species, migrate through and feed on the shelf or offshore. Some species, such as Dan porpoise and humpback whale, may also use the shelf area for calving.

Sustenance and growth of these large and varied animal populations require abundant food supplies, which in turn require high levels of productivity at lower trophic levels. Because the emphasis of OCSEAP research has been on species of direct economic and aesthetic value, systematic studies of lower trophic levels and primary productivity and the determination of functional roles of species which may be of ecological importance have not yet been undertaken. Nevertheless by using available information on the food habits of important Kodiak species (king crab, salmon, shearwaters, ducks, kittiwakes, alcids, pinnipeds, sea

otter, etc.), local circulation, and mixing regimes, extrapolating the available data on primary productivity and plankton, and using the findings from studies of similar areas in other parts of the world, a reasonable speculation about the function of the Kodiak shelf ecosystem can be made. Available data do not permit a community structure analysis of the Kodiak ecosystem and no estimate of its resiliency and stability is presently possible.

The speculative account which follows is based on the following assumptions:

(1) The physical environment affects and modifies population distributions and productivity of smaller organisms (e.g., plankton) more readily than those of larger organisms
(2) Short food chains consisting of large prey species support larger populations of harvestable fish than do long food chains (Greve and Parsons, 1977).
(3) Large mobile species aggregate where food is available and where conditions are suitable for reproduction.

The observed high populations of fish, birds, and mammals on the Kodiak shelf are assumed to be supported by the water column primary productivity, benthic algal productivity, and detritus. The trophic significance of detritus is not well understood.

A significant part of the productivity that results in commercial fish harvest in Kodiak comes not from the immediate region of Kodiak, but from oceanic waters. Chinook salmon juveniles, for example, migrate well out into the Pacific Ocean, as far as ,600 km, and return to coastal water as maturing fish usually in their fourth or fifth year. While offshore this species feeds on herring, other small fish, and euphausiids, grows from about .0 cm to 80 cm, and attains an average mass of .0 kg (length and mass vary according to stocks, environmental conditions, etc.). Thus, the biological productivity of other regions contributes to the fisheries harvest of Pacific salmon on the Kodiak shelf and nearshore.

Water column productivity

There is substantial evidence that physical environment and processes significantly influence the timing and level of biological productivity (Landry, 1977; Greve and Parsons, 1977). It is well known that vernal phytoplankton growth in most areas begins soon after the upper mixed layer becomes shallower than the critical depth (the depth at which the total primary production beneath a unit surface area is equal to total respiration) This phenomenon marks the initial control of productivity by the physical environment. Algal productivity in the water column continues at high levels in the "renewal mode" of nutrient availability and later, at a reduced rate, in the "regenerative mode." In late spring or summer the system shifts from the renewal to the regenerative mode in a relatively short time (Wangersky, 1977). However, a single spring phytoplankton bloom, no matter how large, cannot sustain the variety of life forms and trophic levels on the Kodiak shelf throughout the year. Of particular interest on the Kodiak shelf, as indeed on other highly productive shelves marked with shallow banks such as Georges Bank and Sable Island Bank, are short-term increases in primary productivity observed in late spring and summer that are superimposed on relatively low background levels While of shorter duration and more limited extent, these increases in primary productivity depend on essentially the conditions: mixing of the water column followed by stabilization, nutrients, and sunlight. On the shelf off Kodiak, particularly over the banks, such increases in productivity are facilitated by shallow depth and periodic mixing induced by highly variable winds and the passage of storms. It can be calculated that a persistent 10-m/sec wind is capable of deepening the mixed layer to about 80 m (Sverdrup et al., 1946). However, the extent of mixing depends on the degree of stratification in the water column. Rapid deepening of the mixed layer and replenishment of nutrient-rich water in the photic zone are often observed immediately after a strong wind (Hameedi, 1978). Any internal waves produced by winds or tides can augment mixing either through shear instablities or interactions with topography. It appears that the prevalent water mixing which occurs on the Kodiak shelf is responsible for a high and sustained level of primary productivity, which in turn supports the observed high general productivity.

Although not as widely recognized as the influence of physical oceanographic conditions on primary productivity, the influence of the physical environment on the community structure and individual size of plankton primary producers is also profound. Size-selective feeding at succeeding trophic levels has important implications for apex predator populations and potential fisheries harvests (Landry, 1977; O'Brien, 1979) The predominant phytoplankton size and trophic structure of plankton communities have been to affect the position of fish relative to the source of primary production (diatoms vs. flagellates). The importance of large species of phytoplankters, particularly pelagic diatoms, increases in environments where nutrients are plentiful and leads to a food chain which yields high l ls of harvestable fish.
nutrient levels and increased stratification in the water column shift the growth advantage to dinoflagellates and microflagellates, often leading to food chains which culminate in jellyfish and chaetognaths (Greve and Parsons, 1977).

The effectiveness with which herbivores and succeeding trophic levels utilize primary productivity in the water column is also important in determining the economy of the sea. There seem to be energetic benefits from preferential feeding on larger prey. The seasonal presence of large oceanic copepods, such as Calanus plumchrus and Calanus cristatus, on the Kodiak shelf and the timing of their grazing on plankton are assumed to produce an efficient transfer of organic matter to higher trophic levels. Since no systematic studies of plankton have yet been carried out, only sporadic reports of the occurrence of these species on the Kodiak shelf are available. The onshelf advection of oceanic water which is documented in Kodiak, particularly through the troughs, probably accounts for their presence inshore. In C. plumchrus and C. cristatus, which are characteristic zooplankters of the northern North Pacific and the Bering Sea, neither the onset of breeding nor the size of brood depends on the presence of abundant phytoplankton (in contrast to C. finmarchicus, an Atlantic species, and small copepods). These species reproduce in winter at depths between 200 and 400 m. Early developmental stages ascend toward the surface in early spring. The environmental cue that triggers their breeding at depth and subsequent ascent is not known although temperature is probably important. The early" copepodite stages of these oceanic copepod species are ready to graze the spring production of phytoplankton. There is no lag between intensive grazing pressure and phytoplankton primary production; consequently, only a relatively small loss of organic matter occurs. Smaller neritic and oceanic copepods in the Kodiak shelf region, such as Pseudocalanus sp. and Oithona spp., breed after intensive feeding; the size of their brood depends on the amount of food consumed. Their maximum grazing pressure occurs two to six weeks after spring phytoplankton growth (a phytoplankton bloom will occur if only small copepods are abundant). This delay in maximum utilization of organic matter results in an unbalanced plankton cycle, a loss of a large quantity of organic matter to the bottom, and inefficient resource utilization in the water column. On the bottom, this food resource is consumed by benthic organisms, thus coupling the pelagic and benthic trophic pathways.

The energetic benefits of preferential feeding on large prey by fish have been demonstrated theoretically and experimentally (Kerr, 1971; O'Brien, 1979). Studies of the feeding of young salmonids have demonstrated that juveniles can eat between five and ten times their daily ration from large copepods (4 percent per day growth when fed on C. plumchrus, average mass 3 mg) compared with small copepods (no growth when fed on cyclopoids, average mass 0.1 mg) at the same concentration (LeBrasseur, 1969). Large copepods, on the other hand, are not a preferred food for jellyfish such as Pleurobrachia sp., which shows much larger food intake and growth when feeding on small copepods (Greve and Parsons, 1977). In addition to this experimental evidence, some field data support more effective and desirable (in terms of production of harvestable fish resources) trophic links. In the seasonal succession of plankton, planktivorous fish, and jellyfish, the maximum abundance of planktivorous fish (mainly young salmonids) in the Strait of Georgia, British Columbia, occurs after or in association with the maximum abundance of C. plumchrus. Smaller copepods, such as Pseudocalanus minutus, occur in summer when ctenophore and jellyfish populations are also at a maximum (Parsons et al., 1970). The trophic pathway toward jellyfish and ctenophores could be favored when nutrients are low, usually in summer, on the Kodiak shelf. However, intermittent replenishment of nutrients in the photic zone, as discussed earlier for Kodiak banks, favors diatoms and a trophic pathway toward salmon through large copepods.

These observations have important implications for oil and gas development. Limited data suggest that natural changes toward small phytoplankton, notably flagellates, occur in the marine environment as a result of various forms of pollution, including petroleum (Dickie, 1973; Fisher, 1976; O'Connors et al., 1978). Thus it is not unreasonable to postulate that release of hydrocarbons in oceanic areas could cause a decrease in harvestable fisheries through disturbance of natural food webs.

Other important components of the food web involving carnivorous amphipods and the usually omnivorous euphausiids should also be considered. Amphipods and euphausiids, in addition to copepods, are important and sometimes dominant food items in the pelagic environment. They are consumed by a variety of fish such as juveniles of all Pacific salmon species, herring, capelin, Atka mackerel, Pacific sand lance juveniles, pelagic birds such as shearwaters and alcids, and marine mammals, notably cetaceans (Nemoto, 1970; Harris and Hartt, 1977; Rogers et al., 1979; Smith et al., 1978; Sanger et al., 1979). Food webs involving euphausiids as the principal intermediate element may be similar to those based on large copepods. The significance of amphipods as important food organisms to shelf predators has only recently been recognized. For example, Cross et al. (1978) have shown that of the 55 species of nearshore fish, 53 preyed upon gammarid amphipods. Gammarids composed more than 50 percent of the total Index of Relative Importance (IRI) for 31 fish species, and more than 75 percent for 9 species. The role of carnivorous amphipod species is not yet

established. Food webs leading to or including carnivorous amphipods, such as the genus Parathemisto, are distinct from, but probably exist concurrently with food webs involving large copepods. They may be of this form: small phytoplankton → protozoans, small copepods, larvae → carnivorous amphipods → larger carnivores (Nemoto, 1970). Such food webs will allow food resources to be more available to animals of commercial and aesthetic value and may counteract the formation of food chains culminating in jellyfishes. It is not known whether such a trophic pathway exists in the Kodiak region.

Productivity of the benthos

The richness and productivity of the benthic environment also depends to a large extent on primary productivity in surface layers. Certain species of the Kodiak shelf epifauna, such as king crab, Tanner crab, and pink shrimp, are harvested commercially in large quantities. Some demersal fish species, notably the commercially important Pacific halibut, Pacific cod, and walleye pollock, also depend to a large extent on the benthic environment for food and as a major habitat. Besides benthic microalgae and bacteria, the source of primary organic matter in the benthic environment is sinking phytoplankton and animal remains. Phytoplankton sinks slowly, 1-10 m/day, but it is so concentrated in the surface layers that a steady rain of unconsumed cells falls to the bottom. In shelf or oceanic areas where most of the phytoplankton is consumed in the epipelagic zone, as probably happens on the Kodiak shelf, the amount of unconsumed phytoplankton sinking to the bottom is probably low. Zooplankters and their fecal pellets sink to the bottom much more readily, 100-1000 m/day (Smayda, 1970). They also form an important food source for suspension and deposit-feeding fauna. King crab, Tanner crab, and pink shrimp are omnivorous, but a large part of their food is detritus and detritivores. Pacific halibut, Pacific cod, and walleye pollock are carnivorous and eat miscellaneous benthic and demersal fauna including shrimp and flatfish, which directly or indirectly feed on detritus.

Jewett (KSM, 1979) presented a dramatic example of the opportunistic feeding habits of king crab. In June and July about 80 percent, both by weight and volume, of king crab stomach contents in Izhut Bay were pelagic fish remains. At the same time, shearwaters and sea lions were feeding intensively in the surface layers. Evidently the crabs consumed fish that were wounded but not ingested by the shearwaters and sea lions and had sunk to the bottom; normally king crabs do not feed on fish. It was speculated that these crabs moved from Marmot Bay, their usual habitat, to Izhut Bay in response to food availability, indirectly following feeding activity by vertebrate predators in surface waters.

Although no attempt has yet been made in Kodiak to determine mass balance of organic matter at different trophic levels on the shelf, the contribution of detritus originating nearshore cannot be overlooked. On highly productive shelf banks, such as off Nova Scotia, for which mass balance estimates are available, it is noted that observed primary productivity is not able to sustain the requirements of benthic and pelagic chains simultaneously (Mills and Fournier, 1979). The potential contribution of the extensive littoral and subtidal macrophytes to shelf food chains, including those in Kodiak, is substantial. For example, eelgrass meadows in Izembek Lagoon, Alaska Peninsula, contribute an estimated 10^5 metric tons of organic matter to the adjacent Bering Sea per year (McRoy, 1970).

