Environmental Assessment of the Alaskan Continental Shelf

Northeast Gulf of Alaska Interim Synthesis Report

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NORTHEAST GULF OF ALASKA INTERIM SYNTHESIS REPORT

Prepared under the Guidance of the

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by

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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 Northeast Gulf Alaska (NEGOA) 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 NEGOA 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, MP3, 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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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) begin 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 North Aleutian Shelf 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 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.

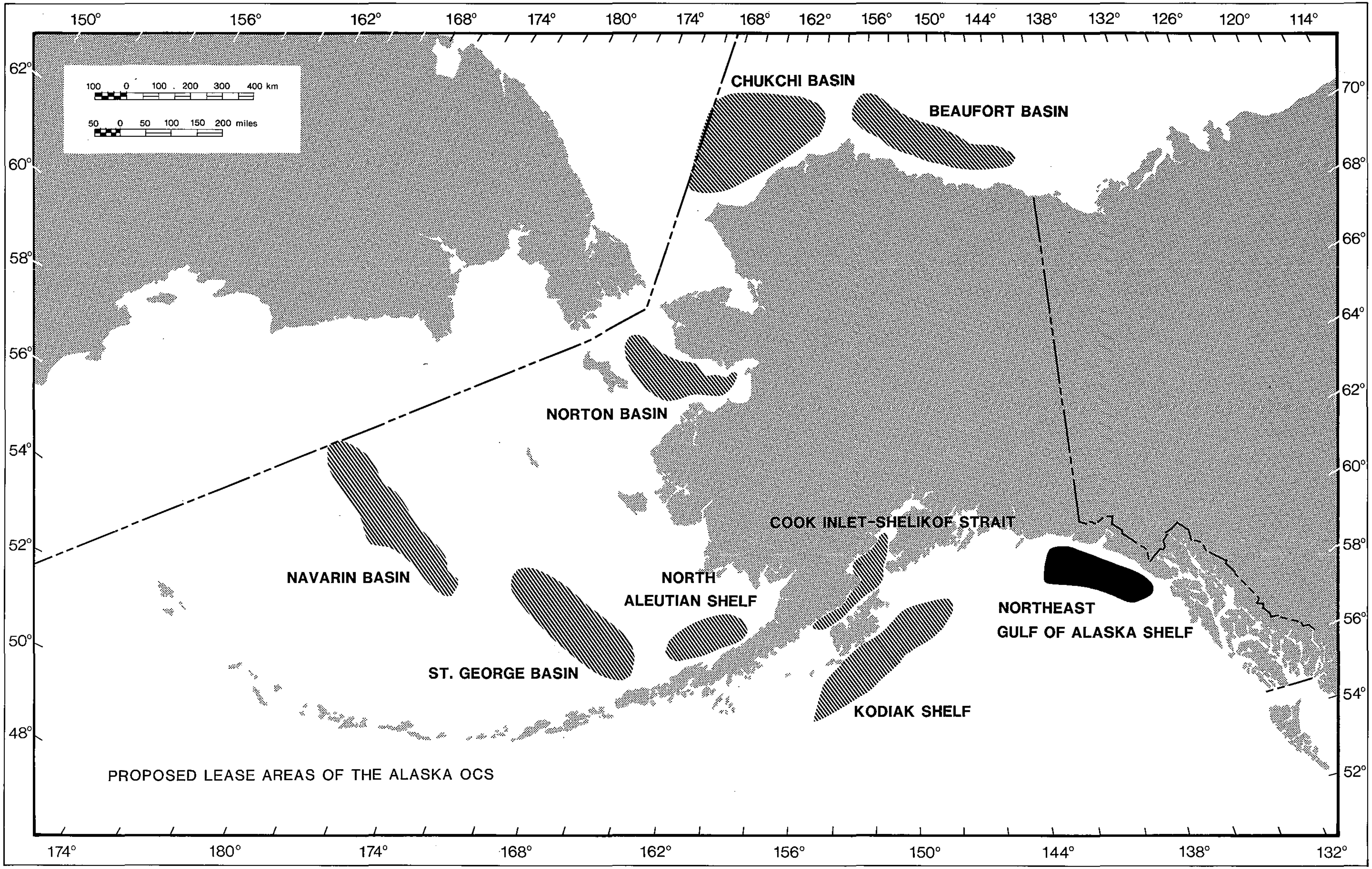
C. Hazards: Identification and assessment of environmental hazards which may affect petroleum exploration and development.

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.

Previous synthesis reports were organized according to the list of tasks. At the Kodiak Synthesis Meeting, Kodiak, Alaska, May 1979, it became evident that this organization hindered use of the reports. 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. The


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
100 0 100 200 300 400 km
50 0 50 100 150 200 miles
PROPOSED LEASE AREAS OF THE ALASKA OCS

disciplinary chapters address the OCSEAP tasks as follows:

Chapter 2	Geologic Hazards:	Task C, Hazards,
Chapter 3	Circulation:	Task D, Transport,
Chapter 4	Hydrocarbons and Metals:	Task A, Contaminants,
Chapters 5-10	Biology:	Task E, Receptors.

Chapter 11 deals with potential petroleum development (Task B), and Chapter 12 is a summary of current knowledge of the lease area. Material on Task F (Effects) has been integrated into the other chapters.

The tracts sold in OCS Sale No. 39 are shown in Fig. 1.2. The results of exploratory drilling in the sale area have been disappointing, and there is little probability that further drilling will be done (see Chapter 11 for details).

A second sale, Sale No. 55, is now planned in NEGOA. The tracts which will be offered (Fig. 1.2) cover an area of about 480,000 hectares.

Each lease block contains 2,304 hectares. For purposes 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).

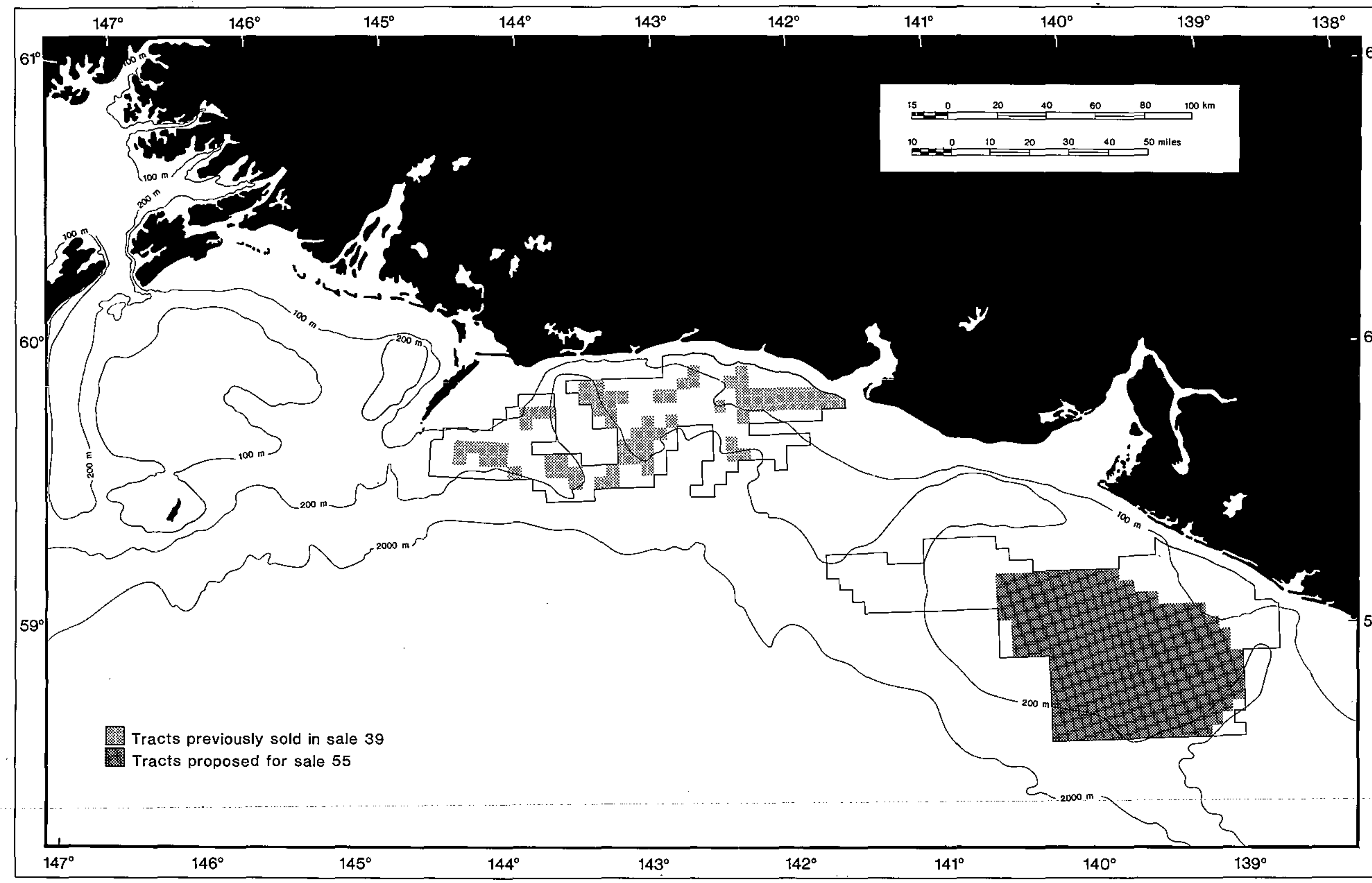


Figure 1.2 NEGOA shelf proposed lease areas (USDI, 1976, 1980b).

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 straight-line coordinates of a surveying grid with the curved-line 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 NEGOA that includes all localities mentioned in the text. Placenames have been listed both alphabetically and numerically.

NEGOA: Alphabetical list of placenames

50	Akwe River	18	Kayak Island
54	Alsek River	78	Kenai Peninsula
83	Anchor Cove	65	Kiliuda Bay
70	Barren Islands	42	Knight Island
21	Berg Lake	85	Latouche
23	Bering Glacier	41	Latouche Point
20	Bering River	94	Lituya Bay
8	Boswell Bay	45	Lost River
84	Cape Fairfield	87	MacLeod Harbor
92	Cape Fairweather	35	Malaspina Glacier
6	Cape Hinchinbrook	37	Manby Shores
82	Cape Resurrection	69	Marmot Island
98	Cape Spencer	1	Middleton Island
17	Cape St. Elias	67	Molina Bay
22	Cape Suckling	2	Montague Island
27	Cape Yakataga	86	Montague Strait
89	Chenega	43	Monti Bay
66	Chiniak Bay	30	Mount St. Elias
61	Chirikof Island	52	Novatak Glacier
79	Chiswell Island	44	Ocean Cape
72	Chugach Islands	10	Orca Inlet
19	Controller Bay	74	Outer Island
14	Copper River	33	Point Riou
13	Copper River Delta	5	Port Etches
99	Cross Sound	81	Resurrection Bay
47	Dangerous River	80	Resurrection River
93	Desolation Valley	40	Russell Fiord
39	Disenchantment Bay	4	Seal Rocks
56	Doame River	60	Semidi Island
53	Dry Bay	59	Shumagin Islands
28	Duktoth River	11	Simpson Bay
55	East Alsek River	36	Sitkagi Bluffs
9	Egg Islands	64	Sitkalidak Strait
12	Eyak River	46	Situk River
95	Fairweather Range	91	Squirrel Point
96	Glacier Bay	71	Sugarloaf Island
73	Gore Point	49	Tongass National Forest
29	Guyot Glacier	63	Trinity Islands
51	Harlequin Lake	24	Tsiu River
7	Hinchinbrook Island	25	Tsivat River
32	Icy Bay	62	Tugidak Island
31	Icy Cape	58	Unimak Island
97	Icy Point	57	Unimak Pass
48	Italio River	90	Whittier
68	Izhut Bay	16	Wingham Island
76	Kachemak Bay	88	Wooded Islands
77	Kalgin Island	34	Yahtse River
26	Kaliakh River	38	Yakutat Bay
75	Kasitsna Bay	3	Zaikof Bay
15	Katalla Bay		

NEGOA: Numerical list of placenames

1	Middleton Island	51	Harlequin Lake
2	Montague Island	52	Novatak Glacier
3	Zaikof Bay	53	Dry Bay
4	Seal Rocks	54	Alsek River
5	Port Etches	55	East Alsek River
6	Cape Hinchinbrook	56	Doame River
7	Hinchinbrook Islan(	57	Unimak Pass
8	Boswell Bay	58	Unimak Island
9	Egg Islands	59	Shumagin Islands
10	Orca Inlet	60	Semidi Island
11	Simpson Bay	61	Chirikof Island
12	Eyak River	62	Tugidak Island
13	Copper River Delta	63	Trinity Islands
14	Copper River	64	Sitkalidak Strait
15	Katalla Bay	65	Kiliuda Bay
16	Wingham Island	66	Chiniak Bay
17	Cape St. Elias	67	Molina Bay
18	Kayak Island	68	Izhut Bay
19	Controller Bay	69	Marmot Island
20	Bering River	70	Barren Islands
21	Berg Lake	71	Sugarloaf Island
22	Cape Suckling	72	Chugach Islands
23	Bering Glacier	73	Gore Point
24	Tsiu River	74	Outer Island
25	Tsivat River	75	Kasitsna Bay
26	Kaliakh River	76	Kachemak Bay
27	Cape Yakataga	77	Kalgin Island
28	Duktoth River	78	Kenai Peninsula
29	Guyot Glacier	79	Chiswell Island
30	Mount St. Elias	80	Resurrection River
31	Icy Cape	81	Resurrection Bay
32	Icy Bay	82	Cape Resurrection
33	Point Riou	83	Anchor Cove
34	Yahtse River	84	Cape Fairfield
35	Malaspina Glacier	85	Latouche
36	Sitkagi Bluffs	86	Montague Strait
37	Manby Shores	87	MacLeod Harbor
38	Yakutat Bay	88	Wooded Islands
39	Disenchantment Bay	89	Chenega
40	Russell Fiord	90	Whittier
41	Latouche Point	91	Squirrel Point
42	Knight Island	92	Cape Fairweather
43	Monti Bay	93	Desolation Valley
44	Ocean Cape	94	Lituya Bay
45	Lost River	95	Fairweather Range
46	Situk River	96	Glacier Bay
47	Dangerous River	97	Icy Point
48	Italio River	98	Cape Spencer
49	Tongass National Forest	99	Cross Sound
50	Akwe River		

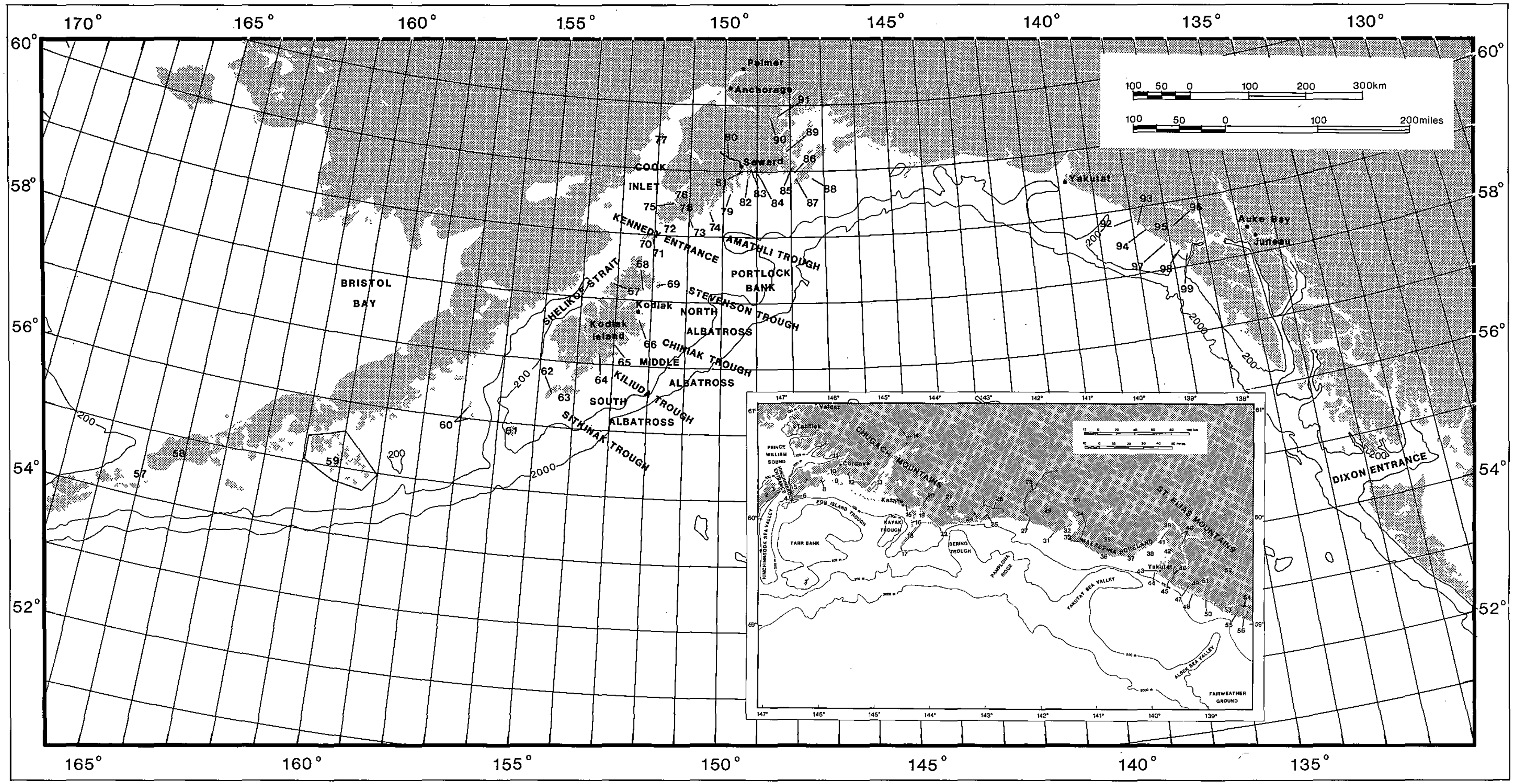


Figure 1.3 Locality map and gazetteer for NEGOA and the Gulf of Alaska.

Chapter 2 GEOLOGICAL HAZARDS

R. E. Peterson, SAI

2.1 INTRODUCTION

2.1.1 Relevance of geological 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 probably the most spectacular hazard posed by this tectonic activity is 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, collapsed 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 (Jackson and Burton, 1978; Okrent, 1980). 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 evaluate. 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 damage pipelines, for instance, as may slumping and sliding of unstable slopes. Dispersion of sediment in the water column, along the seafloor, and along coast lines may influence the fate of spilled oil. Knowledge of the presence and location of gas-charged sediments is important, since encountering such deposits during offshore platform construction and drilling operations is a serious hazard (Thompson, 1979).

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 NEGOA

Interaction between the Pacific and North American lithospheric plates has caused many of the physiographic features and tectonic processes found in NEGOA. The lease areas are situated in a transition zone where plate interaction shifts from primarily strike/slip faulting on the southeast to thrust faulting on the west (Fig. 2.1). These plates are converging at about 6 cm/yr, and the convergence manifests itself as structural deformation and accompanying seismic and volcanic activity.

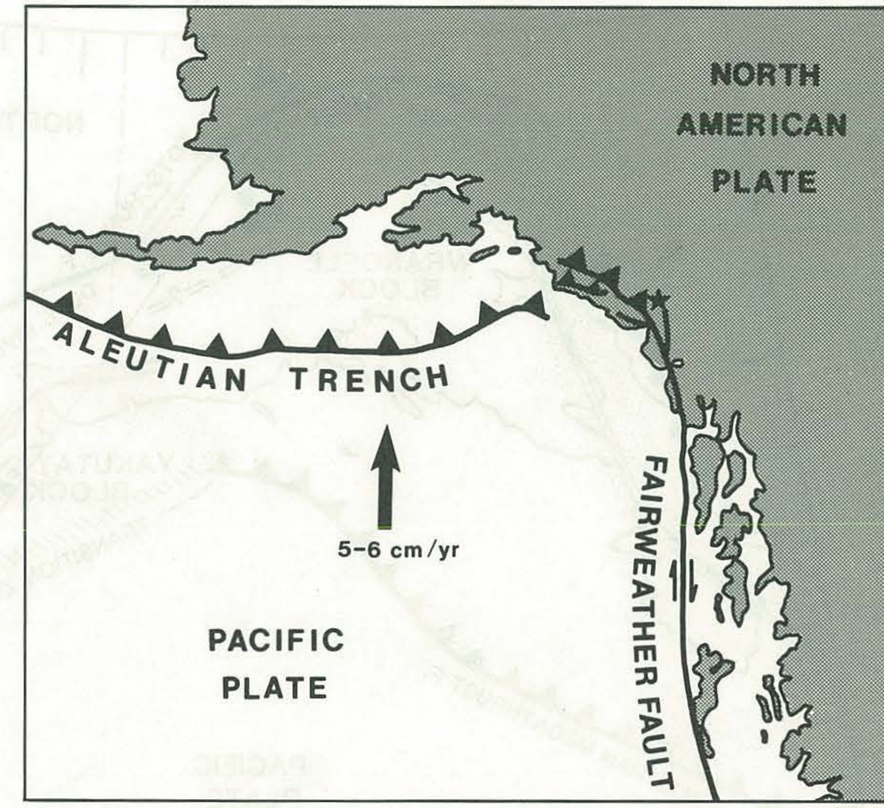


Figure 2.1 Plate tectonic relationships in the NE Pacific Ocean (from Lahr and Stephens, 1979). Star indicates epicenter of 28 February 1979 Mt. St. Elias earthquake.

The complexity of the interaction in this portion of the plate boundary has resulted in several tectonic models for the transition zone (e.g., Lahr and Plafker, 1980; Perez and Jacob, 1980). The details of these models are beyond the scope of this synthesis, but both describe how the strike/slip motion on the east transforms into thrust faulting and subduction on the north and west. Two rigid blocks of crustal material, the Yakutat and Wrangell blocks, are postulated in the transition zone (Lahr and Plafker, 1980). Most of the tectonic deformation in the region occurs along the boundaries of these blocks as the convergence of the Pacific and North American plates is accommodated. Figure 2.2 shows the principal tectonic features of the region.

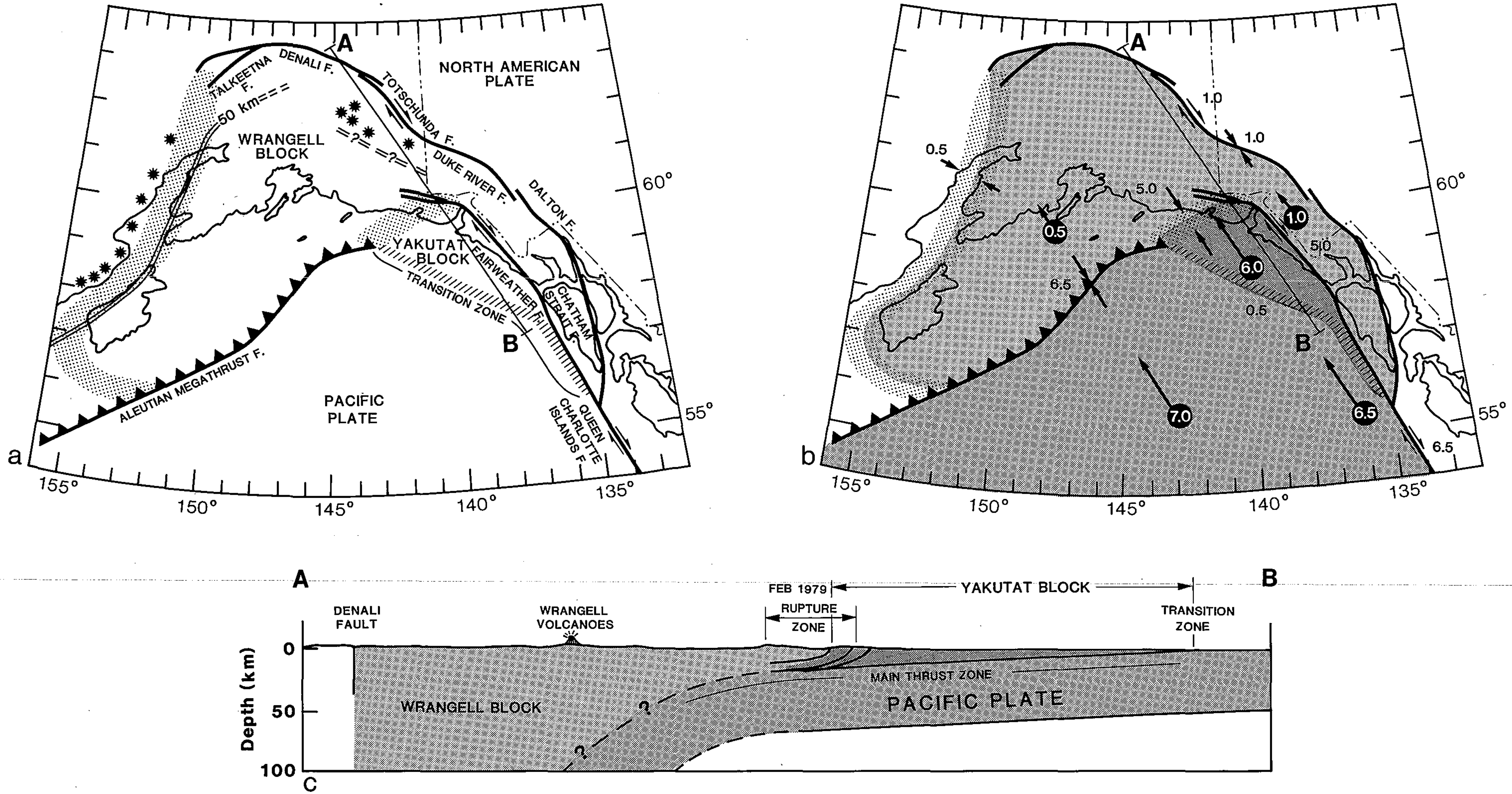


Figure 2.2 Principal tectonic features of southern Alaska and western Canada (modified from Lahr et al., 1980b). In (a) the major fault systems and crustal blocks are shown; stars indicate volcanoes that are associated with crustal subduction. In (b) rates of convergence (circled values) and motion across a zone (uncircled values) are shown relative to the stationary North American Plate. Line A-B is the location of the cross-section shown in (c).

The topography and sediments of the NEGOA shelf and adjacent shoreline reflect the strong influence of glacial activity (Molnia and Carlson, 1980). The coastal region, the shelf, and parts of the continental slope were all covered by ice during the Wisconsin glaciation, which occurred between 35,000 to 11,000 years before present (Sharma, 1979). During glaciation of the shelf many of the faulted and folded structures in sedimentary units were truncated, and considerable amounts of coarse-grained gravels and sands were deposited some distance offshore of the present shoreline. As sea level rose, these materials became relict deposits, since the less energetic deepwater hydrodynamic regime was no longer able to transport the materials.

Several prominent topographic features influence erosion, deposition, and transport of materials on the NEGOA shelf. They include the Yakutat, Alsek, and Cross Sound Sea Valleys, which may act as conduits to transport modern glacial detritus offshore to the continental slope. The Pamplona Ridge and Fairweather Ground are structural highs which have little accumulation of modern sediment. Figure 2.3 is an index map for names and locations of important physiographic features.

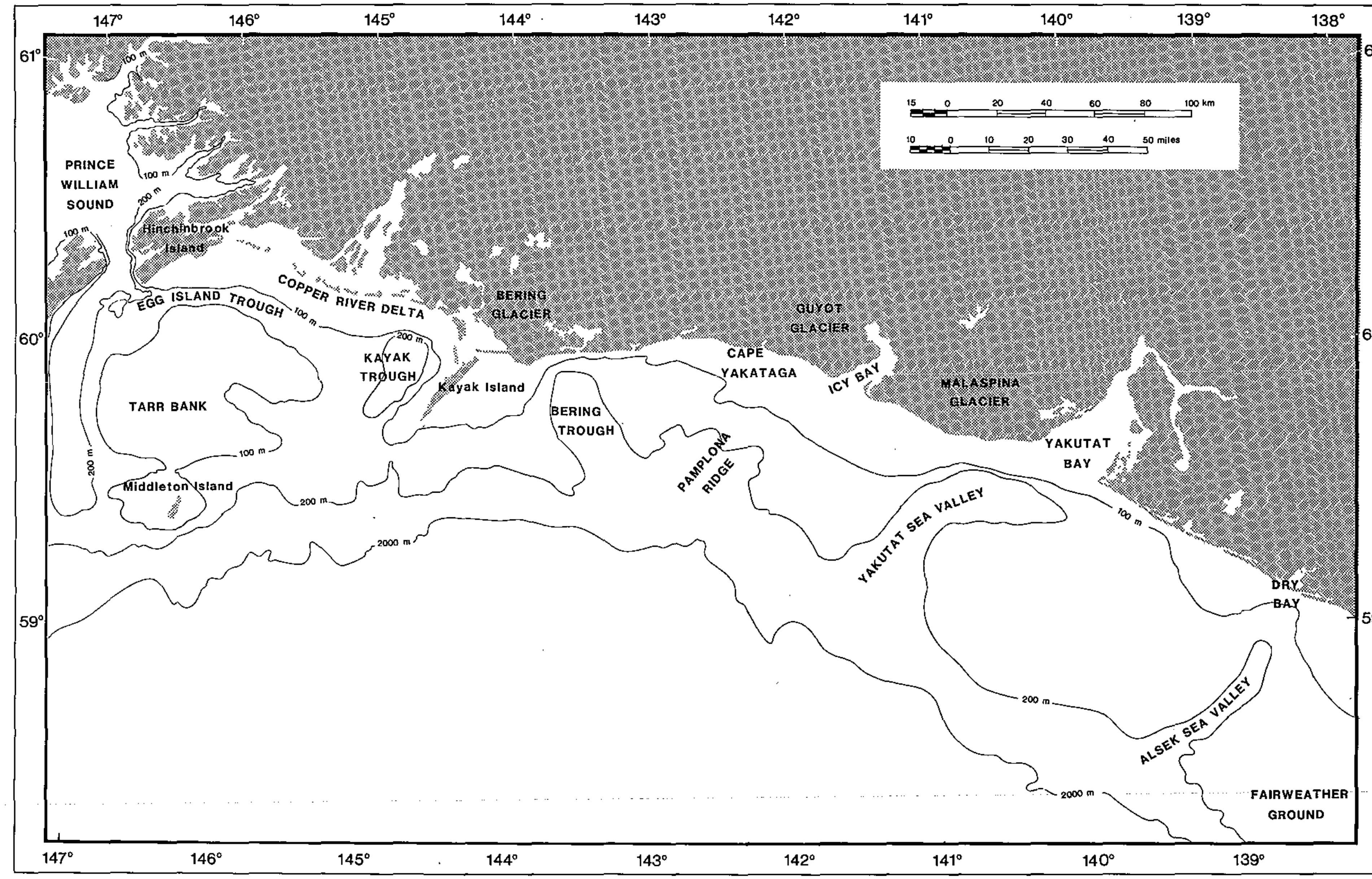


Figure 2.3 Index map for major physiographic features of NEGOA.

2.2 SEISMICITY

2.2.1 Earthquake catalogues and detection capability

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. Data for this file are obtained from a variety of sources which are described by Meyers and von Hake (1976). Several unavoidable limitations 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 variation in accuracy of identifying epicenter locations.

The recent translation of old Russian documents has extended the earthquake record in Alaska back to 1784 (Sykes et al., 1980). In their attempt to better define the recurrence interval of large earthquakes along the Alaska-Aleutian arc, these workers found evidence for large earthquakes in the Kodiak-Shumagin Islands region in 1788, 1792, 1844, 1848, 1854, and 1880, and near Sitka in 1848.

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. In addition to acquiring more data on smaller earthquakes in the Alaskan OCS, efforts are being directed at producing more homogeneous data by standardizing calculations of magnitude and location (discussions at NOAA/OCSEAP-sponsored Alaskan OCS Seismology and Earthquake Engineering Workshop, Mar. 26-29, 1979, Boulder, Colo.). Homogeneity in these data is required for studies of the distribution of seismicity in space and time (e.g., Kelleher, 1970; McCann et al., 1979; Lahr and Plafker, 1980), studies which show promise for improving earthquake forecasts.

In the vicinity of NEGOA the instrumental earthquake record is probably complete for events larger than magnitude 7.75 since 1899, larger than 6 since the early 1930's, and larger than 5 since 1964 (Lahr and Stephens, 1979). A local network of short-period seismograph stations (Fig. 2.4), set up and operated by the U.S. Geological Survey as part of OCSEAP, is capable of detecting events as small as magnitude 1 in some parts of the region (Lahr et al., 1980b), but this capability does not extend throughout all of NEGOA. The utility of the network lies in the identification of active faults and in promoting further understanding of regional tectonics.

The equipment available to detect earthquakes in NEGOA includes the USGS short-period seismograph network (Fig. 2.4) and a USGS network of strong motion

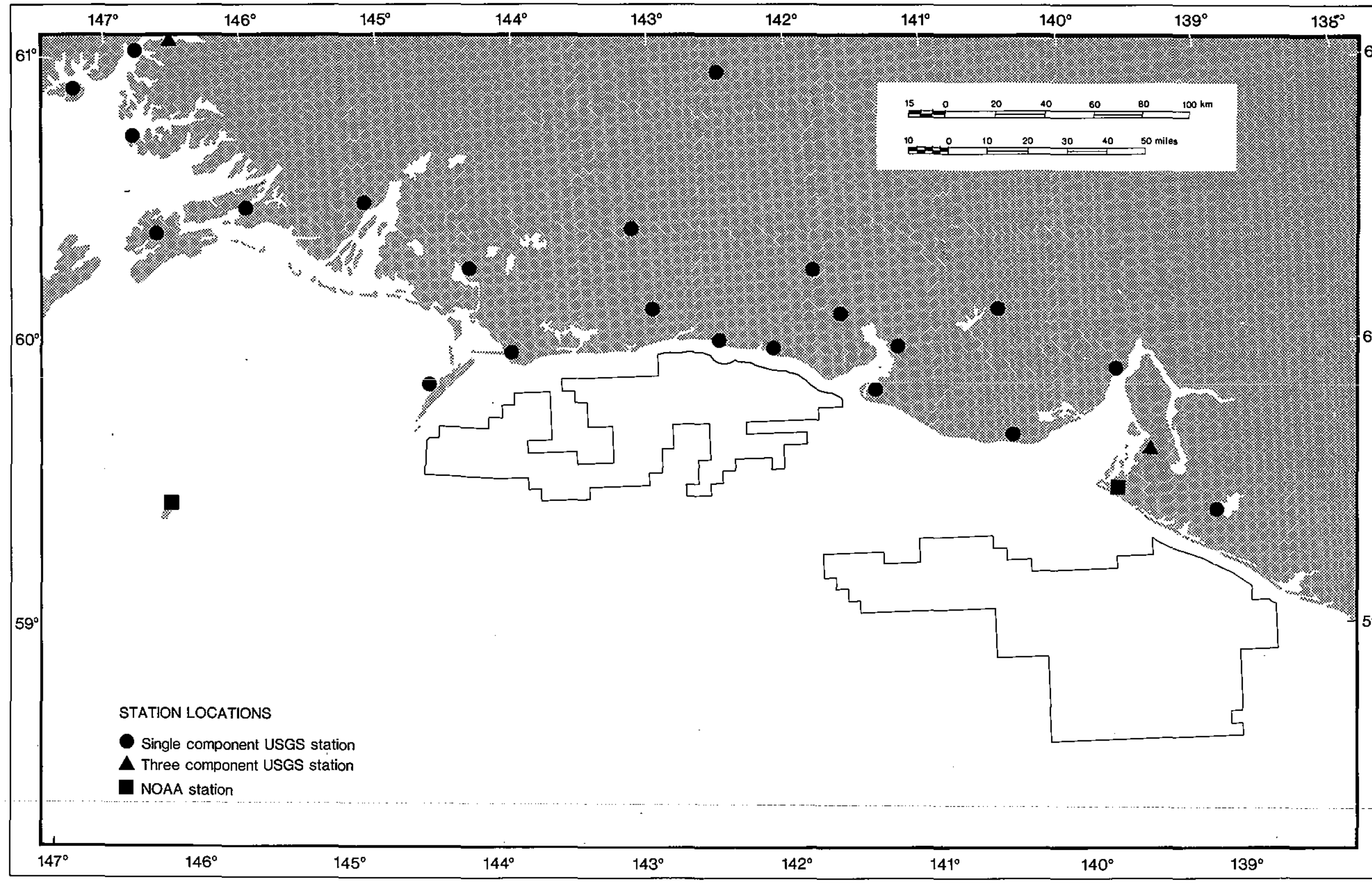
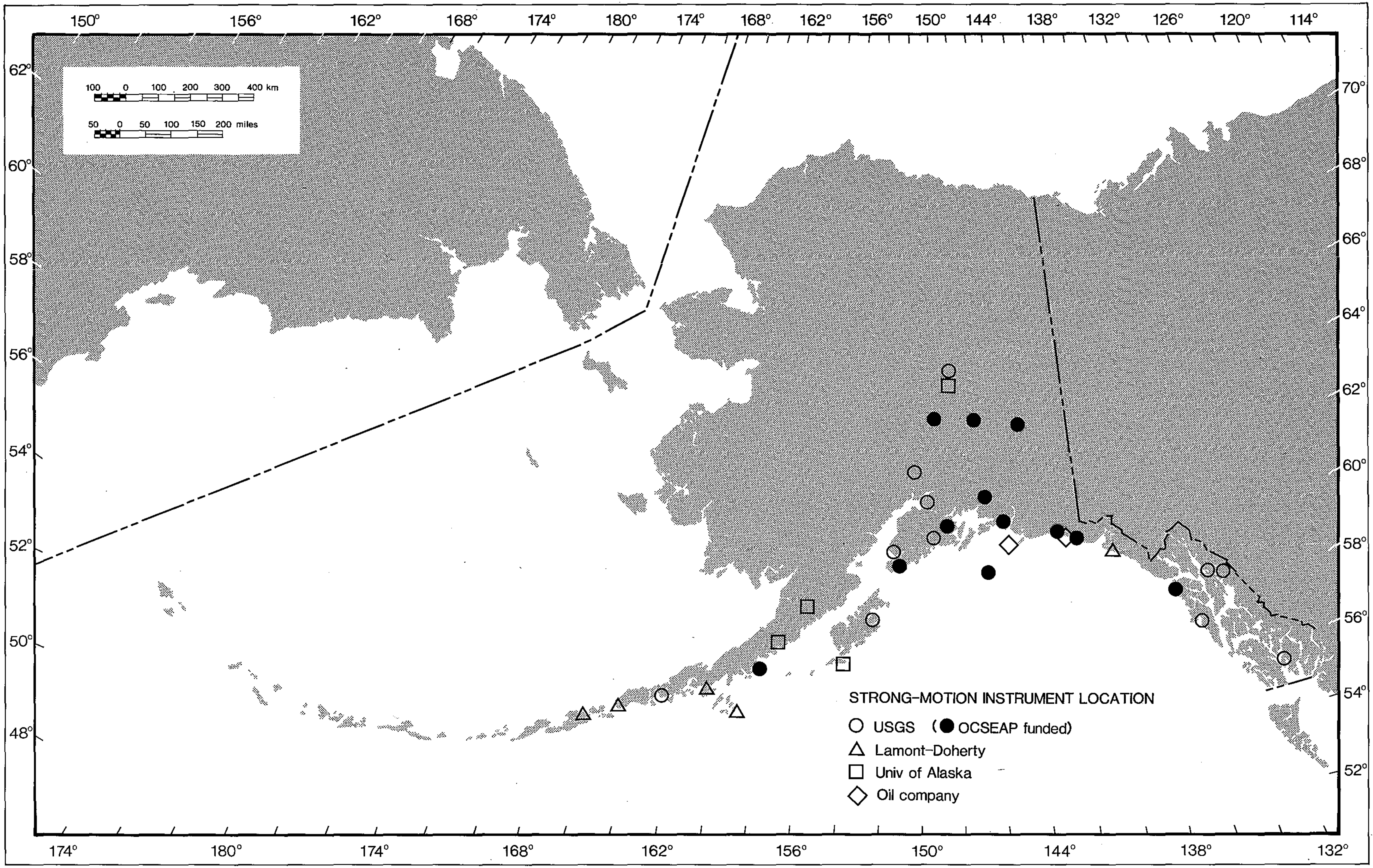


Figure 2.4 Seismic stations operated by the USGS in eastern southern Alaska during September-December 1978. These stations are supported in part by OCSEAP (from Lahr and Stephens, 1979).

instruments (Fig. 2.5). A strong motion instrument is triggered by large earthquakes and records certain parameters of ground motion that are required for purposes of engineering design. At the present, this type of seismic data is extremely limited for Alaska.

Figure 2.5 Distribution of strong-motion instruments in Alaska in 1978. Solid symbols indicate locations of the twelve instruments that were purchased with OCSEAP funding (from Lahr and Stephens, 1979).


100 0 100 200 300 400 km
50 0 50 100 150 200 miles
STRONG-MOTION INSTRUMENT LOCATION
USGS (● OCSEAP funded)
Lamont-Doherty
Univ of Alaska
Oil company

2.2.2 Distribution of earthquakes

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.

Epicenter plots of the instrumental earthquake record (Figs. 2.6 and 2.7) for NEGOA provide a general description of the region's seismicity. The catalogue used to construct these plots is NOAA's Environmental Data Services earthquake file, which includes the earthquake data of the local Alaskan network set up as part of OCSEAP.

The data file was broken down into several categories. Figure 2.6 includes all epicenters of magnitude 4 or greater, between 1964 and 1977 that are found in the NOAA file and excludes the local Alaskan network data. The year 1964 was chosen as a starting point for two reasons: first, epicenter locations prior to that time are less reliable, and second, the record for smaller events has been uniform only since about 1964. By limiting the data, the plots are more representative of the actual distribution of events of various magnitudes. The separation by depth into groups above and below 70 km distinguishes the deeper Benioff zone earthquakes from others. The Alaskan Benioff zone, which is a region of increased seismicity due to an oceanic lithospheric plate descending beneath a continental plate, is most active on the northern side of the Aleutian-Alaska Peninsula arc, outside of

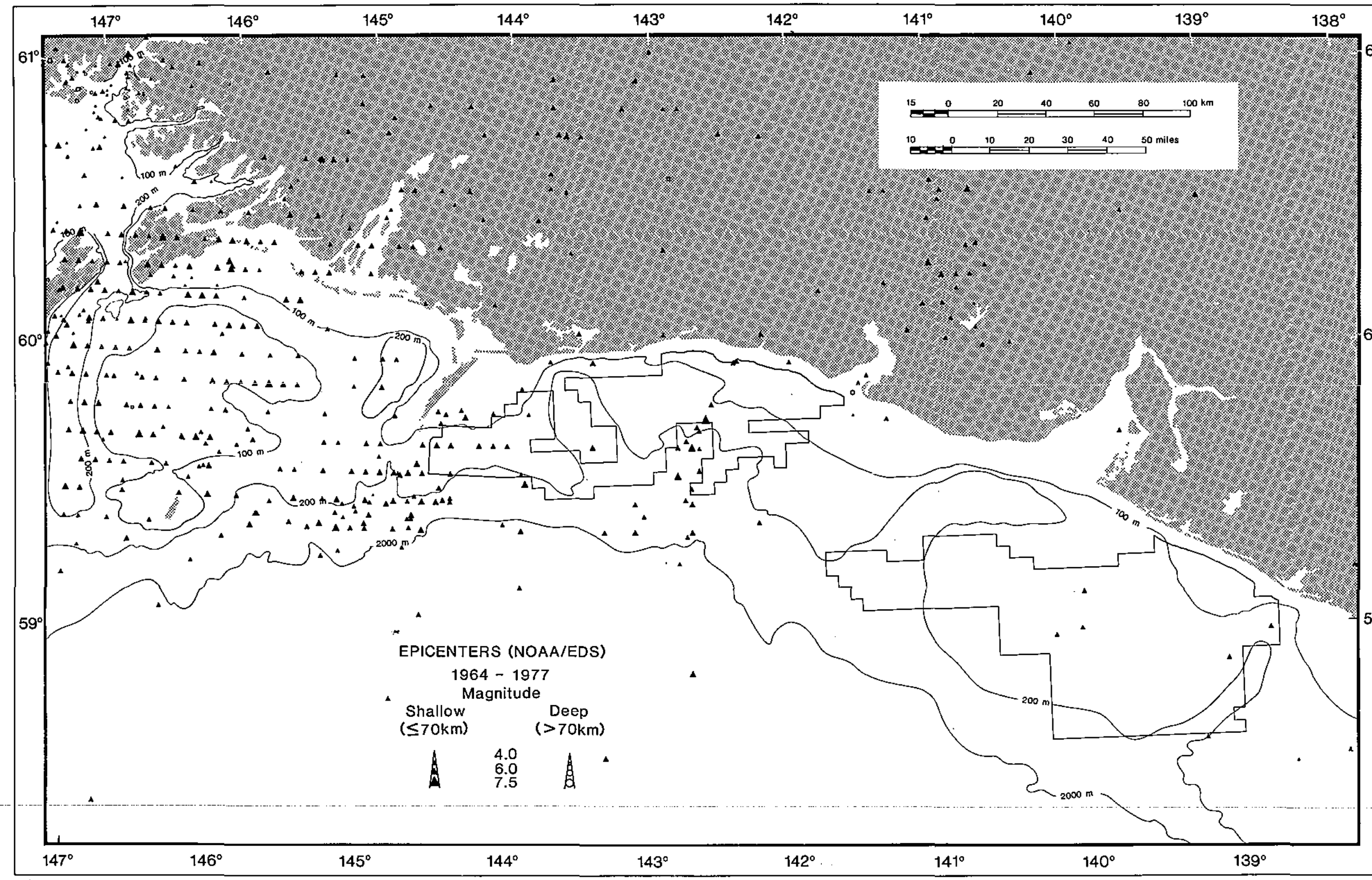


Figure 2.6 Epicenter plot of earthquakes occurring between 1964 and 1977. Data are from NOAA/EDS earthquake file and do not contain local Alaskan network data. Plot produced by NOAA/EDS.

the epicenter plot boundaries for NEGOA. Hence, nearly all earthquakes in this region have a shallow focal depth.

Figure 2.7 shows the distribution of shallow and deep seismicity as detected by the local Alaskan network, which is sensitive to events of much smaller magnitude than those displayed in Fig. 2.6. Note that the period of observation is considerably shorter for the Alaskan network; the plots include data from 1976 to early 1978.

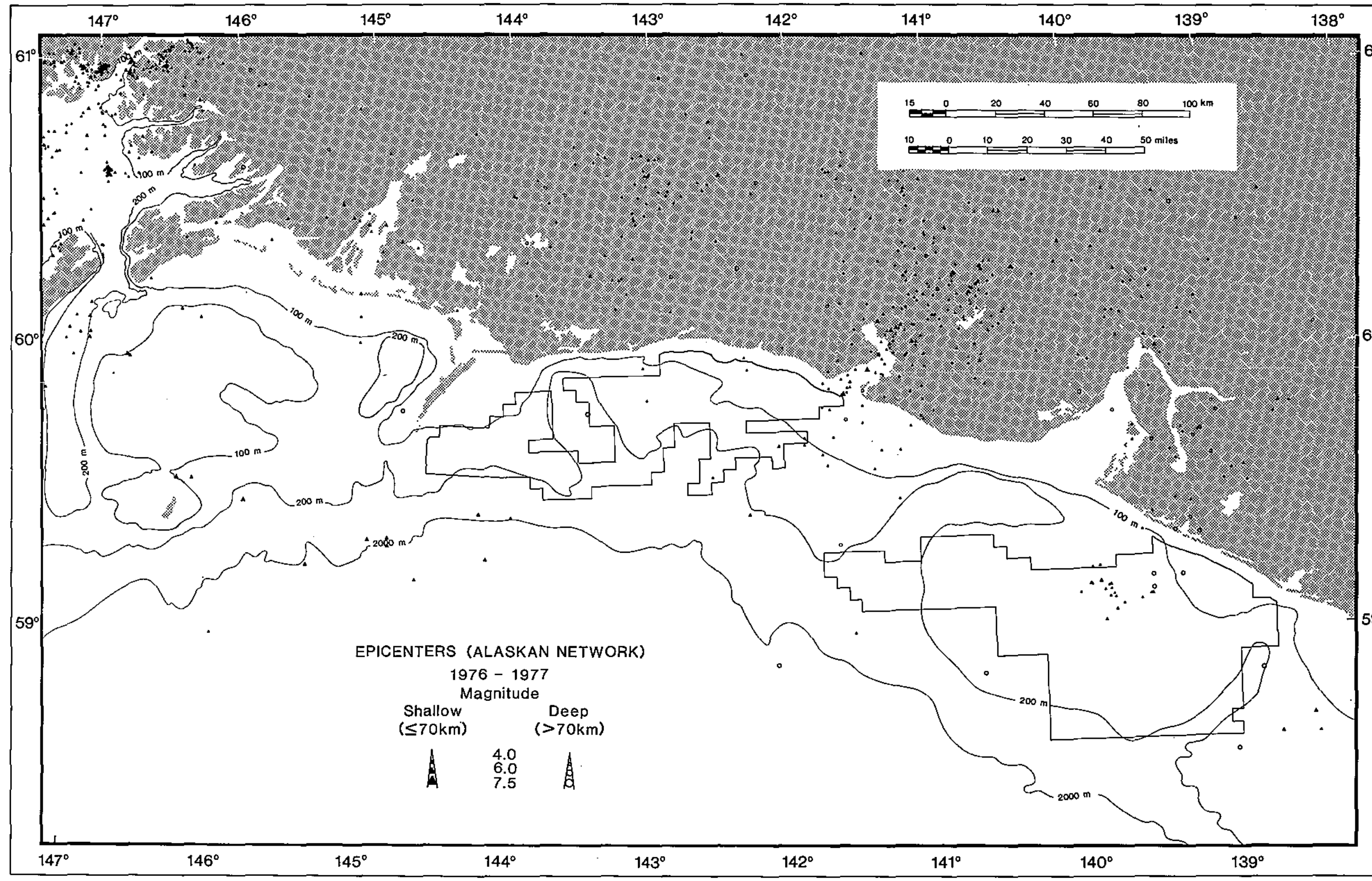


Figure 2.7 Epicenter plot of earthquakes recorded by Alaskan network, which started operating in 1976. Plot produced by NOAA/EDS.

Figure 2.8 shows all seismic events of magnitude 6 or greater. Nearly equal detection capability exists for these large events throughout the entire time span of the NOAA data file. Table 2.1 lists descriptions of the events plotted on Fig. 2.8. Several sources of information in addition to the NOAA/EDS earthquake catalogue have been used to compose this epicenter plot and tabulation, and those sources are cited in the table.

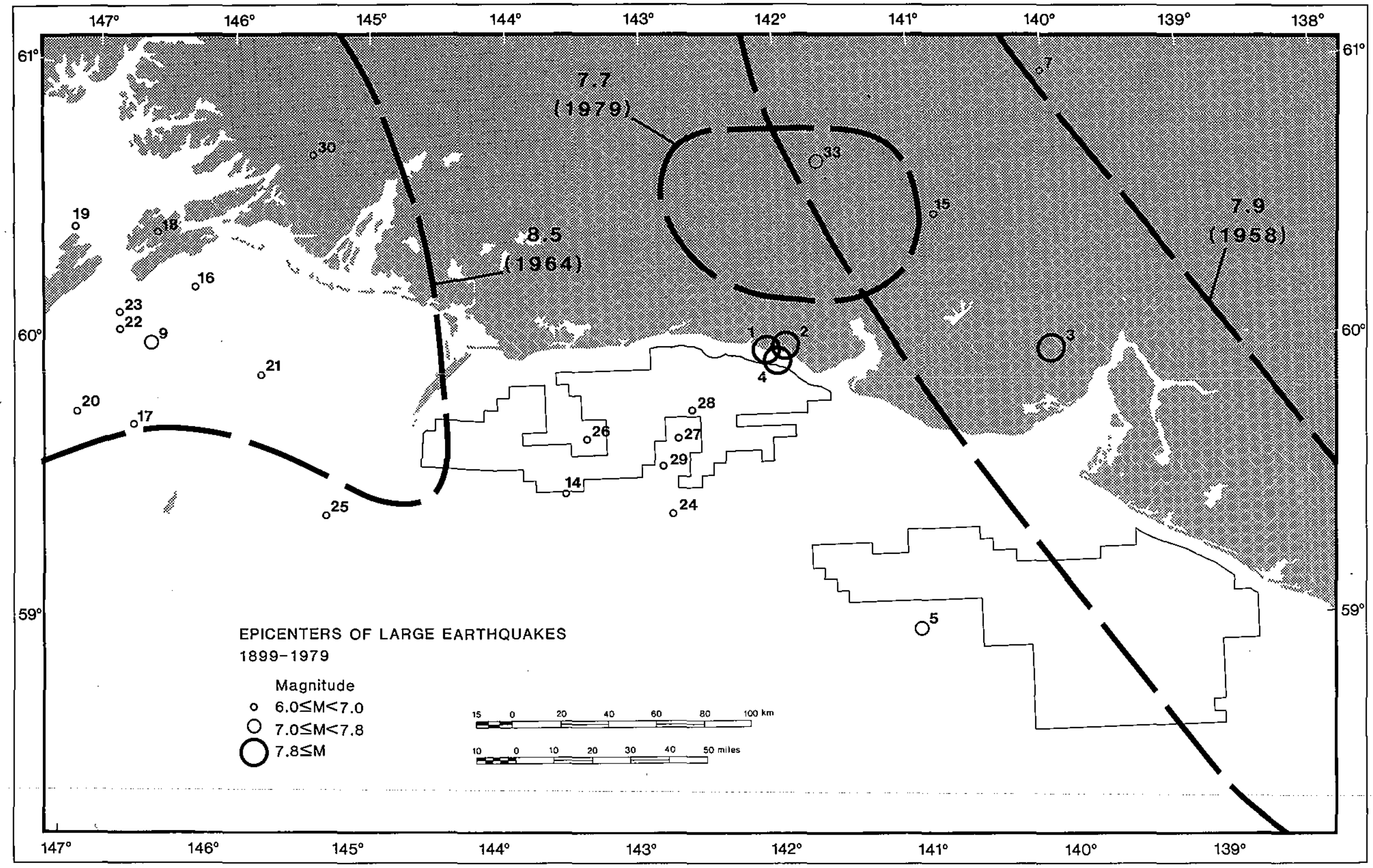


Figure 2.8 Epicenter plot of major earthquakes (mag >6) recorded in NEGOA between 1899 and 1979. Data sources are identified in Table 2.1. The dashed lines are aftershock zone boundaries of major earthquakes and correspond to those shown in Fig. 2.11.

Table 2.1 List of earthquakes of magnitude 6 or greater that have occurred in NEGOA between 1899 and 1979. The epicenters are plotted in Fig. 2.8. The maximum Mercalli intensity observed for the earthquake is also listed (refer to Table 2.2 for scale). Data sources in capital letters are from the NOAA/EDS earthquake file; those in small letters are individual references.

Data source* (No. on Fig. 2.8)	Year	Mo	Day	Hr	Min	Sec	Lat	Long	Focal depth (km)	Magnitudes				Int max
			(Universal time)							Body wave	Surface wave	Unspecified	Local (Richter)	
EQH (1)	1899	09	04	00	22	00.0	60.000N	142.000W	25			8.30		XI
CFR (2)	1899	09	10	17	04	00.0	60.000N	142.000W	25			7.80		VII
CFR (3)	1899	09	10	21	40	00.0	60.000N	140.000W				8.60		XI
EQH (4)	1900	10	09	12	28	00.0	60.000N	142.000W	25			8.30		VII
G-R (5)	1908	05	15	08	31	36.0	59.000N	141.000W	25			7.00		VI
G-R (6)	1912	01	31	20	11	48.0	61.000N	147.500W	80			7.25		V
G-R (7)	1920	07	07	18	41	29.0	61.000N	140.000W	25			6.00		
G-R (8)	1927	10	24	15	59	55.0	57.500N	137.000W	25			7.10		VI
G-R (9)	1928	06	21	16	27	13.0	60.000N	146.500W	25			7.00		VI
G-R (10)	1944	02	03	12	14	59.0	60.500N	137.500W				6.50		
G-R (11)	1946	01	12	20	25	37.0	59.250N	147.250W	50			7.20		IV
USE (12)	1952	03	09	20	00	17.0	59.500N	136.000W				6.00		V
USE (13)	1958	07	10	06	15	51.0	58.600N	137.100W				7.90		XI
CGS (14)	1958	09	24	03	44	14.0	59.500N	143.500W				6.25		
rot (15)	1963	06	17	18	32	09.9	60.500N	140.800W				6.00		
rot (16)	1964	03	28	05	33	52.6	60.200N	146.200W	20			6.00		
CGS (17)	1964	03	28	09	52	55.7	59.700N	146.600W	30	5.50		6.20		
CGS (18)	1964	03	28	14	47	37.1	60.400N	146.500W	10	5.70		6.30		
CGS (19)	1964	03	28	14	49	13.7	60.400N	147.100W	10	5.80		6.50		
rot (20)	1964	03	29	16	40	58.0	59.700N	147.000W	15			6.00		
CGS (21)	1964	03	30	07	09	34.0	59.900N	145.700W	15	5.60		6.20		
rot (22)	1964	04	04	04	54	01.7	60.100N	146.700W	40			6.10		
rot (23)	1964	04	05	19	28	18.1	60.200N	146.700W	15			6.00		
rot (24)	1964	05	17	00	50	17.9	59.400N	142.700W	35			6.00		
CGS (25)	1965	09	18	20	46	36.5	59.400N	145.200W	5	5.30		6.00		
rot (26)	1965	09	20	23	47	40.7	59.700N	143.400W	19			6.00		
USE (27)	1970	04	11	04	05	41.1	59.700N	142.700W	7	5.20	6.2	6.20	5.80	III
USE (28)	1970	04	16	05	33	17.5	59.800N	142.600W	7	5.50	6.8	6.80	6.20	IV
USE (29)	1970	04	19	01	15	46.8	59.600N	142.800W	20	5.80	6.0	5.50	5.80	
CGS (30)	1970	08	18	17	52	06.3	60.700N	145.384W	16	5.60	5.9	6.00	5.90	IV
ERL (31)	1973	07	01	13	33	34.6	57.840N	137.330W	33	6.10	6.7	6.70		V
ERL (32)	1973	07	03	16	59	35.1	57.980N	138.021W	33	6.00	6.0	6.40		V
lah (33)	1979	02	28	21	27	06.1	60.640N	141.590W	15		7.7			

*Data sources:

EQH Coffman and von Hake (1973)
CFR Richter (1958)
G-R Gutenberg and Richter (1954)
ERL Environmental Research Laboratory. This agency operated the PDE program between 1971 and 1973.
rot Rothé (1969)
lah Lahr et al. (1980a)
CGS Coast and Geodetic Survey. This agency operated the Preliminary Determination of Epicenter (PDE) program prior to 1970.
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.

2.2.3 Major earthquakes affecting NEGOA

Several very large earthquakes have occurred in the vicinity of the proposed lease areas since about the turn of the century. Accounts of four of these quakes are found in "Earthquake History of the United States" (Coffman and von Hake, 1973; Coffman, 1979). The following brief descriptions are from those references unless otherwise noted.

In September 1899, two of the largest earthquakes on record in Alaska occurred in the vicinity of Cape Yakataga and Yakutat Bay. The magnitudes (M_s) were 8.5 and 8.4, respectively (Thatcher and Plafker, 1977). Large topographic changes accompanied the earthquakes; in one area an uplift of about 14½ m was observed. A 10-meter tsunami swept across Yakutat Bay, and snowslides large enough to alter the movement of glaciers were generated. Fortunately, damage to life and property was minimal, since the area was only sparsely populated and essentially undeveloped. An evaluation of data concerning these earthquakes (Thatcher and Plafker, 1977) indicates that during a 13-month period from late 1899 extending into 1900, there were four large earthquakes with magnitudes between 7.8 and 8.5 in the Yakutat Bay-Kayak Island region. In spite of these large events, those authors suggest that not all of the accumulated stress in the region was released by these events, unless a significant amount of slow creep has occurred as well.

In July 1958 a major earthquake of magnitude (M_s) 7.9 which was apparently associated with movement on the Fairweather Fault (Tocher, 1960; see Fig. 2.2 for location) occurred near Lituya Bay. Effects described as "moderate" (Davis and Sanders, 1960) occurred at Yakutat, 100 miles northwest of the epicenter, including damage to water and gasoline tanks, pipelines, roads and runways, and miscellaneous equipment. An intensity map for this earthquake is shown in Fig. 2.9. For reference, the Modified Mercalli intensity scale is reproduced in Table 2.2. A massive rockslide at the head of Lituya Bay generated a huge wave which surged up the beach to a height of about 525 m and cleared the shoreline of trees (Miller, 1960). Fishermen aboard their boat were swept out of the bay by a wave they estimated to be 30 m in height. There were two fatalities in the bay.

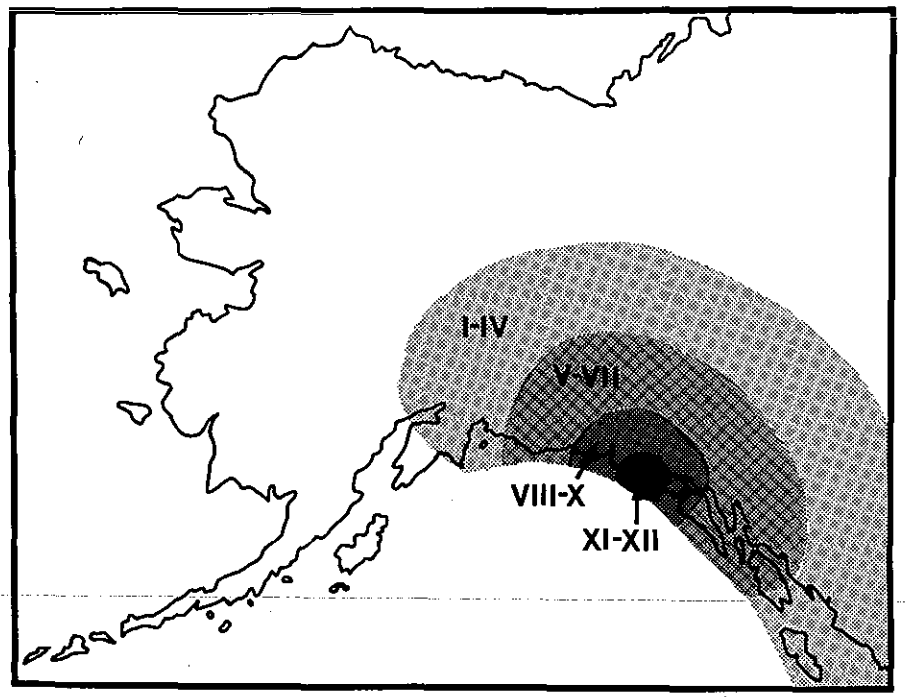


Figure 2.9 Distribution of intensities caused by the July 1958 Lituya Bay earthquake (modified from Davis and Sanders, 1960).

The 1964 Prince William Sound earthquake, with magnitude (M_s) 8.3, was one of the most violent earthquakes ever recorded. The break in crustal rocks occurred along a gently dipping thrust fault, perhaps 800-900 km in length, which is associated with subduction of the Pacific lithospheric plate under the North American plate. Anchorage was damaged

Table 2.2 Modified Mercalli Intensity Scale, 1956 Version (Richter, 1958).

I

Not felt. Marginal and long-period effects of large earthquakes.

II

Felt by persons at rest, on upper floors, or favorably placed.

III

Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV

Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frames creak.

V

Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI

Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.

VII

Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices; also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII

Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX

General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X

Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI

Rails bent greatly. Underground pipelines completely out of service.

XII

Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A - Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B - Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C - Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D - Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

extensively, even though it is situated about 130 km northwest of the epicenter. The effects were so great that a special committee was established by the National Academy of Sciences to study the earthquake. Their efforts resulted in the most comprehensive and detailed account of an earthquake ever compiled (National Academy of Sciences, 1972). An intensity map for this earthquake (Fig. 2.10) shows that intensities of V to VII were experienced throughout NEGOA.

The most recent large earthquake in NEGOA occurred

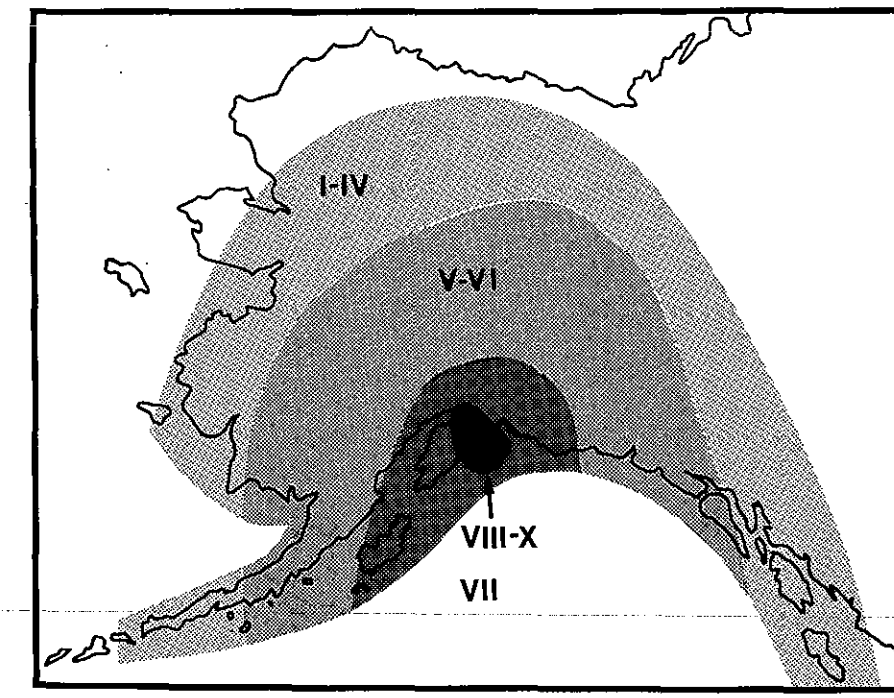


Figure 2.10 Distribution of intensities caused by the March 1964 Prince William Sound earthquake (Meyers et al., 1976).

on 28 February 1979 near Mt. St. Elias, about 50 km north of Icy Bay. It was of magnitude (M_s) 7.3 and produced ground effects indicating intensities of up to VII (Lahr and Stephens, 1979). Fortunately, damage from this earthquake was minimal due to a lack of population in the area.

This earthquake is of particular interest in evaluating geological hazards in NEGOA, for it occurred in the area between two previous large NEGOA earthquakes: the 1964 Prince William Sound and 1958 Lituya Bay events. It represents stress release in a "seismic gap," with implications regarding the recurrence of large earthquakes (Kelleher, 1970; Sykes, 1971; McCann et al., 1979; Lahr et al., 1980a; Lahr and Plafker, 1980).

2.2.4 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 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).

Table 2.3 summarizes tsunamis observed in NEGOA 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 is high. The NEGOA shoreline is exposed to tsunamis generated anywhere in the Pacific, and especially to those generated in the highly earthquake-prone Aleutian/Alaska seismic belt.

Table 2.3 Tsunamis observed in NEGOA (modified from Cox and Pararas-Carayannis, 1976). "Wave height" in remarks column refers to maximum runup elevation on beach or to measured amplitude at shoreline.

Location of observation	Area of origin, earthquake, or volcanic eruption	Observations and remarks
Yakutat Bay	1845 Ice fall in Yakutat Bay	100 deaths; similar waves reported by legend
Lituya Bay	1853 or 1854 Lituya Bay landslide	120 m wave height; cleared trees and brush from shoreline.
Lituya Bay	1874 Lituya Bay landslide	24 m wave height.
Yakutat Bay	10 Sep 1899 Mag. 8.6 Cape Yakataga earthquake	Tsunami originated in Disenchantment Bay; 10 m wave height; wave attenuated rapidly in outer bay.
Lituya Bay	10 Sep 1899 Mag. 8.6 Cape Yakataga earthquake	Trees and brush cleared by waves between 1890-1899; 60 m wave possibly due to landslide triggered by Yakataga earthquake.
Yakutat Bay	4 July 1905 Ice fall in Yakutat Bay	Ice fell from Fallen Glacier into Disenchantment Bay; seiche in Russell Fiord of 4½-6 m amplitude continued for one-half hour.
Lituya Bay	27 Oct 1936 Lituya Bay landslide	Three waves generated in Crillon Inlet, largest 150 m; cleared trees and shrubs.
Yakutat	1 Apr 1946 Mag. 7.4 Eastern Aleutians	0.2 m wave at Yakutat; this was the destructive "Great (Eastern) Aleutian Tsunami" which killed 5 at Scotch Cap.
Yakutat	5 Nov 1952 Mag. 8.25 East Kamchatka	0.3 m wave at Yakutat; great damage from tsunami at Kamchatka.
Yakutat	9 Mar 1957 Unimak Is., Aleutians	0.4 m wave; this tsunami was observed throughout the North and South Pacific.
Lituya Bay	9 July 1958 Mag. 7.9 Lituya Bay	Wave generated by giant landslide cleared forest on opposite side of fiord to 525 m elevation; wave 100 m at mouth of fiord; 2 deaths, 2 boats destroyed.
Yakutat	9 July 1958 Mag. 7.9 Lituya Bay	0.2 m wave generated by crustal displacement during earthquake (not due to landslide in Lituya Bay).
Yakutat	22 May 1960 Mag 8.5 Southern Chile	0.9 m wave at Yakutat; this was the Great Chile tsunami, which resulted in tremendous damage and casualties in Chile, Hawaii, and Japan.
Cape Yakataga Yakutat	27 Mar 1964 Mag. 8.3 Prince William Sound	Wave heights of 3.7 and 2.2 m at Cape Yakataga and Yakutat, respectively; major tsunami which caused extensive damage and casualties in the northern Gulf of Alaska.

2.2.5 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 is not yet possible, progress in "forecasting" the location, general size (e.g., great, large), and time of occurrence to within a few tens of years has been made through the analysis of seismicity gaps (McCann et al., 1979).

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. 2.11 that the aftershock zones of large earthquakes tend not to overlap; the areas separating adjacent aftershock zones have been 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., 1979; Lahr and Plafker, 1980).

A seismic gap has been identified in NEGOA at roughly the transition between the underthrust zone and the strike-slip zone between Icy Bay and Kayak Island. Since the gap was recognized prior to the 1979 Mt. St. Elias earthquake (Sykes, 1971), and since calculations of stress accumulation due to lithospheric plate convergence suggested an impending release, it

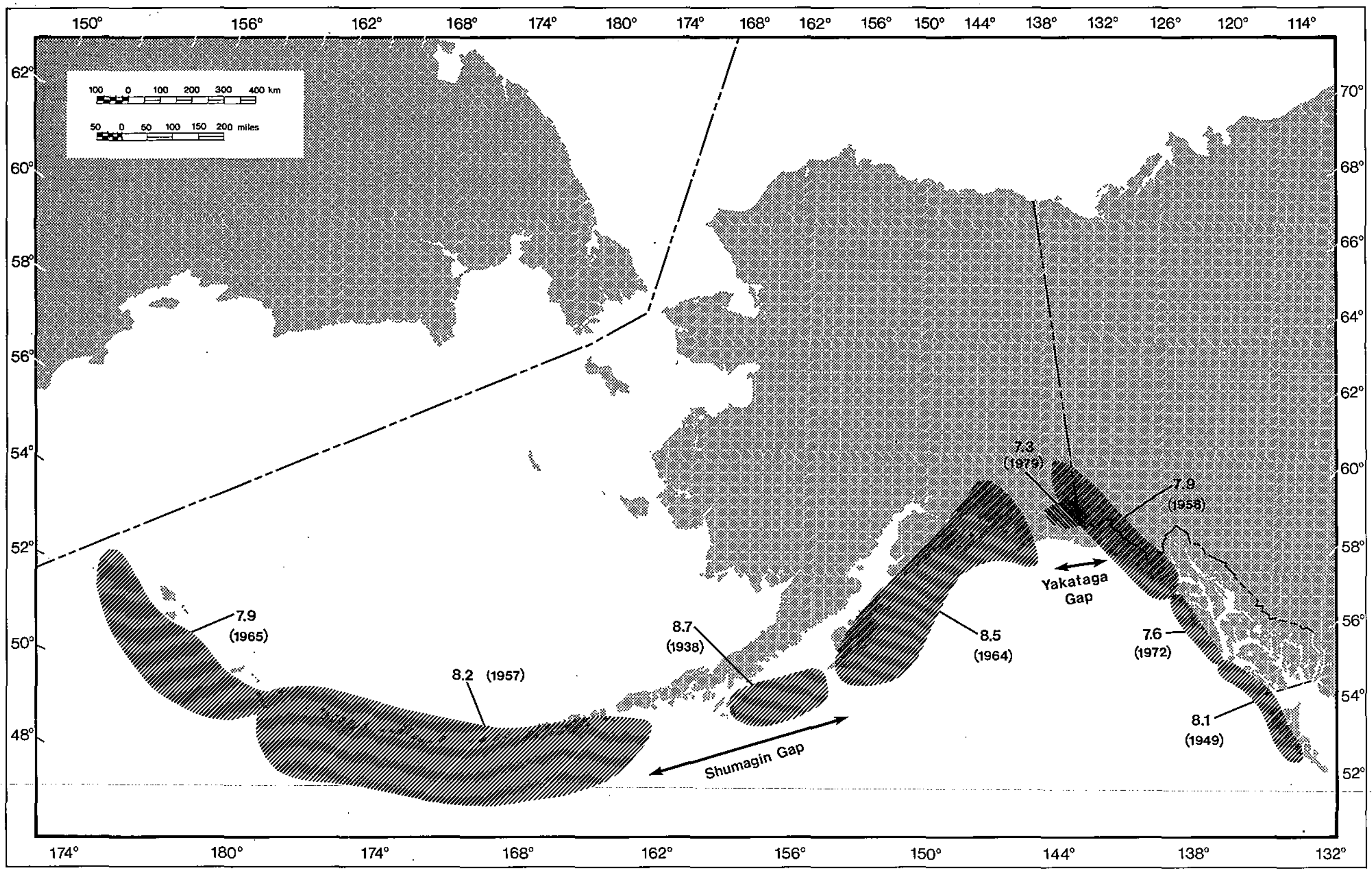


Figure 2.11 Aftershock zones and seismic gaps along the Aleutian Island/southern Alaska plate boundary (modified from Sykes, 1971; Lahr and Stephens, 1979; and McCann et al., 1979).

may be stated that the earthquake was successfully forecast (Lahr et al., 1979b).

However, recent study of the event indicates that the seismic gap in NEGOA has not been completely filled by the aftershocks of that earthquake (Lahr and Plafker, 1980), and therefore should still be considered an area of high potential for a large earthquake. Based on their tectonic model, the accumulated strain in the region which was not entirely released by the St. Elias earthquake could produce an earthquake of magnitude up to 8 if released in one event. The potential for a near-future large earthquake still exists in the region between Icy Bay and Kayak Island (Lahr et al., 1979a).

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. 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 of about 80 to 140 years for the Shumagin Islands region. It is therefore quite possible that a great earthquake will occur in the Shumagin seismic gap during petroleum industry development on the Alaskan OCS.

Another technique to estimate recurrence intervals is based on a comparison of relative motion across a fault (refer to Fig. 2.2 for sample rates) with long-term average slip rates from earthquakes (Molnar, 1979). Lahr et al. (1980b) have applied this technique to five earthquake source regions which are derived from their tectonic model for NEGOA. The results for four of the sources are summarized in Table 2.4. The fifth source category is a "random event" of magnitude about 6 to 7 that could occur with finite probability anywhere within the Yakutat and Wrangell Blocks. Molnar (1979) cautions that the calculated values may be in error by as much as a factor of 3 to 5. Lahr et al. (1980b) state, however, that despite potential errors in the values, "...it would be most prudent at this time to assume that (the Yakataga seismic gap) has been in a period of lower than average seismicity during the past tens of years, and that this condition may not continue long into the future."

The possibility of an unfilled seismic gap between Icy Bay and Kayak Island in this dynamic region of plate boundary interaction increases the potential for a large earthquake sometime during OCS development. Additional evidence for an impending large earthquake is found in the analysis of several terrace levels exposed above the present beach on Middleton Island. These terraces (former beaches) were cut by wave action during long periods of tectonic stability, and were elevated during short periods of uplift during earthquakes (Plafker and Meyer, 1978). Based on the rate and amount of uplift required to explain the elevations of the terraces, and the relatively small amount of uplift which occurred during the 1964 earthquake, those investigators postulate that at least half of the accumulated strain in the region (prior to 1964) has yet to be released.

In summary, analysis of space/time seismicity, development of tectonic models based on geological data and earthquake occurrence, and analysis of elevated beach terraces all suggest that NEGOA is under stress, and that events which may release this stress are overdue in some areas, namely Icy Bay to Kayak Island.

Table 2.4 Seismic source regions and calculated recurrence intervals for NEGOA (Lahr et al., 1980b). The magnitudes shown are "weighted moment" and are typically about ½ to 1 unit larger than the more commonly reported "Richter" magnitudes.

Region	Recurrence interval Magnitude (M_w)	(yrs)
1. Underthrusting of the Pacific plate below the Wrangell block between Kayak Island and southern Kodiak Island	~ 9.2	420
	≥ 8.6	100
	≥ 8.0	22
	≥ 7.3	4.7
2. Underthrusting of the Yakutat block and the Pacific plate below the Wrangell block.	~ 8.9	380
	≥ 8.0	46
	≥ 7.3	10
3. Faulting along the northeast boundary of the Yakutat block.	~ 7.9	240
	≥ 7.3	55
	≥ 6.6	12
4. Underthrusting of the Pacific plate below the Yakutat block.	~ 8.6	3,800
	≥ 8.0	830
	≥ 7.3	180
	≥ 6.6	39

2.2.6 Risk analysis research

Considerable research has been conducted as part of the Offshore Alaska Seismic Exposure Study (OASES) 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 nonexistent, 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 need to design platforms, pipelines, and other structures that are as earthquake-resistant as possible.

In other risk analysis research by the U.S. Geological Survey (Thenhaus et al., 1979a, 1979b) 24 seismogenic zones have been delineated according to geological data and historical seismicity. Maps of probable ground accelerations to be expected in each zone were constructed and include variables such as return periods for earthquakes of various magnitudes.

Risk analysis programs are currently in progress at the Geophysical Institute, University of Alaska, at Lamont-Doherty Geological Observatory, and at the U.S. Geological Survey.

2.2.7 Summary of earthquake hazards

The record of great earthquakes (magnitude > 7.75) in NEGOA is complete since 1899, and of earthquakes greater than magnitude 5 since about 1964. The local network of seismograph stations is presently recording events as small as magnitude 1 in some parts of the network and is producing data useful for identifying active faults and possibly for defining areas of varying stress levels in the earth's crust.

NEGOA has been the site of several large earthquakes (magnitude > 7) during the 20th century. Most notable of these are the Yakutat Bay events of 1899-1900, the July 1958 Lituya Bay quake which caused a huge rockslide at the head of Lituya Bay, the 1964 Prince William Sound event which resulted in extensive damage to Anchorage, and the recent Mt. St. Elias earthquake which fortunately did not affect a populated area.

The region is well-covered geographically by seismograph stations, although improvements are required to the network in the form of (1) more reliable and efficient data telemetry systems, (2) installation of offshore ocean bottom instruments, and (3) experiments to better define the crustal velocity structure. These improvements will result in increased accuracy of epicenter locations and the generation of more uniform data; the latter is especially important for research on recurrence intervals, stress levels, and seismotectonic province boundaries.

At present, the best earthquake potential estimates for NEGOA appear to result from the "seismic gap hypothesis," and suggest a high potential for a large earthquake to occur in the proximity of OCS development sometime during the time period of OCS activities. Our present understanding of earthquake processes does not allow prediction of exact location, time, and magnitude; it does allow identification of regions of crustal stress accumulation (due to lithopheric plate motions) and estimates of the rate of release of that stress.

Additional evidence for stress in crustal rocks in NEGOA is found in data from terrace levels on Middleton Island. These data indicate that only about half of the stress accumulating in the northern Gulf of Alaska prior to 1964 was released during the great earthquake of that year.

The shoreline and bays of NEGOA are exposed to tsunami hazards. Tsunamis can originate anywhere in the Pacific Ocean, but are particularly likely in the Aleutian/Southwest Alaska seismic belt. These giant waves may result from displacements of the seafloor and affect the entire shoreline. Large waves may also occur in bays due to earthquake-induced landslides or rockfalls, and they can cause extensive damage to boats and shore facilities.

2.3 OFFSHORE GEOLOGIC HAZARDS

2.3.1 Sedimentology

The history of sedimentation on the NEGOA shelf is complex and has produced a variety of sediment types. There are four major sedimentary units on the shelf (Molnia and Carlson, 1980):

1. Holocene glacial-marine sediment;
2. Holocene end morainal deposits;
3. Quaternary glacial sediment; and
4. Pleistocene and older lithified sedimentary rock.

These units include at least eleven different facies (i.e. deposits of a particular composition) and reflect the importance of glacial activity in controlling shelf sedimentary processes (Molnia and Carlson, 1980). Molnia and Carlson suggest that glacial activity has controlled shelf sedimentation in NEGOA for perhaps the last 15 million years, since about the middle Miocene. A generalized map of sediment facies is shown in Fig. 2.12.

Sediment is presently being supplied to the shelf via runoff from the numerous glaciers along NEGOA's coast. It consists primarily of fine sand-, silt-, and clay-sized material termed "glacial rock flour." Much of the coarser material observed farther offshore near the 200-m shelf break is relict material from lower stands of sea level during the last ice age.

The thickness of unconsolidated sediment on the NEGOA shelf varies from zero to greater than 300 m. Areas of little or no unconsolidated sediment occur between Hinchinbrook and Middleton Islands, and seaward of the 200-m contour. The thickest area is southeast of the mouth of the Copper River. Here the Copper River prodelta is about 350 m thick, revealing the importance of the Copper River as a source of terrigenous sediment to NEGOA. Carlson and Molnia (1975) indicate four other areas of thick sediment: (1) a 260-m thickness seaward of Icy Bay, (2) a 200-m thickness east of Cape Suckling, off the Bering Glacier, (3) a 250-m section between Montague and Hinchinbrook Islands, and (4) a 155-m section in Kayak Trough southwest of Kayak Island.

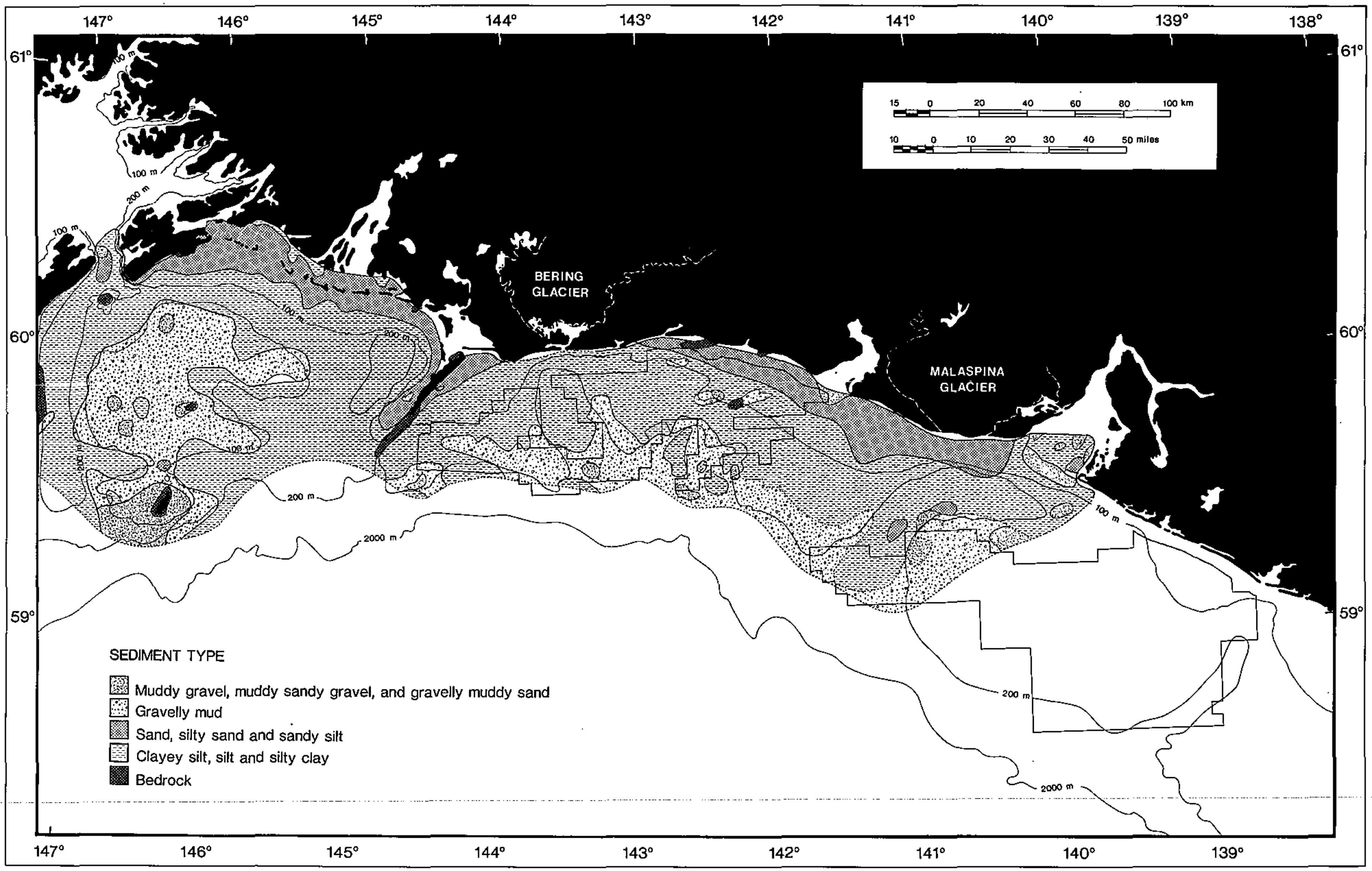


Figure 2.12 Distribution of seafloor sediment by size classification (from Carlson et al., 1977).

An isopach map of unconsolidated sediment (Fig. 2.13) has been constructed by Carlson and Molnia (1975). Data for the map were obtained from high-resolution seismic reflection surveys made during 1974 and 1975. Estimates for some geometrical parameters of unconsolidated sediment (listed in Table 2.5) were derived from this isopach map.

Table 2.5 Geometry and sedimentation rates of Holocene sediment on the NEGOA shelf. Sedimentation rates are for the last 12,000 years (modified from Molnia et al., 1978b).

Parameter	Entire NEGOA shelf	Shelf east of Kayak Island	Shelf west of Kayak Island
Area of shelf	55,885 km^2	25,580 km^2	30,305 km^2
Area of sediment cover	38,490 km^2	19,600 km^2	18,890 km^2
Area devoid of sediment	17,395 km^2	5,980 km^2	11,415 km^2
Volume of sediment (calculated)	3,007 km^3	1,767 km^3	1,237 km^3
Thickness (average):			
Entire shelf	54 m	69 m	41 m
Covered areas only	-	90 m	65 m
Sedimentation rate (average):			
Entire shelf	4.5 mm/yr	5.8 mm/yr	3.4 mm/yr
Covered areas only	-	7.5 mm/yr	5.5 mm/yr
Range in sedimentation rates	0 to 29.2 mm/yr		

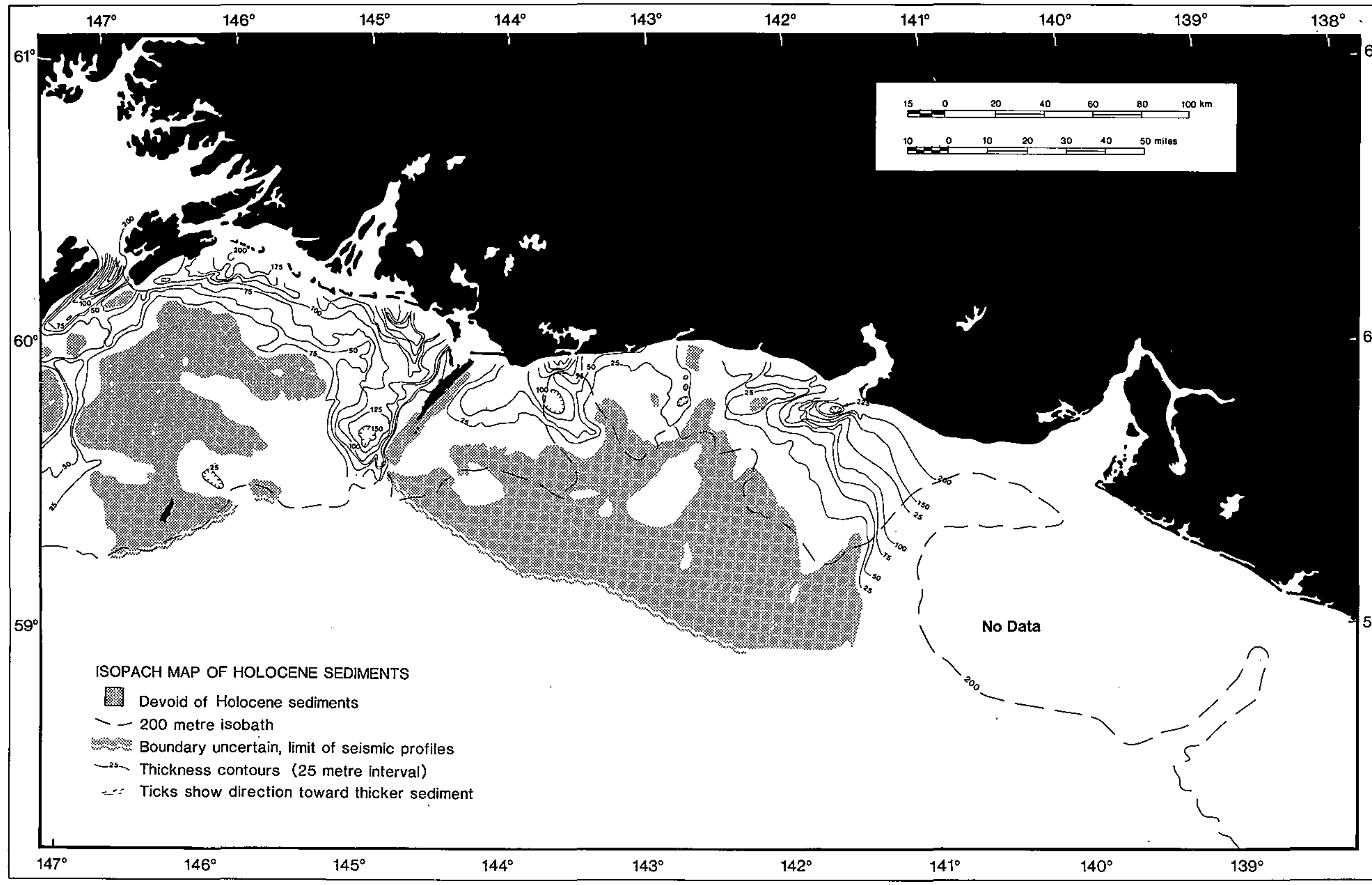


Figure 2.13 Preliminary isopach map of Holocene sediment in NEGOA (modified from Carlson and Molnia, 1975).

Areas of sediment accumulation and erosion (or lack of deposition) on the continental shelf of NEGOA are shown in Fig. 2.14. Most of the shelf is accumulating sediment at relatively high rates of up to 30 mm/yr (Molnia, 1978). Some areas in Icy Bay and Yakutat Bay have sediment accumulation rates of up to 1 or 2 m/yr, an extremely high rate.

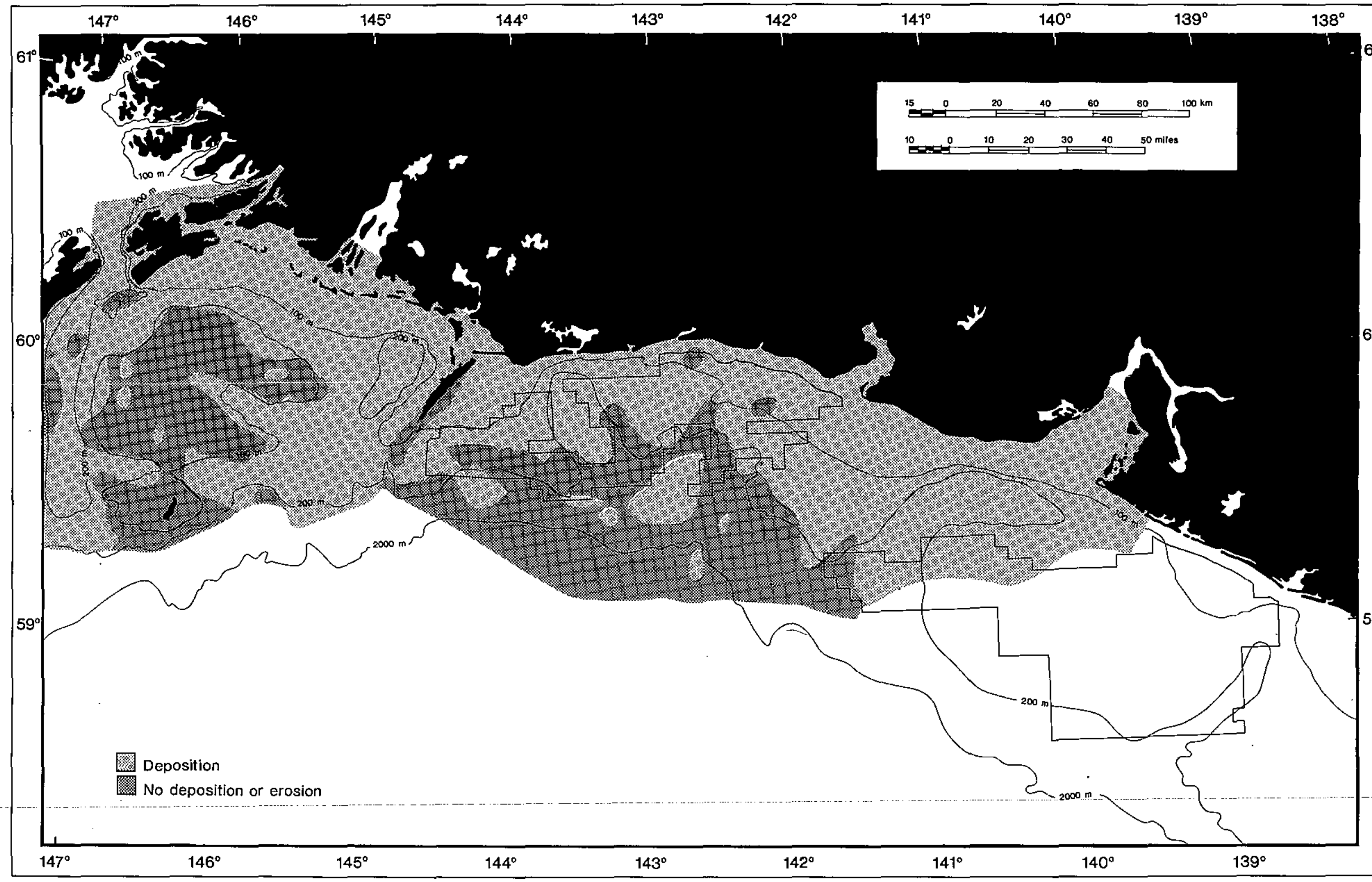


Figure 2.14 Areas of sediment accumulation and erosion (or lack of deposition) on the NEGOA shelf (Molnia and Carlson, 1978).

An exception to the general pattern of sediment accumulation occurs on Tarr Bank south of Prince William Sound, where lack of accumulation or possibly erosion occurs on a topographic high outlined by the 100-m contour. The absence of sediment in this area may be due to nondeposition and bypassing of the area by sediment-laden water, which travels farther offshore before depositing its load. Lack of deposition and possibly scouring and resuspension of seafloor sediment are facilitated by strong currents and large storm waves in this area (Molnia et al., 1978b).

Estimates of geometrical parameters and rates of accumulation of unconsolidated sediment on the NEGOA shelf are listed in Table 2.5. Slightly less than half of the area between Montague Island and Yakutat Bay, out to the 200-m contour, is bare of sediment, indicating either erosion or lack of deposition.

The dispersion of suspended sediment supplied to NEGOA by numerous glacial streams has been described in a general sense by interpreting ERTS-I imagery (Burbank, 1974; Carlson et al., 1975). East of Kayak Island the primary sediment source is drainage from the Bering, Guyot, and Malaspina glaciers, while west of Kayak Island the major source is the Copper River (Feely and Cline, 1977). The suspended sediment plumes drift to the west along the coast, with a portion being trapped in a clockwise gyre southwest of Kayak Island, a second portion entering Prince William Sound, and the remainder continuing southwestward around the perimeter of the gulf (see Fig. 3.23).

OCSEAP-sponsored research on suspended particulate matter in NEGOA has yielded data on seasonal distributions, suspended mass concentrations, and chemical characteristics (Feely and Cline, 1977; Feely et al., 1979). Those authors identify three significant modes of distribution of suspended matter: (1) material from river drainage is carried westward along the shoreline and deposited in calm nearshore areas such as seafloor troughs and depressions; (2) resuspended bottom sediment may be carried offshore during the winter in conjunction with wind-driven downwelling; and (3) resuspended bottom sediment may be carried onshore by tidal currents and storm-generated bottom currents.

The concentration of suspended matter in surface waters is typically 1-2 mg/l (Fig. 3.28). Values in turbid plumes near river mouths may be several orders of magnitude higher. The turbid plumes are composed mainly of fine sand- to clay-sized glacial rock flour. As these plumes disperse and mix with shelf water, the total concentration decreases, and the proportion of biological detritus increases. The finest material in suspension may be transported considerable distances before being deposited on the seafloor; based on mineralogy, one source of very fine-grained sediment on the Kodiak shelf has been identified as the Copper River (Hein et al., 1977), some 400 km distant.

A knowledge of certain geotechnical properties of sediment is extremely important in assessing hazards caused by seafloor instability. Mass movement, as in a slump or slide, occurs when the "load" applied to a sediment mass exceeds the "resistance", or strength of the mass. Typical loading forces are gravity (as a function of seafloor slope and sediment density) and excess pore pressure in the sediment, which is interstitial fluid pressure in excess of the ambient hydrostatic pressure. Excess pore pressure may be caused by the passage of large storm waves, by earthquake ground-shaking, or by the generation or release of natural gas in the sediment.

A large portion of the NEGOA shelf is characterized by geotechnical properties that cause difficulties for engineering design. Table 2.6 lists representative values for parameters used by engineers in the design of offshore platforms and pipelines. The values presented here are from areas known to have experienced seafloor instability. The distribution of sediment by size classification (Fig. 2.12) also reveals areas of potential instability; clayey or silty

Table 2.6 Representative values of geotechnical properties that are useful in engineering design. The three areas shown all contain submarine slides (modified from Hampton et al., 1978).

Geotechnical property	Copper River Prodelta	Kayak Trough	Ice Bay-Malaspina Glacier
Liquid limit (%)	48	30	31
Plastic limit (%)	25	19	20
Natural water content (%)	53	55	31
% Sand	1	17	7
% Silt	34	43	57
% Clay	65	40	36
Specific gravity of solids	2.84	2.74	2.71
Friction angle (ϕ') (no cohesion intercept)	24°	28°	28°
Compression index	0.38	0.32	
Swell index	0.03	0.04	
Coefficient of consolidation ($x10^{-4}$ cm^2/s)	4.5	4.7	
Bulk density (g/cm^3)		1.64	1.77

sediments on relatively steep slopes indicate potential instability, while coarse gravels are suggestive of strong bottom currents (Carlson et al., 1977). Other geotechnical parameters of engineering concern measured by OCSEAP investigators (Carlson et al., 1977) include the shear strength of selected samples and the plasticity and liquid limits for clayey silts and gravelly muds.

The presence of jumbled or highly irregular reflectors in seismic profiling records may indicate gas-charged sediment. Fig. 2.15 shows areas in NEGOA that exhibit unusual acoustic records in Holocene sediment, and these areas may contain natural gas in sediment pore spaces (Molnia et al., 1978a). Note that the area seaward of the Copper River Delta corresponds to an area of slumps and slides (compare Figs. 2.14 and 2.17). This may be an example of gas-charged sediment, which has excess pore pressures, contributing to seafloor instability.

The source of natural gas in NEGOA sediment is probably the decomposition of biological detritus, based on chemical analysis of the gases (Kvenvolden and Redden, 1978). Those investigators found no evidence that the gases are seepage from petroleum or natural gas reservoirs.

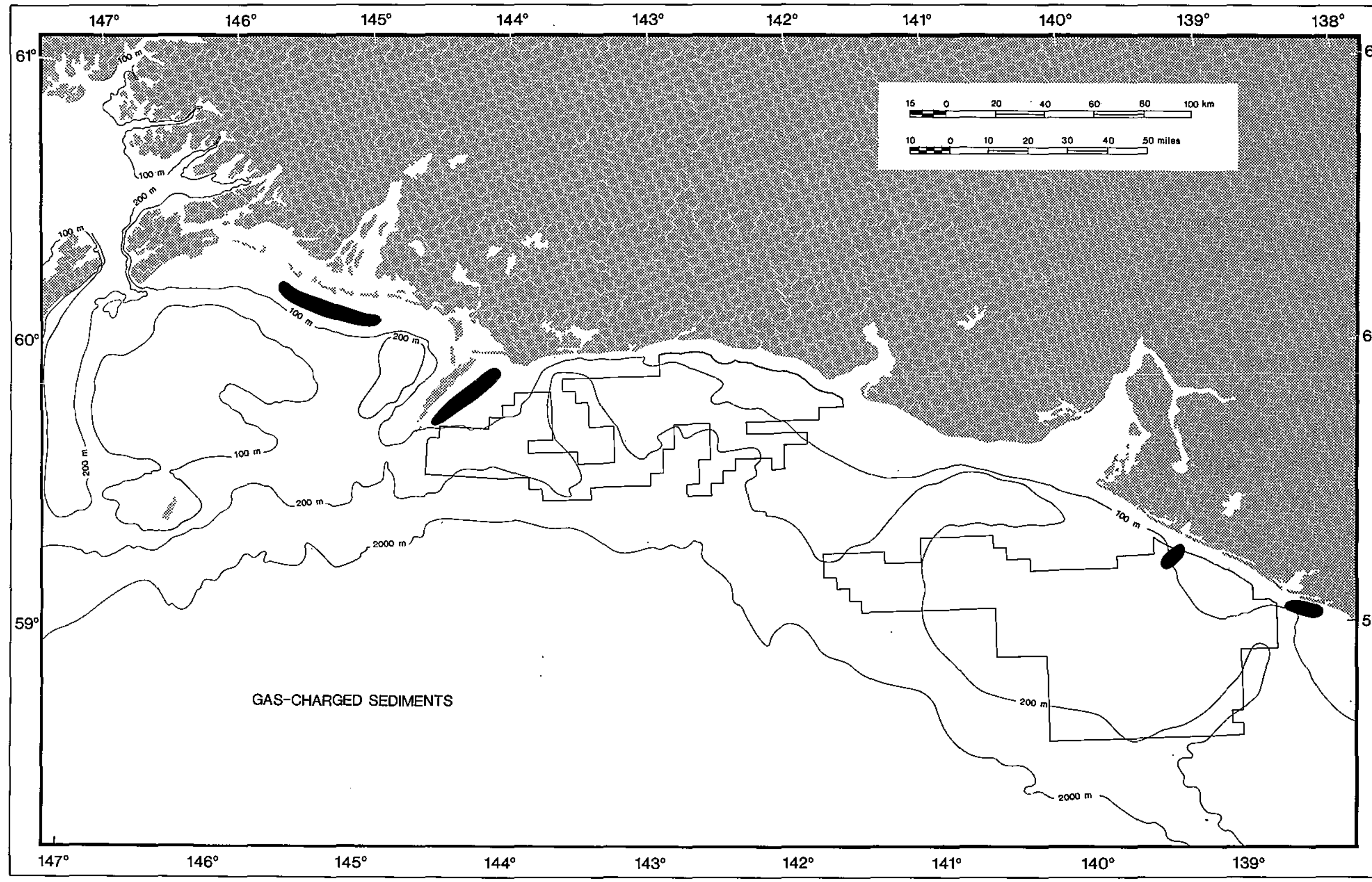


Figure 2.15 Map showing the location of four areas in NEGOA which appear to contain gas-charged sediment (Molnia and Carlson, 1978).

2.3.2 Surface faulting

Faults of Quaternary age (younger than about two million years) have been identified and mapped on the continental shelf of NEGOA (Fig. 2.16). The following description of this faulting is from Carlson and Molnia (1977) unless otherwise noted.

Several groups of faults between Montague Island and Yakutat Bay have been identified on seismic reflection profiles. The general trend of the faulting varies from northeast-southwest to east-west, and parallels the larger structures of the continental margin. Where sense of motion can be ascertained, the faults all show vertical motion, with the upthrown block on the north or northwestern side. The offset on these faults is 5 to 20 m. Due to the short length of these faults relative to the amount of displacement observed, it has been postulated that they indicate episodic movement rather than single events.

The NEGOA continental shelf east of Yakutat Bay was not surveyed with trackline spacings as dense as the central and western sections described above. The spacing between adjacent tracklines (20-30 km) was too great to permit correlation of fault features between tracklines. Faults have been identified on individual tracklines (Fig. 2.16), however; they display vertical offsets of 3-10 m. One large offset is on trend with the onshore location of the Fairweather Fault. This offset is about 25 m, and has the upthrown block on the southwest (or offshore) side, a displacement opposite to that observed for the faults farther west along the shelf.

The faults in NEGOA identified on seismic reflection profiles cut strata that are probably Tertiary in age, indicating that they are at least younger than about 70 million years. In many areas the

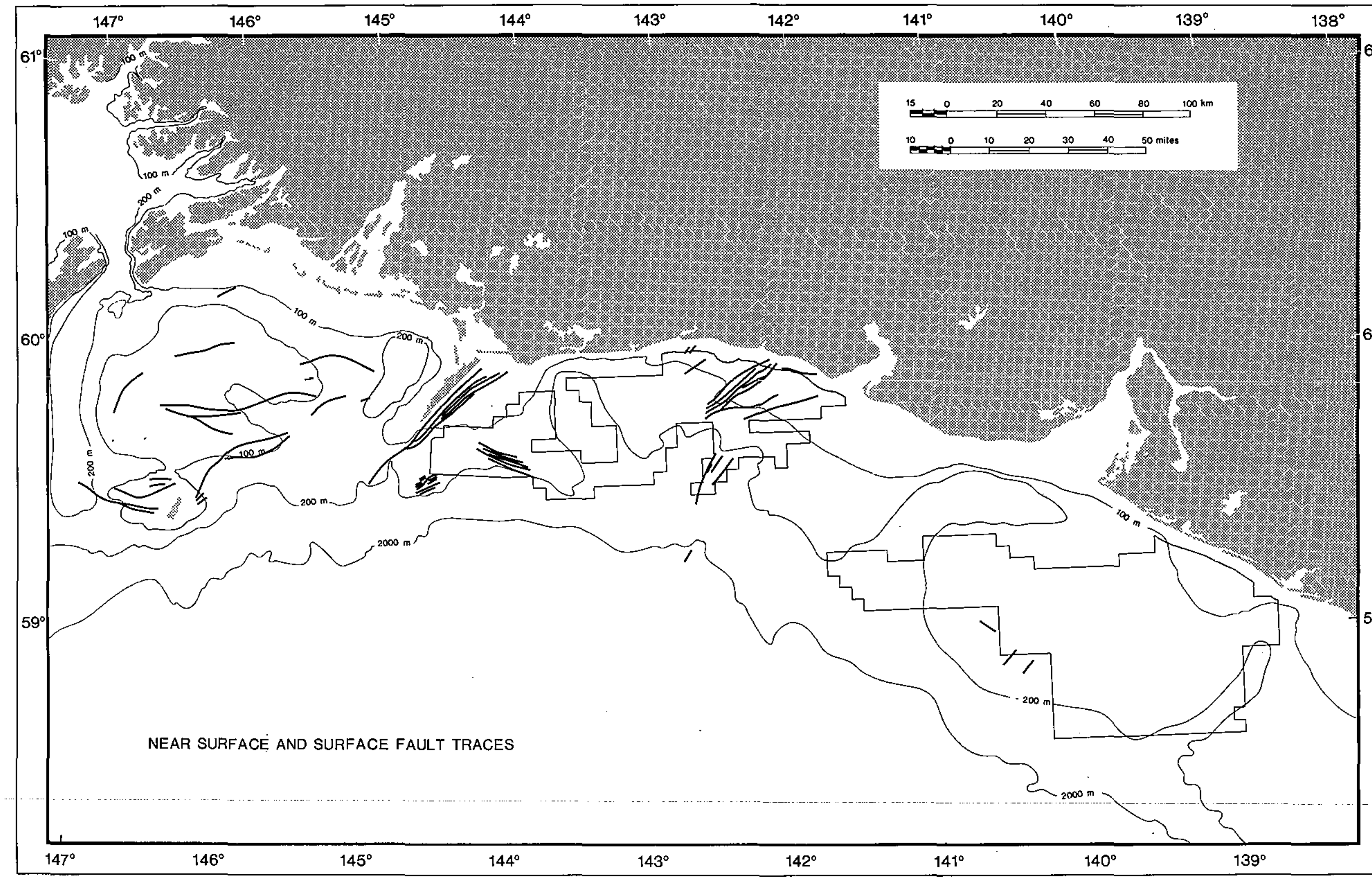


Figure 2.16 Location of known or inferred faults on the continental shelf in NEGOA (Carlson and Molnia, 1977).

Tertiary rocks are covered by thin layers of Holocene sediment (deposited since the last glacial advance; younger than about 10,000 years). Faults have been observed cutting Tertiary rocks and overlying Holocene sediment, but none have displayed offsets or scarps at the seafloor surface. The absence of seafloor scarps may be due to poor consolidation of the sediment or to high accumulation rates, both of which could obliterate surface expressions (Carlson and Molnia, 1977).

Recent activity of near-surface faults in NEGOA is indicated by the occurrence of small earthquakes near the mapped faults. Epicenters located by the local seismic network (Stephens et al., 1978; also Fig. 2.7) are in the vicinity of numerous faults south of Hinchinbrook Island, near Tarr Bank.

2.3.3 Seafloor instability

The U.S. Geological Survey has studied the continental shelf of NEGOA extensively by means of high-resolution seismic reflection techniques. Significant portions of the shelf are characterized by slumps or slides, or appear to be in an unstable posture. Fig. 2.17 shows areas where slumps and slides have been identified and also areas of potential seafloor instability. Four areas which pose geological hazards to OCS development are: (1) seaward of the Copper River Delta, (2) Kayak Trough, (3) Bering Trough, and (4) seaward of Icy Bay (Carlson and Molnia, 1977).

Several factors contribute to seafloor sediment instability. One of the most significant in NEGOA is the high rate of sediment accumulation, which leads to poorly compacted deposits that are susceptible to sliding, given some triggering mechanism such as ground-shaking due to seismic activity. The relative

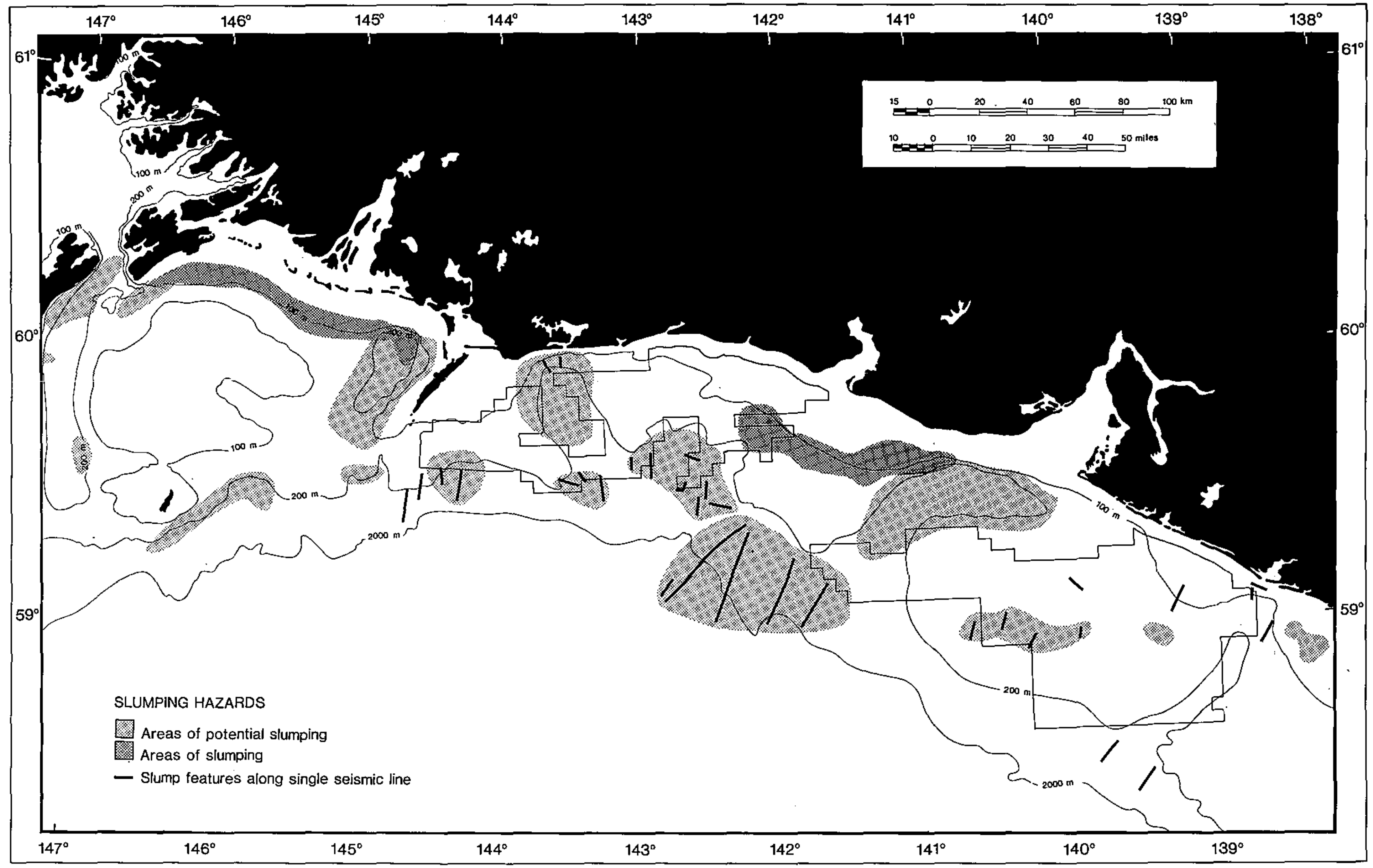


Figure 2.17 Locations of known slump and slide features in NEGOA. Areas of potential instability are also identified (from Molnia and Carlson, 1978).

importance of several factors affecting sediment instability in three slump areas is shown in Table 2.7. Of note is the minor significance given to oversteepening of slopes on the shelf. On the continental slope this factor probably has greater significance.

Examples of slumping on gentle slopes are found seaward of the Copper River Delta (Carlson and Molnia, 1978), in the Kayak Trough (Molnia et al., 1977), and on the slopes seaward of Icy Bay (Carlson, 1978). In all three areas the seafloor slope is one degree or less.

Table 2.7 Relative significance of factors affecting slope stability in NEGOA (from Hampton et al., 1978).

Factor	Copper River Delta	Kayak Trough	Icy Bay/ Malaspina Glacier
Rapid sedimentation	major	major	major
Free gas	intermediate	intermediate	none
Wave loading	intermediate	intermediate	intermediate
Earthquake loading	intermediate	major	intermediate
Oversteepening	none	minor	none

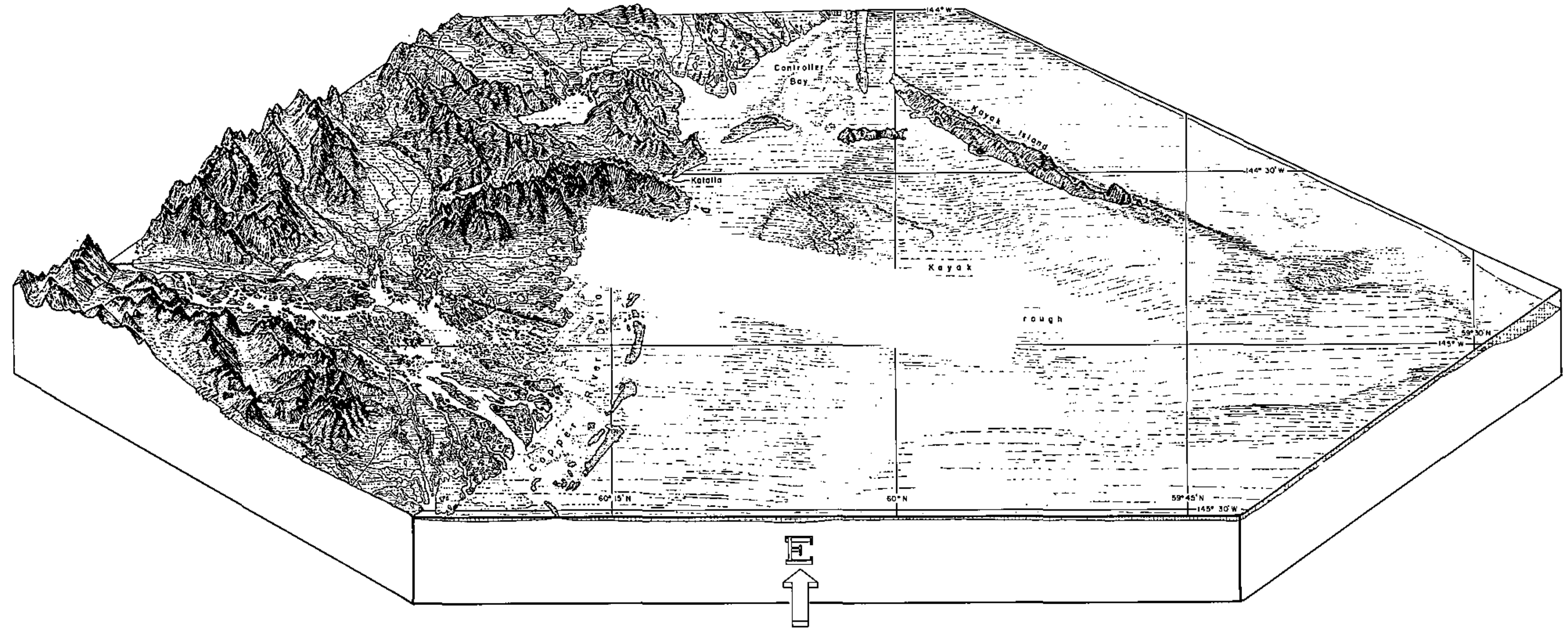


Figure 2.18 Orthographic drawing of the major submarine slide in Kayak Trough (P. R. Carlson, 1976). The vertical exaggeration is 3:1. (Drawing is by Tau Rho Alpha of the U.S. Geological Survey.)

The most striking example of a submarine slide in NEGOA is on the northern end of Kayak Trough (Fig. 2.18). It covers an area of about 18 by 15 km; the volume of material involved is about 5.9 km^3 (Molnia et al., 1977). The recency of this slide is suggested by distinct morphological features (scarps, hummocky surface topography, and sharp boundaries) in spite of high sedimentation rates which tend to obliterate detailed morphological features rapidly. It is possible that either the 1964 Prince William Sound earthquake or the 1899 Yakutat earthquakes triggered this slide (Carlson and Molnia, 1977).

Another area of extensive slumping and sliding that is well-documented by seismic reflection profiles occurs seaward of Icy Bay and the Malaspina Glacier (Fig. 2.17). The area is about 90 km long and 10-20 km wide, and occurs on gentle seafloor slopes of less than one-half degree. Again, distinct morphological features suggest recency of movement. The cause of instability is primarily the rapid rate of accumulation of clayey to silty sediment whose source is the meltwater streams that drain the Malaspina Glacier (Carlson, 1978). The events triggering movement, which may still be continuing, are most likely earthquakes, but storm waves may also be triggering processes (Carlson, 1978).

The areas on Fig. 2.17 that are described as potential slump or slide areas were identified by their thick accumulations of sediment (greater than 25 m) and steep slopes (greater than one degree). These characteristics suggest the potential for slope failure during severe earthquake shaking or under the influence of large tsunamis or storm waves (Carlson and Molnia, 1977).

2.3.4 Summary of surface geology hazards

NEGOA is bounded on the northwest by the major thrust fault system associated with crustal subduction and on the northeast by the major strike/slip faults of the Fairweather system. Zones of faulting that have been identified offshore are either parallel to or are extensions of the larger onshore structural trends. These offshore faults are relatively short and have vertical offsets of 5-20 m; their geometry suggests episodic motion as opposed to large, single event motion.

Some offshore faults show evidence of motion during the past 10,000 years. No offsets or scarps at the seafloor have been observed; however, since the sediment is soft and unconsolidated, such features would not persist for long periods. The detection of offshore earthquakes indicates that offshore faulting is presently occurring.

Several large seafloor slumps have occurred in the Copper River Delta region, Kayak Trough, and seaward of Icy Bay. Large areas of NEGOA's seafloor have a high potential for instability or slope failure during an earthquake or similar triggering event. High rates of sediment accumulation, as in the Copper River Delta, and gas-charged sediment are contributors to seafloor instability.

2.4 COASTAL GEOLOGIC HAZARDS

2.4.1 Shoreline description

The morphology and sediment dynamics of NEGOA's shoreline have been studied in detail since 1969 (e.g., Nummedal and Stephen, 1976; Hayes and Ruby, 1977). The results of NOAA/OCSEAP-supported research are presented by Ruby (1977); this is the source of the following information unless otherwise cited.

Fig. 2.19 shows the shoreline classified as erosional, neutral, or depositional. An erosional shoreline is one which is continuously retreating and is expected to continue to retreat. Rates of retreat can be very high, on the order of tens of meters per year. Neutral shorelines exhibit no net advance or retreat, although they may frequently change extensively. This classification should not be interpreted as indicating stability. Finally, depositional shorelines grow, either offshore or vertically, and are expected to continue to grow, provided the sources of sediment are not interrupted. Table 2.8

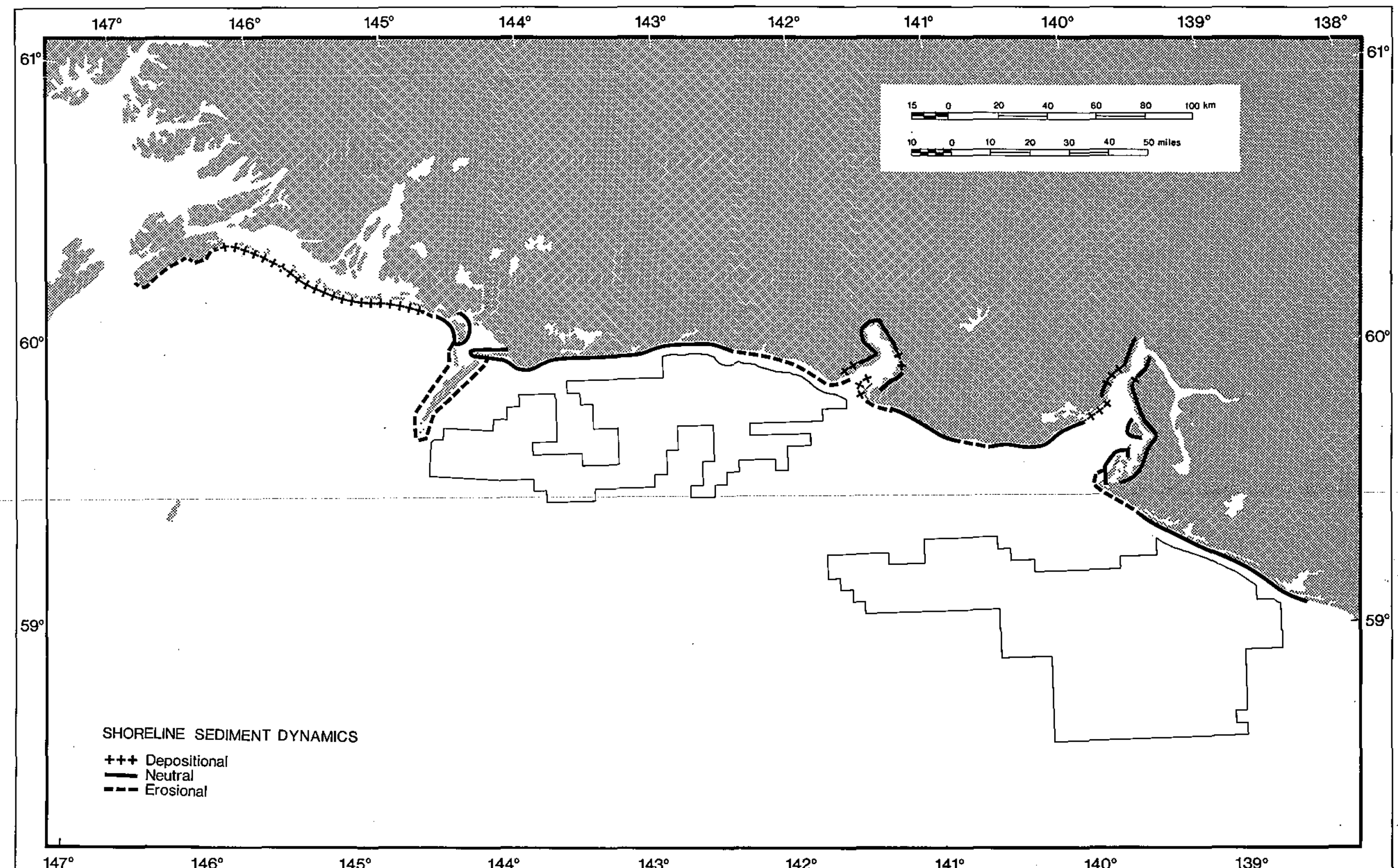


Figure 2.19 Morphological classification of shoreline between Cape Hinchinbrook and Dry Bay (Ruby, 1977).

Table 2.8 Morphological classification of shoreline between Cape Hinchinbrook and Dry Bay (Ruby, 1977).

	Description	Total extent (km)	Percent of total shoreline	Examples
CLASS A	EROSIONAL SHORELINES (23% of shoreline)			
A1	Low erosional scarps in glacial deposits; bedrock or older beach deposits; also sediment starved beaches eroding by overwash	110	12	Point Riou; Icy Cape and beaches immediately downdrift; old Yahtse River spit; Sitkagi Bluffs
A2	High to moderately high erosional scarps in bedrock; often with pocket beaches and wave cut platforms	100	11	Hinchinbrook Island, Kayak Island
CLASS B	NEUTRAL SHORELINES (58% of shoreline)			
B1	Neutral shorelines of sand and gravel, downdrift of glacial outwash streams, eording glacial deposits and rarely bedrock	225	19	Most of the Malaspina, Yakutat, and Bering Foreland beaches.
B2	Neutral embayment beaches of sand and gravel or pure gravel	172	25	Eastern shore of Icy Bay; eastern shore of Yakutat Bay
B3	Neutral embayments with high to moderately high bedrock scarps	65	7	Inner bay heads in Yakutat and Icy Bays
B4	Neutral beaches composed mostly of sand with an equilibrium sediment supply	54	6	Beaches fronting Controller Bay; isolated areas of Hinchinbrook Island
B5	Neutral pure gravel beaches downdrift of activity eroding glacial margins	11	1	Beaches just east of Sitkagi Bluffs
CLASS C	DEPOSITIONAL SHORELINES (19% of shoreline)			
C1	Depositional barrier islands of fine sand fronting the Copper River Delta	110	12	Copper River Delta barriers
C2	Minor depositional fan deltas in neutral embayments	18	3	Deltas in Icy and Yakutat Bays
C3	Larger depositional deltas in neutral embayments	17	2	Kwik Stream delta in Yakutat Bay
C4	Prograding spits of sand and gravel in Icy Bay	14	2	Riou Spit; Clay Bluff Point
	TOTALS	896.0	100	

describes in detail the morphology of the NEGOA shoreline. The classification is used to assign an Oil Spill Vulnerability Index to the various parts of the coast.

Some conclusions from the shoreline research program (Ruby, 1977) which are germane to development of the petroleum industry on the outer continental shelf are as follows:

(1) The NEGOA shoreline is exposed to severe storm waves and storm surge flooding, with Icy and Yakutat Bays and several fiords within those bays the only areas protected from these phenomena.

(2) Much of the shoreline is classified as neutral; significant morphological changes in depositional features, such as sand bars and sand spits, can occur during storms along neutral coastline.

(3) Erosion rates between Icy Bay and Cape Yakataga are extremely high; erosion at the mouth of Icy Bay, especially at Icy Cape, contributes to Riou Spit growth rates of up to 92 m/yr (Molnia, 1977).

(4) The eastern shorelines inside both Yakutat and Icy Bays are more protected from storm waves than the western shores.

(5) The sand and gravel deposits on the shorelines adjacent to Malaspina and Bering Glaciers are strongly influenced by variability in the glacial drainage systems and may exhibit dramatic short-term changes.

(6) Data from the Summary of Synoptic Meteorological Observations (SSMO; U.S. Naval Weather Sevice Command, 1970) may be used to calculate the direction of sediment transport. Geomorphic evidence for direction is highly correlated with direction calculated by modeling.

2.4.2 Oil spill vulnerability

The Coastal Research Division of the University of South Carolina has assessed the probable effects of oil spilled on the shorelines of Lower Cook Inlet (Hayes et al., 1976), the Copper River Delta (Ruby and Hayes, 1978), and the Gulf of Alaska (Ruby, 1977). They have classified shorelines according to the expected residence time of the pollutant oil, with consideration also given to biological sensitivity and natural cleaning ability of the environment. The parameters which affect oil residence time most directly are the intensity of marine processes, the size and textural characteristics of the sediment, and the direction of sediment transport (Ruby, 1977).

Table 2.9 presents the various categories of shoreline and their associated oil spill risk classification. The subclasses referred to are those described in Table 2.8. The discrepancy between the total length of shoreline in Tables 2.8 and that in 2.9 is due to the inclusion of shoreline associated with barrier islands, spits, etc. in Table 2.9, whereas in Table 2.8, only the simple distance along the coast was measured. Most of the additional shoreline considered in the oil spill vulnerability analysis is associated with the Copper River Delta (C. Ruby, pers. comm.). The oil spill risk classification for NEGOA has been mapped in Fig. 2.20.

The area most likely to retain oil for long periods is in the vicinity of the Copper River Delta.

Table 2.9 Oil Spill Vulnerability Index (OSVI) applied to the shoreline between Cape Hinchinbrook and Dry Bay (Ruby, 1977).

OSVI	Kilometers of shoreline	Percent of total shoreline	Discussion
1-2	130	7	Oil easily removed by wave erosion; some problems in areas of gravel accumulation and pocket beaches. This includes most of Subclass A1 and A2 shorelines.
3-4	298	17	Generally low risk areas. Fine sands prevent penetration of oil. Possibility of oil burial. Many of Subclasses B1, B2, B4, and C1 beaches fall into this risk class.
5-6	421	24	Mud tidal flats do not permit deep penetration of the oil, but the relatively low energies require as much as a year to remove the oil. Sand and gravel beaches are highly prone to oil burial and thus fall into this risk class. Many beaches of Subclasses B1, B2, C1, C2, C3, and C4 fall into this risk class.
7-8	514	29	These areas include pure gravel beaches and sheltered rock headlands and cliffs. Oil will remain for periods of years in these areas. Includes Subclasses B2, B3, and B5.
9-10	410	23	These highly sensitive marsh and tidal flat areas can retain oil for more than 10 years. In addition, these areas are of extreme biological importance. Landward areas of Subclasses B4 and C1 fall into this category.
Totals	1,773	100	

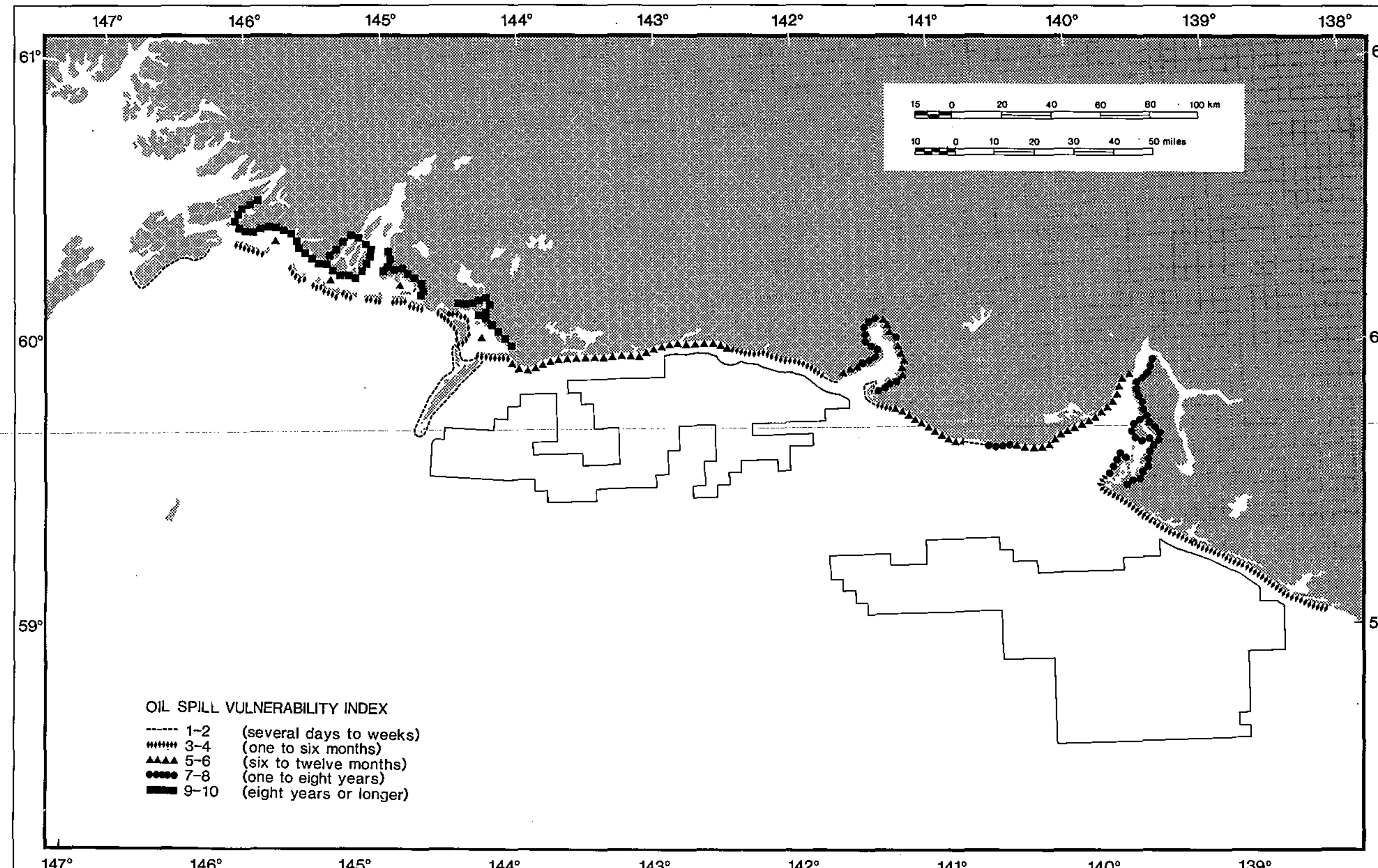


Figure 2.20 Oil spill vulnerability of shoreline between Cape Hinchinbrook and Dry Bay (modified from Ruby, 1977).

When the routes of supertankers departing from Valdez are considered, the threat of pollutant oil in the Delta region is even greater. Ruby and Hayes (1978) describe in detail the application of the oil spill vulnerability index to the Delta region. Only the major features of their analysis are shown on Fig. 2.20.

Other areas in which pollutant oil could remain for more than a year are the eastern shores of Yakutat Bay and Icy Bay, and the western shore of Icy Bay. Shorelines with less than six months residence time are those that are most exposed to waves, or are primarily rocky headlands or well-compacted fine sands. The shorelines between Dry Bay and Yakutat, Icy Cape to Cape Yakataga, Kayak and Hinchinbrook Islands, and the barrier islands off the Copper River Delta are in this category.

The vulnerability of NEGOA shoreline to pollutant oil must be assessed in terms other than residence time alone. The probability of oil spill occurrence, likely trajectories of pollutant oil, and the temporal and spatial locations of vulnerable environmental resources are very important elements of risk analysis. These elements have been included in a recent study by the U.S. Geological Survey (Lanfear et al., 1979), the results of which have contributed to the lease tract selection process. Finally, the isolation and inaccessibility of much of the NEGOA shoreline can make cleanup operations nearly impossible (Ruby, 1977), no matter how desirable ecologically those operations may be.

2.4.3 Hazards in bays

Exploratory drilling and offshore production will require onshore support facilities for shiphandling, supply staging, fuel storage, power generation, and living accommodations. Icy Bay and Yakutat Bay are the nearest harbors to the lease tracts of OCS sales No. 55 and No. 39, respectively, and development has begun in each area. Dry Bay and Lituya Bay farther to the east are the only other potential harbors along the coast, but neither has any facilities at the present time.

All of these bays are exposed to varying risks posed by rapid breakout and draining of nearby glacial lakes, rapid glacier advance or retreat, and high rates of sediment accumulation and erosion. In addition, earthquake shaking can significantly enhance some of the above processes, and may also cause huge landslides into the bays, such as the one which occurred in Lituya Bay in 1958 (Section 2.2.3). Large tidal ranges and high tidal current velocities contribute to difficulties in construction and operation of port facilities in these bays.

Development associated with OCS lease sale No. 55 could occur in Yakutat Bay in the mid-1980's, especially with the expansion of existing harbor facilities at the city of Yakutat (USDI, 1980b). Ultimately this expansion might include an oil terminal and liquid natural gas facility. Serious consideration of earthquake ground shaking, the geotechnical properties of foundation materials, and the rapid movement of shoreline sediments will be required during the design of these facilities.

Icy Bay is a most likely site for shore facilities associated with OCS oil and gas development resulting from sale No. 39. A study of the glacial sedimentary processes occurring in Icy Bay and adjacent shorelines (Boothroyd et al., 1976) makes specific recommendations as to the suitability of the area. The geological hazards that disqualify some sites are glacier-burst floods, glacier movements, buried ice, unstable ground both ashore and in the subtidal zone, coastal erosion and excessive sediment accumulation (especially Icy Cape and Point Riou), and drift ice in the bay. These hazards apply to parts of Yakutat Bay as well.

Because of glacial activity in Icy Bay and active sedimentation processes, the U.S. Geological Survey has made detailed investigations to assess its suitability for industrial development (Molnia, 1979). The morphological history of the bay has been extended as far back as the late 1700's. It has undergone several cycles of extensive infilling by sediment and erosion into bays of various sizes and shapes. Glaciers have advanced and retreated several times from the head of the bay (Fig. 2.21).

2.4.4 Summary of coastal geologic hazards

The shoreline of NEGOA is dynamic with respect to movement of beach material, and rapid changes in morphology occur under the influence of severe storm waves. Careful selection of sites for shoreline facilities will have to be made to minimize the hazards posed by rapid erosion and deposition of beach materials, and also by the highly variable drainage systems of the Malaspina and Bering glaciers.

The Copper River Delta region is highly susceptible to long-term residence of spilled oil; also some parts of the major bays in NEGOA are susceptible. Inaccessibility to much of the shoreline will make future oil spill cleanup operations extremely difficult or impossible.

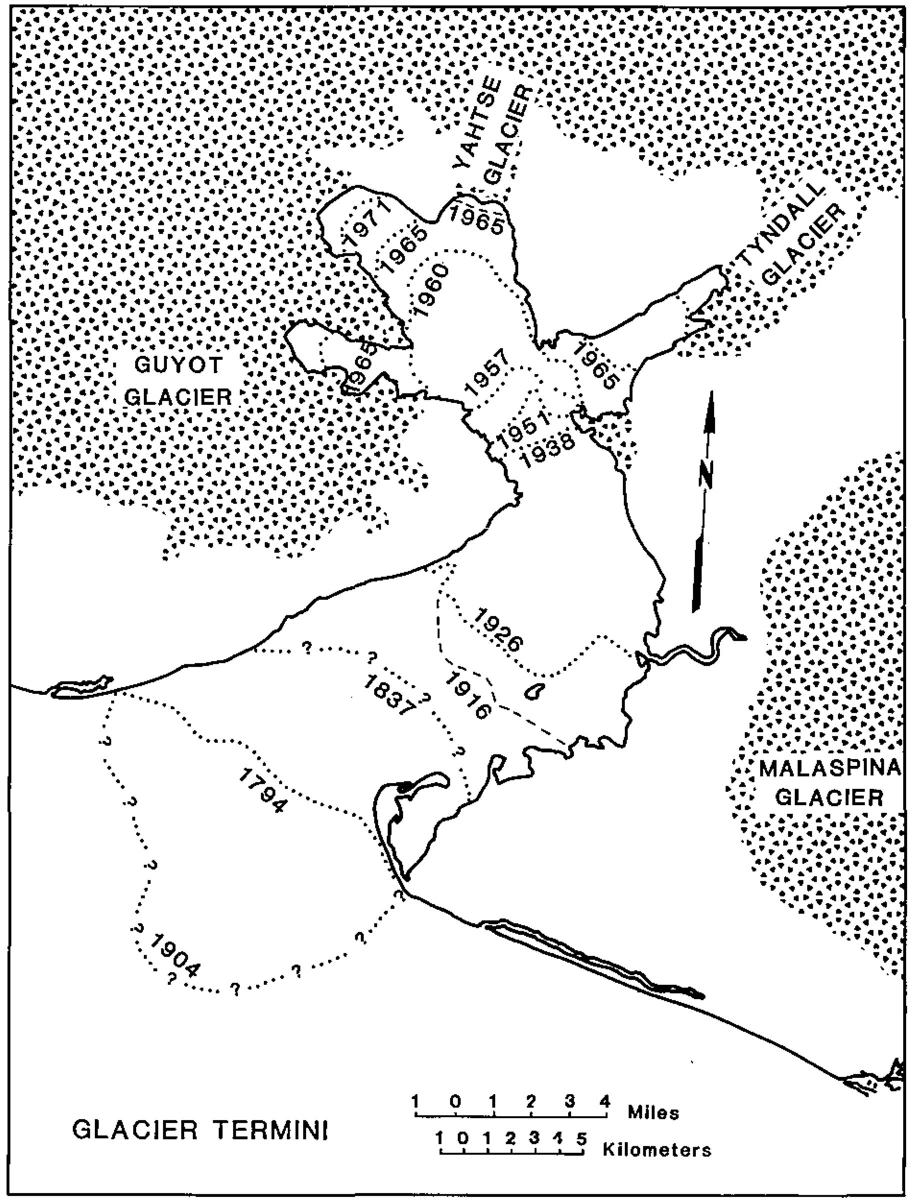


Figure 2.21 Glacier termini in Icy Bay from 1794 to the present (Molnia, 1979).

CHAPTER 3 CIRCULATION

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 make predicting its location difficult. These forces can be categorized as transportation and transformation processes. Transformation processes are those that affect the physical and chemical properties of the oil. Examples are evaporation, emulsification, photochemical oxidation, and solution. Although varying with environmental conditions, these processes are not specific to individual lease areas and thus will not be discussed here. For a summary of these, see Payne and Jordan (1979).

On calm waters gravity and surface tension promote spreading, whereas inertia and frictional forces restrict it. Waves, winds, and currents increase spreading (Malins, 1977). Waves also mix oil with water and break up patches of oil. Kraus (1977) suggests that seas (shorter-period waves) are more important than swell (longer-period waves) in mixing.

Oil drift is 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 is caused by shear stress in the wind. Wind drift is accepted to be about 3 percent of the wind speed at a small angle (e.g., 20°) to the right of the wind. (See Tsahalis, 1979, for a summary of experiments on wind-induced surface drift.)

It is generally assumed that oil drifts in the same direction and at the same speed as surface currents (neglecting wind- and wave-induced drift). Schwartzberg (1970), however, found that wood chips (used as a reference) were not advected at the same rate as oil. He attributed the difference to the depth of penetration (draft). But when waves were added to his laboratory experiments the oil and chips were advected at nearly the same rate. Because the ocean surface is never wave-free, we will assume that floating pollutants, in addition to oil, will be advected with the surface currents.

Wave-induced drift occurs by Stokes mass transport. Stokes drift theoretically can be as high as 2.9 percent of the wind speed. However, experiments have shown that wave-induced drift can be higher than that calculated for the Stokes mechanism (Alofs and Reisbig, 1972).

The drifts induced individually by waves, winds, and currents are not simply additive (Reisbig et al., 1973; and Tsahalis, 1979). Tsahalis (1979) has shown that wind generated waves decrease the net surface drift when the wind is in the same direction as the waves.

Further complicating the transport of oil are the effects of the oil itself on the environment. Oil calms surface water by reducing capillary waves. However, the effects of surface oil on the transfer of energy between wind and currents have received only limited attention (Liu and Lin, 1979).

Predicting oil motion when the circulation and winds are known is inexact, at best. However, experiments have shown that standard oceanographic techniques can provide reliable estimates of oil movement (e.g., Audunson, 1978). The problem of "where will the oil go" has been reduced to "where will the water go." Thus we are assuming that oil movements follow ocean circulation. In numerical predictions of oil movement, wind-induced drift is added to the motion of the ocean surface currents.

3.1.2 Oceanographic setting

The Gulf of Alaska is bounded on the north by the arcuate coastline of Alaska and on the south by the North Pacific Ocean. The adjacent coastal topography is rugged, which has important implications for circulation in the gulf. Weather patterns and winds are influenced by the topography. Precipitation and coastal freshwater runoff are large, due to orographic effects of coastal mountains.

For the OCSEAP study, the Gulf of Alaska has been divided into two major components: the Northeast and the Northwest Gulf of Alaska. The Alaska Current, the dominant oceanographic feature of the gulf, is continuous throughout the gulf. In the Northwest Gulf of Alaska, however, this current intensifies and forms a concentrated stream along the shelf break called the Alaska Stream.

The Northeast Gulf can be subdivided into two areas: Yakutat Bay to Kayak Island, and Kayak Island to Prince William Sound. Kayak Island protrudes almost perpendicularly from the coast. It forces the westward flowing coastal current offshore into the Alaska Current. East of Kayak Island numerous submarine valleys and ridges perpendicular to the coastline cut the continental shelf, which is typically 50 km wide. Also many coastal glacial streams contribute fresh water to the gulf. West of Kayak Island the shelf is wide, typically 100 km, and is less rugged bathymetrically. The Copper River is the principal source of fresh water.

Circulation in the Gulf of Alaska is dominated by the Alaska Current. It flows counterclockwise adjacent to, and offshore of, the continental shelf break. Much of the water in the current comes from the North Pacific Drift.

The horizontal gradient of salinity (and hence, density) across the continental shelf is a major factor in driving circulation. Low salinities are maintained near the coast by the influx of fresh water, whereas high salinities are present seaward of the shelf break.

East of Kayak Island there are three distant flow regimes: the Alaska Current, at the shelf break; the coastal flow; and a flow of high variability in speed and direction between these currents. The coastal flow is pushed offshore at Kayak Island and is indistinguishable from the Alaskan Current beyond the point. Coastal influx of fresh water west of Kayak Island causes another coastal current to form. On the broad shelf west of Kayak Island flow is highly variable and has a weak mean.

3.2 FORCES CONTROLLING CIRCULATION

3.2.1 Tides

Tides in the NEGOA lease area are mixed semidiurnal. There are two high tides of unequal amplitude and two low tides of unequal amplitude in a tidal cycle (approximately 25 hours). The mean tidal range at Cordova is 3.1 m. (The difference between the mean higher high and the mean lower low is 3.8 m.) The maximum tide predicted (for 1974) was 4.7 m and the minimum tide was -1.0 m (referenced to mean sea level) (Brower et al., 1977).

Cartwright et al. (1979) list amplitudes and phase lag of eight tidal species for several pressure gauges in the NEGOA area. From the data it is seen that the semidiurnal principal lunar (M_2) tide is the dominant species. The next most important component is the diurnal soli-lunar (K_1). Other components in order of importance are the principal solar (S_2), the principal lunar diurnal (O_1, the larger lunar elliptic (N_2), and the principal solar diurnal (P_1). Diurnal and semidiurnal tides propagate counterclockwise in the Gulf of Alaska (Muench and Schumacher, 1980).

The tidal excursion can be estimated for the principal diurnal and semidiurnal tidal species. Tidal current amplitudes (for the 50-m current meter at station 61) were supplied by Lagerloef (1980, pers. comm.). The approximate values are 10 cm/s for the M_2 component and 6 cm/sec for the K_1 component. Tidal excursions calculated from these values are 1.4 km and 1.7 km. These are the distances a pollutant would travel over half a tidal cycle by means of tidal advection alone.

Advection of pollutants by tides is important over periods of a few hours. Except in the Alaska Current or in the Coastal Current, where high current speeds (30-100 cm/s) exist, tides may be the major advective force. However, since tides are cyclic, the net advection over several tidal cycles is small.

3.2.2 Winds

In the Gulf of Alaska the coastal wind regime is dominated by the seasonal movements of the Aleutian low and the North Pacific high pressure cells. The average position for the Aleutian low rotates clockwise: in early autumn it moves across the Alaska Peninsula to a mean position of 55^{o}N, 155^{o}W. In winter it moves to 50^{o}N, 175^{o}W and later moves northward to the western Bering Sea (Ingraham et al., 1976). During winter, coastal winds in NEGOA associated with the Aleutian Low are generally from the east or southeast. These winds are reinforced by a high pressure system that dominates the land areas of Alaska, Siberia, and western Canada.

In summer the North Pacific high pressure system moves northward to a mean position of 43^{o}N about 1500 km west of the coast (Bryson and Hare, 1974). From this position it dominates conditions in the Gulf of Alaska and blocks migrating storms from this area. Low pressure systems do not intensify in summer.

In winter, the mean winds are approximately twice as strong as in summer. Storms and the associated variability in wind direction and speed dominate the wind fields in both seasons. In summer, the wind often has an eastward component, whereas in winter the alongshore component is almost always directed westward. Average wind conditions are given in the OCSEAP Climatic Atlas (Brower et al., 1977).

3.2.3 Influence of winds on ocean circulation

Winds influence circulation in four main ways: Ekman forcing, Sverdrup transport, direct forcing, and vertical mixing. Through Ekman forcing, near-surface layers of the ocean are transported perpendicular to, and to the right of, the mean wind. A quantitative measure of Ekman wind forcing is the upwelling index. The index is numerically equal to the offshore component of Ekman transport per 100 meters of coastline (Bakun, 1975). Positive values for the index indicate coastal upwelling. A comparison of upwelling indices to the temperature and salinity fields is found in Section 3.3.

The predominantly westward winds in winter force near-surface waters toward the coast. The seasonal variation in coastal sea level may reflect this onshore flow (see Fig. 3.22). The accumulation of low-density (near-surface) water at the coast causes a downward bend in isopycnals (lines of constant density). This condition is called downwelling.

The opposite condition, upwelling, can occur in summer (Fig. 3.1). Here winds from the west push near-surface waters offshore, sea level falls, and subsurface water upwells to replace the offshore flow. Also, isopycnals bend upward over the continental shelf and shelf break. Upwelling, if persistent, can be important in bringing nutrient rich waters up into the

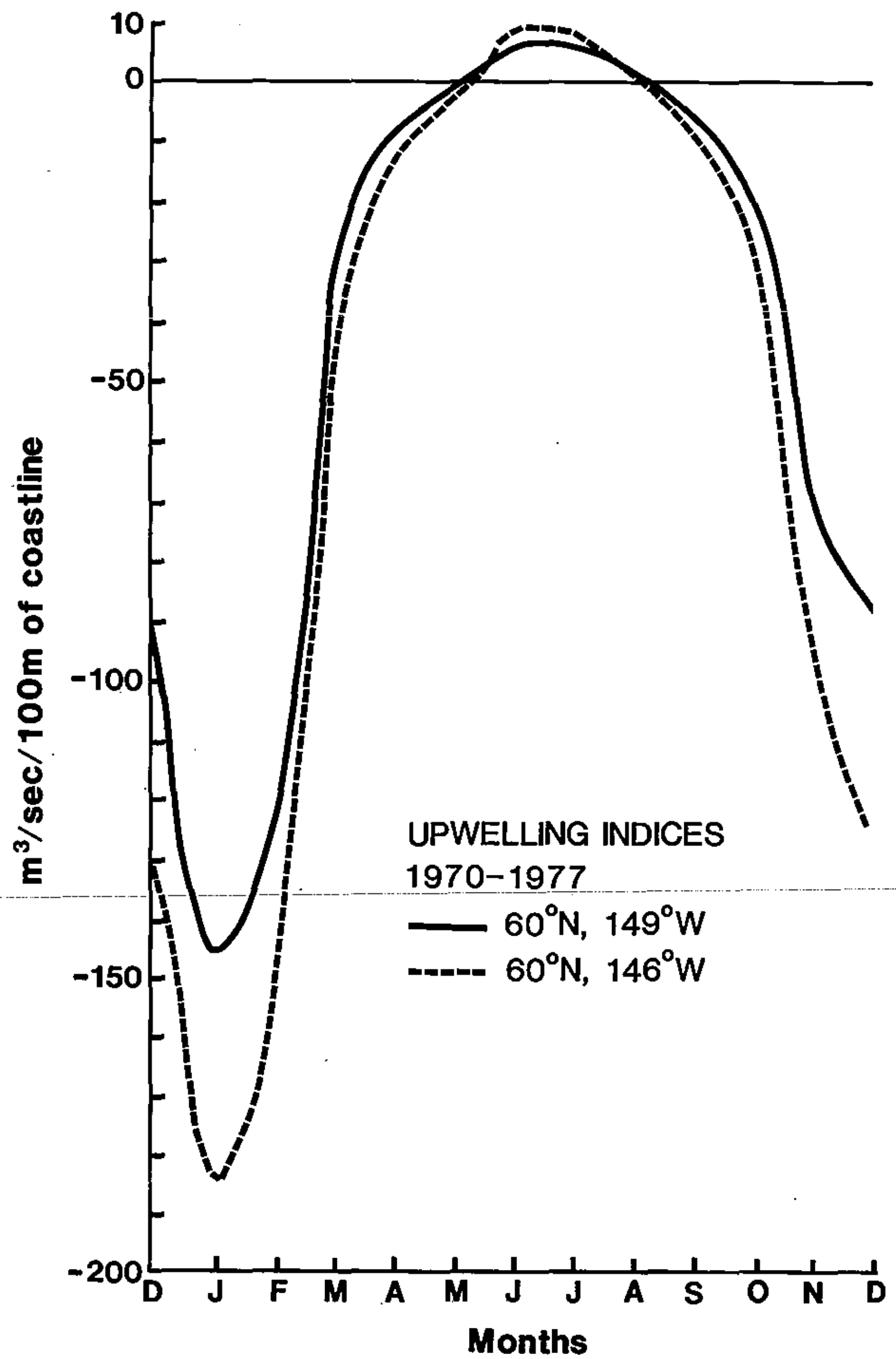


Figure 3.1 Upwelling indices for the Gulf of Alaska, averaged over 1975-77 (Royer, 1978a).

euphotic zone, where they are available to primary producers. In NEGOA, however, the upwelling season is short and is probably too short to be biologically significant.

The second mechanism by which winds drive circulation is Sverdrup transport. The curl of the wind stress (due to the geographical variations in winds that are perpendicular to the wind direction) drives the transport of water. The Sverdrup transport has a distinct seasonal signal (Fig. 3.2): values are maximum in midwinter and minimum in summer. The annual maxima are about 30 x 10^6 m^3/s and show a surprising lack of interannual variability for the three years of data (1975-1978). The summer minima are small, and negative values (corresponding to clockwise circulation in the Gulf of Alaska) do occur. The annual variation in Sverdrup transport spans an order of magnitude.

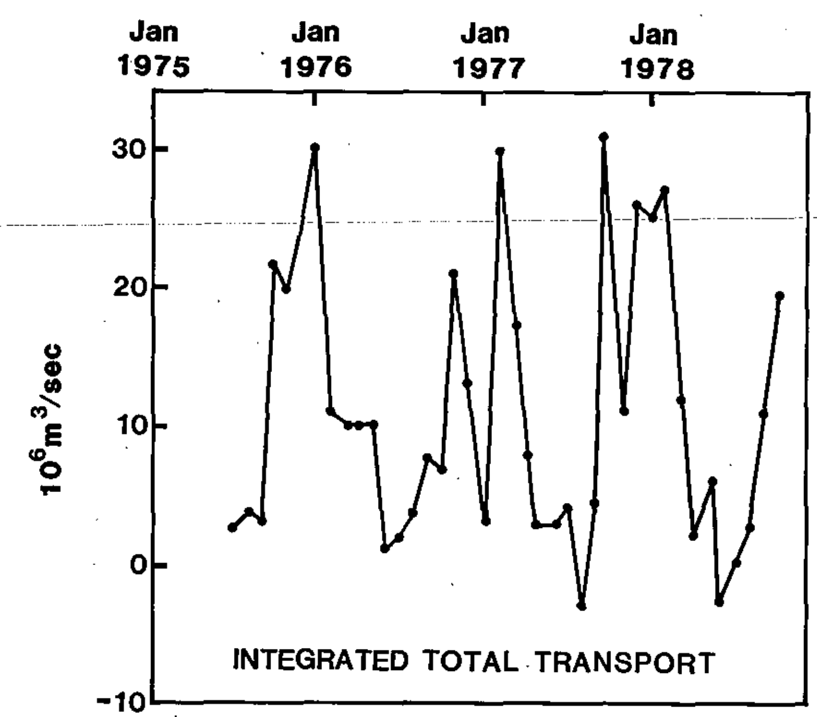


Figure 3.2 Integrated total transport computed from the curl of the wind stress (Reed et al., 1979).

A study conducted off Kodiak Island (Reed et al., 1979) showed that in spite of the large seasonal signal in the Sverdrup transport, there is no seasonal signal in the baroclinic component of the Alaska Stream. At first, the result seems surprising. However, at this latitude (about 58°N) the temporal and spatial scales of baroclinic response are much shorter and smaller than the scales of the variation in Sverdrup transport. The barotropic scales are much closer in size to meteorological scales, and it is possible that any seasonal variation in transport is manifested in the barotropic component (which has not yet been measured). Although the data were gathered off Kodiak Island, the results should be valid throughout the Gulf of Alaska.

The third mechanism is direct driving of surface waters by winds. Surface waters move in the same direction as the winds blow. Direct driving occurs when the depth is small compared to the Ekman depth, estimated to be between 35 and 50 m, (Royer et al., 1979), or when winds fluctuate over periods short compared to the inertial period, which is about 14 hours in the Gulf of Alaska. When these conditions are not met, Ekman forcing will dominate.

Winds can influence circulation by causing mixing, which is the fourth mechanism. Mixing is greater during the winter due to the higher wind speeds and reduced stratification over the shelf. (Reduced stratification is caused by vertical convection induced by atmospheric cooling in winter and by reduced coastal influx of fresh water.) The greater stratification and weaker winds in summer limit wind mixing to shallower depths. The most important effect of mixing is governing the vertical distribution of properties and pollutants.

3.2.4 Synoptic climatology

A synoptic climatology for the Northern Gulf of Alaska (Yakutat to Kodiak Island) has been described by Overland and Hiester (1978). This work was designed to generate surface winds for use in modelling trajectories of currents. The techniques used to generate the winds are discussed in section 3.5.

In this section the climate types are presented and briefly discussed. A climate type is a pattern of sea level atmospheric pressure that depicts a generalized, quasi-steady state of atmospheric circulation. Each type represents a distribution that is frequently observed. Although twelve subtypes (which are slight variations in location or intensity) have been identified by Overland and Hiester (1978), they will not be included in this discussion. The six climate types for the Northern Gulf of Alaska provide a synoptic climatology for the region. Any pattern of sea level pressure can be described in terms of one of the climate types.

The climate types were selected by subjective means. A synoptic meteorologist classified daily weather maps into different categories. The types selected are modifications of those reported by Sorkina (1963) and Putnins (1966).

The six climate types are shown in Fig. 3.3. Type one represents the condition of a low in the Gulf of Alaska. This distribution is common in all seasons except summer (Fig. 3.4). Lows tend to stagnate in the Northern Gulf due to high coastal mountain ranges that border the gulf and due to the cooler air (higher surface pressures) over Alaska.

Type two is the Aleutian Low. This pattern is dominant throughout the year but is at a maximum in spring. In summer the low is usually about 400 km to the northeast of the position shown for type 2.0. This alternate pattern is a subtype of the Aleutian Low.

Type three occurs more than other types in winter. It is described as a high pressure cell over the interior of Alaska and is caused by the cooling of air over the continental land mass. When lows are not present along the coast in winter, this type dominates.

In summer, cyclones or lows are typically found farther to the north than in winter. This situation is

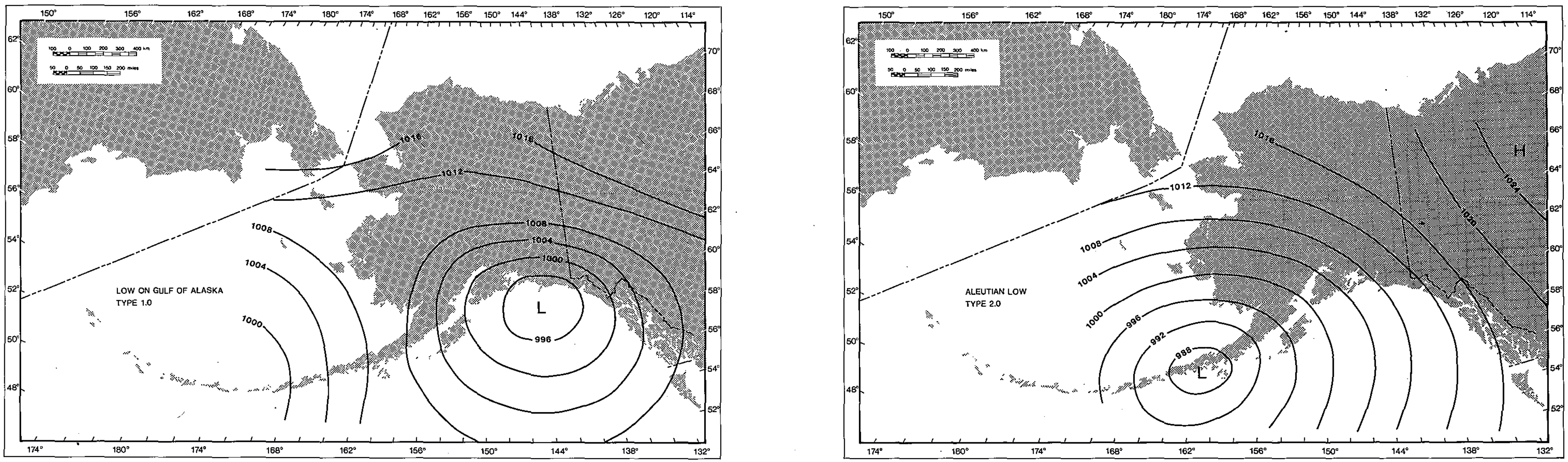
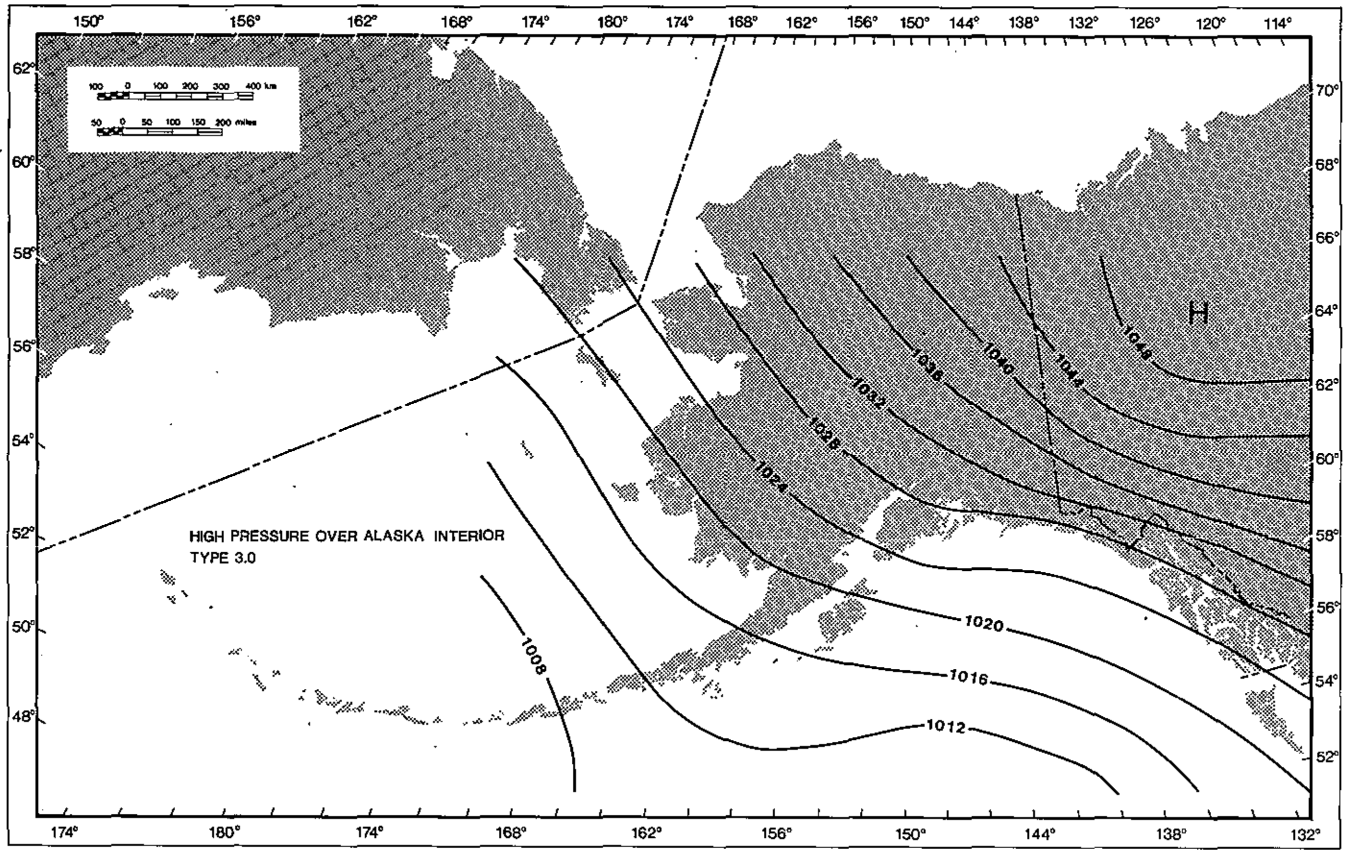
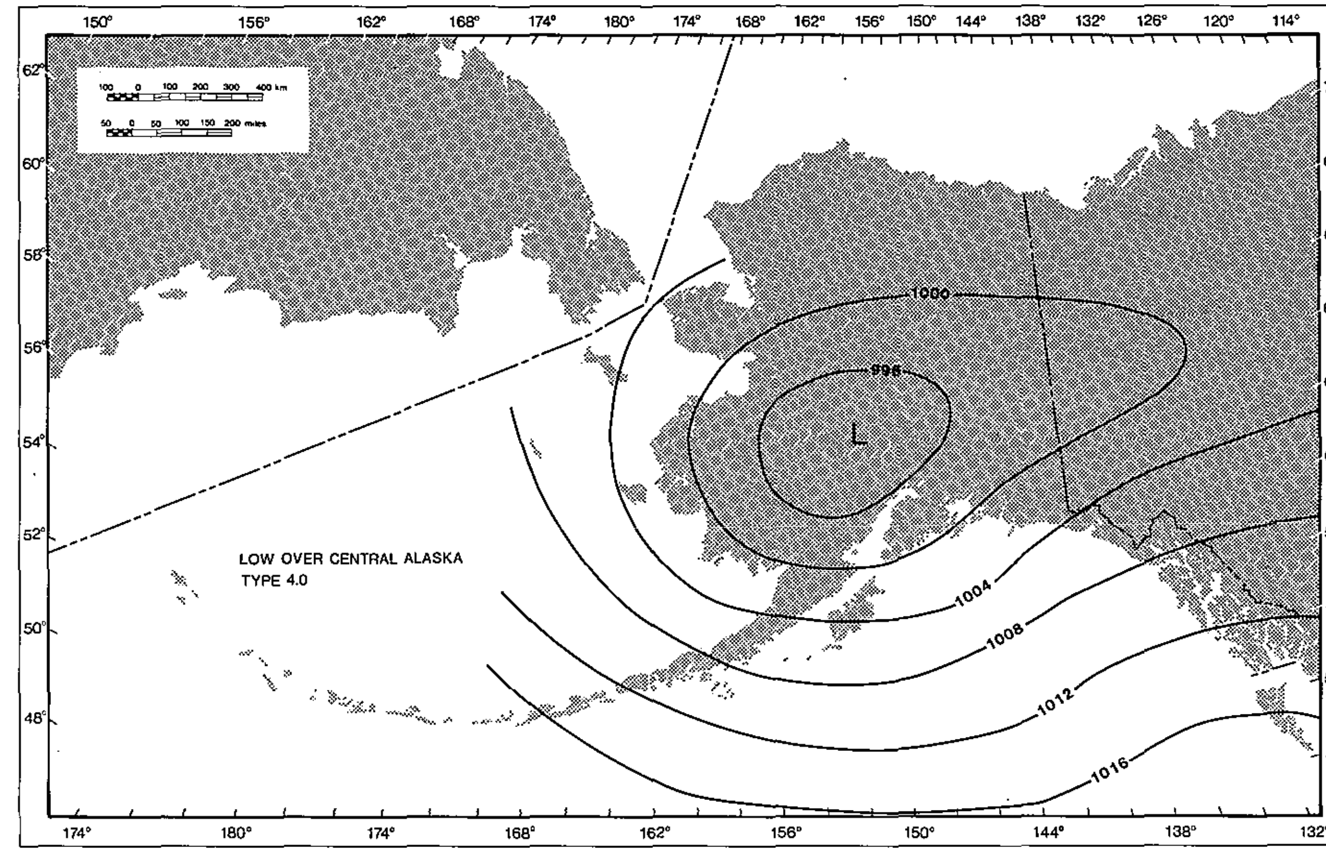
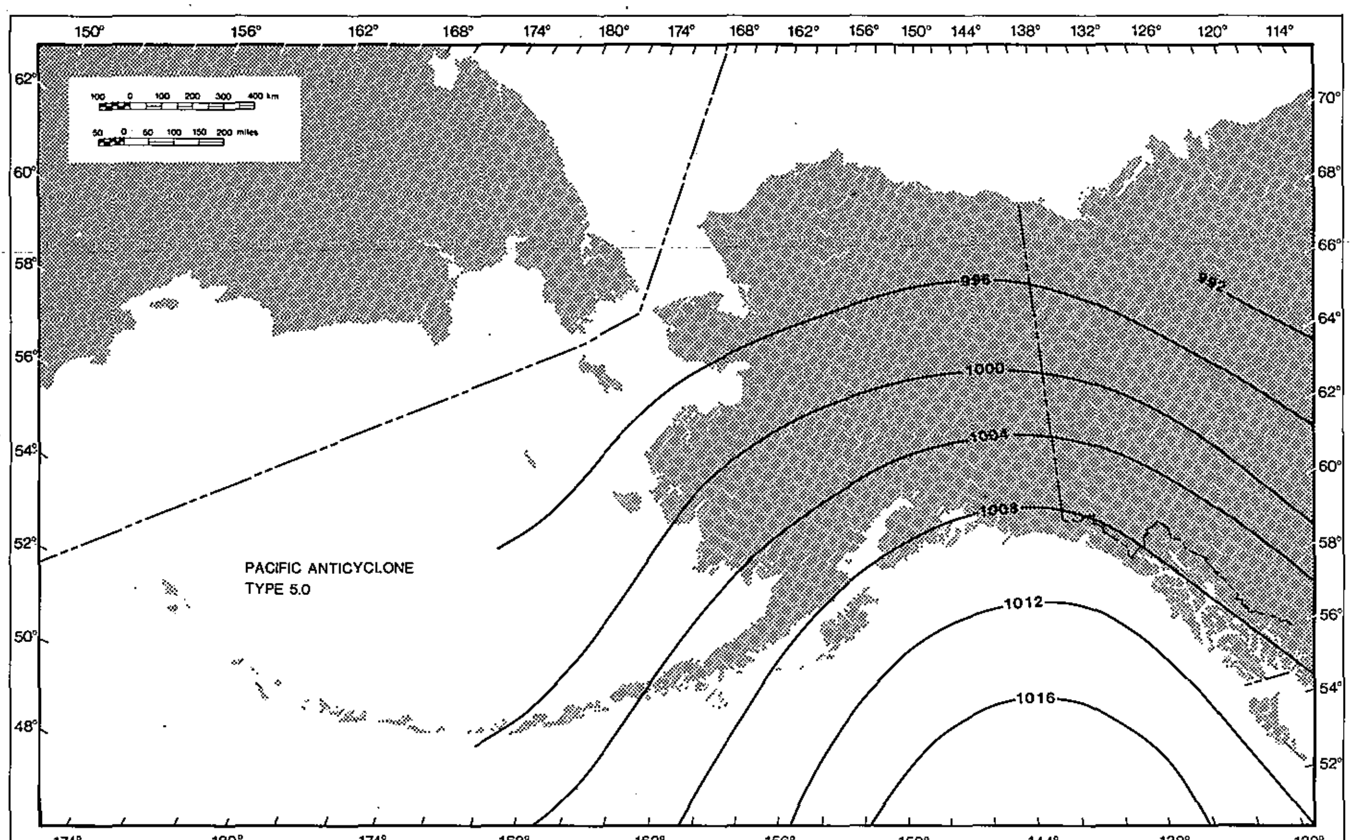
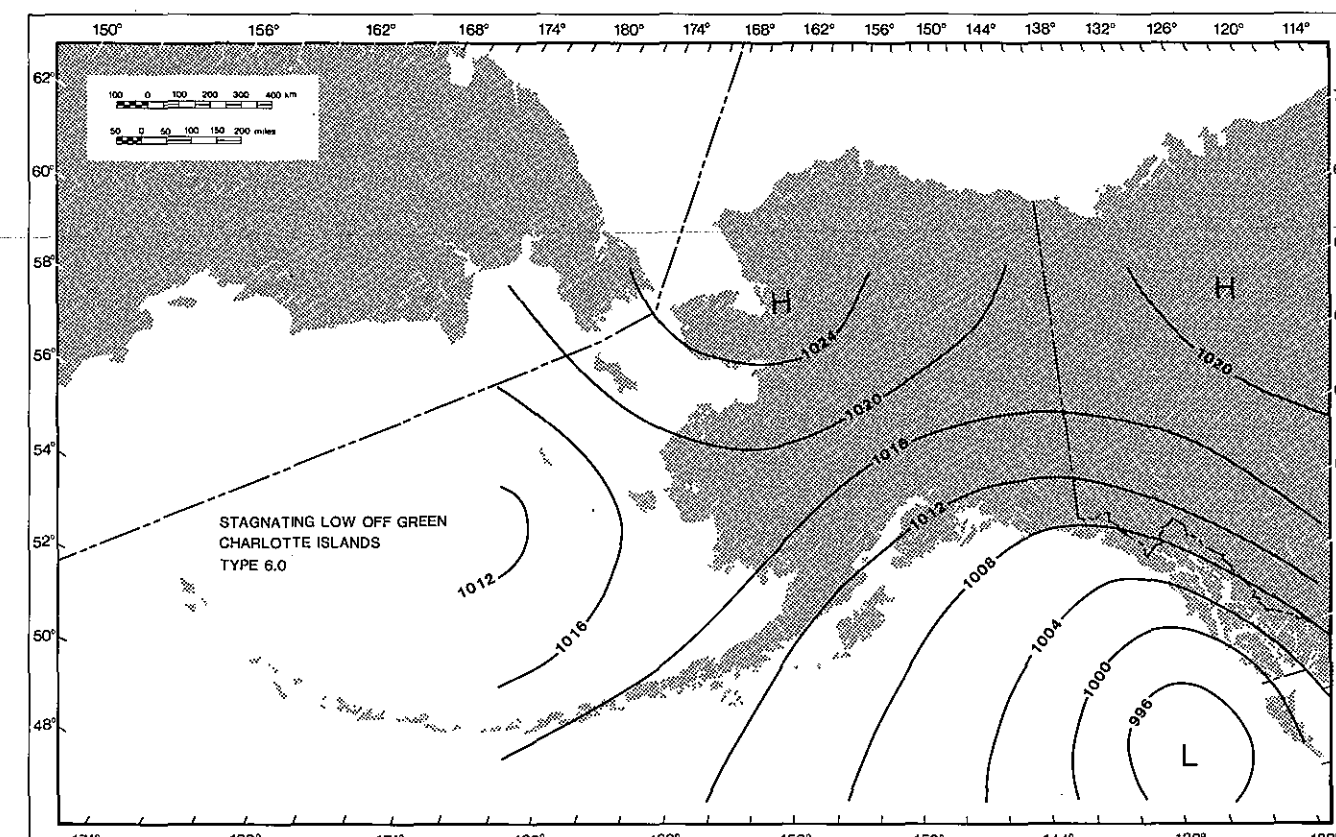


Figure 3.3 Climate types for the northeastern Pacific Ocean. Surface weather charts can be described as a combination of these six climate types. Slight variations in the patterns of these climate types, called subtypes, have been described by Overland and Hiester (1978). Contours show surface atmospheric pressure in millibars.


HIGH PRESSURE OVER ALASKA INTERIOR
TYPE 3.0
H
1044
1040
1036
1032
1028
1024
1020
1016
1012
1008


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


PACIFIC ANTICYCLONE
TYPE 5.0
992
996
1000
1004
1008
1012
1016


STAGNATING LOW OFF GREEN
CHARLOTTE ISLANDS
TYPE 6.0
H
H
L
1024
1020
1016
1012
1008
1004
1000
996

represented by type four. This pattern rarely occurs in winter (7 percent of the time), but occurs frequently (26 percent of the time) in summer.

The North Pacific high pressure cell is represented as type five. This type occurs often in summer (27 percent of the time) but not in winter (4 percent of the time). A subtype of type five has the axis of the high-pressure ridge farther to the west, south of Kodiak Island.

Type six is a stagnating low off the Queen Charlotte Islands. This situation occurs most frequently in winter (21 percent of the time). Associated with it is a high-pressure cell over northeast Alaska and another over the Bering Sea.

To obtain the frequency of occurrence (Fig. 3.4) daily weather charts and each of the climate types were digitized at 24 points. Correlations were run and the climate type that best correlated with each daily chart was used to describe that weather pattern. Overland and Hiester (1978) were able to correlate 75 percent of the data (from 1969 to 1974) with a correlation coefficient equal to or greater than 0.7.

The predominant directions of wind flow for each season can be obtained from Figs. 3.3 and 3.4. The dominant climate types for a season are selected (from Fig. 3.4). The direction of winds at any location for a particular climate type can be estimated as follows: geostrophic winds circulate clockwise around high pressure centers, parallel to the isobars, and counterclockwise around low-pressure centers.

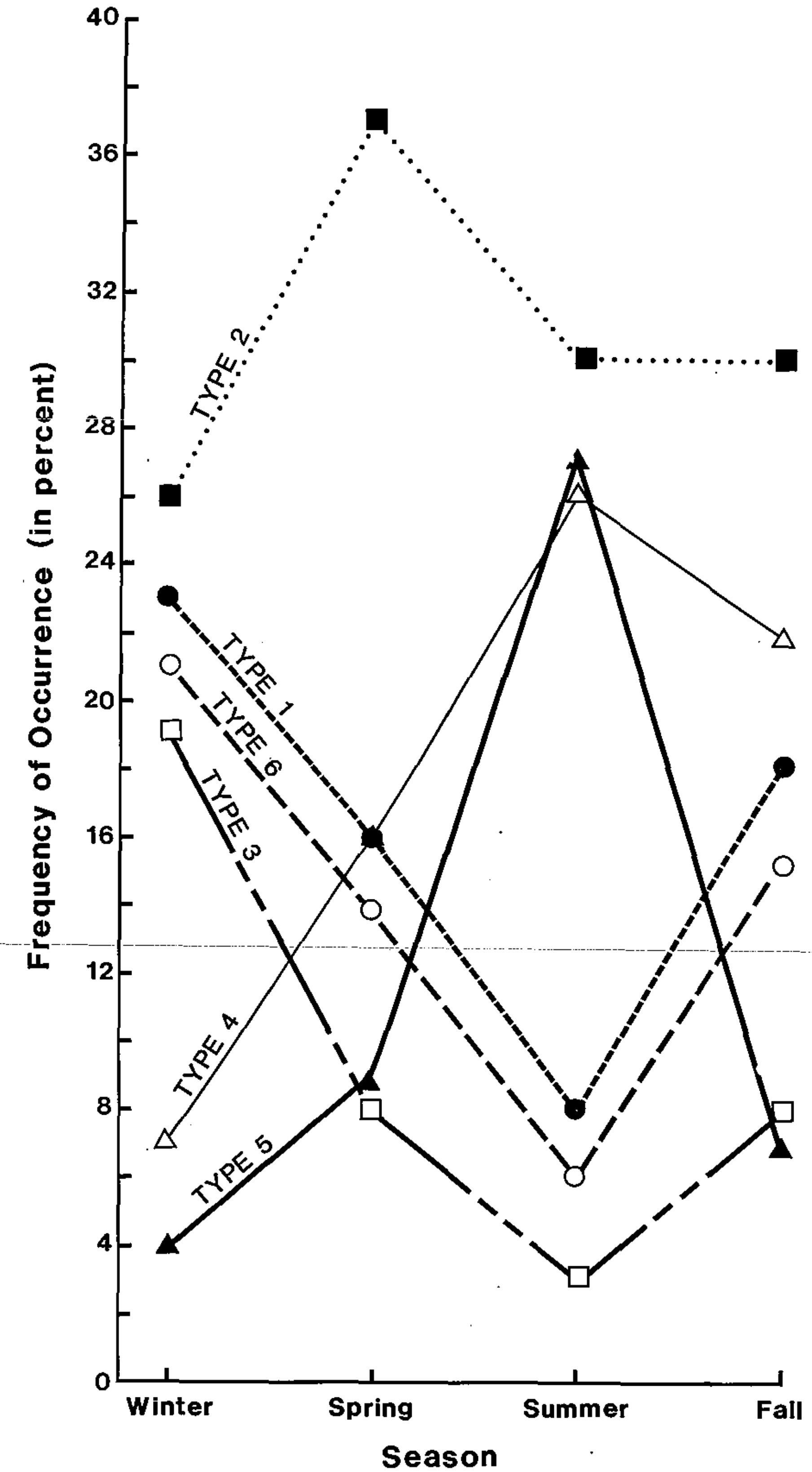


Figure 3.4 Seasonal frequency-of-occurrence curves for the six climate types shown in Fig. 3.3. For example, Type 2 (Aleutian low) occurs on the average 37 percent of the time during spring (Overland and Hiester, 1978).

3.2.5 Description of meteorological conditions

Monthly averages of winds at Middleton Island have been given by Royer (1978a). The longshore wind component (Fig. 3.5) is usually larger than the onshore component, thus reflecting some polarization by topography. Winds are westward and onshore throughout the year except in January when there is an offshore component. Wind direction and vector speed are given in Fig. 3.6. The highest mean velocities occur in May and November. Although scalar wind speeds are maximal in January, the vector mean speeds (maxima in May or November) are more important in accelerating currents.

Because few direct observations of winds are available for NEGOA, synoptic scale winds, derived from distribution of atmospheric pressure, are often used to represent winds over the shelf. Royer (1978b) compared synoptic-scale derived winds to observations from Middleton Island. A simple comparison showed that the synoptic winds overestimated onshore Ekman transport in winter and slightly underestimated it in summer. They also overestimated extreme events and missed short-term fluctuations. There are several possible reasons for differences between synoptically derived winds and observed winds. Mountainous terrain can steer and funnel winds or block them. Effects of coastal mountains have been observed up to 200 km offshore of the Icy Bay-Yakutat Bay region. The coastal mountains can also block the movement of storms, causing them to stagnate over the Gulf of Alaska for several days (Reynolds, 1978). The difference between air temperatures over land and sea can also influence coastal winds. Both seasonal (continentality) and daily (sea breeze) effects occur.

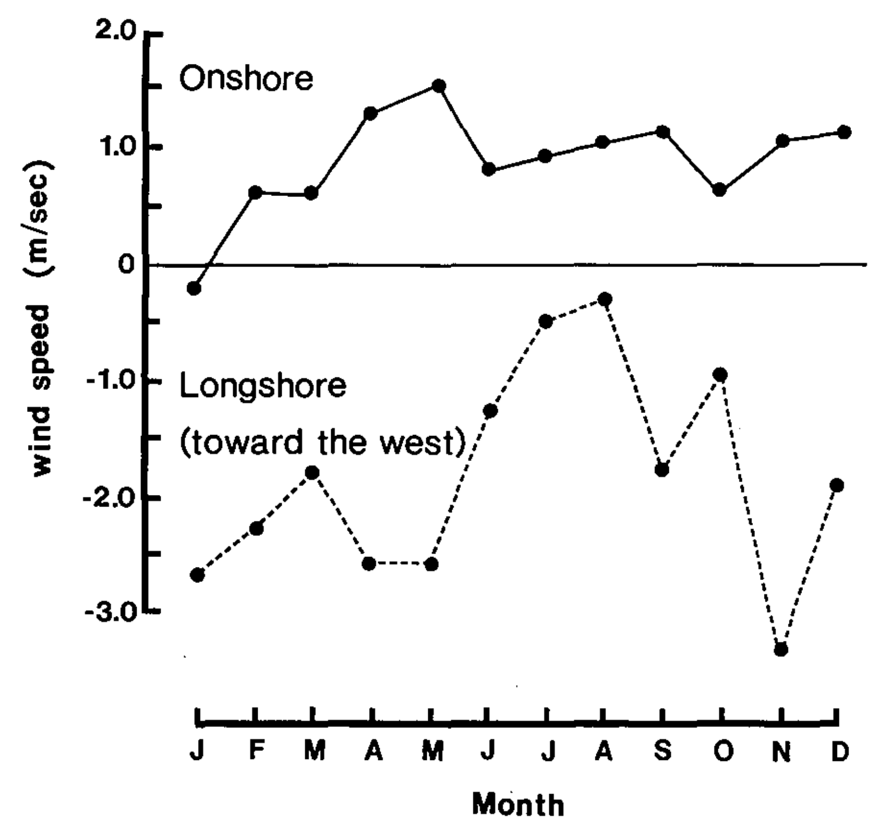


Figure 3.5 Middleton Island wind components, monthly means (from Royer, 1978a).

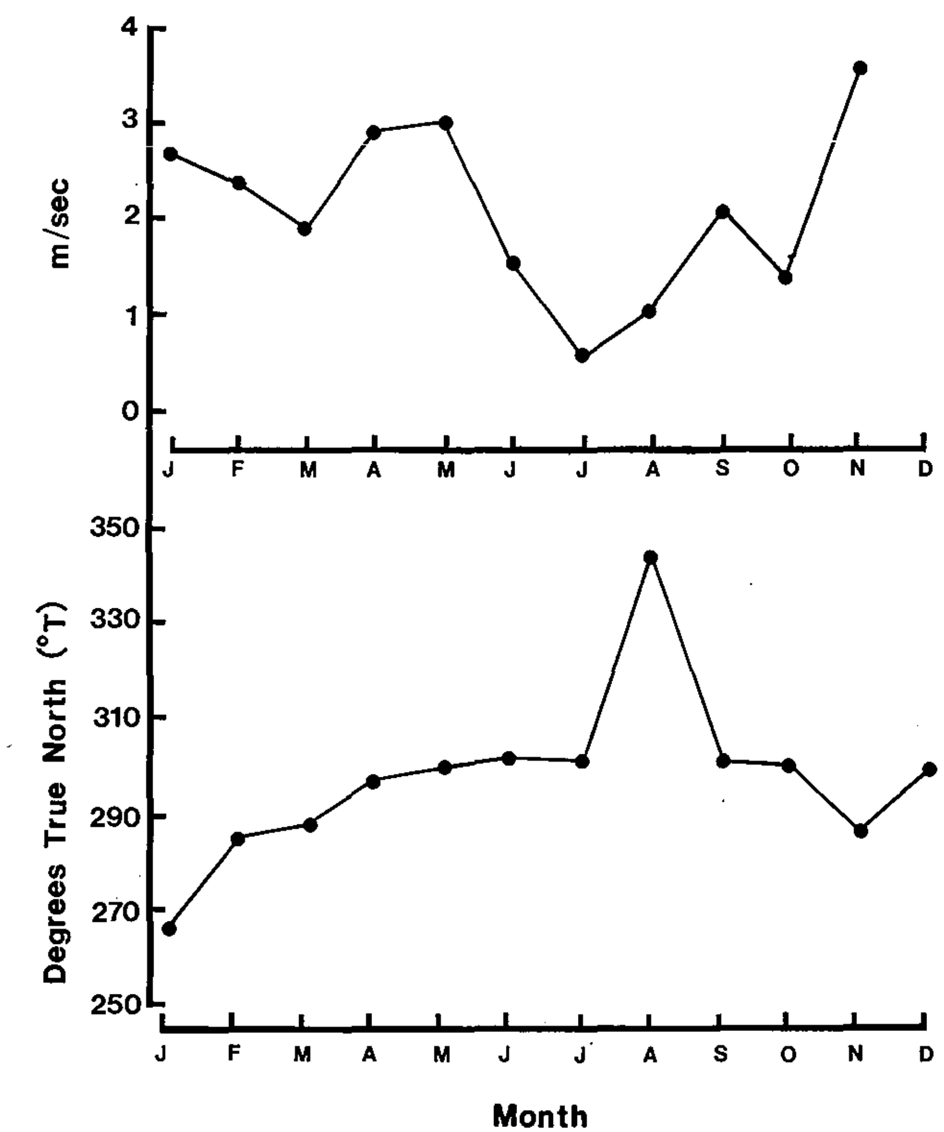


Figure 3.6 Speeds and directions for monthly mean wind data from Middleton Island (from Royer, 1978a).

Katabatic flows, especially in the Icy Bay-Yakutat Bay region, can dominate local wind fields and other processes along the coast of the Malaspina Glacier. These flows occur in winter and at night in summer as the stable boundary layer drains down mountains and glaciers. Katabatic jets form at the coast when these winds are focused by the topography (Reynolds, 1978). As katabatic winds flow over water, a large flux of sensible and latent heat (and water vapor) occurs. The progression of air temperatures can be seen in data (Fig. 3.7) taken from ship observations. (These data are probably biased by diurnal heating.) Air temperature nearest the coast was -2.2°C, and temperatures increased steadily offshore. The same data set shows a dramatic change in wind direction between stations 9 and 10. Winds at, and inshore of, station 9 are approximately northeasterly. Offshore of station 9 the winds shift to northwesterly.

Potential temperature profiles (Fig. 3.8) along the cruise track (shown by stations in Fig. 3.7) show that the katabatic wind is modified over water. The tongue of cold air is seen at low altitudes near the coast. The distinct temperature signal disappears away from the coast due to heat transfer from the ocean surface and possible entrainment of warmer surrounding air. The presence of a cold core of air at 1100 m between 25 and 30 km offshore has not been explained.

Profiles of temperature and wind (speed and direction) 9.6 km offshore (Fig. 3.9) give insight into the structure of the atmosphere. There is a shallow mixed layer (0-30 m) in the temperature data recorded during the descent of the instrument-equipped balloon. The change in wind direction at about 250 m indicates the demarcation between the katabatic tongue moving offshore and westerly winds of the synoptic field above it.

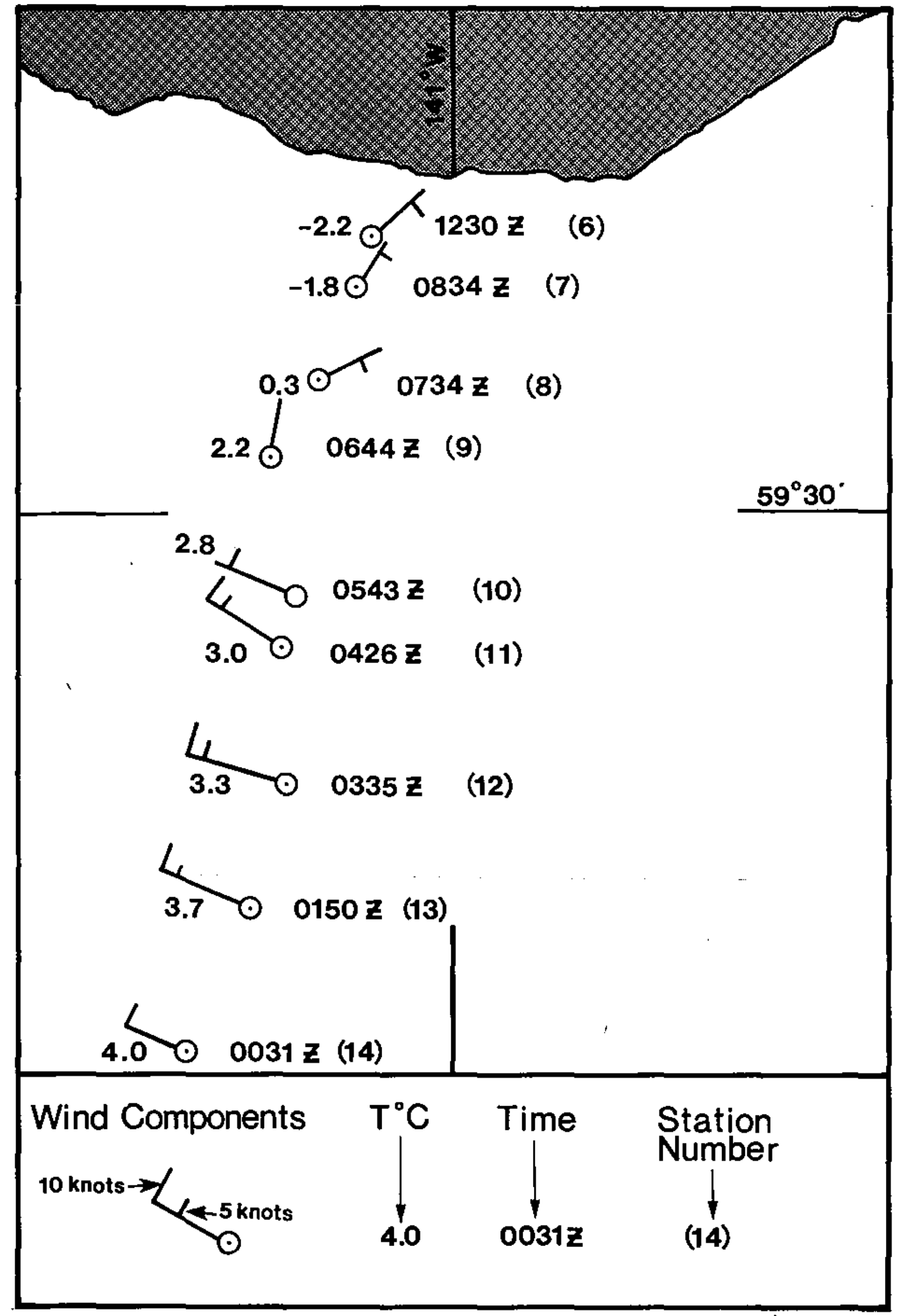


Figure 3.7 Meteorological surface observations for 9 March 1976. Wind banks represent 10 knots; temperature is in °C (from Reynolds, 1978).