The canopy kelp, Alaria fistulosa and Nereocystis luetkeana, and other brown algae such as Laminaria dentigera, are widespread and often very abundant on the east side of the Kodiak Archipelago. The mean standing stock of kelp between 1 and 10 m is of the order of 10-20 kg/m^2, although much higher values are also noted (Calvin and Ellis, 1978). This range is comparable to the macrophyte biomass of some of the richest seaweed producing areas, such as Nova Scotia and Scotland. Although no data about productivity are available for Kodiak brown algae, it is probably high, approximately 1 kg/m^2/year, or an order of magnitude higher than shelf plankton primary productivity. This high growth may be due to the occurrence of kelp and other brown algae in nearshore areas, where sunlight is available throughout the water column, nutrient concentrations are high, and energy subsidy provided by waves (causing water movement over algal surfaces) speeds up the growth process. Experimental work by Westlake (1967) has shown that much increased algal growth occurs under conditions of water movement. However, very little of the macrophyte production, probably less than 10 percent, enters the food web through the grazing pathways; only a few animals, both in terms of species and numbers, feed directly upon macroalgae (Velimirov et al., 1977). The tendencies of marine macrophytes to generate detritus as algal drift and litter, and to export organic matter are considerable and well documented (Mann, 1972b). Such detrital matter can be identified by its mean carbon to nitrogen ratio (13:1), which is markedly different from the normal ratio of phytoplankton (6:1). In the Kodiak region, it is probable that organic matter thus generated is transported to the shelf area, notably on the banks, where it can be retained and recirculated, and utilized for long periods. Kelp blades are often torn

by wave action and carried away by coastal currents. The total amount of macrophytes thus contributed to the detrital mass depends on the season and severity of wave action. A strong storm can uproot as much as 10 percent of the primary producer stock (Velimirov et al., 1977). Although actual data are lacking for Kodiak, significant algal drift and litter can be predicted from the occurrence of high wind waves and severe storms typical of this area. The drift offshore and retention over the banks are probably caused by coastal circulation and eddies over the banks. Detrital matter of appropriate size and state of degradation may be directly consumed by detritivores (e.g., certain crustaceans and molluscs) and indirectly by those organisms which eat the detritivores (e.g., king crab).

Microorganisms are important consumers of marine macrophytes and a very significant link in the detrital food web. It is likely that some detritus-feeding invertebrates derive their nourishment from stripping the microorganisms from the plant material as it passes through their digestive tracts. A plausible scenario for the process of utilization and decomposition of macrophyte litter may include: epiphytic communities are torn off along with blades and fronds and removed from the region; initial autolysis results in dissolved organic matter which is acted on by bacteria (and possibly fungi); populations of small predators such as nematodes and ciliates build up on drifted material; animals feeding on detritus strip off the fauna and their feces are recolonized by bacteria; detritivores are consumed by larger, benthic predacious species, some of which are commercially harvested. The cumulative role of microorganisms may be viewed as making macrophyte energy stores available to higher forms (Mann, 1972b). The pathways taken by dissolved organic matter are much more difficult to describe.

Spatial distribution of biota

It is well recognized that marine biota, most notably the plankton, are neither evenly nor randomly distributed. Many species or taxa are spatially clumped or aggregated in patches. The patchy distribution of plankton and other small prey organisms determines the foraging areas and feeding strategies of various bird, mammal, and fish species. The causes and mechanisms of patchy population distributions are believed to be both biological and physical. Biological factors include feeding and reproductive patterns, social behavior, and species interaction. Physical factors include boundary conditions of light, temperature, and salinity as well as periodic forces such as tides. Many species are sensitive to salinity changes of less than one part per thousand and follow oceanic water masses on the shelf. Patchy distribution in certain zooplankton and benthic invertebrates may be caused by the release of clumps of eggs, suitability of substratum, and food availability. Predominantly herbivorous euphausiids (but not carnivorous euphausiids) are known to occur in swarms following patches of high primary productivity (Nemoto, 1970). Such swarming may determine the foraging areas of some pelagic birds and baleen whales which feed heavily on euphausiids. The occurrence in dense patches of principal food items of harvestable fish. is an important ecological consideration. Several of the large copepods which are a preferred food item of Pacific salmon juveniles are known to occur in dense patches. successful encounters of juvenile salmon with such patches, where they can obtain sufficient ration for growth, probably are important in determining the success of various year-classes. Pelagic birds, marine mamma 1s, and pelagic fish congregate in discrete areas where the abundance of food varies temporally (diurnally, seasonally, etc.), in response to primary productivity, distribution of water properties, tidal cycles, or influxes of eddies from adjacent waters. Kamykowski (1974) showed that the interaction of diel migration with changes in the phase and speed of tidal-period internal waves with depth could produce separation and, ultimately, patchiness of plankton populations. But, in a more general explanation, Riley (1976) demonstrated that the interaction between diel migration with tidal currents and net drift can intensify small horizontals variations in population distribution that can gradually develop and produce patchiness. It is also known that storms can create a periodic forcing function with a time scale between those of tidal forcing and upwelling events (Riley, 1976). This could create patchiness on a fairly large scale, such as is usually observed in open waters. All of these mechanisms may be operative on the Kodiak shelf.

In conclusion, it can be stated that the high biological productivity of the Kodiak shelf and the richness of regional biota are the result of interactions between biological and physical factors which cause:

- high primary productivity through vertical mixing and replenishment of micronutrients in the photic zone, both aided by the presence of shallow banks on the shelf
- e partitioning of energy resources between the water column and the seabed and a potentially crucial input of detritus from coastal areas to the open shelf, particularly over the banks
- a reduced number of trophic links leading to apex carnivores and commercially desirable

fish determined, in part, by environmental control of particle size at lower trophic levels

- spatially aggregated distributions of fauna probably caused by periodic tidal movements, episodic events, and diel migration of organisms, resulting in concentrations of food for higher forms.

7.3 THE PROPOSED ACTION

The Western Gulf of Alaska (Kodiak) Lease Sale #46 includes 564 tracts on the continental shelf, comprising 3.2 million acres (1.3 million hectares), for oil and gas development. The method for developing estimates of petroleum resources involves analyzing and interpreting geophysical and geological data about the subsurface and surface formations. The estimates are subject to revision as more data become available. Earlier resource estimates (Draft Environmental Impact Statement for Sale #46, USDI 1977) of recoverable resources indicated 0.25 to 1.9 billion barrels (1 barrel = 0.159 m^3) of oil and 0.1 to 0.9 trillion cubic feet (1 ft^3 = 0.0283 m^3) of natural gas in this region. Information acquired since 1977 suggests that the proposed lease area has a much higher gas and gas condensate fluid potential and that the probability of oil discovery is very low. In March 1979, the U.S. Geological Survey estimated the 5 percent (maximum) level, the mean, and 95 percent (minimum) levels of recoverable resources as follows:

	Maximum	Mean	Minimum
Gas condensate fluids, million barrels (MMbbl)	501	176	22
Natural Gas, trillion cubic feet (tcf)	13.9	5.35	0.91

Most of the resource is believed to be in Albatross Basin, and the rest, in much smaller quantities, in Tugidak and Portlock Basins.

Because the Kodiak Tertiary Province, a potential zone of hydrocarbon reserves, has no production history, estimates of recoverable resources are speculative. The proposed lease area is, therefore, considered a high-risk area. There is only an 8 percent chance that commercially exploitable resources will be found. It is also believed that no oil field smaller than 110 million barrels is economically producible in the Gulf of Alaska with any production system tested in 100 m of water (BLM, 1979b). The minimum gas field size for development is expected to be between 0.5 and 0.65 tcf in 100 m of water and between 0.7 and 1.75 tcf in 200 m of water (BLM, 1979b). Ordinarily these are very high thresholds for production. Of the 5,374 fields discovered in the United States between 1970 and 1978, only nine exceeded either 50 million barrels of oil or 300 billion cubic feet of gas (Oil and Gas Journal, July 13, 1978). However, the remoteness of the area from major petroleum markets and sources of supplies, and the hazardous working conditions may preclude commitment of resources and equipment for lower reserves, at least in the near future. If petroleum production occurs at all in the Kodiak area, it will be on a moderately large scale but proceeding at a modest and predictable pace.

On the basis of current estimates of mean values, peak daily production of gas condensate and natural gas are expected to be 38.3 thousand barrels and 1.13 billion cubic feet, respectively. The estimated production life of Kodiak resources is 25 years (USDI, 1980b).

It is too early to determine the level of industrial activity in the area. The location of support and supply facilities, liquefied natural gas (LNG) plant and terminal sites, and other onshore facilities will depend mainly upon the location of producing fields. The support and supply facility may be the only onshore industrial development when exploration begins. During exploration existing harbors and airport facilities could be used.

Exploration is expected to begin in 1981 and continue through 1986 with a total of 24 exploration and delineation wells drilled. Jack-up rigs may be used in water less than 60 m deep, and drillships and submersibles in deeper water. It is possible that a base may be constructed in the Chiniak Bay area. Airfields at Seward, Kodiak City, and Cape Chiniak could provide aircraft support.

Commercial development will depend on the amount of proven recoverable resources. Assuming successful exploration and discovery, production could begin in 1987 and involve increased development onshore and offshore starting in 1983 or 1984. An outline of the types of industrial activities contributing to development of the mean estimated resources is given in Table 7.1 The information contained in this table assumes discovery and that only natural gas and true gas condensates will be produced.

Table 7.1. Hypothesized activities for development of mean estimated hydrocarbon resources in the western Gulf of Alaska (Sale #46). Data furnished by BLM, Alaska OCS Office in Anchorage.

Exploration and Development Activities:

a. Exploration and delineation wells: 24
b. Production platforms: 4
c. Production and service wells: 40
d. Workover wells: 0
e. Gas pipeline (2 parallel 56 cm (22") pipes)

Offshore:
Total route length = 384 km (240 mi)
Total pipe length = 768 km (480 mi)

Onshore:
Total route length = 2-3 km (l-2 mi)
Total pipe length = 4-6 km (2-4 mi)
Gas terminal(s): 1

Estimated peak annual transportation of gas and gas condensates

LNG: 122.8 MMbbls
Condensate: 14 MMbbls

Estimated volume of commercial muds and drill cuttings (assume 40 wells with an average depth of 2000 meters)

	Per Well	Total for Field
Cuttings:	131 m^3	5240 m^3
Muds :	59.5 m^3	2380 m^3

Estimated volume of produced formation water: negligible

Estimated land use requirements for onshore facilities:

Support/supply base: 10 hectares (25 acres)
LNG terminal and related facilities: 80 hectares (200 acres)

Estimated pipeline burial disturbance (assuming 1849 m^3 per km of pipe route):

Offshore: 7.10×10^5 m^3
Onshore: negligible

Four steel-jacketed, bottom-founded production platforms may be installed, and by 1989, some 40 production and service wells may have been drilled. It is hypothesized that the extracted hydrocarbons will be transported via pipeline to a cryogenic, air-cooled LNG plant on Kodiak Island, probably near Ugak, Kiliuda, or Chiniak Bay. In view of the size of the proposed lease area and uncertainties about hydrocarbon potential, it is premature to select optimum sites for an LNG plant, support bases, or other petroleum-related development The ultimate selection of transportation routes and sites will be based on transportation management planning, local zoning, land use policies, industry interest, and state and Federal regulations.

7.4 MAJOR ENVIRONMENTAL ISSUES

Offshore petroleum development poses questions of potential environmental impacts, economics, and politics. Major adverse environmental or technological impacts could preclude a sale, result in a reduced number of tracts offered for sale, or necessitate strict mitigating measures. It is important to anticipate areas of conflict, environmental hazards to technology, and potential environmental impacts.

The Bureau of Land Management (BLM) has identified nine major issues related to petroleum development in Alaska: subsistence lifestyles, commercial fishing, recreation, social infrastructure, marine and coastal ecosystems, air and water quality, shipping conflicts, and environmental hazards. All of these issues are applicable to Sale #46 in varying degrees, but only issues related to the natural environment are addressed by OCSEAP. The following issues, as they apply to the Kodiak region, formed the core of the OCSEAP study: impacts on commercial fisheries, geological hazards to structure and facilities, contaminant transport, and protection of regional biota and important habitats.

7.4.1 Commercial fisheries

Commercial fishing is the most important element of the Kodiak economy. According to labor statistics for 1977, commercial fishing and food processing industries accounted for 36 percent (or $23 million) of the total payroll for non-agricultural industries and involved about 40 percent of the non-agricultural work force (Statistical Quarterly, 1977, Alaska Department of Labor). An estimated $50 million was paid to fishermen for Kodiak catches. Present fishing efforts concentrate on shellfish, salmon, and halibut. Because of the overlapping seasons of these fisheries and the diversification of fishing activities, commercial fishing is now a year-round business.

The following species are harvested commercially:

King crab	Paralithodes camtschatica
Tanner (snow) crab	Chionoecetes bairdi
Dungeness crab	Cancer magister
Pink shrimp	Pandalus borealis
King or Chinook salmon	Oncorhynchus tshawytscha
Sockeye or red salmon	Oncorhynchus nerka
Coho or silver salmon	Oncorhynchus kisutch
Pink or humpback salmon	Oncorhynchus gorbuscha
Chum or dog salmon	Oncorhynchus keta
Pacific halibut	Hippoglossus stenolepis

Statistics of commercial and sport fisheries (catch and value) are compiled and maintained by fishery regulatory and management agencies within and outside Alaska, such as the Alaska Department of Fish

and Game (ADF&G) and the International Pacific Halibut Commission (IPHC). Catch statistics are summarized and discussed elsewhere in this report: in Section 5.4 for shellfish and Section 5.6 for salmon. The mean annual catch over the past two decades and standard deviation about the mean for major species are shown in Table 7.2 to emphasize the highly variable nature of individual fisheries. This table does not include the halibut catch, an important element of Kodiak fisheries. The halibut fishery is international and regulated by IPHC; its catch statistics are provided for regulatory areas which are much larger than the management districts of ADF&G used for salmon and shellfish. A marked decline in halibut catch has occurred in the area extending from Cape Spencer to the Aleutian Islands, from 13,000 mt catch in the early 1960's to 5,440 mt in 1978. The Kodiak pink shrimp catch in 1978-79 crashed to less than half of the normal yearly catch in recent years. Weathervane scallop Patinopecten caurinus and razor clam Siliqua patula fisheries, once quite substantial, after declining markedly in recent years, are now abandoned, probably as a result of poor market conditions, loss of habitat resulting from the 1964 Great Alaska Earthquake, and increased state and Federal regulations over processing (BLM, 1979c). There is now great interest in the commercial exploitation of bottom fisheries, mainly Pacific cod Gadus macrocephalus and walleye pollock Theragra chalcogramma. It is possible that large-scale entry into bottom fishery will have an adverse effect on halibut stocks. A modest U.S. fishery for herring Clupea harengus pallasi exists in Ugak, Uganik, and Chiniak Bays and in the Old Harbor area.