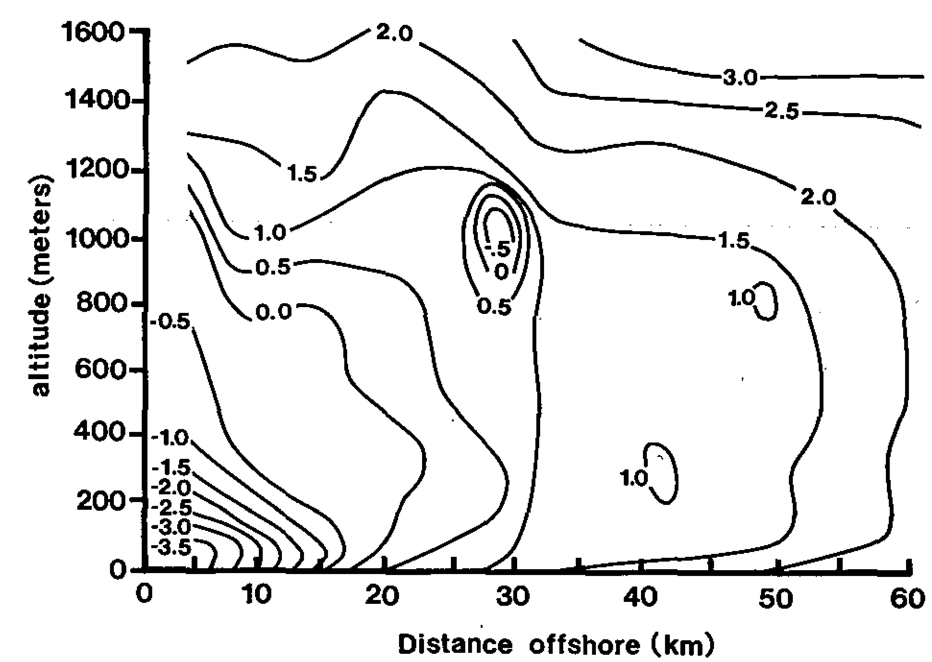


Figure 3.8 Contour plot of potential temperature along the cruise track (indicated by data points in Fig. 3.7) for 9 March 1976 (from Reynolds, 1978).

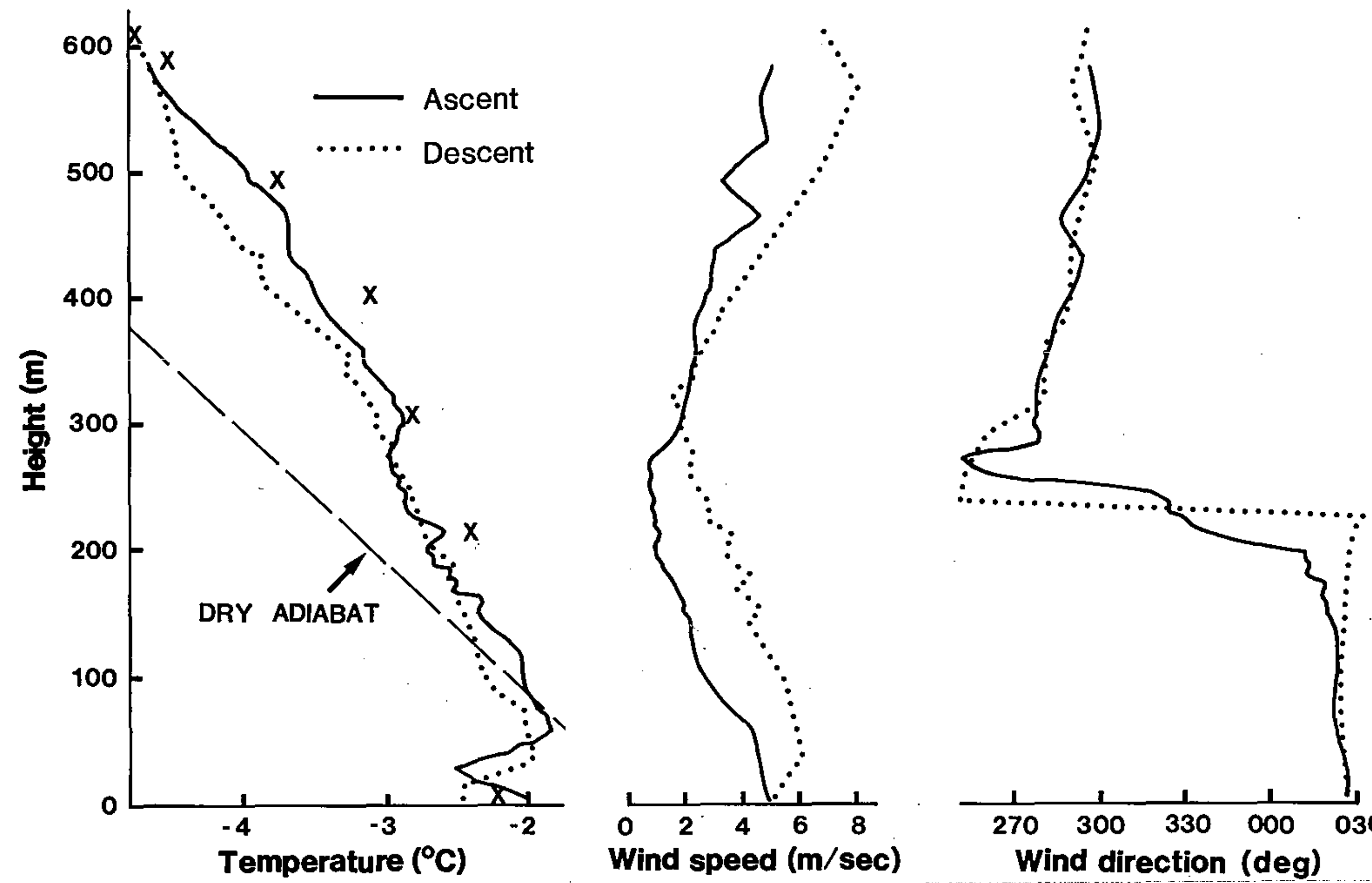


Figure 3.9 Profiles of temperature and wind from radiosonde (x), tethered balloon ascent (solid lines) and descent (dotted lines) taken at station 6 (see Fig. 3.7) (from Reynolds, 1978).

Wind direction changed from 060° to 240° over a distance of about 10 km. Temperature increased by almost 1°C and aircraft observers noticed an increase in turbulence. Subsequent analysis of satellite photographs revealed a thin cloud streak in this area. This area was probably a region of convergence between coastal winds (from the northeast) and offshore winds (from the southwest) (Reynolds, 1978).

Thus, as katabatic winds flow seaward from the coast they are warmed by convective heating from the sea surface below and are probably also warmed from above. The convectively mixed layer at the sea surface grows with distance offshore until the katabatic tongue has been warmed to the temperature of the air above it. Then rapid mixing occurs, and the wind direction shifts to align with the overlying synoptic winds. In the data presented here, this occurs about 24 km offshore. Thus, the direct influence on surface winds of katabatic flows appears to be limited to areas close to shore because convective mixing of heat occurs rapidly (Reynolds, 1978).

Observations of wind speed and direction (and other atmospheric parameters) were collected by Reynolds using an aircraft. An unexplained feature was observed. Over a distance of a few hundred meters along a track directed offshore of Yakutat, a sharp drop in windspeed (from 5 m/sec to 1 m/sec) occurred.

3.2.6 Precipitation and coastal runoff

Precipitation along the northern coast of the Gulf of Alaska is heavy (Table 3.1). Moist, marine air is advected across the gulf by the predominant climate patterns (see Fig. 3.3). Lows tend to stagnate in the gulf pumping marine air onshore. Coastal mountains increase rainfall at the coast due to orographic effects. Precipitation and snowfall are greater east of Prince William Sound, with maximum annual values (335 cm of precipitation and 579 cm of snowfall) occurring at Yakutat.

Table 3.1 Precipitation means and extremes for the Northern Gulf of Alaska (in cm) (Brower et al., 1977).

	Average annual precipitation	Average annual snowfall	Annual maximum snow depth
Yakutat	335	579	243
Yakataga	261	274	132
Cordova	226	330	251
Cape Hinchinbrook	239	241	145
Middleton Island	147	86	30
Kodiak Island	144	241	76

Snow depth is important since large quantities of fresh water are contained in the snow pack and the seasonal peaks in melt water do not coincide with the seasonal peaks in precipitation. Royer (1979a) showed that the annual temperature cycle for southeast Alaska reaches a maximum in midsummer. Peak runoff from snow melt would be expected to occur slightly after this temperature peak. Precipitation for southeast Alaska has an annual maximum in September-October (Fig. 3.10).

The significance of the difference in time between peaks in precipitation and snowmelt is that fresh water is supplied to the coast over an extended period. The discharge from coastal rivers is probably not as sharp a peak as it is for the Copper River (Fig. 3.11). The Copper River, one of Alaska's largest rivers, drains a large interior area and therefore is different from the smaller, coastal rivers. Resurrection River discharge peaks in September rather than in July, when the Copper River discharge is at a maximum (Royer, 1979a).

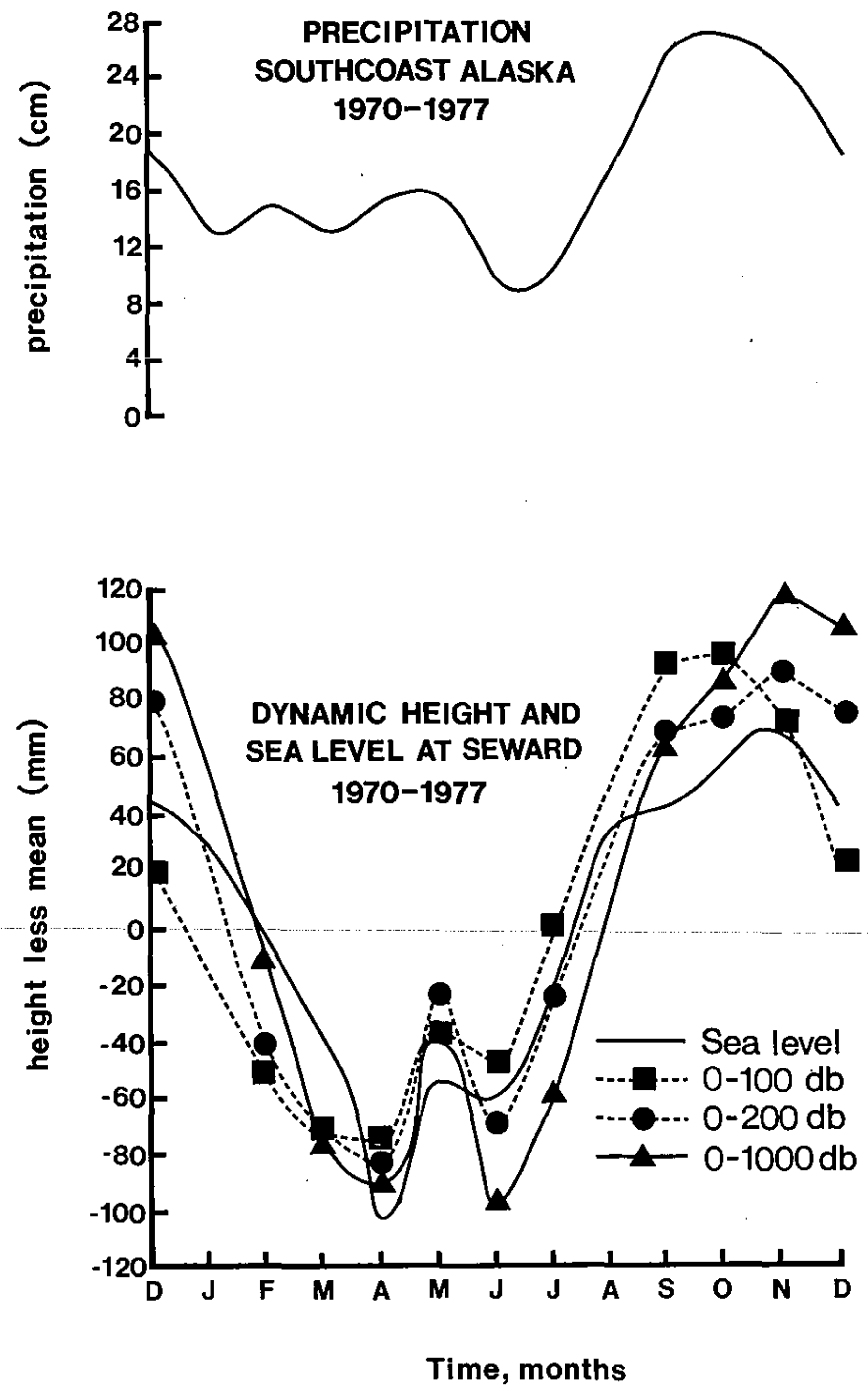


Figure 3.10 Sea level, dynamic height, and precipitation cycles for the south coast of Alaska (from Royer, 1978b).

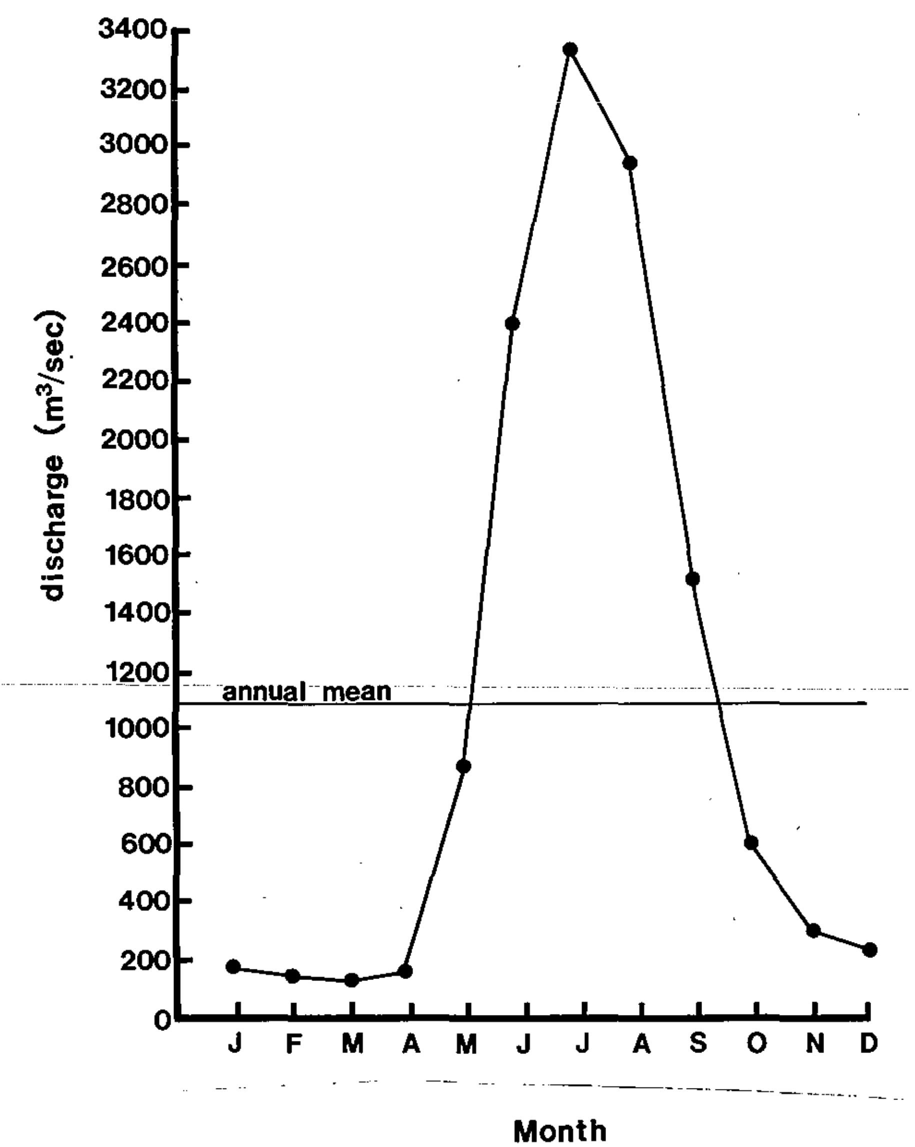


Figure 3.11 Mean monthly discharge of the Copper River near Chitina (from Roden, 1967).

The importance of freshwater discharge on coastal circulation has only recently been understood. Royer (1979a) found that the near-surface (0-200 db) dynamic topography is controlled to a large degree by the levels of precipitation and runoff at the coast. There are high correlations between sea level, dynamic heights near Seward, and precipitation from the south coast of Alaska. Correlation coefficients between precipitation and dynamic height (anomalies) are 0.84 (for 0-200 db) and 0.28 (for 200-1000 db). At Yakutat the correlation between the 0-200 db dynamic height and (southeast) precipitation is even larger (0.97). Thus the effects of freshwater influx on dynamic height are limited to near surface waters. The influx of fresh water along the coast creates a cross-shelf pressure gradient, manifested in dynamic heights, that is in balance with baroclinic geostrophic currents. Thus it appears that coastal freshwater influx drives the coastal current.

Further investigation of this cause and effect has shown that local precipitation alone cannot account for the large increase in near-surface dynamic height anomalies and sea level from September through November. About 5 m of precipitation would be needed along the coast to cause the seasonal increase in dynamic height. When meltwater runoff is included in the calculations, however, enough fresh water is available to account for the dynamic height increase in autumn. Thus, it appears that the seasonal melting of the snow pack combined with the seasonal increase in precipitation account for the increased dynamic heights near shore (Royer, 1979a).

There is a strong correlation (0.84) between the upwelling index (used here as a measure of the wind field) and the deep (100-1000 db) dynamic height anomalies. No correlation (0.05) exists with the near surface (0-100 db) dynamic height anomalies and upwelling indices.

The near-surface dynamic heights are predominantly controlled by precipitation, while the dynamic heights at lower levels are predominantly controlled by the wind. Wind driving of deeper waters occurs through the near-surface waters, but apparently the coastal influx of fresh water is such a strong driving force that it masks seasonal wind effects.

Royer (1979a) lists causes for the strong dependence of dynamic height on the salinity of coastal waters (and thus on the levels of freshwater drainage). The first has been discussed already: the high levels of precipitation and runoff along the south coast of Alaska. It appears that this fresh water accumulates along the shelf, thus having a greater effect than if it were quickly advected away. At the low temperatures usually encountered in the Gulf of Alaska, variations in salinity are the dominant factor in determining variations in density. For example, in the upper 100 m of water the annual variation in salinity can account for 74 percent of the annual variation in density (Royer, 1979a).

As seen in Fig. 3.10, the seasonal cycle of sea level at Seward is similar to that of precipitation and nearshore dynamic heights. The correlation between sea level and the 0-200 db dynamic height is 0.93. Also the annual range in the 0-200 db dynamic height can account for 172 mm of the 174 mm annual range in sea level. Royer (1979a) found that offshore, deeper (0-1000 db) variations in dynamic height had little influence on coastal dynamics. Thus, seasonal variations in sea level can be accounted for by considering changes in local steric properties (temperature and salinity). This implies that seasonal barotropic variations on the shelf are small and that steric changes in deeper water are not important on the shelf.

At Yakutat variations in precipitation largely account for variations in near-surface dynamic heights and coastal sea level. However, the correlation between sea level and 0-200 db dynamic height is not as strong here (0.59) as at Seward (0.93). The correlation between deeper dynamic heights (200-1000 db) is stronger at Yakutat (0.48) than at Seward (0.13). Steric changes in offshore water may play a larger part in the coastal dyanmics at Yakutat than at Seward.

Winds also play a larger role in determining annual variations in sea level at Yakutat than at Seward. The correlation coefficients between sea level at the two locations and the upwelling index (at 60°N, 146°W) are -0.71 and -0.39.

Royer (1979a) suggests that the differences between these two locations are due to the difference in width of the shelf and the difference in available quantities of runoff. The shelf is narrower at Yakutat, and fresh water may escape seaward rather than being confined to the shelf. Also, between Seward and Yakutat there are several large sources of fresh water that can influence coastal dynamics at Seward but not at Yakutat. Therefore, the effects of precipitation and runoff are less important at Yakutat, and other processes (e.g., wind driving) may be more important in controlling coastal dynamics.

The coastal influx of fresh water and its influence on nearshore dynamics are important because they set up a coastal current. Pollutants that enter the coastal zone will be advected quickly to the west, along the coast. The coastal current generated by the influx of fresh water probably varies seasonally, with maxima in October (Fig. 3.10). Speed in the coastal current is estimated to be about 40 cm/sec (see Section 3.4).

3.2.7 Sea ice

Sea ice can form in the partially enclosed coastal basins along NEGOA. It is typically found in Prince William Sound from December through April. Its area is at a maximum in March, when the ice sometimes extends past the islands bordering the mouth of Prince William Sound (Brower et al., 1977).

The heavy winter precipitation along the coast probably contributes greatly to the thickness of sea ice. Snow overlying ice can melt and later refreeze or can be infiltrated by sea or fresh water and then freeze.

Sea ice undoubtedly plays a major role in the seasonal dynamics of any bay that it covers. It acts as an insulator, blocking exchanges of sensible and latent heat between the water and atmosphere. However, sea ice exerts little control on circulation, except in embayments where it is widespread.

Sea ice is important when spilled oil or other pollutants are present because oil can be incorporated into ice until ice breakup. It is difficult to locate and clean up oil incorporated into or covered by ice.

In addition to sea ice, glacial ice is formed in NEGOA. Several coastal glaciers calve into the gulf (see Brower et al., 1977 for locations). The bergy bits from these glaciers probably have minimal impact on the environment. Though their melting can create convection plumes and mixing, these effects are probably of little consequence. Ice is usually not a hindrance to navigation.

3.3 CIRCULATION DETERMINED BY INDIRECT MEANS

3.3.1 Distributions of temperature, salinity, and suspended matter

Profiles of temperature, salinity, and density are shown in Figs 3.12-3.14 for three stations off Yakutat in July 1974. The first station (Fig. 3.12) was about 120 km south of Montague Island in 1400 m of water. The temperature profile has a near-surface thermocline which is seasonal; in winter this upper layer is nearly isothermal. A temperature minimum exists at about 75 m. This feature represents the minimum temperatures for the upper water column during the previous winter and spring. Mixing in winter extends the surface low temperatures to this depth (Royer, 1976), and seasonal surface heating and cooling do not penetrate this deeply (Royer, 1978b). Below the zone of minimum temperatures there is a region of maximum temperatures. Typically this region extends from 130 to 170 m; it is associated with the Alaska Current. The temperature at 150 m (the temperature maximum) is 0.85°C higher than at 75 m (the minimum).

Salinity varies in the near-surface layer, but there is only a slight gradient. Below the depth associated with the temperature minimum (75 m), a halocline (a sharp decrease in salinity with increasing depth) exists and extends down to the depth of the temperature maximum. In some data sets (but not in Figure 3.12; see Galt and Royer, 1975) a maximum in salinity is associated with the maximum in temperature. Royer (1976) believes that water at these depths forms near the subarctic convergence between 38° and 42° N latitude. Hayes and Schumacher (1976a) state that the permanent halocline associated with the Alaska gyre occurs at about 150 m. Below the temperature maximum

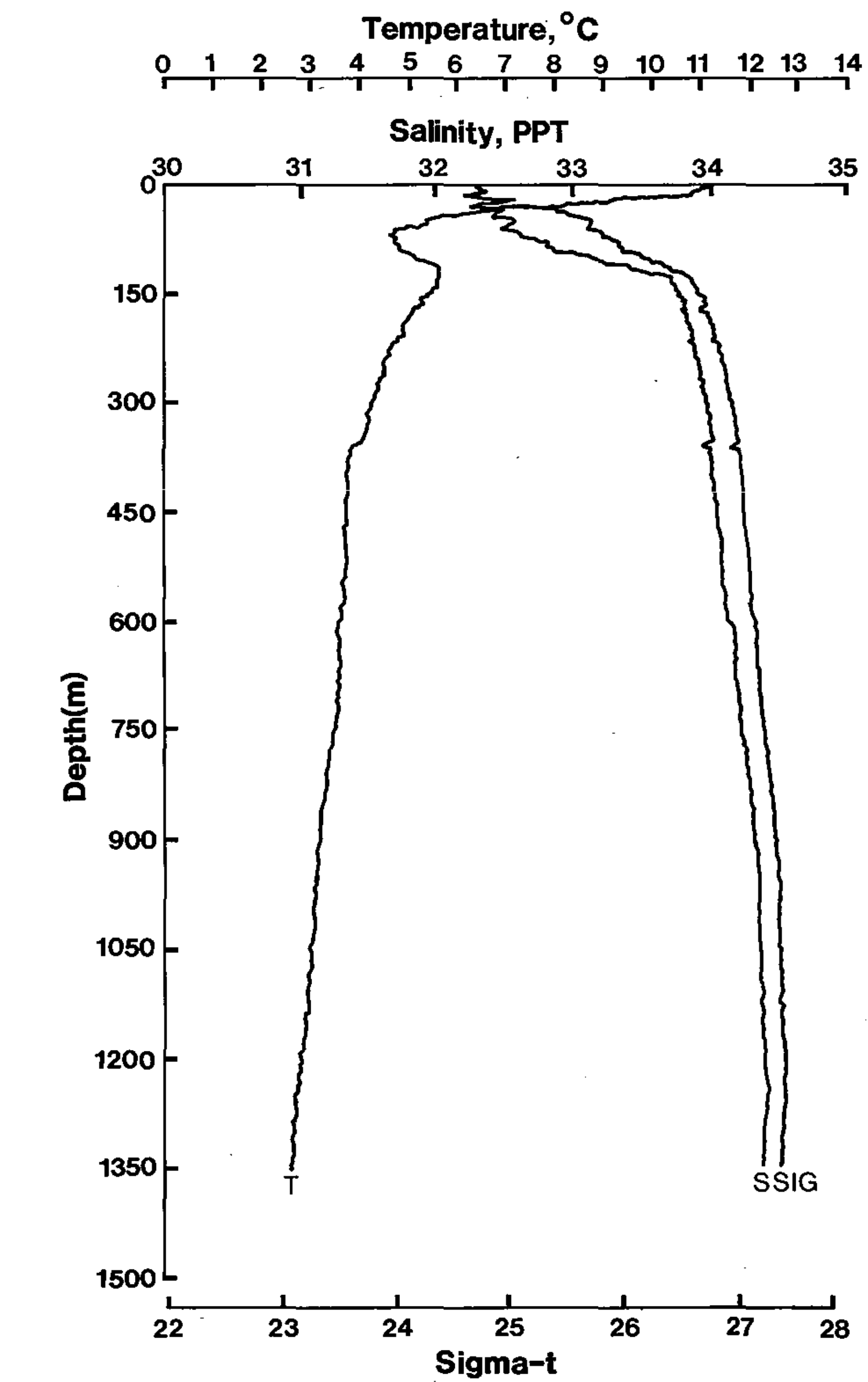


Figure 3.12 Offshore temperature, salinity, and sigma-t versus depth at 58°31'N, 148°15'W in July 1974 (from Royer, 1978a).

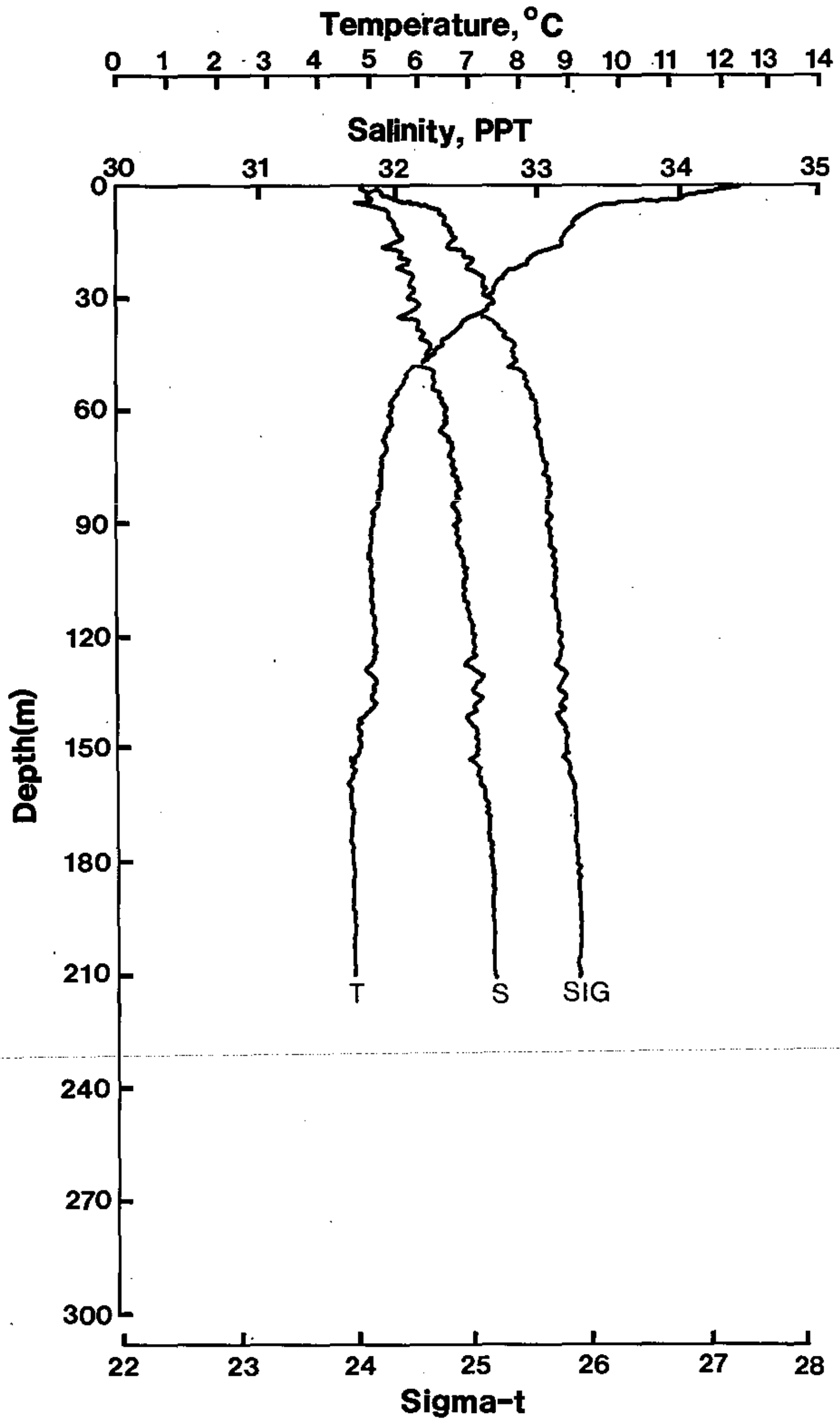


Figure 3.13 Midshelf temperature, salinity, and sigma-t versus depth at 59°33'N in July 1974 (from Royer, 1978a).

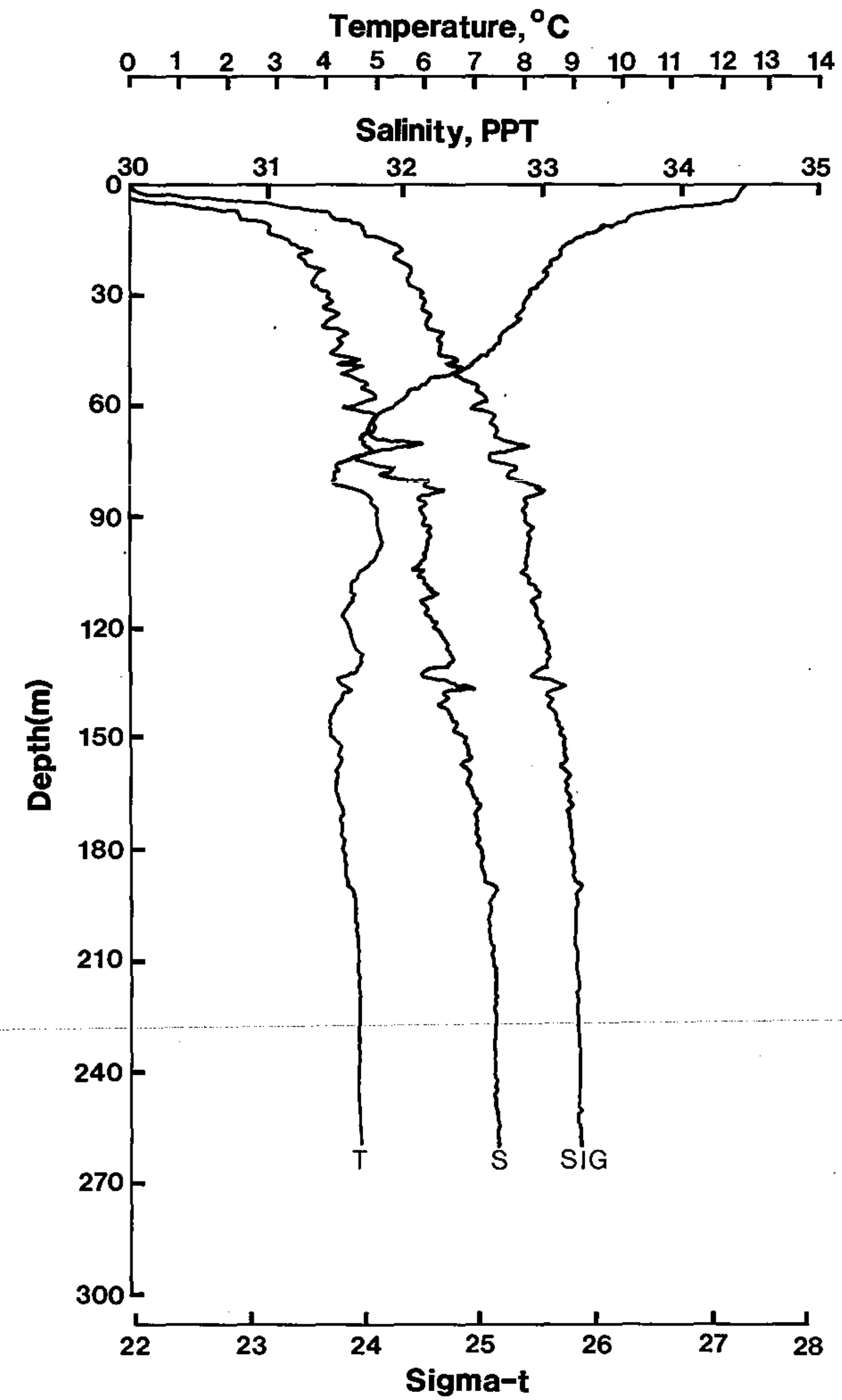


Figure 3.14 Coastal temperature, salinity, and sigma-t versus depth at 59°33'N, 149°31'W in July 1974 (from Royer, 1978a).

and the halocline, or the salinity maximum if it is present, temperature decreases and salinity increases with depth. The σ_t (density) profile is very similar to the salinity profile; in this region salinity variations largely control density variations, due to the low water temperature.

Favorite and Ingraham (1977) describe a band of minimum salinities (<32.5 $^{o}/oo$) on the surface, parallel to the shelf break off Kodiak Island. This band of minimum salinity extends throughout the Gulf of Alaska (Ingraham, 1979). It separates offshore of Cape Fairweather (at 58°30'N, 138°30'W) into coastal and offshore branches (Ingraham, 1979).

Over the mid-shelf region (bottom depth 220 m) the surface temperatures are about 1.4°C warmer and the surface salinities are about 0.5 $^{o}/oo$ lower than farther offshore (Fig. 3.13). The lower salinity reflects coastal dilution. A thermocline (a rapid decrease in temperature with increasing depth) extends from the surface down to about 60 m; below this depth, down to 10 m from the bottom there are no large variations. There is no temperature maximum between 130 and 170 m, which could be caused by the Alaska Current. The salinity profile has a similar lack of features; salinity gradually increases with depth.

In winter the temperature profile over the continental shelf is quite different. The upper 80 to 100 m is nearly isothermal; isotherms are almost vertical in this layer, with coldest waters (2.0°C) near shore. Below the isothermal layer temperature increases with increasing depth (Royer, 1975).

Whereas the vertical gradient of temperature changes sign on a seasonal cycle (coldest at the surface in winter, warmest at the surface in summer), the vertical salinity gradient is almost positive (salinity increases with depth). Since changes in salinity are the predominant cause of changes in density, a positive salinity gradient ensures static stability. The upper 100 m or so are almost isohaline in winter. This is due to the decreased coastal influx of fresh water and strong downwelling winds. The lack of stratification allows winter mixing (due to tides and winds) to greater depths over the shelf than farther offshore. This could permit mixture of neutrally buoyant pollutants into the upper 100 m of the water column.

Compared to winter salinity profiles, summer profiles have lower surface salinity and higher (0.5 $^o/oo$) bottom salinity (Royer, 1975). Royer (1975) suggests that the surface decrease in salinity is due to the seasonal influx of fresh water at the coast. Salinities as low as 25 $^o/oo$ can be found in the top few meters near the coast. The increased bottom salinity, on the other hand, may be caused by upwelling favorable winds (or greatly reduced downwelling favorable winds). An onshore flow of saline water is required to balance an offshore flow of surface water due to upwelling winds.

The third station (Fig. 3.14) lies south of Cape Resurrection, close to shore, in 263 m of water. The surface salinity is quite low (28.5 $^o/oo$), which reflects the influence of freshwater runoff. The effects of coastal freshening extend down to about 100 m. A thermocline extends from the surface down to about 60 m. Immediately below this is a relative temperature maximum which is about 1°C warmer than the water above it.

Although the vertical salinity gradient on the shelf is positive (salinity increases with depth) in both summer and winter, it is larger in summer (Fig. 3.15). Since salinity is more important than temperature in determining density variations in the Gulf of Alaska, the σ_t profiles are similar to those of salinity.

The vertical gradient of temperature on the shelf is positive in winter with an isothermal layer near the bottom (Fig. 3.15). During summer the vertical temperature gradient on the shelf is negative as the surface waters warm. Bottom temperatures are slightly cooler in summer than in winter (Royer, 1975). This could be caused by downwelling, which occurs throughout the winter, and neutral or slight upwelling conditions, which occur in the summer.

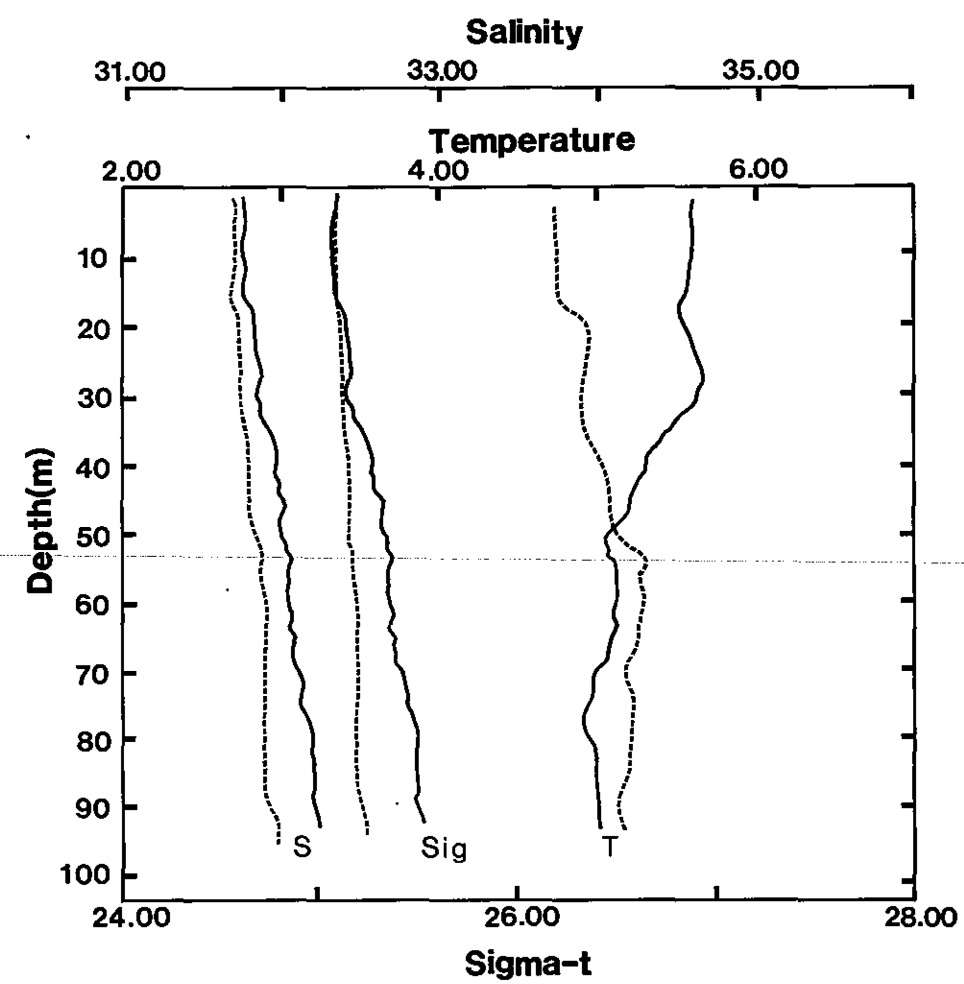


Figure 3.15 Vertical profiles of temperature, salinity, and sigma-t during February (dashed lines) and May (solid lines) at a station on the 100-m isobath off Icy Bay (from Hayes and Schumacher, 1976b).

Surface temperatures on the shelf vary seasonally from 12°C in midsummer to 2° in late winter (Fig. 3.16). Seasonal changes extend down as far as 120 m. Using remote sensing, Royer and Muench (1977) mapped seasonal and spatial changes in sea surface temperatures. In both summer and winter, surface temperatures were lower seaward of the shelf break than those on the shelf. Both regions became cooler in winter, Temperature ranges (from Royer and Muench, 1977) are:

	Shelf	Slope
Winter	3-4° C	1-3° C
Summer	11-15° C	7-11° C

When surface temperature maxima occur in August and September, salinity minima occur at the surface (Fig. 3.16). The salinity minimum can be correlated with the influx of fresh water at the coast. The mean monthly discharge from the Copper River (Fig. 3.11) peaks sharply in summer, with a maximum in July. This peak is caused by snow melt (Muench et al., 1978). Resurrection River has its maximum discharge between May and October and it peaks in September (R. Carlson, 1977). (See Roden, 1967, for hydrological data on rivers that empty into the Gulf of Alaska).

The horizontal gradient of salinity southward from the coast is always positive, that is, fresher waters are always found near the coast. In winter the surface salinity increase seaward from 32 $^o/oo$ at the coast to 32.7 $^o/oo$ above the 2000-m isobath. Coastal salinities are as low as 25 $^o/oo$ in summer due to the addition of fresh water (Royer, 1975).

The increase in bottom salinity in summer (Fig. 3.16) may be related to meteorological conditions. In summer the upwelling index (Fig. 3.1) is nearly zero, but it is strongly negative (indicating downwelling) during the winter. The strength and timing of this annual minimum varies from year to year, but high bottom salinity values coincide with positive values of the upwelling index (Fig. 3.17).

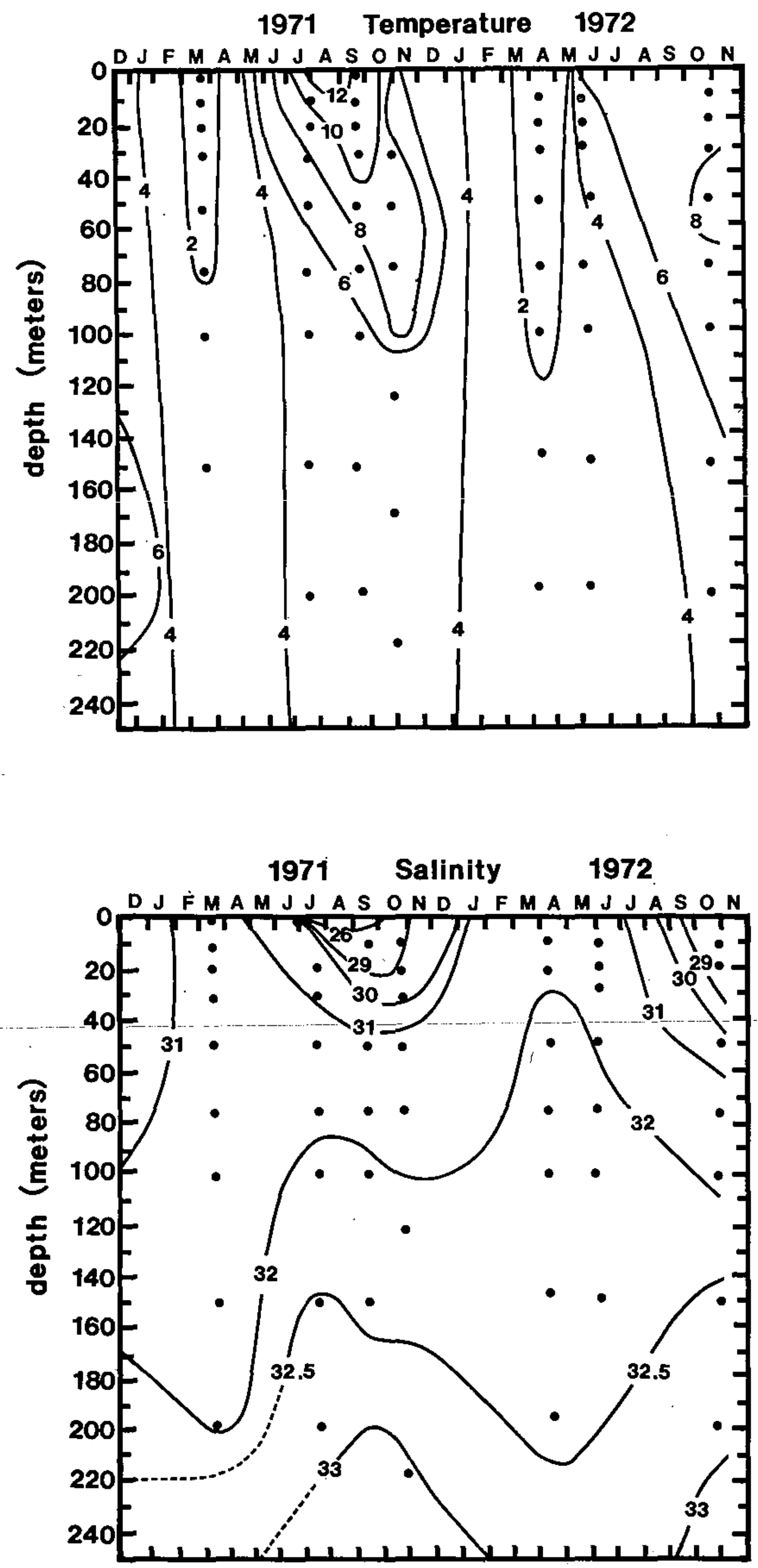


Figure 3.16 Time series of temperature and salinity taken between December 1970 and October 1972, southwest of Resurrection Bay (from Royer, 1975).

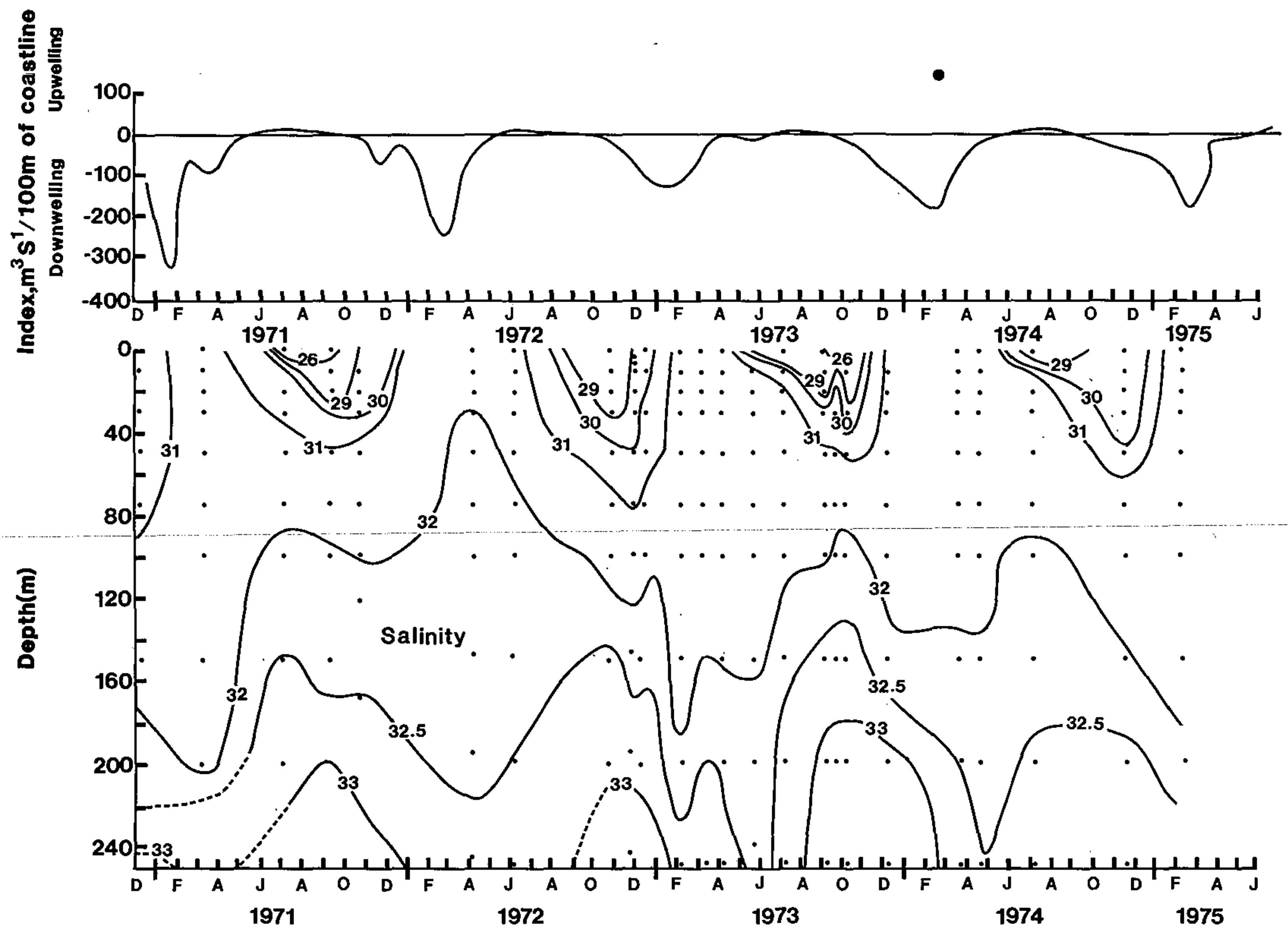


Figure 3.17 Monthly mean coastal upwelling index at 60°N, 149°W (above) and salinity profiles for the most inshore hydrographic station along the Seward Line (below) (from Galt and Royer, 1975).

The relaxation of downwelling in summer allows surface processes (heating and the influx of fresh water) to stratify the water column; hence vertical shears develop. Positive values of the upwelling index can drive surface waters offshore, requiring subsurface replacement (by mass balance). The result is a decrease in bottom temperatures.

Feely et al. (1979) present vertical cross sections of temperature, salinity, density (σ_t), and suspended particulate matter (nephelometer data). These data were collected along a hydrographic line that extends southward from the Copper River Delta.

In April, isolines of temperature, salinity, and density (Fig. 3.18) are nearly vertical over the shelf. Cold (3.8°C), low-salinity (31.8 ^{o}/oo) water is found inshore; temperature and salinity increase seaward. The distribution of suspended matter shows the absence of stratification: there is almost no vertical gradient of suspended matter.

The shelf is vertically stratified in July. Warm (13°C), low-salinity (29.5 ^{o}/oo) water is found at the surface. The influx of fresh water at the coast appears to be the cause of the layer of low salinity over the shelf. The distribution of suspended matter reflects the strong stratification.

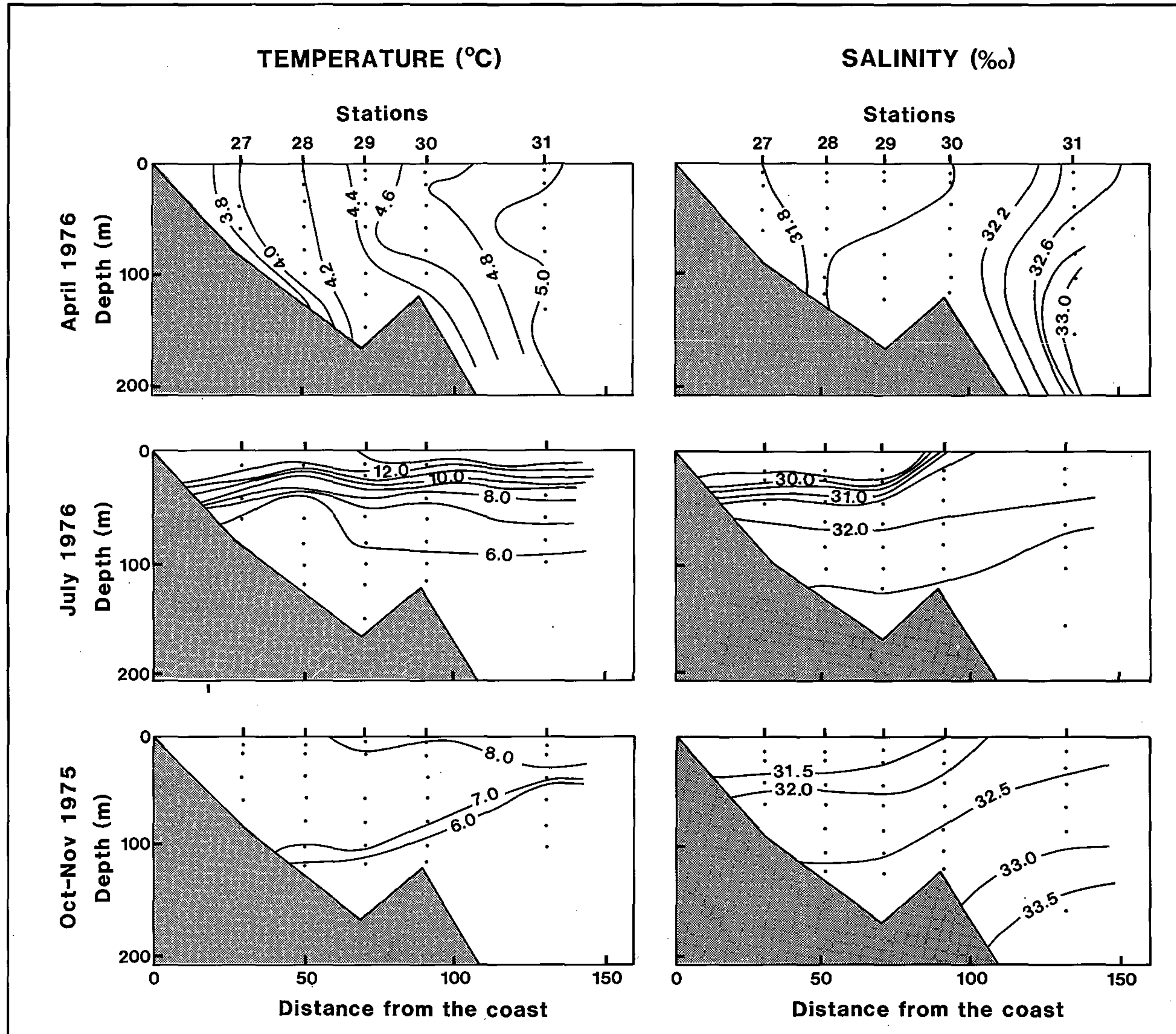
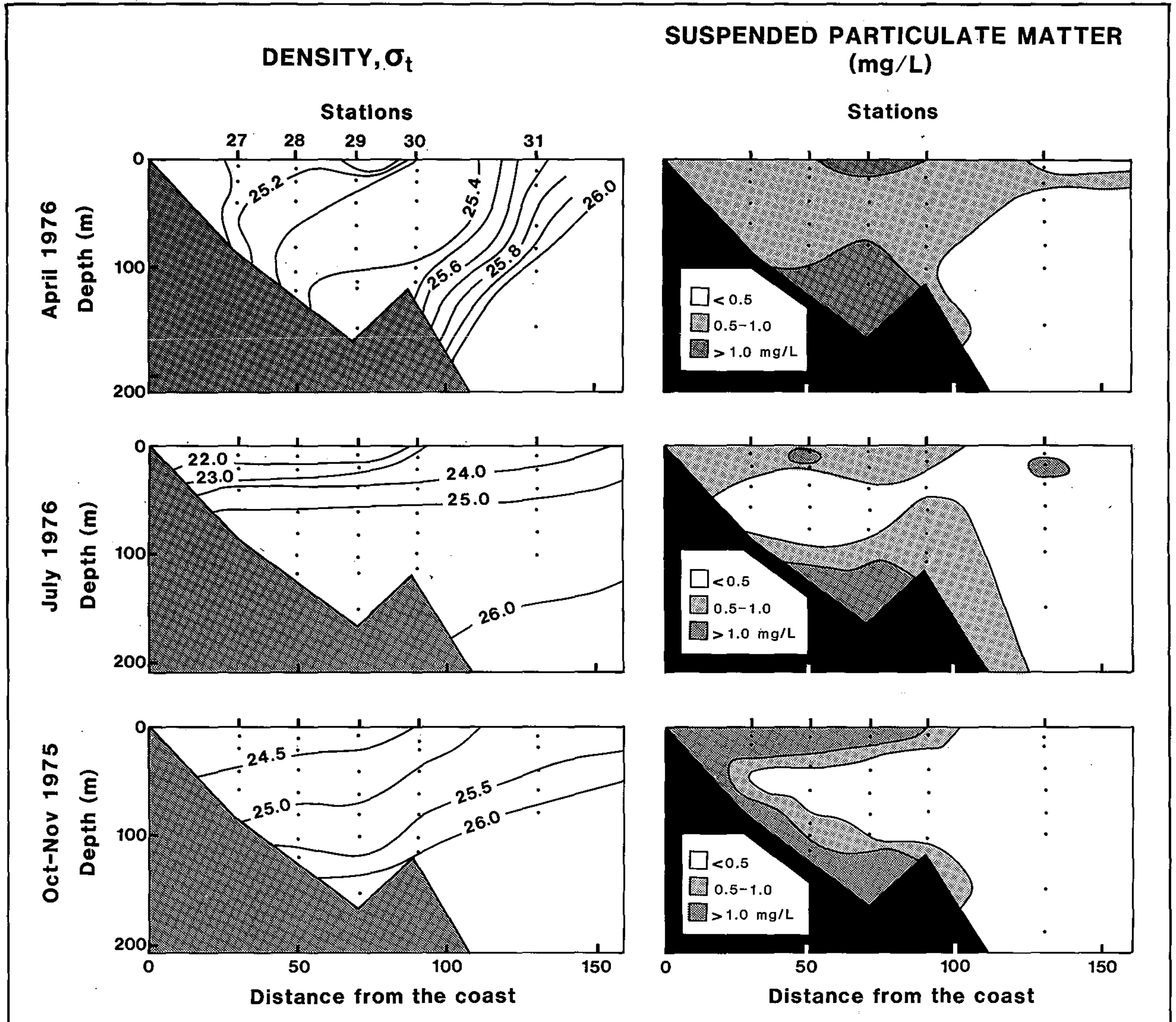


Figure 3.18 Cross-sectional distribution of temperature, salinity, density, and suspended particulate matter observed along cross-shelf survey line off the Copper River Delta (Feely et al., 1979).



In October-November 1975 the vertical stratification was reduced. The apparent causes of this reduction were surface cooling and decreased influx of fresh water. High concentrations of suspended matter occurred in the upper 25 m and within 20-30 m of the bottom. A current meter (number 61) located southwest of Kayak Island and inshore of the 200 m isobath had consistent offshore flow (see Fig. 13, Feely et al., 1979). The authors speculate that winter cooling over the broad, shallow area west of Kayak Island produces a bottom offshore convective flow. The near-bottom nepheloid layer extended beyond the shelf break; thus sediments from the shelf were probably distributed to the deeper waters of the Gulf of Alaska.

These data suggest that the seasonally changing density field controls the vertical distribution of suspended matter. Convection and mixing in the vertical are suppressed by a strong density stratification (Feely et al., 1979). High concentrations of suspended matter at the surface probably are associated with the influx of fresh water at the coast. High values along the bottom could be due either to resuspension of bottom sediments by currents or to seaward flows along the bottom of waters laden with suspended sediment.

Distribution of suspended matter is important as an indicator of physical processes on the shelf. Suspended matter can be important as a flocculating agent in the presence of petroleum pollution. Formation of oil-particle flocculants is an important process in the removal of oil from the water column (Payne and Jordan, 1979).

3.3.2 Geostrophic circulation

Introduction

Currents in the ocean are subject to the apparent forces caused by the earth's rotation. These forces can be balanced by pressure gradient forces. When this balance occurs, flow is perpendicular and to the right of the pressure gradient (in the Northern Hemisphere). Such flows are called geostrophic flows.

There are two types of geostrophic flows. Baroclinic flows are caused by the distribution of mass within the ocean. Because baroclinic geostrophic flows depend on spatial differences in density, these flows can be estimated from a knowledge of the density field. Density data integrated over part of a water column are often represented as dynamic heights. From this representation we can infer the baroclinic flow at one pressure level relative to the flow at another level.

The second type of geostrophic flow, barotropic flow, is related to a tilting of the sea surface (or any other surface of constant pressure). Barotropic flows, unlike baroclinic flows, are not a function of depth and cannot be influenced by the spatial distribution of density.

The geostrophic flow at any location is the sum of the baroclinic and barotropic components. There also may be non-geostrophic current components. Thus, while the density field can give us a good idea of baroclinic geostrophic currents, it may not be a good representation of the total current, which is a sum of many components.

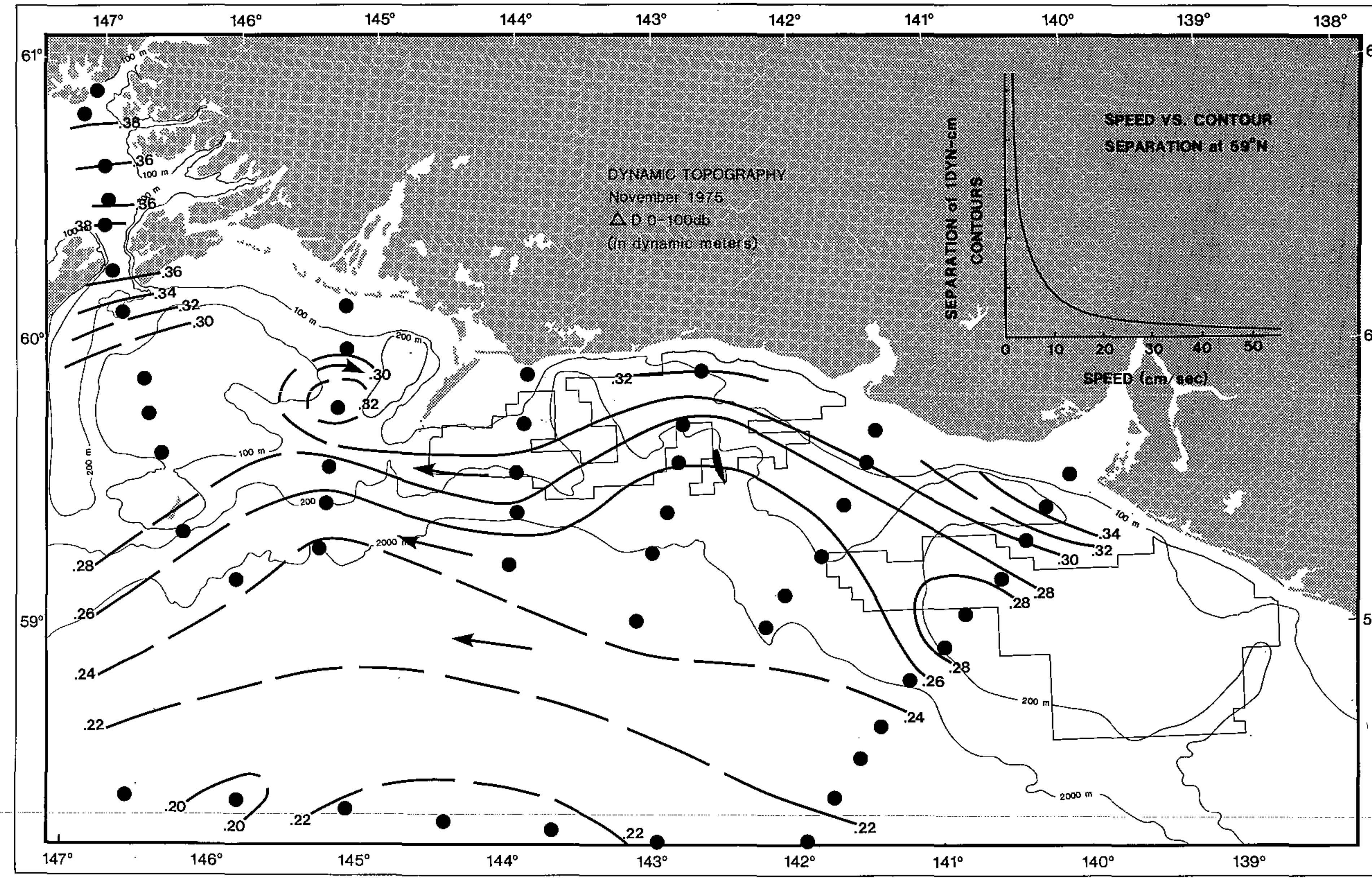


Figure 3.19 Dynamic topography for November 1975 (from Royer, 1977).

Dynamic topographies

The baroclinic geostrophic circulation is parallel to the contours of dynamic height. Speed is inversely proportional to contour spacing. In the data presented here (Figs. 3.19 and 3.20) the speed of surface flow relative to 1,000 db can be found by measuring the contour spacing and reading the speed from the graph inset on each figure. The direction of surface flow is to the right of the local gradient that points from higher dynamic height values to lower ones.

The dynamic topography for November 1975 (Fig. 3.19) is generally aligned with the bathymetry. High values near the coast are the result of heavy precipitation and runoff in autumn. Increased baroclinic flow (to the west) accompanies the higher dynamic height anomalies near the coast. In Prince William Sound, as one progresses northward into the sound, the dynamic height anomalies increase. There is evidence of a clockwise eddy west of Kayak Island. Royer (1978b) states that eddies in this region are driven by salinity. It appears that the coastal flow is guided offshore by Kayak Island. Some of the low-salinity, low-density water from this flow is incorporated into the eddy west of Kayak Island. During periods when the influx of fresh water at the coast is low, the dynamic topography west of Kayak Island has little variation. (See topography for February 1976 in Royer, 1977.)

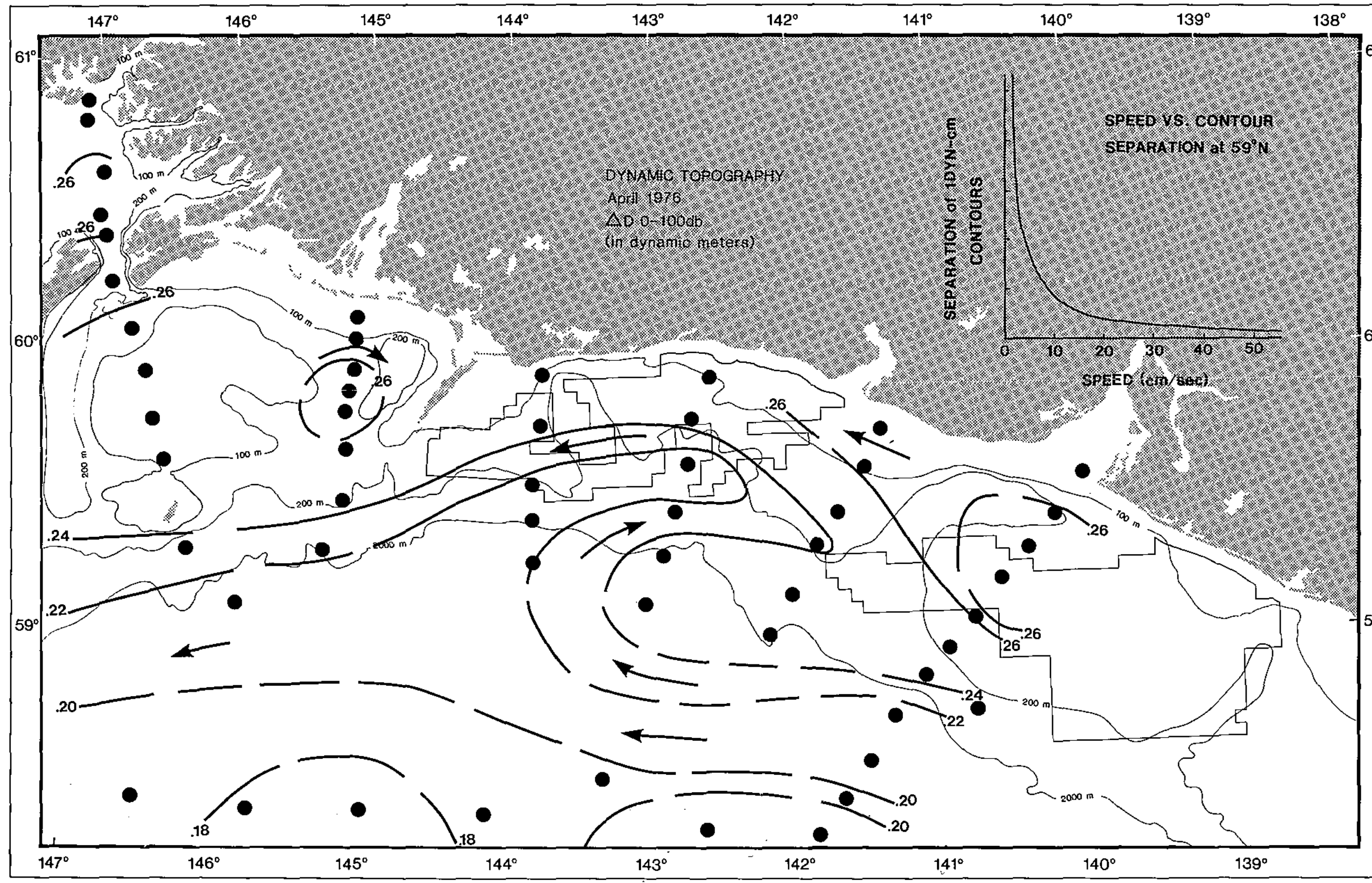


Figure 3.20 Dynamic topography for April 1976 (from Royer, 1977).

The dynamic heights measured in Hinchinbrook Entrance probably do not reflect baroclinic geostrophic flow, as the geostrophic assumptions are not met here. The values indicate that less dense waters are present in the entrance. (In the entrance the water is not sufficiently deep to allow a 1,000-db surface to be reached. The dynamic height from a level near the bottom to the surface is added to an estimate of what might be expected for the dynamic height between the 1,000-db level and the near-bottom level in Hinchinbrook Entrance.)

In April 1976 (Fig. 3.20) the topography is slightly smoother than in November. The April cruise occurred before the maximum seasonal runoff of meltwater (see Fig. 3.11). West of Kayak Island there appears to be an eddy. East of Kayak Island is a large perturbation in the dynamic topography. Large-scale perturbations in dynamic topography are commonly seen in dynamic topographies of the continental shelf.

The general circulation inferred from these dynamic topographies is toward the west. The contours generally parallel isobaths; however, large perturbations can occur (e.g., Fig. 3.20). Seasonal variations coincide with the seasonal variation in influx of fresh water at the coast. The findings of Royer (1979a), that runoff and precipitation cause seasonal changes in steric height over the continental shelf, support this observation. Another reflection of the seasonal changes in the influx of fresh water may be the strength of the baroclinic eddy west of Kayak Island. In the data presented here it is strongest in November; this closely follows the expected peaks in coastal river discharge. This eddy is a ubiquitous feature of the NEGOA circulation and will be discussed further in Section 3.4.1 (Lagrangian descriptions).

Seasonal variations in transport along the Seward line

Royer (1978a) gives the seasonal transport (0-100 db) computed between adjacent stations along the Seward hydrographic line (Fig. 3.21). As one moves offshore both the amplitude and the phase of the annual signals change. Royer (1978a) describes the various signals in terms of the forces which drive them.

The transport computed farthest inshore reflects the presence of a baroclinic coastal jet. High values of transport and large annual variation in transport are associated with the jet, which is estimated to be about 30 km wide. The maximum transport occurs in January, the same period for which upwelling indices are at their annual minimum (Fig. 3.1). The strong downwelling tendency leads to a positive set-up at the coast and compensation of the density field results in a baroclinic jet.

However, more recently, Royer (1979a) has shown that seasonal changes in near-surface (0-200 m) heights are well correlated (0.84) with the seasonal fluctuation in the influx of fresh water (see Fig. 3.10) and only weakly correlated (-0.19) with the upwelling index. Thus, the seasonal high values of transport observed at the inshore stations are probably due to the influx of fresh water along the coast. The lag between precipitation maxima and the maximum in transport observed off Seward is consistent with the time required to advect the fresh water from the eastern gulf. The seasonal change in transport probably reflects the cumulative influence of fresh water throughout the Gulf of Alaska east of Seward.

The next region offshore has weaker transport and smaller annual variation, with maximum transport in October and November. This maximum coincides with, and may be caused by, the precipitation maximum.

The region between stations 6 and 8 may be influenced by the coastal jet. Kayak Island apparently deflects the coastal jet offshore. On the inshore side of the deflected jet the near-surface baroclinic currents tend to be eastward, while those on the offshore side tend to be westward. The phase of annual transport between station 7 and 8 is similar to that between stations 1 and 2; in both regions the effects of the coastal jet occur.

Farther offshore the transport has a very weak annual signal, but the transport values have large standard deviations. Royer (1978a) calls this the "eddy infested" region. The eddies are cyclonic and about 70-100 km in diameter.

The Alaska Current dominates the region farthest offshore. It has a large seasonal signal and a large mean. The cause of the seasonal signal could be shifting of the axis of the Alaska Current onshore, or it could be related to the seasonal signal of wind speeds over the Gulf of Alaska. Note that these transports were calculated for a shallow level (0/100 db) which does not reflect the total transport of the Alaska Current.

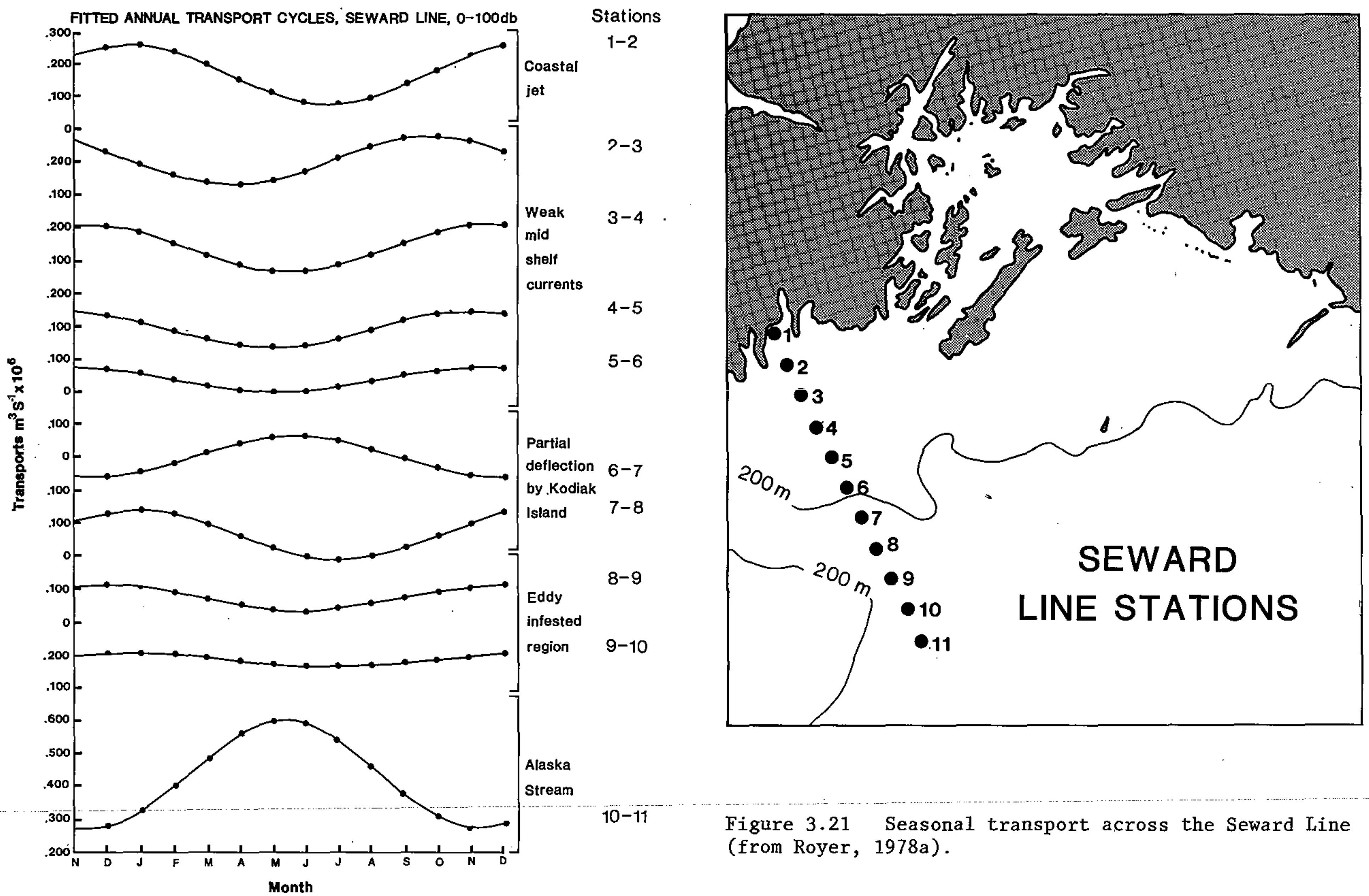


Figure 3.21 Seasonal transport across the Seward Line (from Royer, 1978a).

Transport of the Alaska Current

Royer (1979c) reports estimates of the transport for the Alaska Current. These estimates are based on several data sets taken from 1974-1977. The annual mean transport is 9.5 x 10^6 m^3/s. This compares well with the estimate of Favorite et al. (1976) which is 9.3 x 10^6 m^3/s.

Reed et al. (1979) examined the seasonal variability of the baroclinic transport of the Alaska Stream off Kodiak Island. This study has not been repeated for the NEGOA area but the results should be similar.

They used a reference level of 1,500 db. The mean transport was estimated to be 11.6 x 10^6 m^3/s, with a standard deviation of 2.2 x 10^6 m^3/s. A wide range of values (8 x 10^6 to 17 x 10^6 m^3/s) was found, but there was no seasonal signal to the transport variability (Fig. 3.2). This is surprising, since there is a large seasonal signal in the curl of the wind stress over the Gulf of Alaska. The transports between adjacent stations along the Seward Line (Fig. 3.21) are referred to a 100-db level, which may explain why there is a larger seasonal signal there but not in the 0-1,500-db transport calculations.

Longshore coastal geostrophic flows

Fluctuations in the longshore component of the barotropic geostrophic current are related to changes in coastal sea level elevation. High elevations of sea level are related to strong westward flow over the Gulf of Alaska continental shelf.

Monthly means of sea level (corrected for atmospheric pressure) for Yakutat and Seward show similar seasonal cycles (Fig. 3.22). High values occur between September and February, and lower values (values below the long-term mean) are found throughout the rest of the year. That elevations fall below the long-term mean in summer does not necessarily mean that the longshore flow is toward the east. It could merely reflect a weakening of the westward flow.

The longshore geostrophic flow is driven by two forces: a baroclinic or density-driven force and a barotropic force. In the Gulf of Alaska the relative importance of these two forces probably varies seasonally. Variations in sea level reflect changes in both of these forces as well as in other forces (such as wind set-up: direct driving by the wind). Off Icy Bay the seasonal influx of fresh water appears to change a largely barotropic state to a largely baroclinic one (Hayes and Schumacher, 1976a). In winter, when the coastal influx of fresh water is small and wind stress is at an annual maximum, winds become more important in determining continental shelf dynamics. (Salinity is the most significant parameter causing changes in steric heights and is controlled to a large degree by coastal precipitation and runoff.) Hayes and Schumacher (1976a) showed that shelf dynamics are largely barotropic in winter but become baroclinic in spring (for variations with periods between about two days and a month). A simple barotropic model that adequately described the dynamics in winter did not describe conditions encountered in spring.

Farther to the west, off Seward, Royer (1979a) has shown that seasonal variations in sea level can be accounted for largely by steric changes in water over

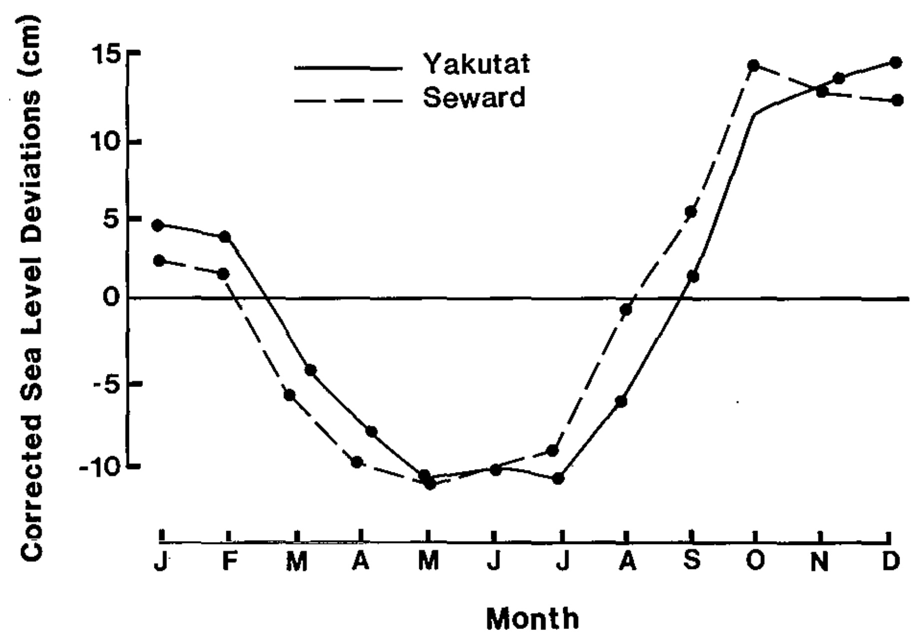


Figure 3.22 Monthly mean values for sea level at Yakutat and Seward for 1950-74. The atmospheric effect and the mean data values have been removed (Ingraham et al., 1976).

the continental shelf. It appears that seasonal variations in the barotropic component of alongshore flow at Seward are very weak compared to those of the baroclinic component.

Assuming that the results from Icy Bay and from Seward are applicable throughout NEGOA, we can summarize our knowledge of longshore coastal geostrophic flow. Seasonal changes in sea level and in longshore geostrophic flow are affected by changes in the influx of fresh water at the coast. Schumacher and Reed (1980) show that seasonal variations in the coastal flow along the Kenai Peninsula are related to seasonal variations in the hydrological cycle. On time scales longer than a day and less than a month, variations are largely barotropic in winter. When the influx of fresh water increases and wind forcing diminishes seasonally, longshore flow becomes more complex, having both barotropic and baroclinic components.

Wave-induced longshore currents

Nummedal and Stephen (1978) have applied synoptic meteorological data, storm track information, and ship wave observations to estimate wave climatology, refraction diagrams, and longshore sediment transport in the Gulf of Alaska. Wave power vectors were computed from synoptic wind data in the Summary of Synoptic Meteorological Observations (SSMO), U.S. Naval Weather Service Command, 1970.

Longshore sediment transports were calculated from the wave power distributions (Fig. 3.23). Wave refraction diagrams were used to obtain breaker angles; 12-second waves were used for these calculations. Waves from the southeast dominated the sediment transport in NEGOA. The net transport was to the west. However, just west of Yakutat Bay the transport was to the east, probably due to the curvature of the coastline. The net sediment transport here was estimated to be 220,000 m^3 per year (to the east). The largest transport occurred in region 3 (south of Icy Bay) and was 1.4 million m^3 per year (to the west).

Refraction diagrams for 8-, 12- and 16-second waves were drawn using the bathymetric chart of Molnia and Carlson (1975). Eight-second waves are typical of small summer storms; they undergo very little refraction while propagating onshore. Twelve-second waves are commonly associated with major storms. Waves of this period that approach the coast from the south and southwest concentrate energy at the entrance to Icy Bay and cause a divergence of energy at the mouth of Yakutat Bay. Refraction patterns for 16-second waves are similar to those for 12-second waves.

The estimates of longshore sediment transport are consistent with the qualitative estimates based on geomorphic features. These features, such as spits and headlands, are analyzed to estimate the long-term net littoral sediment transport. The qualitative estimates of littoral transport are shown as small arrows in Figure 3.23. Direct observations of wave-induced transport have not been made. Assumptions used in these analyses are that waves propagate in the direction of the forcing wind (calculated from atmospheric surface pressure charts) and that all waves generated by a specific atmospheric event have the same period. Other sources of possible inaccuracies are the lack of bathymetric data inshore of the 25-m isobath and the quality of the SSMO wave data. Nummedal and Stephen (1978) believe that the SSMO data may underestimate very high waves and that the wave power values that they calculated may be a lower-limit estimate of the actual annual wave power.

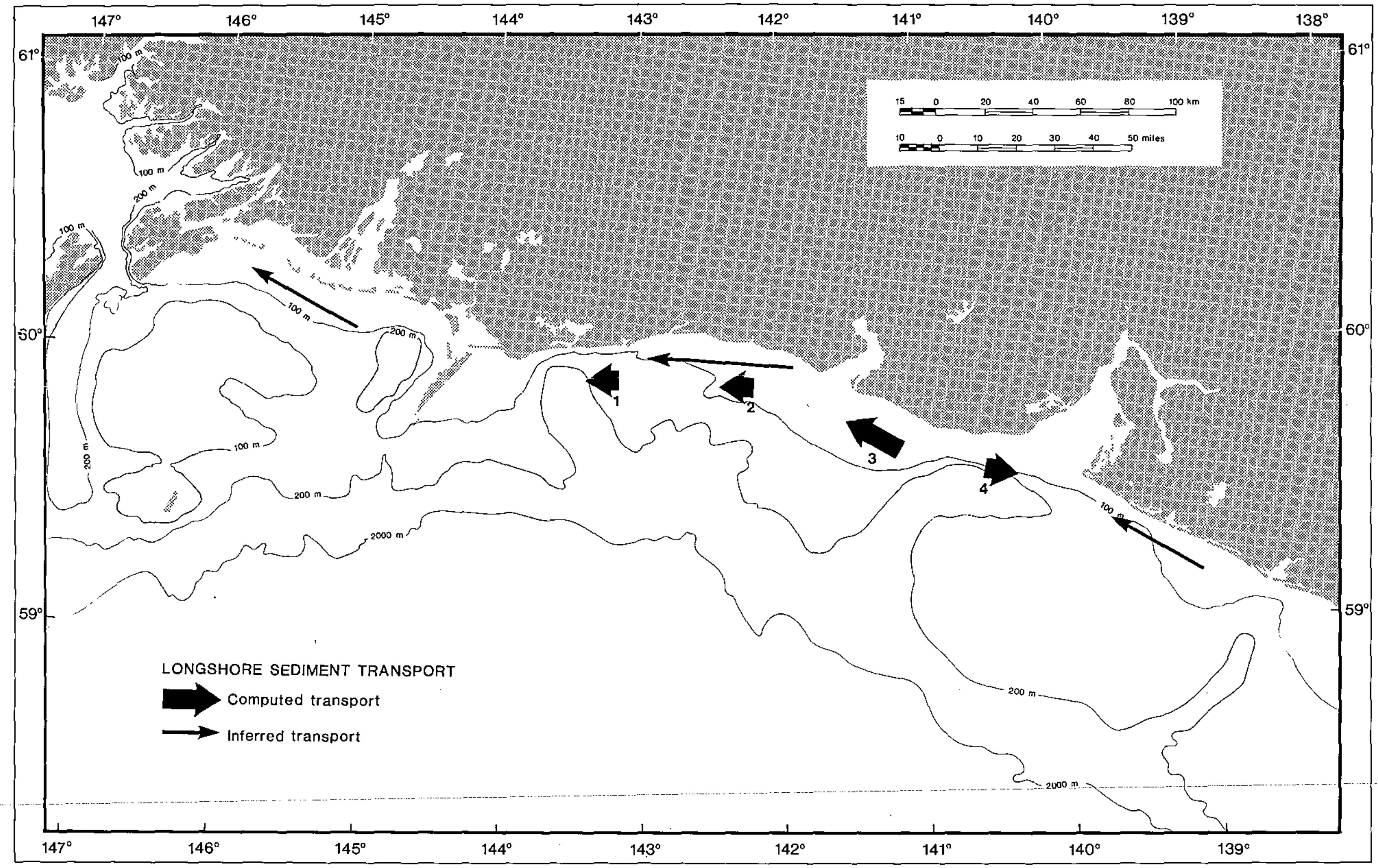


Figure 3.23 Summary diagram of computed longshore sediment transportation rates (from Nummedal and Stephen, 1978).

3.4 CIRCULATION DETERMINED BY DIRECT METHODS

There are two ways to observe ocean currents. One way is to track a parcel of water. A device is placed in the water that will be advected (it is hoped) at the same speed and in the same direction as the surrounding water. This is the Lagrangian method. Examples of Lagrangian devices are drift cards and bottles, sea-bed drifters, and ocean drifters or drogues.

The second observational technique is to moor an instrument at one location and have it record the speed and direction of currents at set intervals of time. This is called the Eulerian method.

The two methods supply different types of data. Lagrangian techniques give either trajectories of flow at the time of the experiment or give only start and stop locations for non-tracked drifters. Eulerian methods give time histories of current fluctuations at a particular point. Using both methods spatial and temporal histories of the flow can be estimated.

3.4.1 Lagrangian descriptions

Gulf of Alaska studies

Several drogue trajectories have been obtained in NEGOA. The drogue buoys were released by ships and were tracked by the NIMBUS-G satellite. Positions (and other data) were relayed by the satellite to ground stations 3-5 times a day. The buoys were 5-m-long fiberglass spars. Drogues were attached to the buoys at a depth of about 30 m (Hansen, 1977a). The drogues measured 2 m x 5 m.

Two drogue buoys were released in September 1975 (Fig. 3.24). Buoy 1745 moved onshore (at about 10 cm/s) up Alsek Canyon and, near the head of that canyon, turned toward the northwest. Only ten days of

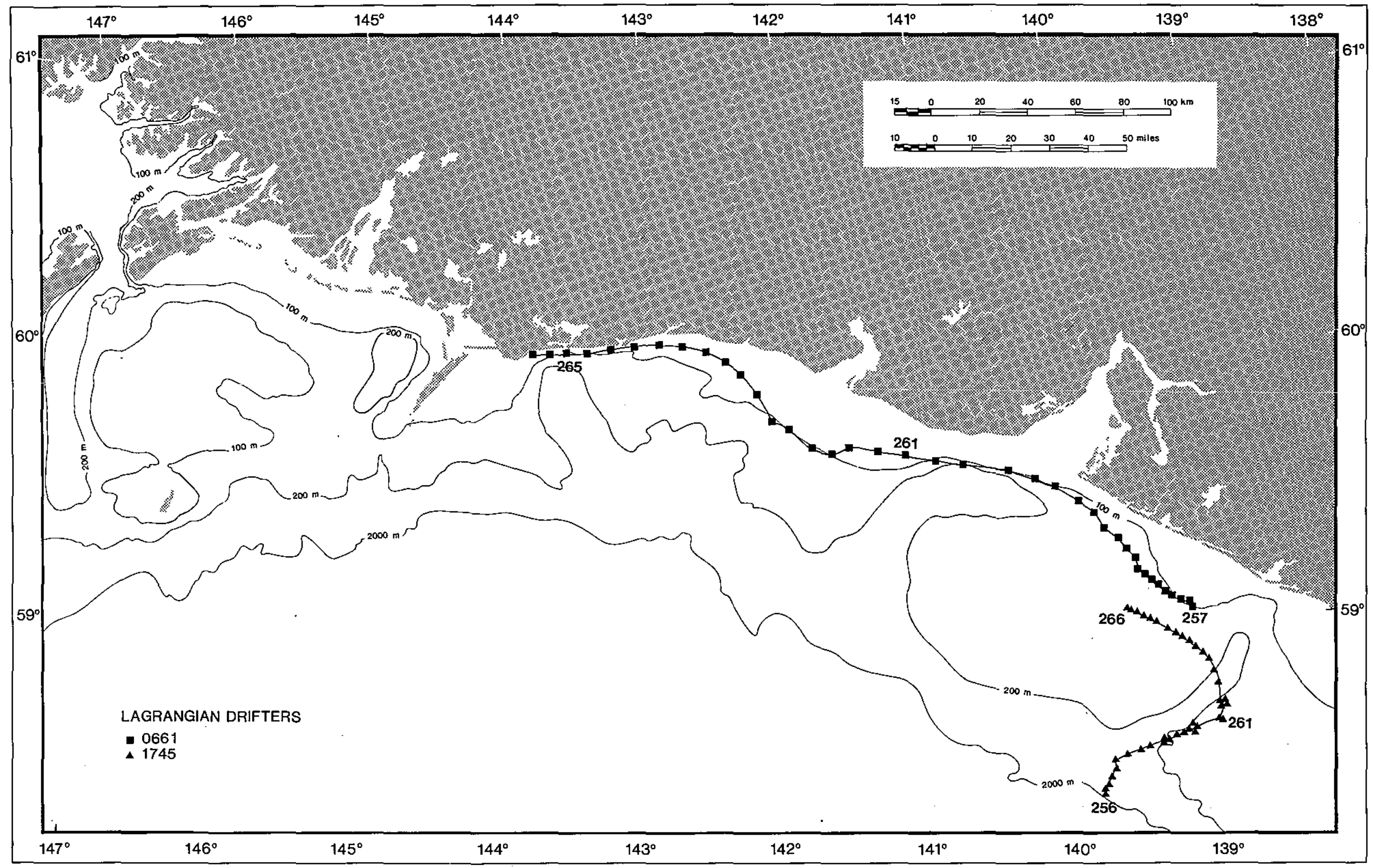


Figure 3.24 Trajectories of drogue buoys deployed in September 1975 (from Hansen, 1977a).

data were recorded. Buoy 0661 went west, parallel to the coast, until it grounded near Cape Suckling. It attained speeds of up to 40 cm/s in the coastal current (Royer et al., 1979).

Three more buoys were released off Yakutat in May-June 1976 (Fig. 3.25). Buoy 1105 operated for about three days, moving southward.

Buoy 1133 moved across isobaths, which suggests that topographic control of currents was weak. Its trajectory was toward the west and meandered widely. When due south of Kayak Island buoy 1133 entered the Alaska Current and moved faster than 65 cm/s. During day 158 the buoy moved shoreward of the shelf break, leaving the Alaska Current. Here current speeds were less than 25 cm/s (Royer et al., 1979). The buoy drifted west of Middleton Island and then reversed direction, eventually grounding on that island. This indicates a quasi-permanent eastward flow in the area west of Middleton Island (Royer, pers. comm.).

Buoy 1174 initially moved southward across isobaths and then northward, again across isobaths. When quite close to the coast it began to move westward, parallel to the coast, at speeds as high as 45 cm/s. It passed Kayak Island and was subsequently entrapped in an anticyclonic eddy west of Kayak Island. While it was in the Kayak Island eddy, speeds of about 20 cm/s were recorded. After three cycles in the eddy (taking more than 27 days) the buoy was slowly advected westward (about 10 cm/s), and it grounded on Montague Island. Near Hinchinbrook Entrance speeds as high as 20 cm/s were measured.

Trajectories for buoys 1133 and 1174 can be compared to the dynamic topography observed two months previously (Fig. 3.20). An anticyclonic meander centered at 59°N, 142°30'W, dominated the initial movements of these buoys. Buoy 1133 subsequently moved

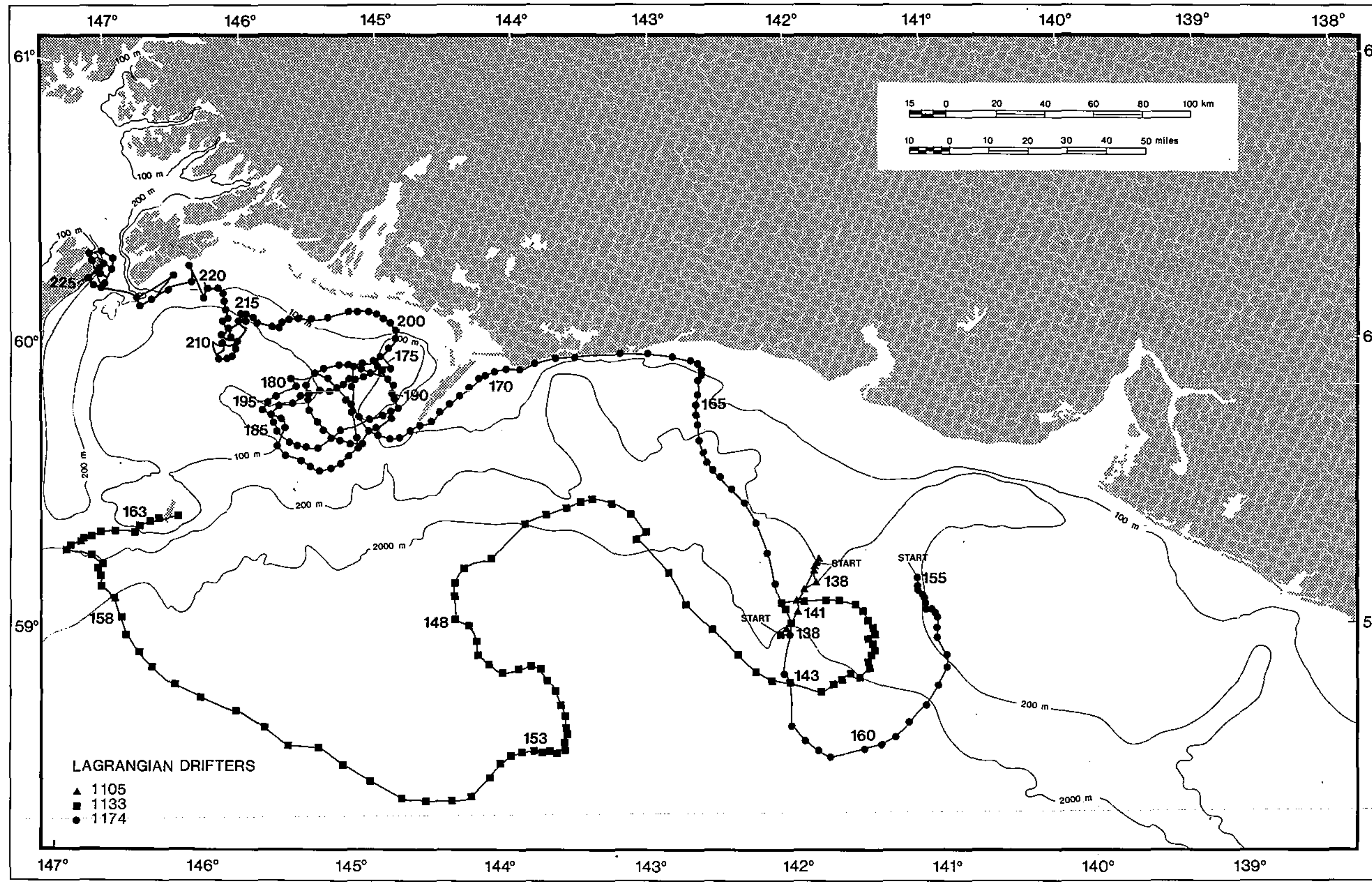


Figure 3.25 Trajectories of drogue buoys deployed in May-June 1976 (from Hansen, 1977a).

into the cyclonic eddy at 59°40'N, 143°W. Royer et al. (1979) show this dynamic topography at a .01 dynamic meter contour interval. At that contour interval they close the 0.22 contour, signifying a closed circulation or eddy. It appears that this eddy has been advected westward from the position observed in April during the interval between the observations of dynamic topographies in April and buoy trajectories in June. Buoy 1174 did not encounter this eddy. Instead, the buoy moved shoreward and entered the coastal current. After it passed Kayak Island, it entered the anticyclonic eddy, shown in Fig. 3.20 (and in Fig. 4, Royer et al., 1979).

In a third experiment, two buoys (1142 and 1235) were released near each other in July 1976 off Yakutat (Fig. 3.26). Their trajectories were identical for the first week or so. Speeds of 40 cm/s were recorded. Then 1142 meandered clockwise, and the buoys separated. About 10 days later buoy 1142 executed another, but smaller, clockwise meander. Speeds of about 15 cm/s were measured in these eddies. Royer et al. (1979) suggest that the two anticyclonic rotations of Buoy 1142 were due to an eddy's being advected westward with the mean flow. The buoy could have entered the same eddy twice. Buoy 1235 slowed to less than 10 cm/s while moving northward. Then, after it entered the coastal current, it moved westward at about 45 cm/s. All three buoys were advected to the west. When on the continental shelf south of Kayak Island, Buoy 1142 moved as rapidly as 50 cm/s. Although they were separated on occasion by more than 300 km, all three drifters were entrapped in the eddy west of Kayak Island and eventually entered Prince William Sound through Hinchinbrook Entrance. Speeds in Prince William Sound were greater than 20 cm/s for Buoys 1235 and 1142, but less than 10 cm/sec for Buoy 1203.

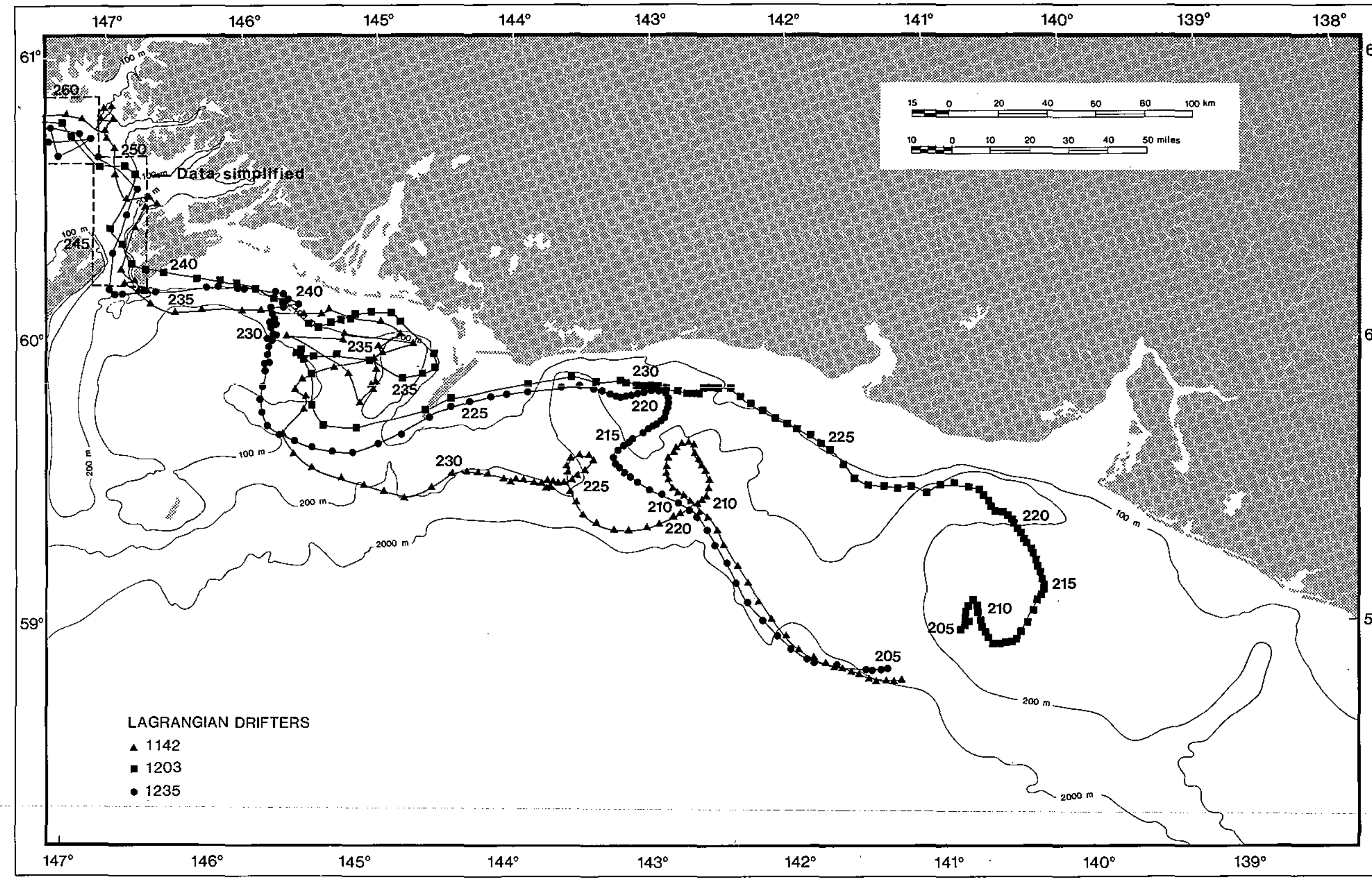


Figure 3.26 Trajectories of drogue buoys deployed in July 1976 (from Hansen, 1977a).

Royer et al. (1979) compared baroclinic geostrophic velocities to observed buoy velocities. The geostrophic velocities were calculated for the 35-db level (approximately the center of resistance for the drogue) relative to a reference level of 1,000 db. (Where depths were less than 1,000 db, estimates were made for the depths from the deepest common level to 1,000 db.) Drifter velocities were consistently greater than the geostrophic velocities. Several possible causes for this are the presence of barotropic currents, incorrect choice of a reference level, or inadequate hydrographic station spacing, leading to underestimation of dynamic height gradients. These possible causes have not yet been evaluated.

Several tentative conclusions can be drawn from these drifter data. In general, there is agreement between the flow inferred from dynamic topographies and that from buoy trajectories. However, there is a fairly consistent cross-dynamic-topography flow to the north. The mean of the cross-shelf flow component for all buoys was 3.9 cm/s toward shore. Speeds during July were about twice those in May. (The mean longshore speed was 9.5 cm/s in May and 10.1 cm/s in June.)

Royer et al. (1979) offer this explanation of the observed onshore and subsequent westward movement of the buoys: with the influx of fresh water at the coast, the upper layer of water would be expected to move seaward. This layer would consist of fresh water, as well as salt water entrained by the offshore freshwater flow. An onshore flow of sea water beneath this near-surface flow would be expected for mass balance. The drogues could be carried shoreward with the onshore flow until they reach the interface between the two layers. The opposing seaward and shoreward forces would tend to stabilize the onshore-offshore position of the buoy while allowing it to be advected parallel to the coast.

The upwelling index during these drifter experiments generally was conducive to offshore surface flow. This is in contrast to the general onshore movement of the buoys. Royer et al. (1979) conclude that drifter drogues (at 35 m depth) are below the surface Ekman layer and thus they could be advected shoreward. Current meter data from the same time of year (but from 1974) support this hypothesis. Currents at all depths show an onshore flow. Since the uppermost current meter was at a depth of 20 m, an offshore-flowing surface Ekman layer must have been less than 20 m deep.

Coastal precipitation and runoff have already been shown to be important in driving coastal flow (see section 3.2). As the coastal addition of fresh water increases seasonally, the offshore surface flow should increase. This increased flow would entrain more deep water up into the offshore-flowing layer, and thus onshore flow speeds would also increase. From June to August the onshore component of mean drifter velocity nearly doubled; precipitation also doubled over this period. Thus the onshore movement of drogues is consistent with entrainment hypothesis suggested by Royer et al. (1979).

Other tentative conclusions are listed here. The presence of the baroclinic eddy west of Kayak Island is confirmed by these drifter trajectories. Speeds in the eddy are estimated to be almost 20 cm/s. A strong (40-50 cm/s) coastal current exists between Yakutat Bay and Kayak Island. Speeds in the Alaska Current were estimated to be greater than 65 cm/s. The shoreward side of the Alaska Current seems to be a region of transient eddies. Using dynamic topography, Royer et al. (1979) estimate them to be about 100 km in diameter. They appear to be advected westward with the mean flow.

The last observation is that a surprisingly large percentage of the drifters grounded near the entrance to, or inside, Prince William Sound. Half of the buoys released grounded there. All of the buoys released in August-September 1976 entered Prince William Sound. Royer et al. (1979) suggest that an ageostrophic baroclinic flow could have advected the buoys into Prince William Sound. The September 1976 dynamic topography (Fig. 8, Royer et al., 1979) shows that the 0-100 db dynamic height is greater outside, on the seaward side of Hinchinbrook Entrance, than on the inside. Thus there could be a cross-dynamic-topography flow into Prince William Sound. In a preliminary analysis of current meter data, Royer (1978c) found a general inflow through Hinchinbrook Entrance and an outflow through Montague Strait.

Nearshore currents

Mapping the suspended matter contributed to the Gulf of Alaska by coastal rivers provides a means of tracking coastal currents. Three rivers that emanate from the Bering, Guyot, and Malaspina Glaciers, together with the Copper River (which drains a large interior area), are important sources of terrigeneous sediments (Feely et al., 1979). The horizontal distribution of suspended matter from these sources suggests the predominant direction of circulation.

A heavy concentration (> 2.0 mg/l) of suspended matter occurs off the Copper River Delta (Fig. 3.27). The plume moves westward along the coast. In October-November and April the plume appears to move into Prince William Sound through the passage east of Hinchinbrook Island. In July part of the plume enters the Sound west of Hinchinbrook Island. Concentrations of 1.0-2.0 mg/l occurred in all three data sets in the southeastern part of Prince William Sound.

Between Yakutat and Kayak Islands the distribution of suspended matter suggests longshore flow to the west. The distribution of sediments near the bottom is similar to that of the suspended sediments (Fig. 6, Feely et al., 1979). In general, little cross shelf flow is apparent in these distributions.

As suspended matter is advected westward, it is pushed offshore by Kayak Island. Satellite images of the region (Fig. 4, Feely et al., 1979) show the suspended matter moving around Kayak Island and northward along the west coast. However, much of the suspended matter then appears to enter the clockwise-rotating eddy west of Kayak Island. This eddy can be inferred from dynamic topography (Fig. 3.20) and from trajectories of drogues (Fig. 3.26) and can be seen in the satellite image cited above. In the July data either the Kayak Island eddy was very weak, or it was located farther to the west, so that the surface suspended matter was not incorporated into it. West of Kayak Island is another westward, coastal flow.

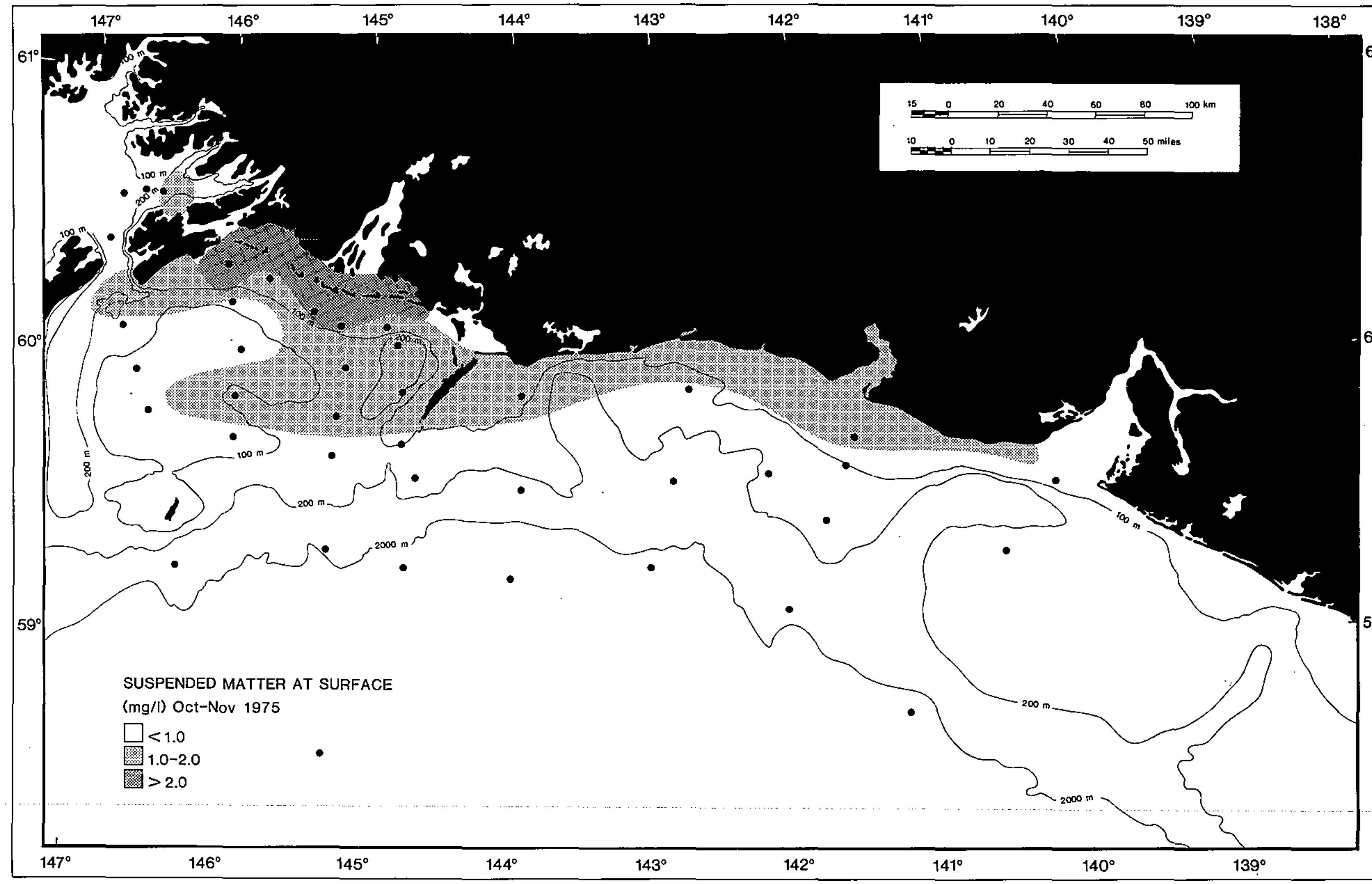


Figure 3.27 Surface distribution of total suspended matter in NEGOA for a) Oct-Nov 1975, b) Apr 1976, and c) Jul 1976 (Feely et al., 1979).

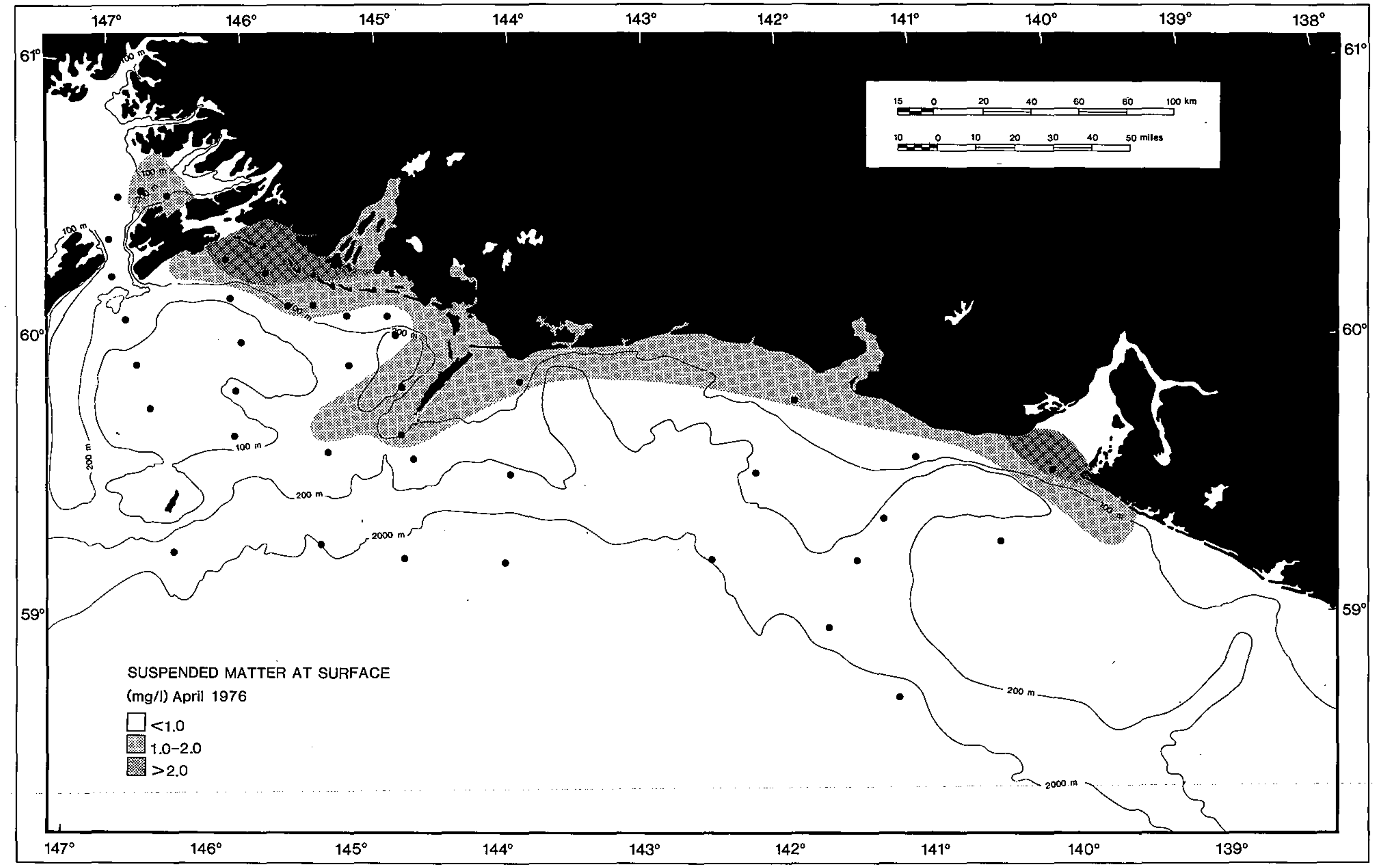


Figure 3.27 continued

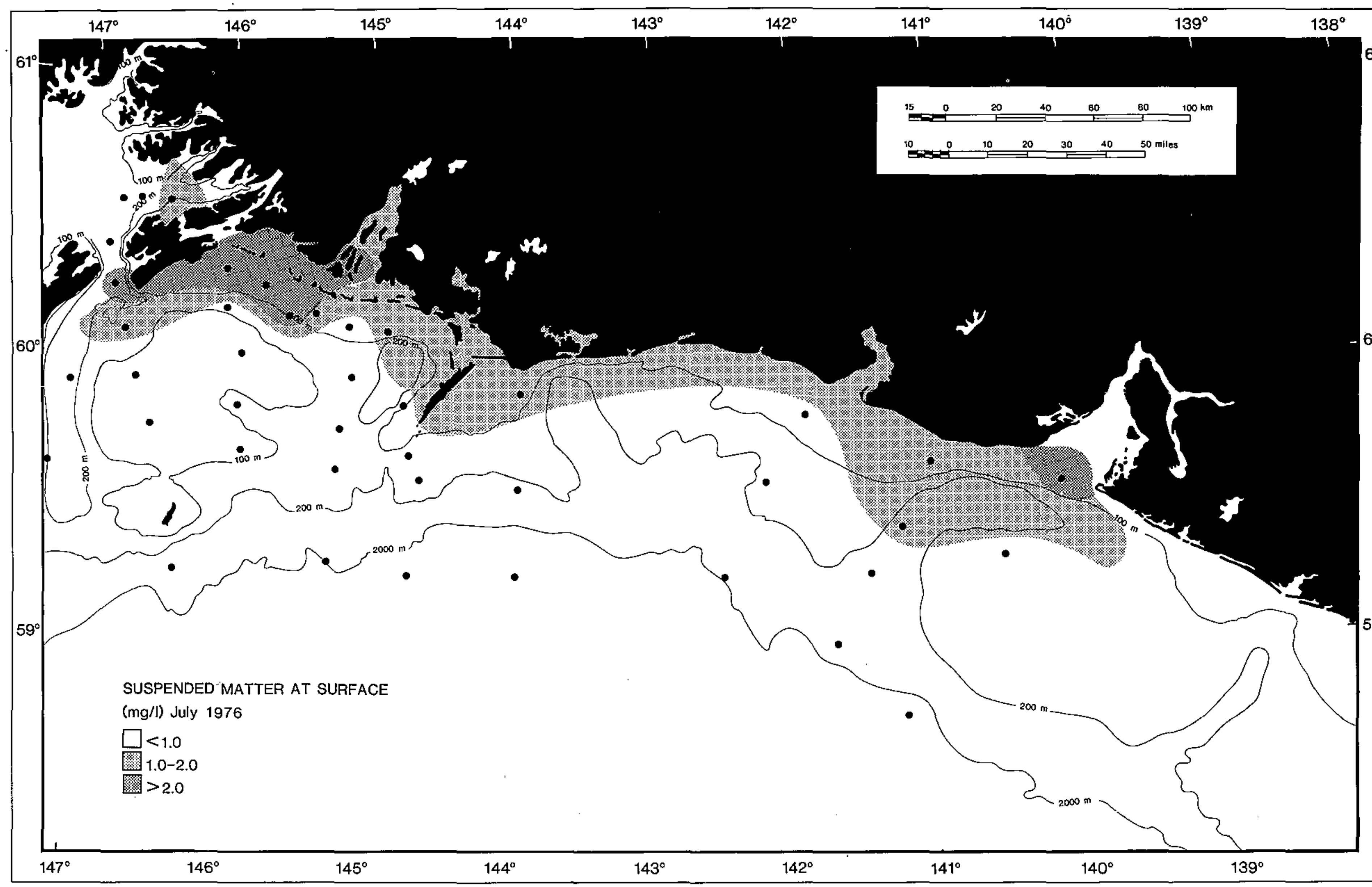


Figure 3.27 continued

Molnia and Carlson (1978) inferred nearshore circulation from satellite imagery taken from September 1972 to November 1973. They used patterns of turbid water coming from coastal streams to make qualitative estimates of the nearshore flow. The general flow is westward. However, a substantial component of the flow is outward from the shore.

The inferred flow reflects processes with short time scales (e.g., tides and winds) that are averaged out of most other circulation patterns in this synthesis report. It also reflects the influence of coastal morphology. For example, the seasonal deflection of nearshore currents by Kayak Island (Fig. 3.28) is shown in the inferred circulation. However, there was no evidence for the eddy west of Kayak Island.

Another feature shown is the flow into Prince William Sound through entrances on both sides of Hinchinbrook Island. The trajectory of Lagrangian drogues (Fig. 3.26) supports the idea that the surface flow through Hinchinbrook Entrance is inward, into Prince William Sound. Molnia and Carlson (1978) point out that the Copper River is a more important source of sediments for Prince William Sound than are streams that empty directly into the sound. Data presented in Section 3.4 imply that there is an offshore component to the surface flow throughout NEGOA. There are strong offshore components of surface flow between Icy Bay and Yakutat Bay, east of Yakutat Bay, and off the Copper River Delta.

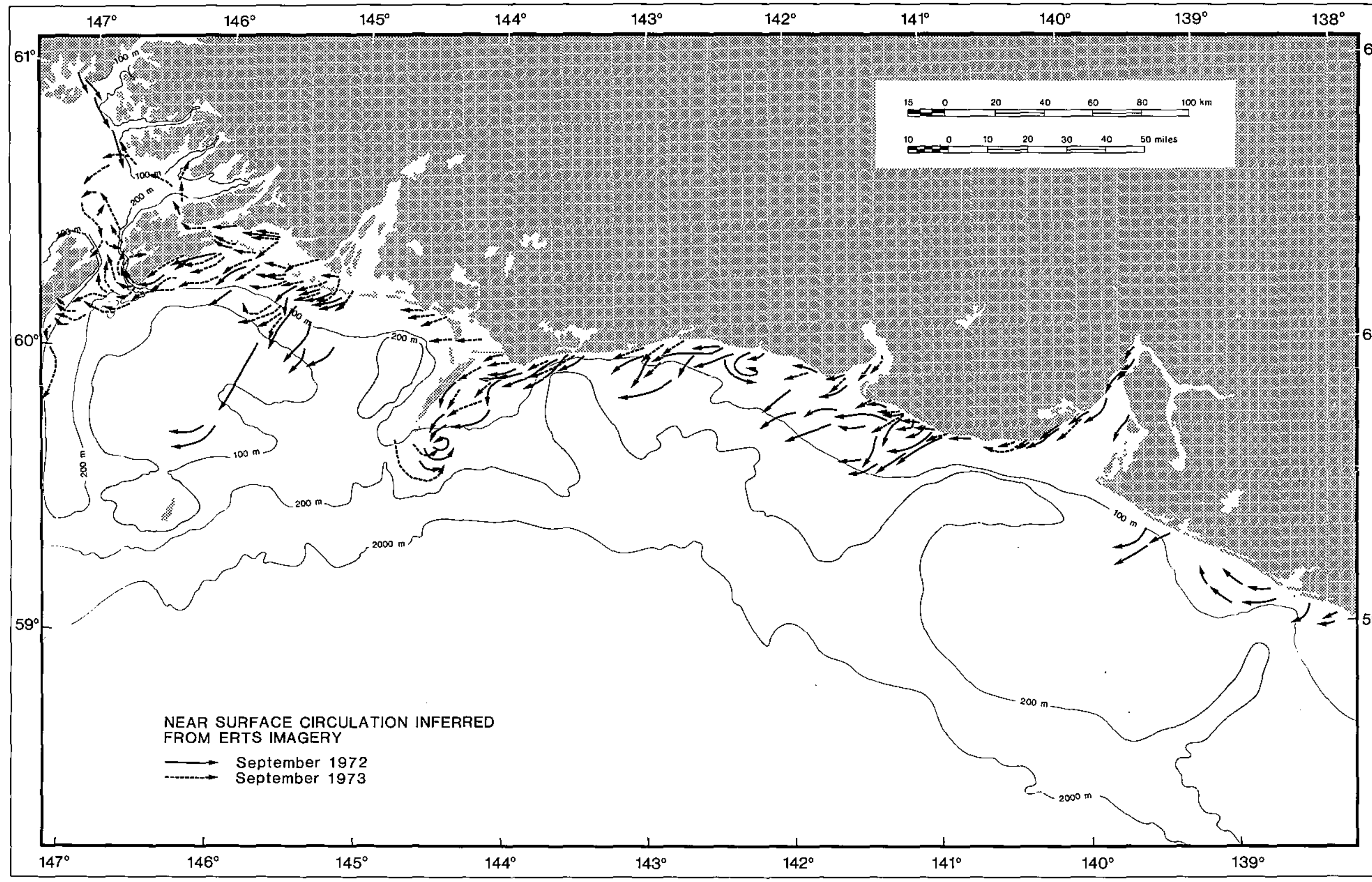


Figure 3.28 Near-surface currents as inferred from ERTS imagery (Carlson et al., 1978).

Long-scale circulation features

Two other sets of information (reported in Hansen, 1977b) show that NEGOA is a region of accumulation for surface drifters. Dotson et al. (1977) made a model to determine where buoys would tend to accumulate in the North Pacific Ocean, given a uniform initial distribution. Data for this simulation were obtained from the Naval Oceanographic Offices file of ship drifts. (Since ship drifts are the result of both current and wind action on the ship, these data may not represent the trajectories taken by a surface pollutant.) After simulations of 700 days the distribution of buoys (Figure 3.29) shows an accumulation along the coast of the Gulf of Alaska (density greater than 200). It can be inferred that pollutants released on the sea surface anywhere in the Pacific Ocean have a high probability of being entrapped and reaching the coast of the Gulf of Alaska.

In another experiment drogue buoys were released in the North Pacific (one at 45°N 162°W; another at 45°N 166°W) in September 1976. The first buoy went aground on or near Montague Island and the second grounded near Icy Cape. (D. Kirwan, cited in Hansen, 1977b) These data are further evidence of the general tendency of surface drifters to accumulate in the Gulf of Alaska.

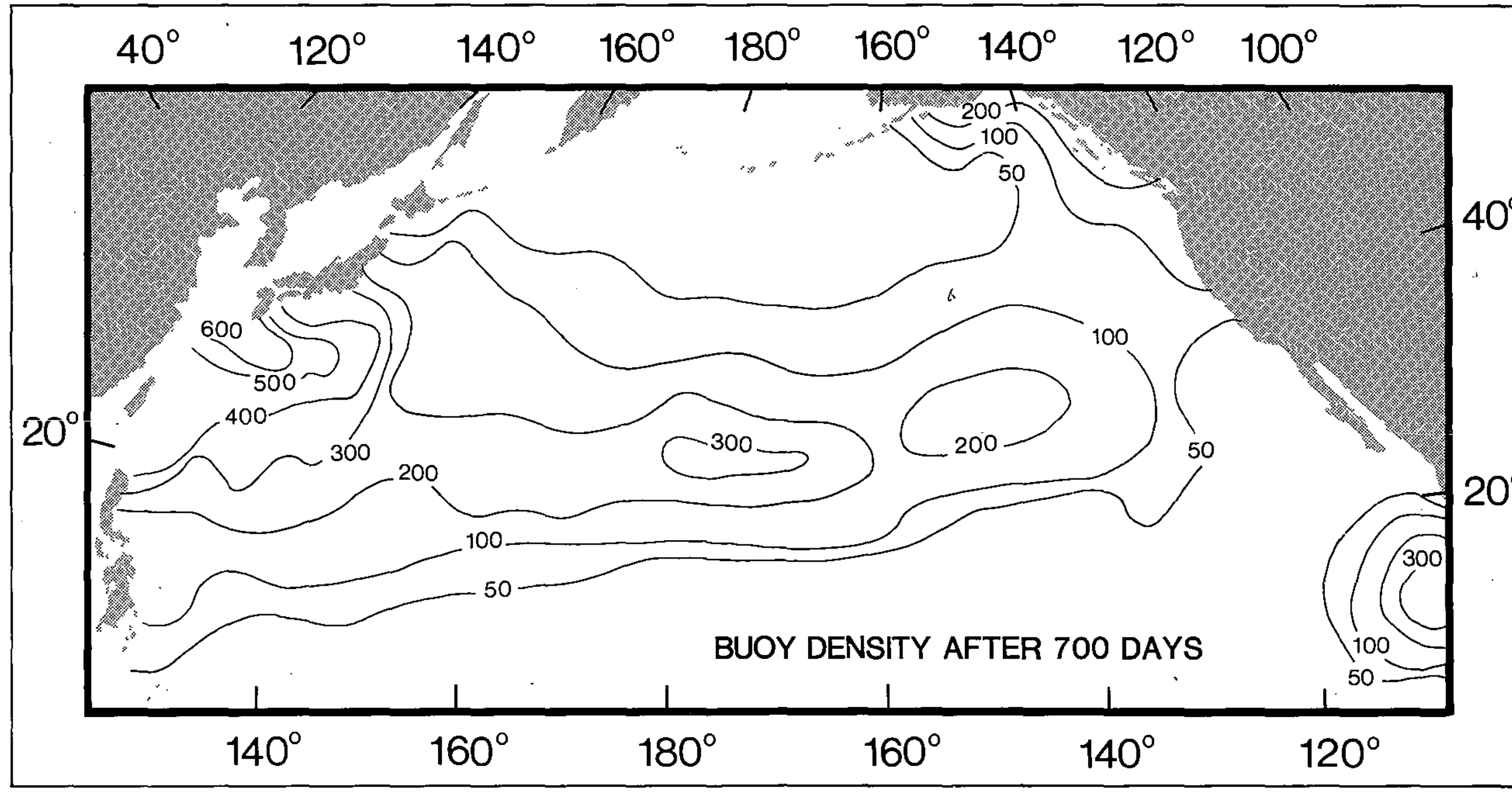


Figure 3.29 Simulated concentrations of drogues after 700 days (from Dotson et al., 1977 as reported in Hansen, 1977a).

3.4.2 Eulerian descriptions

Data from several installations of current meters provide a fairly complete description of the circulation in NEGOA. The net current drift is longshore toward the west or northwest. Current speeds vary seasonally: mean current speeds in winter are about twice those in summer. In general, mean vertical shears (differences in speed and direction at different depths) are small. Monthly mean currents are significantly correlated with mean winds; the winter increase in current speeds can be largely attributed to increased wind intensities (Muench et al., 1978).

The structure of the current regime of the shelf near NEGOA can be ascertained from the data of Hayes and Schumacher (1977). Mean currents are shown in Fig. 3.30 for each of the current meters that was deployed in the period of March to May 1976.

The currents tended to parallel local bathymetry except at Mooring 60. Here the mean currents were weak, typically a few centimeters per second. The currents at Station 69A had a cross-shelf tendency, while those along the shelf break (Station 61B) were longshore, parallel to the bathymetry. Mean currents at the three moorings off Icy Bay (SLS 8 and 4, and G2) were also largely parallel to the bathymetry.

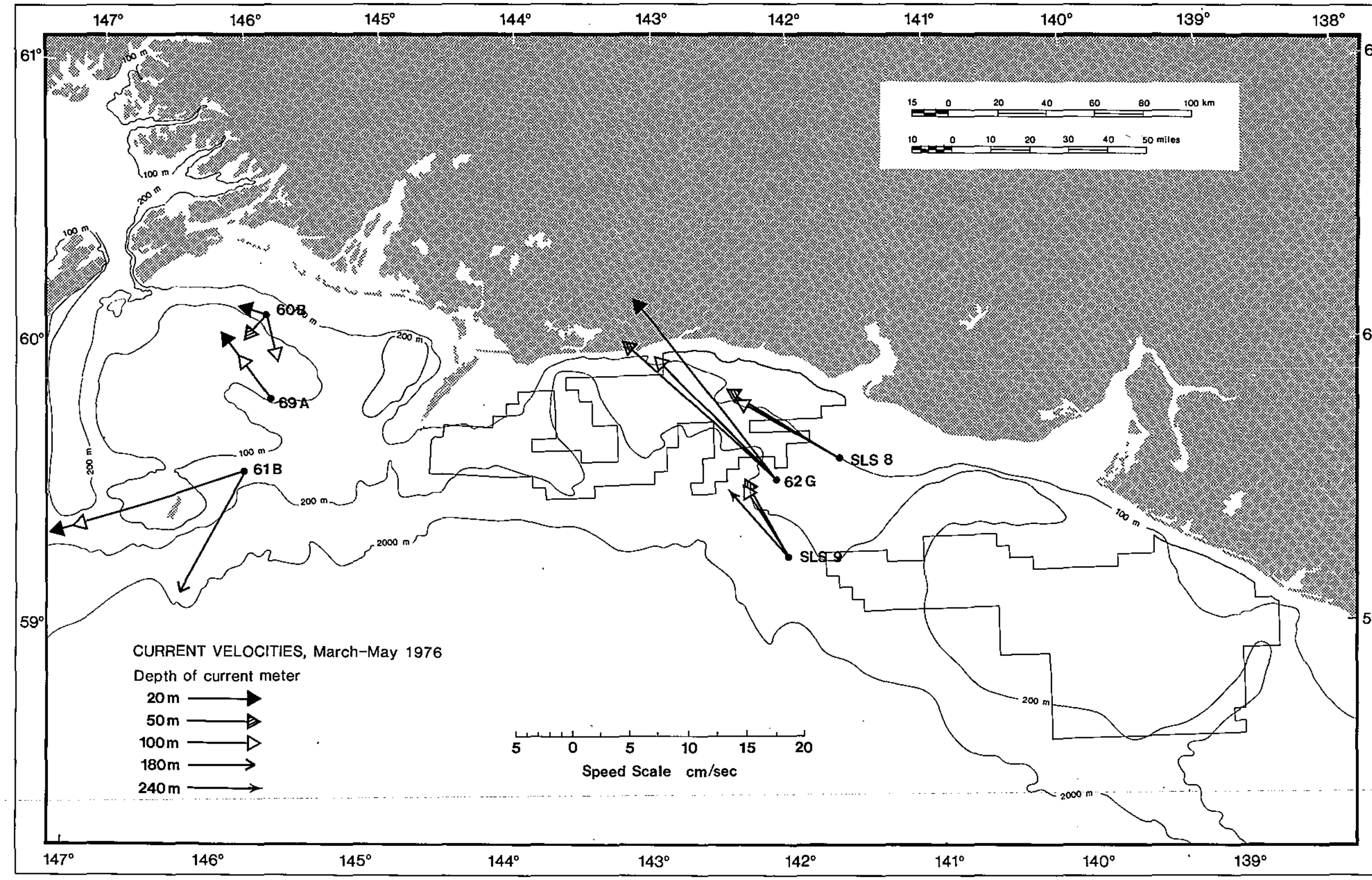


Figure 3.30 Average current velocities for March to May 1976 (from Hayes and Schumacher, 1977).

Mean speeds of the currents vary across the shelf. The 50-m mean speeds for three moorings off Icy Bay are shown in Fig. 3.31, and the 20-m mean speeds for three moorings off Cordova are shown in Fig 3.32. Data were not collected at a common depth. The current structure off Icy Bay shows a maximum mean speed at Station 62. The net flow (or vector average, as opposed to the mean speed, which is a scalar average) was also a maximum at Station 62. However, the variance increased off-shore. At the moorings farther to the west (Fig. 3.32) the mean speed, variance and net flow all increased as the distance from the shore increased. Thus it appears that the cross-shelf structure was different at the two locations. However, both Stations 61 and 62, where the maxima occurred on the different cross-shelf sections, were near the shelf break (see Fig. 3.30). The maximum mean speeds and net flow were associated with the shelf break.

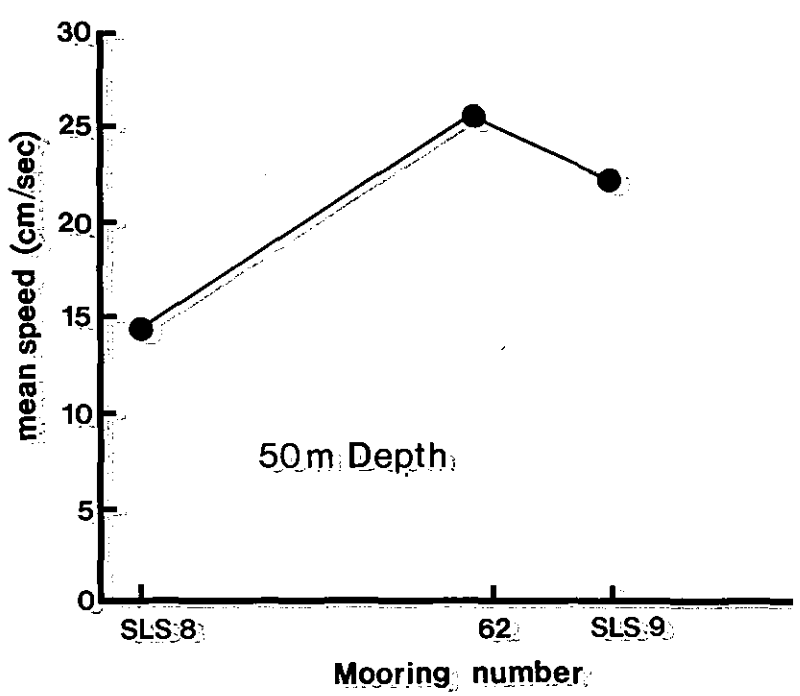


Figure 3.31 Mean current speeds at 50 m depth off Icy Bay (from Hayes and Schumacher, 1977).

The next deployment (May-October) of current meters (Fig 3.33) showed the currents to be again aligned with the bathymetry, but they were smaller than during the earlier period. Currents at Station 60 rotated 45-90° counterclockwise from the previous deployment. The summer southeasterly flow at Station 60C was probably caused by local winds. Both the mean speed (Fig. 3.32) and variance were maximum at Station 69 (for the three moorings off Cordova). However, the net flow was at a maximum at Station 61.

Comparing the May-August mean speeds to those of March-May (Fig. 3.32) showed a decrease at Stations 60 and 61 but not at 69. The variances of the 20-m currents decreased from the first to the second deployments for all stations except Station 69, where the variance increased slightly. The decreases are probably attributable to reduced winds in summer.

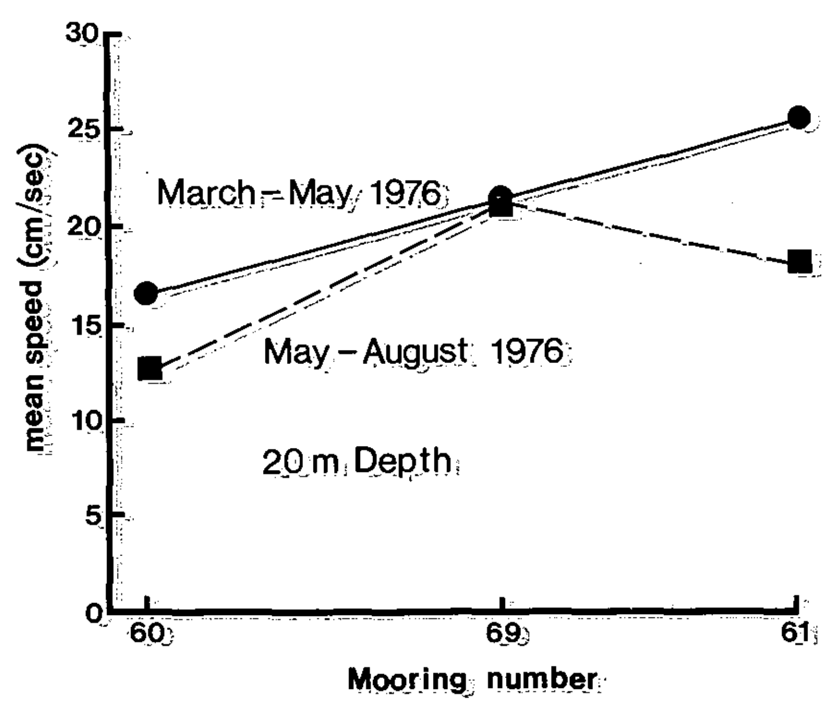


Figure 3.32 Mean current speeds at 20 m depth off Cordova (from Hayes and Schumacher, 1977).

At Station 62, off Icy Bay, the mean speed, net flow, and variance decreased at all observed depths from the first to the second periods. The mean speed dropped by a factor of 4 (Muench et al., 1978). However, all three parameters increased during the subsequent mooring, from August-October. The variance of currents at Station 62 during winter (October 1976 to March 1977) was six times the variance during summer (May-September 1976). Also, whereas in summer tidal components contributed about 60 percent of the total variance, in winter they contributed only 25 percent of the total variance. This was caused by the much higher energy levels present at low frequencies (periods longer than 30 hours) in winter, due to atmospheric forcing.

The circulation off Icy Bay has a mean westward flow with 2- to 3- day, eddylike, low-frequency fluctuations (Hayes and Schumacher, 1977). The low-pass-filtered (tides removed) current speeds can be as high as 30 cm/s, but the mean velocity is typically less because the currents vary in direction.

The energy density at the lowest resolved frequency at the 100-m isobath was an order of magnitude less than that at the shelf break. There were other differences between the current energy spectra at these two locations. On the shelf the spectrum of the longshore current component had more energy than that of the onshore component: low-frequency fluctuations are apparently steered by bathymetry. At the shelf break the spectra of the two components were similar in magnitude; fluctuations were rotary and clockwise at low frequencies (Muench et al., 1978).

Coherences were computed between current meter records across the shelf and vertically between 50-m and 200-m depths) at the shelf break mooring. Rotary coherences across the shelf break were low, indicating

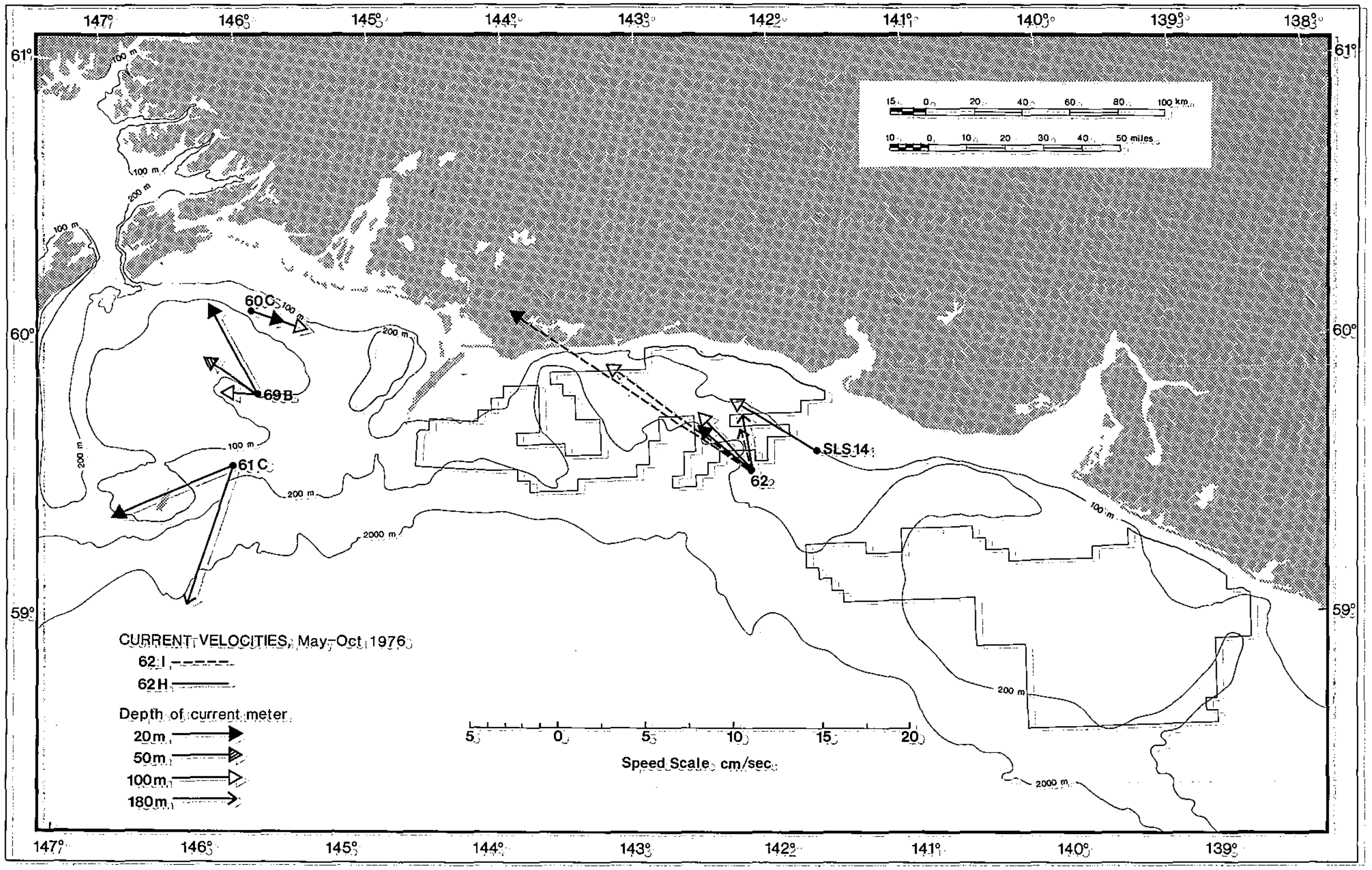


Figure 3.33 Average current velocities for May to October 1976 (from Hayes and Schumacher, 1977).

that the clockwise-rotating fluctuations did not propagate onto the shelf. These fluctuations were coherent in the vertical, with essentially no phase lag. Muench et al (1978) and Hayes (1979) concluded that the rotary oscillations are quasi-barotropic motions occurring along the shelf break and that they are unable to propagate onto the shelf. Other evidence for the presence of these eddies comes from drifter trajectories and dynamic topography. (Although the eddies appear barotropic over a vertical scale of 200 m in the current meter records, a baroclinic component also appears in the dynamic topography.)

Farther west, near Kayak Island, the flow is complex and weak at tidal and low frequencies. The low levels of energy probably indicate that water parcels remain in this region a long time. Fluctuations in velocity similar to those of the mean flow occur during winter storms.

NEGOA can be divided into two circulation regimes: those east and west of Kayak Island (Muench et al., 1978). From Yakutat Bay to Kayak Island the continental shelf is narrow, about 50 km wide. West of Kayak Island it widens to about 100 km. In the eastern section coastal currents and shelf break currents are independent. West of Kayak Island two current regimes have merged. Along the coast another coastal current is established by the influx of fresh water. Also west of Kayak Island the shelf is wide and shallow, and local wind effects may be more important there in driving currents.

Current patterns west of Kayak Island are complicated by the effects of the island on the westerly circulation. One such effect is the formation of vortices such as the permanent anticyclonic eddy west of Kayak Island (Muench et al., 1978).

Seasonal variability

Winds and currents change seasonally on the continental shelf. The winds in late winter and spring are strongly westward and variable. During summer the mean wind speed is substantially less and the direction is eastward. The mean current speed on the shelf decreases by a factor of two between spring and summer (Hayes and Schumacher, 1976a). The discharge of fresh water also has a strong seasonal signal (e.g., Fig. 3.11), which has a major influence on dynamics of shelf circulation.

Hayes and Schumacher (1976b) employed a simple barotropic model (relating temporal variations in the longshore velocity component to the cross-shelf pressure gradient; see Collins, 1968) to data obtained off Icy Bay in February and March-April. During the earlier period the longshore velocity and bottom pressure were linearly correlated and the barotropic model provided a reasonable description of the shelf dynamics. (The variance in the cross-shelf pressure gradient accounted for 50-70 percent of the variance in the longshore current component.) In the second period there was no linear correlation, and the model failed. Baroclinic effects must have become dominant during this latter period.

In the same report Hayes and Schumacher compared the coherence between bottom pressures and longshore winds for January-February and March-April. During the winter there was a strong and significant coherence over the low-frequency band. Only at one frequency was there a significant coherence in the spring. Hayes and Schumacher noted that for isolated events in spring, wind, bottom pressure, and longshore currents were visually correlated. However, the coherence, which was averaged over the sampling period, was not significant. Similar results were obtained for data from a location west of Kayak Island.

Hayes and Schumacher (1977) have suggested a division of seasons on the continental shelf based on current meter observations: summer (April-September) and winter (October-March). During winter baroclinicity is reduced due to the decrease or cessation in the addition of fresh water at the coast, and to the increased mixing in the upper layer. This mixing is caused by the strong winter winds and by surface cooling. Thus, in winter the barotropic model proposed by Hayes and Schumacher (1976b) is fairly accurate. In summer, with the increased coastal influx of fresh water, higher temperatures, and greater stratification in the water column, the model is not an accurate description of the physics of the continental shelf.

Seasonal meteorological conditions are directly correlated with this seasonality. During winter, winds tend to augment local longshore flow (westward), while in summer they often oppose the westward longshore flow and may add an offshore component to the surface flow. The Ekman offshore velocity component in currents is related to the weakly positive upwelling index encountered during summer. Strong downwelling tendencies predominate in winter and lead to Ekman set-up along the coast. Coastal downwelling reduces stratification and the coastal set-up can drive barotropic variations in the longshore flow.

Wind-driven currents

The longshore velocity and bottom pressure both respond rapidly to storm-generated wind changes. In February-March 1975 there were four periods of high wind; the currents observed off Icy Bay responded within several hours to these events. The longshore velocity increased by about 40 cm/s at both the 20-m and 50-m current meters. Changes in current speeds of as much as 30 cm/s occurred down to 100 m depth. Bottom pressures increased by as much as 15 millibars (Hayes and Schumacher, 1976b).

Hayes (1979) investigated the relationship between the cross-shelf pressure gradients and the onshore and longshore wind components. The pressure gradient was calculated from differences between bottom-mounted gauges at the 50- and 100-m isobaths (the inshore gradient) and at 100-m and 250-m isobaths (the offshore gradient). Wind values were placed in 2 m/s classes. Plots of the pressure gradient-wind comparisons are shown in Fig. 3.34. There is a positive correlation between the onshore wind component and the inshore pressure gradient and between the longshore wind component and the offshore pressure gradient.

Hayes (1979) offers an explanation for these correlations. The bottom pressure gradient is related to the longshore wind stress divided by the Ekman depth for Ekman driving and to the onshore wind stress divided by the water depth for direct wind driving. Since the Ekman depth is itself a function of wind speed, the pressure gradient is related to the wind speed for Ekman driving while it is related to wind speed squared for direct driving. At a location where the Ekman depth is equal to the depth of the water column, direct driving will dominate (being related to wind speed squared rather than to wind speed). However, where the depth is much greater than the Ekman depth, Ekman driving will dominate. Thus, inshore, the pressure gradients are related to the onshore wind speeds, and farther offshore, pressure gradients are related to longshore winds.

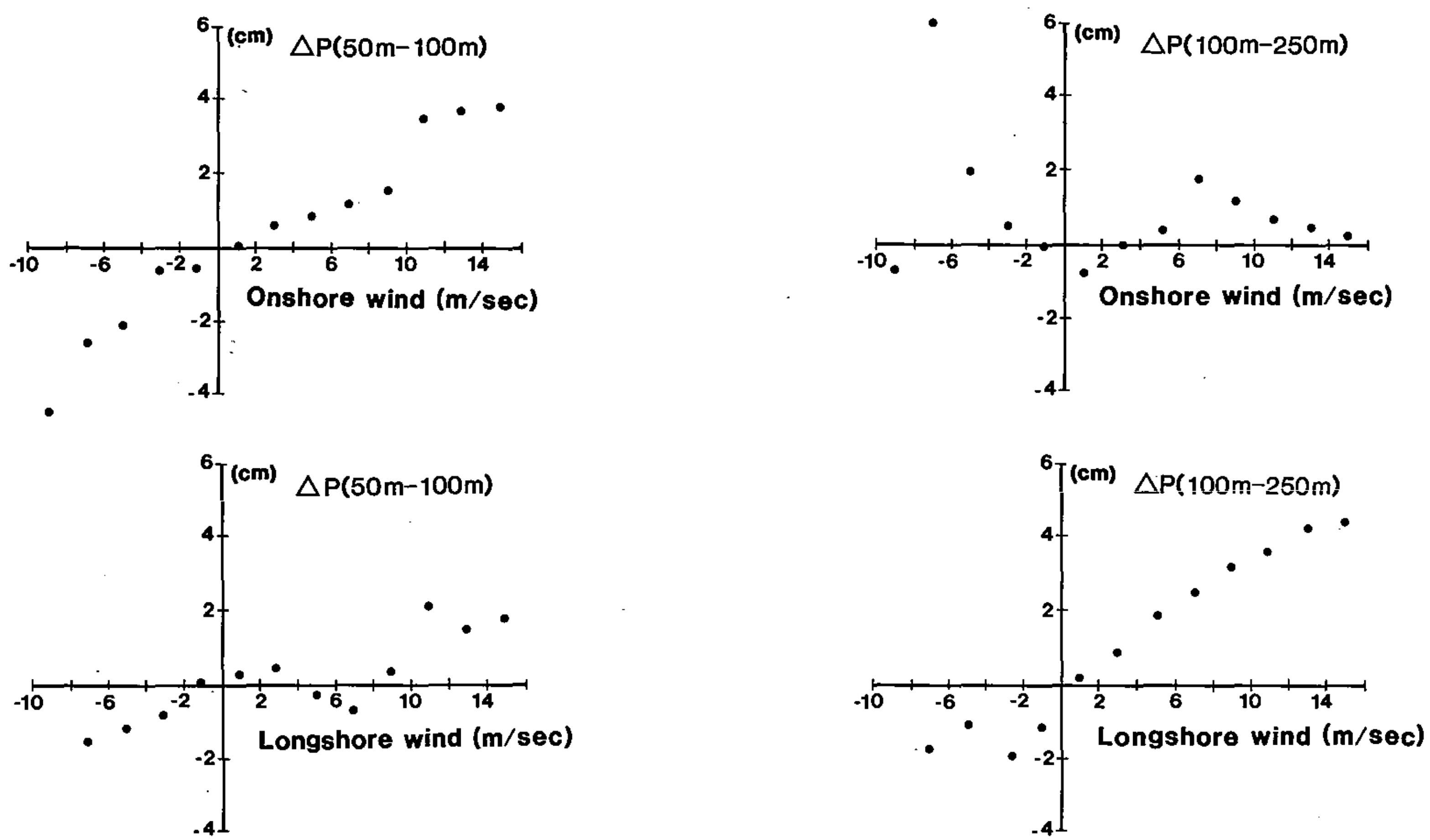


Figure 3.34 Cross-shelf pressure gradient between indicated depth contours versus onshore and longshore wind (Hayes and Schumacher, 1977).

3.5 SIMULATIONS OF CIRCULATION

Galt et al. (1978) made a series of trajectory simulations in NEGOA. Their model is a finite element, diagnostic model presented by Galt (1975). It calculates a velocity field from density and wind field data. It is a linear combination of barotropic and baroclinic geostrophic components and upper and lower Ekman boundary layers.

The barotropic current component is continuously set up by the wind field. Sea surface elevation across the shelf is represented as a linear profile which is stationary (hinged) along the shelf break. Instead of one straight line of zero-sea-level fluctuations throughout NEGOA, there are six such hinges. The cross-shelf slope of the sea surface is modeled to be proportional to the square of the wind speed times the cosine of the angle between the wind and the coastline.

The baroclinic current component is calculated from available hydrographic data and is held constant throughout a simulation. Dynamic heights on the shelf are calculated relative to the bottom and those off the shelf to a reference level of 1200 m. The assumed level of no motion thus follows the bathymetry, and the effects of changes in depth from one location to another are taken into account within the baroclinic component. The baroclinic response is calculated for each set of hydrographic data and this response is stored in an environmental library. The appropriate response is accessed based on the time of year of the simulation to be made.

Ekman stresses are applied to both the top and bottom surfaces. The wind-driven Ekman layer is added to the geostrophic components, and the bottom Ekman layer accommodates a zero slip condition along the bottom. The equations of motion are integrated over the depth of the water column and are cross-differentiated to give an equation for vorticity. The model gives a two-dimensional representation of surface currents that are the resultants of the several components integrated vertically. For analysis of oil spill trajectories an additional forcing of 3 percent of the wind speed is added.

The boundary conditions along the coast allow no transport into or out of the coast. Along the open shelf boundaries of the model no boundary conditions are set.

Large-scale synoptic maps of sea level atmospheric pressure data are analyzed to identify dominant wind patterns. These wind patterns are considered to be quasi-steady states of the atmosphere that are frequently observed. Twelve characteristic patterns, or subtypes, have been identified as representative of the climatologies that exist in NEGOA (see Fig. 3.3). These are modifications of the weather types reported by Sorkina (1963) and Putnins (1966).

Each of the subtypes is correlated with daily pressure maps to determine the best correspondence. The type with the highest correlation across the spatial grid is chosen to represent the pressure data for that day. (Figure 3.4 is a summary of the correlation for each climate type in each season.)

Geostrophic winds are calculated for each grid point from the selected weather type. These values are put into a planetary boundary layer model (similar to that of Cardone, 1969) that computes the surface wind stress. However, other modifications to the geostrophic winds are made for those grid points that are within 50-100 km of the coastline, based on the near-shore meteorology findings of Reynolds et al. (1978). From these calculations a two-dimensional wind field is produced. The wind vector that lies closest to the position of the anemometer on Middleton Island is compared to the observed data. The ratio of calculated to observed wind speed is used to scale all of the other calculated wind speeds on the grid. (The grid spacing is 7.5' of latitude and 15' of longitude.)

Forcing by the curl of the wind stress is not included in the model because it is small compared to the cross-shelf setup. Since sidewall friction is not included, simulation results within a few tens of kilometers of the coastline are not accurate. Shelf waves are not generated by the model. Only low-frequency motions are included and baroclinic shears are assumed to be constant throughout any given simulation.

The magnitude of the calculated wind field at each grid point is scaled by the ratio of the 12-hourly mean wind speed (recorded by an anemometer) to the wind speed calculated for this point. Perturbations in the wind are introduced by subtracting the hourly time series velocities from the scaled wind field at the anemometer. The vector components of the perturbation velocity are scaled for each grid by the ratio of the calculated wind speeds at a grid point to that at the anemometer. Then these scaled perturbation components are added to the velocity calculated at each grid point.

The calculated currents are scaled at each grid point by the ratio of the calculated currents near a current meter location to the observed currents there. Perturbations are calculated by subtracting the geostrophic components from the hourly values of currents recorded by the current meter. The perturbation components are scaled by the ratio of the calculated barotropic components to those observed at the current meter location. The components of the perturbation velocity that are aligned with the local barotropic current are added to this component. The scaling of the perturbation velocity ensures that when there are strong winds there will be strong barotropic currents, and thus there will be strong perturbation velocities.

Five assumptions are basic to the model:

(1) That the surface wind field can be related to large-scale synoptic sea level pressure maps. This assumption is probably valid throughout the grid except near coastlines.

(2) That surface pressure maps can be represented by a few generic patterns. These patterns are approximations of the actual pressure maps; about 75 percent of the records can be correlated with the set of weather types with a correlation of 0.7 or better. A correlation of 0.7 implies that about half of the variance in the pressure map can be accounted for by the selected climate type map. Thus the climate typing is at worst, 50 percent effective 75 percent of the time.

(3) That the current field can be decomposed completely into barotropic and baroclinic geostrophic components. All additional currents are handled through the scaling process and by including the perturbation term and by calculating Ekman currents. However, this process neglects the spatial variability that is associated with these currents. This loss of realism is probably not significant, since the net drift associated with the additional current components (e.g., tidal or inertial) is small.

(4) That the baroclinic current field is constant during each simulation. This assumption is necessary because of the lack of hydrographic data. However, the hydrographic fields can vary over a time period shorter than the two month simulation period.

(5) That barotropic set-up occurs instantaneously with changes in the wind field. The time lag between wind changes and set-up is on the order of hours and probably does not greatly affect the results. Comparisons of sea level, longshore currents, and winds in NEGOA imply that this assumption probably is valid in winter but not in summer (Hayes and Schumacher, 1976a) nor for low-frequency (time scale of a

month or longer) variations (Royer, 1979a) throughout the year.

In the experiments reported by Galt et al. (1978), seven release sites were used during July-August 1974 and February-March 1975. At each location for each season releases of oil were simulated every five days. Trajectories for each release were continued until they exited the model boundaries or until the time limit of two months was exceeded.

Baroclinic currents were dominated by mesoscale eddies along the continental slope. Except for the baroclinic gyre west of Kayak Island, the baroclinic currents on the shelf were relatively weak. The strong winds that exist in winter caused greater displacements in the simulations than do the weaker summer winds.

The release sites are shown in (Fig. 3.35). Those releases made at Site One tended towards the northwest; pollutants in these paths could affect a large area of the coastline. The winter releases traveled farther and spread farther than did those from the summer releases.

The Site Two trajectories seemed to be greatly influenced by strong baroclinic currents at and seaward of the shelf break. Several of the summer trajectories led to the east and appeared to follow the submarine valley that leads to Yakutat Bay. Other releases seemed to oscillate along the edge of the shelf. Two others moved southward off the shelf and across the slope. The winter releases moved eastward initially under the influence of baroclinic currents along the slope. Then some moved northward and reached the coast and one moved offshore and was quickly advected westward by the Alaska Stream.

Most of the releases at Site Three moved onshore over a wide (about 70 km) front. In summer two moved to the east, probably driven by winds. In winter, one

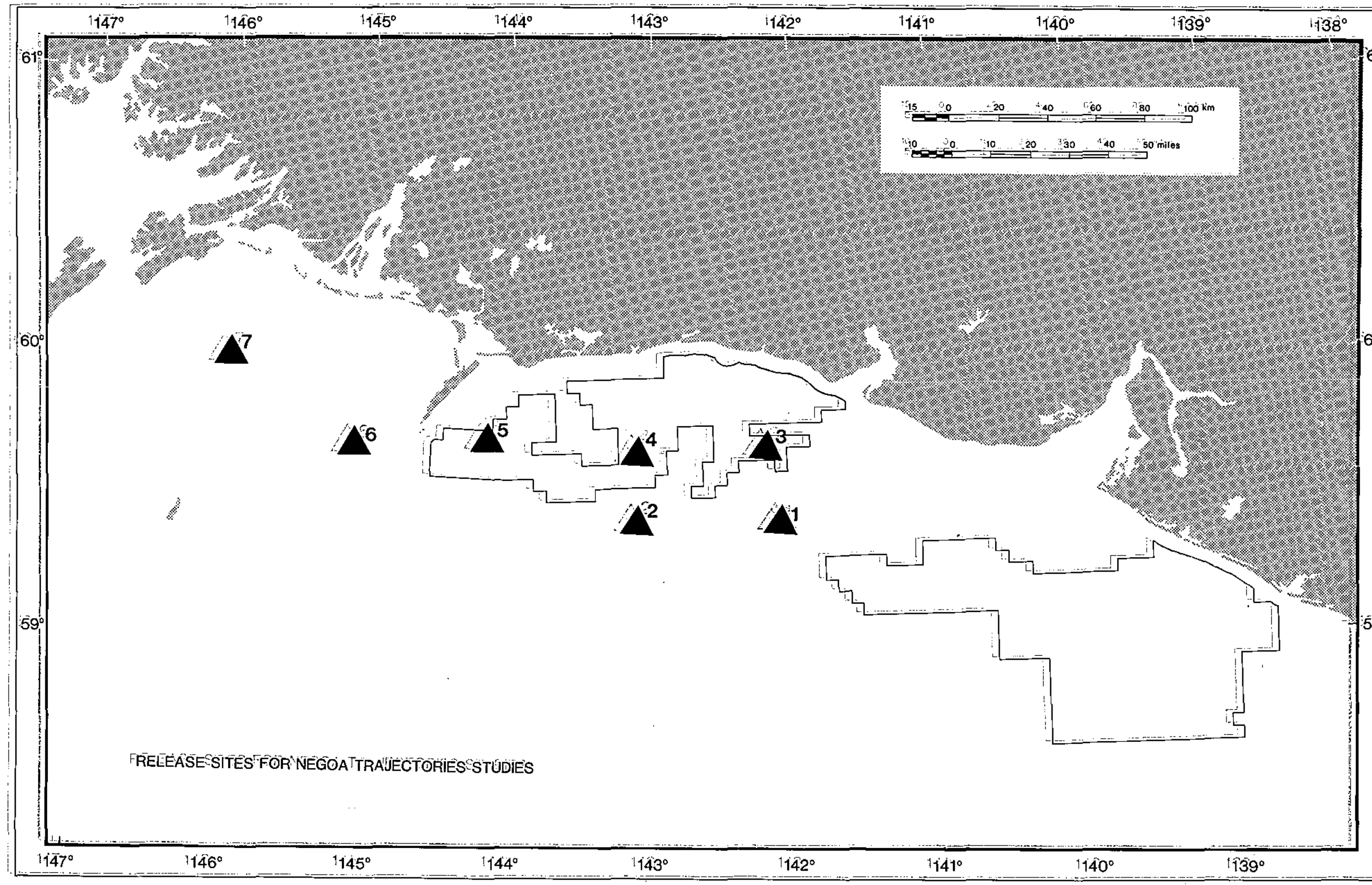


Figure 3.35 Release sites for simulated trajectory studies (Galt et al., 1978).

release moved offshore and eastward under the influence of a baroclinic eddy along the continental shelf. Two others went toward the west and grounded on Kayak Island.

Almost all of the releases made at Site Four moved to the north and west; however, there was a wide spatial scatter in the trajectories that is attributed to the complex bathymetry in the area. These releases appear to reach the coast. In winter a single release traveled to the southeast across the shelf and slope.

From the site southwest of Kayak Island, Site Five, most releases moved north or west and reached the coastline of Kodiak Island. In the summer simulations a few releases travelled eastward as far as Icy Bay.

In the winter simulations one release passed around Kayak Island and went southeastward, again under the influence of baroclinic eddies.

From Site Six many of the releases got caught in the anticyclonic gyre west of Kayak Island. Of those that escaped the eddy, many went northward to the Copper River region. One summer release went to the east and landed half way between Kayak Island and Icy Bay. A few of the winter simulations moved westward, north of Middleton Island, and then northwest to Hinchinbrook and Montague Islands.

The releases made at Site Seven generally moved towards Hinchinbrook Island and Prince William Sound. Some of the summer releases traveled east to the mouth of the Copper River and some went west, as far as the southern region of Montague Island. The spatial variability was less for the winter simulation, but one release left this region by going first south and then west.

When the trajectories of the oil spill simulations and those of current drifters (Figs. 3.24-3.26) can be compared, the differences are striking. Almost all of the drogues moved inshore and then were advected quickly along the coast to the west. Few of them moved off the shelf. In contrast, several of the simulated releases went off the shelf. Interestingly, some of the simulated releases were advected to the southeast instead of toward the southwest. In general, the simulated releases were more dispersed and had smaller net displacements. It is possible that much of the noise in the drogue trajectories was removed by the data-smoothing techniques of Hansen (1977a). Although the simulations do not appear to be good representations of the drogue trajectories, there are a number of differences (time of year, data time increment etc.) in the conditions of the two studies. Also the drifter drogues were deployed at 35 m depth while the simulations were made for the surface.

3.6 SUMMARY

Circulation in NEGOA consists of three major regimes. Seaward of the shelf edge is the Alaska Current, with an eddy-infested region lying inshore of it. Near there is a strong westerly coastal jet, while over the continental shelf there is a weak mean longshore flow (Fig. 3.36).

3.6.1 Alaska Current

The Alaska Current, part of the counterclockwise gyre in the Gulf of Alaska, flows westward just seaward

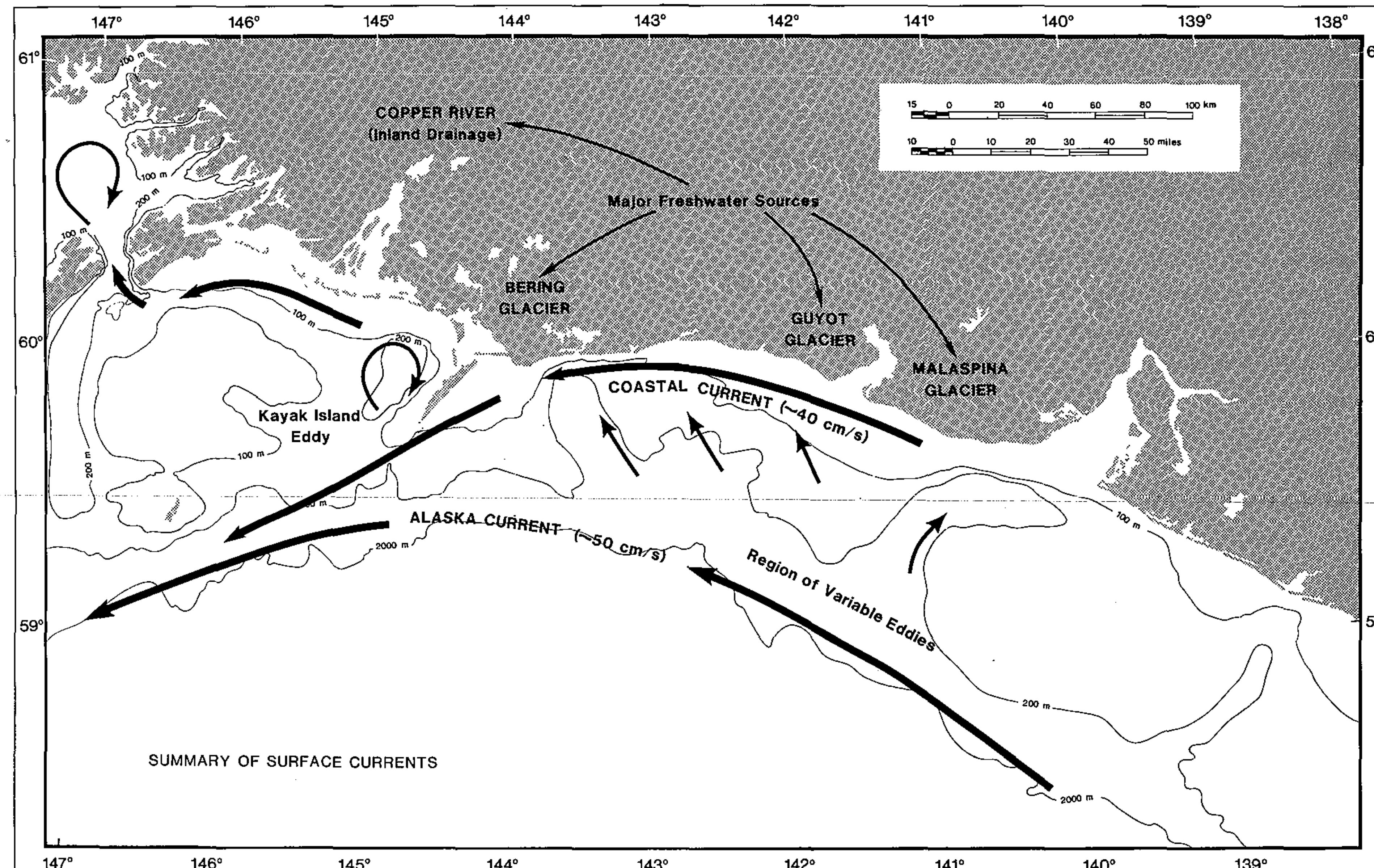


Figure 3.36 Conceptual summary of the surface circulation in NEGOA.

of the shelf break. It has a surface layer of low salinity and a subsurface temperature maximum. Associated with the Alaska Current is a permanent halocline at about 150 m (Galt and Royer, 1975) and warm surface water (Royer and Muench, 1977).

The Alaska Current is a narrow (less than 75 km in width), high speed flow. Mean speeds are probably about 60 cm/s, but extreme speeds greater than twice this value have been reported. Mean transport for the Alaska Current has been estimated by Reed et al. (1979) to be 9.5 x 10^6 m^3/s (0-1,000 db). There is disagreement on whether a seasonal variation occurs in the transport (Royer, 1979c; Reed et al., 1979).

Royer (1979c) describes the Alaska Current as a boundary between the warm, high salinity water of the North Pacific and the cooler, lower salinity water of the continental shelf. It is not stationary, however. Though the Alaska Current generally parallels the shelf break, it does meander inshore and offshore.

Large (100 km in diameter) eddies are found inshore of the Alaska Current. Although they do not propagate onto the shelf, these eddies have a lifetime of about two months. At high frequencies (time scale of two to several days) the eddies are vertically coherent and largely barotropic. However, they also have a baroclinic component. Baroclinic geostrophic speeds of 46 cm/s (0-1,000 db) have been estimated.

3.6.2 Coastal jet

Trajectories of drogues (Royer et al., 1979) have shown the presence of a narrow coastal jet. It has also been observed in nearshore hydrographic data (Royer, 1979b). Distributions of suspended matter (Molnia and Carlson, 1978; Feely et al., 1979) clearly show the advective effects of this current as sediments are carried towards the west with some apparent offshore advection.

The coastal current or jet is 20-30 km wide. Typical baroclinic speeds are 15-40 cm/s. It appears to be stronger in fall and winter, probably in response to increased levels of fresh water discharged along the coast. The barotropic component of the coastal jet is largest during winter when strong winds cause sea level setup.

Royer (1979a) has shown that seasonal variations in coastal sea level are caused by changes in local steric values, which are caused by seasonal changes in the influx of fresh water along the coast. Thus, seasonal changes in speed of the coastal jet are baroclinic. However, on shorter time scales (on the order of a day to a week) the coastal jet varies barotropically with changes in the wind field.

A coastal current appears to be present throughout the Gulf of Alaska. Although it is diverted offshore by Kayak Island, a new current forms west of Kayak Island largely because of the influx of fresh water from the Copper River.

3.6.3 Circulation on the continental shelf

Mean currents over the continental shelf are weak in comparison to the strong Alaska Current and to the strong coastal jet. Flow is longshore towards the west, but there is also considerable cross-shelf flow. Buoys drogued at 35 m depth undergo rapid onshore advection over the shelf (Royer, et al., 1979). Current meter records at one mooring show onshore flow at all depths below 20 m. Thus, although there are few observational data, (see Fig 3.28) there may be a strong offshore flow in the upper 20 m (to conserve mass). If this strong offshore flow does exist, it probably would advect surface pollutants (e.g., crude oil) seaward, away from coastal resources. However, Royer (1979b) states that near-bottom flow measured by current meters is generally offshore. Conservation of mass could be met by this flow.

Low-frequency (time scales longer than a month) dynamics are controlled to a large degree by levels of coastal precipitation and runoff. Variations in steric heights over the shelf near Seward can be accounted for almost entirely by variations in the coastal influx of fresh water. At Yakutat, where there is less precipitation and a narrower shelf on which fresh water can be contained, the influence of the influx of fresh water on sea level is smaller. At higher frequencies (time scales of one to a few days) winds control sea-level fluctuations. Hayes (1979) has shown that the sea level (bottom pressure) responds to onshore winds in shallow waters, while in deeper water (depths greater than 50 m) set-up from longshore wind is dominant.

Kayak Island, which separates the relatively wide continental shelf to the west from the narrower shelf to the east, is an important topographic feature that controls circulation. It also forces the coastal jet and the Alaska Current into close proximity. Directly west of Kayak Island is a permanent, clockwise eddy. It has a strong baroclinic component, with speeds estimated to be 15-30 cm/s (for 0-100 db). Apparently, low-density water is supplied to the eddy by the coastal current, and this water provides at least some of forcing for the eddy. Galt (1976) postulates that this eddy is a potential site for the accumulation of surface pollutants.

On the shelf west of Kayak Island mean currents are weak. Local wind forcing dominates this large, shallow region. Near the coast flow is controlled largely by freshwater discharge from the Copper River.

Baroclinic geostrophic currents toward the west are established by this outflow. Suspended matter from the Copper River appears to be advected westward and into Prince William Sound, largely through Hinchinbrook Entrance (Feely et al., 1979).

On the seaward edge of the continental shelf the Alaskan Current influences circulation. Eddies formed on the landward side of the Alaskan Current transfer momentum to the shelf. However, it appears that the eddies do not propagate onto the shelf (Hayes, 1979). Royer (1979b) suggests that eddies observed on the shelf formed in the western Gulf of Alaska and propagated eastward.

3.6.4 Exchange with Prince William Sound

Prince William Sound is a deep (450 m) basin connected to the Gulf of Alaska through two relatively shallow (100 m and 200 m) channels (Schmidt, 1977). Exchange of water between the sound and the gulf is important to the dynamics of each and is important in assessing the potential effects of pollutants.

Recent drogue studies (Royer et al., 1979) have shown that there is a flow into the sound in the near surface layers. This could be an ageostrophic flow due to differences in density of the water in the sound and just outside it (Royer et al., 1979). Schmidt (1977) states that water at depths greater than the sill depths are exchanged through advective inflow at depth and turbulent diffusion. Below the surface mixed layer but above the sills, exchange is affected by advective intrusions of ocean water. Diffusion processes probably occur throughout the year, whereas advective ones may occur only in the summer (Schmidt, 1977).

Since direct observations of currents very near the surface have not been made, it is uncertain whether surface-borne pollutants would enter Prince William Sound. However, the observation of suspended matter in surface (5 m deep) waters (Fig. 3.28) suggests that there is inflow through the eastern entrances to the sound.

3.6.5 Forces controlling circulation

Winds drive barotropic motions on the time scale of a few days. On shorter scales, winds undoubtedly cause surface advection and mixing. However, there is no evidence that seasonal changes in the wind field cause seasonal changes in the circulation.

The coastal influx of fresh water is a major driving force. Seasonal changes in the discharge drive seasonal changes in the nearshore region. Precipitation and runoff are the source of low-density water that sustains the horizontal pressure gradient which drives the Alaska Current.

Winds and the influx of fresh water act in concert in determining coastal dynamics. Low-salinity surface water is held against the coast by the strong downwelling tendency in winter winds. In summer, when the magnitude of the upwelling index is small, surface waters are not pushed onto the coast and, partially as a result of this, the baroclinic forcing of longshore currents is reduced.

Bathymetry plays an important role in determining circulation through the gulf. Mean flows are largely parallel to bathymetry. Troughs in the shelf appear to divert flow shoreward. Kayak Island diverts the coastal current seaward which provides low-density water that drives the clockwise-rotating, baroclinic eddy west of Kayak Island. Also, Middleton Island shoals block the westward current and force it inshore or offshore.

The Alaska Current is important as a source of momentum. However, the mechanisms by which momentum is transferred onto the shelf are not understood.

CHAPTER 4 CHEMISTRY

K. W. Fucik, SAI

4.1 INTRODUCTION

Terrigenous, biogenic, and petrogenic hydrocarbons all occur in the marine environment. Terrigenous and biogenic hydrocarbons occur naturally. One of the goals of OCSEAP is to assess changes in the Alaskan marine environment 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 measured. 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 about 20 m 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 effect of the *Metula* spill is unknown but may be significant at heavily oiled sites (Straughan, 1978). The *Amoco Cadiz* spill contaminated littoral communities immediately (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 (Armstrong et al., 1979). If these toxic metals are incorporated into the marine food web, they could 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 Water column concentrations

Hydrocarbon levels in the surface waters of NEGOA were measured at a series of standard hydrographic stations (Fig. 4.1) at various times from 1974 to 1976 (Shaw, 1975; 1976; 1977). The analyses indicated low levels of hydrocarbons that are characteristic of unpolluted areas (Table 4.1). The results are similar to those from other areas of the Alaskan Outer Continental Shelf. Higher levels in April and May than in winter probably reflect the higher biological activity during the spring. This suggests that hydrocarbons are biogenic. No spatial trends in hydrocarbon distributions are evident, although a larger sample might reveal one.

Gas chromatograms from samples collected near known oil seeps between Katalla and Icy Bays showed that these oils are highly weathered petroleum. They are quite unlike the hydrocarbons found in the surface waters and sediments of this area.

Tar was found in only 8 of 37 seston tows. Less than 10 mg of tar were collected from every station but

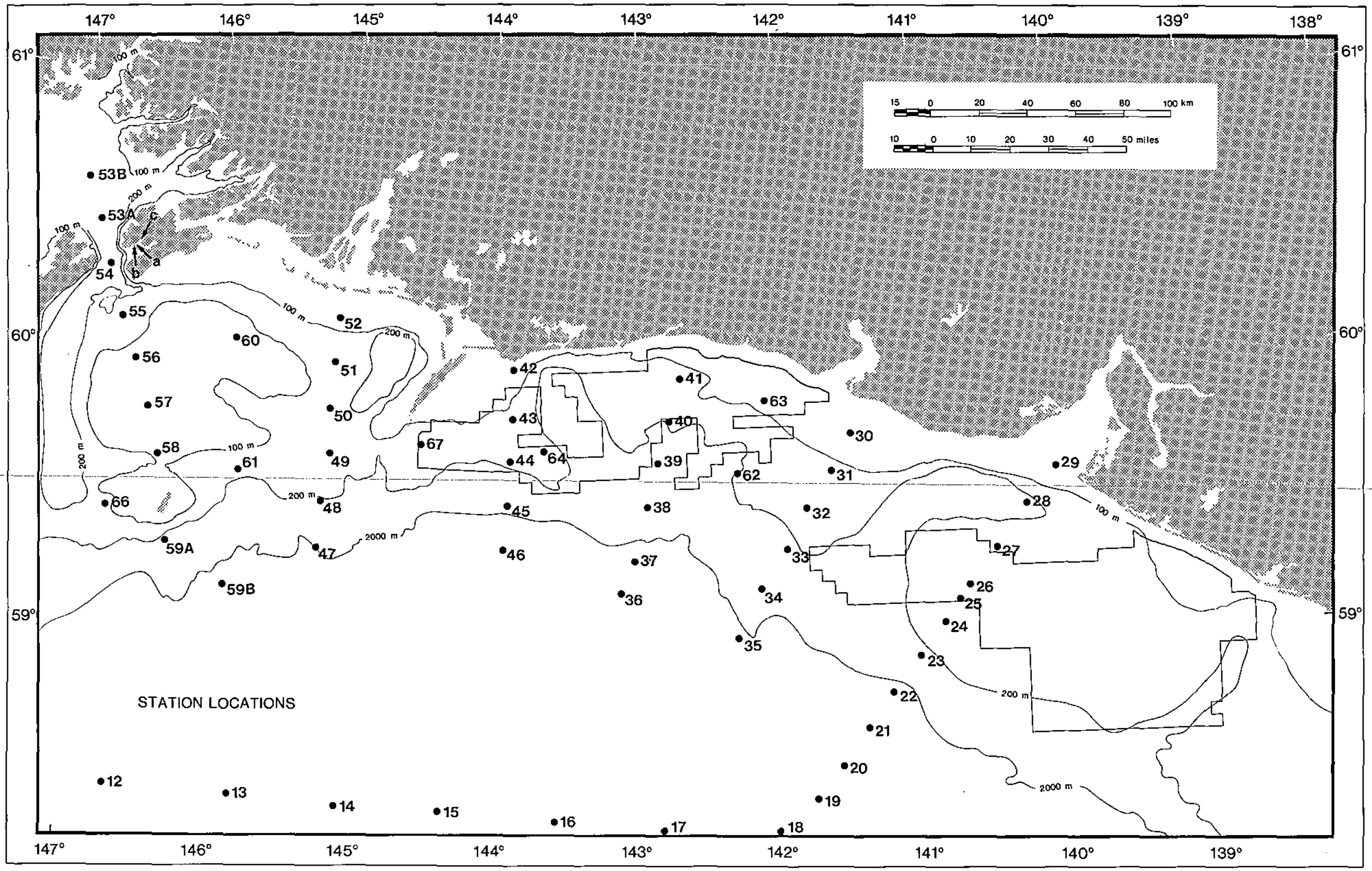


Figure 4.1 Chemical sampling stations in NEGOA.

Table 4.1 The levels (mg/kg) of hydrocarbons in the waters of NEGOA at various times in 1975 and 1976, (Shaw, 1975; 1976; 1977).

Station No.	DATE 2/75*	5/75	9/75[1,2]	11/75[1]	2/76[1]	9/76[1]
1			ND ND	C C	0.11 ND	
2					0.07 ND	ND 0.08
3					0.17 0.02	
4					0.32 0.02	
5					0.03 ND	
6		12.8	C C	C C	0.02 ND	1.53 0.16
7					0.04 ND	
8					0.12 0.10	
9			C C		ND 0.09	
10					0.11 0.24	
11					0.15 0.22	
15				0.32 0.87	0.09 0.15	1.00 0.95
22	10.0					
23				ND ND		
24			C C		0.17 ND	0.54 0.33
26	10.5					
29			ND 0.86	C C	0.56 0.16	
30				C C		0.86 0.59
32	<1 (3.1)			C C		
33	<1 (4.2)					
39				C C		
37	(3.1)	19.7	ND 1.16		0.04 0.08	0.86 0.19
39	<1 (2.5)		C C		0.06 0.07	0.37 0.14
40	<1 (4.2)					
41	(3.4)	13.8	C C		0.18 0.03	1.81 7.72
42	(2.6)					
44	(3.0)					
47	(7.0)		ND 4.25	0.04 0.45	1.51 0.04	1.02 0.36
48	(3.3)					
50			ND <7.0		0.05 ND	2.06 0.08
51	54.2 (offscale)		0.57 2.45			
52			C C		0.05 ND	0.58 0.55
53	(3.9)		ND ND	0.46 0.33	0.11 0.08	
55	(3.3)					
57	(2.5)				0.19 0.07	
58					0.18 0.05	
59	(1.4)					
70					0.49[a] 0.36	
75	9.7				0.06 0.33	
PWS 12	<1 (5.8)					
PWS 107		22.1				

* The number in parentheses was derived from a Tenax extract; the first number was derived from a CCl_4 extract.

1 The two numbers represent hydrocarbons in fraction 1 and fraction 2, respectively. Fraction 1 is a hexane extract and includes saturated and some olefinic hydrocarbons. Fraction 2 contains larger and more extensively unsaturated hydrocarbons, aromatic hydrocarbons, and some non-hydrocarbon organic compounds.

2 ND = Not detected; C = Contaminated sample.

one (48), where 127 mg were found. Seventy-seven seston tows in Alaskan waters covering 740 m^2 of sea surface yielded a mean tar concentration of 2.17×10^{-3} mg/m^2. Overall, these tar levels were lower than those found in other parts of the world's oceans.

4.2.2 Sediment concentrations

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 emulsification (Clark and MacLeod, 1977). Several examples in which the incorporation of petroleum hydrocarbons into the sediments has resulted in chronic pollution have been reported (e.g., Blumer and Sass, 1972; Vandermeulen and Gordon, 1976; Armstrong et al., 1979).

Sediment hydrocarbons have been analyzed from only a few locations in NEGOA. Shaw (1975) found total hydrocarbon levels ranging from 1.1 to 26.3 μg/g wet sediment (Table 4.2). The C_{14}-C_{30} hydrocarbons represented a small fraction of the total hydrocarbons present, with weights ranging from 0.2 to 17.5 μg/g wet sediment. Kaplan (1976) found that the amount of organic matter in the sediments was less than 1 percent. The total weight of the hydrocarbons ranged from 141 to 196 μg/g dry sediment. When broken down to its component parts, the saturated fraction contained the lowest amount of extractable material and the polar component contained the most.

Table 4.2 Weights of total hydrocarbons in the sediments of NEGOA.

Station	Shaw (1975)[a]	Kaplan (1976)[b]				
		% organic carbon	Solvent extractable	Liquid chromatography Saturated	Aromatic	Polar
1	4.5					
3	16.2					
6	13.7					
9	2.4					
13	10.9					
16	5.3					
19	1.4					
22	1.2					
26	3.7, 1.1					
30	3.1					
32	13.0					
37	5.0					
39	7.2					
41	17.2	0.84	143.1	7.07	31.80	70.67
42	12.5					
43		0.66	141.1	18.71	18.71	76.92
44	11.1					
48	16.0, 14.8					
50	22.1, 15.1	0.78	170.4	29.77	47.97	82.70
51		0.73	195.8	26.11	11.19	143.60
52	14.4	0.81	146.4	15.52	28.83	88.73
53	15.9					
55	7.8	0.92	162.3	20.55	26.71	100.68
57	26.3					
59	18.5					
75	16.7					
PWS 107						
PWS 12	3.0	0.92	159.6	12.27	39.27	98.18

[a] μg hydrocarbons/g wet sediment.

[b] μg hydrocarbons/g dry sediment.

Attempts to determine the origin of the hydrocarbons were inconclusive. Shaw and Kaplan found no traces of phytane in the sediments. Shaw noted the absence of a large unresolved envelope in the chromatogram traces. This is in contrast to sediment samples collected near known oil seeps in NEGOA that were characterized by highly weathered petroleum (hence, a large, unresolved envelope). Both findings suggest that the hydrocarbons are biogenic. A petroleum origin for these hydrocarbons is supported by the absence of odd chain lengths in the hydrocarbons of the benthic sediments (Shaw, 1975) and by Kaplan's (1976) finding that the odd/even ratio for his samples was greater than 1 but did not approach the higher values (∿2) often observed in young sediments. This ratio is near unity for petroleum, whereas biosynthesized n-alkanes usually have odd carbon numbers. Further evidence for a petroleum origin was an absence of C_{17} or C_{22} olefinic hydrocarbons, often associated with young sediments in which the organic matter is largely derived from plankton (Kaplan, 1976).

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 Hydrocarbon levels in the biota

Marine organisms accumulate petroleum hydrocarbons either directly from the water or by ingestion. Laboratory and field studies have shown that some organisms accumulate hydrocarbons until they die or are removed from the hydrocarbon source. Once removed from the source, most organisms can rid themselves of the hydrocarbons accumulated in their tissues. Crustaceans and fish can also metabolize hydrocarbons. Little is known of the 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 species, life stage, nature of the oil (i.e., crude or refined), and the degree and duration of exposure (Rice et al., 1977). Most of our present knowledge comes from laboratory studies.

Only ten samples of biota collected from NEGOA have been analyzed for hydrocarbons. These include samples of *Fucus distichus*, *Mytilus edulis*, *Chionoecetes opilio*, and the flesh of *Theragra chalcogramma* (Table 4.3).

Analyses of *F. distichus* collected throughout Alaska showed that the variability of biogenic hydrocarbon composition is less than for animals with variable diets. Nevertheless, hydrocarbon changes occur with changes of season, growth, and reproductive cycle. The *M. edulis* samples from Simpson Bay in Prince William Sound were very low in hydrocarbons. None of these were petroleum hydrocarbons, suggesting that the area is free of petroleum contamination. The samples of *C. opilio* had a negligible level of hydrocarbons, while those of *T. chalcogramma* had none.

Table 4.3 Hydrocarbon concentration (mg/g) in plant and animal species collected in NEGOA (Shaw, 1977).

Species	Location	Total hydrocarbons concentration
Fucus distichus	Katalla Bay	22.0
F. distichus	Resurrection Bay	26.3
Mytilus edulis	Simpson Bay	3.4, 0.68
Chionoecetes opilio (entire)	59°37.0'N-141°35.0'W 59°35.0'N-141°29.0'W	62.8
Theragra chalcogramma (flesh)	59°37.0'N-141°35.0'W 59°35.0'N-141°29.0'W	3.36

4.3 DISTRIBUTION OF METHANE, ETHANE, PROPANE, BUTANE, AND OLEFINIC HOMOLOGS IN THE WATER COLUMN

4.3.1 Concentrations of low-molecular-weight hydrocarbons in NEGOA

Low-molecular-weight hydrocarbons (LMWH) are ubiquitous in waters of the Alaskan shelf (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, supports the theory of cyclonic circulation in the outer part of Norton Sound and the clockwise gyre south and west of Kayak Island in the Gulf of Alaska.