Table 7.2. Mean and Standard Deviation of Annual Commercial Catch of Salmon and Shellfish in the Kodiak Region, 1960-78. N represents the number of years for which statistics are given. (Source data from Alaska Department of Fish and Game, Division of Commercial Fisheries.)

Catch	Mean	Standard Deviation	N
Shellfish (metric tons)			
King crab	13,625	10,255	18
Tanner crab	7,016	5,187	12
Dungeness crab	1,280	1,056	16
Pandalid shrimp	18,624	9,769	18
Scallop	301	222	10
Razor clam	70	66	16
Salmon (number of fish)			
Pink Salmon	6,651,000	4,483,000	18
Chum salmon	692,000	592,000	18
Sockeye Salmon	481 , 000	218,000	18
Coho Salmon	34,000	20,000	18
King salmon	1,000	400	16

The highly variable commercial catches of shellfish and fish species are not unusual and are to be expected. They probably result from diversification of fisheries, depletion of certain stocks or year-classes due to overexploitation, the naturally fluctuating survival rate among larvae and juveniles, and changes in fecundity and growth due to yearly fluctuations in the physical environment. It would be impossible to distinguish nondramatic effects of OCS oil and gas activities from other effects at the population level of the commercially harvested species. However, there are several notable features of seasonality and area-specific activities during the life cycle of these species that must be considered in the light of future petroleum development.

A review of literature and commercial and experimental trawl catch data and tagging studies by the Alaska Department of Fish and Game (ADF&G) has shown that there are six relatively distinct stocks of king crab around Kodiak. The boundaries of the areas occupied by these studies coincide with bathymetric features and have been designated as ADF&G management districts (Fig. 5.8). For example, the Marmot-Chiniak and Sitkalidak-Chirikof stocks on the east side of Kodiak Island are separated by the Kiliuda Trough. Available data suggest that these stocks vary in population size and migratory behavior. Crabs of one stock are believed to move to particular inshore areas for spawning, fertilization, and early development. After the mating season, adults move back offshore to deep water within the stock's area. For example, stock I (Marmot-Chiniak) crabs, when moving to shallow water to mate, inhabit bays and inlets only from Kizhuyak Bay south to Sitkalidak Strait. After mating, these crabs move offshore to deeper waters of Portlock Bank or northern Albatross Bank. Populations of other stocks are also believed to migrate consistently within distinct environmental zones (Buck et al., 1975). This phase of the life history has important implications, as depletion or significant reduction of one stock (as a possible result of OCS activities) will probably not be compensated for by juvenile recruitment and migration of adults from other stocks.

It is not known whether populations of other shellfish species are comparably segregated but the timing and areas of larval release and the period of early development are unique for each species. Certain phases of life history are probably related to requirements for specific temperature, salinity, or other physical properties of the environment. For example, razor clams, which spawn in summer, require a specific water temperature for incubation and fertilization, and weathervane scallops, also summer spawners, depend on

the weak and inconsistent circulation over the shelf banks, e.g., Portlock and Marmot Banks, for the aggregated settlement of larvae and food supplies.

The coastal and shelf environments are heavily used by salmon. On the average, 11.6 million fish return to the Kodiak area annually from the open sea to spawn and complete their migratory cycle. An estimated average of 300 million juvenile salmonids enter the Kodiak marine environment annually from lakes, rivers, streams, and the intertidal zone. The five Pacific salmon species found in the Kodiak area exhibit markedly different life cycles (Fig. 5.38). Salmonids en route from offshore waters to the spawning grounds segregate spatially and temporally within specific streams. The return of salmon to a spawning stream occurs at about the same time each year and is believed to be a function of. genetic makeup and environmental conditions such as temperature. Because salmon rely on environmental cues to find spawning areas, contamination of the environment or impairment of the habitat could interfere with breeding. Such contamination, depending on its extent and duration, could cause the loss of a year-class or even of entire breeding population units of the coastal areas affected.

The timing of spawning, larval development, and juvenile outmigration vary with species and environmental characteristics, such as the type of substratum and water temperature, specific to the region. Because pink salmon spawn in intertidal regions or at the mouths of small coastal streams and the juveniles soon migrate to the sea, this species is vulnerable to physical disturbances and contamination of coastal waters. Other species, such as the sockeye salmon, spend a long period of time in freshwater streams and lakes (12-36 months). Their juvenile forms in the sea are strong and active swimmers and have greater ability than the pink salmon juveniles to avoid or tolerate environmental contamination.

Recognizing the importance and economic consequences of potential adverse effects of OCS oil and gas development on regional fisheries (commercial, sport, subsistence) , BLM/OCSEAP created several research units to address this issue and obtain data that would complement the information already in the hands of the fisheries management agencies. We are now able to delineate areas and seasons of consistently high commercial catch and large population aggregation, are learning about the reproductive phenology of principal shellfish, and are determining major trophic pathways within the nearshore fish communities. Two OCSEAP research units studying density distributions of ichthyoplankton, planktonic fish eggs, and decapod larvae on the shelf and in selected bays, and one studying fish trophic relationships are expected to complete studies in FY81. Despite our efforts to date, it is still virtually impossible to distinguish among natural sources of changes in fish population or communities. Some of these sources may be physical properties and parameters of varying dimensions and scale. Overlapping with those but of more significance, because they are not necessarily associated with physical changes, are biological interactions, such as predation, spatial exclusion, repopulation potential, and ontogenetic behavior. A wide spectrum of environmental factors continuously affects the composition of specific populations and communities; our understanding of the interactions among these factors on the Kodiak shelf is only rudimentary.

7.4.2 Geological hazards

The high level of seismic activity in the western Gulf of Alaska represents a substantial risk to petroleum industry structures and facilities. Several earthquakes of high magnitude have occurred in this area during the past 75 years. The 1964 Great Alaska Earthquake was perhaps the most significant event, and caused extensive damage to Anchorage and neighboring communities. The earthquake generated a tsunami which caused great damage on Kodiak Island and along the coasts of Washington, Oregon, and California. The epicenter of this earthquake was 450 km from Kodiak, and yet there was widespread seafloor deformation throughout the region of the Kodiak lease tracts, in the form of uplift and downwarping.

Since the inception of OCSEAP studies in the Kodiak region, research efforts have been attempting to assess the environmental risks associated with oil and gas development over the shelf and to evaluate geological hazards to structures and facilities. The Shumagin Islands region is of particular concern. This region has had subdued seismic activity over a number of years and is considered a probable site for a major earthquake in the future. If a major seismic event does occur in the Shumagin "seismic gap" and it is typical of those that have occurred along the Aleutian/Alaska plate margin in the past, the epicenter will be located near the eastern edge of the gap (Hans Pulpan, pers. comm.).

Even though the Shumagin region is at a considerable distance southwest of the proposed lease tracts and expected industrial activities, a major earthquake in the seismic gap might cause damage to onshore and offshore structures and facilities on Kodiak Island and its eastern shelf.

A network of seismic stations has been in existence in the western gulf/Aleutian area since the early 1970's. In its present configuration, the network extends over an 1,100 km arc of the Alaska/Aleutian region. Continued monitoring and compilation of seismic events, including those of low magnitude, are expected to yield the required long-term data to evaluate seismic hazards. Nearly all of the available seismic data are from land-based instruments. As a result, the detection threshold for offshore events is higher than for onshore events, and the accuracy of hypocentral locations is much less. To alleviate these two problems with offshore events, portable arrays of ocean bottom seismometers are being used to monitor seismic activity offshore and possibly to identify active offshore faults. In addition, data from instruments which measure strong ground motion during an earthquake are being collected, and will provide important information to seismic risk analysis for the Kodiak shelf.

Many shallow faults, some offsetting the seafloor, cross the shelf. Two northeast-trending fault zones occur in the area, one off the southeast coast of Kodiak Island, roughly coinciding with a zone of aftershock activity from the 1964 Great Alaska Earthquake, and the other near the shelf break. The latter zone is probably related to slumping and other gravity processes. More recently, studies have concentrated on improving the accuracy of location and determining the recency of movement of faults. This information is useful in identifying and delineating particularly hazardous areas. Any wells that cut through or pipelines that traverse a fault would have an added risk related to movement of the fault. Any structures near an active fault along which rupture occurs during a major earthquake could be subjected to extreme ground accelerations.

Sediment slumps and slides are not known to occur on the Kodiak shelf although the shallow troughs intersecting the shelf have slopes conducive to their formation. They do occur on the upper continental slope on the seaward side of a structural arch which parallels the shelf break. Areas of apparently rapid sediment movement seaward have been identified in the Stevenson Trough; much of the sediment spills through breaches in the arch onto the slope. The sill created by the arch across the mouths of Chiniak and Kiliuda Troughs blocks seaward movement of bottom sediments, creating quiet depositional regimes in the troughs (Hampton et al., 1979b).

There is evidence of gas-charged sediments on the Kodiak shelf. A sample taken at the Chiniak Trough contained natural gas, probably biogenic. Samples from other locations (portions of middle Albatross Bank and Kiliuda Trough) show anomalous concentrations of gas. Continued studies will determine the hazard potential of these sediments and serve as guides for future research on geotechnical properties at specific localities.

7.4.3 Contaminant transport

OCSEAP studies to determine the mechanisms and pathways of transport of released contaminants are designed to:

- o provide data that can be used to minimize risks to environmentally sensitive areas during the various stages of oil and gas development
- o determine probable trajectories and landfalls in the event of an accidental release of contaminants
- o provide information for cleanup operation plans in coastal and nearshore areas.

OCSEAP studies, initiated in FY76, have provided a substantial amount of data needed to accomplish the stated objectives. These studies included literature summaries, analysis of hydrographic data, description and analysis of current meter data, drift buoy trajectories, interpretation of satellite imagery data, mesoscale wind fields, and a preliminary circulation model.

It is now possible to describe shelf and oceanic circulation off Kodiak on a seasonal basis and make statements on the diffusive and advective processes affecting the dispersion and trajectories of released contaminants. A comparision of the relative magnitudes of kinetic energy components (mean flow and its fluctuations) shows that currents seaward of the shelf edge are characterized by a strong mean flow and moderate-to-weak high-frequency fluctuations. This implies a rapid transport of contaminants in the direction of mean flow. On the other hand, currents over the shelf, notably on the banks, are characterized by a weak mean flow (as much as an order of magnitude lower than those off the shelf), but a high-energy tidal component.

This implies that, over the shelf, contaminants will remain for a longer period of time but reduction in their concentration will occur more rapidly through relatively high dispersion and mixing. There is now evidence of flow into and out of shelf troughs.

A contaminant trajectory model for the Kodiak shelf is under development. Its primary purpose is to describe, synthesize, and communicate observational and theoretical studies on the distribution and movement of hydrocarbon contaminants in the sea. The model is expected to incorporate three submodels which describe the regional winds, circulation regime, and oil weathering. Since no crude oil reserves are assumed to be present in this area (and consequently no production or transportation of crude oil), the utility of this model will probably be limited to accidental spills from vessel traffic on the shelf and along tanker routes to and from the lower Cook Inlet.

Site-specific studies along stretches of coastline and in fiords have not yet been undertaken to determine flushing rates, pollutant retention potential, or probable effects of the construction of jetties, piers, or causeways. These and atmospheric pollution studies will be done after petroleum development areas have been identified.

7.4.4 Protection of regional biota and important habitats

The ultimate goal of the biological research programs in Kodiak is to determine which populations, communities, and ecosystems are at risk from either acute or chronic impacts of offshore petroleum development and to develop strategies to mitigate adverse effects. Particular attention is given to seabirds and marine mammals because of their vulnerability to environmental disturbance (noise, physical barriers, chemical pollution), their recreational value, wide public concern for their welfare, and legislative mandates for the protection of certain species. The Kodiak Archipelago supports large populations of birds and mammals, some of which are the largest in the Gulf of Alaska or the world. Besides being important elements of the regional ecosystem, some of the species are of great aesthetic significance and an important part of local culture and tradition.

The largest seabird colonies are on the Barren Islands, dominated by Fork-tailed Storm-Petrel (300,000 birds), Common Murre (60,000), and Tufted Puffin (95,000) on East Amatuli Island. Other large colonies, over 30,000 birds, are located at Flat Island and Triplet (Tufted Puffin), Boulder Bay (Blacked-legged Kittiwake), and Nerd Island (Common Murre). Furthermore, millions of shearwaters visit the Kodiak area from the Southern Hemisphere during spring and summer and feed intensively in the pelagic zone. The largest single concentration of harbor seals in the world, 13-20 thousand animals, is at Tugidak Island. Northern (Steller) sea lions are abundant throughout the Kodiak region, with major population aggregations in the Barren Islands, Marmot Island, Twoheaded Island, and Chirikof Island. These islands are also major rookeries, supplying the majority of pups to other areas of the Gulf of Alaska.