Three cruises were conducted in NEGOA during October and November 1975 and April and July 1976 (Cline et al., 1978). Levels of methane, ethane and ethene, propane and propene, and butanes were measured.

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	100-1,500	100-900	60-600	200-2,000[3]	200-3,000[3]	150-2,000
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	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05
n-Butane	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05
$C_{2:0}/C_{2:1}$	< 0.5	≤ 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 levels in the surface shelf waters usually ranged from 100 to 300 nl/l. Surface concentrations sometimes exceeded 300 nl/l southwest of Kayak Island, possibly because of the anticyclonic gyre observed in the area. Concentrations of 600 nl/l were measured near Icy Bay in July 1976; these were probably related to the high biological productivity observed at this time (Fig. 4.2). The highest methane concentration measured was 1680 nl/l at the entrance to Yakutat Bay. It is not known, however, whether this concentration was caused by high primary productivity or by the surface entrainment of petrogenic hydrocarbons from the bay.

Offshore concentrations (from those samples taken beyond the shelf) were less than 100 nl/l and were presumably approaching saturation with the overlying atmosphere.

Methane levels were higher and more variable in the near-bottom waters, reflecting the proximity of these waters to a bottom source. The variability suggests intermittent sources and/or variable circulation patterns. Methane concentrations in the bottom waters ranged from 100 nl/l to about 1,500 nl/l. Very high levels in the bottom waters were observed near Tarr Bank, where fine-grained sediments rich in organic matter are prevalent. The major source of methane in the 1975 samples was the Hinchinbrook Sea Valley near Montague Island, where near-bottom waters drift toward the east. This area had variable methane concentrations, usually above 400 nl/l. There was little indication of advective drift in April and July 1976. The major source of the methane during July appeared to be an area north of Tarr Bank. The April methane levels were lower than either the October-November or July concentrations and reflected the distribution of fine-grained sediments.

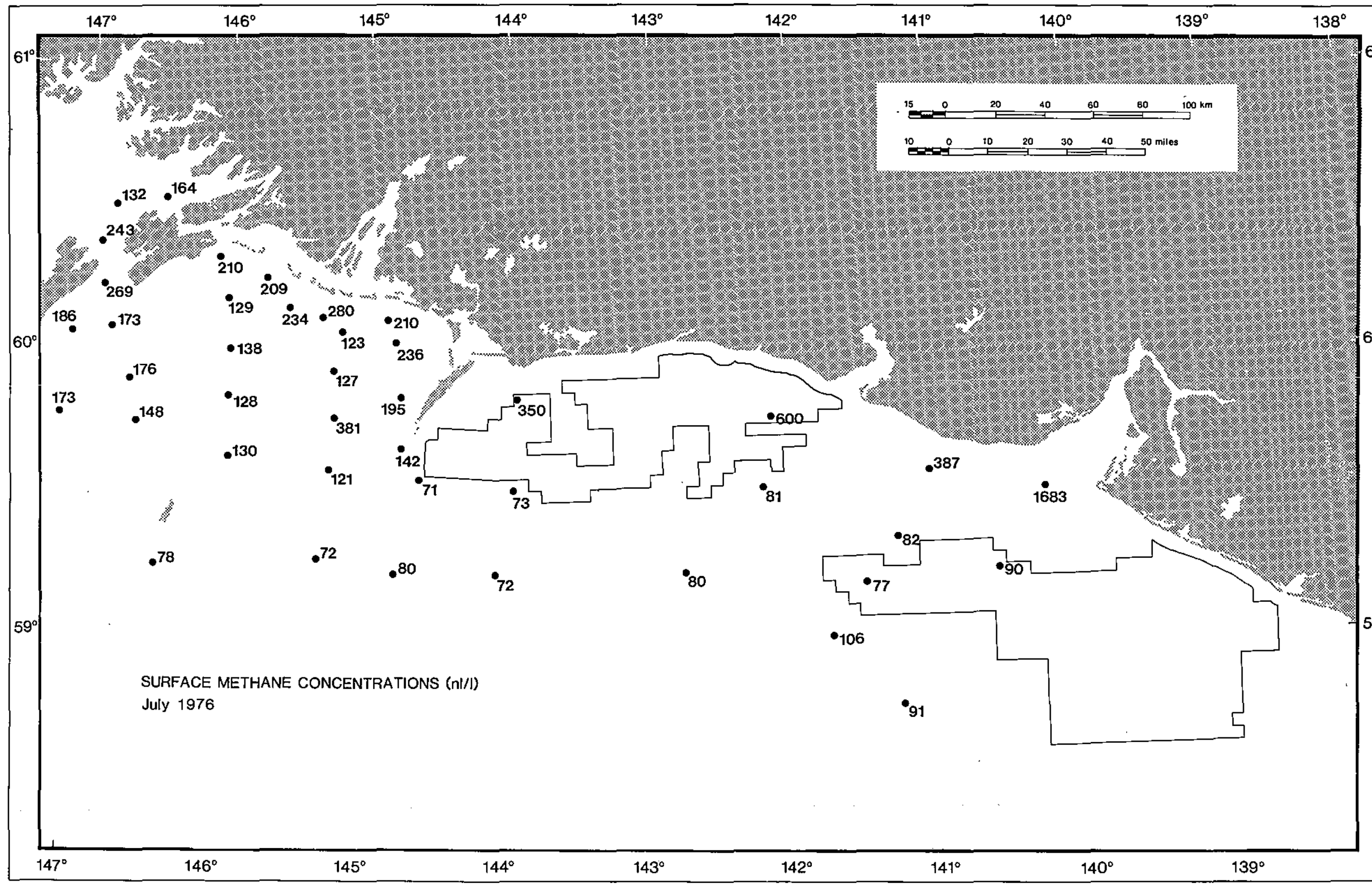


Figure 4.2 Areal distribution of methane (nl/l) in surface waters during July 1976 (Cline et al., 1978).

Ethane and ethene

The concentration of ethane in the surface waters showed little seasonal variation between October and November 1975 and April 1976. The average concentration ranged between 0.2 and 0.5 nl/l. No localized sources were apparent, suggesting that these levels represent a near-equilibrium with respect to the atmosphere. In July 1976, however, average concentrations increased sharply, and a strong source was evident near Yakutat Bay (Fig. 4.3). The area with the highest concentration measured, 11.4 nl/l, also had high concentrations of methane and propane. The presence of a phytoplankton bloom would suggest a

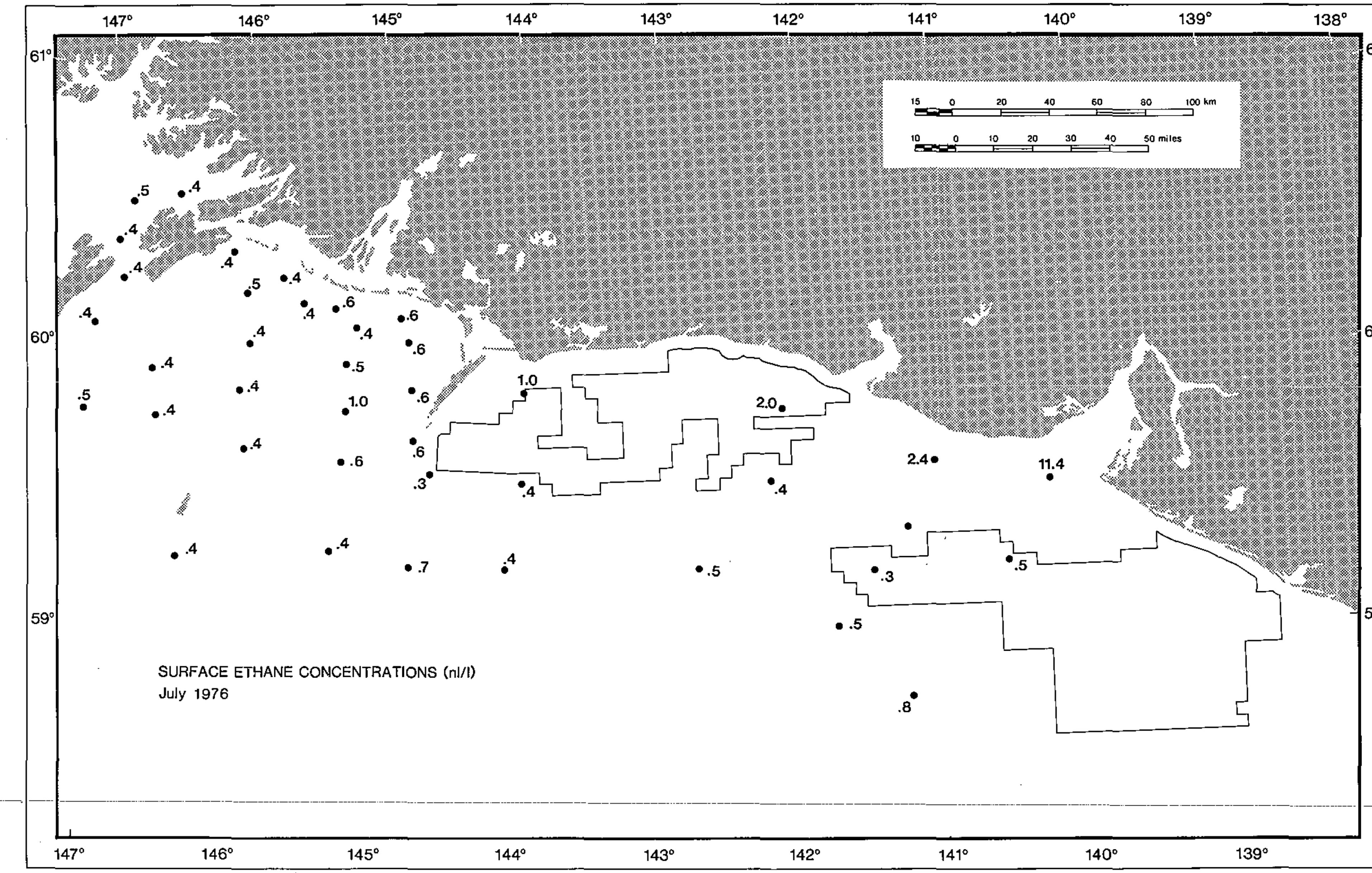


Figure 4.3 Areal distribution of ethane (nl/l) in surface waters during July 1976 (Cline et al., 1978).

biological origin except that ethene concentrations were not abnormally high (Fig. 4.4). Previous measurements in Alaskan waters showed that ethene concentrations exceed those of ethane by a factor of two or more during periods of high productivity. This suggests that the source of low-molecular-weight hydrocarbons may have been a gas or oil seep. The highest concentrations of ethane and propane were found at the surface, indicating that the source was within Yakutat Bay and had been advected seaward.

Bottom ethane concentrations ranged from 0.2 to 1.3 nl/l, averaging 0.4 nl/l. The single high value was recorded near Tarr Bank.

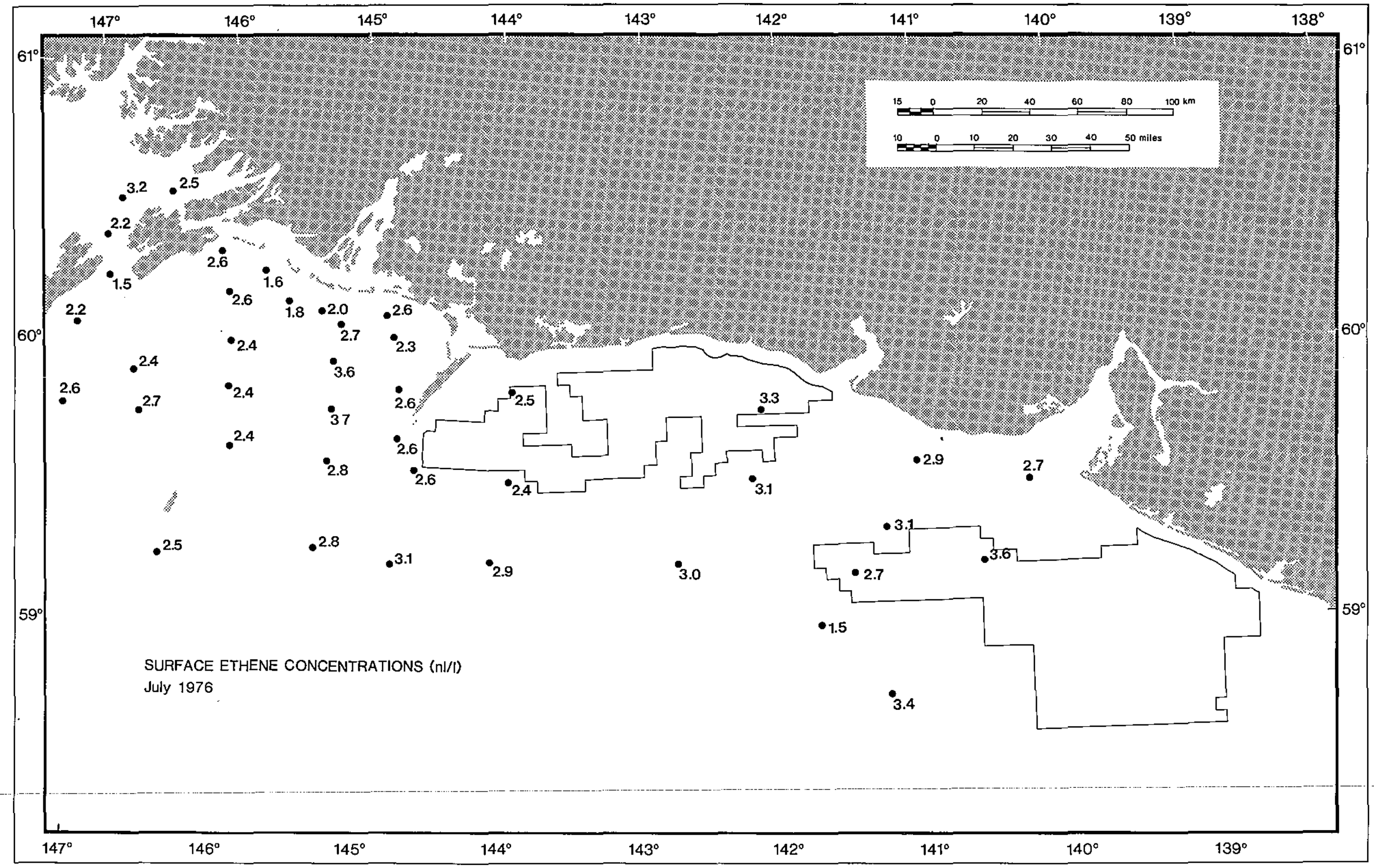


Figure 4.4 Areal distribution of ethene (nl/l) in surface waters during July 1976 (Cline et al., 1978).

Propane and propene

Propane, too, showed little seasonal variation between October and November 1975 and April 1976. Concentrations averaged 0.4 nl/l, decreasing to 0.2 nl/l toward the east (Fig. 4.5). High concentrations were noted at the entrance to Yakutat Bay during July 1976 but were not accompanied by similar increases in propene (Fig. 4.6). Levels of propane at the near-bottom were similar to those observed at the surface. Levels were near 0.2 nl/l with a high of 0.6 nl/l near Hinchinbrook Island and Tarr Bank in July. These values, however, are similar to those observed over the slope and do not suggest the presence of either oil or gas seeps.

Butanes

Concentrations of iso- and n-butanes were very low or undetectable at all locations in both surface and near-bottom waters.

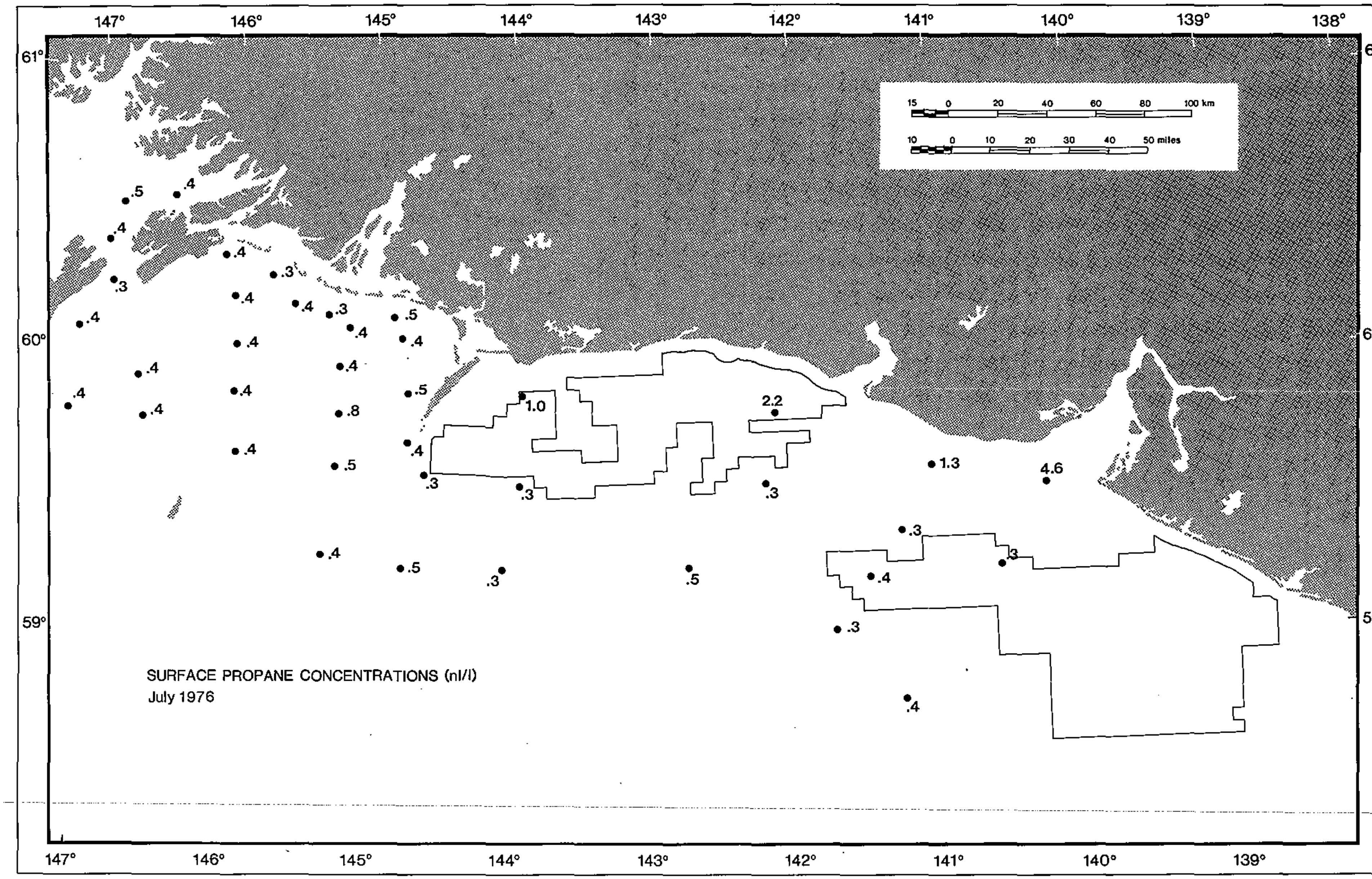


Figure 4.5 Areal distribution of propane (nl/l) in surface waters during July 1976 (Cline et al., 1978).

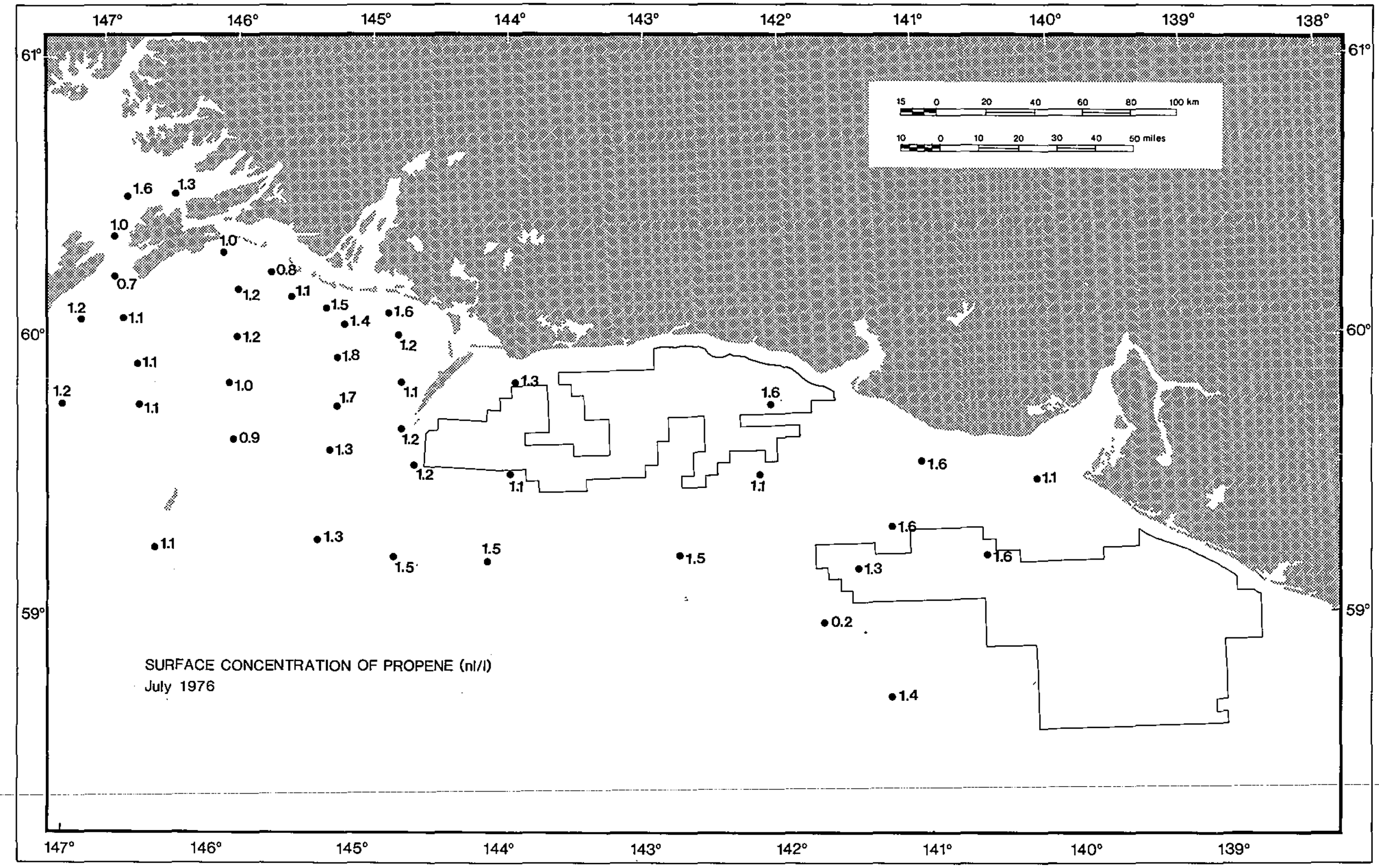


Figure 4.6 Areal distribution of propene (nl/l) in surface waters during July 1976 (Cline et al., 1978).

4.4 DISTRIBUTION AND CONCENTRATION OF TRACE METALS

4.4.1 Concentrations of trace metals in the water column

The water column in NEGOA was sampled for trace metals during several periods (Burrell, 1976; 1977; 1978; Robertson and Abel, 1979). Sampling was conducted at standard hydrographic stations between Yakutat Bay on the east and Resurrection Bay in the west (Fig. 4.1). Levels of cadmium, lead, copper, zinc, antimony, uranium, cesium, rubidium, iron, cobalt, inorganic and total mercury, and vanadium were measured.

The results from NEGOA waters were similar to those from other Alaskan OCS areas and were uniformly low for all metals. On the whole, average levels of trace metals throughout the Gulf of Alaska are lower than the generally accepted oceanic means (Table 4.5).

Table 4.5 A comparison of soluble trace element concentrations (mg/l) in Gulf of Alaska bottom waters and the oceanic means. The soluble fraction includes particles less than 0.4m (Burrell, 1978).

Element	Gulf of Alaska mean	Oceanic mean[a]
Ag	0.009[b]	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

[a] Brewer (1975)
[b] surface estuarine-fiord water

In addition to the survey work on the shelf, Burrell (1978) studied the vertical distribution of manganese and vanadium at two stations in Yakutat Bay. Vanadium was evenly distributed throughout the water column, but manganese showed increased concentrations with depth (Fig. 4.7). These data suggest that metals, important fluxes of at least some heavy metals occur at the sediment-water interface.

Robertson and Abel (1979) measured trace metal concentrations in particulate matter suspended in the water column. Metals concentrations were generally higher in nearshore versus deep waters and in near-bottom versus surface waters. However, higher surface than near-bottom concentrations were measured at Stations 44, 49, 50 and 59A, suggesting a surface plume of high suspended sediment load or intense plankton blooms.

The trace metals concentrations in the suspended particulate matter were consistent with those found in mid-latitude, uncontaminated coastal regions. Concentrations on the Alaskan shelf varied greatly from station to station, however, precluding comparison of lease areas. This variability reflects fluvial influx and transport of terrigenous materials, storm resuspension of sediments, and biological processes.

Robertson and Abel (1979) found that the concentrations of dissolved vanadium, antimony, uranium, cesium, and rubidium tended to be uniform in Alaskan waters and independent of the amount of suspended particulate matter in the water. In contrast, concentrations of manganese, zinc, cobalt, and iron were quite variable and influenced by the amount of suspended matter. The uniform distribution of dissolved vanadium levels on the Alaskan shelf would make this metal a sensitive indicator of oil contamination.

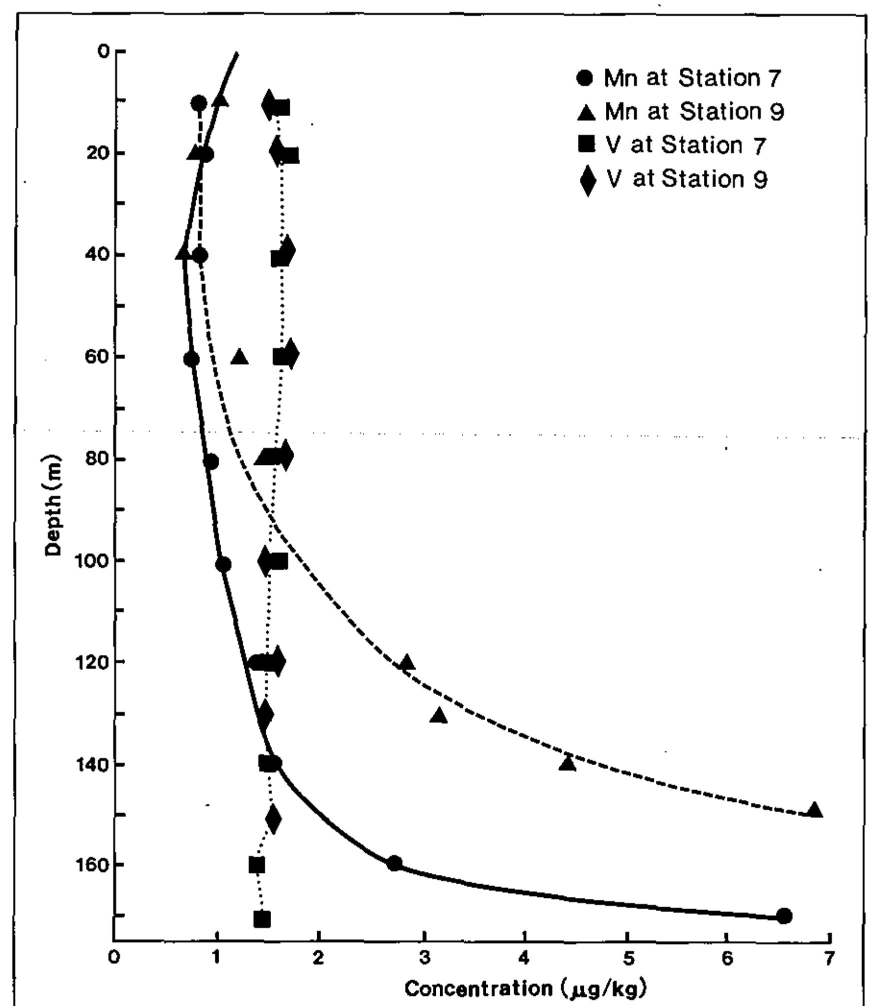


Figure 4.7 Soluble (0.4 m) manganese and vanadium at Stations YAK-7 and -9, Yakutat Bay, June 1977 (Burrell, 1978).

4.4.2 Concentrations of trace metals in sediments

The levels of heavy metals in the sediments at several stations in NEGOA were determined by Burrell (1978) and Robertson and Abel (1979). Metals concentrations in the sediments increase nearly twofold from the Bering Sea to the Western Gulf to the eastern Gulf of Alaska. Nevertheless, metals concentrations in all of the Alaskan shelf areas are typical of those of uncontaminated, mid-latitude coastal regions.

Leaching experiments were performed to determine the fraction of metals readily available from the sediments. This "available" fraction is thought to represent that part of the total sediment repository which are subject to biological assimilation or alteration and/or release of metals due to petroleum related activities (Robertson and Abel, 1979). Burrell (1978) reported that the percent of extractable metals correlated with sediment grain sizes and increased from the Bering Sea to NEGOA. Available Mn, Co, V, Fe, and Sc ranged from 21-82 percent, 11-59 percent, 8-29 percent, 5-27 percent, and 1-10 percent, respectively, of their total concentration in the sediments (Robertson and Abel, 1979).

4.4.3 Concentrations of metals in the biota

Concentrations of sixteen heavy metals in the biota of NEGOA have been determined for the alga *Fucus*, the bivalve *Mytilus*, the snail *Neptunea*, rock sole, pollock, and king crab (Burrell, 1977; 1978; Robertson and Abel, 1979). Concentrations of metals in these organisms are consistent with values obtained from the water and sediments and indicate the generally clean nature of the Alaskan marine environment system. Mercury concentrations, which are the most intercomparable with other areas of the world because of the amount of baseline data, were typical of those found in uncontaminated shelf areas of the world (Robertson and Abel, 1979).

In comparison to the other organisms, king crab (Zn, Ag, As) and *Neptunea* (As, Se, Zn, Hg, Fe, Sb, Co, V) tended to accumulate high levels of certain metals (Table 4.6). This tendency to concentrate these metals is not unusual in these organisms. The variability of metals concentrations in *Mytilus* was sufficiently small to make this species a good indicator organism for metals contamination.

Table 4.6 Mean concentrations of selected metals in Alaska OCS biota, (Burrell, 1977; 1978; Robertson and Abel, 1979).

	Number of samples	Ag	As	(Metal ppm dry weight) Cr	Hg	Se	Zn
Crab	12	1.17±0.48	41±10	<0.50	0.33±0.14	5.6±4.2	117±18
Rock sole	9	<0.038	18±9	1.3±1.9	0.27±0.10	2.0±0.7	32±5
Pollock	14	<0.035	4.7±2.4	0.26±0.10	0.12±0.08	1.4±1.2	23±4
Neptunea	5	35±32	71±48	1.1±0.6	2.0±1.5	33±48	3260±26
Mytilus	18	0.087±0.036	7.5±2.8	3.9±3.9	0.23±0.09	2.6±0.5	88±29
Fucus	15	0.130±0.04	17±7	1.9±1.8	0.056±0.026	0.049±0.022	14±3
Seaweed	10	0.062±0.037	11±5	1.7±1.3	0.046±0.034	0.064±0.063	8.6±3.9

4.5 SUMMARY

As in other areas of the Alaskan OCS, the measured hydrocarbon levels indicate an essentially unpolluted environment. Soluble hydrocarbons were probably biogenic, and the levels 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 over three seasons. Their distribution and composition indicate that they are 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.

Sampling of the water, sediments, and biota of NEGOA indicated no contamination by trace metals.

CHAPTER 5 NUTRIENTS, BACTERIA, AND PLANKTON

K. Fucik, SAI

5.1 LOWER TROPHIC LEVELS

Trophic dependencies in ecosystems are often depicted for simplicity as a food chain, i.e., a straight linkage between successively higher trophic links. A more realistic idea, however, is the food web, in which organisms in the ecosystem show trophic dependencies on other organisms at the same or higher trophic levles.

Phytoplankton make direct use of free nutrients and form the basis of the food web in most marine ecosystems. They are the major source of food for zooplankton and some larval forms. In turbid waters, such as some estuaries, where phytoplankton populations are low, detritus and attached bacteria are often directly consumed by zooplankton.

In subarctic marine waters phytoplankton grow most rapidly during the spring or early summer. Light is a major factor limiting primary production during the winter in the subarctic regions, and the increased light levels in spring, coupled with the availability of nutrients (primarily nitrates, phosphates, and silicate) and stabilization of the water column, trigger the accelerated growth, or bloom.

Stability of the water column occurs when density stratification is positive (i.e., density increases with depth). In NEGOA, stability can be induced by either freshwater runoff from land or heating of the surface waters by the sun in the spring and summer. The water column in NEGOA is unstable during the winter, as high winds thoroughly mix the surface layer. Because of the low light levels in the winter, the mixed layer often exceeds the depth of the euphotic zone (the region where active photosynthesis occurs), and primary productivity is lost when phytoplankton are carried out of the euphotic zone. Stabilization of the water column in the spring and summer results in a euphotic zone that extends deeper than the mixed layer.

The stabilization of the water column further affects phytoplankton and their utilization of nutrients. Most of the nutrients utilized by the phytoplankton during the spring bloom have been brought to the surface from the nutrient-rich deeper waters by turbulence. With stabilization of the water column the influx of nutrients from deeper waters ceases, and phytoplankton productivity is eventually limited as nutrients are utilized in photosynthesis.

Bacteria are the primary recyclers of nutrients in the water column. A generalized picture of bacterial distributions in the open ocean shows high numbers immediately below the level of maximum photoplankton activity and at the ocean bottom (Fig. 5.1). The rate of nutrient recycling corresponds closely to the vertical distribution of the bacteria, so that much of the remineralization occurs just below the compensation depth (the depth at which photosynthesis equals phytoplankton respiration) (Russell-Hunter, 1970). In nitrate renewal the organic nitrogen in feces, excreta, and dead tissues is broken down and converted to ammonium, then to nitrite, and finally to nitrate (see Russell-Hunter, 1970, p. 161).

Another source of nitrogen in the euphotic zone is ammonia excreted by zooplankton. This source is particularly important after the water column stabilizes because it represents a continuous source of recycled nitrogen while other forms of nitrogen in the euphotic zone are being depleted, sometimes to undetectable levels. Dugdale and Goering (1967) have termed primary production associated with ammonia

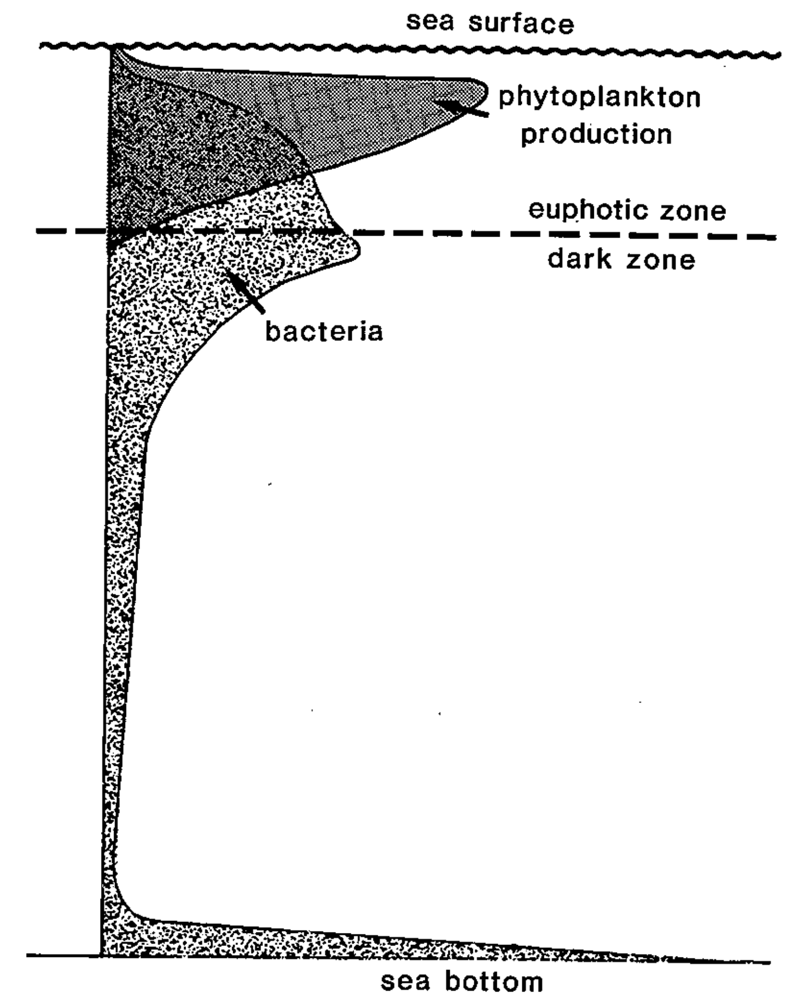


Figure 5.1 Vertical distribution of bacteria compared to that of phytoplankton and to location of the euphotic zone (from Russell-Hunter, 1970).

assimilation "regenerated" production, while that associated with nitrate assimilation they call "new" production. The distinction is that only new sources, such as nitrate from deep water or nitrogen fixation, allow increases in population or production to be passed on to higher trophic levels. The regenerated ammonia, then, maintains existing populations during a period when nitrates are limiting.

In addition to the limits placed on phytoplankton growth by nutrient availability are the effects of predation by zooplankton. As phytoplankton populations begin to increase during the spring bloom, so also do the populations of the zooplankton which feed on them. As zooplankton growth lags behind that of the phytoplankton, however, maximum zooplankton populations are reached sometime after the phytoplankton peak. As this algal food source becomes limiting and predation from higher trophic levels increases, zooplankton populations also decline. In some areas, secondary phytoplankton and zooplankton maxima may occur in the fall. This happens as the water column becomes less stable once again, allowing mixing of the deeper and surface waters, thus providing a renewed source of nitrates in the euphotic zone. Because light levels are diminishing, however, the fall increase is not nearly as dramatic as that observed in the spring.

5.1.1 Bacteria

In the previous section, the role of bacteria in the regeneration of nutrients for phytoplankton production was discussed. However, data on the importance of bacteria for the productivity of marine ecosystems are still scarce. The rate of microbial production in most biotopes is unknown (Sorokin, 1978). Microbes in NEGOA during March 1976 were estimated at an average 1.9×10^5 cells/ml in the water (range: $1.2 - 2.7 \times 10^5$ cells/ml) and an average 1.5×10^9 cells/g dry wt of sediment (range: $0.01 - 3.1 \times 10^9$ cells/g dry wt sediment) in the sediments (Atlas, 1977; Morita and Griffiths, 1977). These values are probably representative of mesotrophic waters (Table 5.1).

Relative microbial activity refers to the breakdown of dissolved organic substances and the resulting formation of microbial biomass. This parameter was measured in NEGOA during March 1976 (Morita and Griffiths, 1977). The relative microbial activity obtained by measuring the uptake of glutamic acid averaged 1.4 ng/l/hr in the water (range: 0.3-3.4 ng/l/hr) and 45 μg/g dry wt sediment/hr) in the sediments (range: 0.1-27.5 μg/g dry wt sediment/hr). Respiration values in the water samples averaged 72 percent of glutamic acid uptake (range: 53-93 percent); respiration in the sediment populations averaged 44 percent (range: 27-72 percent). High respiration percentages indicate that more of the organic substrate taken up by microorganisms is being utilized for energy requirements, with less channeled into biosynthesis that results in increased cell mass. The high respiration percentages can result from bacteria being in a stressed environment, such as one with an inadequate supply of required growth factors. In the water samples the high percentages probably reflect the absence of an adequately balanced nutritional source (Morita and Griffiths, 1977).

Table 5.1 Generalized ranges of total bacterial number (N), estimated by direct count, and of bacterial biomass (B) in surface sea and fresh water and in sediment exhibiting different levels of productivity during the warm season. (from Sorokin, 1978).

	Surface water			Sediment	
Habitat type	N($^{x}10^6$/ml)	B(mg C/m)	Ratio direct count: plate count	N($^{x}10^9$/g)	B(μg C/g)
Polluted estuaries and lagoons	2-10	100-1,000	20-100	5-10	500-1,000
Eutrophic waters	1-3	50-150	100-1,000	2-10	100-1,000
Mesotrophic waters	0.2-1	5-50	1,000-2,000	0.1-1	5-1,000
Oligotrophic waters	0.04-0.2	1-5	2,000-20,000	0.01-0.1	0.2-5

Recent studies (Smith and Wiebe, 1976; Larrson and Hagstrom, 1979) have demonstrated that much of the carbon produced by the phytoplankton is excreted in soluble form and then converted into bacterial biomass. Sorokin (1978) suggests that the major role of bacteria in temperate waters is to transform the excess organic matter produced by phytoplankton into a usable food source for zooplankton. This food source may be important during the period when phytoplankton populations are low. In Kasitsna Bay, Lower Cook Inlet, bacterial activity closely paralleled that of the phytoplankton (Griffiths and Morita, 1980). The relative microbial activity in 1979 increased by three orders of magnitude, from 0.7 (winter) to 135 (summer) ng C/l/hr, leading these workers to suggest that the bacteria could be an important food source in this area. The March samples indicated low microbial activity in NEGOA. This is a period before phytoplankton growth has reached a maximum. More extensive sampling may suggest a more important role for the bacteria in NEGOA.

A large number of organic compounds can be found in the world's oceans. It has been postulated that there is no complex organic molecule ever synthesized by plant or animal that cannot be broken down by one or more forms of marine bacteria (Russell-Hunter, 1970). The wide diversity of the NEGOA microbial community is indicated by the ability of bacteria from NEGOA water and sediment samples to grow on a wide range of organic sources, including carbohydrates, alcohols, carboxylic acids, amino acids, amines, and hydrocarbons (Atlas, 1977). The microbes also exhibited adaptive features such as the ability to grow at low temperatures (Atlas, 1979). The ability to function at low temperatures (Atlas, 1979) as well as the diversity of the microbial communities in NEGOA (Atlas, 1977) are important in maintaining the flow of energy through the system, particularly under variable conditions. Another important function of the bacteria, particularly with regard to offshore oil leasing, is the ability of some bacteria to degrade hydrocarbons and other toxic materials. Some hydrocarbon-degrading bacteria occur in NEGOA, but their numbers are small (≤ 1/ml in water; ≤ 10/g in the sediments; Atlas, 1977). No data are presently available on hydrocarbon degradation rates in NEGOA.

5.1.2 Phytoplankton

Koblentz-Mishke et al. (1970) summarized productivity estimates for the world's oceans. Their data for the Pacific Ocean (Fig. 5.2) indicate that the Gulf of Alaska is among the most productive areas in the Pacific Ocean, with primary productivity ranging from 10 to 100 mg C/m^3/day in the surface waters and an integrated productivity of 0.25 to 0.50 g C/m^2/day. These highly productive areas are generally restricted to coastal areas in the northwest Pacific, the Mexican and Peruvian coasts, and the Alaskan Gulf.

Anderson et al. (1977) summarized the literature from 1958 to 1974 on the factors influencing phytoplankton distributions and production in the Gulf of Alaska according to geographical and oceanographic areas. Data on phytoplankton in areas 17, 18, and 35 of NEGOA (Fig. 5.3) are discussed below. OCSEAP-sponsored field studies of phytoplankton in NEGOA have been limited. Larrance et al. (1977) sampled such phytoplankton parameters as standing crop, productivity, and nutrients at a series of stations in NEGOA and Prince William Sound during October and

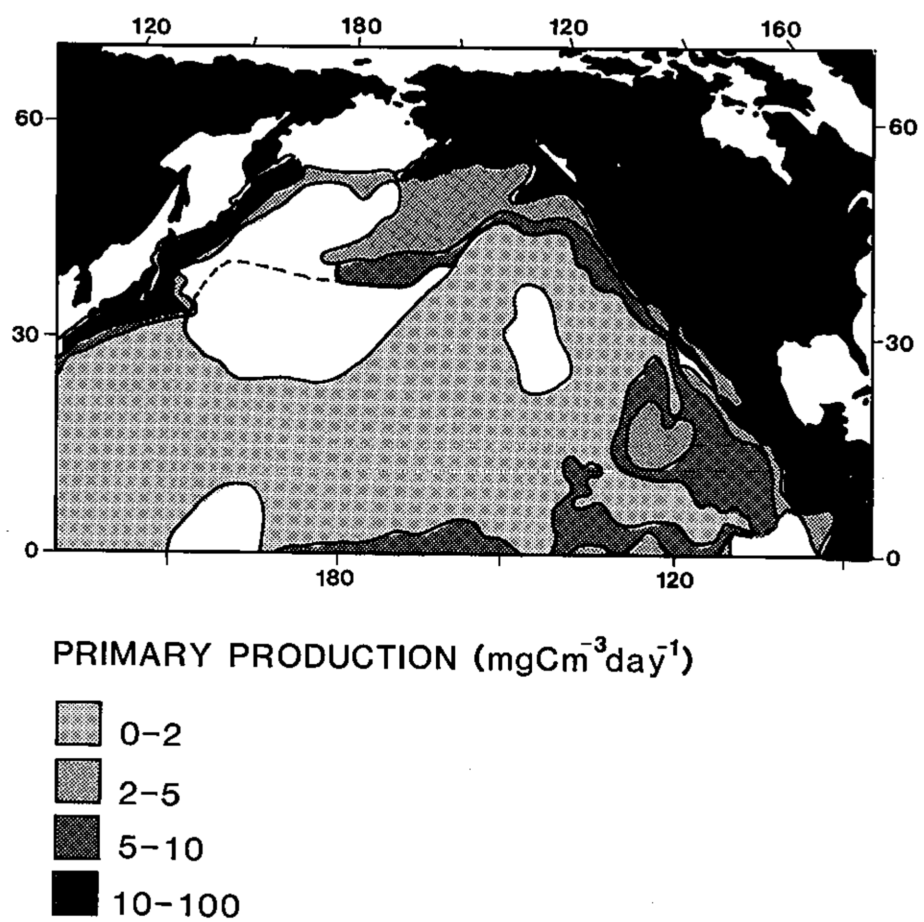


Figure 5.2 Distribution of primary productivity in the surface waters of the North Pacific (Koblentz-Mishke et al., 1970).

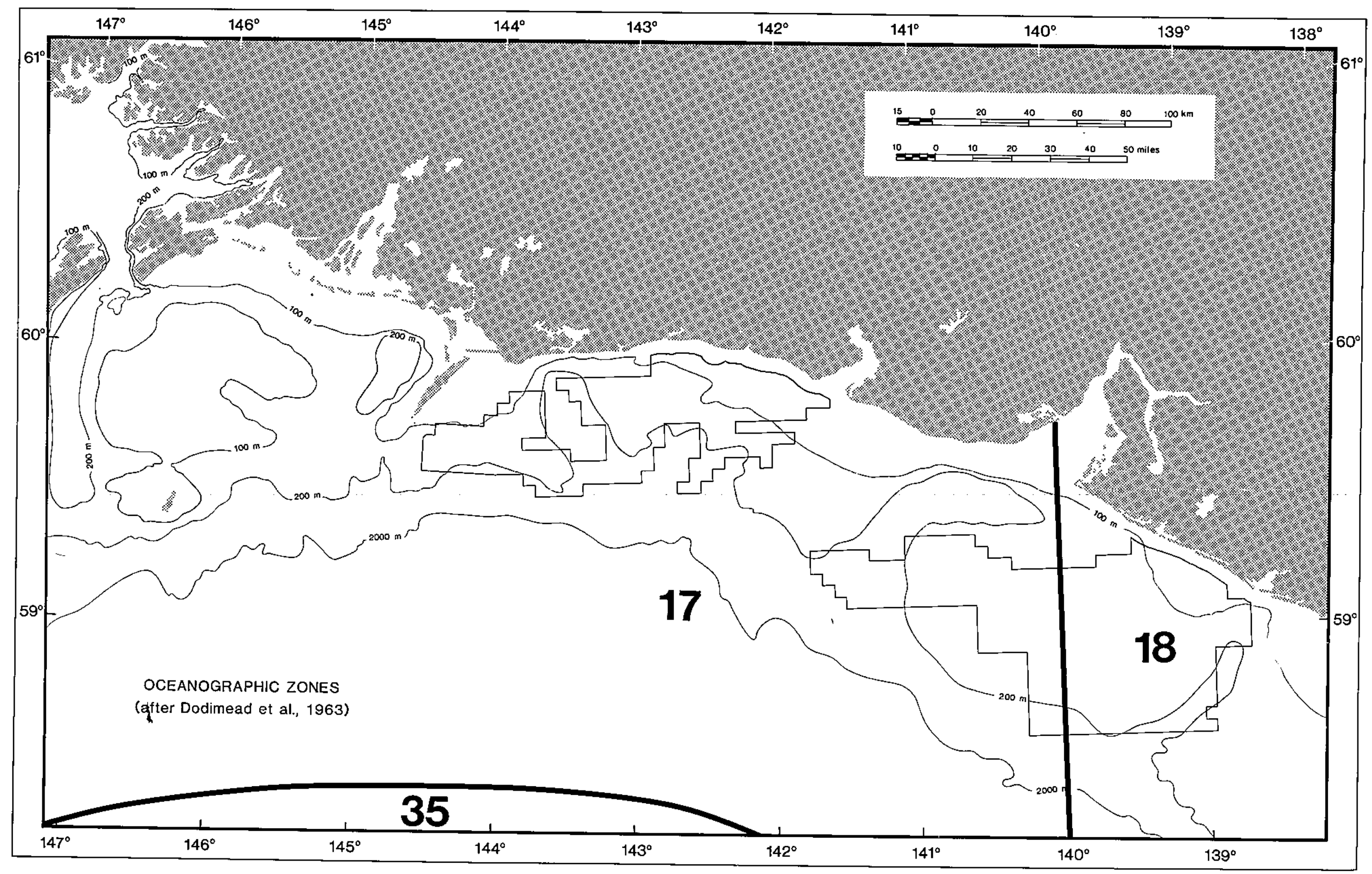


Figure 5.3 The oceanographic zones of the eastern subarctic Pacific (Anderson et al., 1977).

November 1975 and at three stations in NEGOA shelf waters and one in Prince William Sound between April and August 1976.

Anderson et al.'s (1977) average productivity values for areas 17, 18, and 35 of NEGOA were somewhat lower than those values quoted by Koblentz-Mishke et al. (1970). However, Larrance et al.'s (1977) data for integrated productivity measured in NEGOA during April through August and October and November were similar to or higher than that reported by Koblentz-Mishke et al. Averaged over the year the productivity values would probably be similar to those of Koblentz-Mishke et al.

Anderson et al.'s (1977) and Larrance et al.'s (1977) productivity data are consistent with what would be expected concerning phytoplankton patterns in NEGOA. Phytoplankton standing crops (as measured by chlorophyll a) and productivity show surface maxima, with highest values in the spring (Fig. 5.4), intermediate values in summer and fall, and lowest values in winter. Most of this productivity takes place in the upper 25 m of the water column. Larrance et al. (1977) found increasing productivity with distance from shore. Chlorophyll a on the shelf averaged 18 mg/m^2 compared to 33 mg/m^2 off the shelf. These values are much less than the 81 mg/m^2 measured in Prince William Sound. Daily productivity averaged 141 mg C/m^2 in nearshore waters and 522 mg C/m^2 off the shelf. This trend is unusual but probably can be attributed to the inhibitory effects of the turbidity inshore originating from the Copper River and Icy Bay. The lower levels near shore may also be indicative of low nutrient concentrations in the runoff waters. This is supported by Larrance et al.'s (1977) finding that the highest nitrate levels occurred in offshore waters.

If nutrient levels in runoff waters are indeed low, then the importance of nutrient regeneration and

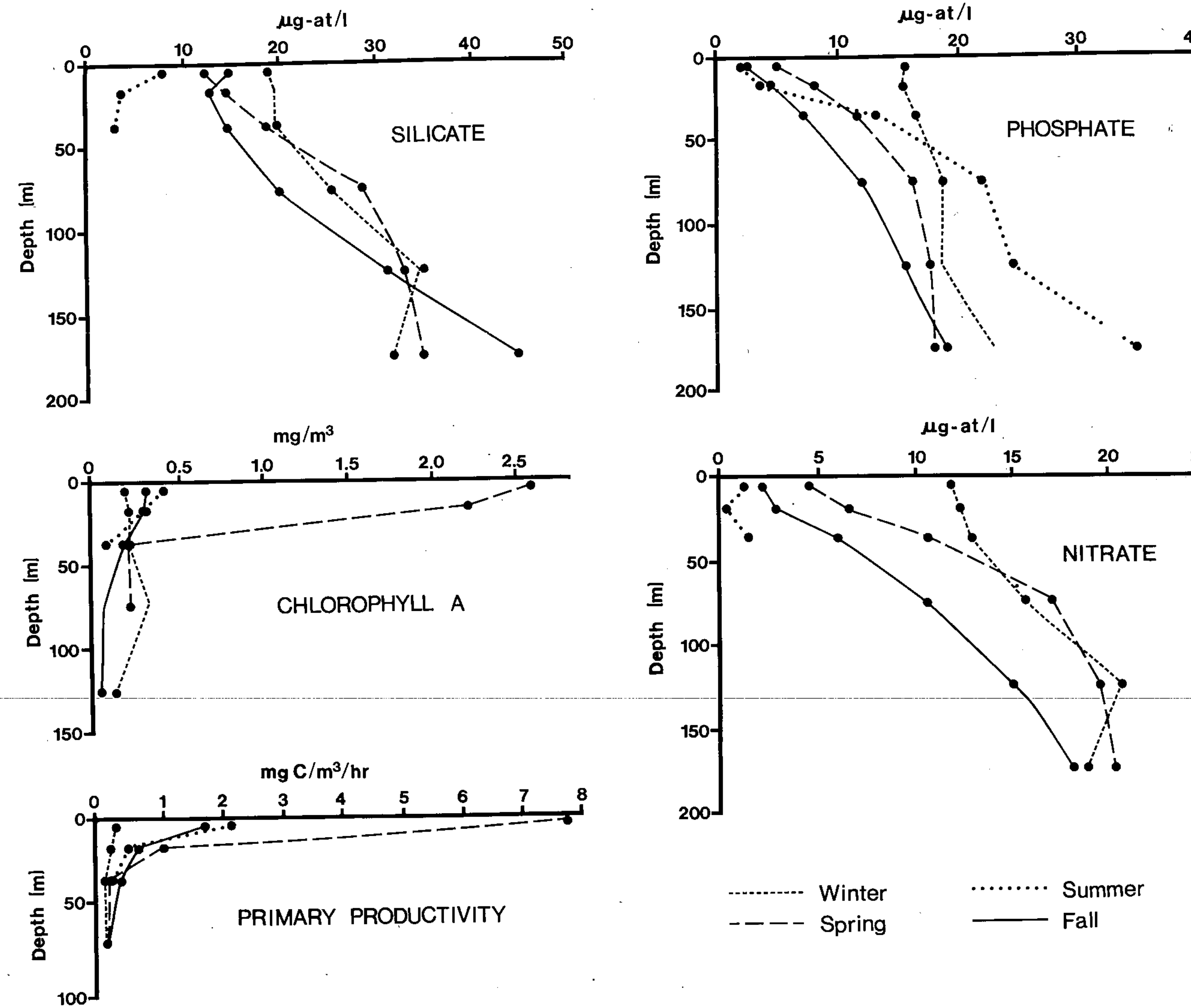


Figure 5.4 Seasonal averages with depth of nitrate, phosphate, and silicate concentrations, chlorophyll a, and primary productivity for Area 17 in NEGOA, 1958-74 (Anderson et al., 1977).

replenishment from deep waters takes on added significance. Nutrient profiles derived from Anderson et al. (1977) show expected patterns for this area (Fig. 5.4). Concentrations of silicate, nitrate, and phosphate increase with depth. The highest surface concentrations occur in winter, when phytoplankton activity and utilization of the nutrients is restricted because of low light levels and a mixed layer that extends below the euphotic zone. Nutrient levels decrease through the spring to summer minima and then begin to increase in the fall when the summer thermocline disappears and the water column becomes less stable. At this time nutrient-rich deep water mixes with the nutrient-depleted surface water. Nutrient levels at depth are similar for most seasons except for higher phosphate levels in the summer. It is not presently known what is causing the increased phosphate levels at depth. Larrance et al. (1977) found no evidence that nutrients limited phytoplankton production during the summer. This suggests that zooplankton grazing is a major limiting factor.

The vertical distributions of nutrients provide some information on water column dynamics. The nearly uniform distributions with depth in the winter, particularly of phosphate, indicates that the water column is well-mixed. Stratification of the water column is more apparent in the summer distributions.

Nannoplankton (phytoplankton smaller than 35μ or 10μ, depending on the author) are the dominant photosynthetic organisms in the NEGOA waters (Anderson et al., 1977; Larrance et al., 1977). Larrance et al. (1977) also found that the large, chain-forming *Chaetoceros concavicornis* and *Thalassiosira aestivalis* reached moderately high concentrations during the spring and summer. The large diatoms grow most vigorously at high nutrient levels and so generally reach their maximum concentrations during the spring, when nutrient levels are optimum. As nutrient levels are depleted in the summer, the large diatom species are less able to compete, and populations of microflagellates and dinoflagellates (which can grow at low nutrient concentrations) increase.

The importance of phytoplankton size in community structure and trophic efficiencies has been discussed by Landry (1977). Large copepods and large crustaceans require the larger food particules for optimal growth. Microzooplanton, ciliates, and smaller nauplii are restricted to exploiting the smallest food particles (e.g., microflagellates, bacteria). Beers and Stewart (1969) have suggested that these smaller zooplankters may function as trophic level intermediates, converting the energy in small particles into larger particles which are more effectively used by small- and medium-sized omnivores. This would be very important in an area such as the subarctic Pacific, where the nannoplankton are the dominant photosynthetic organisms (Anderson, 1965; Larrance et al., 1977; Anderson et al., 1977). This is discussed in more detail in the zooplankton section.

5.1.3 Zooplankton

Information on zooplankton population dynamics in the Gulf of Alaska is scarce. Damkaer (1977) provides the most recent data from OCSEAP-sponsored studies in Lower Cook Inlet, Prince William Sound, and NEGOA. Although seasonal sampling was limited, zooplankton populations on the NEGOA shelf appear to reach maximum numbers from late May through mid-July. Copepods dominated zooplankton collections from the shelf and from Prince William Sound (Damkaer, 1977). The most abundant copepods were the small surface-living *Acartia longiremis*, *Oithona similis*, and *Pseudocalanus* spp. These species breed following intensive feeding, with the size of their brood depending on the amount of food consumed. This means that the period of maximum breeding activity for these species does not occur until phytoplankton activity is at a maximum. Hatching of eggs occurs some weeks later, hence the lag between phytoplankton and zooplankton peaks.

Common copepods found in the deeper waters (though possibly migrating toward the surface early in the year) were *Calanus cristatus*, *C. marshallae*, and *C. plumchrus*. Five species of euphausiids (*Euphausia pacifica*, *Thysanoessa inermis*, *T. longipes*, *T. raschii*, and *T. spinifera*) were also found but in much lesser numbers than the copepods. These zooplankters are much larger than the *Acartia*, *Oithona*, and *Pseudocalanus* spp. referred to above.

Parsons and LeBrasseur (1970) have suggested that there are two basic types of food chains in the oceans. The first, which is characteristic of the subarctic Pacific including NEGOA, is: nannophytoplankton → microzooplankton → macrozooplankton → fish. The second, which appears to characterize coastal waters, upwelling areas, and Antarctic waters, is: phytoplankton → macrozooplankton → fish. Trophic dynamic theory states that the efficiency of energy transfer is lower in an ocean environment in which the predominant primary producers are nannoplankton (as in NEGOA) than in one dominated by microphytoplankton (Parsons and LeBrasseur, 1970). This is because the larger the phytoplankton, the larger their prey, and thus, the fewer the traffic lines between the producer and fish. Theoretically, the nannoplankton-based food chain should produce fewer fish. The biological productivity of NEGOA is not fully explained, however, by a single food chain dominated by microflagellates

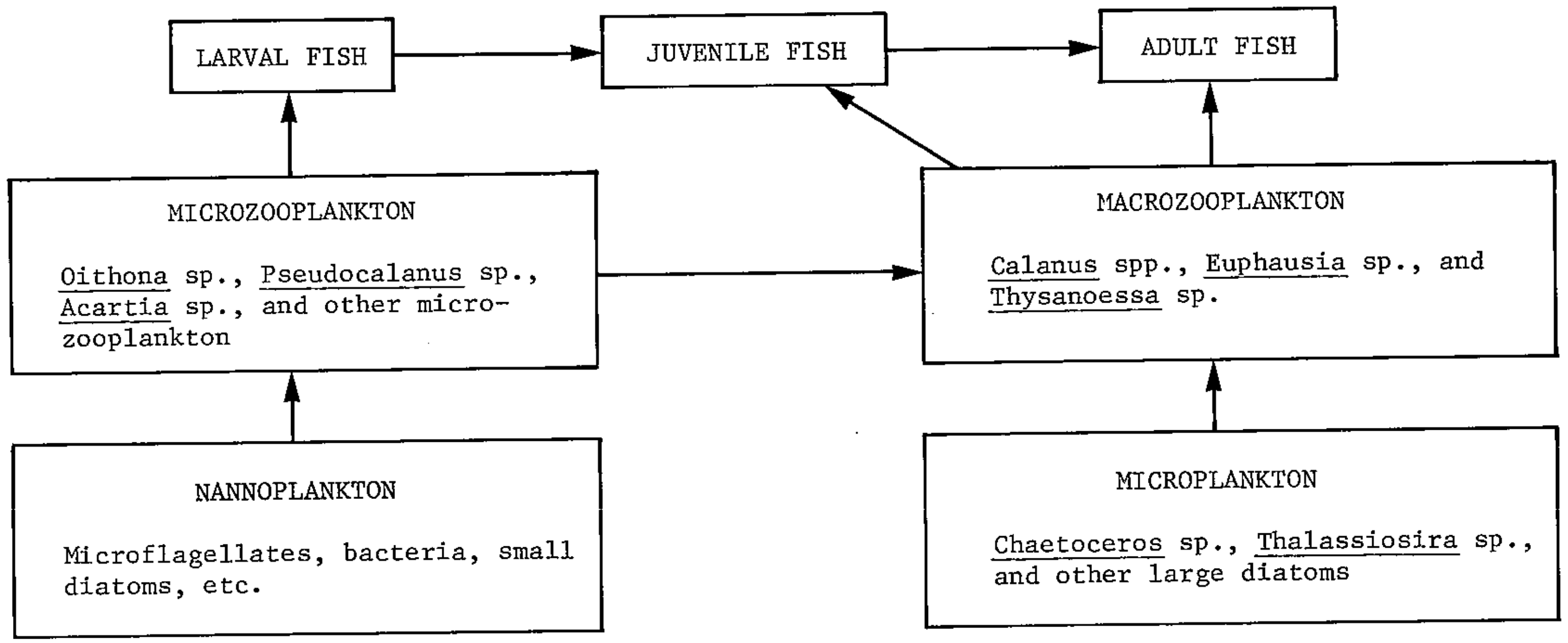


Figure 5.5 A possible food web for NEGOA.

and microzooplankton at the lower trophic levels. The system is obviously much more complex.

Figure 5.5 shows the trophic structure as it might exist for fish in NEGOA. Parsons and LaBrasseur (1970) have found that smaller zooplankters graze most efficiently on the nannoplankton. They found that the prey of the larvae of two species of fish (*Hexagrammos* and *Ammodytes*) are in the 0.5-1.5 mm size range (i.e., the same size range as the *Pseudocalanus* and *Oithona*). Thus, the microplankton are important in sustaining a large larval fish population.

As the larval fish grow, their food habits change, and they become dependent on larger zooplankters. Parsons and LeBrasseur (1970) found that juvenile pink salmon (90mm) were best able to satisfy metabolic requirements when feeding on the large copepod *Calanus plumchrus*. Feeding solely on the smaller *Pseudocalanus minutus*, even when available at much higher concentrations than *C. plumchrus*, would have led to eventual starvation.

The larger zooplankters *C. plumchrus* and *C. cristatus* breed in the winter at depths of 200-400 m. The ascent of the young zooplankton to the surface in the spring allows them to take maximum advantage of the spring bloom of phytoplankton. The large diatoms, which reach their peak development under the high-nutrient, spring conditions are more available then. The larger phytoplankton also satisfy the nutritional needs of these zooplankters better than do the nannoplankton.

The food chain to the adult fish probably follows two pathways: (1) nannoplankton → microzooplankton → macrozooplankton → fish; (2) microplankton → macrozooplankton → fish. The link between the microzooplankton and the macrozooplankton may be more important following the spring bloom after the numbers of larger phytoplankton have decreased. Beers and Stewart (1969) have suggested that an important function of the small zooplankters may be as trophic level intermediates that convert the energy in small particles into larger particles which can be more effectively used by small and medium-sized omnivores.

5.2 EFFECTS OF OIL

Most of our predictions on the effects of oil on marine systems come from laboratory studies. Often these laboratory studies present a different picture from that observed in nature. For instance, the effects of most actual oil spills seem to be negligible or short-lived. In open ocean waters chronically exposed to oil, the effects appear to be less serious than anticipated (for a more detailed discussion of some of these studies, see Chapter 4). This suggests that marine systems are very resilient and have a high assimilation capacity for pollutants, or that our present methods for measuring the effects of oil are not sophisticated enough to measure subtle changes in the marine environment.

Atlas (1978a) and Griffiths and Morita (1979) observed that exposure to petroleum reduces the diversity of bacterial populations while increasing that of hydrocarbon utilizers. Griffiths and Morita (1978) also observed a reduction in the heterotrophic potential when the microbes were exposed to oil. The effect of this exposure was short-lived, and a stimulating effect was observed as the oil was degraded. In view of their rapid growth rate and ubiquitous distribution, bacteria would probably recover quickly from an oil spill. When oil contamination is chronic, however, the effects are more difficult to predict. A long-term decrease in microbial heterotrophic potential could affect those marine processes which are dependent on microbial functions. Similarly, a long-term decrease in microbial diversity could result in a structural or functional change in the biological communities in the area of the pollution source. Presently, there are not sufficient data to quantify these predictions.

Gordon and Prouse (1973) found that hydrocarbon levels in the Bedford Basin, Nova Scotia, were sufficient to decrease photosynthesis rates by a few percent. However, Dunstan et al. (1975) showed that same species of phytoplankton are stimulated by exposure to oil. In a natural, mixed population some species would probably be stimulated while others would be inhibited by the oil. This stimulation may actually be a response to reduced competition from species that are unable to function in the presence of the oil. O'Connors et al. (1978) have suggested that such changes in phytoplankton production and community structure due to pollutants could alter trophic relationships and decrease production of higher trophic levels.

Zooplankton populations show large seasonal fluctuations; they have generation times of weeks or months. This suggests that effects of oil spills on open-water populations would be negligible or short-lived. 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). However, no permanent effects on the zooplankton were observed after either this spill or the Torrey Canyon spill (Smith, 1968).

CHAPTER 6 LITTORAL ZONE BIOTA

William H. Lippincott, SAI

This section deals with hard-bottom (rocky) and soft-bottom (sand, mud) intertidal and bordering shallow subtidal zones in NEGOA. With 0 ft. (mean lower low water: MLLW) as a reference, the NEGOA intertidal zone extends maximally between -4 and +16 ft. Few sites exhibit this large tidal range; wave-exposed sites with regular, moderate-to-steep slopes usually have the greatest vertical range. In these places surge and splash elevate and spread out the intertidal biotic zones. The depth limit of the shallow subtidal is defined as 30 m, which corresponds to the seaward limit of large, brown macroalgae or kelps.

The intertidal may be especially vulnerable to damage from oil spills because of the tendency for floating slicks to strand in that zone when they reach the coast. The vulnerability at a given substrate will depend on the substrate, wave exposure, the degree and type of natural disturbance, and other factors.

6.1 REGIONAL OVERVIEW

The coastline of NEGOA has been mapped in detail by aerial survey from Yakutat Bay to East Chugach Island, off the southern Kenai Peninsula (Sears and Zimmerman, 1977). The maps show major substrate types as well as beach gradient and biological cover. Substrate types throughout the area are mixed, with sand predominating east of Hinchinbrook Island and rocky substrates most prevalent west to the tip of the Kenai Peninsula (Zimmerman et al., 1977, Fig. 6.1).

The principal substrate categories and their extent are shown below for NEGOA, excluding Prince William Sound.

Type	Kilometers	Percentage
Bedrock	297.7	19.9
Boulder	218.8	14.6
Gravel	321.8	21.5
Sand	540.6	36.1
Mud	117.5	7.8
Total	1496.4	99.9

The substrate at Yakutat Bay is predominantly gravel, with some boulder, sand, and bedrock. Beach gradients are low in the outer parts of the bay but are medium to vertical in the inner parts. The exposed coast between Yakutat Bay and Icy Bay consists mostly of sand, with boulder and gravel near Malaspina Glacier. The sandy parts have a low slope, while the boulder and gravel beaches have a medium slope. Icy Bay beaches are a mixture of sand, gravel, boulder, and bedrock. Slopes are predominantly low, with moderate to vertical slopes mainly in the western sides of the upper bay. The beaches are low and sandy on the exposed coast between Icy Bay and Kayak Island. Mud is the predominant substrate east and west of the Copper River. Most of the offshore islands have sand beaches, but Wingham and Kayak Islands have predominantly bedrock coastline and some boulder and gravel beaches. Slopes are low to steep on Wingham Island but are low throughout the rest of the area. From Hinchinbrook Island westward to East Chugach Island, beaches are composed of bedrock, boulders, and gravel. Bedrock predominates, although beach types vary considerably throughout this area. Slopes are low except west of Montague Island, where they are usually steep to vertical.

Eighteen study sites were surveyed in NEGOA from 1974 through 1976 (Fig. 6.1). They are representative of most of the principal substrate types found in the region.

Tides in the NEGOA area are classified as irregular diurnal. They are mainly diurnal with a tendency toward mixed frequencies during neap tides (O'Clair and Chew, 1971).

6.2 ROCKY INTERTIDAL

Rocky shores in NEGOA exhibit a conspicuous intertidal zone of macroscopic seaweeds, seagrasses, and invertebrate animals (Rosenthal et al., 1977). Many of these organisms have broad latitudinal distributions, occurring from the southern Bering Sea to California and Baja California. In other instances the same genera and ecologically functional roles are represented in subarctic and temperate environments, but the species vary with latutude.

Vertical stratification or zonation is the most conspicuous feature of rocky intertidal communities. It has been the subject of much discussion by, for example, Lewis (1964), Ricketts and Calvin (1968), and Stephenson and Stephenson (1972). So variable is this feature that the universal scheme of Stephenson and Stephenson (1949) includes only three zones: the supralittoral fringe (or splash zone), characterized by littorine snails and lichens; the eulittoral, characterized by barnacles, mussels, limpets, and a host of frondose, crustose, and turf-forming algae; and the sublittoral fringe, populated by large brown algae, or kelps, as well as large, mobile invertebrates.

Fine-scale zonal patterns vary from site to site according to substrate stability, wave exposure, slope, and slope regularity. These physical factors are the stage on which biotic interactions are played. Many species have their upward or inshore limits established by tolerance to desiccation and their downward or offshore limits by competitive exclusion (Connell, 1972).

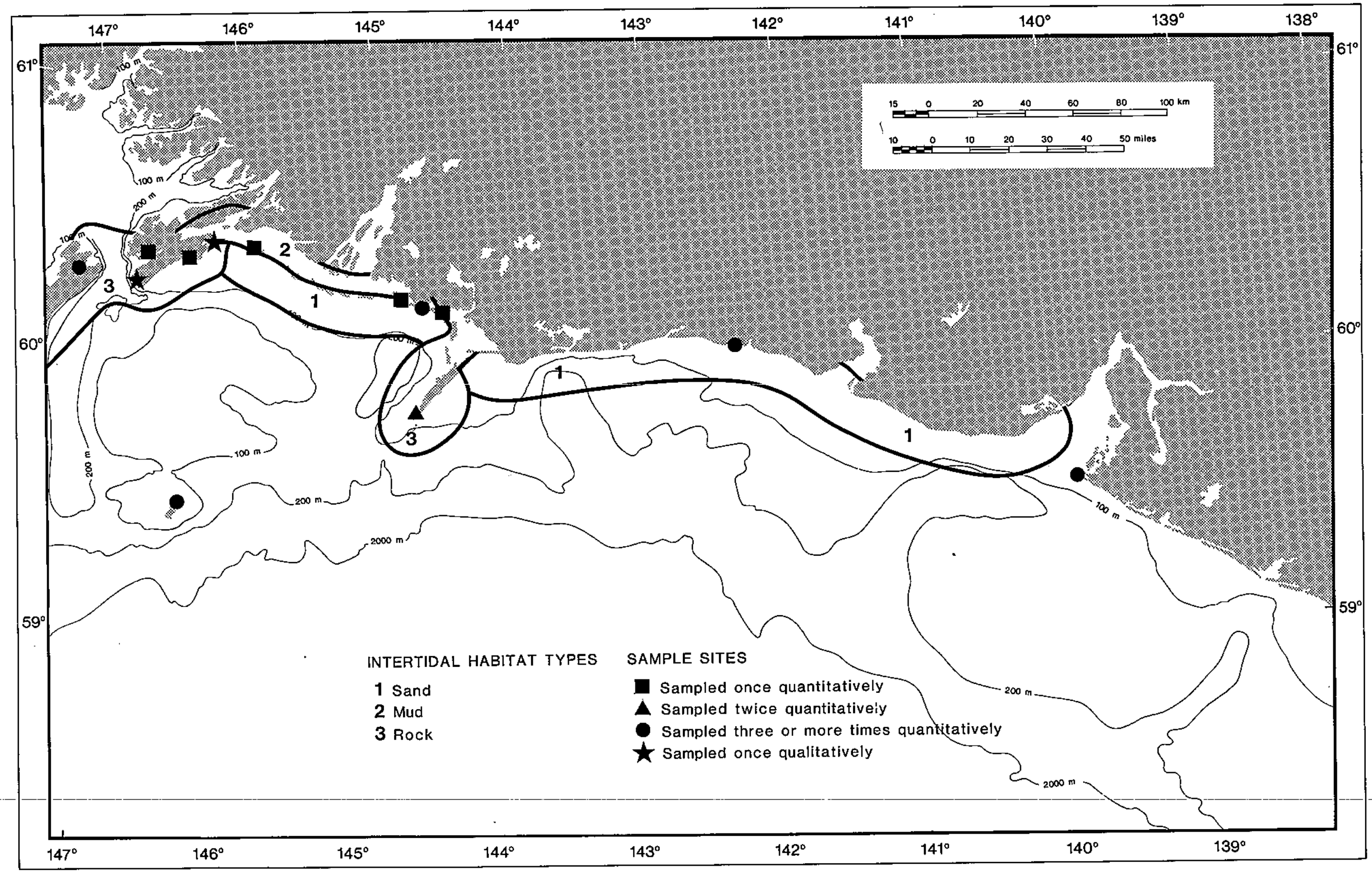


Figure 6.1 Distribution of intertidal habitat types in NEGOA. Bedrock, boulder, and gravel have been combined (Sears and Zimmerman, 1977).

Intertidal zones are usually defined by the presence and high abundance of conspicuous species. For example, the rockweed Fucus distichus is found nearly everywhere in the upper-to-mid-intertidal, while one or more species of the Laminarialean brown kelp Alaria flourish in the low intertidal. The following discussion presents a composite of the potential occurrence of zonal patterns. Few areas exhibit all of these features.

The rocks of the splash zone (+10 to +15 ft.) 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, being found principally in the splash zone in areas frequented by guano-depositing seabirds. The leafy red alga Porphyra is also found in the splash zone, though it is more common in the mid-intertidal.

The overall dominant seaweed in the true littoral zone (MLLW to +10 ft.) is the brown alga F. distichus. Within this zone four subzones may be distinguished. The uppermost (+7 to +10 ft.) 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. pelta. 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 Fucus. Although Fucus may be prominent throughout the littoral zone, making designation of this subzone somewhat arbitrary, it is in this height interval that the rockweed shows true dominance. That is, above the mid-littoral Fucus are not well-developed and canopy-forming, while below it they are being replaced by red algae. Other constituents of the mid-littoral are the sac-like red alga Halosaccion glandiforme, the red algae Odonthalia/Rhodomela, and the polysiphonous red alga Pterosiphonia. Odonthalia floccosa and Rhodomela larix, which are sometimes difficult 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. Although Mytilus californianus, the common sea mussel of Pacific northwest exposed coasts, is not found in the Gulf of Alaska (Zimmerman et al., 1977), M. edulis does occur as a local mid-littoral dominant in protected waters or on the protected sides of large hummocks. Mytilus is an important competitor for space that provides secondary interstitial space and substrate for many small invertebrates. The barnacle Balanus cariosus may occur throughout the littoral zone, but is most prominent in the mid-littoral. It is a significant competitor for space and provides habitat for worms and other small invertebrates. Two predatory snails of this subzone, Nucella lima and N. lamellosa, feed on mussels and barnacles by drilling through their shells.

Below the mid-littoral is a dense band of red algae called the Rhodymenia subzone, named for its principal component Rhodymenia (= Palmaria) palmata. While this subzone is a prominent feature of the Gulf of Alaska above 55°N, it is apparently absent at lower latitudes in the north Pacific. These red seaweeds can vary in density from scattered to thick; at their heaviest densities they may exclude all barnacles, snails, whelks, and limpets. Several other species have their upper distributional limits in the Rhodymenia subzone. The ephemeral green algae Monostroma and Ulva may be common, especially if Rhodymenia is not prominent. They are rapidly colonizing, leafy seaweeds often indicative of mechanical disturbance. They are also found as epiphytes on old Rhodymenia plants. Among the numerous chitons whose distributions begin in the Rhodymenia subzone are the leather chiton Katharina tunicata, the mossy chiton Mopalia muscosa, and the lined chiton Tonicella lineata. The last two tend to occur lower in the intertidal than Katharina. Chitons are grazing herbivores and are preyed upon by birds and sea stars. The limpet Notoacmaea scutum, the six-rayed sea star Leptasterias hexactis, and the small sea cucumber Cucumaria pseudocurata are also often found in the Rhodymenia subzone, though their intertidal distribution extends above and below.

The true subtidal zone, or sublittoral fringe, has its upper boundary at the lowest spring tides. The large brown kelp Laminaria begins its dominance at the shoreward extreme of this zone. Red, calcified coralline algae also attain prominence 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 their subtidal abundances. The limpet Acmaea mitra is found only in lower subtidal elevations and large tide pools. Large, predatory sea stars and other invertebrates are also important.

At any particular location this composite zonal scheme may lack various components, exhibit a mosaic character, or be modified by unusual numbers of one or more organisms. The published work in NEGOA (Zimmerman et al., 1977; O'Clair et al., 1978) is inadequate to make comparisons between sites in this respect. However, one can see a general pattern in departures from the composite scheme. The most zonally developed sites are those on exposed, wave-swept coasts with moderately sloping bedrock substrates and large boulders or hummocks. Wave surge and reduced slope have the effect of spreading out the zones and obscuring their interfaces (Fig. 6.2; Ricketts and Calvin, 1968).

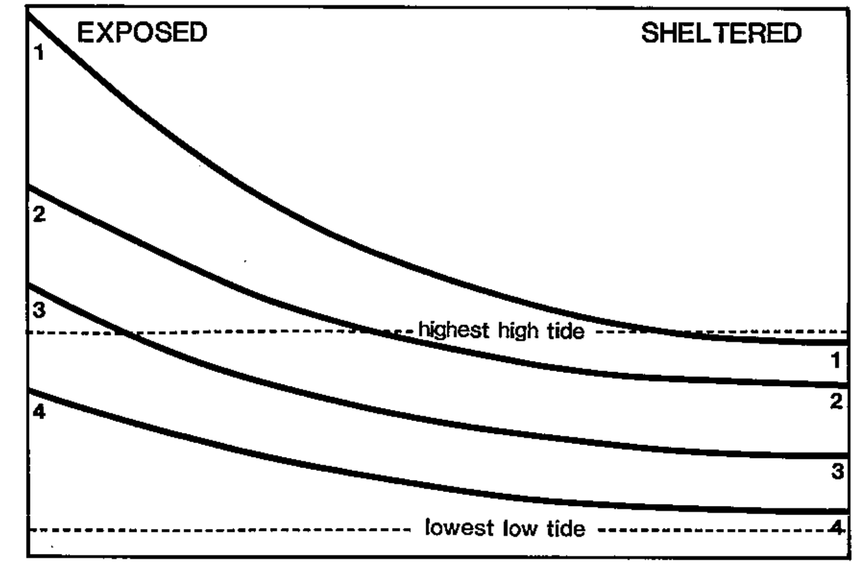
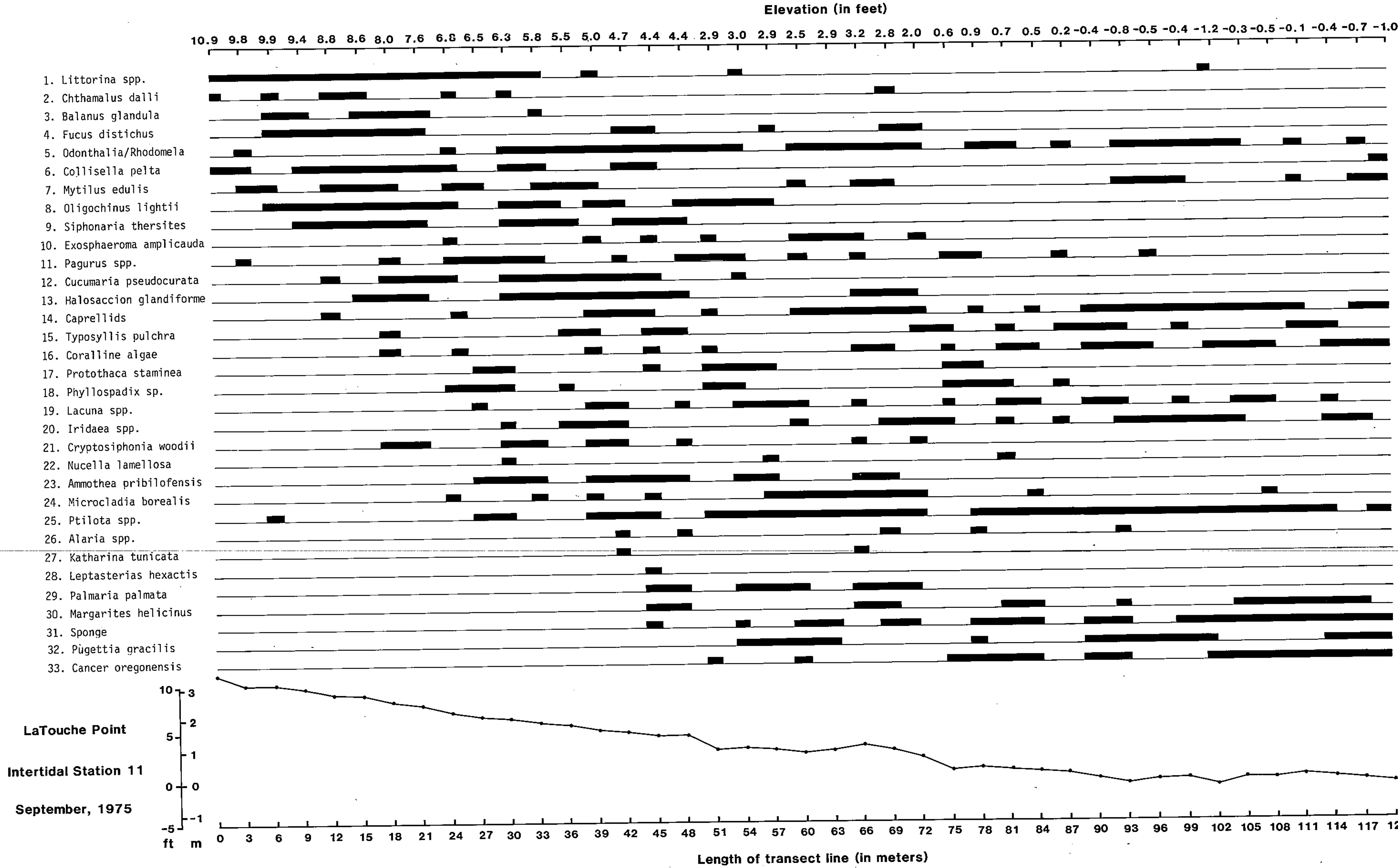


Figure 6.2 The displacement of zones with exposure. Such displacement is often found on rocky headlands (Ricketts and Calvin, 1968).

An example of this phenomenon is shown in the diagram of vertical stratification at Latouche Point, a rich rocky intertidal area (Fig. 6.3; O'Clair et al., 1978). To the casual observer the subzones are often more conspicuous than the data in the diagram suggest. This is because recruitment of juvenile organisms to the intertidal often occurs over a much broader vertical range than the one the adults ultimately inhabit after surviving competitive and physiologic stress. An indication of relative abundance as a function of vertical interval would give a better picture of zonation; these data were not presented in the principal investigators' reports.



LaTouche Point

Intertidal Station 11

September, 1975

Figure 6.3 Distribution of selected plants and invertebrates in 1/16-m^2 quadrats at Station 11 at Latouche Point, September 1975 (O'Clair et al., 1978).
←

At one extreme of the slope continuum, the horizontal bench, distance from low water assumes importance in the absence of vertical relief. Figure 6.4 (Lebednik et al., 1971) shows the hypothetical flow of water in such situations, which establishes the

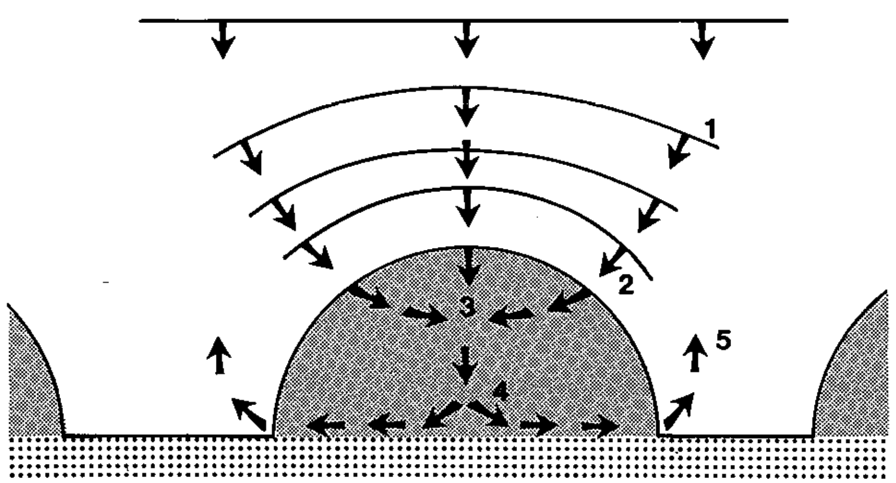


Figure 6.4 The pattern of wave-induced water movement over a littoral rock beach, showing (1) approaching wave fronts, (2) area of breaking waves, (3) piling up of water on the outer beach, (4) shoreward and lateral flow of water, and (5) return via channels between rock benches (Lebednik et al., 1971).

gradient of wave and desiccation exposure. The seaward end of the bench attenuates the force of incoming waves, limiting the shock to inshore areas. In addition, however, the bench drains slowly, reducing the stress of desiccation. The study site at Cape St. Elias is representative of this topography. As depicted in Fig. 6.5 (O'Clair et al., 1978), the red

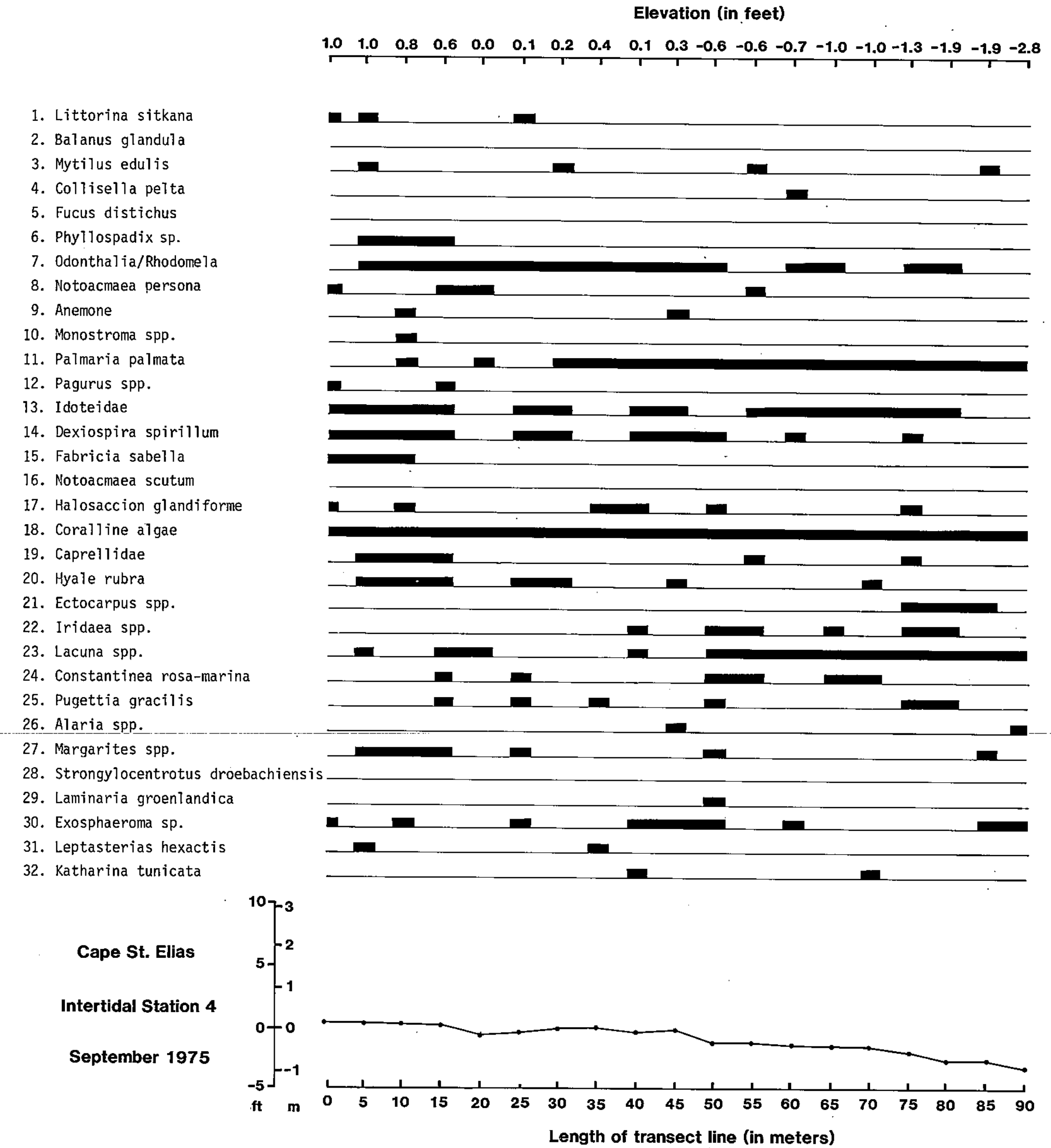


Figure 6.5 Horizontal and vertical distribution of selected algae and invertebrates, Cape St. Elias, Intertidal Station 4, September 1975 (O'Clair et al., 1978).

algal taxon Odonthalia/Rhodomela has a broad horizontal distribution at Cape St. Elias. It occurs widely in low bench areas with poor drainage. The upper-to-mid-intertidal seaweed Fucus distichus is absent here.

Unstable substrates and sand or ice scour modify community development and zonal patterns in a different way. As an example, Cape Yakataga is a low-lying bedrock reef flanked on either side by kilometers of uninterrputed sandy beach. Sand scour is chronic, with accumulations of 10 cm following storms (O'Clair et al., 1978); ice scour may also occur. Most species are ephemeral and patchy in distribution. This pattern of immature community development and relatively high abundance of weed-like opportunistic species is common in areas of natural disturbance. The space created by the removal of sessile organisms by scour allows these rapid growers to colonize the area. If the disturbance is chronic, the more advanced and permanent successional assemblages never have an opportunity to become established. Lebednik and Palmisano (1977) listed the sequence of colonizers after disturbance at a study site of Amchitka Island as (1) diatoms and filamentous brown and green algae, (2) ulvoids (leafy green algae), (3) macrophytic red and brown algae. Table 6.1 shows the number of species represented among these groups along three transects during three sampling periods at Cape Yakataga (O'Clair et al., 1978). The predominance of early colonizers and the perennial nature of the pattern is evident. Other locations such as Katalla Bay show reduced diversity and relatively high abundance of opportunistic species because small boulders and rocks rolling about in storm surf dislodge colonizing organisms.

Further clarification of the zonal structure of specific study sites in NEGOA is not possible because of inconsistencies in field methods and the lack of data presented in the final report on this region. Substrate characteristics and intertidal ranges are given for the study sites in Table 6.2. The ranges define the sampled area; in some cases the tidal extremities were not sampled because of sand or gravel in the upper zone or heavy surf in the lower.

To sample vertical rock surfaces as well as nearly horizontal surfaces, two different sampling methods were employed. The data from these methods are not readily comparable but are representative of different microhabitats. In Tables 6.3 and 6.4 the abundance dominants for each site are accordingly separated. Thus, the same microhabitat may be compared where it occurs among the study sites, and also the sites may be compared as to the occurrence of these two microhabitat features.

Table 6.1 Number of species of (1) filamentous green and brown algae, and diatoms, (2) ulvoids, (3) macrophytic red and brown algae collected along three transects during three sampling periods at Cape Yakataga (O'Clair et al., 1978).

Algal group	Number of species: October 1974	June 1975	September 1975
Group 1	21	25	26
Group 2	3	6	4
Group 3	9	17	12

Table 6.2 Characteristics of rocky intertidal study site.

Study site	Substrate	Sampled vertical range (ft)*
Ocean Cape	Boulder, sand	+11.9 to -3.8
Cape Yakataga	Bedrock, sand	+15.6 to -2.3
Cape St. Elias	Bedrock, boulder	+ 9.2 to -2.8
Katalla Bay	Boulder, bedrock	+ 8.7 to -0.9
Boswell Bay	Mud, boulder	--
Middleton I.	Mud, boulder	+ 5.5 to -1.6
Port Etches	Bedrock	+10.2 to -2.4
MacLeod Harbor	Bedrock	+10.2 to +0.3
Latouche Point	Bedrock	+10.9 to -1.22
Squirrel Bay	Bedrock, boulder	+15.1 to +2.2
Anchor Cove	Bedrock	+10.9 to -0.3
Gore Point	Bedrock, boulder	+13.2 to +1.1
Cape Hinchinbrook	Boulder, bedrock	+11.38 to -0.35

* Heights are given in feet to correspond with U.S. Hydrographic Office tide tables.

Table 6.3 Mean abundance (g wet weight/m^2) of dominant macroalgae on horizontal and vertical rocky substrates at NEGOA study sites surveyed September 1975.