Seven species of whales (gray, sei, finback, blue, humpback, Pacific right, and sperm) and three species or subspecies of birds (Aleutian Canada Goose, American Peregrine Falcon, and Arctic Peregrine Falcon), which occur in the Kodiak Archipelago or the adjacent ocean waters seasonally or at irregular intervals, have been designated as endangered (Federal Register, 42 (135), July 14, 1977). The species and their habitats, including the migratory range, must be protected from adverse effects of human activities or industrial development.

The following general topics have been addressed as part of the Kodiak biological research program:

- identification and delineation of areas of major population aggregations, especially those used for feeding, breeding, or migration
- identification of species (including juvenile forms) that are highly sensitive to physical disturbance or chemical pollution
- description and analysis of trophic relationships, including identification of key trophic links to predict the potential consequences of selective population reduction or removal of important food organisms.

Species-specific studies have not been uniform. Sometimes high resolution (index level) data have been obtained on population densities, feeding areas, reproductive phenology, and habitat dependence at selected sites--for example, for Black-legged Kittiwake, Tufted Puffin, harbor seal, northern sea lion, and sea otter. It would be possible to specify mitigating measures and recommend stipulations governing OCS activities to protect these species and their major habitats. For other species (e.g., whales), only reconnaissance level information is available through fragmentary, and often unreliable, sighting records.

An issue of critical environmental concern, impacts on coastal and nearshore ecosystems, has not yet been addressed directly. Ecological balance within the entire region, and consequently biological productivity, can be disrupted by adverse effects on species of functional significance in an ecosystem. These species, however, may not be the ones for which most data have been obtained in the Kodiak area, i.e., those of commercial, sport, or aesthetic value. The identi-

fication of such species requires intensive studies of local ecosystems. The sites of such studies will be selected on the basis of realistic estimates of the nature and amount of potential contamination and habitat disturbance likely to occur due to OCS development. Such information is not currently available.

7.5 RELATIVE SIGNIFICANCE OF DIFFERENT AREAS

One of the major objectives of OCSEAP is to develop a comprehensive understanding of the natural environment of the Kodiak Archipelago and to identify specific sensitive regions with respect to possible impact from oil and gas development on the continental shelf. These regions are usually geographically limited and can be distinguished by their physical characteristics, biotic communities, and susceptibility to damage. The environmental criteria for identifying these regions include one or more of the following:

- areas located along or near the end of waterborne contaminant trajectories
- potential sites of offshore or onshore placement of structures and facilities or areas likely to receive physical disturbance or chemical contaminants from such activities
- areas recognized as being highly susceptible to geological or other natural hazards, including those with high seismic risk, rapid sediment movement, potential for ground failure, and suspected geotechnical problems
- areas of major population aggregations, especially feeding and breeding grounds of species of commercial, sport, or aesthetic value or those used for subsistence or preservation of native cultural heritage and tradition
- offshore areas or embayments where contaminants may be retained or recirculated for long periods of time
- habitats of species (including larval and juvenile forms) that are highly sensitive to petroleum-related contaminants and physical disturbance.

Since the inception of OCSEAP studies in Kodiak, significant progress has been made toward obtaining the necessary data and acquiring the amount of environmental knowledge necessary to classify areas according to these criteria. A broad overview of the results obtained and reported so far suggests that, for several reasons, the entire east coast of the Kodiak Archipelago and adjacent shelf waters must be considered a unique and highly productive habitat. The most obvious feature of the coastline and shelf waters is the abundance and richness of the biota, a large part of which sustains commercial fish and shellfish fisheries. Other areas represent migratory corridors for fish, shellfish, birds, and mammals, pose serious geological hazards, and are conducive to long-term retention of contaminants.

Participants at the Kodiak Synthesis Meeting, May 1979, were asked to evaluate the relative sensitivity or vulnerability of three geographic lease tract clusters in an attempt to assess different alternatives. The three lease tract clusters suggested by the BLM Alaska OCS Office were composed of tracts off Trinity Islands (area A), those east of Kodiak Island (area B), and those northeast of Kodiak and Afognak Islands (area C) (Fig. 7.1). Available data on the oceanography, geology, and biology of the areas were discussed along and across disciplinary lines in an attempt to rank these areas. Several overlapping areas along the coast and on the shelf are unique or significant in terms of vulnerability to potential environmental hazards, contaminant transport, and damage to important biotic populations and areas of high productivity. It was concluded that the available data do not permit us to distinguish an area of the shelf as more or less vulnerable or sensitive than another. No specific tracts within these clusters were recommended for deletion on the basis of available environmental data. It was assumed that the design and engineering criteria of the industrial installations will take into consideration the geological hazards of specific sites and that areas with highly irregular topography, gas-charged sediments, sediment slumps, and shallow fault zones will be avoided.

The following examples will amplify the significance of certain areas of the Kodiak Archipelago.

(1) The shallow seismicity over the shelf area is diffuse and does not correspond to any known fault system. There is evidence of tectonic segmentation (areal concentration of earthquake epicenters and structural deformation), implying possible areal variation in the severity of tectonic hazards (Hampton et al., 1979b). A large earthquake is less likely to occur on the Kodiak shelf than in the Shumagin seismic gap, especially the eastern portion, to the southwest of the shelf. However, the risk of damage as a result of a large event in the Shumagin gap is still high. If the event occurs in the eastern portion of the gap, damage to offshore structures could result from ground shaking and tectonic deformation. The southwest part of Kodiak Island, the Trinity Islands, and lease tracts in Area A may be more vulnerable to strong ground shaking, tectonic deformation, and tsunami damage than other parts of the archipelago.

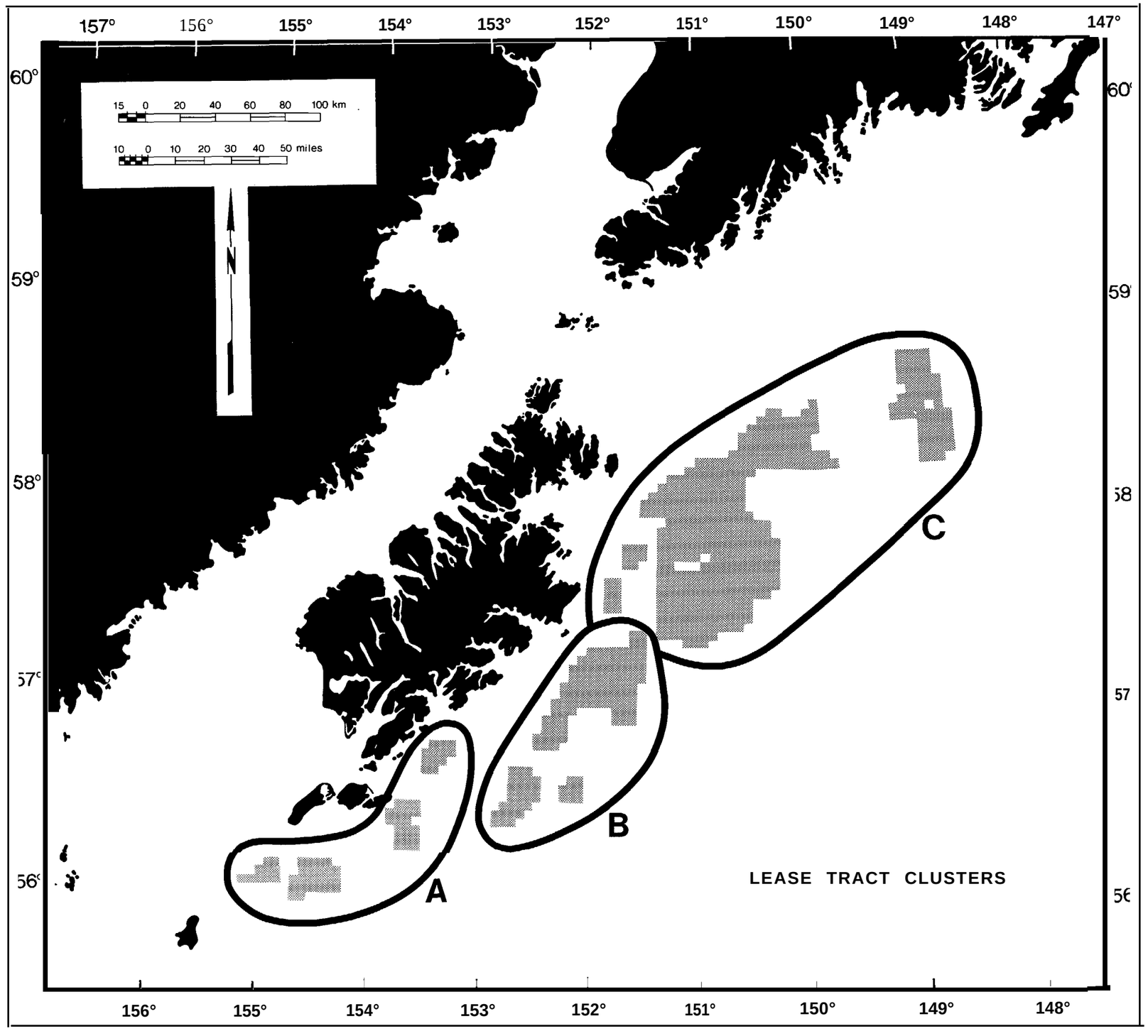


Figure 7.1 Kodiak lease tract clusters discussed at the Kodiak Synthesis Meeting (KSM, 1979).

(2) Shelf areas northeast and south of Kodiak Island have weak and inconsistent circulation, as evidenced by the presence of eddies and frequent flow reversals. Hydrographic and current meter data imply that water could remain in these areas, notably over the shallow banks, for a considerable period of time, possibly one to two months. Such long residence time probably promotes localized high productivity and probably favors the settlement of larvae in geographically restricted areas. The same features of the circulation regime would cause contaminants to be retained in a small area and increase contaminant exposure and contact with the biota.

(3) A weak flow in and out of Kiliuda Trough, possibly separating the circulation regimes on the Middle and South Albatross Banks, is also observed. Such a flow may play an important role in population segregation of biota and biological productivity of the embayments at the head of the trough. Such a flow may also advect contaminants from offshore waters into the highly productive Kiliuda Bay.

(4) Very large (possibly some of the largest in the world) northern (Steller) sea lion rookeries and hauling grounds are located on Sugarloaf Island, Marmot Island, Chirikof Island, and Chowiet Island and in Puale Bay. Each of these rookeries is known to contribute pups to other areas of the Gulf of Alaska. Smaller populations are scattered all along the coast.

(5) The world's largest known concentration of harbor seals is at Tugidak Island. Large numbers are also found at Sitkinak Island, Geese Island, Aiaktalik Island, Ugak Island, and Shuyak Island.

(6) Dozens of seabird colonies and areas of migratory waterfowl concentrations have been identified. There are major seabird colonies at the Barren Islands, in the Sitkalidak Strait/Dangerous Cape area, and in the Puale Bay/Portage Bay area. The dominant breeding species in these areas include Glaucous-winged Gull, Black-legged Kittiwake, Common Murre, and Tufted Puffin.

(7) Pink salmon spawn throughout the archipelago, particularly in Alitak and Uganik Bays. Chum salmon spawning areas are also widespread, but the southwest side of Kodiak is especially important. In particular, sockeye salmon spawn in several river drainage systems on the southwest side of Kodiak Island and the west side of Shelikof Strait.

(8) Extensive macrophyte assemblages and kelp beds around Kodiak Island manifest the high biological productivity of the region. Kelp beds are particularly important and unique biological environments because they serve as a protective habitat to a large number of species, such as larval and juvenile salmon and juvenile king and Tanner crabs. Macrophytes and the associated fauna and flora are heavily utilized as food by mammals, birds, and fish. Kelp beds probably export large quantities of detritus as algal drift, to be consumed as food elsewhere over the shelf. Kelp is also sensitive to environmental disturbances such as increased sediment, thermal pollution, and coating of blades or sporophylls by oil. Major kelp beds and other assemblages of macrophytes are found at Sitkinak Island, the Aiaktalik/Cape Trinity area, Sitkalidak Island, Right Cape/Kiliuda Bay areas, Ugak Island, and north Afognak Island.

(9) All of the bays and fiords in the Kodiak area are heavily used by fish and shellfish species for feeding, spawning, and rearing. The intertidal and subtidal area is important for pink salmon juveniles for feeding and migration from July to October. King crab feed on the rich intertidal biota in spring. Herring, greenlings, sandfish, capelin, and sand lance, which are important food species for other fish, birds, and mammals, are also abundant throughout in appropriate habitats, i.e., gravel, sandy or muddy beaches, rocky intertidal and subtidal areas, or kelp beds.

In view of the obvious overlap in population distributions along the Kodiak coastline and the high productivity of the entire region, it is not practical to delineate specific regions as being more significant than others in susceptibility to impact and recovery potential from contamination or serious damage. Neither is it feasible to eliminate particular regions from consideration. Detailed information on the seasonality and abundance of biota and habitat utilization by different taxa (outlined in the main body of this report and described in OCSEAP principal investigators'

reports) will be useful in guiding OCS oil and gas decisions so as to minimize habitat disturbance and protect important biotic resources of the region through regulations, stipulations, and deletion of lease sale blocks.

7.6 ENVIRONMENTAL IMPLICATIONS OF THE PROPOSED ACTION

This section provides a general account of the types and nature of potential environmental disturbances and implications of these for possible effects on the quality of the environment as a result of petroleum exploration, development, and production activities. Because the current petroleum development scenarios are provisional and imprecise, site-specific information could not be included, nor could possible effects of increased sport fishing, hunting and recreational activities, competition for harbor facilities and space, and marine traffic which, even though pertinent to the marine environment and biota, are more appropriately included in the socioeconomic and sociocultural analyses of impacts.

7.6.1 Loss of habitat

Coastal and marine habitats would be lost or altered by dredging to maintain navigational channels, leveling of land for the construction of shore facilities including an LNG plant, construction of breakwaters to provide sheltered harbors, placement of pipelines and platforms, and the settlement of dredged sediment, drilling muds, and cuttings.

It was pointed out during discussions at the Kodiak Synthesis Meeting (May 1979) that primary principles for selecting a particular location will be economic and sociopolitical; physical and biological considerations may well be secondary. However, it was stressed that shore facilities should be sited away from critical biological habitats (e.g., major rookeries, salmon spawning streams), and areas of landslide and potential delta failures, and be designed to compensate for seismic and tsunami hazards. The loss of habitat along small stretches of coastline and offshore is not considered a major problem, especially when compared with socioeconomic effects and the requirements of the increased human population induced by petroleum development.

7.6.2 Impacts on air and water quality

The quality of the environment around the Kodiak Archipelago is good. There is no evidence that ambient concentrations of total suspended particulate, sulfur dioxide, carbon monoxide, petrochemical oxidants, and oxides of nitrogen exceed primary air quality standards (USEPA, 1978). Concentrations of air pollutants under conditions of temperature inversion could reach higher levels locally for short periods. No data are available for Kodiak during temperature inversions. Marine waters in the bays and fiords and offshore are considered pristine. Large quantities of seafood processing waste used to be dumped near Kodiak Harbor in Chiniak Bay. This waste, high in organic content, caused high oxygen demand upon decomposition and resulted in very low dissolved oxygen concentration in the bay. However, water pollution control measures and sewage treatment facilities, undertaken since 1972, have markedly improved the marine water quality (Buck et al., 1975).

Impacts, mostly local but significant, on regional environmental quality will be caused by emissions, effluents, and noise resulting from or associated with petroleum actitivies. There might be increased turbidity (e.g., from drilling muds, drill cuttings, pipeline burial, dredging, etc.), microbial populations (e.g., pathogens, fecal coliform bacteria), oxygen demand (from decomposition of organic matter), plant nutrients (e.g., inorganic micronutrients such as phosphate, nitrate, ammonia, urea), noise (e.g., from operations of aircraft, supply boats), and air pollutants (e.g., from LNG carrier loading and unloading, boat traffic). Some of these environmental disturbances may last throughout the petroleum development period, 25 years. All discharges into the atmosphere and the marine environment must be regulated in accordance with criteria established by the U.S. Environmental Protection Agency and the Alaska Department of Environmental Conservation.

7.6.3 Well blowouts

OCS regulations require detailed information from operators on the drilling platform, casing program, mud program, blowout prevention equipment, and well control measures to ascertain that safe procedures and technology are employed. Blowout preventers and related pressure-control equipment must be installed, used, and tested in such a manner as to ensure well control. Blowout prevention equipment is essentially a series of valves, usually operated remotely and hydraulically, that can be activated to shut the well in case of an emergency. The system is usually reliable, but equipment failure and human error can cause a well blowout during either the exploration or production phase.

According to estimates based on petroleum development in the Gulf of Mexico, one blowout occurs for every 2,860 wells drilled (USDI, 1977). Since the Kodiak region is a frontier petroleum development area

and subsurface pressures are unknown, BLM estimates that one blowout may occur in this area during petroleum development and production (USDI, 1977).

A gas well blowout does not pose environmental hazards comparable to an oil well blowout, since escaping gas is either advected from the area in solution (very small quantities) or reaches the sea surface in bubble-phase and is dispersed into the atmosphere. The water-soluble fractions, such as propane and butane, may dissolve in seawater but owing to the low temperature at which they vaporize, they will also be dissipated into the atmosphere. A gas well blowout would probably have only a very temporary and local effect on the marine environment; other events associated with a well blowout, such as fire, collapse of the drilling rig, and discharge of muds would probably cause more serious human and environmental damage near the accident site.

The environmental consequences of a well blowout involving gas condensates may be more serious. According to Hunt (1979), gas condensate is a low-molecular-weight hydrocarbon mixture that is gaseous in the ground but condenses into fluid when produced. It may include natural gas liquids (propane, butane, pentane) and short-chained paraffins with five to ten carbon atoms (comparable to the gasoline fraction). Gas condensate, if spilled in fluid state, will evaporate rapidly because of the volatile nature of its constituents. McAuliffe (1977) has shown that short-chained hydrocarbons (with nine or fewer carbon atoms) evaporate from the water surface in less than one hour. Only small amounts of low-molecular-weight hydrocarbons remain dissolved in water; they quickly evaporate near the water surface (McAuliffe, 1977). Because many short-chain petroleum fractions are more toxic than long-chain spilled fractions, gas condensate fluid could cause physiological stress or death to organisms upon contact. The trajectories of spilled gas condensate fluid will be short, both in time and space.

7.6.4 Liquefied natural gas (LNG) release

There is a remote possiblity that operational mishaps, natural events (e.g., an earthquake), or an accident (e.g., ship collision) would cause release of a large amount of liquefied natural gas into the open environment. Such a release can be caused by rupture in the tanks, pipes, or other components of an LNG plant or loading system, the failure of a relief valve or an automatic shutdown device, or human error. The probability of any such occurrence is very slight; the estimated probability of a tank rupture is 1×10^{-6} per year and of a relief valve failure 1×10^{-5} per demand. Offshore, probability of collision of an LNG carrier is 5.5×10^{-7} per year and of a cargo tank rupture 1×10^{-7} per year (SAI, 1976).

Although the probability of a major accident involving LNG is very slight, the potential consequences of such a release can be very serious. The LNG immediately upon release is so cold and dense that its cloud spreads along the ground. Outside its specialized storage tanks, it causes flash-freezing and can crack metal and asphyxiate people (Davis, 1979). LNG vapor (mainly methane) upon release at atmospheric pressure is 40 percent more dense than air. Mixing with air will warm LNG vapor but also cool the air, so that the density of the mixture will remain above that of air. The LNG vapor will remain negatively buoyant until entirely mixed and the gas is dispersed. When heat from the surface of water is significant, the vapor cloud can become neutrally buoyant. The diameter of the negatively buoyant vapor cloud (thus the horizontal area of spread) will be much greater than its height, since the vertical spreading will be inhibited by the higher density of the vapor cloud. The formation of the cloud will also depend on the wind direction and speed. Once the plume is dispersed over an area and mixed with air, it may be ignited by one of the many sources usually found in industrial or residential areas. The minimum spark energy for ignition of a methane cloud is 0.3 millijoule; flammable LNG vapor may be ignited by any kind of open flame, electrical sparks, and even hot surfaces (SAI 1976).

Depending on the extent of the flammable plume, damage and destruction due to fire and explosions could be very severe (see example of the East Ohio Gas Company LNG Plant accident in Chapter 6). However, it must be reemphasized that the probability of such an occurrence is very low. For the planned LNG plant at Nikiski (Lower Cook Inlet), it was estimated that the probability of fatality is one in 190 million per person within 1 km of the site and the probability of an accident causing 1,000-2,000 fatalities is one in 9 trillion per year (SAI, 1976).

7.6.5 Oil spills

According to the current provisional development scenarios, no crude oil production or transportation will occur as a result of OCS Sale #46. Therefore, the possibility of an oil spill from production in the Kodiak area is nil. However, an oil spill affecting the region could occur along tanker routes to and from lower Cook Inlet and Shelikof Strait lease areas (OCS Lease Sale #60), or from accidents involving fishing vessels and OCS structures and supply vessels. Because accidental spills occur as a result of random events such as equipment failures, operational mishaps, and

human error, the problem of predicting the magnitude, location, and frequency of spills is difficult. Most spills have occurred within 75 km of shore when a vessel ran aground, rammed a fixed structure, or collided with another vessel. Despite some recent large and well-publicized oil tanker accidents and the resulting large spills, e.g., the Argo Merchant spill off Nantucket Island, U.S.A., and the Amoco Cadiz spill off the coast of Brittany, France, there is evidence of reduction in the frequency of tanker spills from about 0.45 incidents per million barrels of oil handled between 1969 and 1972 to 0.07 in 1973-74 (Stewart, 1975).

An oil spill of unknown quantity and source (probably "slop" or waste oil discharged by a tanker or tankers) was reported in Kodiak in February 1970. During February and March, oil clumps were found over Portlock Bank. Small stretches of beaches, including kelp beds from Afognak to Sitkinak Island, were found smothered with oil.

According to the documentation of the spill (Federal Water Pollution Control Administration, U.S. Department of the Interior, unpublished report), hundreds of birds, including seaducks, were found oiled and dead on the Barren Islands, Old Afognak Village, Shuyak Island, Marmot Island, Spruce Island, Gibson Cove, Pasagshak Beach, and Kitoi Bay. Over fifty harbor seals were found oiled and dead on Flat Island and Geese Island, two sea lions at Long Island, one sea otter at Mill Bay, and one fur seal at St. Paul Harbor. A Bald Eagle with oiled talons was found dead at West Amatuli Island.

It is virtually impossible to make a general prediction of oil spill trajectories and landfalls in Kodiak owing to the highly variable wind regime, regional differences in water circulation, and the unknown nature of the spilled oil. Participants at the Kodiak Synthesis Meeting (May 1979) discussed a hypothetical case of 20,000 tons of oil spilled on the northern edge of the North Albatross Bank as a result of a tanker accident. The spill location is inshore from the strong, southwesterly flowing Alaska Stream and offshore from coastal circulation. In the spill area, currents are weak, variable in direction, and dominated by winds. In the worst possible circumstances, oil would be expected to flow toward the coast under the influence of strong northeasterly winds. Landfalls in Marmot and Chiniak Bays could be expected. Nearshore, oil would smear long stretches of coastline as it was advected by winds and the coastal current. It would reach the coastline in two to four days depending on the strength and consistency of winds. It is reasonable to assume that the effects of such an oil spill would be seen over distances of hundreds of kilometers. The area of impact would not be uniform, as spilled oil would concentrate in bays with a windward exposure and along headlands exposed to winds. Bays or fiords in the lee of capes or protected from wind would hardly be affected (Gait, KSM 1979). Any fraction (probably an insignificant amount) of oil incorporated in bottom sediment or detritus might be stored in the headward portions of Chiniak Trough for a long time (Hampton, KSM, 1979).

Under conditions of variable wind speed and direction, spilled oil might stay over the North Albatross Bank for weeks and be dissipated by evaporation, dissolution, and flocculation of its constituents. If consistent, strong winds were blowing to the northeast, spilled oil would drift offshore toward the Alaska Stream. Once such oil was picked up by the Alaska Stream, it would be advected out of the area. Such advection of spilled oil offshore was observed in the Argo Merchant spill (Gait, KSM 1979).

During discussion at the Kodiak Synthesis Meeting, it was not possible to determine the extent of spreading of spilled oil. The total area covered by an oil spill is important in determining the extent of faunal mortality and other effects, particularly on birds, planktonic fish eggs, and larval fish, which make extensive use of the upper layers of the water column. It is known that spreading occurs in three stages, each governed by a different physical process (Fay, 1969). Gravitational (inertial) effects control spreading during the initial stage. This stage ends after one minute to one hour for oil volumes of about 1 to 10^4 m^3 respectively and, in axisymmetrical spread, diameters of spread between 10 m and 1 km may be reached. The second phase (governed by gravity effects related to viscous friction in the water) may last for about 10 minutes for a 1 m^3 spill to a few days for a 10^4 m^3 spill. The diameter of the slick increases with time. The third phase (governed by surface tension balanced by viscous forces) starts at some critical thickness of the oil film, less than one cm. In this phase spreading is determined by the "spreading force," that is, the difference between the surface tension of water and the sum of the surface tensions of the oil and the oil-water interface. Theoretically, the spreading could continue till a monomolecular layer is attained,

but weathering and the increase of water-oil interfacial tension resulting from dissolution of oil fractions in water cause the spreading process soon to end (Otto, 1973). In actual occurrence, the spreading tendencies are greatly affected by wind, waves, and currents, as well as by the physico-chemical nature of the spilled oil (Fay, 1969).

The effects on biota at the spill location and along and at the end of oil trajectories depend on the relative amounts of the toxic fractions at different locations and times after the spill, and on the seasonal abundance of the biota. Without this information, it is not possible to estimate environmental damage. The example of the 1970 oil spill in Kodiak illustrates the potential for widespread damage to the environment and biota. Possible effects include:

- direct mortality in the water column and on the coast
- sublethal and possibly long-lasting effects on biota, particularly physiological and behavioral aberrations
- changes in species succession or competition, affecting normal phenology and ecological balance
- indirect effects through ingestion of contaminated food or loss of feeding grounds
- synergistic effects of oil pollution with pathogens, municipal sewage, and other contaminants.