OCEAN CAPE:

VERTICAL ROCK SURFACE

Odonthalia floccosa	783
Alaria taeniata	394
Fucus distichus	368
Palmaria palmata	253
Alaria	222
Odonthalia	85
Phaeophyta	42
Fucus spiralis	35
Endocladia muricata	26
Ulva	25

CAPE YAKATAGA:

AREA A HORIZONTAL ROCK SURFACE

Sphacelaria	4102
Palmaria palmata	383
Fucus distichus	219
Pylaiella littoralis	159
Porphyra	98
Elachista fucicola	49
Enteromorpha linza	45
Odonthalia floccosa	34
Ulva lactuca	29

AREA B HORIZONTAL ROCK SURFACE

Fucus distichus	1141
Pylaiella littoralis	346
Odonthalia floccosa	330
Fucus spiralis	227
Elachista fucicola	128
Palmaria palmata	30
Rhodomelaceae	25
Porphyra	19
Porphyra perforata	10
Soranthera ulvoidea	5

AREA A VERTICAL ROCK SURFACE

Enteromorpha linza	226
Palmaria palmata	195
Pylaiella littoralis	148
Scytosyphon lomentaria	67
Rhodophyta	35
Chaetomorpha	29
Chlorophyta	23
Phaeophyta	19
Laminaria groenlandica	13
Alaria praelonga	11

KATALLA BAY:

HORIZONTAL ROCK SURFACE

Fucus distichus	191
Porphyra	84
Palmaria palmata	29
Pterosiphonia bipinnata	23

VERTICAL ROCK SURFACE

Fucus distichus	535
Odonthalia floccosa	394
Laminaria groenlandica	270
Palmaria palmata	43
Bossiella	19
Pterosiphonia bipinnata	4

CAPE ST. ELIAS:

HORIZONTAL ROCK SURFACE

Odonthalia floccosa	990
Palmaria palmata	718
Alaria marginata	282
Corallinaceae	154
Rhodomela larix	145
Laminaria groenlandica	88
Petrocelis middendorfii	69
Corallina vancouveriensis	66
Constantinea simplex	43
Neoptilota asplenioides	40
Corallina	30

BOSWELL BAY:

VERTICAL ROCK SURFACE

Chlorophyta	2.653
Phaeophyta	.952
Rhodophyta	.121
Corallinaceae	.105

HORIZONTAL ROCK SURFACE

Fucus distichus	1881
Rhodomela larix	356
Halosaccion saccatum	137
Alaria marginata	91
Halosaccion glandiforme	78
Alaria taeniata	75
Delesseriaceae	63
Odonthalia floccosa	55
Pterosiphonia bipinnata	34
Iridaea cornucopiae	24

MACLEOD HARBOR:

HORIZONTAL ROCK SURFACE

Alaria marginata	644
Fucus distichus	554
Alaria taeniata	119
Pterosiphonia bipinnata	114
Odonthalia floccosa	112
Rhodomela larix	37
Alaria praelonga	36
Soranthera ulvoidea	10
Porphyra	4

VERTICAL ROCK SURFACE

Fucus distichus	390
Porphyra	180
Odonthalia floccosa	27
Pterosiphonia bipinnata	25
Halosaccion glandiforme	10
Navicula	8
Rhodophyta	2
Phaeophyta	1

LATOUCHE POINT:

AREA A HORIZONTAL ROCK SURFACE

Fucus distichus	891
Zostera marina	775
Odonthalia floccosa	634
Palmaria palmata	373
Ptilota filicina	288
Halosaccion glandiforme	179
Iridaea heterocarpa	86
Alaria taeniata	74
Pterosiphonia bipinnata	60
Cryptosiphonia woodii	53
Rhodomelaceae	52

AREA B HORIZONTAL ROCK SURFACE

Iridaea	9218
Ptilota filicina	2088
Odonthalia floccosa	1113
Zostera marina	458
Neoptilota asplenioides	405
Laminaria groenlandica	360
Iridaea heterocarpa	227
Laminaria yezoensis	190
Iridaea cornucopiae	41
Microcladia borealis	30
Bossiella plumosa	23

ANCHOR COVE:

AREA A HORIZONTAL ROCK SURFACE

Palmaria palmata	481
Alaria	412
Fucus distichus	303
Odonthalia floccosa	272
Ptilota filicina	261
Fucus spiralis	201
Halosaccion glandiforme	190
Corallinaceae	125
Pylaiella littoralis	100
Alaria marginata	69
Polysiphonia pacifica	69

AREA B HORIZONTAL ROCK SURFACE

Odonthalia floccosa	883
Fucus distichus	640
Pterosiphonia bipinnata	376
Halosaccion glandiforme	273
Porphyra	218
Pylaiella littoralis	203
Alaria taeniata	194
Soranthera ulvoidea	178
Fucus spiralis	143
Palmaria palmata	121
Odonthalia	74
Spongomorpha spinescens	40

ANCHOR COVE:

AREA A VERTICAL ROCK SURFACE

Fucus spiralis	2195
Palmaria palmata	661
Fucus distichus	381
Pylaiella littoralis	234
Halosaccion glandiforme	118
Alaria	40
Elachista fucicola	34
Phaeophyta	28
Porphyra	12
Fucus	11
Iridaea cornucopiae	7

Table 6.4 Mean abundance (counts/m^2) of dominant macroinvertebrates on horizontal and vertical rocky substrates at NEGOA study sites surveyed September 1975.

OCEAN CAPE:

VERTICAL ROCK SURFACE

Mytilus edulis	72057
Enchytraeidae	10630
Turbellaria	5220
Balanus glandula	2549
Gnorimosphaeroma oregonensis	2419
Littorina sitkana	1751
Typosyllis alternata	663
Anurida maritima	580
Dynamenella glabra	313
Balanus cariosus	290
Collisella pelta	194
Nereis	141

CAPE YAKATAGA:

AREA A HORIZONTAL ROCK SURFACE

Mytilus edulis	8737
Spionidae	5178
Balanus glandula	4464
Enchytraeidae	1022
Littorina sitkana	679
Turbellaria	484
Amphithoe simulans	483
Chironomidae	320
Lacuna marmorata	248

AREA B HORIZONTAL ROCK SURFACE

Mytilus edulis	3857
Chironomidae	1357
Gastropoda	1357
Amphithoe simulans	693
Typosyllis	544
Littorina sitkana	426

AREA A VERTICAL ROCK SURFACE

Mytilus edulis	27776
Balanus glandula	15559
Enchytraeidae	5705
Chironomidae	1087
Chthamalus dalli	974
Littorina sitkana	903
Lacuna marmorata	815

KATALLA BAY:

HORIZONTAL ROCK SURFACE

Balanus glandula	8192
Littorina sitkana	3131
Mytilus edulis	2534
Carophium	842
Gnorimosphaeroma oregonensis	553
Amphithoe simulans	482

VERTICAL ROCK SURFACE

Balanus glandula	48505
Mytilus edulis	45043
Porifera	4537
Littorina sitkana	3161
Coleoptera	1548
Cerithiopsis stejnegeri	1287

CAPE ST. ELIAS:

VERTICAL ROCK SURFACE

Hayale rubra frequens	2402
Amphipoda	1450
Parallorchestes ochotensis	1325
Dexiospira spirillum	942
Amphithoe simulans	543
Fabricia sabella	476

BOSWELL BAY: VERTICAL ROCK SURFACE

VERTICAL ROCK SURFACE

Balanus glandula	22935
Mytilus edulis	1552
Littorina sitkana	205
Emplectonema gracile	161

ZAIKOF BAY:

HORIZONTAL ROCK SURFACE

Mytilus edulis	18844
Lacuna marmorata	2901
Balanus glandula	2485
Enchytraeidae	856
Chironomidae	757
Balanus cariosus	710

MACLEOD HARBOR:

HORIZONTAL ROCK SURFACE

Mytilus edulis	16353
Enchytraeidae	1602
Margarites helicinus	1515
Balanus glandula	928
Munna	838

VERTICAL ROCK SURFACE

Mytilus edulis	39376
Enchytraeidae	12139
Balanus glandula	3247
Coleoptera	1940
Collisella pelta	1688

LATOUCHE POINT:

AREA A HORIZONTAL ROCK SURFACE

Caprellidae	2063
Hyale rubra frequens	1570
Parallorchestes ochotensis	1345
Asabellides sibirica	782
Onuphis geophiliformis	731

AREA B HORIZONTAL ROCK SURFACE

Dexiospira spirillum	7252
Hyale rubra frequens	5914
Caprellidae	4404
Stenopleustes uncigera	1409
Ischyrocerus	1016

ANCHOR COVE:

AREA A HORIZONTAL ROCK SURFACE

Mytilus edulis	57661
Enchytraeidae	5493
Fabricia sabella	2863
Nematoda	2335
Dexiospira spirillum	1745
Balanus cariosus	1668

AREA B HORIZONTAL ROCK SURFACE

Balanus cariosus	5194
Enchytraeidae	3390
Typosyllis alternata	819
Mytilus edulis	801
Onchidella borealis	665
Chthamalus dalli	614
Dynamenella glabra	498

AREA A VERTICAL ROCK SURFACE

Mytilus edulis	21298
Anurida maritima	1838
Enchytraeidae	1193
Balanus glandula	1032
Balanus cariosus	879

6.3 SHALLOW SUBTIDAL

Subtidal studies were conducted by Rosenthal et al. (1977) at three of the intertidal sites: Latouche Point, MacLeod Harbor, and Zaikof Bay. These sites are on two of the large islands bordering the seaward edge of Prince William Sound. They are representative of the sublittoral zone, extending seaward to a depth of about 30 m. Whereas the intertidal zone is marked by conspicuous and often regular zonal stratification, the sublittoral is characterized by its lush growth of marine plants. This is the zone of domination by the kelps, or large brown seaweeds (phaeophytes), some of which (e.g., bull kelp, Nereocystis luetkeana) grow long enough to form a canopy or bed at the water surface. Most of the biomass on rocky shores is found in the sublittoral.

Marine plant communities are extremely productive (see the review by Mann, 1973). The primary production of the seaweed zone in St. Margaret's Bay, Nova Scotia, was estimated to be 1750 g $C/m^2/yr$, which is about three times the phytoplankton production of the bay (Mann, 1972). This narrow band of high-density marine plants is obviously important to the marine ecosystem of Prince William Sound (Rosenthal et al., 1977). Moreover, the forest-like larger kelps provide a home for many invertebrate and fish species, some of commercial or sport fishing importance.

Figure 6.6 is a schematic representation of some of the trophic interrelationships of intertidal and subtidal organisms. The food web reflects a generally

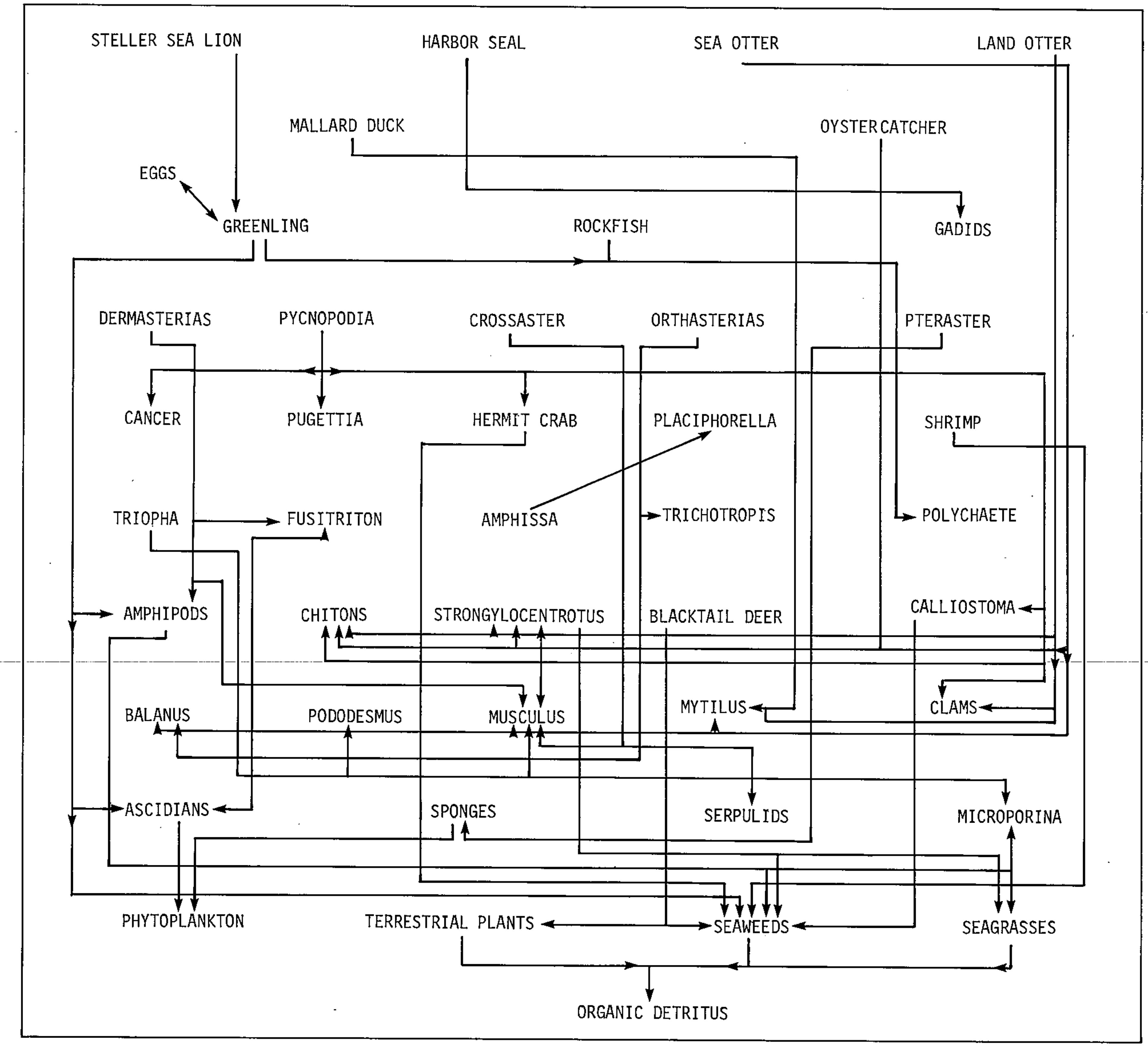
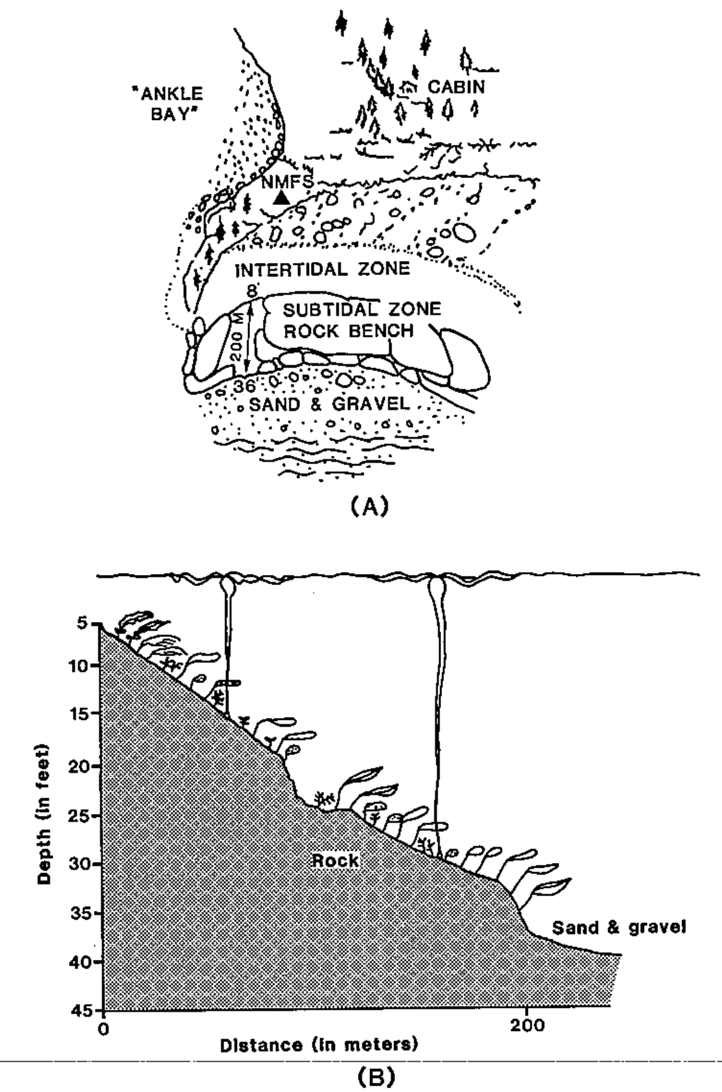


Figure 6.6 Food web for the rocky sublittoral zone at Latouche Point (Rosenthal et al., 1977). Except for the contribution of plant material to the organic detritus, the arrows point to the organisms consumed. In a diagram of energy flow the direction of the arrows would be reversed.

seaward flow of energy, with a large contribution to a detrital nutrient base. However, the landward flow is significant, if smaller than the seaward trend. Blacktail deer (Odocoileus columbianus) regularly browse on intertidal seaweeds, both attached and drift, during the winter, and secondary consumers such as the river otter (Lutra canadensis) take clams, mussels, chitons, and sea urchins from the littoral and sublittoral fringe (Rosenthal et al., 1977).

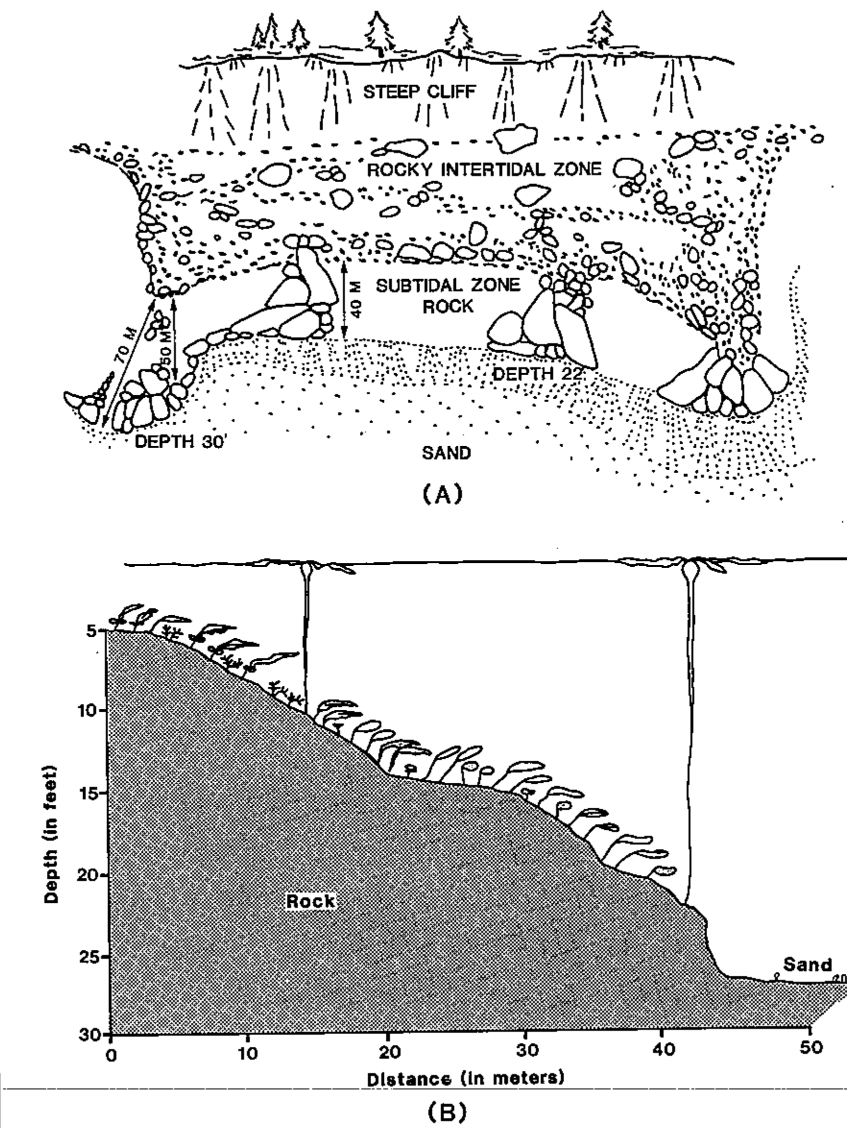
Many fish species derive shelter and/or subsistence from the subtidal kelp beds. Commercially important species such as Pacific salmon migrate past the waters of Latouche Point, MacLeod Harbor, and Zaikof Bay to the spawning streams of Prince William Sound. Schools of juvenile salmon were seen in the kelp beds at Latouche Point in August 1974 and early September 1976 (Rosenthal et al., 1977). Much remains to be learned about the use of kelp beds by salmon.

The study sites are shown diagrammatically in Figs. 6.7, 6.8, and 6.9 (Rosenthal et al., 1977). The most conspicuous difference is that the Zaikof Bay subtidal lacks the surface canopy formed by Nereocystis. The absence of this species may be due to the paucity of stable rock substrate at suitable depths (see Fig. 6.9). Other, less obvious differences include the relatively high tidal current velocity and water clarity at Latouche Point. At that site the bottom was generally free of silt, while at MacLeod Harbor and Zaikof Bay the hard substrate and bottom plant communities were usually dusted with silt (Rosenthal et al., 1977). The seaweed communities at the latter two sites form a relatively narrow belt. A comparison of dominant species composition and relative abundance for the three study sites is given in Table 6.5 (data from Rosenthal et al., 1977).



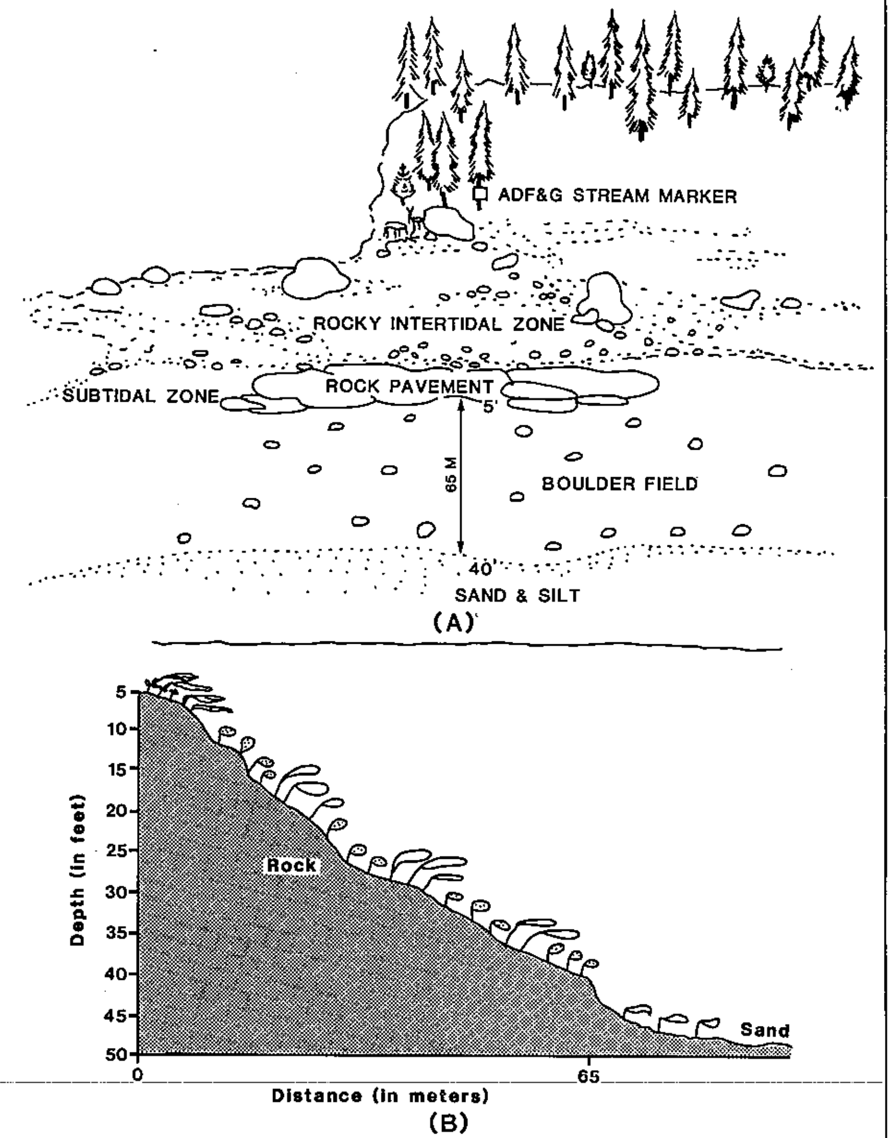
LATOUCHE POINT
Drawing of the study site (A) and the subtidal vegetative canopies (B)

Figure 6.7 Diagram of Latouche Point and its subtidal vegetative canopies (Rosenthal et al., 1977).



MACLEOD HARBOR
Drawing of the study site (A) and the subtidal vegetative canopies (B)

Figure 6.8 Diagram of MacLeod Harbor and its subtidal vegetative canopies (Rosenthal et al., 1977).



ZAIKOF BAY
Drawing of the study site (A)
and the subtidal vegetative canopies (B)

Figure 6.9 Diagram of Zaikof Bay and its subtidal vegetative canopies (Rosenthal et al., 1977).

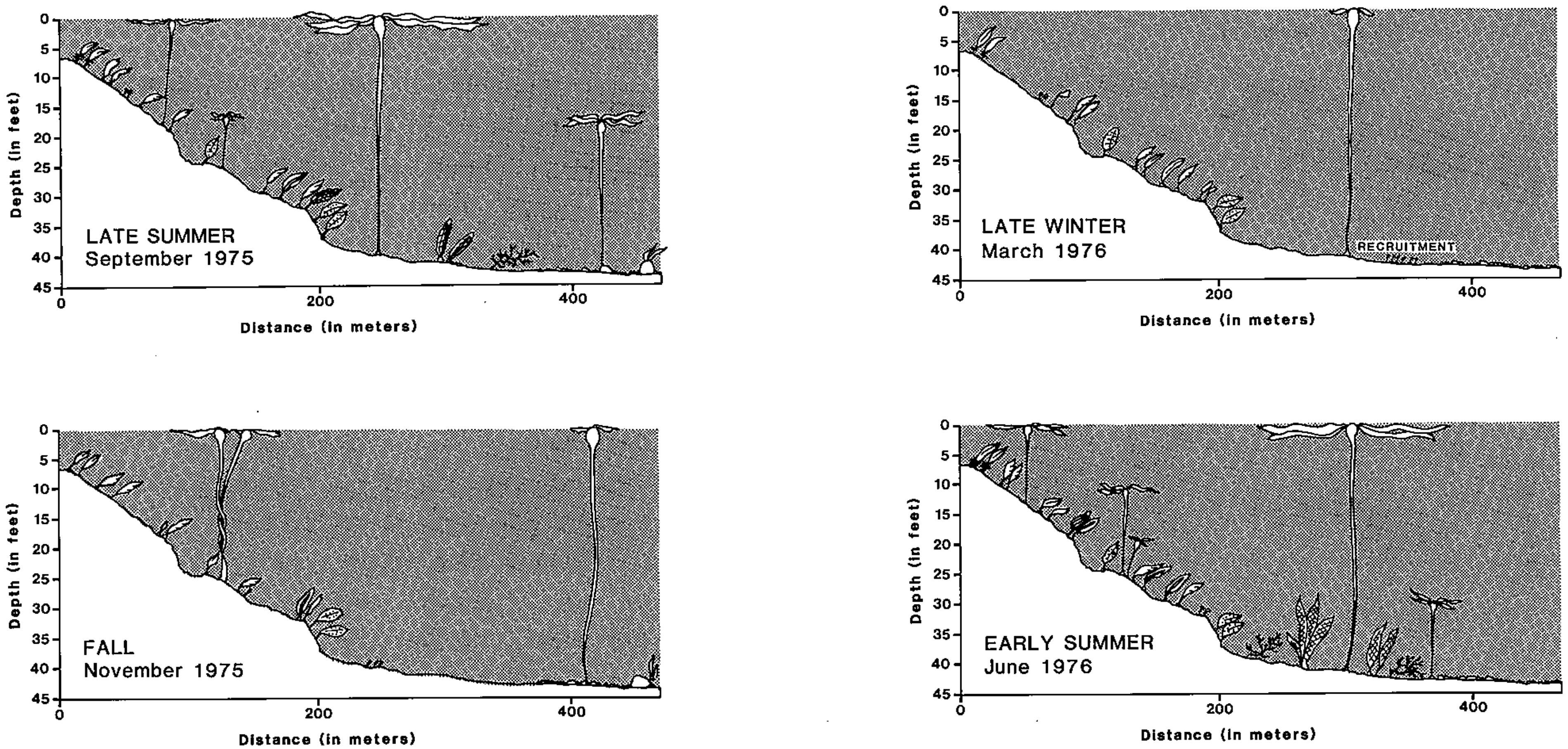
Table 6.5 Taxonomic composition and relative abundance at three subtidal study sites.

Species	Occurrence 1	2	3	Description	Trophic Category
Agarum cribrosum (P)	A	A	A	Brown alga	Producer
Laminaria groenlandica (P)	A	A	C	Brown alga	Producer
Laminaria yezoensis (P)	A	C	C	Brown alga	Producer
Pleurophycus gardneri (P)	A	C	C	Brown alga	Producer
Desmarestia viridis (A)	-	-	C	Brown alga	Producer
Nereocystis luetkeana (A)	A	C	-	Brown alga	Producer
Costaria costata (A)	-	C	-	Brown alga	Producer
Cymathere triplicata (A)	C	-	-	Brown alga	Producer
Ralfsia spp. (P)	-	C	C	Brown alga	Producer
Encrusting coralline (P)	A	A	A	Red alga	Producer
Microcladia borealis (?)	-	-	C	Red alga	Producer
Constantinea spp. (P)	C	C	C	Red alga	Producer
Callophyllis spp. (?)	-	C	C	Red alga	Producer
Opuntiella californica (?)	C	C	-	Red alga	Producer
Rhodymenia spp. (?)	-	C	-	Red alga	Producer
Hildenbrandia ? occidentalis	-	C	-	Red alga	Producer
Delesseria decipiens (A)	-	C	-	Red alga	Producer
Ptilota filicina (?)	C	-	-	Red alga	Producer
Microporina borealis (A)	C	C	C	Bryozoan	Suspension feeder
Flustrella gigantea (P)	-	-	C	Bryozoan	Suspension feeder
Heteropora sp. (P)	-	-	C	Bryozoan	Suspension feeder
Balanus spp. (P)	-	-	A	Barnacle	Suspension feeder
Grammaria sp.	-	-	C	Hydroid	Suspension feeder
Pycnopodia helianthoides (P)	C	C	C	Sea star	Predator
Orthasterias koehleri (P)	-	C	C	Sea star	Predator
Dermasterias imbricata (P)	C	C	C	Sea star	Predator
Crossaster papposus (P)	C	-	C	Sea star	Predator
Henricia spp. (P)	C	C	C	Sea star	Suspension feeder/predator
Evasterias troschelii (P)	-	-	C	Sea star	Predator
Fusitriton oregonensis (P)	-	C	C	Snail	Predator/scavenger
Margarites pupillus	-	-	C	Snail	Herbivore
Tonicella spp. (P)	C	C	-	Snail	Herbivore
Acmaea mitra (P)	C	C	-	Snail	Herbivore
Thais canaliculata (P)	-	C	-	Snail	Predator
Searlesia dira (P)	C	-	-	Snail	Predator
Calliostoma ligatum (P)	C	-	-	Snail	Herbivore
Musculus discors (A)	-	-	C	Mussel	Suspension feeder
Musculus spp. (A)	-	C	-	Mussel	Suspension feeder
Musculus vernicosus (A)	A	-	-	Mussel	Suspension feeder
Tonicella spp. (P)	-	-	C	Chiton	Herbivore
Pagurus spp. (P)	A	-	A	Hermit crab	Herbivore/scavenger
Enhydra lutris (P)	C	C	C	Sea otter	Predator
Halocynthia aurantium (P)	-	C	-	Ascidian	Suspension feeder
? Distaplia occidentalis (P)	C	-	-	Ascidian	Suspension feeder
Ophiopholis aculeata (P)	C	-	-	Brittle star	Predator
Strongylocentrotus spp. (P)	U	U	-	Sea urchin	Herbivore

Key: (P) = perennial
(A) = annual
A = abundant
C = common
U = uncommon

1 Latouche Point
2 MacLeod Harbor
3 Zaikof Bay

Seasonal changes were apparent at all three sites. An example of the gross features of these changes is presented schematically in Fig. 6.10 (Rosenthal et al., 1977). Like canopy-forming kelps in temperate regions, the Nereocystis canopy was seasonally reduced. But unlike Macrocystis, which dies back in summer in California, Nereocystis in NEGOA was at a minimum in winter. Annual brown algae such as Nereocystis luetkeana, Cymathere triplicata, and Costaria costata began to germinate in early spring, forming dense canopies or stories by mid- to late summer. Severe dieback had taken place by late fall of the same year. The perennial kelps Agarum cribrosum, Laminaria spp., and Pleurophycus gardneri, however, attained maximum standing stocks during late winter and early spring. The abundance of epiphytic invertebrates also varied seasonally during the year of study, corresponding to changes in seaweed abundance. As an example, the population of mussel Musculus vernicosus at Latouche Point was augmented by heavy sets of spat (juveniles) in the spring and summers of 1974 through 1976. By late November during these years, the population had declined. Similarly, the hydroids Campanularia, Grammaria, and Abietinaria were least abundant in late fall and winter at Zaikof Bay. These seasonal patterns are assumed by Rosenthal et al. (1977) to be characteristic of the NEGOA rocky subtidal zone.



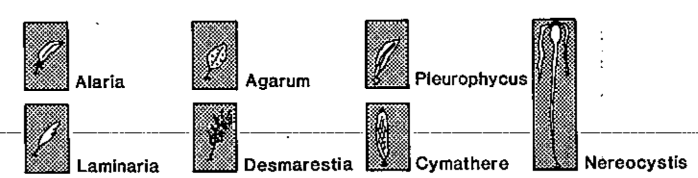


Figure 6.10 Seasonal variation in the subtidal vegetative profiles, Latouche Point (Rosenthal et al., 1977).

6.4 SOFT-BOTTOM BEACHES

Personnel from the Auke Bay Fisheries Laboratory surveyed six study sites with sandy or muddy substrates (O'Clair et al., 1978). Two sites (Boswell Bay and Middleton Island) also have scattered low boulders or low reefs which were surveyed by methods used in the rocky intertidal. Characteristics of the study sites are given in Table 6.6.

Table 6.6 Characteristics of soft-bottom intertidal study sites.

Study site	Substrate	Sampled intertidal range (ft)*
Kanak Island	Sand, mud	+ 6.3 to -2.3
Softuk Spit	Sand	+ 3.4 to -1.4
Big Egg I.	Sand	+11.5 to -3.0
Boswell Bay	Mud	+ 7.9 to -2.2
Hook Point	Sand, mud	+ 5.8 to -1.4
Middleton I.	Mud	--

* Heights are given in feet to correspond with U.S. Hydrographic Office tide tables.

The biomass of sandy and muddy beaches were observed to be about two orders of magnitude lower than those of rocky intertidal shores; the number of sampled taxa was lower at muddy beaches and lowest at sandy beaches. These findings must be viewed with caution, however. First, the beaches were hardly sampled; few sites were surveyed and few samples were collected, and the sieve mesh size of 1 mm would not retain many of the infaunal species (up to 90 percent of the nematodes would be lost). Second, it is clear that no major clam beds, such as the Siliqua beds of the Kodiak Island area, were included in the sampling. Such inclusion, if possible in NEGOA, would greatly increase estimates of biomass.

Some evidence of vertical zonation was observed, as shown in the diagram from Boswell Bay (Fig. 6.11; O'Clair et al., 1978). The normalized abundances of dominant soft-bottom infauna from the six study sites are given in Table 6.7.

Salt marshes and tidal flats in the NEGOA area were not included in the OCSEAP sampling plan. Wolf et al. (pers. comm.) found a rich and diverse biological assemblage in an estuarine salt marsh in Kachemak Bay. *Mytilus* sp. was dominant on the tidal flats, and other species of bivalves were common. These areas served as hauling-out grounds for harbor seals and as feeding grounds for numerous birds, including juvenile bald eagles. Juvenile salmonids of several species were common in the streams that flowed through the salt marsh, and sticklebacks and sculpins were abundant in tidal pools on the marsh. Transport of detritus from the marsh into the surrounding bay also appeared to be substantial. It is likely that the salt marshes and tidal flats of NEGOA are similarly productive and important to the total productivity of the area.

Table 6.7 Mean abundance (counts/m^2) of dominant macroinvertebrates in soft substrates at NEGOA study sites surveyed September 1975.

OCEAN CAPE: SOFT SUBSTRATE	
Amphipoda	150
Archaeomysis grebnitzkii	125
CAPE YAKATAGA: SOFT SUBSTRATE	
Mytilus edulis	450
Amphipoda	125
BOSWELL BAY: SOFT SUBSTRATE	
Macoma balthica	1173
Littorina sitkana	343
Eteone longa	156
Balanus	146
Pholoe minuta	100
Haploscoloplos elongatus	80
Mya elegans	73
MIDDLETON ISLAND: SOFT SUBSTRATE	
Pygospio elegans	6700
Capitellidae	3200
Rhynchospio	1600
Enchytraeidae	1200
Abarenicola pacifica	775

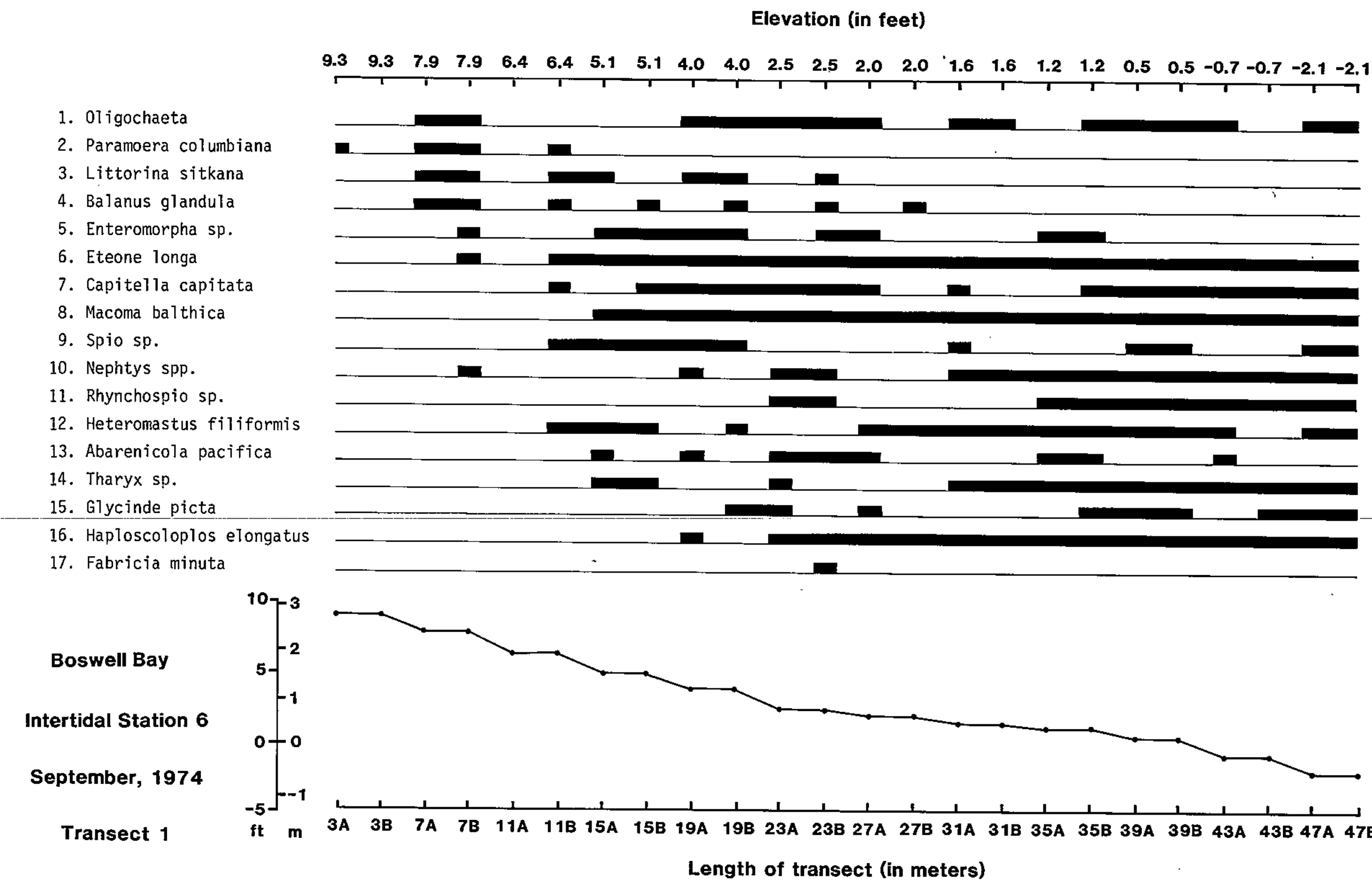


Figure 6.11 Horizontal and vertical distribution of selected algae and invertebrates, Boswell Bay, Intertidal Station 6, September 1974 (O'Clair et al., 1978).

6.5 VULNERABILITY TO OIL SPILLS

Hayes and Ruby (1979) studied oil-spill vulnerability in the Kodiak Island region. Their principal criterion for estimating vulnerability was the interaction of waves with substrate type. They believe that wave exposure promotes rapid clearing of rocky surfaces, while coarse-grained (i.e., gravelly) substrates in protected areas may accumulate and retain stranded oil for long periods. According to Ruby (1977), the NEGOA areas least vulnerable to spilled oil include most of Kayak Island, Hinchinbrook Island, and Wingham Island. Their wave-exposed coastlines could be naturally stripped of oil within a few days or weeks. Many of the rock-covering seaweeds do not retain crude oil on their surfaces, and some invertebrates (e.g., mussels, limpets, chitons, and snails) could protect themselves temporarily by closing their valves or tightening their hold on the rocks. The vulnerability of any given site cannot be predicted at this time, however. It would depend on the composition of spilled oil, its degree of weathering, the condition of the sea at the time of the spill, the particular community composition, the physiologic state of resident organisms, and the occurrence of natural disturbance factors.

Slightly more vulnerable, according to the Hayes and Ruby scheme, are the eroding, wave-cut platforms present to some degree (see maps in Sears and Zimmerman, 1977) on Kayak, Hinchinbrook, and Wingham Islands.

The flat, fine-grained sand beaches of the Yakutat foreland and all of the Copper River Delta barriers are next on the vulnerability scale. The hypothesis is that, while burial of stranded oil would be minimal in the fine-grained environment, cleaning could take several months. Infauna of sandy and muddy beaches are generally more mobile than rocky intertidal invertebrates, but this would confer no advantage if access to the surface were denied by a thick layer of stranded, weathering crude oil. Exposed tidal flats with poor drainage would also be at risk because of the well-developed infaunal communities found there. In the protected heads of bays or fiords stranded oil could well become a long-term, serious problem. The extensive salt marshes of the Copper River Delta and Controller Bay could be polluted in this manner.

Mixed sand-and-gravel and gravel beaches, such as those in Icy Bay and near the Malaspina Glacier, may retain oil for long periods because of their relatively high percolation rates and the lack of cleansing wave action. Gravel beaches just east of Sitkagi Bluffs are more exposed and might be more rapidly cleaned under natural conditions.

CHAPTER 7 INVERTEBRATES

D. R. Hancock, SAI

7.1 INTRODUCTION

Large populations of commercially valuable crabs, shrimp, and molluscs inhabit the coastal and oceanic waters of NEGOA. A host of other invertebrate species also occur in the region. Many of these organisms are the basic food of dense populations of fishes. The latter are important prey of marine birds and mammals of NEGOA. A number of these fishes--salmon, halibut, flounder, pollock, and cod--are the principal target of the Alaskan commercial fisheries. Thus a change in the composition and size of invertebrate populations by either natural events or human disturbance could affect populations of fishes and, ultimately, those of marine birds and mammals.

Species discussed in this review may be important commercially, or they may dominate in biomass or number of individuals. Some species have a major role as "keystone" predators (Paine, 1969) or as the principal prey of dominant species (as Euphausia spp. and Thysanoessa spp. are the principal prey of capelin). Other species are highly vulnerable to industrial contamination.

In this review the greatest attention will be devoted to invertebrate populations that occur in NEGOA from Cape Fairweather to Prince William Sound. The region includes the tracts leased in Sale No. 39 and those proposed for sale in Lease Area No. 55 (see Chapters 11 and 12). The region here considered as NEGOA has been called by other names by different research groups, depending on their own needs. For example, the Southeastern, Yakutat, and outer portions of the Prince William Sound Shellfish Management Districts lie within the bounds of NEGOA (ADF&G, 1979a, 1979b). Similarly, Ronholt, et al. (1978) subdivided NEGOA into Fairweather, Yakutat, and Prince William Sound districts when reporting the catch rates of crabs, shrimp, and fish. Differences in boundaries have made it difficult to estimate the size and distribution of populations and the extent of the commercial harvest in NEGOA.

The 1978 ex-vessel value of the NEGOA commercial shellfish catch was $10 million, not including the minor fisheries for marine snails and octopi (ADF&G, 1979a, 1979b, 1979c, 1979d) The principal commercial invertebrate species in NEGOA fishery is the Dungeness crab; this species accounted for about 45 percent of the entire Alaskan catch in 1978.

The remainder of this chapter is a summary of information on the distribution, abundance, population fluctuations, life histories, and feeding relationships of key invertebrates. Commercially valuable and noncommercial but ecologically valuable types are discussed separately except in the section on feeding relationships.

7.2 COMMERCIALLY IMPORTANT SPECIES

Distributions of commercially important invertebrate species have been reported by the International Pacific Halibut Commission (IPHC), International North Pacific Fisheries Commission INPFC), Bureau of Commercial Fisheries (BCF), National Marine Fisheries Service (NMFS), and other workers. The Alaska Department of Fish and Game (ADF&G) reports catch data of the commercial fisheries by region and season. The recently formed North Pacific Fisheries Management Council (NPFMC) also maintains commercial statistics and regulates foreign and domestic catches. Feder and Jewett (1979) collected epifauna from stations occupied by the NMFS Resource Assessment trawl survey of 1975. The distribution of trawling stations is shown in Fig. 7.1. Ronholt et al. (1978) reviewed the historical demersal fish and shellfish resources of the Gulf of Alaska. Within NEGOA, epibenthic invertebrates were trawled in highest densities south and southeast of Prince William Sound, where the average (geometric mean) catch per unit effort (CPUE) was 119 kg/hr trawled during a NMFS survey (1975-76; Ronholt et al., 1978). Concomitant catch rates of epibenthic invertebrates in the Yakutat and Fairweather regions were 44 and 37 kg/hr trawled, respectively. Major concentrations of invertebrates in NEGOA as determined by trawls are shown in Fig. 7.2. Invertebrates occurred in highest concentrations (119 kg/hr trawled) on the inner continental shelf (1-100 m water depths) but were less dense on the outer shelf (58 kg/hr trawled: 101-200 m) and upper continental slope (81 kg/hr: 201-400 m; Ronholt et al., 1978).

Nearly 60 percent of the epifaunal invertebrates taken during NMFS cruises (1975-76) in NEGOA were of

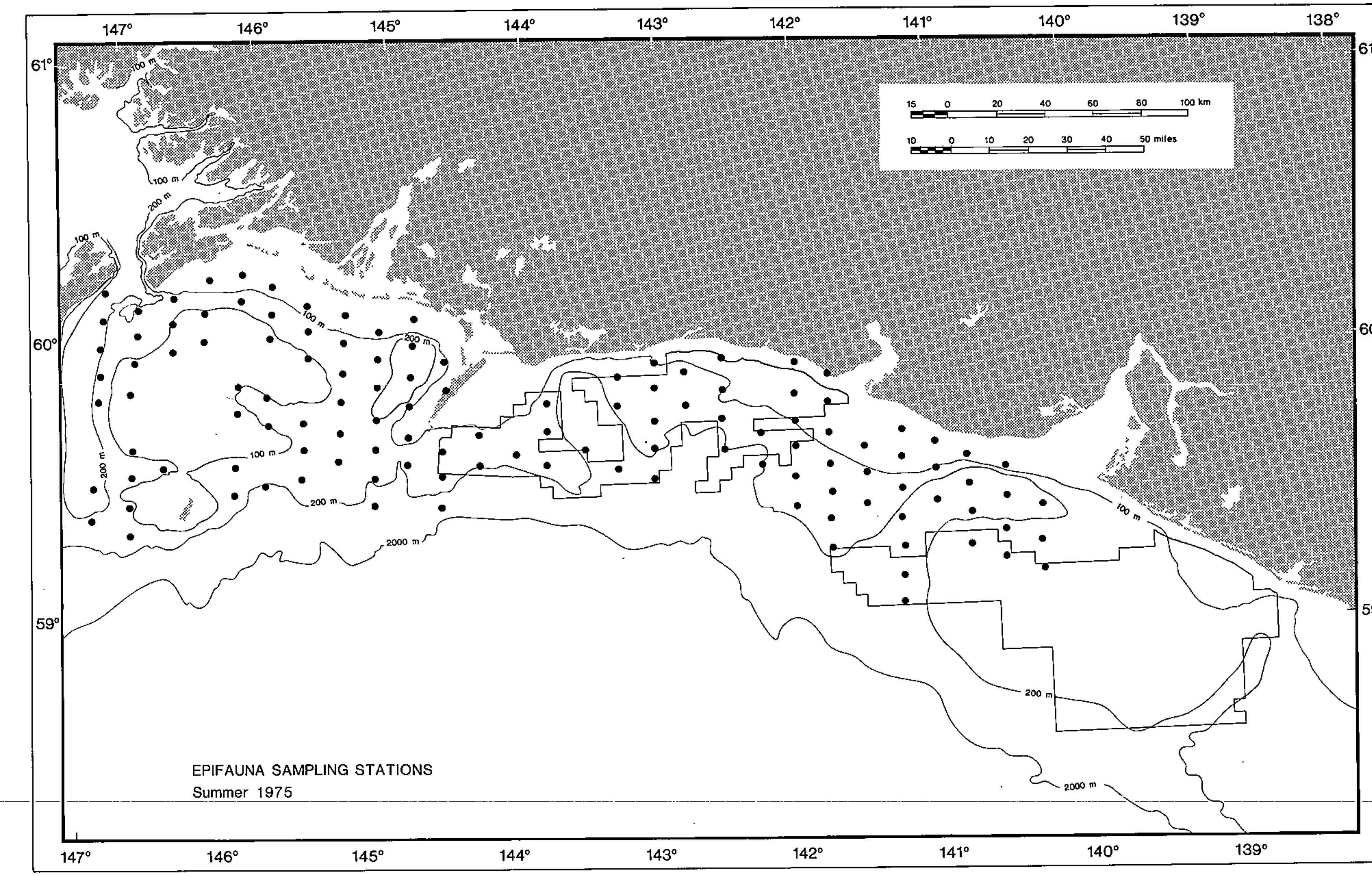


Figure 7.1 Station grid established for trawl survey on the shelf of NEGOA (Feder and Jewett, 1979).

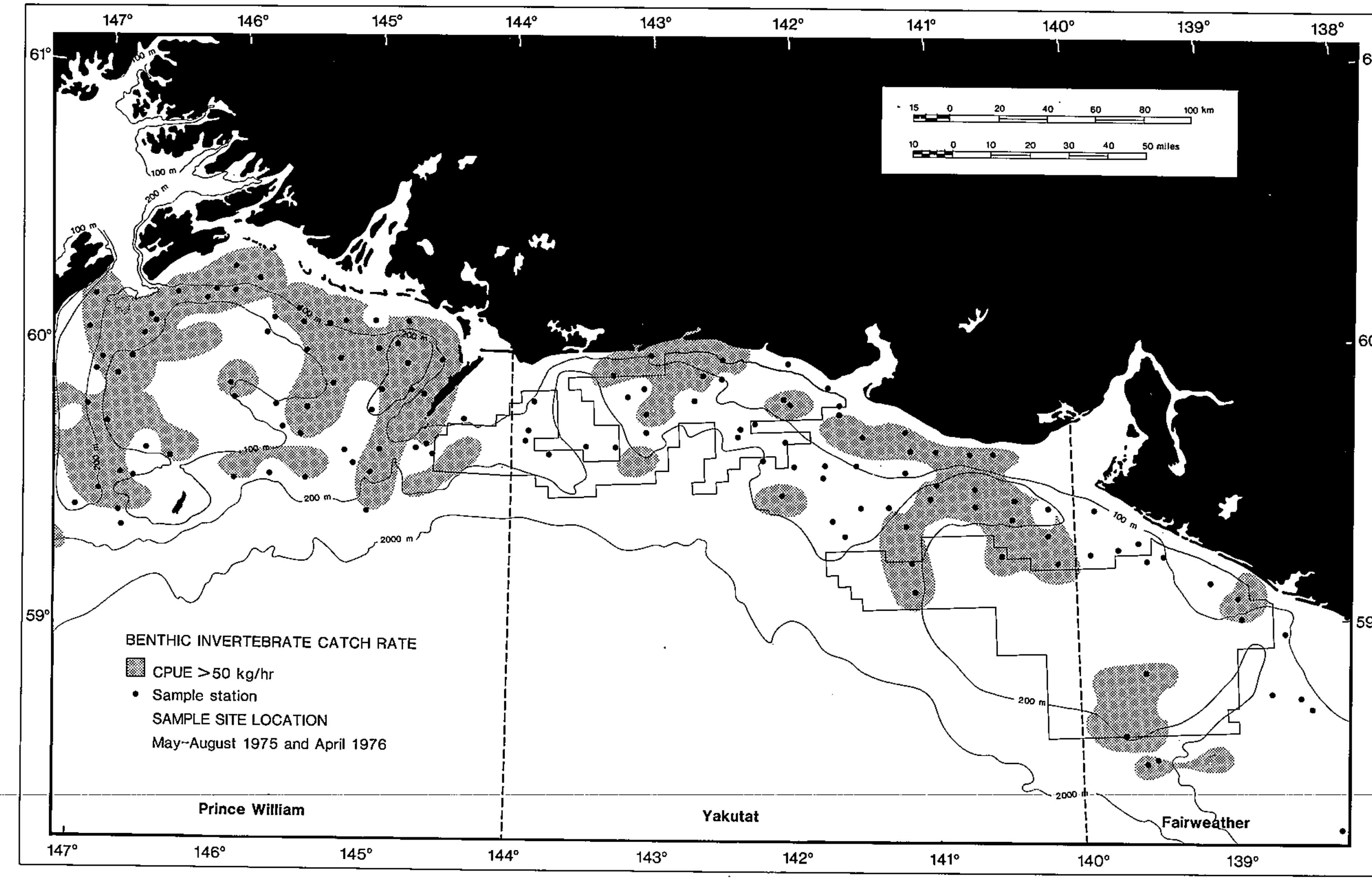


Figure 7.2 Areas of major concentrations of benthic invertebrates in NEGOA, May-August 1975 and April 1976, with sampling locations indicated (Ronholt et al., 1978).

commercial value (see Table 7.1 for species list). An estimated standing stock of 45,000 mt of commercially valuable invertebrates was available to trawl gear in May-August 1975. The bulk of these were Tanner crab (85 percent), pink shrimp (9 percent) and weathervane scallop (3 percent) (Ronholt et al., 1978).

Pereyra and Ronholt (1976) and Ronholt et al. (1978) compared the catch data of the NMFS 1975-6 survey with an earlier (1960's) trawl survey by the IPHC. They found that while invertebrate populations in the Fairweather and Yakutat regions have remained steady (mean CPUE: 37-73 kg/hr trawled); in the Prince William region the mean CPUE of invertebrates was 23 times greater in 1975-76 than in 1961.

Table 7.1 Commercially important invertebrates in NEGOA.

Common name	Scientific name
	Arthropoda, Decapoda
Tanner (snow) crab	Chionoecetes bairdi
Dungeness crab	Cancer magister
Red king crab	Paralithodes camtschatica
Pink shrimp	Pandalus borealis
Ocean pink shrimp	P. jordani
Coonstripe shrimp	P. hypsinotus
Dock shrimp	P. danae
Spot shrimp	P. platyceros
Sidestripe shrimp	Pandalopsis dispar
	Mollusca, Pelecypoda
Weathervane scallop	Patinopecten caurinus
Razor claim	Siliqua patula
Butter clam	Saxidomus gigantea
Cockle	Clinocardium nuttallii
Surf clam	Spisula polynyma

7.2.1 Tanner crab (snow crab)

Three species of Tanner crabs, Chionoecetes bairdi, C. tanneri, and C. angulatus, occur in NEGOA (NPFMS, 1978a). C. bairdi is the most ubiquitous epibenthic invertebrate in NEGOA, occurring at 89 percent of the stations sampled in 1975 (Ronholt et al., 1978). While molluscs, crustaceans, and echinoderms were the dominant invertebrate groups on the NEGOA shelf, the commercially important crab C. bairdi was by far the most abundant species (Eldridge, 1972a; Feder and Jewett, 1979).

Tanner crabs occur from the shallow littoral zone to depths of 475 m, with greatest numbers found below 100 m (Eldridge, 1972a; ADF&G, 1975a). The population density varies regionally and temporally. Highest densities of crabs in NEGOA were found on the upper continental slopes, in particular the area south of the Copper River Delta, where catch rates averaged 215 kg/hr trawled in 1975-76 (Ronholt et al., 1978). The distribution and abundance of Tanner crabs in NEGOA are shown in Fig. 7.3. Feder and Jewett (1979) suggested that these high crab densities are related to high productivity in that area. The high productivity may be the result of strong vertical mixing of oceanic waters. Average catch rates of Tanner crabs in the three NEGOA regions (0-400 m) during the 1975-76 survey were 127 kg/hr (Prince William Sound), 8 kg/hr (Yakutat), and 4 kg/hr trawled (Fairweather), whereas in 1961 they were 16 kg/hr, 12 kg/hr, and 77 kg/hr trawled, respectively (Ronholt et al., 1978).

The reproductive biology, growth, and sexual maturity of Tanner crabs in NEGOA have been described by Brown and Powell (1972), Powell et al., (1972), Hilsinger (1976), and Donaldson et al., (1979).

In juvenile Tanner crabs the frequency of molting and growth is inversely proportional to age. A growth model for the species is shown in the Tanner Crab Fisheries Management Plan (NPFMC, 1978a). Males and females have similar growth rates until maturity. Females do not molt after their puberty molt, whereas males continue to molt annually. Tanner crabs mature at 70-100 mm carapace width (CW) (Brown and Powell, 1972). At the puberty molt females mate and ovulate for the first time. At 68 mm CW fifty percent of the females exhibit orange ova, while at 83 mm one-half of the females have undergone the puberty molt. Males mature at 90-100 mm CW (Brown and Powell, 1972). Smaller Tanner crab males molt more than twice a year; males larger than 88 mm CW molt less frequently, about once every 16 months. At 150 mm CW, males molt once every 18-24 months. Males may attain a maximum CW of 185 mm, females 125 mm. Tanner crabs are thought to live 12-17 years (Pereyra et al., 1976).

The average size of commercially caught Tanner crab is 150 mm CW. Donaldson et al. (1979) have studied aging and growth in this species; by assuming an annual molt, they calculated that it takes over 6 years for the average male to achieve maturity. Males would reach legally harvestable size (140 mm CW) after an average 7.5 years of growth. If molting every other year is assumed, then the average commercial crab (150 mm CW) is 10-12 years old, and the present fishery is thought to be removing animals between 7.5 and 12 years of age.

In early spring, adult Tanner crabs move into shallower depths to spawn (Bright, 1967; AEIDC, 1974; ADF&G, 1975a; Pereyra and Ronholt, 1976; NPFMC, 1978a). Depth preferences in NEGOA have not been reported, but on the Aleutian shelf Tanner crabs are found at depths of 50-130 m during their reproductive period (AEIDC, 1974). In the fall crabs move back into deeper water.

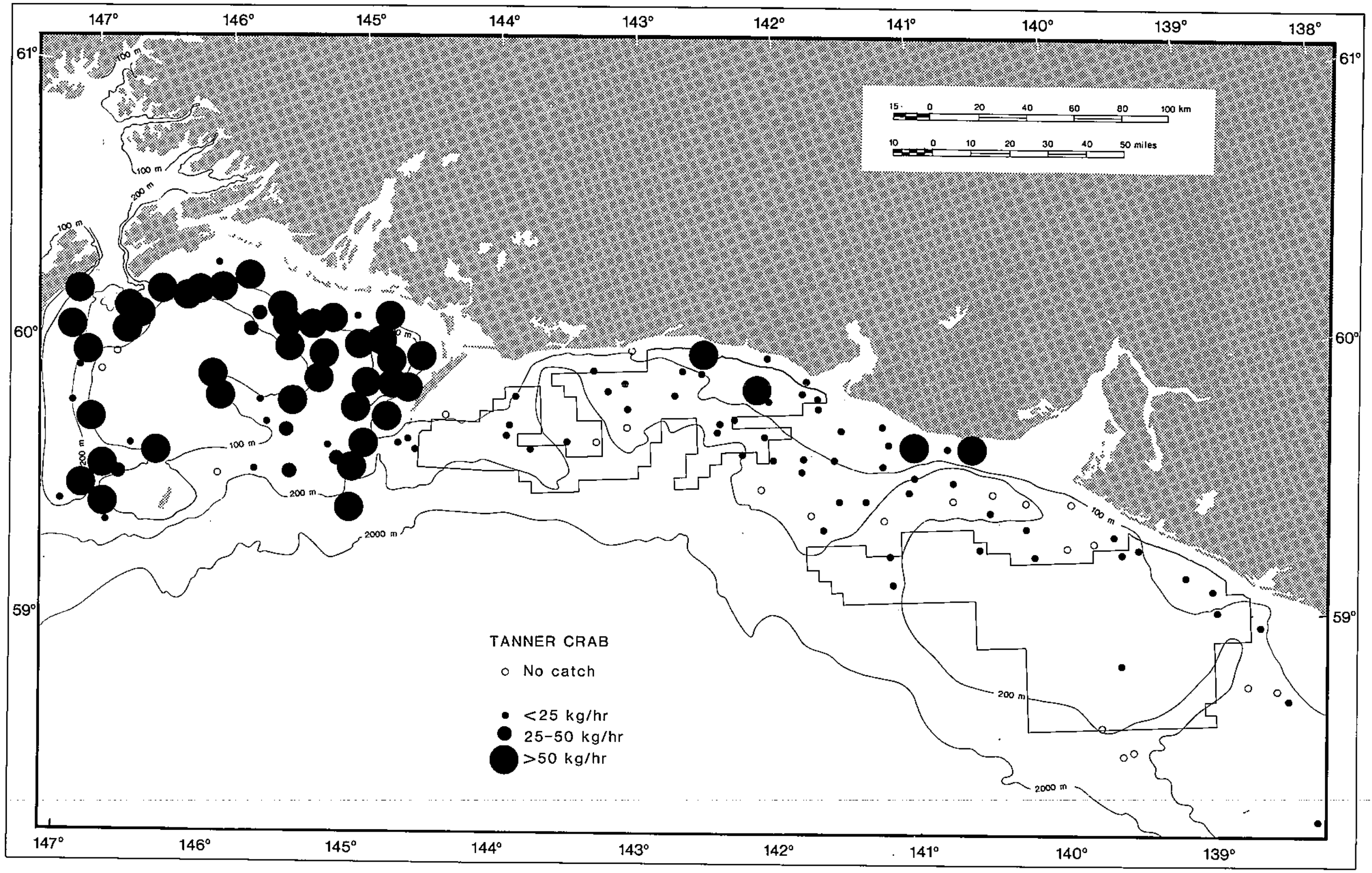


Figure 7.3 Distribution and abundance of the Tanner crab, Chionoecetes bairdi, May-August 1975 and April 1976 (Ronholt et al., 1978).

Tagging studies have shown that except for spawning migrations male Tanner crabs do not wander over great distances (Watson, 1970). Though the distribution of juvenile crabs in NEGOA has been described as "widespread," details of spatial and temporal distributions have not yet been reported.

The timing of Tanner crab spawning has not been documented for NEGOA but is inferred from adjacent areas. Tanner crabs move onto the inner Aleutian shelf to breed from January through May. AEIDC (1974) and Bright (1967) found that the species migrates into the Cook Inlet area to spawn from March through September with peak spawning occurring from May to August. Tanner crabs spawn in the Copper River Delta in April-May (Hilsinger, 1976). Mating commences shortly after the puberty molt of the females while they are still soft-shelled. Males breed when hard-shelled. Successful matings between two hard-shelled adults can occur (Hilsinger, 1976; NPFMC, 1978a), but they are less common. Mature male Tanner crabs are probably attracted to females by chemical odors released by the females, as is true of other decapods (Kittredge and Takahashi, 1972).

After eggs have been extruded and fertilized, females carry egg masses for about 11 months. Females brood an average of 30,000-80,000 eggs (Eldridge, 1972a; ADF&G, 1975a), although egg masses of 318,000 ova have been recorded (Hilsinger, 1976). In the Copper River area about 80 percent of the eggs are produced by females of 90-109 mm CW (Hilsinger, 1976). Larval release appears to coincide with plankton blooms (ADF&G, 1975a). The development of Tanner crab larvae takes from 12 to 90 days, depending on the temperature (Pereyra et al., 1976). Other factors such as food availability most assuredly affect the rate of development also. Larvae molt through up to a dozen instars, finally metamorphosing into juveniles. Juvenile Tanner crabs generally resemble adults (ADF&G, 1975a).

Information on natural mortality in Alaskan Tanner crab stocks has been summarized by Pereyra et al. (1976). Disease, parasites and predation are the main causes of death. Recently, mortality due to fishing pressure was examined by the NPFMC (1978a).

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). Since then catches have increased yearly.

Between 1969 and 1976 26,400 mt of Tanner crabs valued at $9.7 million were caught by the domestic fishing fleet (130°-149° W longitude) (NPFMC, 1978a). The report does not specify whether these animals were caught within Prince William Sound or in the Gulf of Alaska, however.

During the 1977-78 season 1,400 mt of Tanner crab from the Southeastern-Yakutat area were landed by 38 vessels. Ex-vessel prices exceeded $1.2 million (ADF&G, 1979c).

The Prince William Sound Management Area of the ADF&G lies between Cape Suckling on the east and Cape Fairfield on the west. Before the 1976-77 season, catch information had been reported from two areas inside and outside of Prince William Sound. Since 1976-1977 four new districts have been established in the Prince William area. The current Hinchinbrook, Eastern, and Western Districts lie within the NEGOA of this report.

The Tanner crab season begins in the Prince William Management Area on November 15 and, as weather conditions improve, the fishing effort shifts away from the northern district (not in NEGOA) and into the Hinchinbrook, Eastern, and Western Districts. Most Tanner crabs are caught between February and May (ADF&G, 1974). For the past four seasons the Eastern district has been relatively unfished except for its westernmost portions; it thus shows the greatest potential for an increase in catch in the future.

The total catch of Tanner crabs in the three Prince William Sound districts lying within NEGOA was 1,700 mt in 1977-78 (ADF&G, 1979c, 1979d). Figure 7.4 illustrates the combined Tanner crab catch from the Prince William Sound and the Southwestern-Yakutat Management Areas. The total ex-vessel price for 1977-78 exceeded $6.9 million.

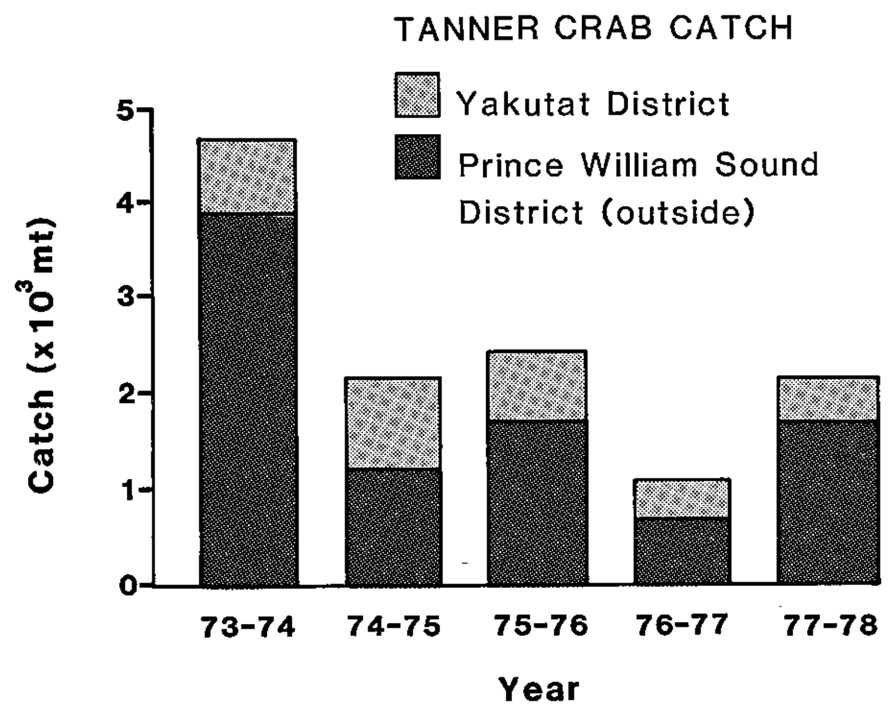


Figure 7.4 Tanner crab catch for NEGOA (ADF&G, 1979c).

Assessing absolute changes in population size over time based on catch rate data alone is difficult, at best. Complementary mark/recapture programs and egg and larval surveys would be of great value in assessing stock size. Currently, the NPFMC (1978a) asserts that a healthy reproductive stock of Tanner crabs exists in NEGOA, one capable of supporting a catch of 2,700-4,500 mt per year. Alverson (1977) however, believes that the fishing has been overexploited, that stocks are already declining, and that by 1982 only 20 percent of the present population will remain.

7.2.2 Dungeness crab

Dungeness crabs are distributed from central California northward to the Aleutian chain, inhabiting bays, estuaries, and the open ocean along the coast from the intertidal zone to 90 m water (McKay, 1943; Hoopes, 1973; ADF&G, 1975a). At all depths Dungeness crabs are found in intertidal and subtidal waters, often associated with algal or eelgrass shelter (Butler, 1960) or buried in the sand (McKay, 1943). The planktonic larvae in late spring are found near shore, as are the spawning females (Mayer, 1972). The abundance of Dungeness crab in NEGOA is unknown. In his review of experimental trawl data from 1950 to 1968, Murturgo (1975) concluded that the area of greatest concentration of Dungeness crab in NEGOA was between Hinchinbrook Entrance and Kayak Island near the mouth of the Copper River Delta. A second major concentration was located at Yakutat Bay and along the adjacent coastline south to Cape Fairweather. Ronholt et al. (1978) estimated their biomass, but these estimates are only for offshore populations in June and August 1962 and may not reflect the present standing stock, which is mainly inshore.

The life cycle of Dungeness crab has been summarized by Mayer (1972), Hoopes (1973), and ADF&G (1975a). The Dungeness crab is sexually mature after 3 years (110 mm CW) and may live 8-10 years. Adult crabs move into the deepest part of their range in winter, apparently to avoid the low temperatures and salinities of the nearshore zone. They move inshore again in spring with the onset of the reproductive period, and mating occurs in June, July and August near shore after females have shed their carapace (Mayer, 1972; Hoopes, 1973). Females spawn in early spring and summer in shallow water. They may produce as many as 1.5 million eggs and carry them for 7-10 months before releasing the planktonic larvae. During the next three to four months, larvae metamorphose through six instars the last form being a megalops stage. Megalops larvae molt into benthic-dwelling juveniles, which resemble adults in form.

Dungeness crabs mature in about three years. Mature males and females are approximately 140 mm and 100 mm CW, respectively. Growth is more rapid in Dungeness crabs than in Tanner or king crabs. Male Dungeness crabs may reach 200 mm CW in eight years; females attain 150 mm CW. Data on natural mortality is lacking; these crabs presumably confront the same natural hazards as Tanner and king crabs.

The Dungeness crab fishery is one of the oldest in Alaska. These crabs are primarily sought by the U.S. fishing fleet. They are caught by pots set in waters 7-50 m deep (Mayer, 1972). Peak catches occur from June through September (ADF&G, 1971, 1974). The fishing effort in nearshore waters decreases in autumn, when crabs begin to move offshore (Mayer, 1972). In the offshore waters north and west of Cape Spencer, the fishery consists of a fleet of large vessels (>50 gt). In these ships, crabs can be held alive for weeks in storage tanks. These large crab vessels are usually based in Washington ports.

About 23 percent of the entire Dungeness crab catch in the Gulf of Alaska is taken in ADF&G's Yakutat District, while another 11 percent is caught inside Icy Bay. The Copper River Delta is a third area where crabs are harvested in large amounts (Mayer, 1972; Ronholt et al., 1978; ADF&G, 1979e). The area referred to as NEGOA in this report comprises the ADF&G's Yakutat and Copper River Districts. During the 1978-79 fishing season, 851 mt of crab were sold at dockside in the Yakutat District, with another 591 mt landed in the Copper River District. The total ex-vessel value of the catch was about $2.2 million (ADF&G, 1979e).

7.2.3 King crab

King crabs inhabit the North Pacific Ocean, Bering Sea, and Okhotsk Sea (Marukawa, in Bright, 1967). In NEGOA they are distributed from the sublittoral zone (Powell and Nickerson, 1965; Feder and Jewett, 1979) to water depths of about 275-350 m (Bright, 1967; ADF&G, 1976a). The fishery typically takes adult crabs in 36-200 m of water (AEIDC, 1974). Juvenile crabs are usually found at shallower depths than adults.

Adult crabs annually migrate into shallower areas and onto offshore banks (Powell, 1964; McMullen, 1967). During migrations males and females school separately. Females precede males to the spawning grounds by a month or so. While migrating shoreward, king crabs probably follow submarine valleys on the shelf, which often 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, 1976a).

In Kodiak waters king crabs breed from February through May (Gray and Powell, 1966). They remain in shallow waters after mating and spawning, returning to deeper waters by early autumn (Powell and Reynolds, 1965).

After spawning, females carry ova for 11 months before larvae hatch. Fecundity increases with the size of the female, the largest producing 400,000 eggs. Larvae molt through four pelagic instars, then develop into benthic-dwelling glaucothoe larvae, and finally mature into a juvenile form that resembles the adult (Weber and Miyahara, 1962; Eldridge, 1972b; Buck et al., 1975).

Juveniles live solitarily on rock substrates until they are two to three years old. They are distributed from the intertidal zone to 200 m of water (Rietze, 1975). At two to three years of age juveniles begin to move about actively and aggregate, forming dense pods of up to several thousand individuals (Powell and Nickerson, 1965; Bright, 1967). With age, juveniles again disperse, and, like adults, they move offshore to feed in summer and fall, then return to shallower waters in spring. King crabs reach maturity in their fifth or sixth year (Rietze, 1975). Most studies have shown that king crabs are segregated by sex and age class on their offshore feeding grounds (literature cited in Pereyra et al., 1976).

King crab growth, 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 in carapace length (CL). After three years of age both sexes usually molt once a year. Males increase about 16 mm CL per annum; females grow more slowly. As they reach maximum size (100 mm CL for males and 160 mm CL for females), king crabs molt only once every two or three years (Weber, 1967). King crabs probably live for about 20 years (Pereyra et al., 1976).

King crab populations appear to be low in NEGOA (Eldridge, 1972b; Ronholt et al., 1978). During the NMFS 1975-76 survey, less than 1 kg/hr of king crabs were trawled in the Fairweather region, and no crabs were taken in either the Yakutat or Prince William region (Ronholt et al., 1978). Murturgo (1975) states that king crabs occur in Prince William Sound on the west side of Montague Island and that scattered populations exist in many of the fiords of the sound (Fig. 7.5). The actual abundance of king crab on the NEGOA continental shelf and slope is unknown.

The king crab commercial fishery in NEGOA is insignificant; only 140 mt of crabs were harvested from 1965 through 1969 (Mayer, 1972). In the Prince William Sound-Copper River Delta area catches ranged from 29 to 135 mt per year during 1970-74 (ADF&G, 1974), and in Yakutat Bay 2.3 mt were taken in 1978-79 (ADF&G, 1979a).

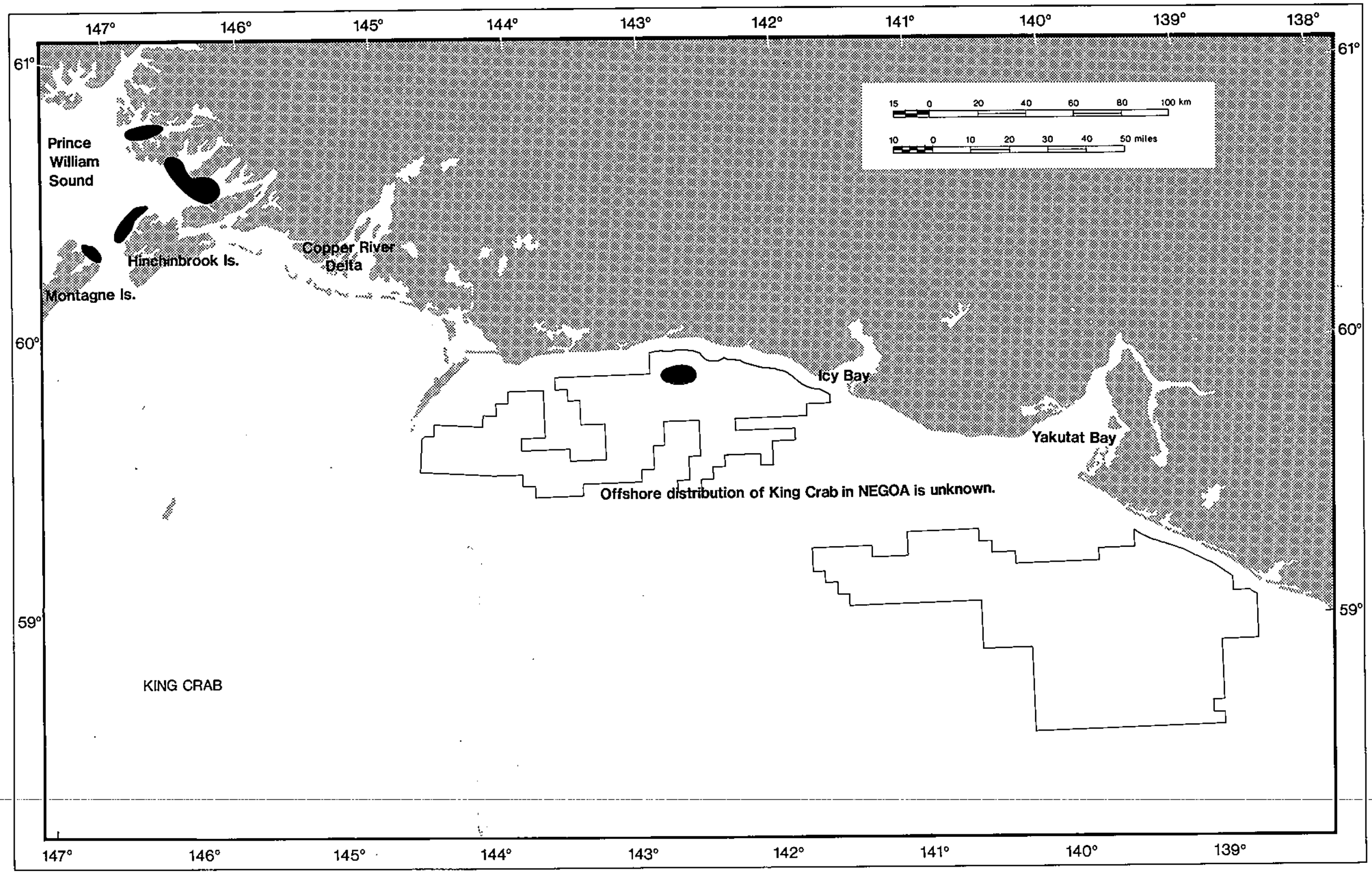


Figure 7.5 Probable distribution of king crab populations in NEGOA (Murturgo, 1975; ADF&G, 1975b).

7.2.4 Shrimp

Six species of pandalid shrimp belonging to two genera (Pandalus and Pandalopsis) are found in NEGOA (Table 7.1; see Fox, 1972 for a complete listing of shrimp). Three species: *Pandalus borealis* (pink shrimp), *Pandalopsis dispar* (sidestripe shrimp), and *Pandalus jordani* (ocean pink shrimp), constitute the bulk of the fishery.

Adult pandalid shrimp inhabit waters from the intertidal region to beyond the continental shelf. Pink shrimp prefer depths of 75-180 m (Fox, 1972; AEIDC, 1974) and are found mainly within 40 miles of the coast in submarine ravines on muddy bottoms (Ivanov, 1969). The preferred green mud habitat of both pink and ocean pink shrimp may be correlated with the high organic content of these clayey substrates (Fox, 1972) and with the food of these species: small benthic polychaetes, small clams, and small crustaceans that are characteristic of muddy substrates. Pink shrimp avoid water warmer than 8°C and are concentrated between the 3.5 and 4.2°C isotherms (Ivanov, 1964). Sidestripe shrimp probably prefer greater depths than pink shrimp (Ronholt et al., 1978). Depth preferences for other pandalid shrimp in NEGOA are unknown. One difficulty in determining depth distributions is that researchers in the past have lumped all shrimp collected at sampling locations as "pandalids". Furthermore, although the shrimp species prefer different habitats, these habitats have not been sampled with the same effort. For example, smooth muddy bottoms are sampled much more easily than irregular, rocky substrates. Thus, information on the distribution and relative abundance of the pandalids inhabiting areas with irregular, rocky substrates is scarce.

Pandalid shrimp occur throughout the Gulf of Alaska and its larger bays and inlets (Fox, 1972). Pink shrimp were caught at 60 percent of the stations sampled in the gulf during 1975, sidestripe shrimp were found at 39 percent, while ocean pink shrimp occurred at 13 percent. Other shrimp were taken in trawls only occasionally (Ronholt et al., 1978). The distribution and abundance of pink shrimp in NEGOA are shown in Fig. 7.6.

Shrimp migrate seasonally. In August and September, they move into shallow bays and adjacent to islands to spawn (Ivanov, 1969). The migratory routes

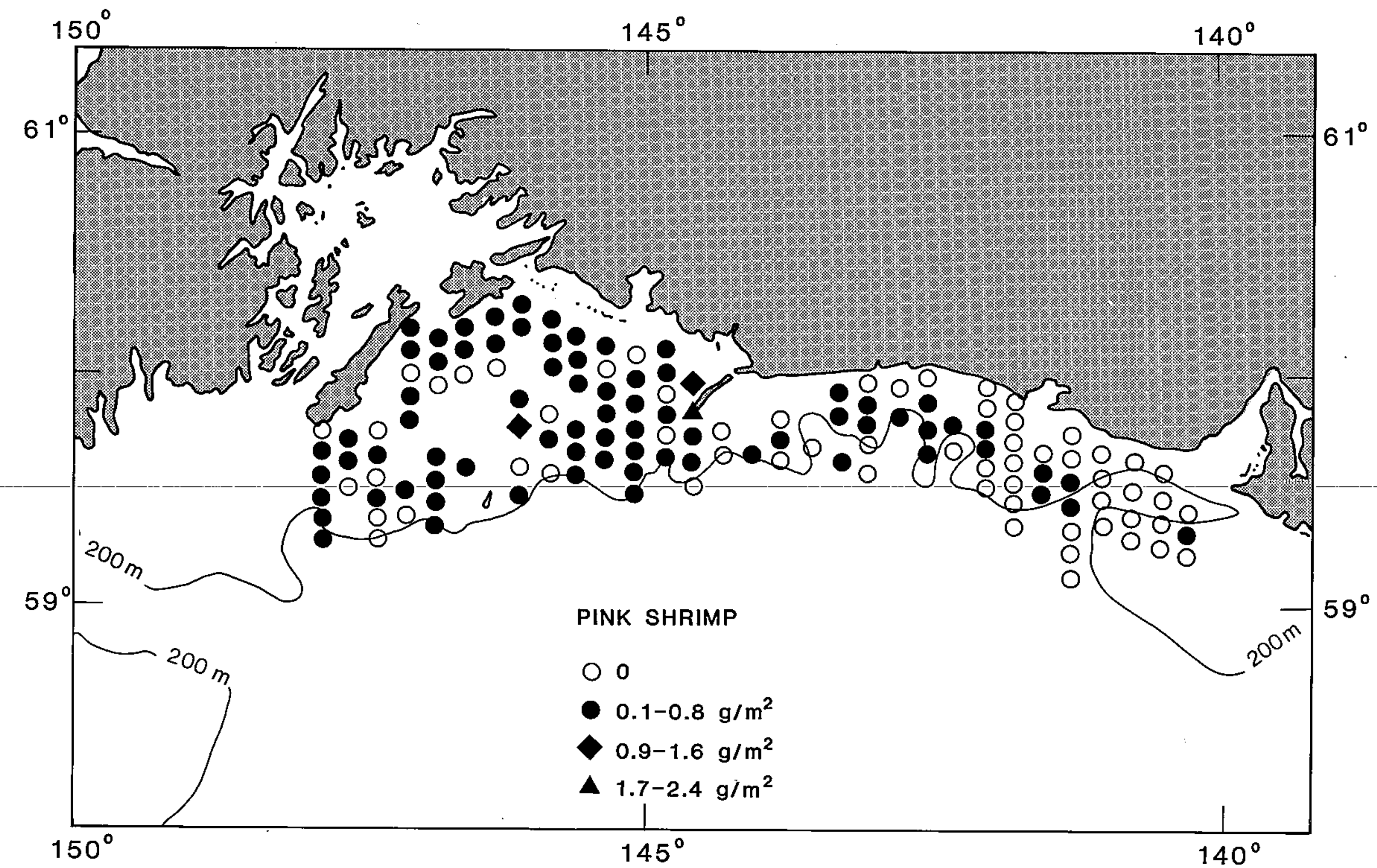


Figure 7.6 Distribution and abundance of the pink shrimp, *Pandalus borealis*, from NEGOA trawl survey, summer 1975 (Feder and Jewett, 1979).

and spawning locales have not been documented for NEGOA (ADF&G, 1975a), but such knowledge is most important for predicting the effects of oil and gas development and transportation on shrimp populations. Juvenile shrimp are found in waters less than 40 m deep in winter but live at greater depths in summer. Larvae are found near shore throughout their 2-1/2-month life stage (AEIDC, 1974).

The principal shrimp species have similar life cycles. Females spawn in August and September in shallow bays and around island groups. Each female produces 900-3,000 eggs and carries her egg mass for about six months. Except for humpy and coonstripe shrimp, the dominant shrimp in NEGOA develop as males, mature in two years, breed as males through their third or fourth year, then change into females and continue to breed as females until six years of age (Fox, 1972; ADF&G, 1975a; Pereyra et al., 1976). Data on growth, recruitment, and mortality are lacking for pandalids in NEGOA.

Shrimp are found near the bottom during the day, but at night all species migrate off the bottom to feed (Fox, 1972; ADF&G, 1975a). Pandalid shrimp species usually are segregated vertically during their nocturnal movements (AEIDC, 1974).

Catch rates for all pandalid shrimp in NEGOA averaged 9 kg/hr trawled in 1975. Pink shrimp were the most abundant species, with a catch rate of 7 kg/hr trawled. Highest catch rates of pink shrimp were recorded at stations south of Prince William Sound and the Copper River in 0-100 m of water. The estimated standing stocks of pink, sidestripe, and ocean pink shrimp were 3,800 mt, 800 mt, and 100 mt, respectively, in the 1975 survey. Only small quantities of other pandalid shrimp were reported (Ronholt et al., 1978).

The shrimp fishery in NEGOA is negligible. From 1969 to 1975, 1.3 mt of pandalid shrimp were harvested in the region (Ronholt et al., 1978).

7.2.5 Scallops

Major beds of weathervane scallops (*Patinopecten caurinus*) occur from Cape Fairweather to Cape St. Elias, with small concentrations found east of Montague Island. Beds are generally found in 55-130 m water depths, 30-70 km offshore (Hennick, 1970, 1973; ADF&G, 1975a, 1975b). The preferred substrate is a mixture of gravel, sand, and mud (ADF&G, 1975a). Scallops were found at 35 percent of the stations sampled by the NMFS in 1975 (Ronholt et al., 1976).

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, and become filter-feeders (Eldridge, 1972c). Scallops mature in three years, when they are 80-125 mm from umbo to outer shell margin. As scallops grow, they add additional bands of shell at a probable rate of one per annum (Hennick, 1970). Scallops may live for more than 15 years. Some specimens measure 225 mm or more from umbo to outer shell margin (Hennick, 1970).

The standing stock of scallops in 1975 was estimated at 1,300 mt (140-184°W longitude, 0-400 m water depths), with 77 percent found between Cape St. Elias and Yakutat Bay. Maximum average catch rates of 15 kg/hr were trawled in 0-100 m of water between Icy and Yakutat Bays. For the entire NEGOA survey area, an average 3 kg/hr of scallops were trawled (Ronholt et al., 1978).

Scallops have been commercially exploited in NEGOA since the fishery began in 1967 (Eldridge, 1972c). An average of 126 mt (round weight) of scallops was harvested per year (1969-75) in the Fairweather and Yakutat regions, representing 23 percent of the Gulf of Alaska catch. The two areas of highest commercial production of scallops in NEGOA are shown in Fig. 7.7, and distribution and abundance are shown in Fig. 7.8 (Ronholt et al., 1978).

In 1968, the first full year of fishing, eight vessels landed 395.9 mt of scallops. In late 1968, the fishery expanded to beds off Yakutat. Initial catches exceeding 22.7 mt of shucked meats per delivery drew wide interest in the scallop fishery. During 1969 (the peak harvest year), 14 vessels landed 727 mt of shucked meats and 682 mt of unshucked scallops. Since 1969 only 2 to 5 vessels have fished annually, and catches have declined. From 1971 through 1975 the harvest declined to an average of 384 mt, and in 1974 only three vessels remained in the fleet (McCrary, pers. comm.).

The ex-vessel value of shucked scallops for the Alaskan fishery ranged from $1-1.5 million in 1968-73 but declined to about $600,000 in 1974-75. The shucked weight ex-vessel price per pound rose steadily from $0.80 in 1968 to $1.45 in 1975. During 1978 and 1979 some fishing took place in November and December but the harvest was expected to be less than 80,000 pounds statewide (McCrary, pers. comm.).

Many factors contributed to the decline of the Alaskan scallop fishery after its intensive and rapid development: 1) limited stocks in the Gulf of Alaska; 2) regulation by area and season to minimize mortality of incidental dredge-caught king and Tanner crab; 3) relatively static ex-vessel price per shucked pound, and 4) entry of scallop vessels into more lucrative fisheries such as king and Tanner crab (McCrary, pers. comm.).

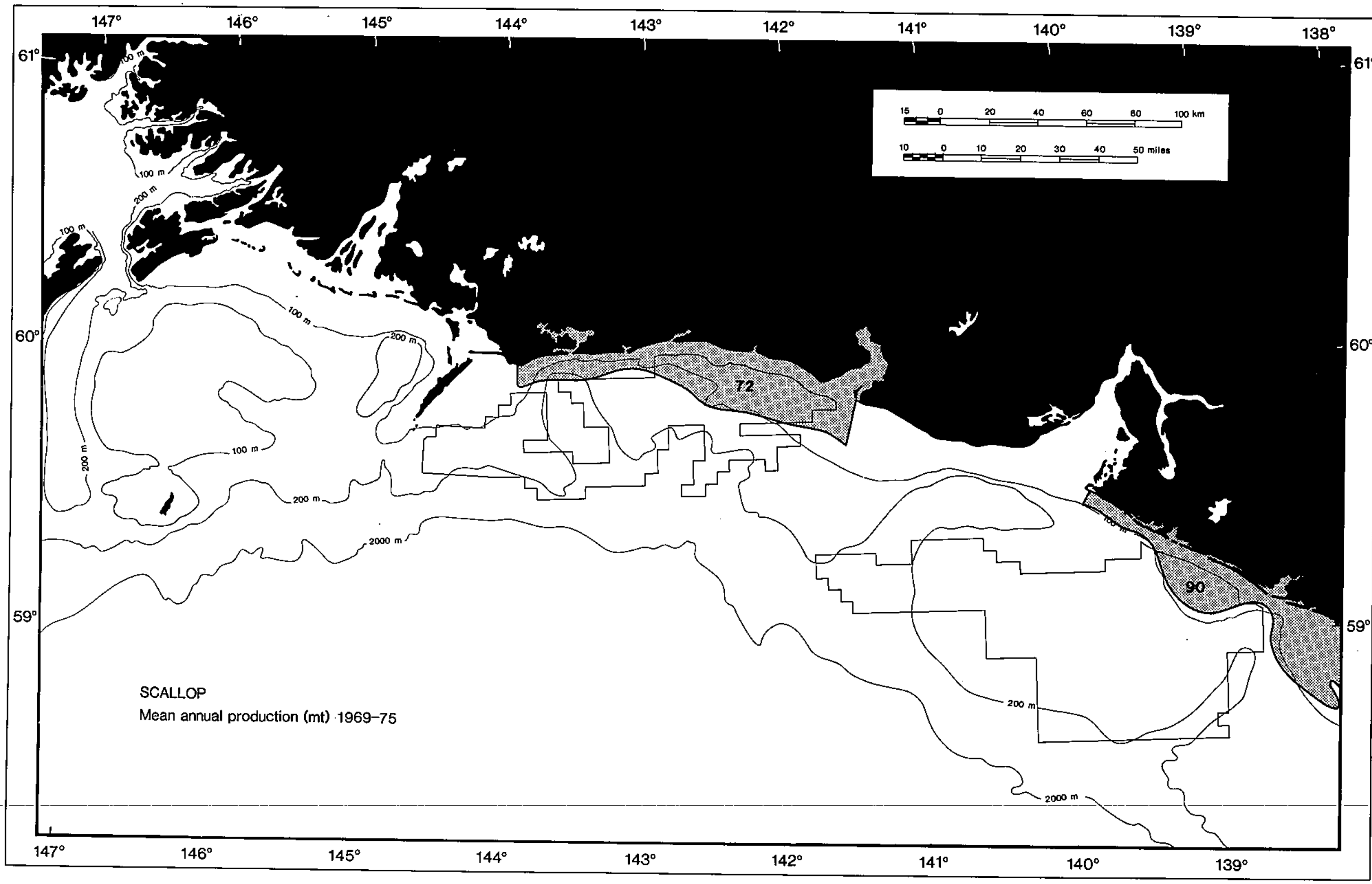


Figure 7.7 Areas of high commercial harvest of scallops by U.S. fishermen 1969-75 (Ronholt et al., 1978).

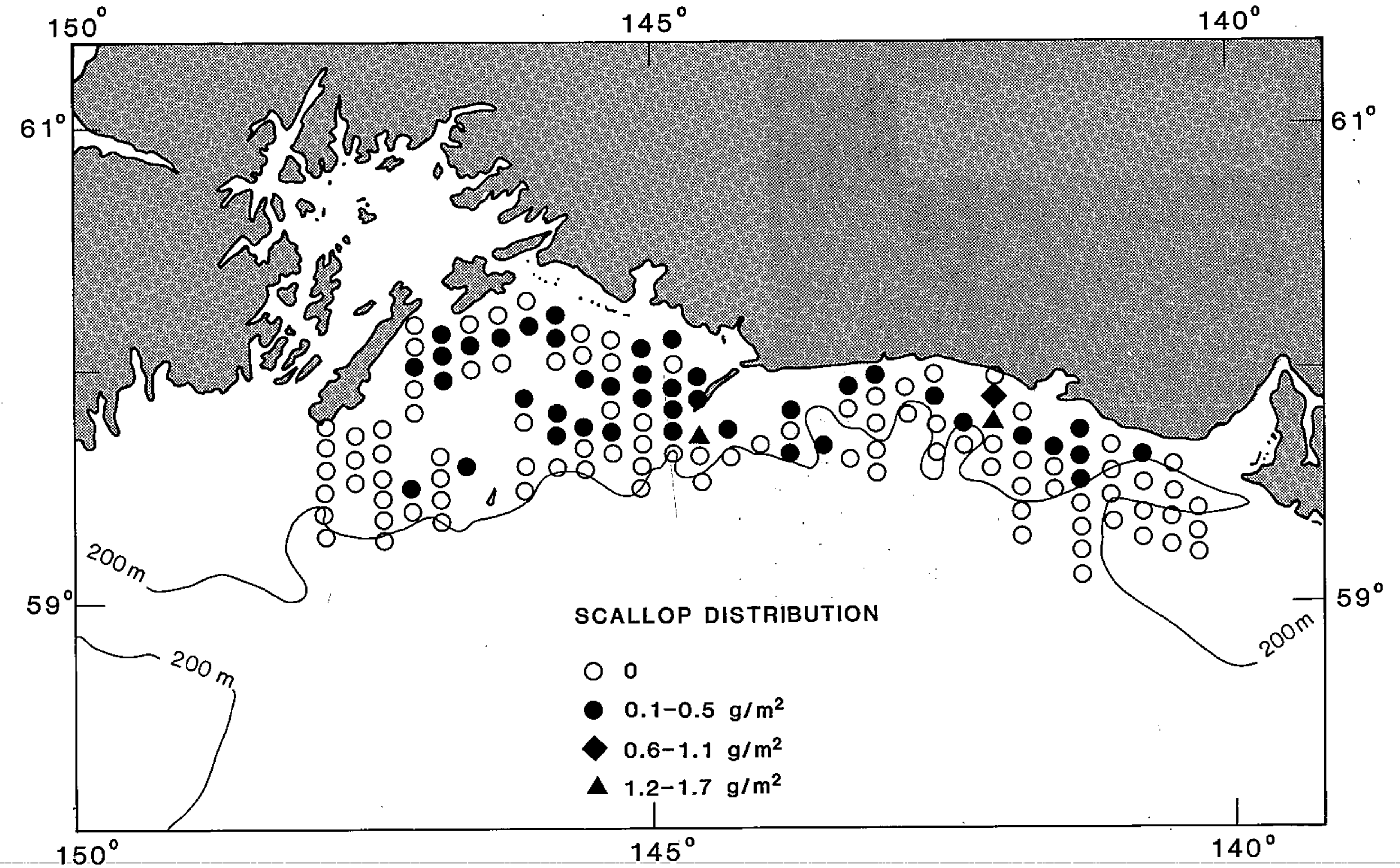


Figure 7.8 Distribution and abundance of the scallop Patinopecten caurinus, from the NEGOA trawl survey, summer 1975 (Feder and Jewett, 1979).

7.2.6 Clams

Razor clams, butter clams, surf clams, and cockles all occur in NEGOA, but the total clam resource is unknown. Clams harvested in Alaska have traditionally comprised three intertidal species: the razor clam, Siliqua patula, which accounts for about 95 percent of the catch; the butter clam, Saxidomus gigantea, and the cockle, Clinocardium nuttallii. Other species of clams are abundant but unexploited: the littleneck clam, Protothaca staminea; the softshell, Mya arenaria; and the pink neck or redneck clam, Spisula polynyma. Information on stocks, recruitment, and paralytic shellfish poisoning is available only for the razor clam (Paul and Feder, 1976).