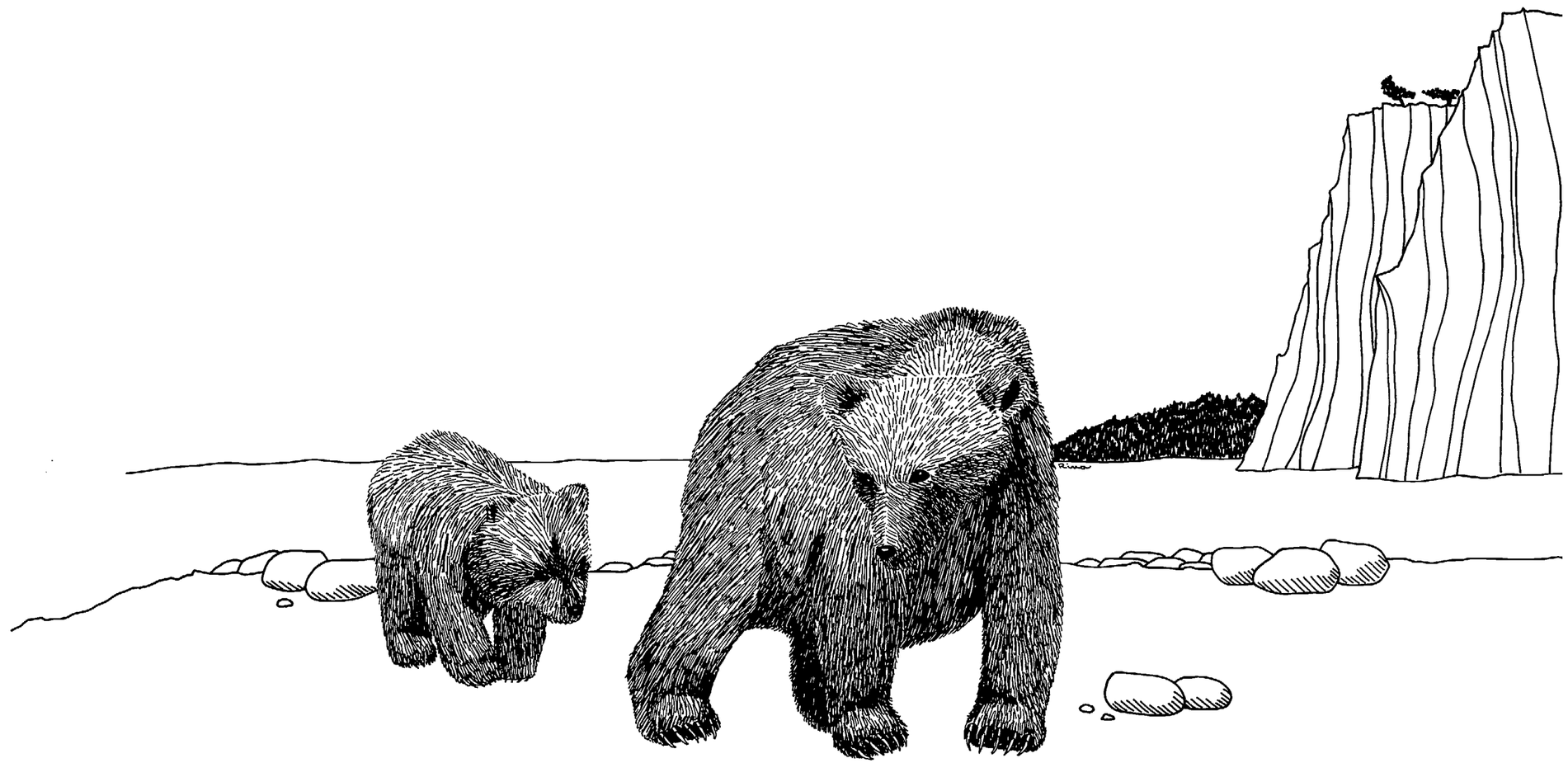
7.7 SUMMARY AND CONCLUSION

The continental shelf east of the Kodiak Archipelago has been selected for the exploration and development of petroleum resources (OCS Sale #46). The available geological and geophysical data suggest that this area may be expected to contain natural gas and gas condensates rather than crude oil. If economically recoverable gas reserves are found and developed, production is not likely to start until 1987. Since there is no major local market and no system of pipelines to transport natural gas to other areas, virtually all of the natural gas will be liquefied and shipped to the west coast of the United States. For this reason, petroleum development off Kodiak will also include construction and operation of a liquefied natural gas (LNG) plant ashore and emplacement of extensive pipelines to transport natural gas and gas condensates from offshore wells to the plant.

The Kodiak Archipelago and adjacent shelf waters are noted for high biological productivity, a number of unique habitats, and the seasonal occurrence of some endangered species of whales. The entire coastline is described as highly vulnerable to damage from spilled oil. A variety of probable impacts on the natural environment and biota from normal operations and activities (i.e., dredging, emplacement of pipelines, construction of shore facilities, waste discharges) and accidental spills, well blowouts, or liquefied natural gas releases have been noted. In addition, the relatively high probability of the occurrence of a major earthquake during OCS development in this area poses a substantial risk to industrial structures, facilities, and human populations.

OCSEAP studies in Kodiak have resulted in an extensive data base on the biology, chemistry, geology, microbiology, and physics of the marine environment, as well as interpretive reports and proceedings of principal investigators' interdisciplinary workshops. Four major environmental issues have been identified and form the core of the studies program: impact on commercial fisheries, geological hazards, contaminant transport, and protection of the regional biota and important habitats. These issues, along with other pertinent environmental implications of planned petroleum development, must be addressed and the problems resolved or mitigated in order to guide petroleum development in this area in a manner that is environmentally safe and minimizes conflicts among users of the resources. The studies have not yet been completed. Additional data of value in the decision-making process will become available before the planned lease sale date (December 1980).

Glossary



GLOSSARY

ACCRETION: a process of continental growth resulting from convergence of two lithospheric plates; as the subducted (or underthrust) plate descends, material originally between the plates or on the surface of the descending plate is compressed and added (accreted) to the upper stationary plate.

ALCID: any member of the avian family Alcidae, a group of marine diving birds. The family is confined to the northern hemisphere and its members breed in colonies on cliff ledges and in burrows. Includes auks, murres, guillemots, murrelets, auklets, and puffins.

ADF&G: Alaska Department of Fish and Game, a state regulatory agency which conducts research on sport, commercial, and other wildlife species.

ADVECTION: in oceanography, the horizontal or vertical flow of seawater as a current without mixing with the surrounding water.

AFTERSHOCKS: smaller earthquakes which follow the largest earthquake of a series; all shocks occur in a restricted crustal volume and are related to the same strain release event.

ALEUTIAN ARC: prominent geographical feature which includes the Aleutian Island chain and extends into the Alaskan mainland; it is expressed topographically by volcanic peaks and ranges, and by the Aleutian Trench; the arc is a product of subduction of the Pacific Plate under the North American Plate. (See also PLATE TECTONICS.)

ANADROMOUS: pertaining to the life history of such fish as salmon and shad, in which young hatch in fresh water and migrate to marine waters where most of the adult stage is spent. Adults migrate back to natal fresh water to spawn.

ANDESITIC: pertaining to Andesite, a rock type composed of plagioclase feldspar and one or more mafic minerals, commonly associated with volcanism on the perimeter of the Pacific Ocean (the "ring of fire" which surrounds the Pacific lithospheric plate).

ANNELID: any member of the phylum Annelida, including the polychaete and oligochaete worms and the Hirudinea (leeches). They are found in marine, freshwater, and terrestrial environments. The major distinguishing characteristic is the division of the body into similar rings or segments.

ANNULUS: the space around a pipe suspended in a wellbore; its outer wall may be either the wall of the borehole or the casing.

ANTICLINE: a fold in a geological formation which is convex upward, generally forming ridge or hill topography. The oldest strata are in the core of the fold.

AROMATICS: a group of organic compounds containing at least one six carbon ring (benzene ring): abundant in crude oil and derived petroleum products.

ATOMIC ABSORPTION: a spectrographic method for detecting elements based on their characteristic absorption of specific wavelengths of radiation.

AVIFAUNA: species of birds in a specific region.

BAROCLINIC CURRENT: A current that is driven exclusively by the internal distribution of density within a water mass.

BAROTROPIC CURRENT: A current that is driven by the slope of the sea surface.

BASALT: in general, any fine-grained, dark-colored, extrusive volcanic rock. The principal component of the crustal rock of the ocean floor.

BATHYMETRY: the topography of the ocean bottom or a display of ocean depths.

BCF: Bureau of Commercial Fisheries, currently, National Marine Fisheries Service. An agency within NOAA for the research, development, and maintenance of U.S. fishery resources.

BENIOFF ZONE: planar zone (within the earth) of intense earthquake activity dipping in the direction of a descending (subducting) lithospheric plate.

BENTHIC: refers to organisms (the benthos) living in or on, or occasionally associated with aquatic sediments. These organisms include bacteria, plants, and animals.

BIOGENIC HYDROCARBONS: organic compounds containing only carbon and hydrogen, formed by the physiological activities of organisms. Biogenic hydrocarbons include saturated and unsaturated aliphatic hydrocarbons, as well as branched-chain hydrocarbons, especially the isoprenoids. Naphthenic and aromatic hydrocarbons occur at very low levels in marine organisms.

BIVALVE MOLLUSC: any member of the class Pelecypoda, phylum Mollusca. Distinguishing characteristics include two laterally compressed hinged shells and a large, muscular, wedge-shaped foot for locomotion and burrowing. Most are sedentary and are filter-feeders involving gills. They range from 1 mm to 1 m in length. Examples are clams, scallops, mussels.

BLOWOUT PREVENTER: equipment installed at the wellhead to control pressures in the annular space between 'the casing and drill pipe, or in an open hole during drilling and completion operations.

BOTTOMFISH: bottom-living or demersal fish. They usually enter the benthos as larval forms. They prey on all size groups of bottom-dwelling organisms. Most demersal fish species remain at or just above the bottom as epifauna but some browse or bury themselves in the sediment surface. Example: flounder, sole.

BRYOZOA (POLYZOA): sea-mats, corallines. Phylum of small, aquatic, usually fixed and colonial animals, superficially resembling hydroid coelenterates but considerably more complex. They have ciliated tentacles with which they feed; anus; coelom; some have horny or calcareous skeletons. Contains two classes, Ectoprocta and Endoprocta, which are sometimes regarded as distinct phyla.

CALANOID: any member of the order Calanoida, subclass Copepoda, class Crustacea. Most species are marine, freeliving, and planktonic, with global distribution. The body is divided into differentiated segments with varied appendages for swimming and feeding. An important source of food for many other marine organisms. Size ranges from 0.1 to 1.0 cm.

CARNIVORE: an animal that feeds principally or entirely on other animal tissues, either living or dead.

CASH BONUS TRACT: a tract on which the bidder offers a front end cash value on a dollars-per-acre basis; a minimum of 16.6 percent of oil/gas profits passes to the federal government.

CEPHALOPOD: Any member of the class Cephalopoda, phylum Mollusca. Characterized by a crown of tentacles surrounding the head and often a reduced shell; highly mobile swimming animals. Examples: squid, octopus.

CETACEAN: any member of the mammalian orders Mysticeti and Odontoceti, all members of which are adapted for a completely aquatic existence. The Mysticeti consist of the baleen whales, which feed by straining small organisms from the water through baleen plates (or "whale bone"). The Odontoceti include the toothed whales such as sperm whales and killer whales, porpoises, and dolphins.

CHEMOTROPHS: microbial organisms (bacteria) which synthesize organic compounds from energy derived through chemical reactions rather than from the sun.

CIRQUE : erosional morphologic feature remaining after a mountain glacier has melted away; characterized by a smooth, curved slope at the head of the valley which the glacier occupied; similar in shape to a Roman armchair.

COHORT : in a demographic (population) study, a group of individuals having a statistical factor in common, such as age or class membership.

COMMUNITY : an association of interacting populations occupying a specific locality.

COMPACTION: decrease in volume of sediments due to compression, usually resulting from continued deposition above them, but also from drying and other causes.

COPEPOD: Any member of the subclass Copepoda, class Crustacea. Exist in a variety of aquatic habitats, have elongated segmented bodies, forked tails. May be herbivorous or carnivorous. Often dominate planktonic communities and are important food items for fish and baleen whales. Size range is on the order of mm.

CORIOLIS FORCE: apparent force due to the earth's rotation, causing a moving particle to be deflected to the right of motion in the northern hemisphere, and to the left in the southern hemisphere; it is proportional to the speed and latitude of the moving particle and cannot change the speed (only the direction) of the particle.

CPUE : catch per unit effort, i.e., the number of fish or shellfish caught by a particular method over a specified period of time.

CRITICAL HABITAT: (a) a limited area composed of special physical qualities (i.e., temperature, substrate type, food availability) used by a species as a necessary site for some biological function (e.g., spawning, denning, breeding). As a consequence of an area's use, it may be a location of high productivity (e.g., rookery, fishing grounds). Impairment of the space may jeopardize the viability of one or more species. (b) A critical habitat may also be a "fragile" area, vulnerable to physical perturbations, easily altered in character, such as an area supporting high species diversity, or an area that requires a long recovery period following damage (i.e., tundra, coral reefs, estuarine marshes). High-latitude ecosystems are particularly susceptible because temperature and climatic regimes preclude rapid growth of many of the life forms. (c) An area may also be considered as critical economically or culturally. In this category are areas of economic resources such as commercial fisheries and areas of archaelogical and scenic value. (d) Any air, land, or water area, including any elements thereof, that the Secretary of the Interior, through the Director, U.S. Fish and Wildlife Service, or National Marine Fishery Service, has determined is essential to the survival of wild populations of a listed species or to their recovery to a point at which the measures provided pursuant to the Endangered Species Act of 1973 are no longer necessary. Such determinations are published in the Federal Register.

CRYPTIC SPECIES: a species adapted by color, size, texture, or morphology to appear as inconspicuous as possible in its surroundings.

DEMERSAL SPECIES: organisms which spend most of their life history at or near the ocean bottom, including remaining at or just above the bottom or burrowing or browsing in the sediment surface.

DEPOSIT-FEEDING: consuming of edible material from sediment or detritus, either by ingesting material unselectively and excreting the unusable portion, or selectively by ingesting discrete particles.

DEPURATION: with reference to petroleum, the active or passive discharge of hydrocarbons from the tissues of an organism.

DETRITUS: non-living particulate debris in the sea, including inorganic and organic materials and particulates originating from dead organisms. An important source of food for many organisms.

DEVIATION WELL: a well drilled at an angle from the vertical.

DOWNWELLING: the downward motion of water caused by the convergence of two or more water masses.

DYNAMIC TOPOGRAPHY: the height of the ocean surface above some reference level, usually a level of constant pressure. Differences in height are caused by differences in the density of water between the surface and the reference level.

ECHINODERM: any member of the invertebrate phylum Echinodermata. They are characterized by radial symmetry, no segmentation or well-defined head region. All are marine, most are nearshore bottom-dwellers. Examples: sea stars, sea cucumbers, sand dollars, sea lilies, sea urchins.

EDDY: circular movement of water, usually formed where currents pass obstructions, between two adjacent currents flowing counter to one another, or along the edge of a current such as the Gulf Stream.

EDIS: Environmental Data and Information Service (formerly EDS). Department within National Oceanic and Atmospheric Administration composed of five data collection and dissemination facilities on various aspects of environmental sciences, including oceanography, weather, marine geology, and geophysics.

EKMAN LAYER: that part of a water column influenced by frictional forces. Wind blowing over the ocean surface causes a surface Ekman layer and the friction of currents flowing across the bottom causes a bottom Ekman layer.

ELASMOBRANCH: any member of the class of fish Elasmobranchii. Characterized by an internal skeleton which is entirely cartilaginous. Includes sharks, skates, and rays.

EPIBENTHOS: organisms that live at or just above the sediment surface. Includes animals (epifauna) and plants (epiflora) such as king crab and algae respectively.

EPICENTER: point on the surface of the earth directly above the focus (or hypocenter) of an earthquake.

EPIFAUNA: See EPIBENTHOS

EULERIAN MEASUREMENTS: Eulerian current measurements taken at a fixed point, such as a current meter attached to a buoy. They differ from Lagrangian measurements which are made by following a device that drifts with the currents.

EUPHAUSIIDS: members of the order Euphausiacea, class Crustacea. These are shrimplike animals differing from true shrimps in not having the first three pairs of thoracic limbs modified as mouthparts; entirely marine, often occurring in dense populations. They constitute the main food of baleen whales. Also known as krill.

FAULT : a fracture or zone of fractures in rock along which there has been relative displacement of the adjacent sides; amount of displacement varies from centimeters to kilometers and direction may be vertical or horizontal.

FAULT SCARP: the cliff formed by vertical movement along a fault.

FECUNDITY: rate at which a female individual produces offspring.

FINES : the fine fraction of a sediment; finer than 0.074 mm in particle diameter.

FLUX : in oceanography, the rate of transport of fluid properties such as momentum, mass, heat, or suspended matter by advection or turbulent motion.

FOOD CHAIN: an abstract representation of the transfer of energy from its primary source (the sun) to plants and the various animals in a community. Example: algae--insects--small fish--larger fish--fish-eating birds or mammals.

FORMATION WATERS: water naturally occurring in sedimentary strata.

FUMAROLE : hole or vent associated with volcanism, through which fumes or vapors issue.

GADIDS : fish belonging to the family Gadidae; include the cod fishes, hakes, and haddocks.

GAMMARID AMPHIPOD: any member of the suborder Gammaridea of the order Amphipoda, class Crustacea. Like other amphipods, these marine invertebrates are laterally compressed. The gammarids comprise a large and important group and are often associated with the bottom of freshwater and marine systems. An example is the sand hopper. Size range in mm.

GAS CHROMATOGRAPHY: a method for identifying molecules based on their characteristic retention times on liquid or solid substrates.

GASTROPOD: any member of the class Gastropoda, phylum Mollusca. Aquatic and terrestrial, most possess a shell which may be whorled. Locomotion is by means of large muscular foot. Examples: snails, limpets, slugs .

GEOSTROPHIC CURRENTS: ocean currents resulting from the balance of the pressure gradient force and the Coriolis force, q.v. The distribution of geostrophic currents can be inferred from charts of dynamic topography.

GEOTECHNICAL PROPERTIES: the physical properties of sediments and rocks that are especially important for engineering purposes; these properties include porosity, permeability, and shear strength.

GRAVIMETRIC ANALYSIS: laboratory analytical procedure made in terms of weight or mass units.

GYRE : a closed or nearly closed circulation pattern in the horizontal plane.

HABITAT: the environment of animal or plant species, characterized by the physical and biological components that are necessary for the survival of the species.

HEAVY METALS: transition elements on the periodic table. Generally present in sea water in trace amounts, i.e., quantities less than one μg/l. Examples: zinc, nickel, lead.

HERBIVORE: an organism that feeds principally or entirely on living plants or plant products.

HARPACTICOID: any member of the order Harpacticoida, subclass Copepoda, class Crustacea. Marine and freshwater invertebrates usually living on or in the bottom sediments. See COPEPOD. Size range in mm.

HETEROTROPH: an organism incapable of synthesizing its own food; it depends on other organisms, such as green plants, as its source of food . Includes all animals, fungi, parasites.

HEXAGRAMMID : fish belonging to the family Hexagrammidae. Examples: greenings, lingcod.

HOLOPLANKTON: any animal species which spends its entire life in a planktonic form. Example: copepods.

HYPOCENTER: point within the earth where rupture first occurs during an earthquake; also referred to as focus or source.

INFAUNA: animals which live within the sediment, utilizing either the interstitial space between sediment particles, or burrows or tubes. Example: razor clam.

INPFC: International North Pacific Fisheries Commission. Member countries include the United States, Canada, and Japan. Its purpose is primarily to determine the oceanic distribution, abundance, and migration of salmon.

INSTAR: in arthropods, the stages between molts.

INTENSITY: a subjective measure of earthquake size based on felt effects and damage to structures; the Mercalli scale sets forth the commonly used criteria for various levels of intensity (described with Roman numerals).

IPHC: International Pacific Halibut Commission. Member countries include the United States and Canada. Its purpose is to regulate catches of Pacific halibut in order to keep the population healthy and sustain maximum catches.

ISOPYCNAL: in oceanography, a line connecting all points of equal water density on a map; an isopleth of density.

ISOSEISMAL: a line or contour on a map connecting observations of equal intensity of felt effects or structural damage due to an earthquake.

KATABATIC WIND: any wind blowing downslope; a "foehn" is a warm, dry downslope wind which has been heated by adiabatic compression during descent; a "fall" wind is a cold downslope wind.

KELP: any large brown seaweed of the family Laminariaceae.

KEY SPECIES: a species that plays an important ecological role in determining the structure and dynamic relationships within a biotic community: a component species of a biotic community whose presence is essential to the integrity and stability of a particular ecosystem. Key species may be unimportant as energy transformers in a biotic community (i.e., they may not be very abundant nor consume large portions of the biotic productivity of a community), but slight variations in their abundance may result in great changes in the abundance of other species and/or in biotic-community relationships and structure (example: sea otter).

LAGRANGIAN (DRIFTER) MEASUREMENTS: current measurements made by tracking a device such as a drogue, which drifts with the ocean currents. The trajectory of the drifter is assumed to represent the trajectory of the surrounding water.

LC_{50}: (lethal concentration$_{50}$) the concentration of a toxic substance necessary to kill 50 percent of a test population. (Usually defined for a specific time period.)

LIQUEFACTION: process during which soil and sand behave as a dense fluid rather than as a wet solid; may occur spontaneously in marine sediments during an earthquake and result in severely reduced bearing strength of the sediment.

LITHOSPHERE: the solid outer shell of the earth; the earth's crust; contains the relatively rigid plates, both oceanic and continental, which are in motion and produce the near-surface physiography of the earth. (See PLATE TECTONICS.) Primarily granite in continental areas, basalt in oceanic areas.

LITTORAL: pertaining to intertidal and shallow subtidal waters. Sunlight is able to penetrate and large seaweeds can grow.

MACROPHYTE: a macroscopic plant. In aquatic communities, these include seaweeds and emergent vascular plants (sea grasses).

MAGMA: naturally occurring mobile rock material generated within the earth at high temperature and pressure; may contain both solid and liquid phases; the source of volcanic rocks extruded on the earth's surface.

MAGNITUDE: a rough measure of earthquake size based on the ground motion recorded by a seismograph. It is calculated by taking the common logarithm of the largest motion recorded during the arrival of a seismic wave (as a deflection on the seismograph). A correction for distance between the seismograph station and the epicenter is applied. A unit increase in magnitude indicates a tenfold increase in earthquake size. Ground motion is represented by three seismic wave types, any of which may be used to determine magnitude: two are body waves (P and

S), which travel through the earth, and the third is a surface wave, which travels near the surface of the earth. Magnitudes are identified by the wave type used during the calculation: body wave magnitude (m_b) and surface wave magnitude (M_s). "Richter" magnitude (ML) is based on the largest seismograph deflection only and does not specify wave type.

MARINE RISER: a telescopic pipe running from a floating drilling rig to the ocean floor, used to direct the drill stem and carry mud.

MARMAP: Marine Monitoring, Assessment, and Prediction, a program of the National Marine Fisheries Service to evaluate the fisheries resources of the United States.

MEIOFAUNA: animals between 0.1 and 1 mm long usually living in the interstitial areas of the upper layer of sediments in aquatic environments.

MERCALLI SCALE: See INTENSITY.

MEROPLANKTON: any species which spends only a portion of its life in a planktonic form, such as fish larvae (ichthyoplankton).

MESOPHILIC: of or pertaining to microbial organisms which grow well at temperatures from 20° to 45°C but which will not grow well at temperatures outside this range.

MESOPLANKTON: phytoplankton, zooplankton, or larvae between 0.5 and 1 mm in size.

MESOSCALE: a size scale of 10 to 100 km for measuring oceanographic features.

MICROFLAGELLATE : microscopic plant or animal species having one or more flagella, long whiplike structures used for locomotion.

MOHO : Mohorovicic discontinuity; boundary between crust and mantle as indicated by a rapid increase in seismic wave velocity; occurs at a depth of 5 km under the oceans and 30 to 45 km under continents.

MYSID : any member of the higher crustacean order Mysidacea. Shrimplike animals which are characterized by having eight or nine thoracic appendages. The females possess a brood pouch, are planktonic in lifestyle. Size ranges on the order of mm. Also called opossum shrimp.

NAUPLIUS: the first larval stage of crustaceans.

NEARSHORE : a term that is loosely defined and whose meaning is dependent on the discipline of the user, referring to: (1) that area of an aquatic environment between the high water mark and the point offshore where the wind influences currents in the entire water column; (2) the area between the high water mark and the point where the depth of the water column becomes shallow enough to cause waves to break; (3) oceanic waters of depths shallower than 200 m (cf. NERITIC).

NEKTON : all swimming marine animals which are able to migrate freely over considerable distances.

NEMERTEAN : any member of the invertebrate phylum Nemertina or ribbon worms. Elongated, flattened body with distinctive proboscis (an anterior feeding appendage). They live in shallow marine habitat uncle r stones, or in sand or mud. All are carnivores. Range in size from an inch to several feet.

NERITIC : referring to oceanic waters of depths shallower than 200 m.

NEUSTON : organisms resting or swimming on the surface, primarily bacteria and plankton.

NGSTDC : (or NGSDC) National Geophysical Solar-Terrestrial Data Center, part of the Environmental Data and Information Service within the National Oceanic and Atmospheric Administration. One of the five major facilities of the EDIS, its purpose is to acquire and disseminate data in the fields of seismology, marine geology and geophysics, geomagnetism, and related fields.

NMFS : National Marine Fisheries Service, a branch of the National Oceanic and Atmospheric Administration, whose purpose is to research the development and maintenance of fish resources. (Formerly Bureau of Commercial Fisheries.)

NODC : National Oceanographic Data Center, part of the Environmental Data and Information Service within the National Oceanic and Atmospheric Administration. One of the five major facilities of the EDIS, its purpose is to acquire and disseminate oceanographic data.

NONSAPONIFIABLE: organic compounds which are not soluble in an alkali solution.

NORTH AMERICAN PLATE: lithospheric plate which includes most of the North American continent. See PLATE TECTONICS.