Razor clams are found from mean low water to 54 m depths (Kaiser and Konigsberg, 1977) in sandy, exposed beaches which contain some glacial silt. Such habitat is found in Orca Inlet and the Copper River Delta (Nosho, 1972). This species spawns in summer and requires specific water temperatures for incubation and fertilization (Nickerson, 1975). The razor clam is prolific (6-10 million eggs) but also has high rates of 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 migrate inshore, offshore, and along the coast. By their third year however, they are more sedentary and remain 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).

Razor clams have been traditionally harvested in Orca Inlet in Prince William Sound and the Copper River Flats/Controller Bay areas. The 1978 razor clam harvest was 14 mt, most of which was sold as Dungeness crab bait (ADF&G, 1979b). Catch data (Fig. 7.9) show a marked decrease in the razor clam harvest in the Prince William Sound area. The decreased harvest has been attributed to decreased survival of juvenile razor clams caused by changes in the substrate. Deposition by the Copper River and uplifting caused by the 1964 earthquake are thought to be the major causes of the substrate changes (ADF&G, 1979b).

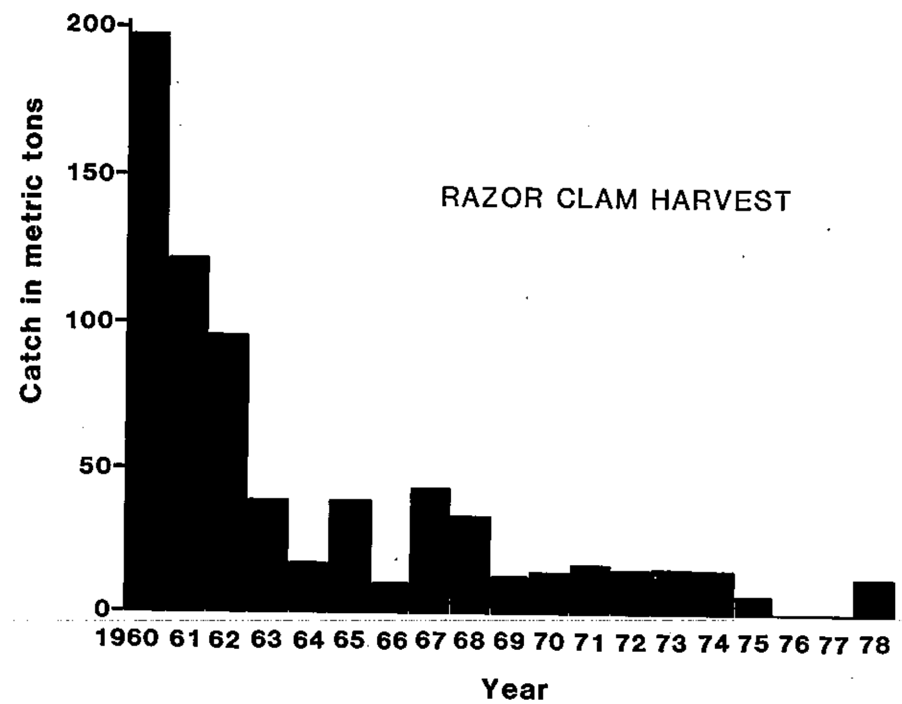


Figure 7.9 Razor clam harvest, Prince William Sound Area 1960-78 (ADF&G, 1979b).

Butter clams occur in 0-10 m of water in well-protected bays on a mixed gravel, sand, and mud substrate (Paul and Feder, 1976). Cockles are often found in eelgrass beds (Nosho, 1972; Paul and Feder, 1976). Both species occur in harvestable quantitites near Cordova in Prince William Sound (ADF&G, 1975a). At present there is no commercial fishery of hardshell clams in NEGOA. However, the State of Alaska plans to initiate a fishery (ADF&G, 1979b).

7.3 NONCOMMERCIAL INVERTEBRATES

A large variety of invertebrates of no direct commercial value inhabit the gulf, Prince William Sound, and the coastal bays (Table 7.2). These invertebrates are important as food for fish and crustaceans of commercial importance (Alton, 1974) and in decomposition and nutrient recycling. The presence of benthic infauna may also increase the stability of the substrate. The biomass of invertebrates can be very high. Many benthic invertebrates are sessile and long-lived and are sensitive to pollution of their environment by heavy metals, hydrocarbons, or other organic compounds. Adequate knowledge of these invertebrates is important to predict the effects of OCS development.

Current knowledge of the noncommercial invertebrates in the Gulf of Alaska comes from studies of the northwestern part of the gulf. The benthic fauna of NEGOA has not been as well studied as those of the Bering Sea, Aleutian chain, and northwestern gulf. The benthic fauna of the Gulf of Alaska was first investigated by Steller in 1741 (Shevtsov, 1964a). However, the Albatross expedition (1903-1905), Harriman expeditions in 1910 and 1911, and the American-Alaskan crab expeditions (1940 and 1941) gathered the first detailed systematic information on the benthic fauna of the region. Although much of the data from earlier Soviet workers is not available, several summaries of their findings provide background information on NEGOA (Vinogradov, 1964; Shevtsov, 1964a, 1964b).

Recent OCSEAP studies on NEGOA have contributed to our knowledge of the abundance, distribution,

Table 7.2 Important noncommercial invertebrate species and species groups in NEGOA.

Segmented worms	Annelida, Polychaeta Onuphis iridescens
Bivalve molluscs	Mollusca, Pelecypoda Macoma spp. Nuculana spp. Siliqua sloati Spisula polynyma Yoldia spp.
Snails	Mollusca, Gastropoda Fusitriton oregonensis Neptunea lyrata Nucella lamellosa
Cephalopods Squids (unidentified) Octopods	Mollusca, Cephalopoda Octopus spp.
Barnacles	Arthropoda, Cirripedia Balanus spp.
Cumaceans	Arthropoda, Cumacea Eudorella spp.
Amphipods	Arthropoda, Amphipoda Anonyx spp. Parathemisto spp.
Euphausiids	Arthropoda, Euphausiacea Thysanoessa spinifera
Decapod crustaceans Sand shrimp	Arthropoda, Decapoda Crangonidae Crangon dalli
Other shrimp	Eualus spp. Spirontocaris spp.
Hermit crabs	Paguridae Pagurus ochotensis
Spider crabs	Hyas lyratus Hyas spp.
Other crabs	Pinnixa spp. Oregonia gracilis
Brittle stars	Echinodermata, Ophiuroidea Ophiura sarsi Ophiopenia disacantha
Urchins Green urchin	Echinodermata, Echinoidea Strongylocentrotus droebachiensis

diversity, and faunal associations of the NEGOA continental shelf and slopes. The benthic infauna was sampled at 41 stations from July 1974 to March 1976, by means of a Van Veen grab (Fig. 7.10). The epifauna was sampled at 133 stations (Fig. 7.1) from May to August 1975 with otter trawl gear. Far more forms of infauna (14 phyla, 457 species) than epifauna (9 phyla, 168 species) were found. Benthic infaunal groups with the greatest diversity were polychaete worms (132 spp.). The trawl samples contained 30 species of polychaetes, 47 species of molluscs, 42 species of arthropods, and 36 species of echinoderms (Feder et al., 1976; Feder, 1977; Feder and Jewett, 1978; Feder and Matheke, 1979).

Infaunal organisms such as the clams Axinopsida serricata, Nucula tenuis, and Nuculana pernula, the echinoderms Ctenodiscus crispatus, Brisaster townsendi, and Molpadia sp., and the polychaete Sternaspis scutata have patchy distributions over wide geographic areas (Feder et al., 1976). The distribution of infaunal deposit-feeders, filter-feeders, scavengers, and predators appears to be correlated with sediment type. Sediment accumulation and bottom stability in the Gulf

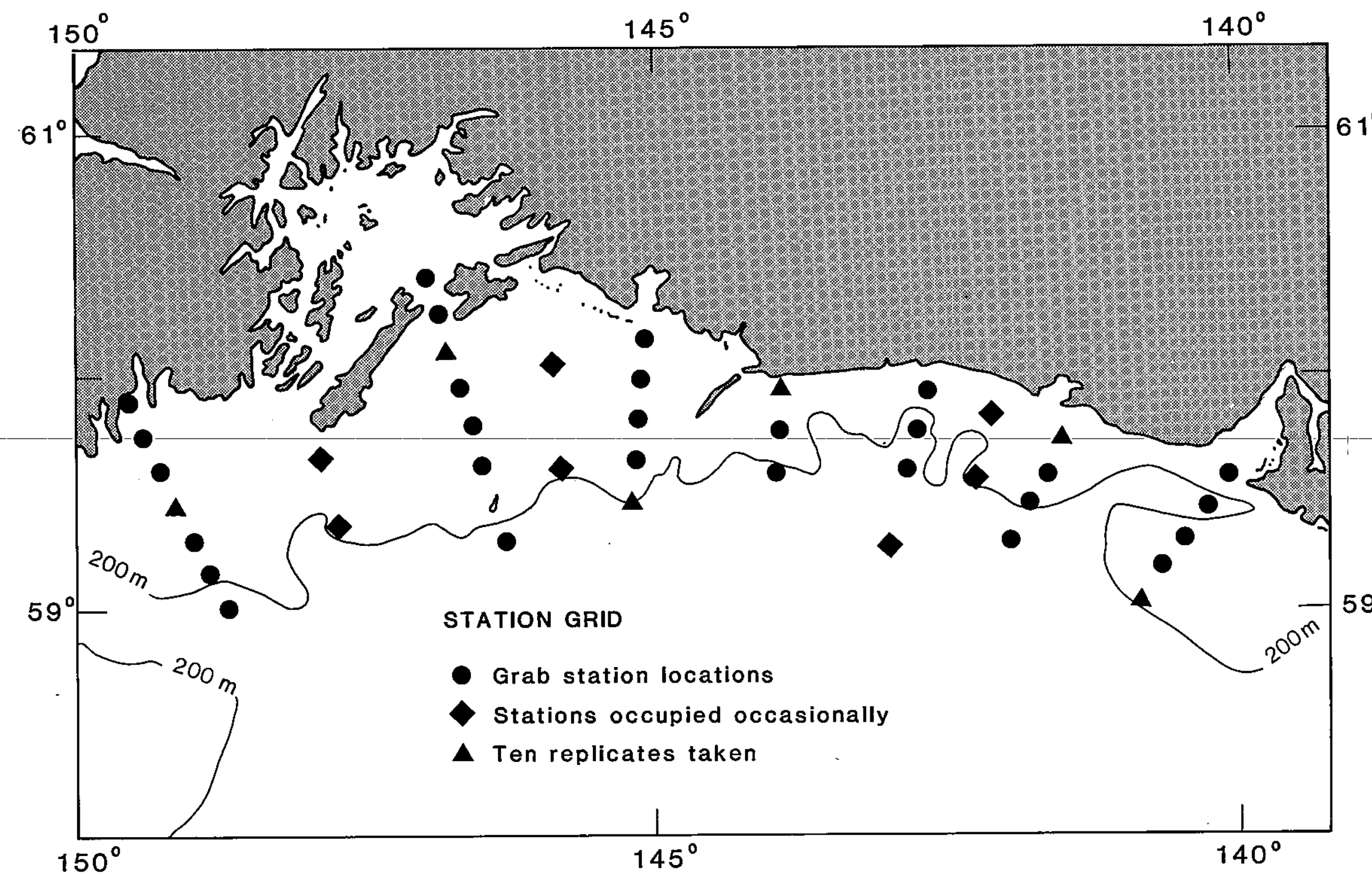


Figure 7.10 Station grid established for oceanographic investigations in NEGOA (Feder et al., 1976).

of Alaska are related in turn to the submarine physiography and currents of the region. The principal sediment sources are the Copper River and the drainages of the Bergin, Guyot, and Malaspina Glaciers, which supply silts and clay to the gulf. The fine sediment is transported in broad plumes offshore and westward, except in the Kayak gyre area. On banks, the sides of canyons, and the continental slope sedimentation rates are likely to be lower. Feder and Matheke (1979) found that mobile deposit-feeders such as polychaetes are characteristic of the silt-clay sediments of many inshore stations. Suspension-feeders are at a disadvantage in these areas because the readily resuspended fine-grained sediments can easily clog their feeding structures. In NEGOA, biomass, numerical abundance, and diversity appear to be greater in areas of increasing substrate heterogeneity, such as Tarr Bank, Hinchinbrook Entrance, and the continental slope, where greater amounts of sand and gravel are mixed with the fine sediments (Feder et al., 1976; Feder, 1977; Feder and Matheke, 1979). Substrates with more sand and gravel provide less hazard of siltation and more suitable locations for permanent attachment of suspension-feeding and sessile organisms.

Among the epifauna, highest densities of pink shrimp (Pandalus borealis), the brittle star Ophiura sarsi, and the sea star Ctenodiscus crispatus were recorded near the Copper River Delta southeast of Kayak Island (Feder, 1977). Little is known of the productivity of this area, but secondary production is probably high as a result of nutrients supplied by the Copper River and by gyres which extend vertically from the surface to the substrate (Jewett and Feder, 1976).

Faunal assemblages at two other sampling areas were distinctive (Jewett and Feder, 1976). At a location immediately south of Hinchinbrook Entrance, diversity (47 spp.) was high. The epifauna included 14 species of crustaceans, 13 echinoderms, and 13 molluscs. Seven species of fish, including numerous Pacific halibut, were also caught by the trawl. At another site immediately west of Icy Bay, the samples were characterized by the paucity of epifaunal invertebrates. Instead, three species of fishes (starry flounder, walleye pollock, and butter sole) accounted for nearly all the biomass trawled. Starry flounder predominated in the catch. All the stomachs were full and contained large quantities of clams (Yoldia seminuda, Siliqua sloati, and Macoma dexiosttera). As noted in section 7.2, the Tanner crab (Chionoecetes bairdi) accounted for more than 66 percent by weight of the epifaunal biomass. Pink shrimp (Pandalus borealis) accounted for almost 3 percent. The third most common crustacean was the box crab (Lopholithodes foraminatus). At most stations numerous echinoderms were taken, but each species was usually represented by only a few individuals. The exceptions were a brittle star (Ophiura sarsi), two sea stars (Ctenodiscus crispatus and Pycnopodia helianthoides), and a heart urchin (Brisaster townsendi), which were all found in large numbers. Sea cucumbers occurred at only seven stations, yet constituted nearly 3 percent of the total epibenthic biomass. The weathervane scallop (Patinopecten caurinus) accounted for 2 percent of the total biomass. The whelk (Neptunea lyrata) and the Oregon triton (Fusitriton oregonensis) were the most common molluscs (Feder and Jewett, 1978). The distribution and relative abundance of selected epibenthic species are shown in Figs. 7.11-7.13. Table 7.3 shows the percent composition by weight of the dominant invertebrates collected in NEGOA.

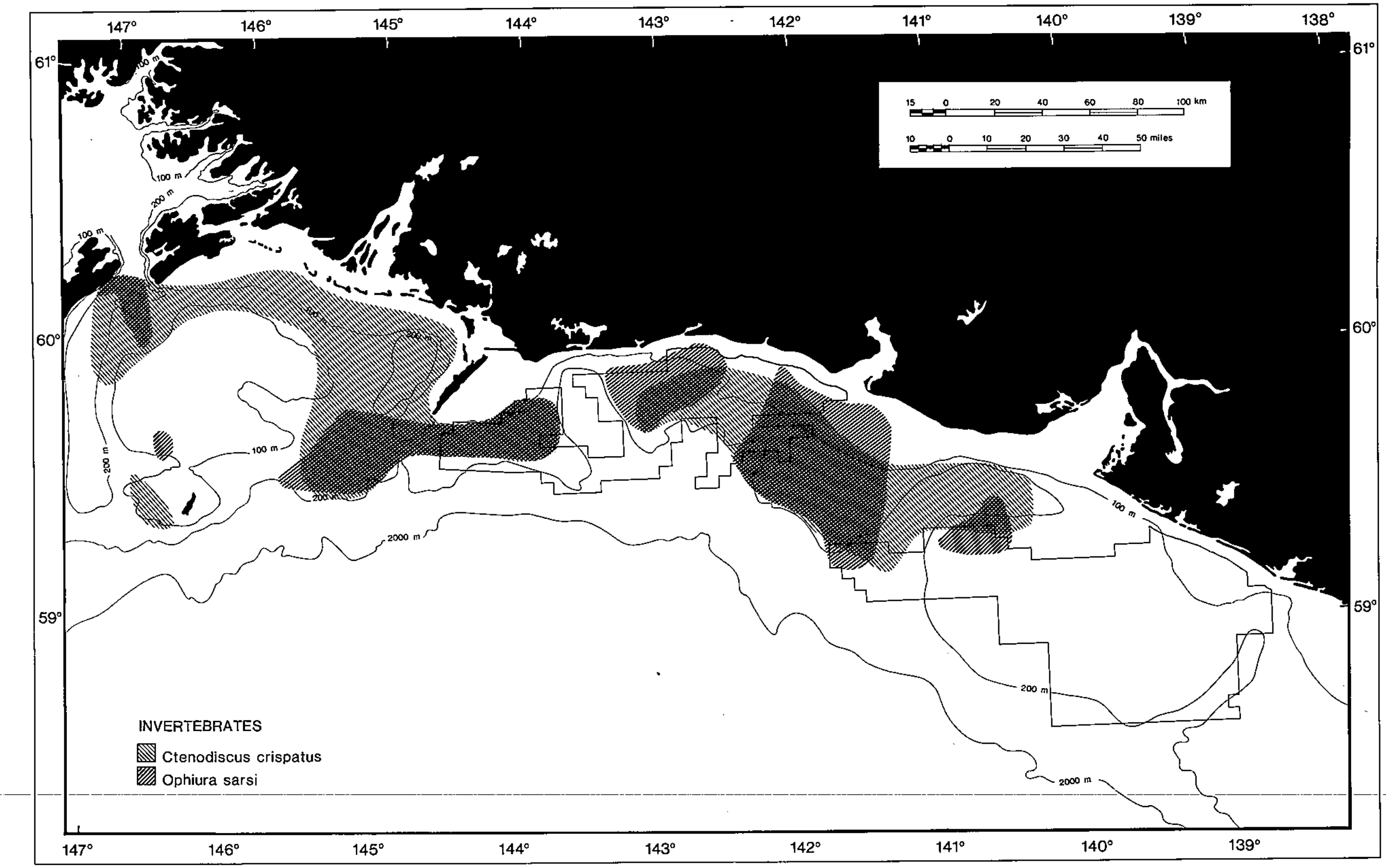


Figure 7.11 Distribution of Ctenodiscus crispatus and Ophiura sarsi in NEGOA, from trawl surveys, May-August 1975 (Feder, 1977).

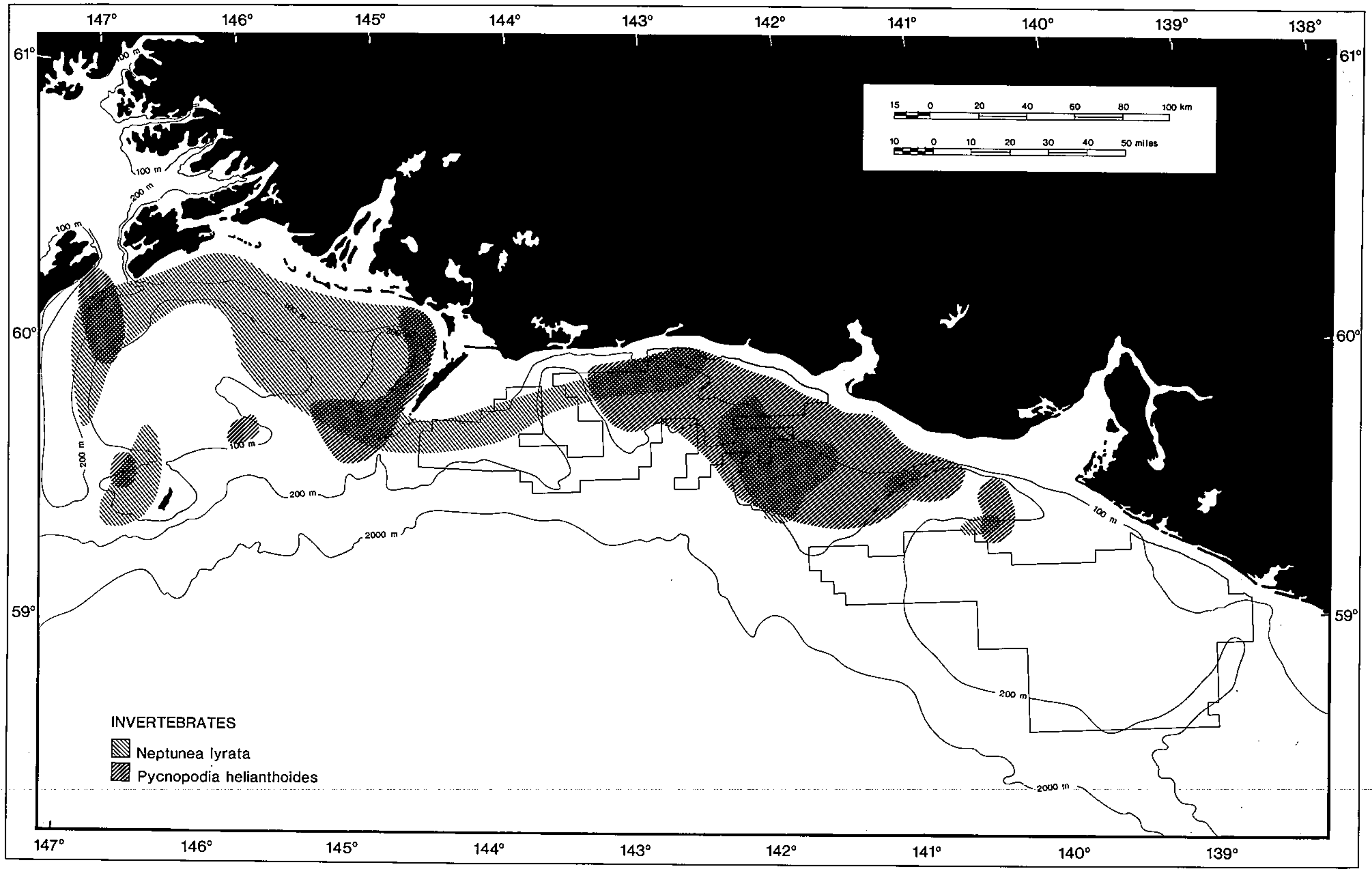


Figure 7.12 Distribution of Neptunea lyrata and Pycnopodia helianthoides in NEGOA (Feder, 1977).

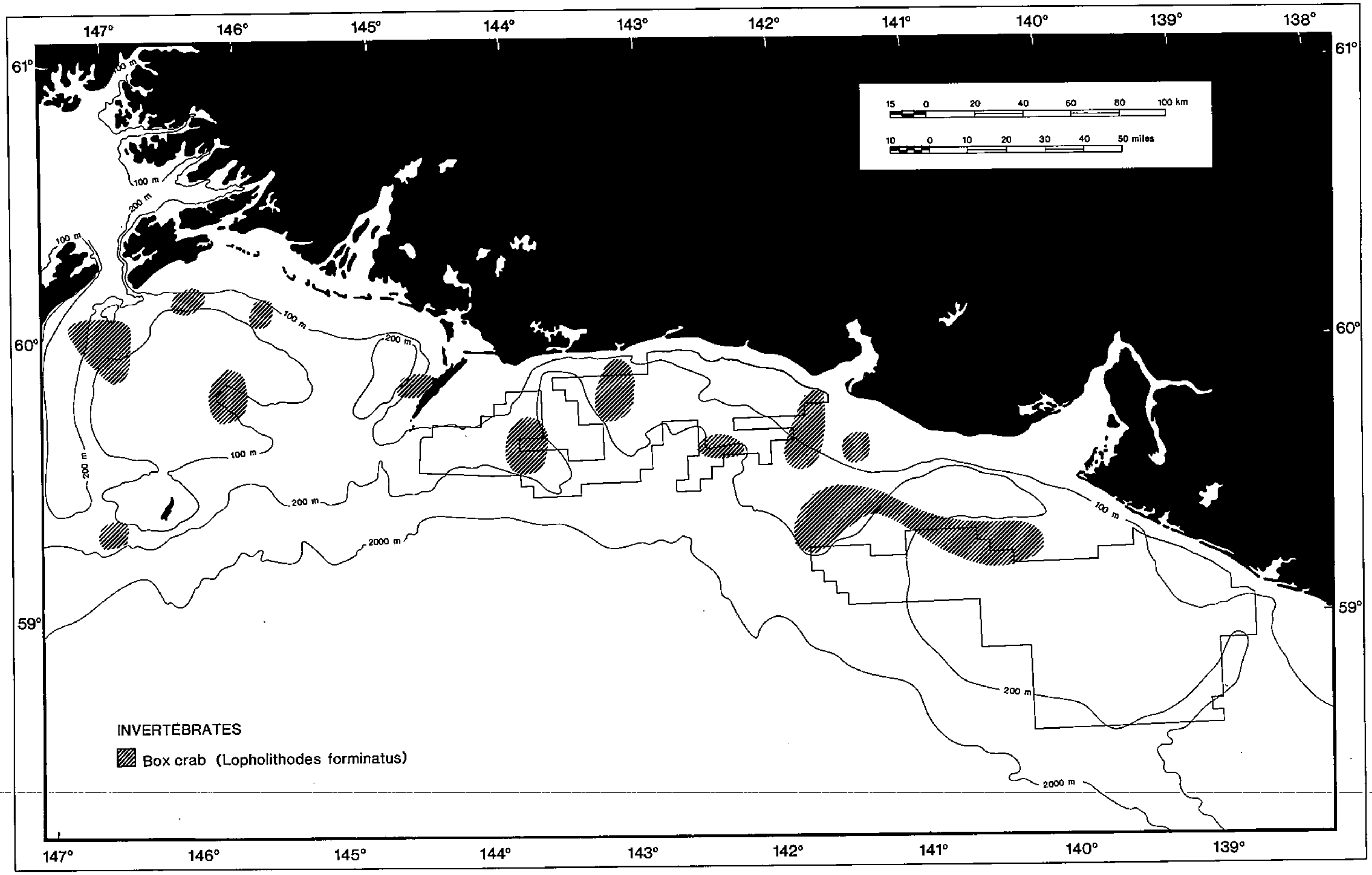


Figure 7.13 Distribution of box crab (Lopholithodes foraminatus) in NEGOA (Feder, 1977).

Table 7.3 Percentage composition by weight of dominant invertebrate species collected in NEGOA trawling samples, summer 1975 (Feder and Jewett, 1979).

Phyla	Percentage of weight	Dominant species	Percentage weight within phylum
Arthropoda	71.4	Chionoecetes bairdi	92.6
		Pandalus borealis	4.0
		Lopholithodes foraminatus	0.6
			Total 97.2
Echinodermata	19.0	Ophiura sarsi	23.2
		Ctenodiscus crispatus	15.7
		Brisaster townsendi	11.2
		Pycnopodia helianthoides	10.3
			Total 60.4
Mollusca	4.6	Patinopecten caurinus	43.4
		Neptunea lyrata	12.5
		Fusitriton oregonensis	11.5
			Total 67.4
Total	95.0		

7.4 NEKTONIC INVERTEBRATES

Large, free-swimming invertebrates such as squid, euphausiids, pelagic shrimp, coelenterates, and mysids are distributed throughout NEGOA. Walleye pollock, Pacific cod, flatfishes, and salmon all rely heavily on these organisms for food (see Chapter 8 for details), as do some marine birds (Chapter 9) and mammals (Chapter 10). Extensive data on the distribution, abundance, and population dynamics of nektonic invertebrates in the Gulf of Alaska are lacking. Some information is available from the Japanese and Soviet literature, but it is mostly anecdotal.

7.4.1 Cephalopods

Squid are preyed upon by a variety of commercially important species of fish and whales. Squid and octopi are also important predators of fish and shellfish. Because they are fast swimmers, they easily avoid trawls and nets and quantitative estimates of their abundance and biomass are not yet known.

Little is known of the life histories of the squid in NEGOA and adjacent waters (Akimushkin, 1965). Sexes are separate, copulation occurs by transfer of spermatophores from male to female. The eggs are attached to the bottom or to algae or seagrass. Females protect the eggs and fast during this period. In California squid eggs mature in about 30 days (MacGinitie and MacGinitie, 1968). Eggs of some pelagic octopods are brooded in the mantle cavity.

Cephalopods are stenohaline, requiring high salinities (30 $^{o}/oo$) and unpolluted water (Akimushkin, 1965). A small incidental Japanese squid fishery occurs in the Bering Sea and the Gulf of Alaska; however, catch statistics are currently unavailable. Jefferts (pers. comm.) is studying squid from the North Pacific Ocean; however, most of his specimens were collected incidentally to fishery catches and will provide little quantitative information on distribution and abundance.

7.4.2 Euphausiids

Euphausiids are important members of NEGOA food webs and are the major prey of several species of marine birds and mammals (see Chapters 9 and 10). The distributions of Gulf of Alaska species, based on collections made by the International Fisheries Commission in 1929-41 have been reported by Banner (1949). The predominant species in NEGOA are *Euphausia pacifica*, *Thysanoessa inermis*, *T. longipes*, *T. raschii*, and *T. spinifera*. In the southeastern Bering Sea *T. longipes* was most abundant in the open ocean, *T. inermis* was most abundant on the outer shelf, and *T. raschii* was most abundant on the central shelf.

In the Prince William Sound, *T. longipes* were the most numerous euphausiid (density: 1-3/m^3). Their maximum depth during the day was 300 m, and no animals were found above 100 m. Adults migrated vertically. At night they were found in between 0 and 50 m of water, with maximum concentrations between 25 and 50 m. Euphausiid juveniles were abundant (2-3/m^3) and did not appear to migrate vertically (Damkaer, 1976).

7.5 BENTHIC COMMUNITIES

Quantitative descriptions of benthic communities can provide important insights into the structure and population dynamics of invertebrate populations. Understanding structural components of benthic assemblages (biomass, species composition, diversity, population fluctuations, and trophic complexes) is necessary to estimate the food resource of fishes (Thorson, 1957) and provides a powerful tool in evaluating faunal changes brought about by both acute and chronic environmental perturbations. High-resolution community assessment requires close attention to both the sampling design and to the selection of quantitative samples. Some quantitative information on the subtidal infaunal benthic assemblages is available for NEGOA between Yakutat and Resurrection Bays (Feder, 1977; Feder et al., 1976; Feder and Matheke, 1979). Epifaunal community structure is less well known, but appears to be roughly correlated with substrate type. As substrate type changes rapidly with short distances in the Gulf of Alaska (Ronholt et al., 1978), community composition would be expected to exhibit sharp gradients.

The infauna was sampled with a Van Veen grab sampler at 40 stations along seven transects in NEGOA. Recurrent group analysis on these data showed that the stations sort into four major groups of similar species composition (Fig. 7.14). The species groupings frequently appeared to have specific substrate affinities (Feder, 1977; Feder and Matheke, 1979). One infaunal species grouping occupied nearshore sites on the continental shelf with predominantly silt-clay sediments. Deposit-feeding invertebrates predominated; these were also present at all other sites except those rocky or sandy sites with very low concentrations of silt and clay. Another infaunal grouping occurred at Hinchinbrook Entrance, where the sediments were about 28 percent sand mixed with silt and clay. The two groupings had similar species composition, but the biomass and numerical abundance were greater at Hinchinbrook Entrance.

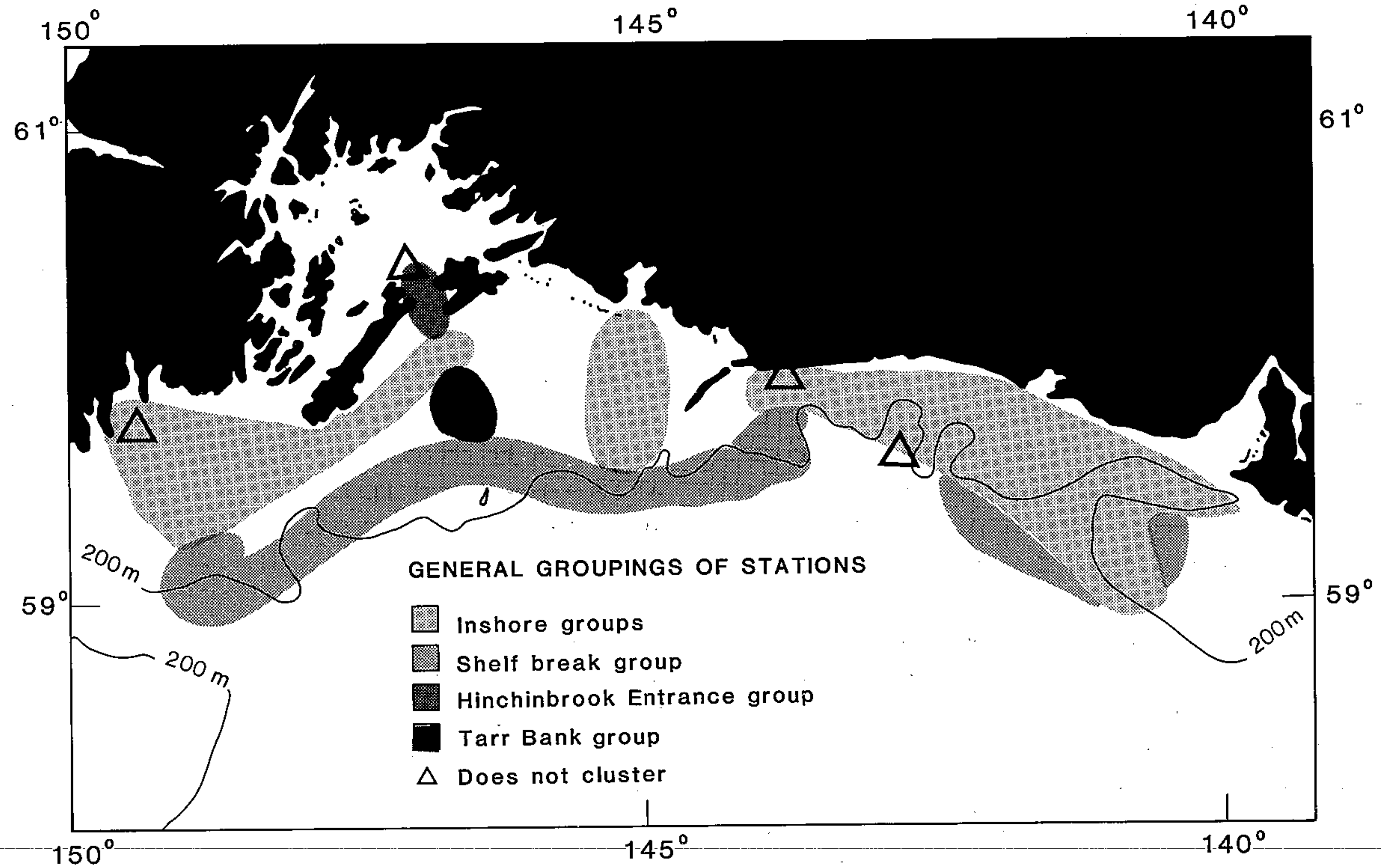


Figure 7.14 Station groups formed by cluster analysis of all data collected in Feder and Matheke (1979) study.

At the edge of the continental shelf the sediments contained higher amounts of sand and gravel mixed with silt and clay. Two other stations (at Tarr Bank and at the shelf break) had a greater abundance of suspension-feeding invertebrates and species which require a solid substrate. Diversity was higher at these sites.

Feder and Matheke (1979) found no evidence of discrete communities; rather, they suggest that species found in NEGOA are distributed independently along environmental gradients. At least 53 species groups were required to describe spatial and temporal distribution patterns over a 21-month period.

Because sampling intensity was low and physical factors other than sediment particle size were not considered, the suggestion that sediments are the major factor controlling infaunal abundance needs further documentation.

It is difficult to identify epibenthic communities solely from samples gathered in otter trawl tows. During a single tow several communities may be sampled. Often samples taken from the same station show large differences in the number of species and individuals captured (Feder and Jewett, 1978). Thus extensive field sampling, including stomach analyses, is required to determine the species composition of epibenthic communities. The complexity of the seasonal movements of such predators as king crab, Tanner crab, and Pacific halibut and the annual life cycles of many organisms of the meiobenthos (Thorson, 1966) further complicate the structure of the benthic community.

7.6 FOOD WEB RELATIONSHIPS

Food webs provide insight on community structure and function and increase our understanding of how energy flows through the ecosystem. They are constructed by the analysis of the gut contents of organisms and, when possible, by directly observing their feeding activities. Food webs of marine organisms deomonstrate dependencies among infauna, epifauna, pelagic fishes, birds, and mammals. Although they are oversimplifications of reality, they help identify critical pathways in ecological systems and are useful for understanding the transfer and storage of industrial contaminants in a community of marine organisms.

Feeding studies in NEGOA, Lower Cook Inlet, and two bays on Kodiak Island (Feder, 1977; Feder and Jewett, 1977) demonstrate the importance of benthic infaunal invertebrates in the diet of commercially valuable crabs and demersal fishes.

Feeding information presented here is often not site-specific for NEGOA but has been extrapolated from contiguous areas such as the Lower Cook Inlet and the Kodiak shelf. Although general feeding patterns are similar, regional differences have been demonstrated (Feder and Jewett, 1979). Most information concerns the food and feeding of the adult stages of commercially important species. Little information exists for the larvae and juvenile stages of most benthic invertebrate species.

Inferring trophic relationships from gut content analysis has limitations. Many soft-bodied infaunal forms may be highly significant items in epifaunal diets, but are digested before they can be identified. The "gastric mill" of crustaceans rapidly grinds most food into unidentifiable pieces. The paucity of feeding information for benthic invertebrates in NEGOA has necessitated extrapolation of feeding data from adjacent areas. There are inherent uncertainties in making such extrapolations because the diets of many species are known to vary spatially and temporally. Feder and Jewett (1979) found that king crabs from Izhut Bay ate mostly fishes while crabs from Kiliuda Bay preyed primarily on molluscs, specifically clams.

More information is needed on the food habits of the major commercial species of NEGOA, particularly those of female and juvenile crabs, on important predators, and on seasonal changes in diet (collections were made only in March and in June-August). Since prey density often regulates both diet and feeding rate, feeding studies should be conducted concurently with quantitative studies of distribution and abundance. Such studies coupled with studies designed to determine feeding rates would aid in understanding the carrying capacity of the NEGOA marine environment and provide a basis for evaluating stresses on the environment.

7.6.1 Tanner crab

Tanner crab (*Chionoecetes bairdi*) larvae prey on other planktonic organisms. Juveniles eat diatoms, algae and hydroids (Bright, 1967), and detritus (ADF&G, 1975a). Adults are more opportunistic but prefer molluscs, echinoids, polychaetes, barnacles, and shrimp. The food of Tanner crabs includes four phyla and 17 genera, with clams, hermit crabs, and barnacles being the principal food items (Feder and Jewett, 1979; Paul et al., 1979). The diet of crabs in Kodiak waters differs from that of crabs in Cook Inlet (Feder and Jewett, 1979; Paul et al., 1979). The large hardshelled molluscs and echinoderms consumed by king crabs are rarely seen in adult Tanner crabs (Bright, 1967; Feder, unpub.); this may be an example of resource partitioning that allows king and Tanner crabs to occupy the same areas at the same time. Amphipods prey on Tanner crab eggs (Hilsinger, 1976); a variety of fishes eat juvenile Tanner crabs. Octopus, gadids, liparids, and yellowfin sole eat adult crabs (Pereyra et al., 1976; Feder and Jewett, 1977).

7.6.2 Dungeness crab

Dungeness crabs feed on shrimp, crabs, barnacles, bivalves, and polychaetes (Hoopes, 1973), but appear to prefer clams (Mayer, 1972). Predators of Dungeness crab larvae include herring, salmon, and smelt. Adult crabs are eaten by Pacific halibut, gadids, sculpins, and rock fishes (Mayer, 1972).

7.6.3 King crab

King crab larvae consume mostly diatoms and barnacle nauplii. Juveniles eat large numbers of diatoms; Bright (1967) found them in 4 percent of the crab stomachs he examined. Juvenile king crabs also eat algae, sponges, ostracods, harpacticoid copepods, polychaetes, small clams, gastropods, and echinoids. Adults are omnivorous, taking molluscs, echinoderms, other crustaceans, polychaetes, coelenterates, algae, and fishes (Bright, 1967; Pereyra et al., 1976; and Feder, 1977). King crabs have few predators as adults. Walleye pollock, Pacific cod, and Pacific halibut are known predators (AEIDC, 1974; 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.

7.6.4 Shrimp

Pandalid shrimp larvae feed on zooplankton, preferring brachyuran crab larvae (AEIDC, 1974; Pereyra et al., 1976). Juvenile shrimp are opportunistic scavengers. Adults are carnivorous, benthic feeders whose main prey are polychaetes and small crustaceans (AEIDC, 1974). Shrimp predators are numerous and include other marine invertebrates, fishes, birds, and mammals.

7.6.5 Scallops and clams

Scallops and clams are filter-feeders. Phytoplankton, small zooplankton, and resuspended detritus are their chief food. They are thus important links between benthic microfauna and macrofauna populations. Since scallops and clams of northern waters are long-lived and can store heavy metals in their tissues (Malins, 1977), they may be good indicators of man's impact on Alaskan ecosystems.

7.6.6 Noncommercial invertebrates

Trophic relationships of many of the noncommercial invertebrates in NEGOA are little known. Many of these species are ecologically important processors of energy. Polychaetes have been classified according to feeding methods by Jumars and Fauchald (1977). Feeding classes for benthic invertebrates of NEGOA have been assigned by Feder and Matheke (1979).

7.7 EFFECTS OF OCS DEVELOPMENT

Knowledge of the distribution, abundance, life history, population dynamics, and trophic relationships of NEGOA benthic invertebrates is inadequate for reliable predictions and quantification of the effects of toxicants, effluents, or construction activites related to OCS development on these organisms. Long-term studies of natural fluctuations in populations are needed to differentiate between natural variations in population characteristics and those caused by development activities. Extrapolation from other studies is presently the only method of predicting the effects of OCS development on the NEGOA marine environment.

Many factors complicate the prediction of the effects of a pollutant or disturbance. The physical or chemical composition of the pollutant are important, as are density, solubility, and toxicity, and the time and duration of exposure.

OCS development such as dredging or construction will directly alter the environment. Williamson et al. (1977) found that undisturbed marine systems exist in easily disrupted hydrodynamic and chemical equilibria with respect to the composition of bottom sediment. Stress from ship traffic, dredging, or increased pollutants could shift the system from its equilibrium resulting in increases in the numbers of opportunistic species.

Deposit-feeders are common in the Gulf of Alaska and are an important source of food for many organisms (Feder et al., 1976). OCS activities could harm deposit-feeders, resulting in decreased sediment stability and decreased food sources for many other dependent species. Correlations between feeding type and bottom stability have been reviewed by Rhoads (1974). A diesel fuel spill resulted in the death of many deposit-feeders living on sublittoral muds. With the death of these deposit-feeders, bottom stability was altered and a new complex of species became established.

The following information on benthic invertebrates inhabiting the North Pacific is based on laboratory evidence. 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 decreased following 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 of Cook Inlet crude oil, there was extensive vacuolization in the gill cytoplasm and disruption of the cell surfaces. Impaired respiratory activity may have been the immediate cause of the decreased larval survivorship (Smith, 1976, reported by Mecklenberg et al., 1976). In other static bioassays pandalid and crangonid shrimp, king crab, and the littleneck clam, Protothaca staminea, showed high sensitivity to Cook Inlet crude (Rice et al., 1979).

Several aspects of the life histories of crabs make them particularly sensitive to exposure to oil, gas, waste water effluents, and heavy metals. During the spawning season, males are attracted to mature females by pheromones released by the females. The extreme sensitivity of male decapods to these pheromones is well documented (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 ultimately the viability of the species may be drastically affected.

Marine crustaceans find their food by chemoreception (Pearson and Olla, 1977). Sensitivity to various amino acids and other substances has been measured by studying the feeding behavior of lobsters (Homarus americanus (McLeese, 1970, 1974), H. gammarus (Mackie and Shelton, 1972; Mackie, 1973), and Panulirus argus (Levandowsky and Hodgson, 1965); crabs (Gnathophausia ingens, Pleuroncodes planipes, Cancer magister, and Callinectes sapidus (Fuzessery and Childress, 1975; Pearson and Olla, 1979a, 1979b); and shrimp (Spirontocaris taylori and Penaeus merguiensis). Minute quantities of crude oil were sufficient to affect feeding behavior in the crab, shrimp, and lobsters.

American lobsters were attracted to and consumed food contaminated with oil derivatives (Atema and Stein, 1974). Although king, Tanner, and Dungeness crab may respond similarly, recent studies suggest that oil affects crabs differently. Callinectes sapidus detected naphthalene at 10^{-7} mg/1 (Pearson and Olla, 1979a), and exposure to low levels of petroleum hydrocarbons interfered with sensory cues in the Dungeness crab (Pearson, pers. comm.). Feeding efficiency declined (Basch, pers. comm.) and in some instances food was avoided entirely. In an actual oil spill crabs might thus be at a competitive disadvantage in the natural environment.

Water-soluble fractions of oil impaired respiration in certain shrimp species (F. G. Johnson, 1977); spot shrimp were narcotized and eventually died (Sanborn and Malins, 1977). As in other crustaceans, molting may be disrupted and mortality increased by exposure to oil and its derivatives.

OCS development in NEGOA increases the likelihood of industrial contamination of the marine environment. The severity of contamination in a given area depends on the amount of contaminant released, weather conditions, and a host of other factors. During construction and exploration, the most likely type of contamination would be localized, chronic, low-level pollution around oil platforms. Construction wastes and drilling muds could settle to the substrate and smother some species, predominantly sessile forms. Some deposit-feeders would probably ingest these wastes, but it is not known how they would be affected. The species composition in the vicinity of the platforms would probably change. Using in situ models, Atlas et al. (1978) showed that after 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, larger quantities of hazardous material could be carried downstream or drift to the substrate over a wide area. The pollutant could admix with the fine-grained sediments. As the chemical activity of the pollutant will vary with physical location, temperature, depth, and the nature of the sediment, its effects on the biota are difficult to predict. Deposit-feeders in the infauna and epifauna probably would ingest some of the contaminants and transfer them to detritus-based food chains. King and Tanner crabs are known to feed extensively on deposit-feeding clams (Feder and Jewett, 1979; Feder et al., 1979). Thus, a large oil spill in NEGOA would probably have both direct and indirect deleterious effects on local crab and shrimp populations.

The effects of OCS development on the nearshore benthos would probably be more severe and apparent than on offshore populations. If petroleum products were discharged 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 rotted vegetation or algae, and settle out onto the substrate. Since the different hydrocarbons would be breaking down at different rates, the resident organisms would thus become chronically contaminated by varying concentrations and forms of hydrocarbons.

The preference of Dungeness crab for shallow-water muddy habitats (Hoopes, 1973) during spring and summer and when they are molting makes them particularly vulnerable to direct fouling by oil. An oil spill or even the chronic, low-level oil seepage expected to come from oil platform operations could threaten the survival of these crabs. Oil fractions could damage their gill membranes as they do those of king crabs

(Smith, 1976). If respiration were impaired, then locomotion, feeding, molting, and reproduction would all be affected. Low levels of crude oil have been shown to decrease the viability of larval (Wells and Sprague, 1976) and adult decapods (Krebs and Burns, 1977) and to decrease feeding in adults (Atema and Stein, 1974).

In addition to direct hydrocarbon contamination, Dungeness crabs may also be affected indirectly. The deposit- and filter-feeders which Dungeness crabs eat concentrate hydrocarbons and heavy metals in their tissues (Malins, 1977). Although adult Tanner and king crabs usually live in deeper waters than Dungeness crabs, their larval and juvenile stages mature in shallow water and thus probably are as vulnerable to contamination as Dungeness crabs.

The sedentary habits of filter-feeders make them highly vulnerable to oil that washes in and accumulates on beaches or in bays. Oil may kill razor clams directly (NFS, Auke Bay), or contaminants may enter the food web of the littoral ecosystem.

OCS development on the NEGOA shelf may be accompanied by increased industrial activity in and around Seward, Cordova, and Yakutat. Tanker docks, water and sewage treatment plants, and housing will be built; LNG facilities or oil refineries may also be required. Water quality is almost certain to decline, and the biota will either adapt to the altered environmental conditions or die. Careful planning is essential to protect the marine environment and to minimize the deleterious effects of OCS development on the biota.

CHAPTER 8 FISH

G.R. Tamm, SAI

8.1 INTRODUCTION

Continental shelf and slope waters in NEGOA are biologically productive. Large populations of salmon, herring, pollock, halibut, and other groundfish 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 benthic (e.g., halibut, pollock, cod) fishes that are far-ranging as adults. 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 of NEGOA.

The oil industry and BLM are considering the leasing of 792,000 hectares (mean case) of offshore tracts in the Yakutat-Fairweather area for OCS development. These tracts are located 6 to 93 km from shore in 30 to 400 m of water. The center of land-based operations will be the city of Yakutat. Lease Area No. 55 sales are scheduled for October 1980. Potential conflicts between exploration, refinery, and transportation of gas and oil and the fishing industry are major issues that resource managers and the Alaskan populace must face. These decisions will be aided by the past experiences of the fishing industry, coastal cities, and the oil industry in the development of the Sale No. 39 lease tracts to the north, between Icy Bay and Kayak Island.

A thorough understanding of the fish populations is one requisite to assess the consequences of development on the NEGOA 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 to commercial fishing are examples of the kinds of decisions which will have to be made.

This chapter provides an overview of fish populations in NEGOA 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. Fish populations and commercial fisheries within the entire gulf will be reviewed, but emphasis will be placed on those lying within the area bounded by Cape Suckling on the north and Cape Fairweather on the south.

8.2 DISTRIBUTION, ABUNDANCE, AND POPULATION DYNAMICS

8.2.1 Introduction

The type and abundance of fishes in NEGOA change dramatically with physiography, depth, current regime, substrate seasonal fluctuations in temperature, salinity, and a host of biological factors. In general, the nearshore marine environment in NEGOA is less complex than that of the Kodiak and Cook Inlet regions. Large amounts of sediment are washed down from the Malaspina, Bering, and Novatak glaciers into shallow water, where they are transported northward and seaward by coastal currents. The sublittoral substrate comprises mainly coarse sand and gravel and is relatively unstable. Consequently, the fish fauna found along the shores of NEGOA from Cape Suckling to Cape Fairweather is not particularly diverse. Occasional rocky heavily vegetated areas have sufficient stable shelter and an adequate assortment of prey to support locally complex fish associations. Several large bays (Yakutat, Icy, Dry, and Lituya) along the coast provide a more varied habitat, and thus more niches for a greater number of fish species. The continental shelf of NEGOA varies in width from 40 to 100 km. The Fairweather Ground, Tarr Bank, and Middleton platform are the major rises; the Yakutat, Alsek, and Bering Troughs the major depressions that cross the shelf. These physiographic features cause the prevailing bottom currents to change velocity and direction, affect the distribution of sediments and associated infauna, and thereby influence the distribution of fish fauna. Beyond the shelf the seafloor slopes down steeply into the Aleutian trench (Fig. 2.3). The irregularity of slope topography, water depths, substrate types, and benthos within relatively short distances provide many potential niches for marine fishes.

The preferred habitats of many marine fishes found in NEGOA waters vary with life stage and season. For instance, immature salmonids feed in oceanic surface waters hundreds of kilometers beyond Alaskan shores, yet these anadromous fishes are abundant as maturing adults in coastal waters from June through September each year, staging for their spawning runs (ADF&G, 1976a). Salmon smolts emigrate in spring and summer from freshwater streams and lakes into estuaries, where they remain from several weeks to months before migrating to the open ocean (Buck et al., 1975; Gosho, 1977; Sibert, 1979; Healey, 1980). Many fishes which as adults occur in deeper water on the continental shelf and slope inhabit littoral and sublittoral areas 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) are found in shallower depths in summer than in winter (Hughes, 1974; Ronholt et al., 1978, IPHC, 1978; Rosenthal, 1979).

Dunbar (1970) discusses the marked seasonality in primary production and cycling of zooplankton in northern waters. Apparently, many fish schedule their spawning so that their young soon drift or swim into habitats where they can readily find food of the appropriate size and shape. Pacific herring in southeastern Alaska is a good example of a fish that displays this reproductive strategy (Carlson, 1980). Larval fish feed on such microzooplankton as radiolarians, foraminiferans, and crustacean nauplii (Ryther, 1969; Parsons and LeBrasseur, 1970). As fish grow, their diets generally comprise larger food items (Landry, 1977; Healey, 1980), whether they are principally pelagic feeders like herring (Cushing, 1975) or benthic feeders like chum salmon (Healey, 1979).

The distribution of fish populations is constantly changing. Typical distributions and levels 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 distinguish 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 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 to the study of 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, direct comparison of data has been difficult. Most scientific sampling has taken place from April through October; consequently, there is a paucity of 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.

8.2.2 Salmonids

Salmon and trout are commonly found in oceanic waters and estuaries of NEGOA and in freshwater watersheds draining into the gulf. All of these habitats are exploited by salmonids at various times in their lives. Their movements from one environment to another are quite regular and are related to seasonal changes in water temperature and food availability and to their spawning migrations (see, for example, Foerster, 1968). The principal species inhabiting the coastal regions of NEGOA are: pink (Oncorhynchus gorbuscha), chum (O. keta), sockeye (O. nerka), coho (O. kisutch), and chinook salmon (O. tshawytscha), rainbow or steelhead trout (Salmo gairdneri), cutthroat trout (S. clarki clarki), and Dolly Varden char (Salvelinus malma) (ADF&G, 1975a).

In general, maturing salmon are found in distant epipelagic waters hundreds of kilometers from the Alaskan coast (Shepard et al., 1968; Godfrey et al., 1975; French et al., 1976; Neave et al., 1976; Major et al., 1978). Pink, sockeye, and chum salmon are widely distributed in the Gulf of Alaska south to 41°N latitude in winter and 48°N latitude in summer (Royce et al., 1968). Stocks originating in Asia, Alaska, Canada, Washington, and Oregon are all found in this broad region, and cohorts move across the continental shelf of NEGOA when returning to their sites of origin (Foerster, 1968; Royce et al., 1968; Stern et al., 1976; NPFMC, 1978b). Many coho and chinook salmon inhabit coastal areas during their entire oceanic phase. Trout and Dolly Varden char are widely distributed seasonally along the entire coastline of NEGOA (Stern et al., 1976).

Following an oceanic phase of variable duration (Table 8.1) in which salmon feed abundantly and reach

Table 8.1 Life history data for five species of Pacific salmon in NEGOA (Burner, 1964; Bailey, 1969; Merrell, 1970; Hartman, 1971; Hart, 1973; Stern et al., 1976).

	Species				
Characteristics	Pink	Sockeye	Chum	Coho	Chinook
Freshwater habitat	Short streams	Streams, rivers, and lakes	Short and long streams	Streams and rivers	Large rivers
Length of time young stay in fresh water after hatching	several days to several weeks	1-4 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 5 years	1 to 2 years	1 to 5 years
Year of life at maturity (years)	2	3 to 7	2 to 6	2 to 4	3 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
Fecundity (number of eggs)	2,000	3,700	3,000	3,500	4,800

maximum size (Hart, 1973), maturing cohorts return to coastal waters and search the shorelines for environmental cues (Hasler, 1966) that will lead them to their natal streams, lakes, and estuaries, where they spawn. Maturing salmon usually enter NEGOA waters from the south and east, but routes are not fixed, and fish may wander about before entering their spawning waters (Fig. 8.1).

Each of the five salmon species has a characteristic reproductive period (Fig. 8.2). Times of peak spawning runs in NEGOA are shown in Fig. 8.3. The spawning season of a given species of salmonid often extends for several months in the region, but the timing of runs up specific rivers or streams is usually consistent year after year, especially for some populations of sockeye salmon (Foerster, 1968; Royce et al., 1968; Stern et al., 1976).

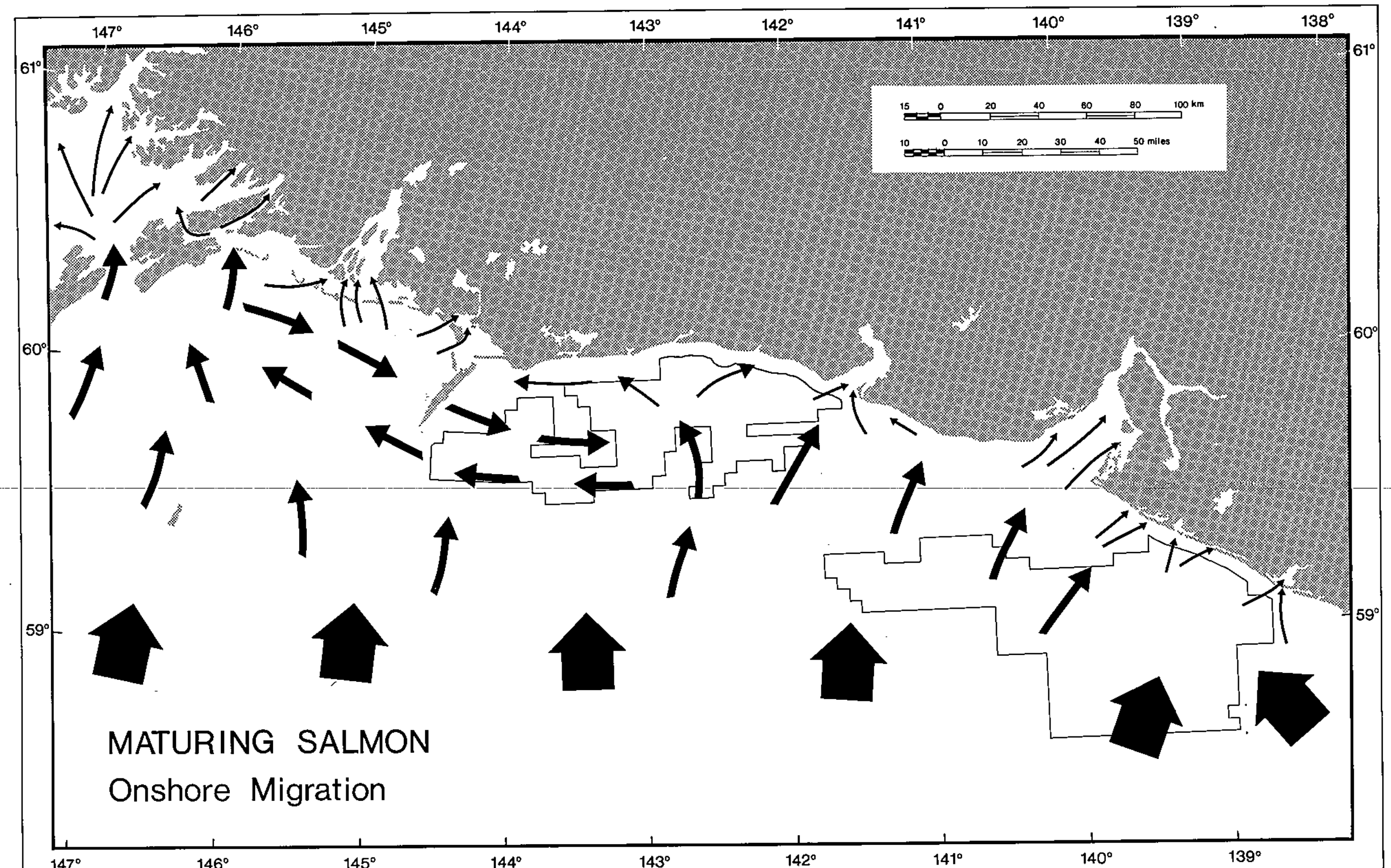


Figure 8.1 Generalized migratory pathways of maturing Pacific salmon approaching their spawning habitat adjacent to NEGOA.

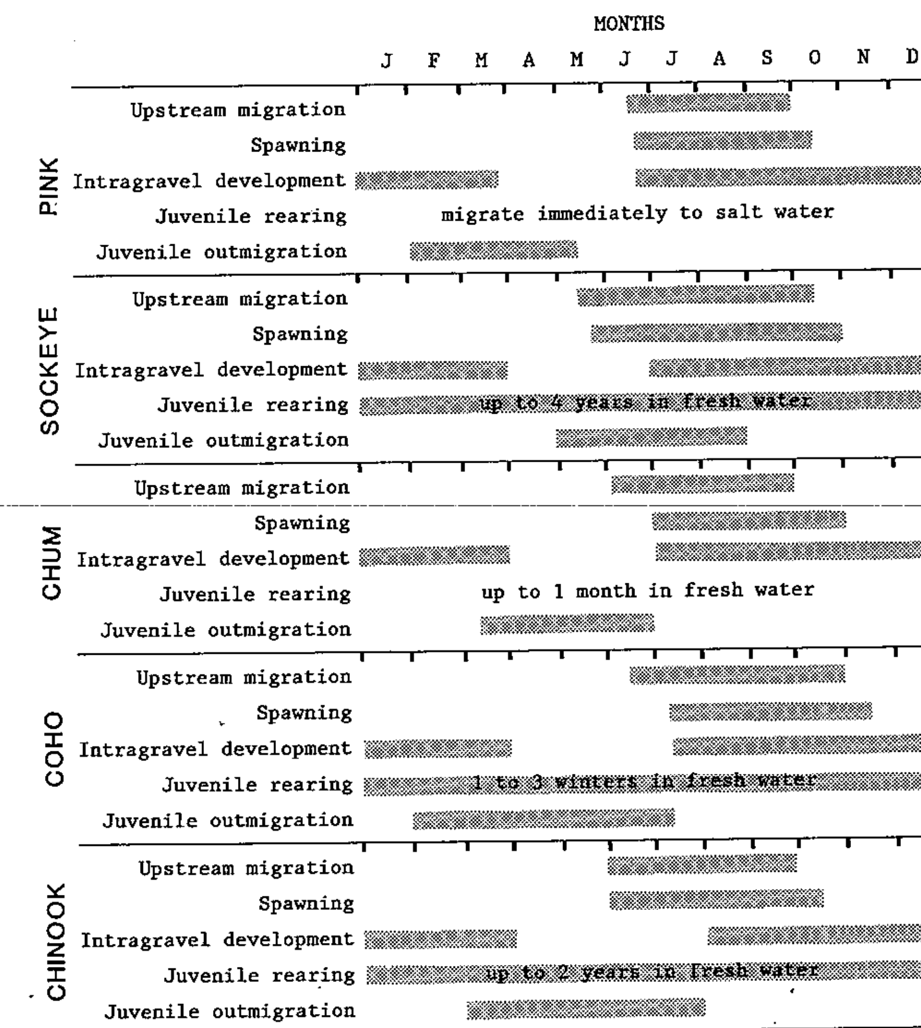


Figure 8.2 Timetables of Pacific salmon life histories (Buck et al., 1975).

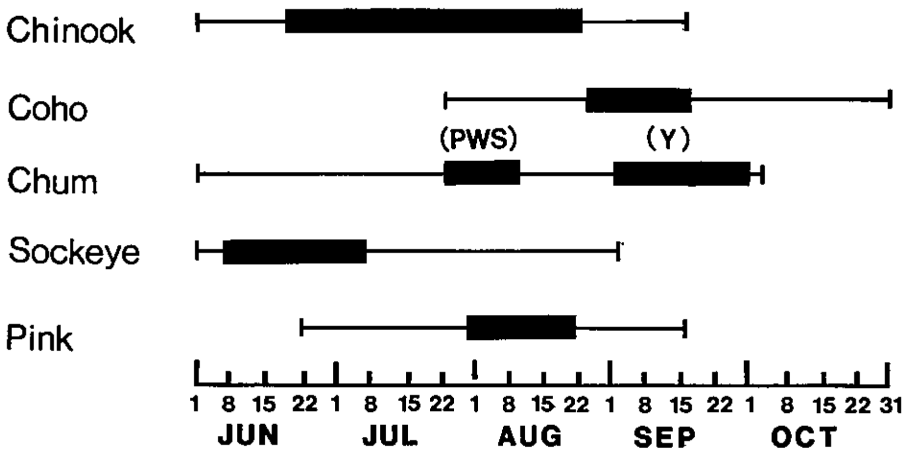


Figure 8.3 Time of peak spawning of Pacific salmon in NEGOA. Chum salmon spawn at different times in Prince William Sound (PWS) and Yakutat (Y) (ADF&G, 1975a).

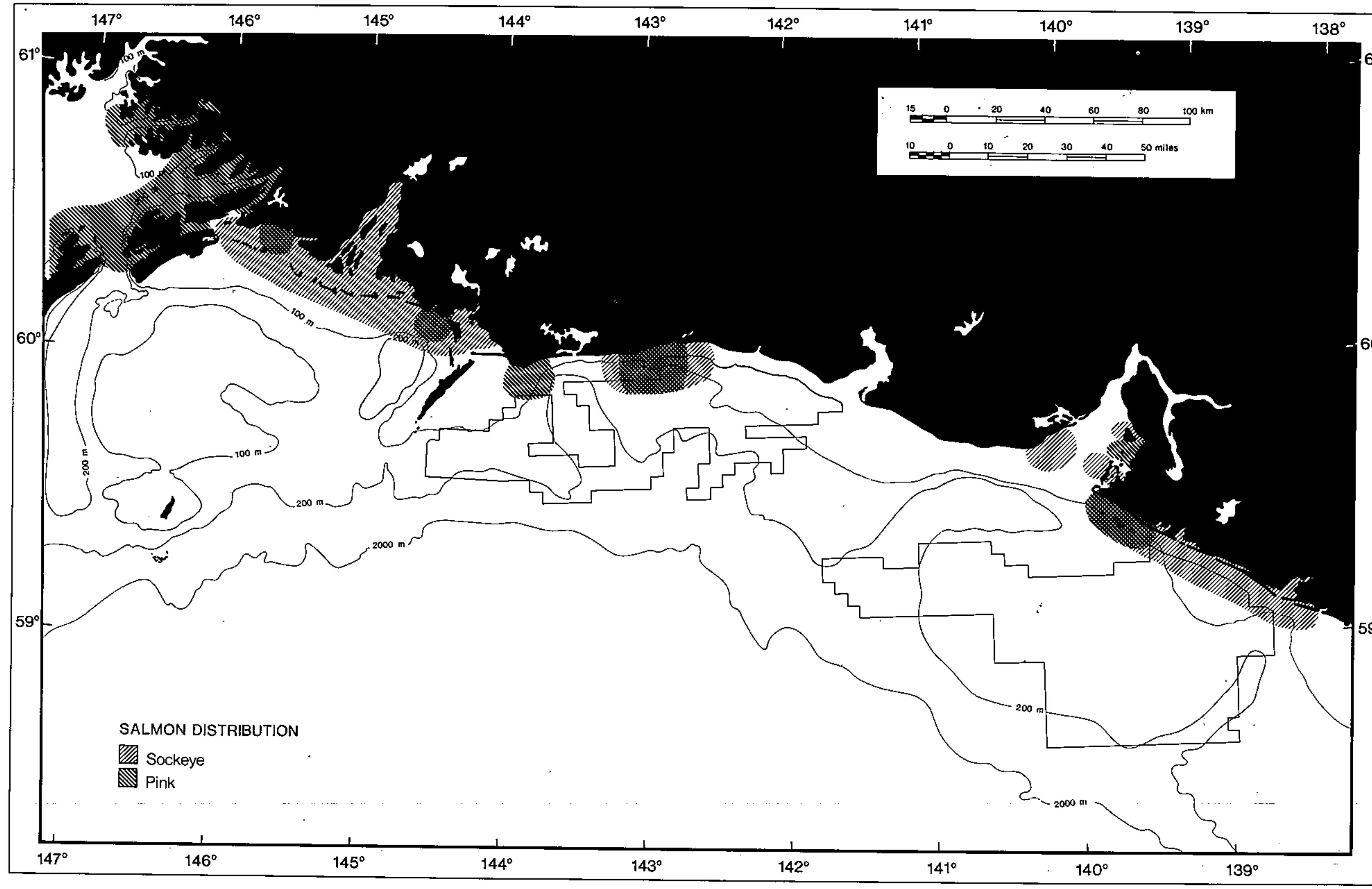


Figure 8.4 Coastal distribution of Pacific salmon prior to spawning in NEGOA (ADF&G, 1975a, 1977, 1978).

Major spawning areas for salmon in NEGOA are depicted in Fig. 8.4. In addition to these important locations, all species of salmon occasionally spawn in most watersheds along the entire Alaskan coast (ADF&G, 1977, 1978; NPFMC, 1978b).

Pink and chum salmon typically spawn in the numerous short coastal streams and intertidal marshes of Prince William Sound (Helle et al., 1964). Areas of less importance for pink salmon spawning include Humpy Creek in Yakutat Bay, the complex tributary system of the Situk River, streams draining into Controller Bay, those near Cape Suckling, and the Kaliakh-Duktoth drainage west of Cape Yakataga (ADF&G, 1975a; 1977).

The Copper River and its associated lakes and tributaries are the principal spawning sites for sockeye salmon. Other large spawning populations are found in the Coghill district of Prince William Sound and the Bering River. East of Cape Suckling to Cape Fairweather (ADF&G's designated Yakutat Area) are 20 or more larger river systems that have the appropriate habitat to support moderately-sized spawning populations of sockeye. The Situk, Alsek, East Alsek, and Doame are the main rivers; other rivers with smaller populations are the Tsiu-Tsivat, Kaliakh, Yahtse, Lost, Dangerous, Italio, and Akwe (ADF&G, 1975a, 1975b, 1977, 1978).

Coho salmon spawn in more than 2,000 streams from

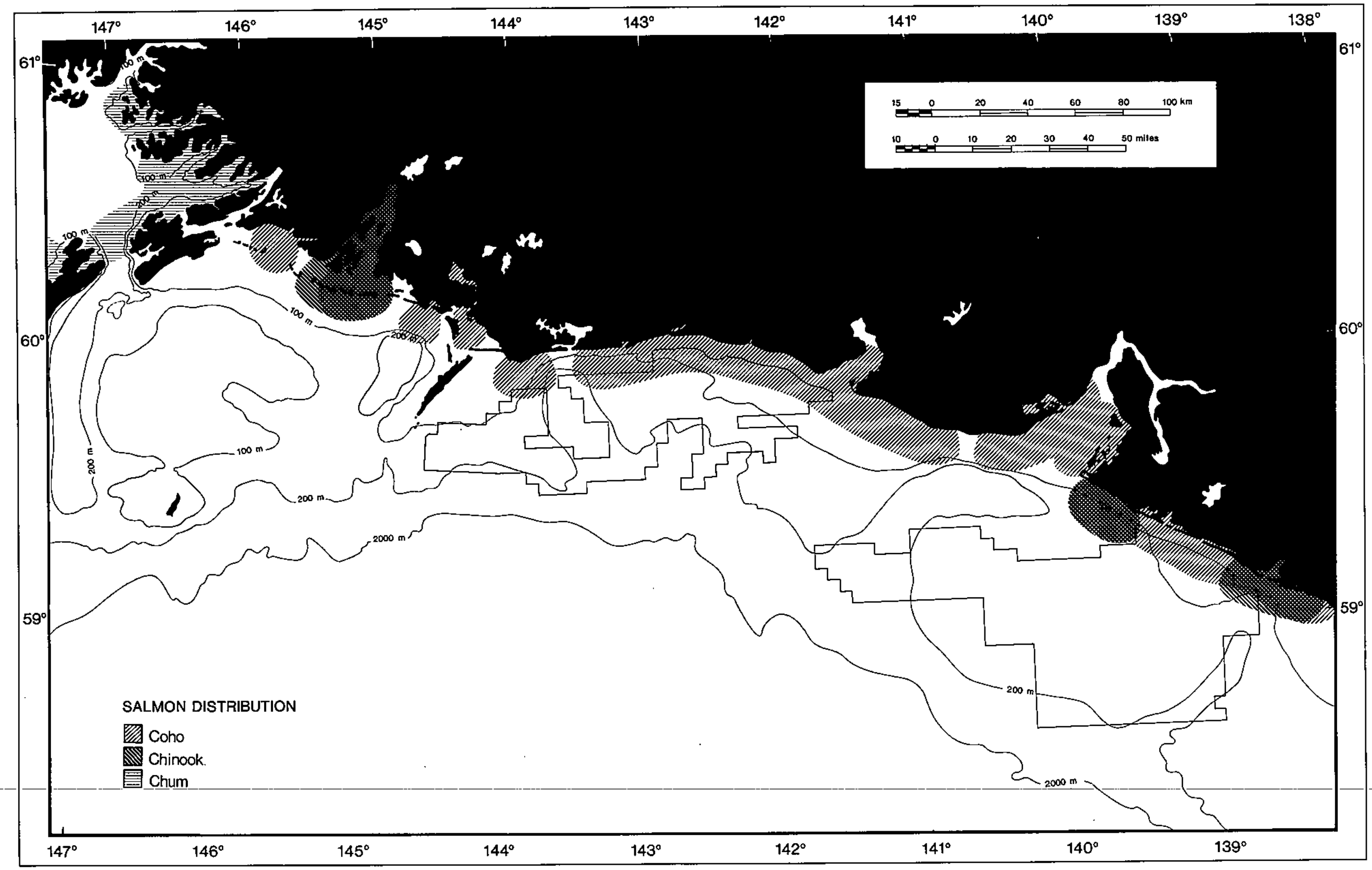


Figure 8.4 continued

Cape Suckling to the Canadian border (NPFMC, 1978b). In NEGOA, the Copper and Bering Rivers are the prime spawning sites. Spawning success, based on catch records, has improved noticeably in the Copper and Bering Rivers in recent years (ADF&G, 1978). It may also be improving in the Yakutat Area, especially in the Situk, Alsek, and Akwe Rivers and the Manby Shores area of Yakutat Bay (ADF&G, 1977).

Chinook are the least likely salmon to spawn in NEGOA. They require large fast-flowing rivers to reproduce (ADF&G, 1975a). In British Columbia, 14 rivers account for 90 percent of the total escapement of chinook in Canada. The Copper River is the only important spawning locale for this species in NEGOA (Major et al., 1978; ADF&G, 1978). The Alsek and Situk Rivers support smaller spawning populations (ADF&G, 1977; NPFMC, 1978)b.

Rainbow and cutthroat trout and Dolly Varden char are also anadromous, spawning in the coastal streams emptying into NEGOA. Rainbow trout spawn in early spring, Dolly Varden char in autumn. Juvenile rainbow trout remain in fresh water for two to three years, then migrate to the ocean, where they stay for another two to three years until they return to spawn. Seaward movements may be as extensive as those of pink salmon. In contrast, cutthroat trout remain in coastal marine waters until maturity. Unlike salmon, all three species can spawn a second or third time in subsequent years (Hart, 1973; ADF&G, 1977).

Abundance estimates of salmon are based on catch records, escapement and age-specific mortality estimates, and a knowledge of the average fecundity of a species. Stern et al. (1976) estimated the average annual population size of spawning salmon for NEGOA from 1955 to 1975 (Fig. 8.5). Virtually all of the pink and chum salmon in the region occurred in the

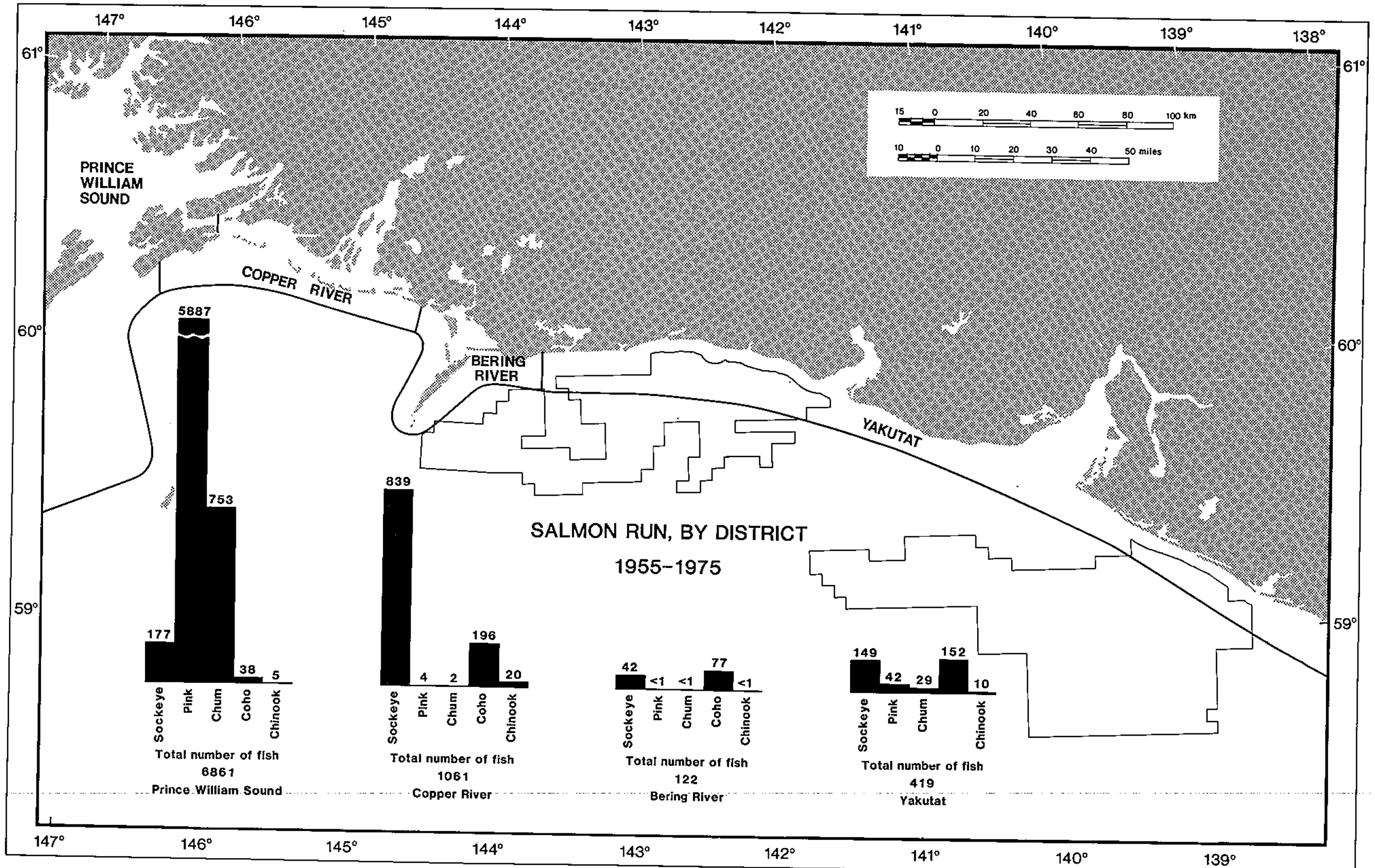


Figure 8.5 Population estimates for average total Pacific salmon run (1000's) in NEGOA districts, 1955-75 (ADF&G data in Stern et al., 1976).

Prince William Sound district. Sockeye salmon occurred mainly in the Copper River district. Only 5 percent of the average annual spawning population (all species combined) was thought to occur in the Yakutat area. Sockeye and coho salmon were the predominant species on the coast from Cape Suckling to Cape Fairweather. The distribution and relative abundance of salmon appear to be stable in NEGOA (ADF&G, 1978). A more detailed account of the regional commercial catch is presented after a discussion of the life history of juvenile salmon.

Anadromous salmon spawn and die; unattended, eggs develop through the winter in the subsurface gravel of Alaskan streams and rivers. In spring fry emerge and migrate to sea immediately, or after one or more years of development in fresh water (Table 8.1). Salmon smolts (young juveniles adapting to salt water) use coastal estuaries as nurseries and feed voraciously on an assortment of pelagic and benthic invertebrates (LeBrasseur et al., 1969; Carlson, 1976; Harris and Hartt, 1977; Gosho, 1977; Sibert et al., 1977; Healey, 1979, 1980; see Trophic relationships section for details). Taylor (1980) showed that the survival of pink salmon fry was greater when coastal waters were warmer and food was more abundant. Presumably, larger fish are better able to avoid predation, and water temperatures have been positively correlated with food production. These factors should affect survivorship of other species of salmon in a similar manner. Following a variable period of up to about a year, spent in estuaries and coastal waters, juvenile salmon migrate offshore (Foerster, 1968; Stern et al., 1976; Major et al., 1978).

The principal migration route of juvenile salmon heading to sea is along the periphery of NEGOA then southwest past Kodiak Island (Royce et al., 1968) (Fig. 8.6). Juvenile pink salmon move into oceanic waters from streams and estuaries during July, August, and September (Fig. 8.2). They do not scatter randomly but migrate in a narrow band (about 30 km in width) along the coast. Other salmon migrants travel a similar route (Royce et al., 1968). The migration includes not only locally spawned fish but also some spawned in streams hundreds of kilometers to the southeast (Stern et al., 1976). The coastal movement continues into October and November; then young salmon proceed south to distant feeding grounds (Royce et al., 1968) where they grow, mature, and eventually migrate back to their natal streams to spawn.

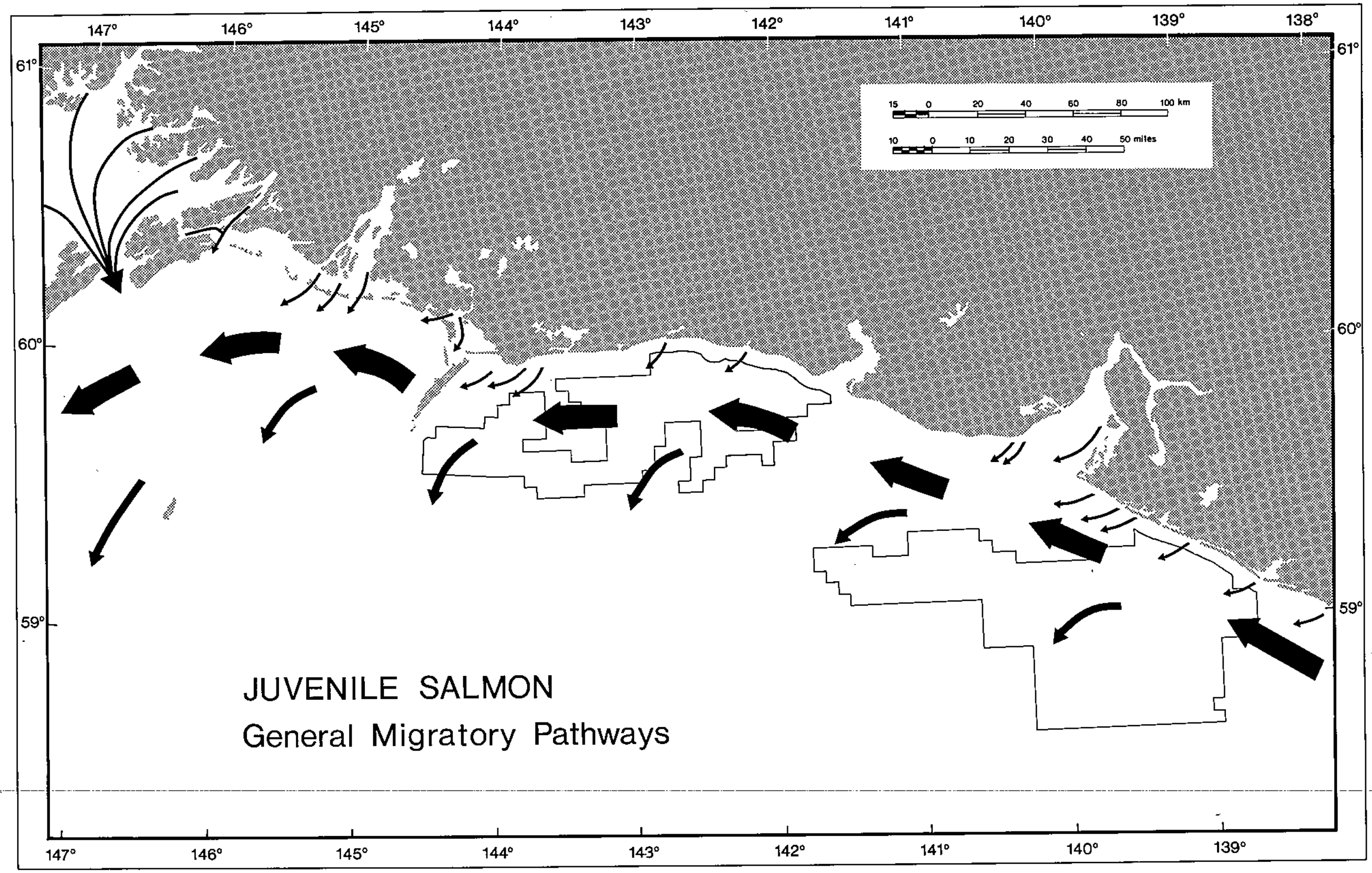


Figure 8.6 General seaward migratory routes of Pacific salmon smolts in NEGOA (adapted from Stern et al., 1976).

Estimates of juvenile salmon populations made annually by ADF&G are typically based on assumptions of escapement rates, sex ratios, and survivorship of the young fish. These estimates are at times difficult to verify, and the rates may vary considerably with environmental conditions. Juvenile salmon populations for 1955-75 were calculated by Stern et al. (1976). By their formula, an average 180 million pink salmon survived to their juvenile stage annually. In peak years, nearly 450 million young entered the marine environment. According to Stern et al.'s assumptions of escapement equal to 0.43 of the catch, an even sex ratio, average fecundity (Table 8.1), and a 10 percent survivorship from the egg phase, about 120 million young pink salmon entered oceanic waters of NEGOA in 1978. Smolt production of the other species has been much lower (Table 8.2). Estimates of smolt production of the other salmon were close to their average annual value in 1978: 10.9 million sockeye, 31.9 million chum, 6.7 million coho, and 0.7 million chinook.

Table 8.2 Population estimates of salmon smolts by species and statistical area (1955-75) based on escapement estimates of parent stocks. Numbers reported in millions of fish (Stern et al., 1976).

Statistical Area	Species						
	Pink (even year)	Pink (odd year)	Sockeye	Chum	Coho	Chinook	Total
Prince William Sound							
Average year	192.0	161.6	11.1	34.0	3.3	0.4	225.4
Peak year	452.8	434.6	24.3	98.8	5.7	0.8	574.0
Yakutat							
Average year	0.6	1.9	1.6	1.3	1.6	0.1	5.9
Peak year	2.6	5.8	4.3	6.6	5.6	0.3	21.0

Salmon have been sought by commercial fishermen in NEGOA for well over a hundred years. Fish are caught with purse seines, drift gillnets, set gillnets, fish traps, and troll gear. Both an inshore and offshore salmon fishery exist. The inshore fishery is conducted from May through October when the fish are spawning (Fig. 8.3). Fishing activity is concentrated at the mouths of rivers and bays in which large runs pass through and head upstream. Pink and chum salmon are most often caught with purse seines, sockeye are gill netted, and coho and chinook are taken with trolling gear (ADF&G, 1975a, 1977, 1978). The offshore fishery is primarily a troll fishery. Chinook and coho are the species most sought, and a fair number of sockeye and pink salmon are taken incidentally. Offshore salmon fishing north of the highly productive Fairweather Ground is limited; most fish are caught farther south in the waters of southeast Alaska and British Columbia (NPFMC, 1978b). In NEGOA, almost all of the commercially caught salmon are taken in nearshore waters less than 20 km from the coast. A record of the commercial catch in NEGOA from 1925 to 1978 is given in Fig. 8.7. The commercial catch of salmon in the ADF&G's Prince William Sound and Yakutat Areas for the past two decades is shown in Figs. 8.8 and 8.9, respectively.

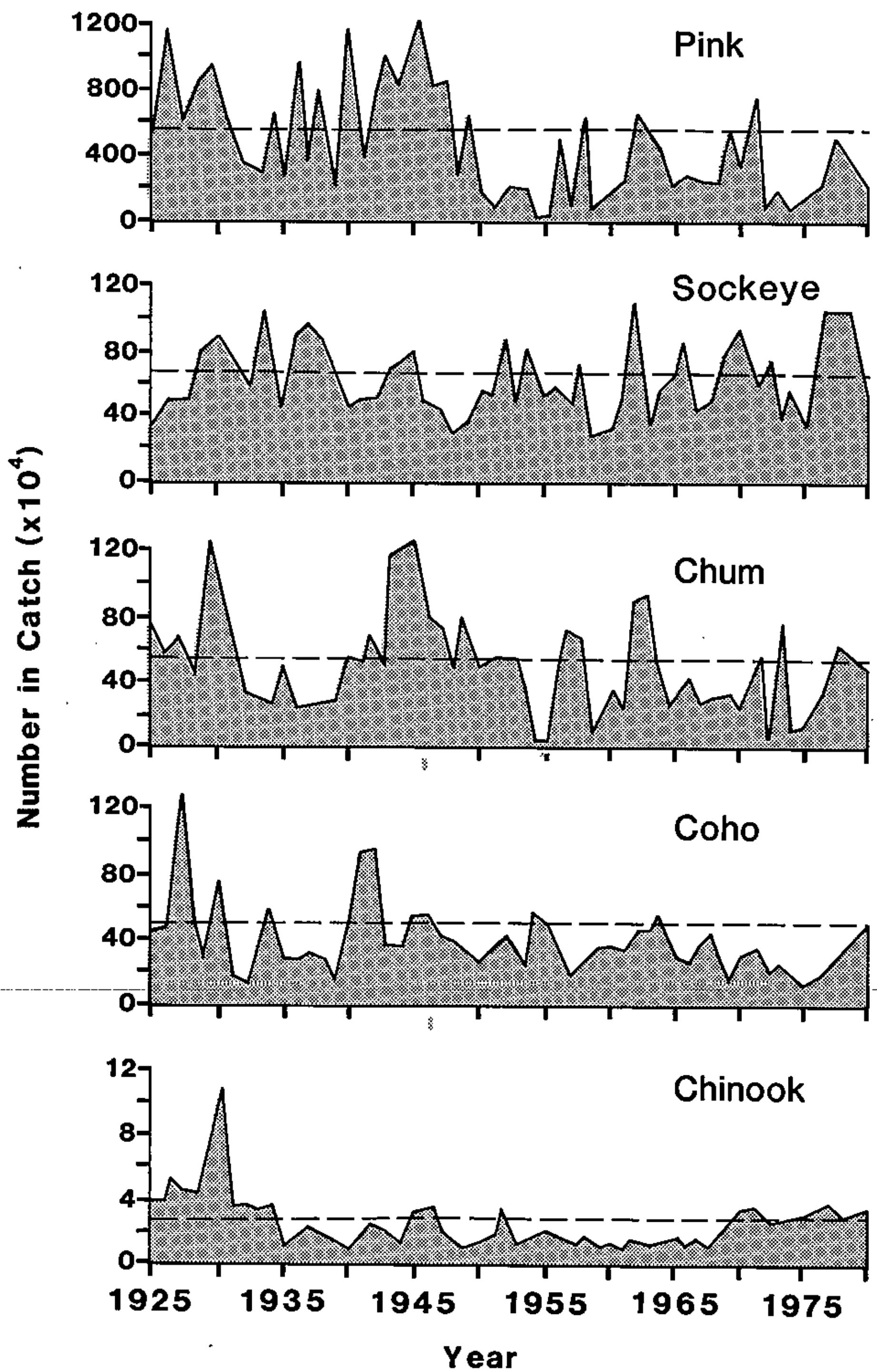


Figure 8.7 Commercial catch of Pacific salmon by species and year (1925-78) in NEGOA (Stern et al., 1976; ADF&G, 1977, 1978; R. Pirtle, in litt.).

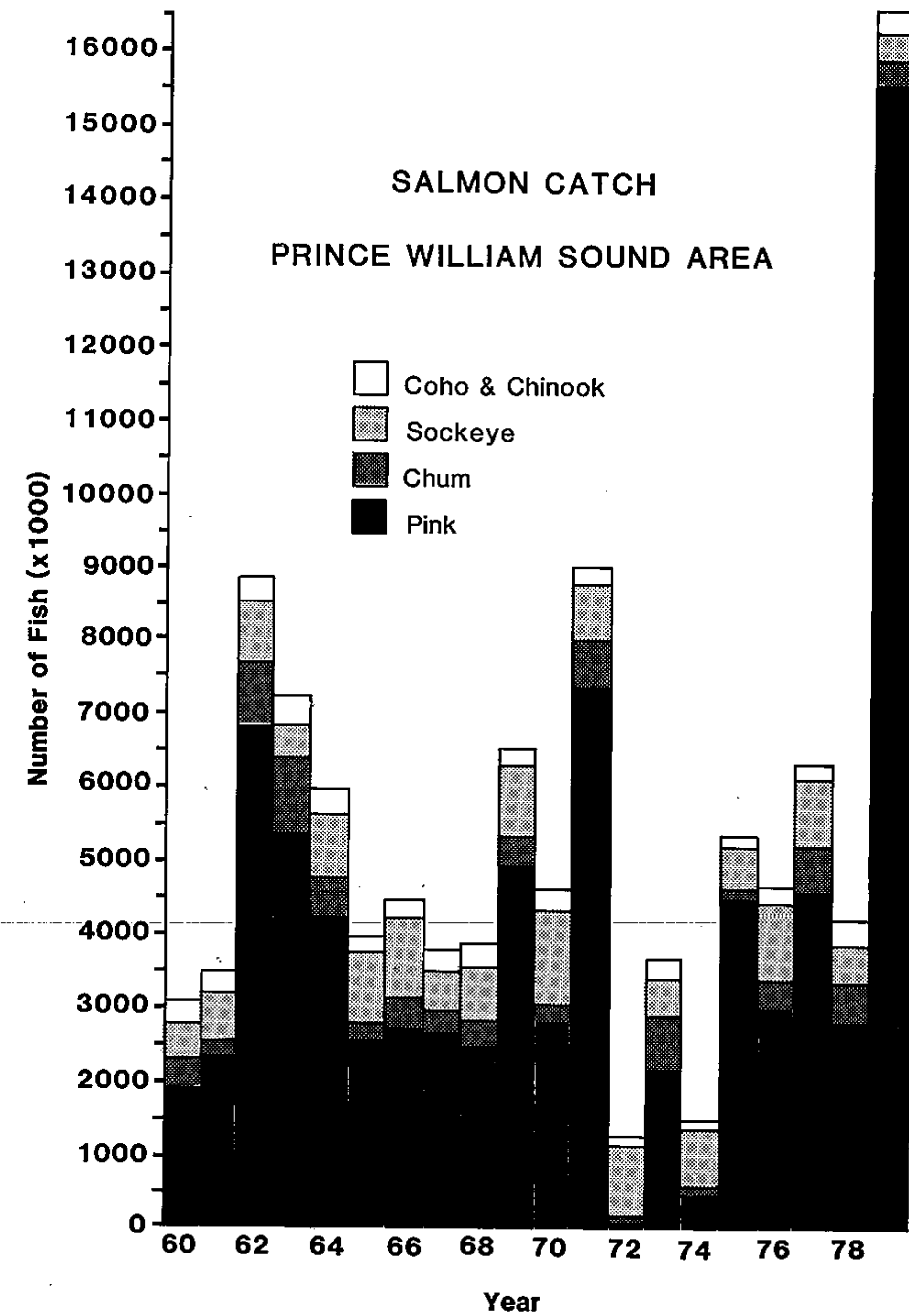


Figure 8.8 Commercial catch of Pacific salmon by species and year (1960-79) in the Prince William Sound Area (ADF&G, 1978; R. Pirtle, in litt.).

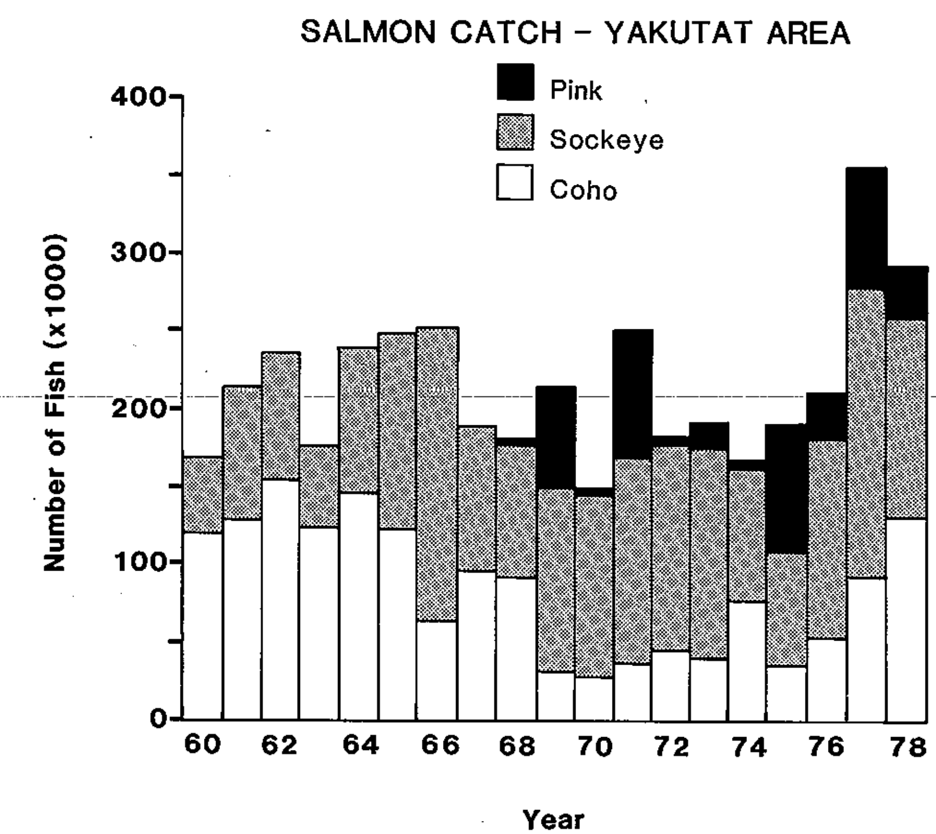


Figure 8.9 Commercial catch of Pacific salmon by species and year (1960-78) in the Yakutat Area (ADF&G, 1977, 1978).