NPDES: National Pollution Discharge Elimination System: a program in which the EPA regulates permissible discharges from drilling platforms through monitoring, establishment of standards, and issuance of permits.

NUEE ARDENTE: extremely hot gaseous cloud of volcanic ash ejected during an explosive eruption; may flow downslope like an avalanche at high speeds; associated with pyroclastic ash flows. (Also known as "glowing avalanche.")

OFFSHORE: (1) those deeper waters beyond the nearshore zone seaward to the edge of the continental shelf. See NEARSHORE. (2) All area of an aquatic environment seaward of the high water mark, as opposed to the onshore environment.

OLEFINIC HYDROCARBON: an unsaturated (i.e., containing at least one carbon-to-carbon double bond), straight or branched hydrocarbon in which the carbon atoms are arranged in an open chain.

ONSHORE: landward from the point of highest tidal influence.

OROGRAPHY: branch of physical geography dealing with mountains.

OSMERID: fish belonging to the family Osmeridae; mainly small marine fish which spawn in fresh water. Examples: smelts, eulachon, and capelin.

PACIFIC PLATE: lithospheric plate underlying most of the Pacific Ocean. See also PLATE TECTONICS.

PELAGIC: relating to, or living or occurring in the open sea; oceanic.

PELECYPOD: See BIVALVE MOLLUSC.

PHENOLOGY: the study of the periodically recurring natural phenomena and their relation to climate and changes in season.

PHEROMONE: a substance secreted by an organism that influences the behavior or physiology, or both, of other organisms of the same species.

PHYTOPLANKTON: algae which live in the open water, passively drifting with the currents. Size ranges from microns to a few centimeters.

PINNIPED: any member of the mammalian suborder Pinnipedia, a group of carnivores adapted to marine life, but which breed on land; for example, sea lions.

PLANKTON: organisms inhabiting aquatic environments which are weak swimmers or passive drifters. Includes phytoplankton (algae) and zooplankton (invertebrates and larval fish).

PLATE TECTONICS: contemporary hypothesis which explains the continuing evolution of the earth's crust; proposes that the surface of the earth is composed of approximately 12 rigid, relatively thin (100 to 500 km) lithospheric plates which are in continuous motion relative to one another; earthquakes, volcanism, and mountain building are concentrated at plate margins as a result of plate motions; mechanism explaining Continental Drift.

PLEURONECTIDS: fishes which are members of the family Pleuronectidae. These are the right-eyed flounders (the eyes of the flatfish migrate to the right side of the head at metamorphosis). Examples: halibut and flounder.

PLUG DOME: a steep-sided protrusion of viscous lava forming a dome-shaped or bulbous mass over a volcanic vent.

POLYCHAETE: any member of the class Polychaeta of the phylum Annelida. Segmented worms that are chiefly marine, including sedentary (living in self-secreted tubes or burrows) and free-moving forms. Distinguishing characteristics include lateral appendages (parapodia) on each segment for food gathering and locomotion. The majority are 5-10 cm in length.

PSYCHROPHILIC: of or pertaining to a type of microbial organism which grows fairly rapidly in temperatures of 10° to -8°C; these organisms may also grow well in the mesophilic range (20° to 45°C).

PYROCLASTIC MATERIAL: hot, often incandescent, ash and other debris ejected during an explosive volcanic eruption.

RICHTER MAGNITUDE: See MAGNITUDE.

RISER: a pipe through which liquid travels upward.

ROYALTY TRACT: tract lease for which the bidder offers a minimal cash payment but instead proposes to pay the federal government a significant royalty on any oil/gas profits. Royalties in excess of 60 percent have been proposed.

SALMONID: fish which are members of the family Salmonidae. Examples: salmon, trout, char, whitefish.

SATURATED HYDROCARBON: a hydrocarbon in which all the carbon-to-carbon bonds in the molecule are single bonds.

SEISMIC GAP: geographical area within a larger seismic trend which displays a relative scarcity of seismic activity; may also be used in a temporal sense to indicate an inactive period during a longer period of seismic activity.

SEISMICITY: physical disturbances in the earth caused by earthquakes or explosions; the occurrence of earthquakes.

SEISMIC REFLECTION SURVEY: technique of measuring the depth to various geological horizons, such as the bottom of unconsolidated sediment deposits and various rock formations. An energy pulse is projected into the earth and the travel time for the pulse to penetrate and reflect back to the surface is measured; this travel time is converted to distance (i.e., depth, thickness, etc.) by knowing the velocity at which the energy pulse travels through the geological formation.

SEISMOGRAPH: an instrument which detects and records ground motions caused by the passage of seismic energy waves through the earth.

SESTON : all suspended particulate material in the marine environment, including living organisms (plankton) and detritus.

SHALE SHAKER: a vibrating sleeve that removes cuttings from the circulating fluid stream in rotary drilling operations.

SHELF BREAK: the transition seaward from continental shelf to continental slope, marked by an abrupt change in the bottom slope.

SIGMA-T (σ_T): abbreviated value of the density of a seawater sample after the effect of pressure on density has been removed. To find the equivalent value of density expressed in gin/cm^3, divide σ_T by 1000 and add 1.0.

SLIDE : mass of unconsolidated material moving downslope, with little coherency.

SLUMP : mass of material moving downslope, primarily as a unit and along a single surface; often occurs with a backward rotation on an axis parallel to the strike (plane of inclination) of the slope.

SPARKER : a type of seismic reflection equipment for marine surveys which uses an electrical spark to generate an energy pulse.

SPUD : to commence actual drilling operations.

STD MEASUREMENTS: STD stands for salinity, temperature, and depth. Measurements of the salinity and temperature at various depths allow dynamic topographies to be constructed. (See also DYNAMIC TOPOGRAPHY.)

SUBDUCTION ZONE : lithospheric plate margin where one crustal plate (generally oceanic) is thrust under another (generally continental) as a result of the convergence of two plates; a deep trench may be formed, such as the Aleutian Trench or Peru-Chile Trench. See PLATE TECTONICS.

SUBLITTORAL: pertaining to the area of an aquatic environment below the littoral zone where sunlight is able to penetrate.

SUSPENSION-FEEDING : filtering or trapping edible particles that are suspended in the water; a feeding mode typical of many zooplankters and other marine organisms of limited mobility.

SVERDRUP : in oceanography, a unit of mass transport of water equal to 10^6 m^3/s.

SYNCLINE : fold in a geologic formation in which the strata dip inward from both 'sides toward the axis, generally forming valley topography, i.e., the oldest rock strata are on the outside of the feature.

TECTONIC SUBSIDENCE (or UPLIFT): a lowering (or raising) of sections of the earth's crust resulting from adjustment to stresses within the earth; "tectonic" generally refers to physical deformation in the lithosphere.

TEMPLATE PLATFORM: an offshore platform whose supporting legs fit into a frame constructed earlier and anchored to the sea floor. The platform, constructed on shore, is taken to the location and set into the frame using a crane-barge.

TERRIGENOUS: land based or originating from a land source.

TEXTURE: (in reference to sediments) geometrical aspects of the component grains, including size, shape, and arrangement.

THERMOCLINE: in some layer of a water body, a vertical negative temperature gradient (temperature decreasing with increasing depth) appreciably greater than the gradients above and below it; a layer in which such a gradient occurs. Principal thermoclines in the ocean are either seasonal, due to heating of the surface water in summer, or permanent.

THERMOGENIC HYDROCARBONS: hydrocarbon compounds produced through alteration of organic materials by temperature and pressure. Examples: crude oils and products of industrial combustion.

TRAMMEL NET: a three-layered net with the center layer finely meshed and slack so that fish passing through carry some of the center layer through the coarser opposite layer and are thus entangled.

TRY NET: a small trawl net towed behind a boat to capture organisms within the net's path.

TSUNAMI: "seismic sea wave"; great wave generated by submarine crustal displacement or landslides; associated with major earthquakes and volcanic eruptions. Tsunamis travel at high speed and low wave height in deep water, but slow in speed and build to tremendous heights upon reaching shorelines.

TUNICATE: marine chordate animals of the subphylum Tunicata. Most are sessile as adults after passing through a planktonic larval stage. Widely distributed in all seas from nearshore to great depth. They vary in size from microscopic forms to several inches in length and have internal organs surrounded by a non-living "tunic." Common name is sea squirt.

UMBO: a lateral prominence just above the hinge of a bivalve shell.

UNIBOOM: type of seismic reflection equipment.

UNIVALVE MOLLUSC: animal of the phylum Mollusca possessing a shell that is attached to the body at one point. Examples: snails, limpets, abalone.

UNSATURATED HYDROCARBONS: hydrocarbons in which at least one of the carbon-to-carbon bonds is a double or triple bond.

UPWELLING (COASTAL): the upward motion of water caused by forcing of surface waters away from a coastline. The importance of upwelling is that it can bring nutrient-rich waters into the surface layers where they can be used by phytoplankton.

USGS: United States Geological Survey, Department of the Interior. Primary responsibility is research and development in seismology, geology, and geophysics.

VAN VEEN GRAB SAMPLER: bottom sediment sampler having two hinged jaws and a clamshell-like operation.

VELOCITY SHEAR: in oceanography, rate of change of velocity with horizontal or vertical distance.

WIND STRESS CURL: the torque imposed on surface currents in a non-uniform wind field.

ZOOPLANKTON: animals occupying aquatic environments but considered weak swimmers or passive drifters. Maximum size of organisms falling in this category is a few cm and includes small jellyfish, larval fish, and larval and adult forms of many invertebrates.

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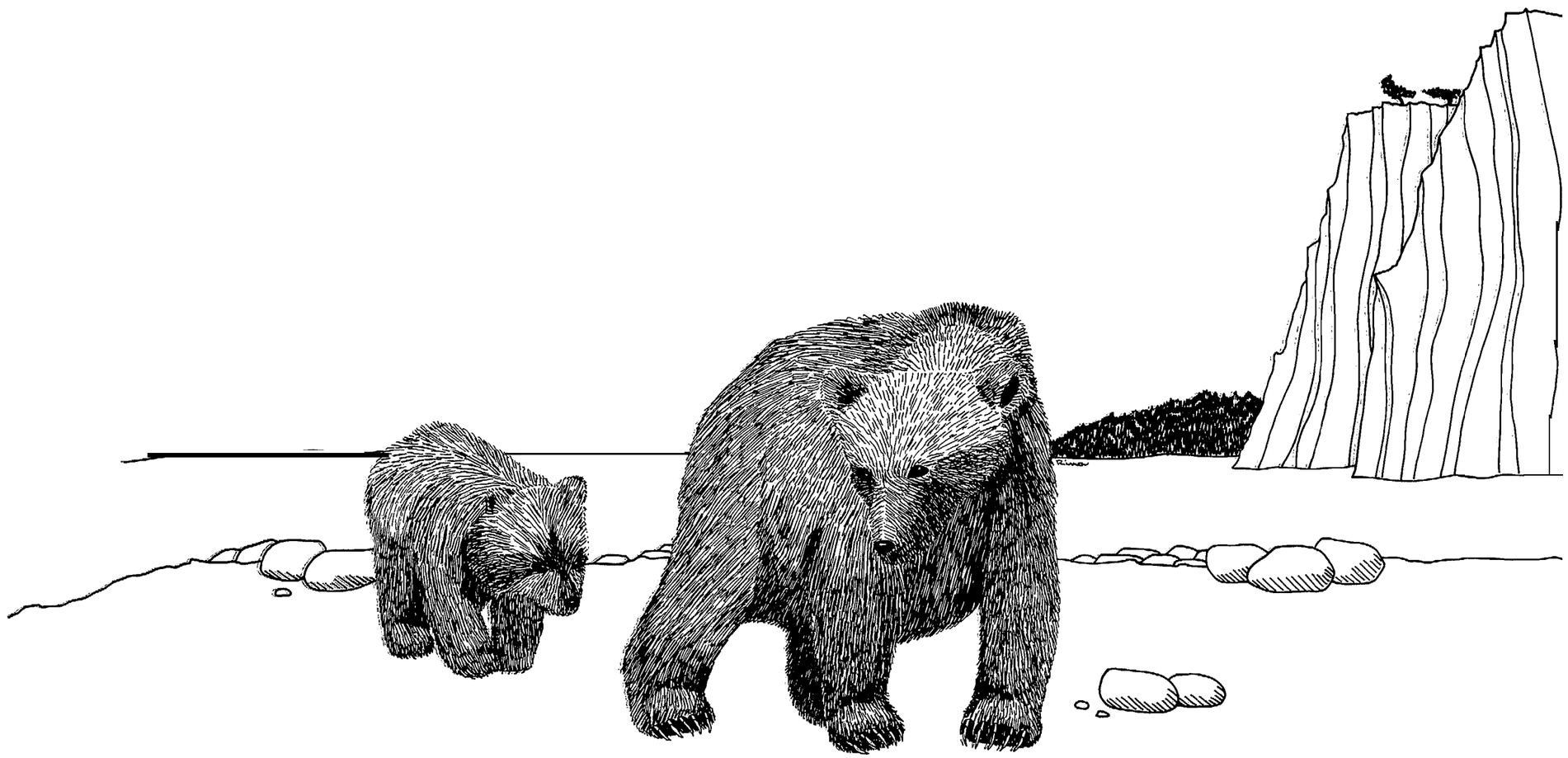

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