Catches of pink salmon in NEGOA have declined from an average of 6 million fish from 1925 through 1945 to about 3 million fish from 1946 through 1978 (Fig. 8.7). The 1978 catch was 2.8 million fish, which, combined with an estimated escapement of 1.1 million fish, yielded a total spawning run of 3.9 million pinks. The forecast was for 4.2 ± 1.5 million fish in the 1978 run (ADF&G, 1978). The average weight of the fish caught was 1.63 kg, and the average price paid to the fisherman was $0.88 per kg. Thus, the ex-vessel value of the 1978 catch was $4.0 million (R. Pirtle, ADF&G, in litt.). In 1979 a record 15.4 million pink salmon were caught in the Prince William Sound Area, worth an estimated $21.5 million to the fisherman. A record escapement of 3.0 million fish also occurred. Fishing effort in 1979 was comparable to that of 1978. The usually warm sea temperatures from June through October are thought to be the major factor in the high survival rate of returning pink salmon (R. Pirtle, in litt.) For the past 25 years, pink salmon have accounted for about 70 percent of the average annual catch and 25 percent of the ex-vessel salmon revenues in NEGOA (Stern et al., 1976; ADF&G, 1978).

Pink salmon catches fluctuate widely from year to year (Figs. 8.8 and 8.9). The species has a fixed two-year life cycle, and two races have evolved, one that spawns in an odd year (e.g., 1977), the other in an even year (e.g., 1978) (Hart, 1973). Because environmental conditions are rarely the same from one year to the next, survivorship varies, too. Major environmental perturbations in one year may significantly affect that year-class, and consequently have an effect on the sizes of subsequent odd- or even-year stocks. For example, the March 1964 Prince William Sound earthquake caused considerable uplifting and disruption of spawning habitat in the sound (Kramer et al., 1978). Catches of both odd- and even-year stocks were depressed for several years, but the even-year stocks were affected more severely (Fig. 8.8). The even-year populations in the Yakutat Area are also much less abundant than the odd-year ones, judging from the catch record (Fig. 8.9). The causes remain unknown, but may be related to adverse weather, inadequacy of prey, overfishing, and/or a severe geological event like an earthquake.

Sockeye are the second most abundant salmon species caught commercially in NEGOA. Since 1925 annual catches have varied from about 0.3 to 1.1 million fish, with no long-term increases or decreases in the catch (Fig. 8.7). The 1978 catch of 632,000 fish was close to the annual average. Eighty percent of the catch was taken in the Prince William Sound Area; 20 percent was caught in the Yakutat Area. The most productive fishing ground is the Copper River. However, the 1978 catch there was only 250,000 fish, the least in the past 20 years (ADF&G, 1978). Only 367,200 sockeye were caught in the entire Prince William Sound Area in 1979 (R. Pirtle, in litt.). Because of low escapement in the mid 1970's, the predicted catch for the next few years is low. Increased catches from the Coghill district in Prince William Sound may offset the lower Copper River catches. The total ex-vessel value of the 1978 and 1979 catches in the Prince William Sound Area was $5.2 and $3.7 million, respectively, based on average weights per fish and prices per kg paid to the fishermen. The Alsek, Situk, and East Alsek Rivers are the three most productive rivers for sockeye fishing in the Yakutat Area; 89 percent of the 1978 catch was harvested there (ADF&G, 1978). The value of the catch in the Yakutat Area in 1978 was about $750,000.

Chum salmon catches for the past 54 years are shown in Fig. 8.7. They, like pink salmon, are sought almost exclusively in the Prince William Sound Area, where catches have averaged over 500,000 fish annually. The annual catch in the Yakutat Area, 1968-78, ranged from a mere 3,700 to 14,900 fish (ADF&G, 1978). Chum salmon were worth $1.9 and $1.7 million dockside in 1978 and 1979, respectively. A price increase from $0.97 to $1.17 per kg helped to offset the decrease in the 1979 catch (Fig. 8.8). Figure 8.7 shows a close correlation between the amount of chum and pink salmon caught annually since 1964. The spawning habitats of both these species are similar and were disrupted by the 1964 Prince William Sound earthquake. This resulted first in an apparent decline but more recently in an expansion of their populations. The parallel variation in the yearly catch of the two species probably reflects similar oceanographic conditions, food supply, and fishing effort.

The two most productive rivers for commercial fishing of coho salmon in NEGOA are the Copper and Bering Rivers. Catches from these two rivers accounted for more than 99 percent of all coho taken in the Prince William Sound Area in 1978 (ADF&G, 1978). The catch had an ex-vessel value of $3.3 million in 1978, and $3.2 million in 1979 (R. Pirtle, in litt.). As seen in Fig. 8.9, large numbers of coho are also taken in the Yakutat Area. Since 1958 the annual catch has ranged from 30,000 to 155,000, with the average being 88,000 fish. Most fish are caught in the Situk and Alsek Rivers (ADF&G, 1977, 1978). Coho populations appear to be increasing, judging from the catch in 1976-78. The North Pacific Fisheries Management Council believes that increased catches are a direct result of increased attention to the management of offshore coho fishing (NPFMC, 1978b). The value of the coho catch for the Yakutat Area in 1978 is estimated at

$1.4 million, assuming that each fish weighed an average of 4.3 kg and $2.42 per kg was the average price paid (weights and prices the same as for the Prince William Sound Area). The 54-year record of the commercial catch of coho in NEGOA is shown in Fig. 8.7.

Chinook salmon are the largest and most valuable salmon, but they are not taken in NEGOA in large numbers. The total annual catch has rarely exceeded 30,000 since 1930 (Fig. 8.7). In 1979, 19,700 chinooks with an ex-vessel value of $645,000 (R. Pirtle, in litt.) were caught in the Prince William Sound Area. About 95 percent of the catch is taken in the Copper River District (ADF&G, 1979f). Several thousand chinook salmon are also caught annually by the troll fishery in Yakutat Bay and the Alsek and Situk Rivers (ADF&G, 1977).

A commercially important offshore troll fishery occurs south of the proposed OCS Lease Area No. 55 tracts in "outside" waters beyond 19.3-km demarcation line. The Fairweather Ground (Area 157) is the most productive area. There an average of 40,300 chinook and 29,400 coho were caught annually from 1971 to 1976. These catches represent 99 and 95 percent, respectively, of the total offshore troll catch of chinook and coho salmon in a region bounded by the Dixon Entrance to the south and Cape Suckling to the north (NPFMC, 1978b). Based on current prices (R. Pirtle, in litt.), the chinook and coho catch is worth about $1 million annually to the fisherman. The fishing industry, however, claims that the NPFMC has underestimated the extent of the landings taken from the Fairweather Ground. According to the Halibut Producers Cooperative, the catch has an ex-vessel value of over $5 million (Stafne and Hemphill, 1977). The exact value of the catch is difficult to determine because many fish caught on the Fairweather Ground are landed in several southeastern Alaskan ports and some in British Columbia and Washington. There is general agreement that the salmon caught in Area 157 have a comparable value to those taken inshore throughout the entire Yakutat Area (L. Jarvela, in litt.).

The offshore fishery for salmon on the Fairweather Ground has been in operation since 1952. Because of its high economic value and its lengthy tradition as a prime fishing ground, any threat of disruption of the fishery has been met with organized and strong opposition. This response was evinced when the NPFMC prepared its Fishery Management Plan that increased the regulation of the salmon industry. Activities by the oil and gas industry in Lease Area No. 55 may evoke a similar response. The fishing season for chinook now extends from April 15 to October 31; fishing is permitted for coho from June 15 to September 20 in "outside" waters (NPFMC, 1978b).

8.2.3 Non-salmonids

Pelagic species

Information on distribution and abundance of non-salmonid pelagic fishes in NEGOA is for the most part limited to data on species commercially sought, or those prominent in the catches of U.S. and foreign commercial fishing fleets. A synoptic review of the 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 surface; they often feed or migrate over long distances; some form dense schools, making them easier to catch; and they provide valuable forage for many commercially and ecologically important fishes, birds, and mammals in NEGOA. For example, Pacific herring (*Clupea harengus pallasi*) and capelin (*Mallotus villosus*) are major prey species of salmonids (Hart, 1973). Cetaceans and pinnipeds consume large numbers of Pacific herring, capelin, eulachon (*Thaleichthys pacificus*), and deepsea smelts (*Bathylages* spp.) (ADF&G, 1975a; Macy et al., 1978).

Pacific herring are distributed widely in the coastal waters of NEGOA (Fig. 8.11). Major concentrations of herring occur in Prince William Sound, especially in the outer areas of fiords and around Montague Island (Rounsefell, 1930; Reid, 1972; ADF&G, 1975a; Macy et al., 1978). In aerial surveys, additional large concentrations were observed in the Copper River Delta, Upper Russell Fiord, and in Yakutat Bay between Ocean Cape and Knight Island. Few herring were seen east of Yakutat Bay (ADF&G, 1975a).

In the Prince William Sound-Copper River Delta area herring spawn from early March to early June (Reid, 1972). In the Kodiak area spawning occurs

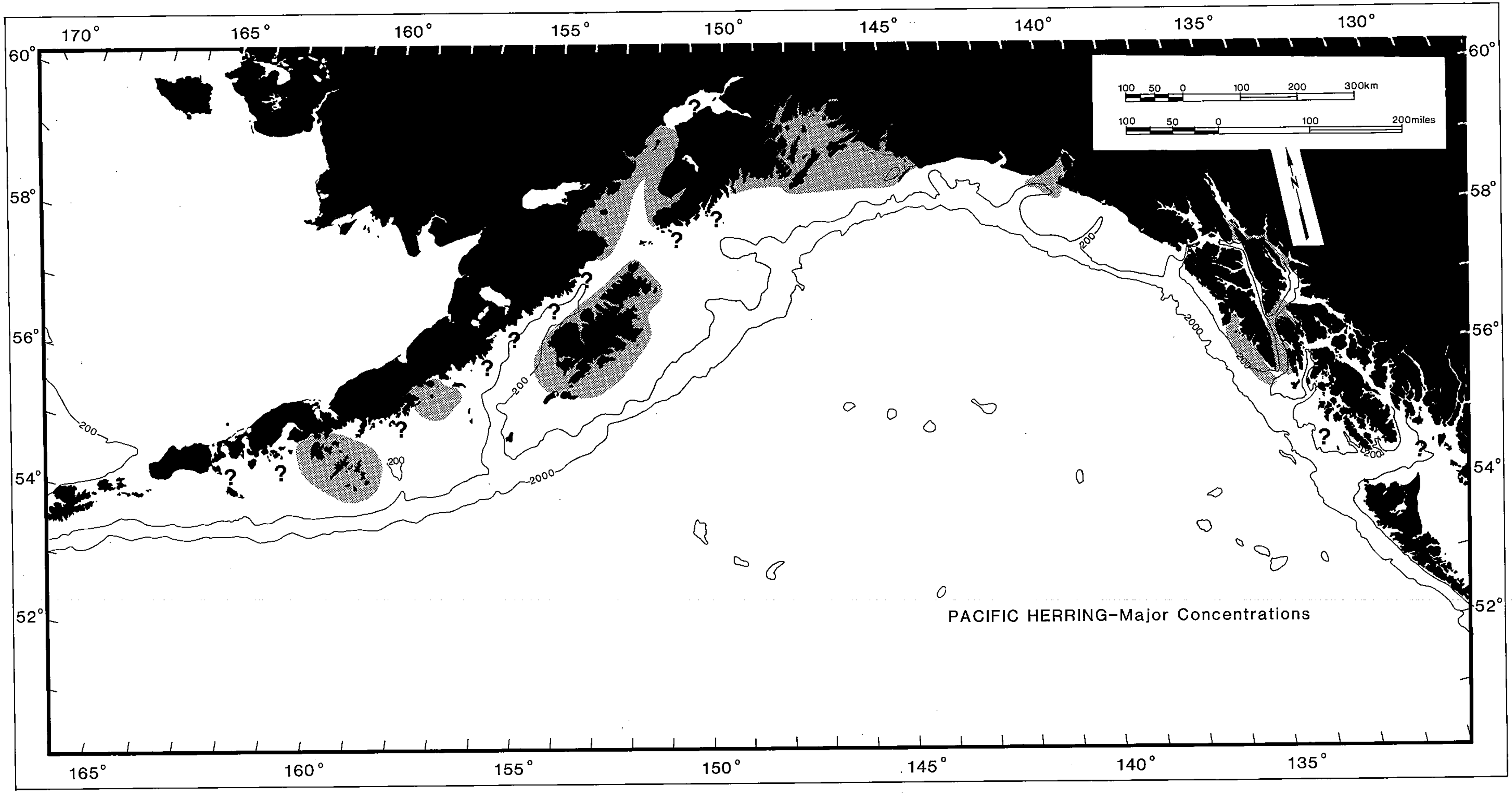


Figure 8.10 Major concentrations of Pacific herring in the Gulf of Alaska (Rounsefell, 1930; Reid, 1972; ADF&G, 1975a; Macy et al., 1978; Taylor, 1980).

primarily from May through mid-June (Rounsefell, 1930; ADF&G, 1975a). Peak spawning times vary from year to year, and populations do not always return to the same area in successive years to spawn. Water temperatures may be an important determinant of the timing and location of spawning (ADF&G, 1975a).

Gravid females extrude their eggs onto algae, submerged tree branches, and other stable 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 from the air.

Most schools of mature herring leave the shallows after spawning and swim into deeper, offshore water to feed (Taylor, 1964). They return to shallower waters in autumn to overwinter.

Larval and juvenile herring use bays in Prince William Sound and other protected embayments as nursery grounds, feeding extensively on calanoid copepods (Cushing, 1975; 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).

The size of Pacific herring populations in NEGOA has been difficult to ascertain, mainly because of wide fluctuations in year-class numbers. Years in which herring were abundant coincided with the passage of dominant year-classes through the commercial fishery (Rounsefell and Dahlgren, 1932). These dominant year-classes, though, occur at random intervals and are not closely correlated with annual egg production or fishing pressure (Reid, 1972). Years of high and low catches of Pacific herring in NEGOA have been described by Hanamura (1961) and ADF&G (1975a, 1979f).

A small herring fishery presently exists in NEGOA, principally in Prince William Sound. Since 1964, herring roe has been commercially harvested and sent to Japan for human consumption (ADF&G, 1975a). Roe is collected from gravid females or harvested once the eggs are extruded onto algae. Eggs attached to kelp have the highest value. A bait fishery for herring also exists in the sound, but the catch is insignificant. The catch of herring taken for roe has ranged from 900 to 7,000 mt during the past decade. Years of peak harvest were 1973-1975. In 1978 only 1,350 mt were taken. The roe constitutes about 10 percent of the total weight of the fish (ADF&G, 1979f). The estimated ex-vessel value of the catch in 1978, based on prices paid Kodiak fishermen, was $165,000.

Capelin are abundant in NEGOA waters (Hart, 1973). They live in oceanic waters at mesopelagic depths for most of the year, rising in the water column and migrating shoreward to spawn (Trumble, 1973). They spawn along exposed pebbly beaches (Hart, 1973) that have rather narrowly defined habitat characteristics. Water temperatures, substrate grain size, tidal stage, and ambient light conditions all affect spawning (Jangaard, 1974). The exact location of spawning beaches in NEGOA has not yet been reported. Spawning probably occurs in NEGOA in May and June as it does in Kodiak waters (J. Blackburn, ADF&G, Kodiak Office, pers. comm.). It occurs in September and October in the Strait of Georgia, British Columbia (Hart, 1973), and in June through July in the Bering Sea (Musienko, 1970). Spawning individuals are mainly 3 and 4 years old. Most fish die after spawning. Demersal eggs attach to beach substrates and hatch in 15-30 days at 5-10°C. (Jangaard, 1974).

Capelin are the main prey of many fishes (Harris and Hartt, 1977; Rogers and Rogers, 1978; Rogers et al., 1979). Marine birds and pinnipeds also eat large amounts of capelin (Calkins and Pitcher, 1978; Pitcher and Calkins, 1978); Sanger et al., 1978.)

Apart from recent OCSEAP surveys and anecdotal data, little information is available on the seasonal movements of capelin in NEGOA. Considering the apparent importance of the species, more investigations are necessary to further describe its seasonal distribution, abundance, life history, and trophic relationships.

Pacific sand lance (Ammodytes hexapterus) probably occur throughout the continental shelf region from near shore to the edge of the shelf. 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 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 in shallower water 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 Trophics section). They are common in both pelagic and benthic fish assemblages and are important in energy transfer between systems.

Atka mackerel (Pleurogrammus monopterygius) are widely distributed in epipelagic waters of the North Pacific Ocean and Bering Sea. It is taken most frequently along the continental shelf break. 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 in NEGOA 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 Bank region in spring (Dunn et al., 1979a), but sites of their origin are unknown. In recent years this species has been a major target of Soviet fisheries (Ronholt et al., 1978). It is not harvested by domestic fishing fleets operating out of Kodiak, Cordova and Yakutat. 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). Their distribution, population dynamics, and feeding habits have been summarized by Macy et al. (1978).

Demersal fishes

Demersal (bottom-dwelling) fishes are often simply called 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 latter classification is used. To date, 138 species representing 26 families of demersal fishes have been captured in the Gulf of Alaska. Families with the most species represented are Hexagrammidae (30 spp.), Cottidae (24 spp.), and Pleuronectidae (16 spp.) (Quast and Hall, 1972). Common demersal fishes in NEGOA are listed in Table 8.3. Each species appears to have preferred habitats and depths throughout the region; therefore, a particular species may be "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 of the Gulf of Alaska 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 310 stations in NEGOA. Fish were taken with otter trawl gear from water depths down to 400 m. (Ronholt et al., 1978). The NMFS sampling occurred from April through October; distributions probably differ in winter. Hughes (1974) has shown this to be true for fish populations sampled in this vicinity in 1961. No single survey can describe the distribution of fish populations completely. The study of Ronholt et al. (1978) is the most comprehensive to date. Additionally, their comparisons of survey data from the 1960's and the 1970's provide insight into long-term fluctuations of standing stocks of demersal fishes.

Table 8.3 Common demersal fishes in NEGOA (Buck et al., 1975; ADF&G, 1975a; Harris and Hartt, 1977; Ronholt et al., 1978; Rogers et al., 1979).

Flatfish

* Pacific halibut (Hippoglossus stenolepis)
Rock sole (Lepidopsetta bilineata)
Yellowfin sole (Limanda aspera)
Flathead sole (Hippoglossoides elassodon)
Starry flounder (Baltichthys 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. octogrammos)
Masked greenling (H. stelleri)
Whitespotted greenling (H. stelleri)
Lingcod (Ophidon elongatus)
Yellow Irish lord (Hemilepidotus jordani)
Red Irish lord (H. hemilepidotus)
Great sculpin (Myxocephalus 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

Roundfish, particularly walleye pollock, and several flatfish are abundant throughout NEGOA; rockfish and elasmobranchs are less frequently caught. The rate at which these four classes of fish were taken at each sampling location in NEGOA is indicated on Figs. 8.11-8.14. This information is summarized in Fig. 8.15 in which average catch rates for each fish group in three regions and depth ranges are shown.

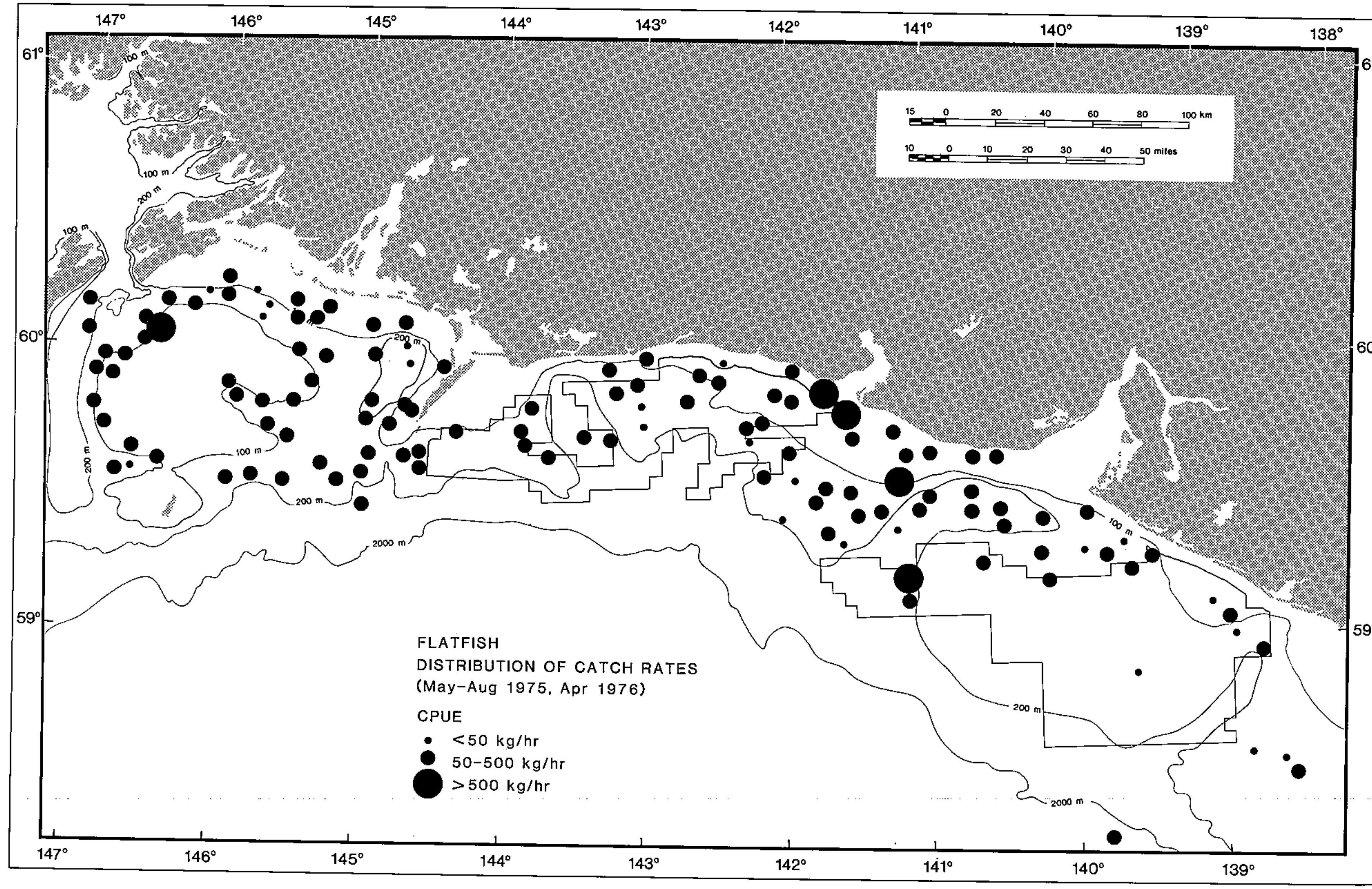


Figure 8.11 Distribution of standardized catch rates (CPUE) of flatfish, based on NMFS survey data (Ronholt et al., 1978).

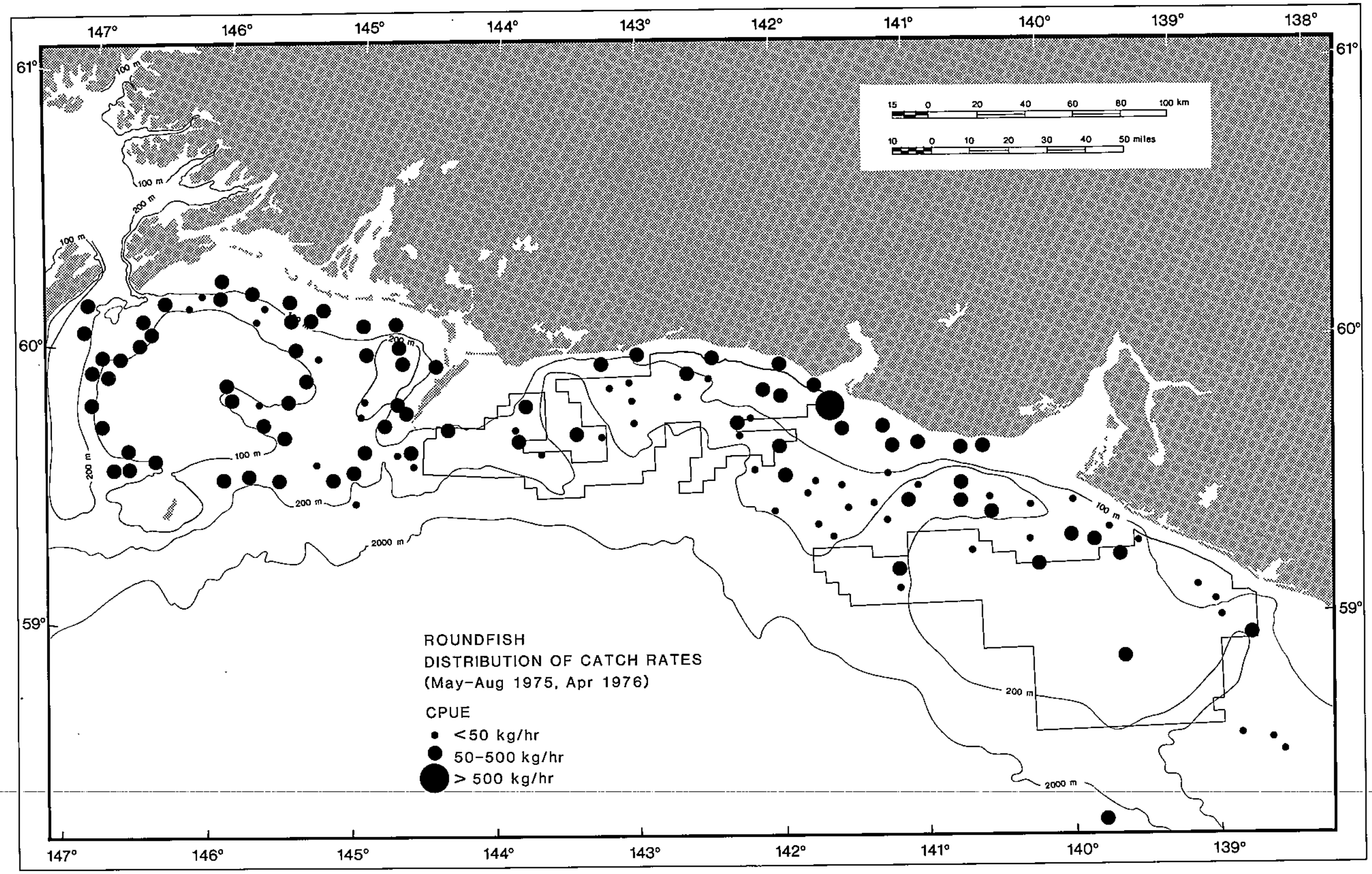


Figure 8.12 Distribution of standardized catch rates (CPUE) of roundfish, based on NMFS survey data (Ronholt et al., 1978).

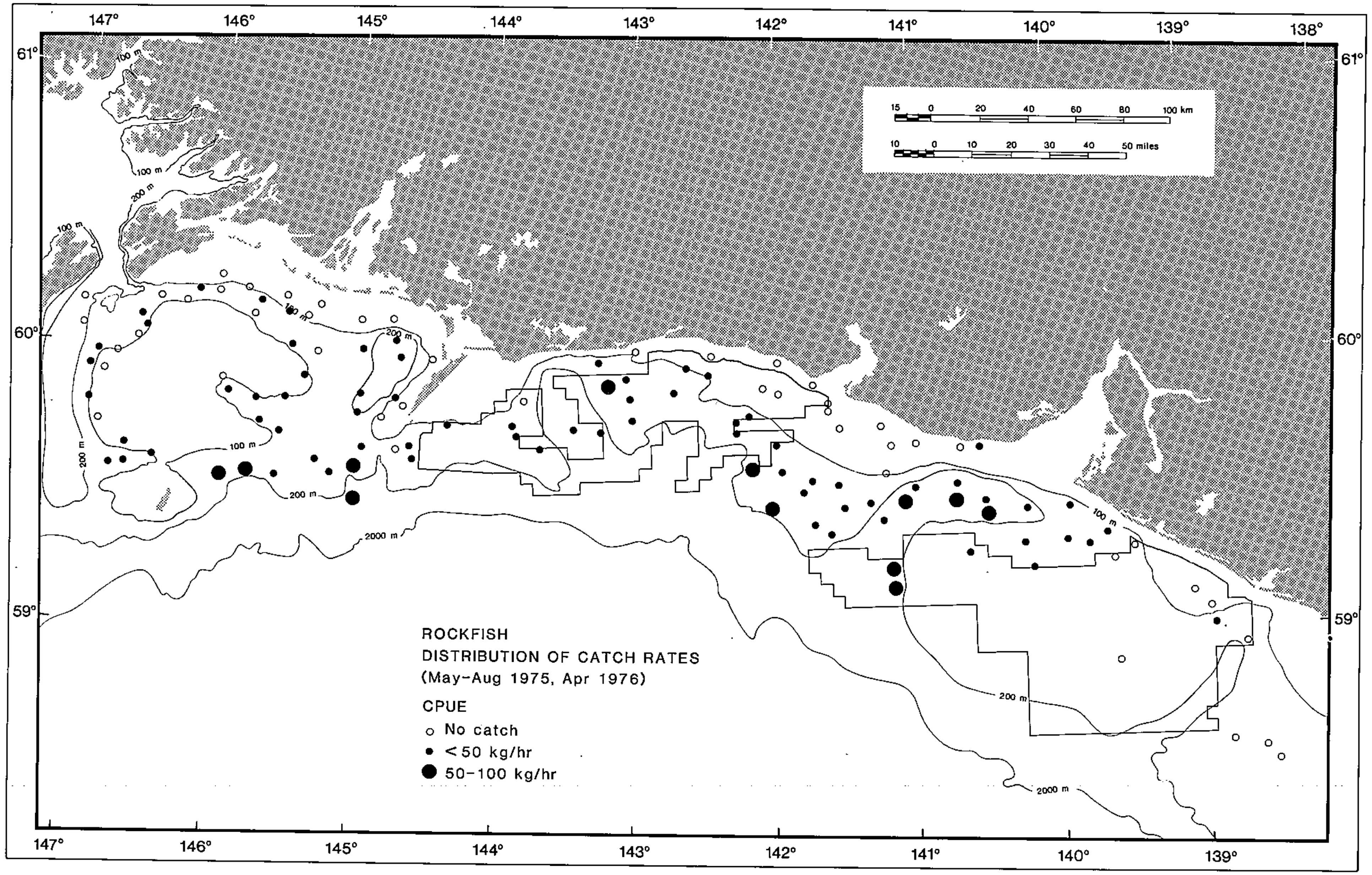


Figure 8.13 Distribution of standardized catch rates (CPUE) of rockfish, based on NMFS survey data (Ronholt et al., 1978).

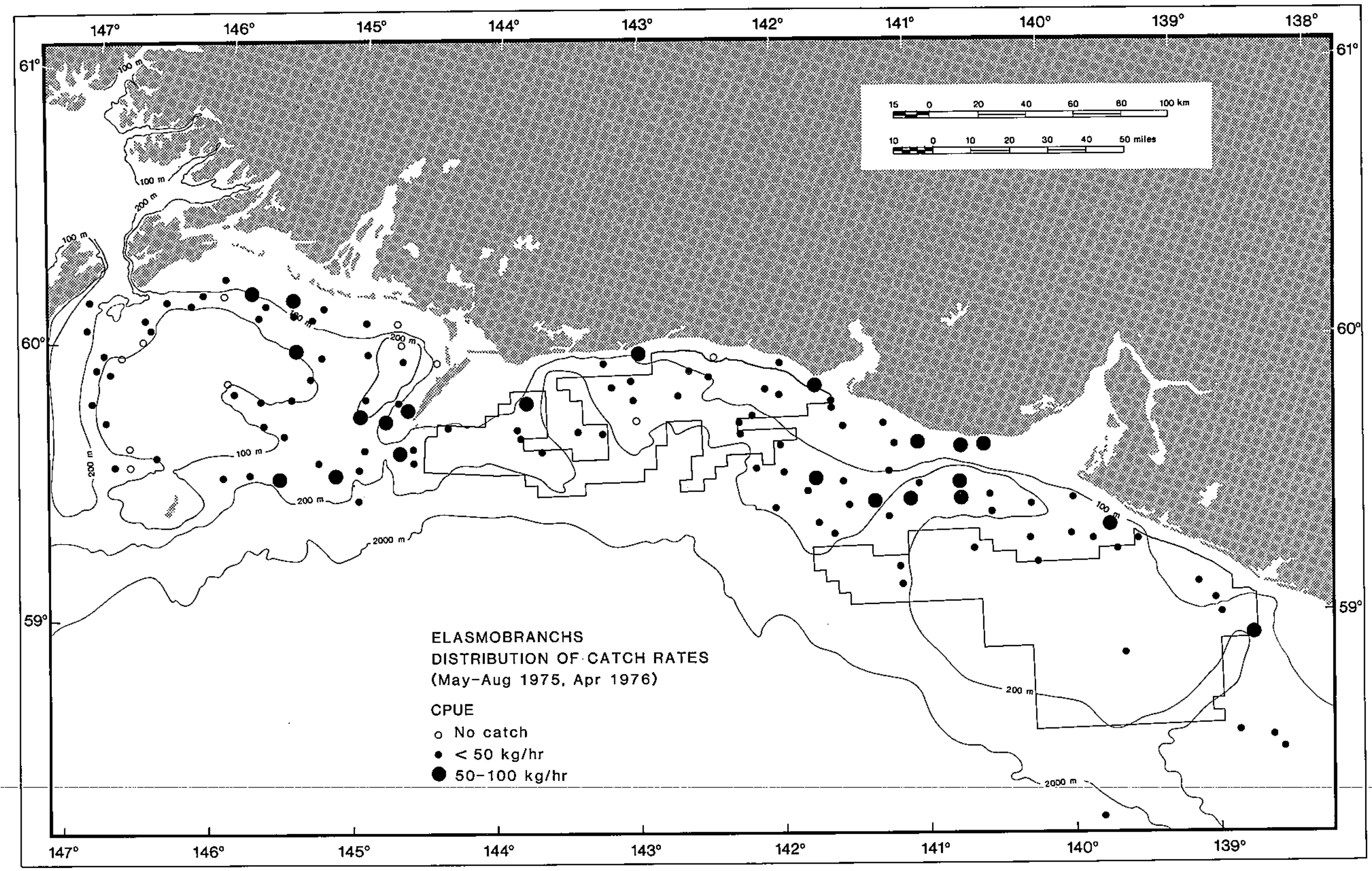


Figure 8.14 Distribution of standardized catch rates (CPUE) of elasmobranchs, based on NMFS survey data (Ronholt et al., 1978).

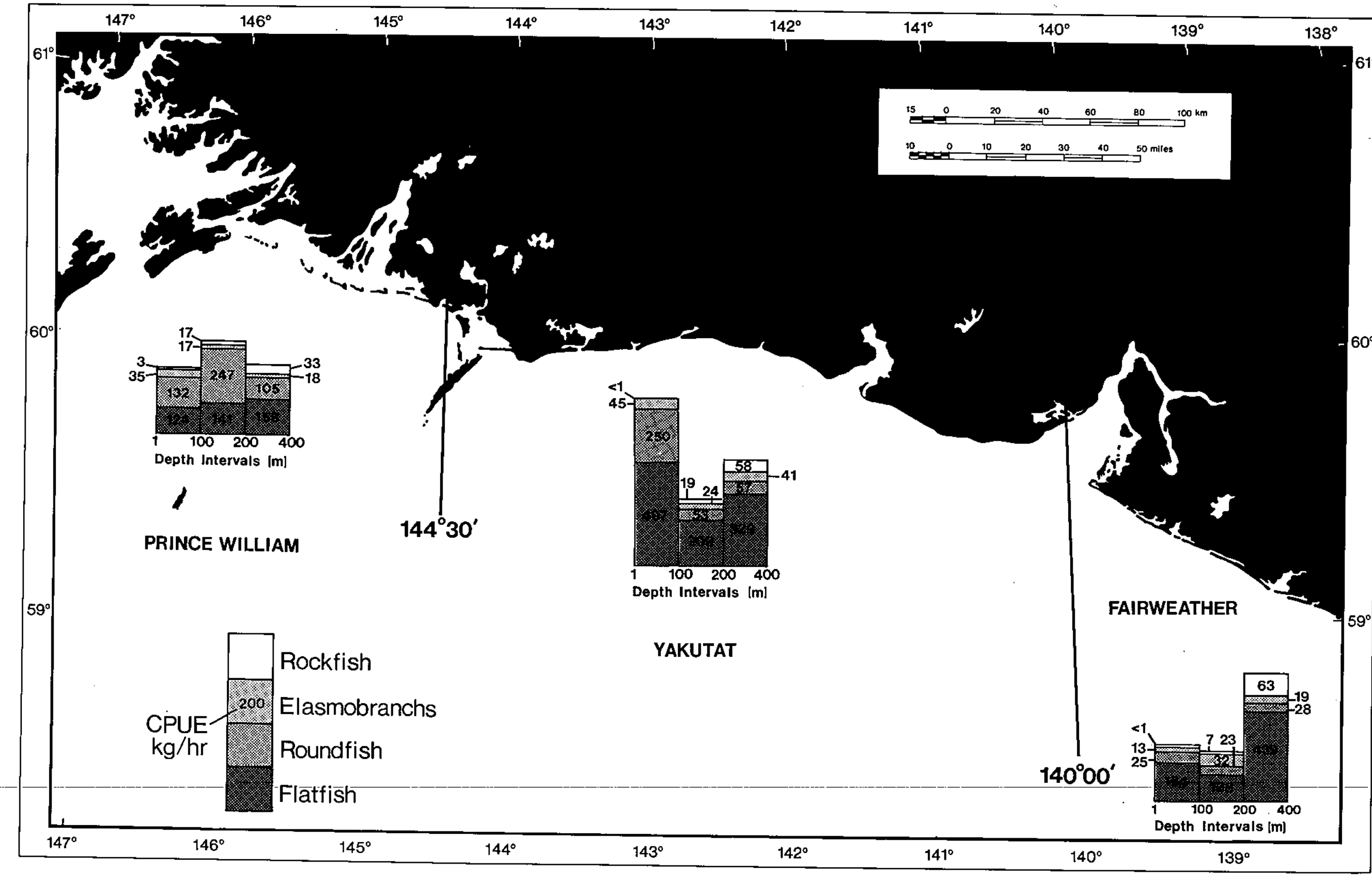


Figure 8.15 Average catch per unit effort (CPUE) of groups of demersal fishes in NEGOA, based on NMFS trawl survey data, May-August 1975 and April 1976 (Ronholt et al., 1978).

Biomass estimates derived from the catch data (Table 8.4) represent the apparent abundance of each group of fish. Although the method of capture, season, ease of sampling the substrate, and a host of other factors may influence estimates, they are the best recent data on the size of fish populations in NEGOA. Estimates for NEGOA are compared to estimates for all of Alaska in Table 8.5.

Table 8.4 Estimated biomass in metric tons of demersal fish groups by region and depth zones in NEGOA, May-August 1975 and April 1976 (Ronholt et al., 1978).

Depth Interval (m)	Flatfish	Roundfish	Rockfish	Elasmobranchs	All Fish
Fairweather					
1-100	5,900	900	a	500	7,300
101-200	20,800	3,800	1,200	5,300	31,100
201-400	13,200	900	1,900	600	16,600
All depths	39,900	5,600	3,100	6,400	55,000
Yakutat					
1-100	30,800	15,500	a	2,800	49,100
101-200	30,600	7,700	3,300	3,500	45,100
201-400	22,600	3,900	2,300	2,800	31,600
All depths	84,000	27,100	5,600	9,100	125,800
Prince William					
1-100	13,700	14,600	300	3,900	32,500
101-200	17,700	31,200	2,200	2,100	53,200
201-400	5,800	3,800	1,200	600	11,400
All depths	37,200	49,600	3,700	6,600	97,100
TOTAL					
1-100	50,400	31,000	300	7,200	88,900
101-200	69,100	42,700	6,700	10,900	129,400
201-400	41,600	8,600	5,400	4,000	59,600
All depths	161,100	82,300	12,400	22,100	277,900

a Biomass <20 mt.

Table 8.5 Percentage of total Gulf of Alaska fish populations (estimated biomass) occurring in three statistical districts in NEGOA (0-400 m), based on 1975-76 data (Ronholt et al., 1978).

Fish group	Statistical area: Prince William	Yakutat	Fairweather	NEGOA
Roundfish	5.2	2.7	0.6	8.5
Flatfish	6.3	14.3	6.8	27.4
Rockfish	13.0	19.7	10.8	43.5
Elasmobranchs	23.4	31.9	22.2	77.5

In another set of important comparisons, Ronholt et al. (1978) show that fish populations have changed from the early 1960's to mid-1970's. According to their methods of comparison, the only significant change in abundance was for roundfish in the Prince William Region and elasmobranchs in the Kenai Region (Table 8.6). When fish populations were compared by decade, region, and depth zone, some additional differences appear (Table 8.7). Although not statistically significant, the following trends were evident: (1) flatfish were much more abundant on the inner shelf of the Prince William Region and much less so in the Fairweather Region in the mid-1970's; (2) roundfish populations have decreased appreciably in the Kenai and Prince William areas; (3) rockfish populations have decreased appreciably in the Kenai and Prince William areas.

Table 8.6 Comparison of mean (geometric) catch rates (CPUE) of fish groups caught during two resource surveys conducted in NEGOA (Ronholt et al., 1978).

	IPHC (1961-1963) $\bar{x}$ CPUE (kg/hr)	NMFS (1973-1976) $\bar{x}$ CPUE (kg/hr)
Flatfish		
Kenai	118	104
Prince William	32	107
Yakutat	76	166
Fairweather	191	83
Roundfish		
Kenai	56	112
Prince William	7	101*
Yakutat	18	46
Fairweather	16	3
Rockfish		
Kenai	21	4
Prince William	4	2
Yakutat	10	9
Fairweather	5	3
Elasmobranchs		
Kenai	20	2*
Prince William	5	8
Yakutat	9	22
Fairweather	12	14

* Significant decrease in population.

Table 8.7 Ratio of "1970"/"1960" geometric mean CPUE index (from Ronholt et al., 1978).

	Depth zones (m): 1-100	101-200	201-400
Flatfish			
Kenai	-	1.23	0.40
Prince William	11.29	1.41	1.52
Yakutat	1.85	2.29	2.29
Fairweather	0.09	0.30	3.05
Roundfish			
Kenai	-	3.01	0.80
Prince William	18.87	18.28	3.98
Yakutat	11.31	1.14	3.94
Fairweather	0.17	1.40	0.72
Rockfish			
Kenai	-	0.28	0.06
Prince William	-	0.41	0.14
Yakutat	0.99	1.12	0.55
Fairweather	0.98	0.52	0.54
Elasmobranchs			
Kenai	-	0.10	0.06
Prince William	2.02	1.11	1.94
Yakutat	2.25	1.91	4.37
Fairweather	1.88	1.17	0.67

Pacific halibut (Hippoglossus stenolepis) have been the primary target species since 1888 of a commercial fishery in the North Pacific, 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, notably Kodiak City (IPHC, 1977).

Halibut occur on or near the continental shelf from California northward into the Bering Sea. Preferred water depths vary with season and age. During the NMFS survey, the species constituted about one percent of the flatfish catch in NEGOA (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. 8.16; Bell and St. Pierre, 1970; IPHC, 1978).

The seasonal movements, migratory routes, spawning, and early life history of Pacific halibut have been studied in detail since 1923, when the IPHC was organized (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 Bank, to deeper winter spawning grounds, then return to their summer grounds. Some adults migrate long distances and do not return to the same grounds (Bell and St. Pierre, 1970; Skud, 1977; IPHC, 1978). Mechanisms that trigger these pioneer immigrations are unknown. Most tagged fish were recovered within 150 km of their initial release site (Table 8.8).

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 Bank, Cape Spencer, Cape St. Elias, Chirikof, and the Trinity Islands "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 probably occurs 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 Bank (Thompson and Van Cleve, 1936). Currents in the Gulf of Alaska carry the eggs and larvae northward and westward for six to seven months. At first the larvae passively drift in water deeper than 200 m, but later they rise slowly toward the surface (Thompson and Van Cleve, 1936; Skud, 1977; IPHC, 1978). Favorite and Ingraham (1977) have concluded that eggs released along the southeastern coast of Alaska would be transported to NEGOA and advected shoreward at speeds of 5-10 cm/s, 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; they are found in shallow bays along the coast of Alaska and 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 are prerecruits four to eight years old according to IPHC (Best, 1974) and NMFS (Ronholt et al., 1978) trawl survey data from stations throughout the Gulf of Alaska. Important

Table 8.8 Release and recovery locations of tagged adult Pacific halibut, 1925-76 (Skud, 1977).

		Recoveries by region							
Release region	Number released	Bering Sea	Shumagin	Chirikof	Kodiak	Yakutat	SE Alaska	B.C.	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	1,078	62	52	1,773
SE Alaska	9,729	0	0	0	1	4	1,945	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	2,361	17,524	25,135

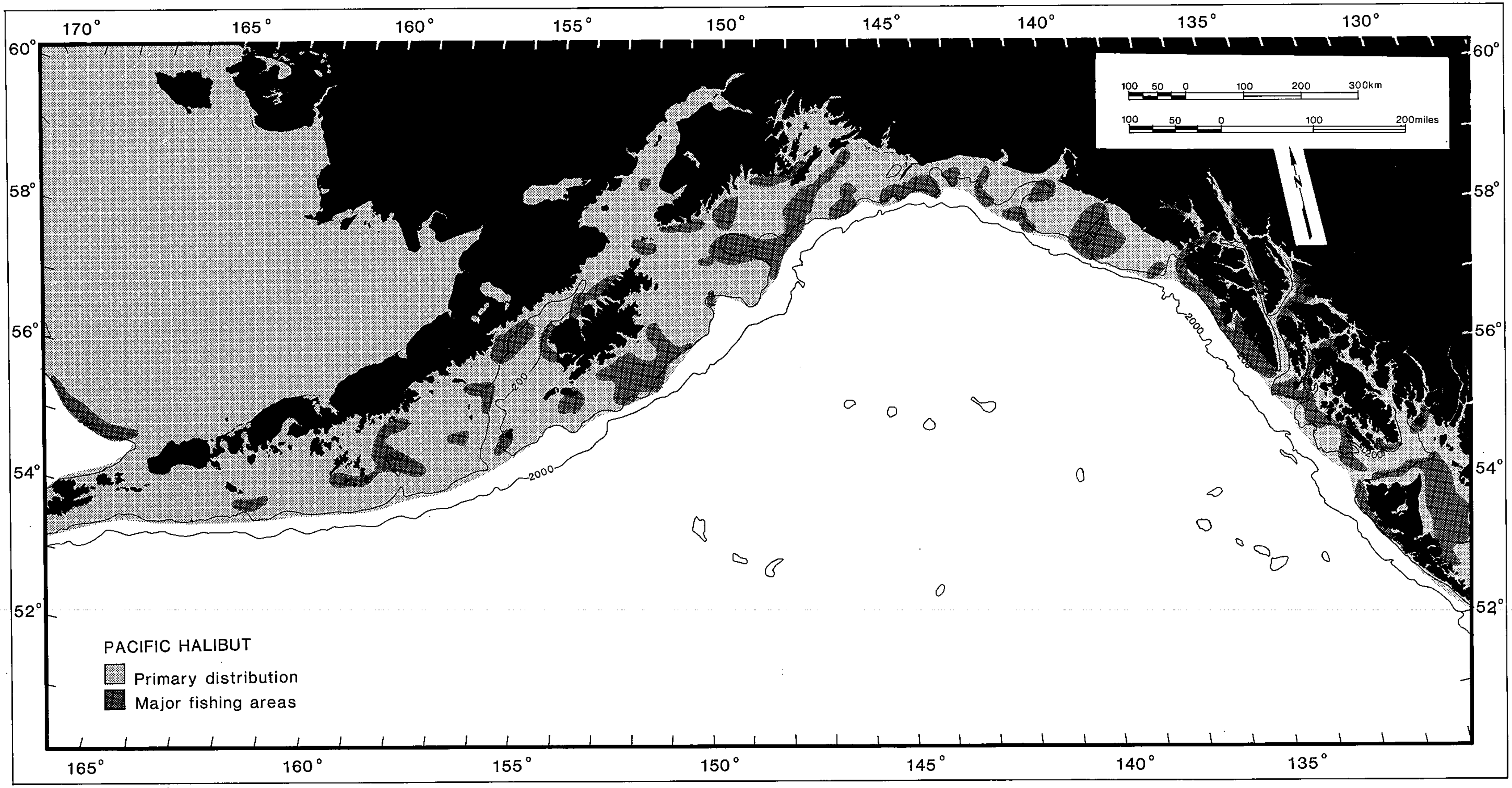


Figure 8.16 Distribution of Pacific halibut in the Gulf of Alaska, with major fishing grounds highlighted (IPHC, 1978).

halibut nursery grounds near the OCS lease areas are in Yakutat Bay and the Fairweather Grounds, 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 extensive (Skud, 1977).

Skud (1977) hypothesizes that the emigration movements of juvenile halibut 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 increases from west to east. Three-year-olds were dominant at Unimak and Chirikof, four-year-olds at Chiniak, five-year-olds at Cape St. Elias, and five- and six-year-olds in British Columbia (Best, 1968, 1974). In addition, 30 percent of the juvenile halibut tagged west of Cape Spencer (IPHC'S Area 3) were recovered in British Columbia. This evidence suggests that, contrary to earlier findings (Thompson and Herrington, 1930), there is extensive intermingling of halibut stocks north and south of Cape Spencer (Skud, 1977). Furthermore, it is principally the juvenile fish, not the adults, that maintain the population distributions.

The abundance of Pacific halibut has been estimated from catch and age data using a cohort analysis technique. The 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. 8.17. 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. Stocks declined to about 5

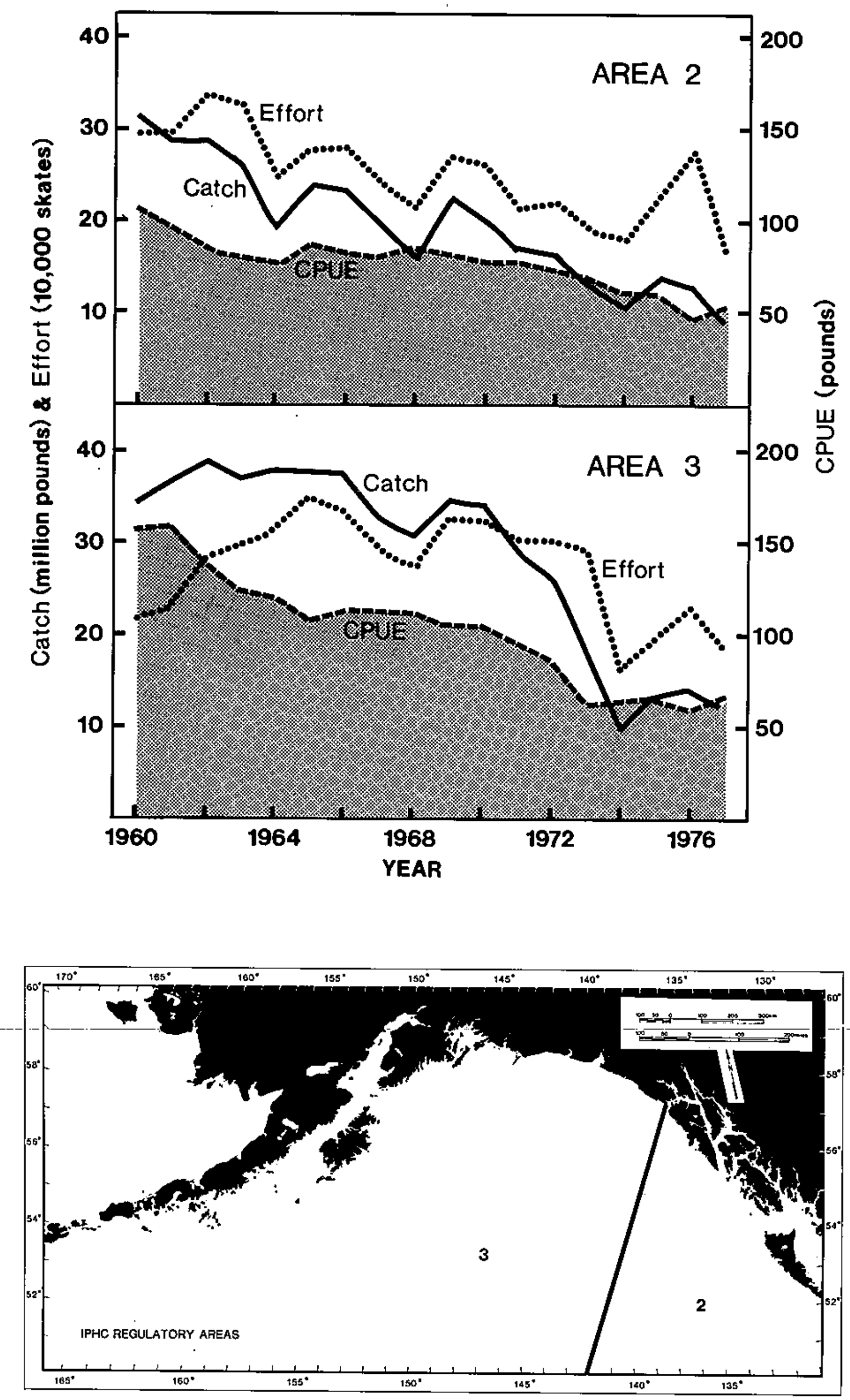


Figure 8.17 Catch statistics of Pacific halibut based on U.S. and Canadian setline fishing in IPHC Regulatory Areas 2 and 3, 1960-77 (IPHC, 1977, 1978).

million fish in the late 1940's. Occasional strong year-classes appeared in the 1950's and 1960's, but stocks generally 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).

Arrowtooth flounder (turbot) (Atheresthes stomias) is another commercially important flatfish. It was the most abundant flatfish caught in the Gulf of Alaska during the 1973-76 NMFS survey. This species is widely distributed throughout the region (Fig. 8.18). Arrowtooth flounder constituted 52 and 44 percent of the flatfish catch in the Kenai and Prince William Statistical Areas, respectively; and 42 and 44 percent in the Yakutat and Fairweather Areas (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 numbers of arrowtooth flounder were taken in a small area between Yakutat and Icy Bays during the 1975-76 survey (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 NEGOA waters. In the Bering Sea, it spawns from December to February (Shuntov, 1970), but its spawning grounds have not been determined (Pereyra et al., 1976).

Other flatfishes (flathead sole, rex sole, rock sole, and Dover sole) were caught regularly in 1975-76. Details of their distribution and relative abundance

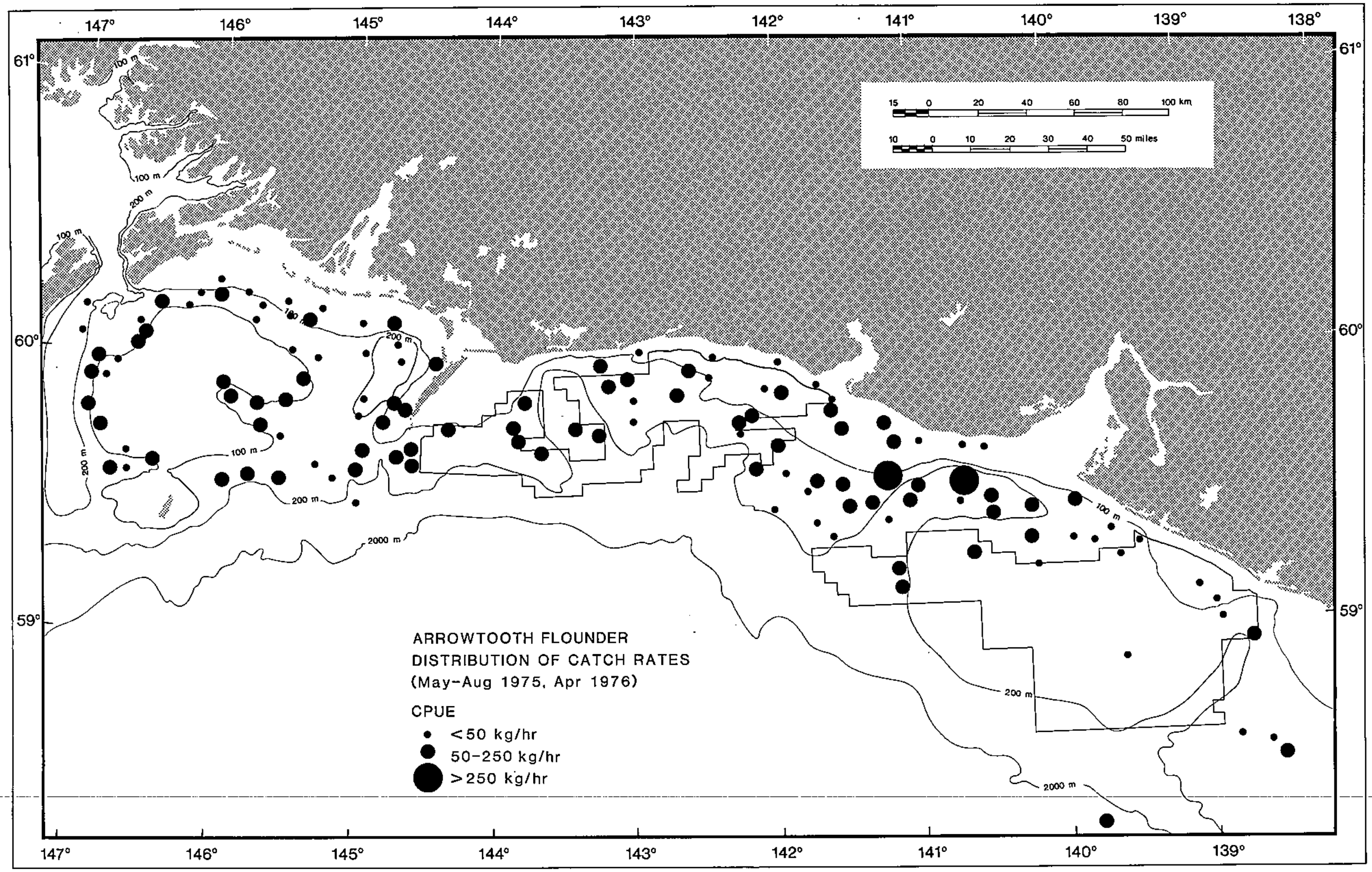


Figure 8.18 Distribution of standardized catch rates (CPUE) of arrowtooth flounder, based on NMFS survey data (Ronholt et al., 1978).

are reported by Ronholt et al. (1978). Feeding relationships of these species are discussed in a subsequent section.

Walleye pollock (Theragra chalcogramma) is perhaps the most important roundfish, commercially and ecologically, in the entire Gulf of Alaska. They were found at 87 percent of the stations in NEGOA in 1975-76 (Fig. 8.19; Ronholt et al., 1978). Pollock appear to be replacing Pacific ocean perch as the dominant fish of the Amchitka region (Simenstad et al., 1977). Walleye pollock inhabit the outer continental shelf region and the troughs at depths between 100 and 200 m (Ronholt et al., 1978). Commercial fishermen in the Shelikof Strait, however, report large catches from depths up to 300 m (J. Blackburn, ADF&G, Kodiak office, pers. comm.). Juvenile pollock inhabit more coastal waters and are routinely taken in the bays and fiords (Rogers et al., 1979; Feder et al., 1979).

Walleye pollock was the most common fish in the Gulf of Alaska from Cape Spencer to Unimak Pass, during the NMFS resource survey of 1973-76. The biomass of pollock was nearly 740,000 mt, or 46 percent of all fish (Ronholt et al., 1978). In NEGOA the estimated biomass of pollock was 121,000 mt. Pollock accounted for 79 percent of the roundfish catch in Kenai, 78 percent in Prince William, 55 percent in Yakutat, and 22 percent in Fairweather (Ronholt et al., 1978). During the past several years fishermen trawling in the Shelikof Strait from Malina Bay south to Chirikof Island have reported catches of up to 1.8 mt/hr; these comprised 80 percent pollock, 7 to 8 percent Pacific cod, and 2 to 3 percent sablefish (J. Blackburn, pers. comm.).

Walleye pollock were far less abundant in NEGOA in the early 1960's. In the May-October 1961 sampling period the estimated biomass of pollock was 27,400 mt, or 23 percent of the biomass thought to occur there 12 to 15 years later (Ronholt et al., 1978).

Life history data for pollock in NEGOA have not been reported. In the Kodiak region they probably spawn 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, pers. comm.). Though the spawning grounds are unknown, high concentrations of eggs taken in March and April and larvae taken in summer in the region of the Kiliuda and Chirikof-Shelikof Troughs suggests these areas as probable spawning grounds (Dunn et al., 1979; Dunn, pers. comm.).

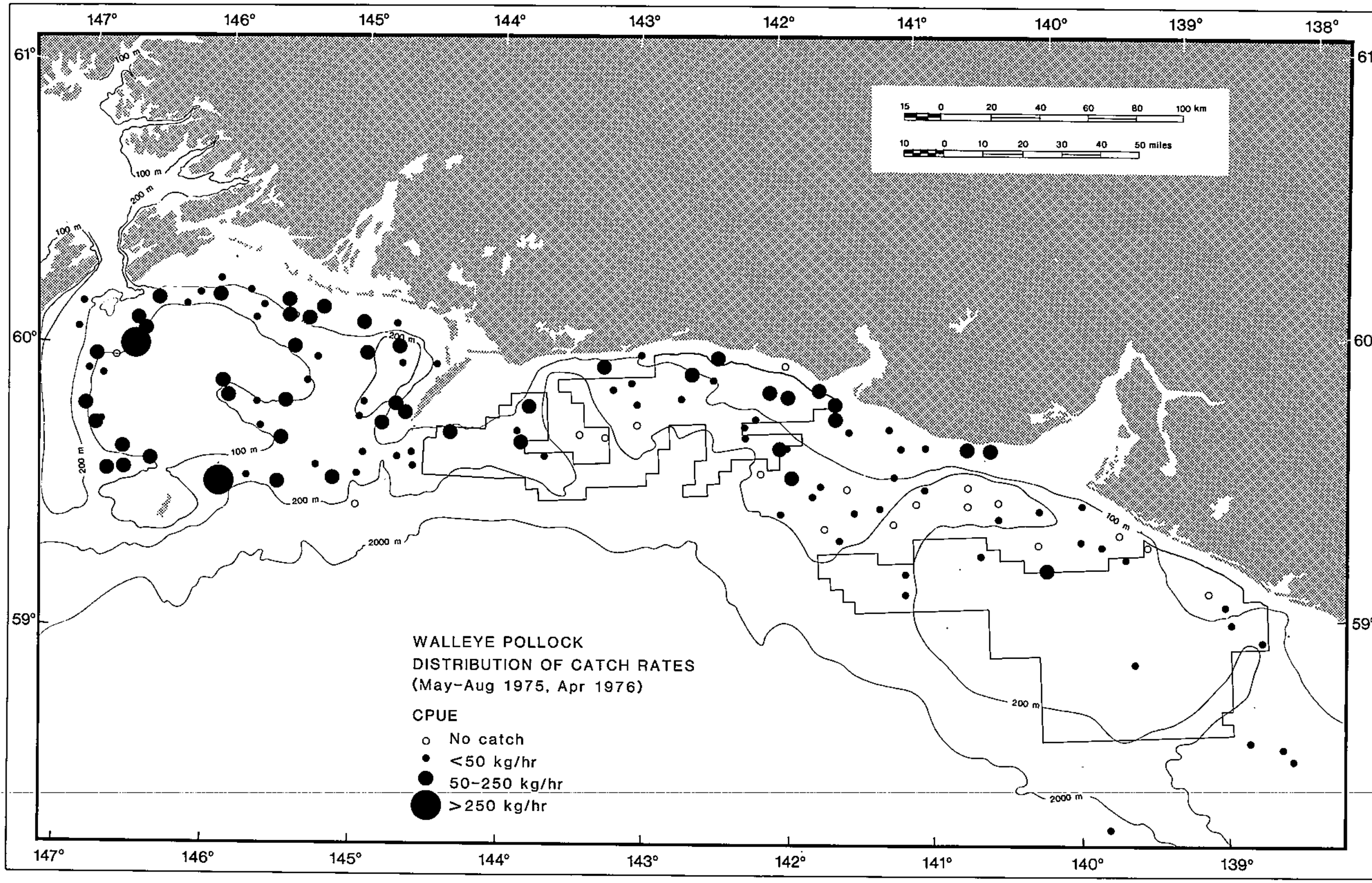


Figure 8.19 Distribution of standardized catch rates (CPUE) of walleye pollock, based on NMFS survey data (Ronholt et al., 1978).

Pacific cod (Gadus macrocephalus) is another abundant roundfish in NEGOA waters. It is distributed from inshore embayments (Harris and Hartt, 1977; Rogers et al., 1979) to the continental slope (Hart, 1973). Around the Kodiak archipelago it is usually taken in waters less than 100 m deep, but in NEGOA it is found somewhat deeper (Ronholt et al., 1978). During the NMFS 1975-76 survey, in NEGOA the estimated biomass of Pacific cod was 26,100 mt or about 16 percent of the roundfish biomass for this region. During May-October 1961, an estimated 121,100 mt of cod inhabited the region, 77 percent of which inhabited the Kenai/outer continental shelf zone (Ronholt et al., 1978).

Little information on the life history and seasonal movements of Pacific cod in NEGOA waters is available. They are believed to migrate to deeper waters in autumn, spawn in winter, and return to shallower areas in spring (Hart, 1973). Along the British Columbia coast, cod move to offshore banks (90-145 m) in winter and return to 30-75 m water depths in spring and summer (Ketchen, 1961) but remain within the 6-9°C isotherms. (Ketchen also provides growth and mortality data for Pacific cod in Canadian waters.)

Sablefish (blackcod) (Anoplopoma fimbria) is another commercially important roundfish. It is common along the continental slope from the Queen Charlotte Islands to the Shumagin Islands, where about 67 percent of the North Pacific stocks occur (Low et al., 1976). Its distribution in the Gulf of Alaska is shown in Fig. 8.20. The species was caught only occasionally by NMFS crews in 1973-76 (Ronholt et al., 1978), but they were sampling in areas shallower than the preferred habitat of the species. Sablefish constituted 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 among demersal fishes (Low et al., 1976).

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).

Sablefish mature at five to seven years of age. They spawn 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). The 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).

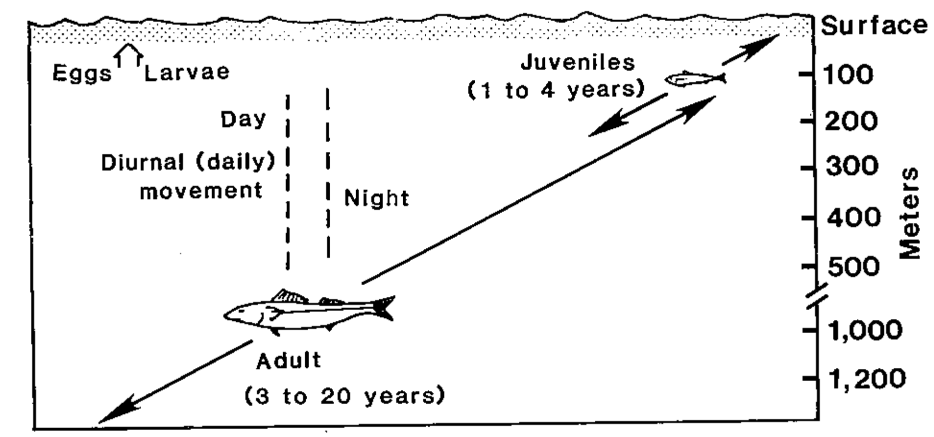
Pacific ocean perch (Sebastes alutus) is the primary rockfish commercially sought in the Gulf of Alaska. Its range extends northward from southern California into the Gulf of Alaska and westward along the Aleutian chain. Populations also occur in the Bering Sea along the shelf break and as far west as 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).

Pacific ocean perch migrate seasonally. Major concentrations of perch forage south of Unimak Pass from May through September in 100-150 m of water. The Portlock and Kodiak Banks and Shumagin grounds are of secondary importance to feeding rockfish. Dense schools composed of both sexes consume vast quantities of pelagic euphausiids and calanoid copepods. In September they stop feeding and probably mate on the feeding grounds (Lyubimova, 1963). After mating, females migrate into NEGOA and are widely dispersed from October through April. Males remain in their primary foraging grounds; small schools are sharply localized at 250- to 450-m depths from November through March (Lyubimova, 1963). The species is viviparous; the times of fry emergence at different latitudes are given by Major and Shippen (1970). Around Kodiak, fry begin to emerge 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 reported by Lisovenko (1964). However, as taxonomic identification of scorpaenid larvae is difficult, Lisovenko assumed that 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. Young juvenile Pacific ocean perch inhabit surface waters during daylight hours; they probably are demersal at night (Alverson and Westrheim, 1961). 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, 68,500 mt were estimated to be present in NEGOA. By 1975-76, however, the estimate was only 4,149 mt (Ronholt et al., 1978). This sharp decline probably resulted, at least in part, from heavy fishing pressure by Soviet and Japanese fleets in the intervening years (Major and Shippen, 1970).

Except for Pacific halibut and small numbers of pollock and cod, domestic fishermen are not fishing for demersal fishes in NEGOA. This is not true of foreign fishing fleets.



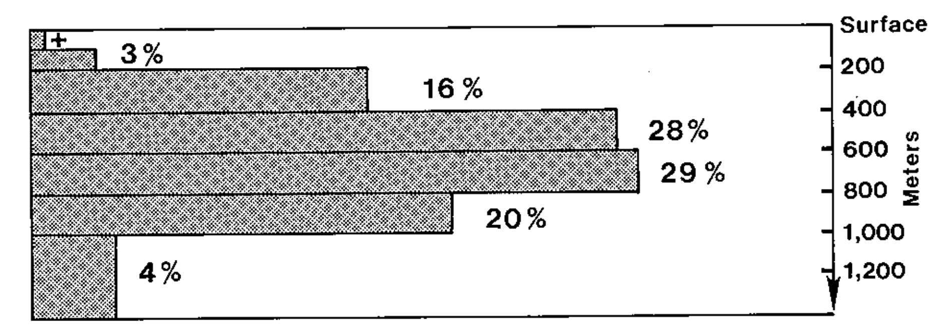


Figure 8.20 Distribution of sablefish (adults) in the Gulf of Alaska (Low et al., 1976; Ronholt et al., 1978).

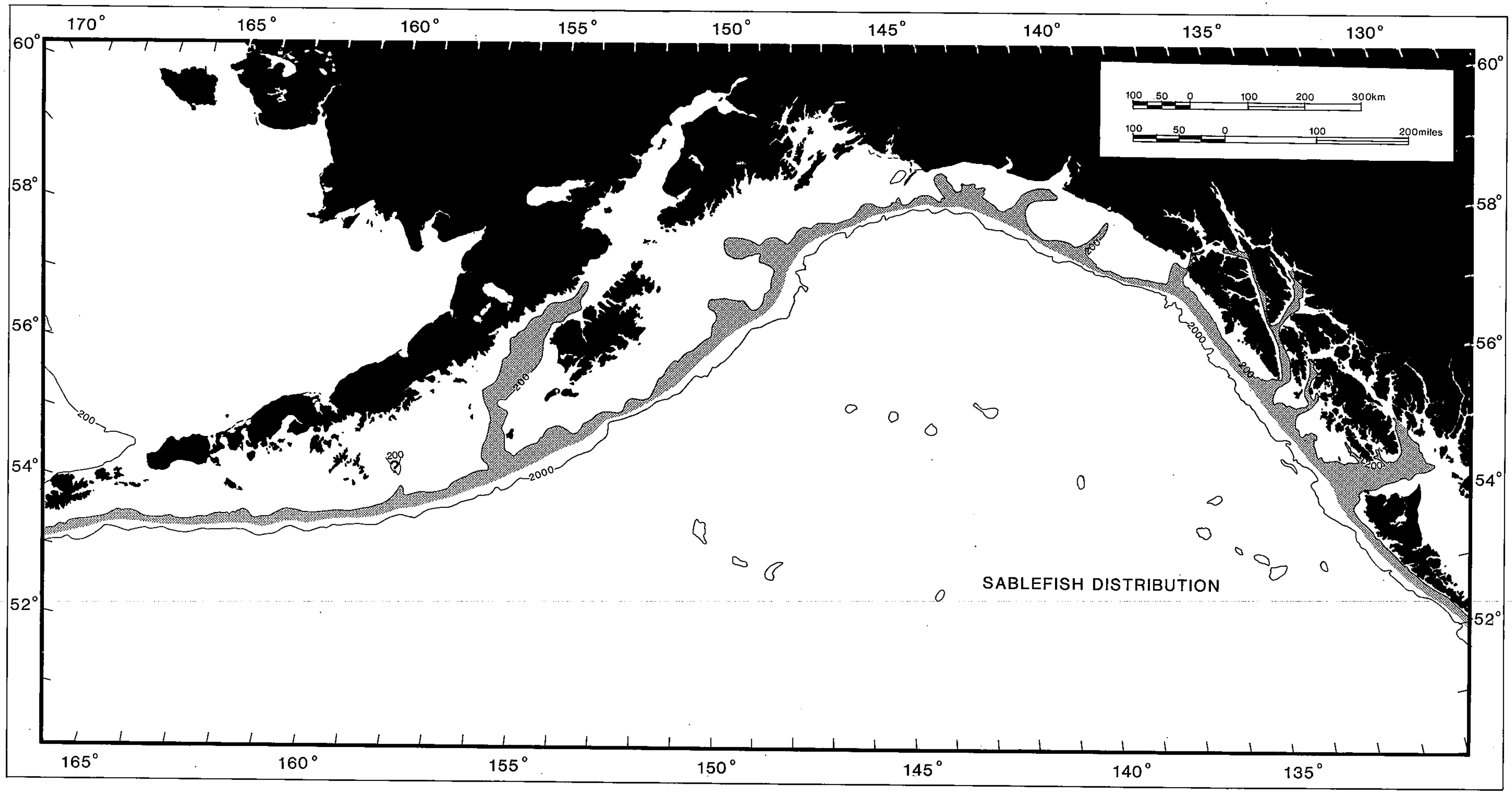


Figure 8.20 continued.

Japanese and Soviet fleets catch most of the fish taken by foreign nationals; Poland, the Republic of Korea, and Taiwan also fish in NEGOA (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 mainly by trawling; sablefish are harvested by longlining (Ronholt et al., 1978). The total Japanese fisheries catch for 1969-1974, reported by species and regions is presented in Table 8.9. Japanese fishing productivity for 1964-1974 is illustrated geographically in Fig. 8.21.

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 caught. 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. 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 NEGOA within the last decade, but catch and effort have not been well documented (Ronholt et al., 1978). Some information is available for fishing farther to the west. The overall foreign groundfish catch in the Kodiak region was 100,305 mt in 1978 (Table 8.10), 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 damaging their reproductive potential (M. Alton, NMFS, Seattle, pers. comm.). The conclusion that perch are underutilized (Table 8.10) differs from the earlier findings of Ronholt et al. (1978). Optimum yield values are based on factors in 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 program to regulate all fisheries in the Conservation Zone. Domestic and

Table 8.9 Total Japanese trawl and longline catch of fishes harvested in NEGOA, 1969-74. Data are reported in metric tons (Ronholt, et al., 1978).

Species	Statistical areas: Kenai	Prince William	Yakutat	Fairweather	Total	Percent Gulf of Alaska (each species)
Pacific ocean perch	33,800	14,200	51,200	31,600	130,800	69
Sablefish	17,100	10,200	20,200	31,200	78,700	70
Walleye pollock	10,000	2,600	4,600	1,600	18,800	30
Arrowtooth flounder	3,200	1,000	2,900	1,400	8,500	60
Miscellaneous fishes[a]	6,100	3,600	10,100	8,300	28,100	68
Total	70,200	31,600	89,000	74,100	264,900	
Percent Gulf of Alaska[b] (all species)	17	7	21	18		

[a] Miscellaneous fishes are mainly Pacific cod, flatfishes, rockfishes, and elasmobranchs.
[b] The reported Japanese catch for the entire Gulf of Alaska was 419,000 metric tons.

Table 8.10 Total foreign and domestic groundfish catch in the "Chirikof-Kodiak" INPFC areas in 1978 by species and groups related to optimum yield (OY) (M. Alton, NMFS, Seattle, unpubl. data).

Species or group	Foreign catch	Domestic catch*	Total foreign & domestic	Optimum yield	Percent 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	81
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).

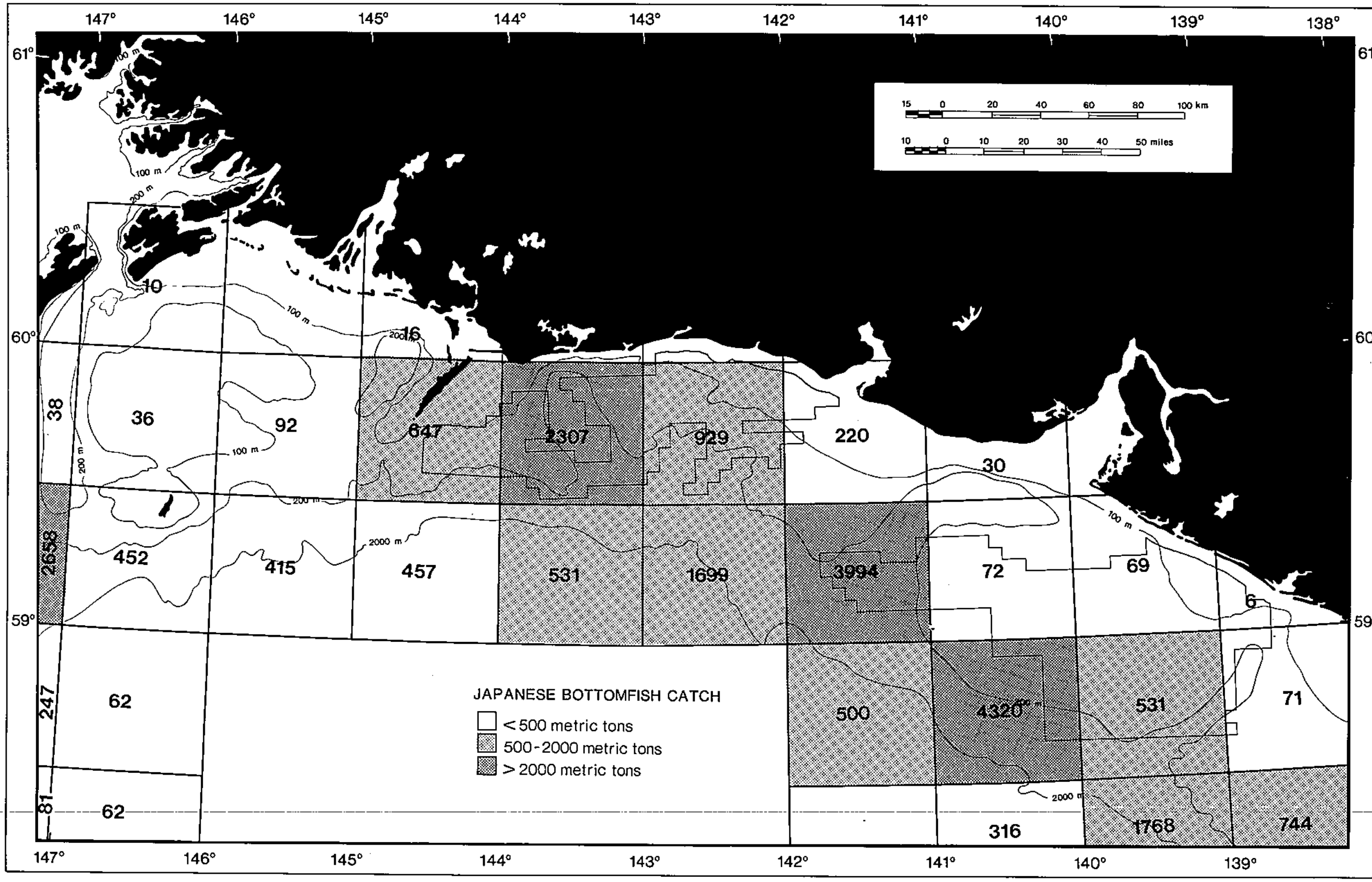


Figure 8.21 Distribution of mean annual demersal fish catch, in metric tons, by Japanese trawl and longline fisheries, 1964-74 (Ronholt et al., 1978).

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, NPFMC, pers. comm.). The implications of this change in fisheries resource utilization are still unclear, but domestic fisheries and foreign policy may be appreciably altered.

8.3 TROPHIC RELATIONSHIPS

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.

Fishes of NEGOA thrive on a rich assortment of zooplankton, larger benthic and pelagic organisms, and other fishes. The trophic relationships are complex and vary with life stage, season, habitat, prey availability, 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. Nonetheless, some typical feeding relationships and common energy pathways may be mentioned.

In coastal waters of NEGOA the production and release of larvae of many fishes tend to coincide with local zooplankton blooms (LeBrasseur et al., 1969; Carlson, 1980). Spring runoff from coastal rivers transports detritus and nutrients into nearshore waters. At this time day length and water temperatures are increasing rapidly, and primary production may also be increasing as it does in more temperate waters (e.g., Pratt, 1965). Zooplankton populations, in turn, increase as they graze on the abundant phytoplankton (Martin, 1965). Microzooplankton such as protozoans and nauplian stages of copepods are the prey of larval fishes (Parsons and LeBrasseur, 1970), while the larger plankters like calanoid and harpacticoid copepods, chaetognaths, hyperid and gammarid amphipods, and euphausiids are the principal prey of numerous juvenile fishes (Gosho, 1977; Sibert et al., 1977; Simenstad et al., 1977; Rogers and Rogers, 1978; Smith et al., 1978; Rogers et al., 1979; Healey, 1980). Abundant food of the appropriate size at the right time promotes rapid growth and enhances survivorship of young fish (LeBrasseur, 1969).

Juvenile fish change their diet as they grow. The variety of prey taken increases with age, which probably is related to their larger mouth and more developed dentition and digestive tract as well as to increased swimming prowess. Table 8.11 shows the changing diet of fingerling pink salmon during their first summer in the marine environment. Most of the prey of young walleye pollock are benthic: polychaetes, majid crabs, and amphipods in NEGOA. As walleye pollock grow, they take increasing amounts of pelagic prey (Fig. 8.22), especially euphausiids (Euphausia spp., Thysanoessa spp.) conspecifics (Smith, in press) Pacific sand lance (Smith et 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); adult pollock are cannabalistic farther north in the Bering Sea (Takahashi and Yamaguchi, in Smith, in press). Changes in diet with increasing age of some common fishes in Kodiak waters are shown in Figs. 8.23 and 8.24.

Table 8.11 Major prey of age 0.1 pink salmon in nearshore waters of the Kodiak archipelago. Number of stomachs examined in parentheses. Size of prey spectra reported as number of taxa (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	0	0	14	1
Cumacea	0	4	4	17
No. of taxa	3	12	21	26
Mean fish length (mm)	?	?	49	68

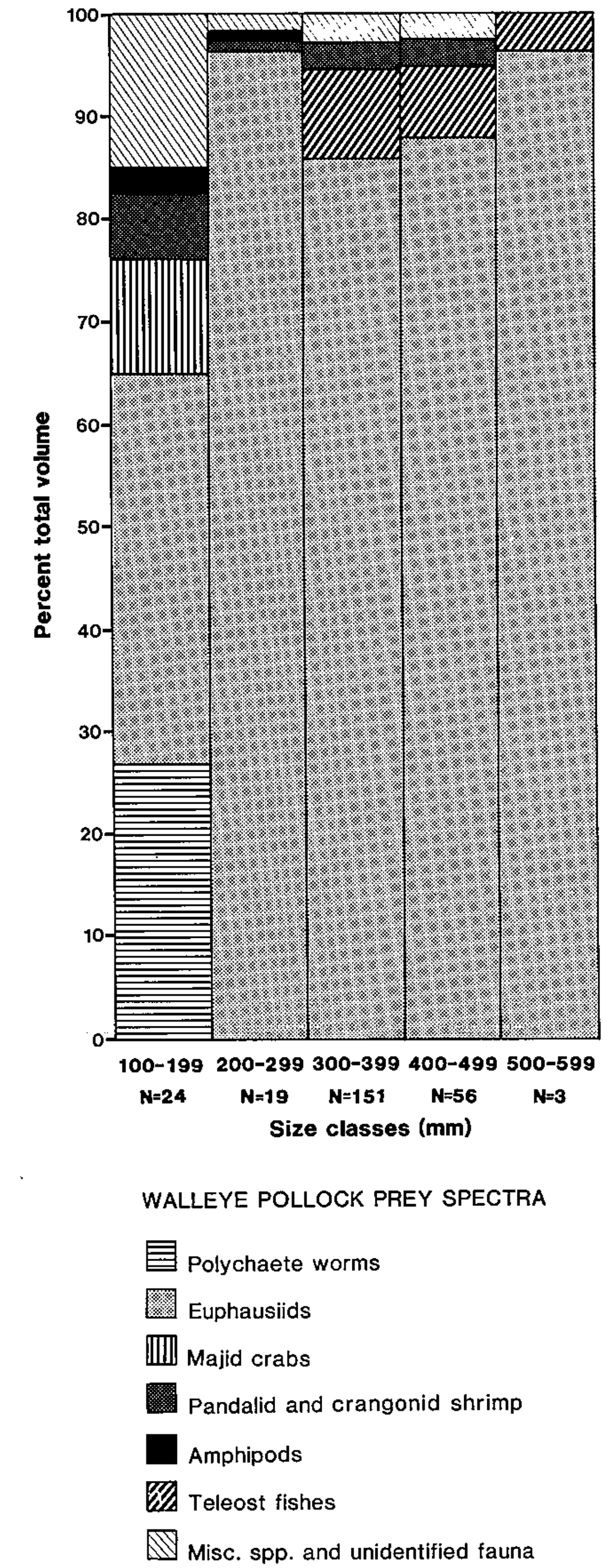


Figure 8.22 Diet of walleye pollock taken in NEGOA by fish size class. Number of stomachs analyzed is given (Smith et al., 1978).

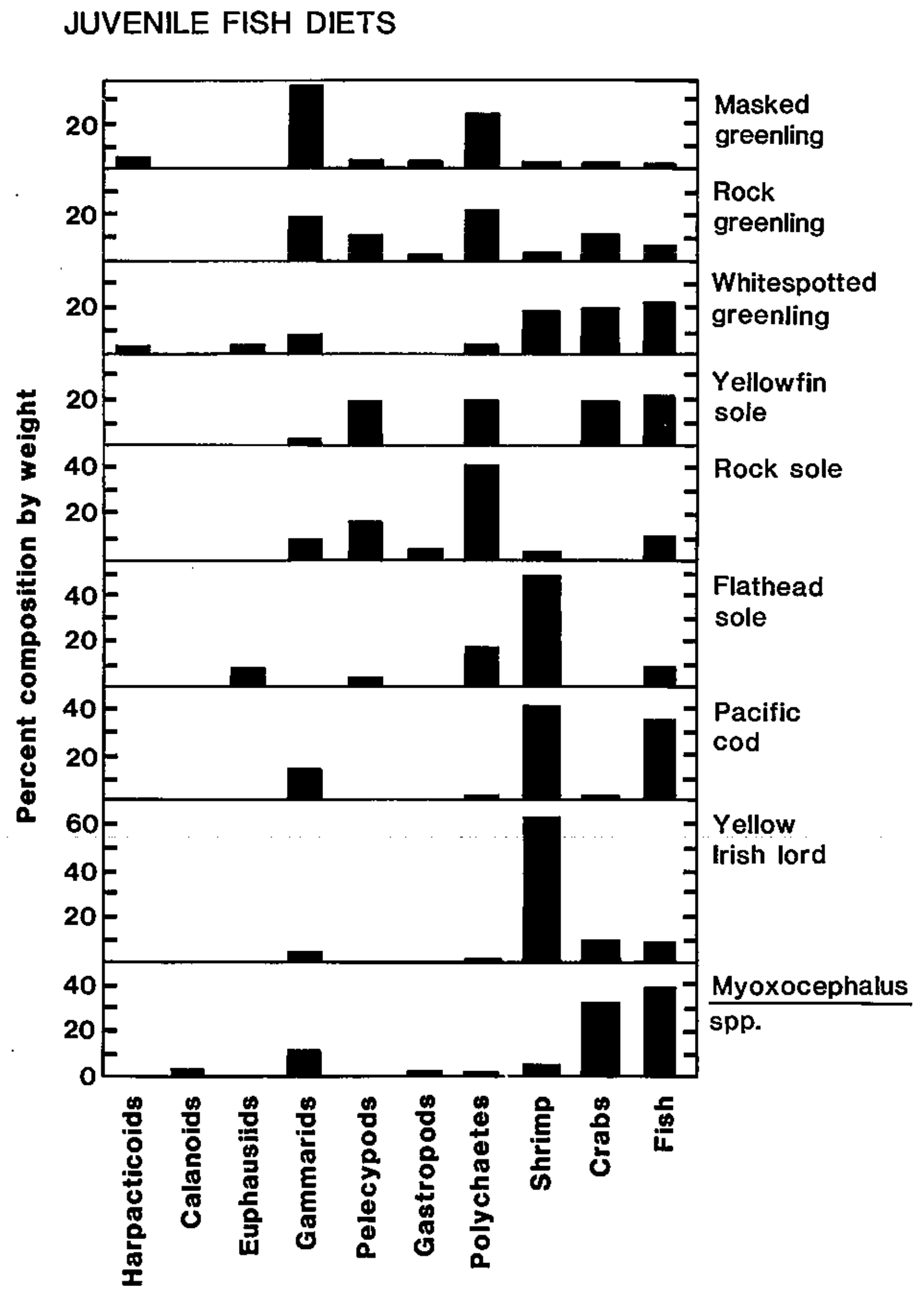


Figure 8.23 Percent composition by weight of major food items in the stomach of juvenile fishes, taken from Kodiak nearshore waters (Rogers et al., 1979).

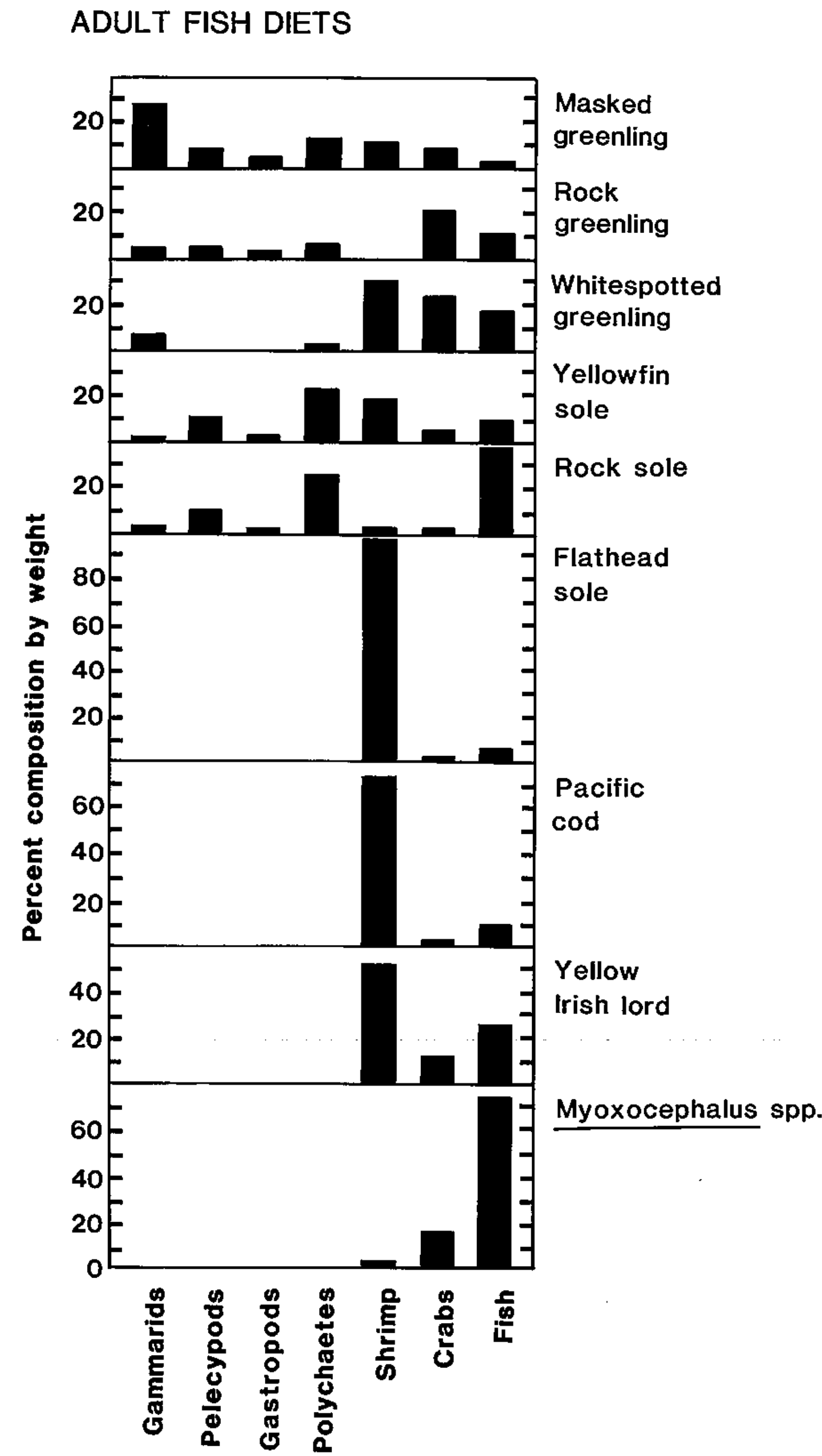


Figure 8.24 Percent composition by weight of major food items in the stomach of adult fishes, taken from Kodiak nearshore waters (Rogers et al., 1979).

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 2), which, in turn, affects the distribution of benthic fauna (Thorson, 1957; Rhoades, 1974; see Chapter 7 for further discussion). Dover sole fed on crustaceans and molluscs in water depths of about 100 m off the coast of Oregon, but ate polychaetes at greater (100-150 m) depths (Pearcy and Hancock, 1978). This modification in diet corresponds to substrate type (Pearcy, 1978) and changes in prey availability (Bertrand, 1971). In NEGOA, 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 by Smith et al.; thus prey availability was not determined. Bottom sediments in NEGOA have been mapped, however (Carlson et al., 1977). They change markedly with depth, suggesting probable changes in the distribution of benthic fauna. Pacific cod are also opportunistic predators. Populations of cod inhabiting different areas feed on different prey, probably those that are most readily available. Cod preyed mostly on juvenile Tanner crab, Chionoecetes bairdi, on the Kodiak shelf (Jewett, 1978). In the bays of the Kodiak archipelago, cod fed mainly on pink shrimp, Pandalus borealis (Feder et al., 1979).

Though some fishes alter their diet considerably with life stage, season, geography, depth, and prey availability, most species tend to feed on specific sizes or classes of prey. For instance, DeGroot (1971) groups pleuronectids (flatfishes) according to three main feeding strategies: those that specialize in feeding on either fish, crustaceans, or a combination of polychaetes and molluscs. In addition, all flounders are known to take a variety of incidental prey. Pacific halibut and arrowtooth flounder have large symmetrical jaws and sharp teeth suited for grasping mobile organisms like fish and pelagic macroinvertebrates. Rex and rock sole have asymmetrical, small mouths and an alimentary tract adapted to digesting benthic organisms; they feed on polychaetes, molluscs, and amphipods. 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 NEGOA (Smith et al., 1978). Rex sole preyed on onuphid polychaetes in NEGOA (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), whereas euphausiids are their principal prey in the Gulf of Alaska (Smith et al. 1978). That arrowtooth flounder and walleye pollock populations are increasing in the Gulf of Alaska (Ronholt et al., 1978) may be related to their ability to take a wide variety of prey.

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 found together in the Kodiak region (Harris and Hartt, 1977; Hunter, 1979). Their diets are quite different. The proportion of each prey type found in the stomachs of these four flatfish is displayed in Fig. 8.25. Sand sole and starry flounder appear to be feeding specialists, taking mysids and gammarid amphipods, respectively. Some caution is necessary in drawing inferences from these data, however, because of the limited number of stomachs examined. Jewett and Feder (1980) have shown that starry flounder in the Northern Bering Sea have a rather varied diet. In Kodiak waters yellowfin and rock sole fed on an assortment of prey, suggesting that they are opportunists in feeding here (Harris and Hartt, 1977). However, both yellowfin and rock sole fed heavily on sand lance during the study period. A detailed analysis of food resource partitioning of other pleuronectids from the Kodiak shelf is presented by Hunter (1979). Partitioning of food resources by hexagrammids (greenlings) in nearshore waters of Kodiak has also been reported (Rogers et al., 1979). An overview of prey consumed by fishes common to NEGOA is shown in Table 8.12.

Pacific halibut, although not studied in detail in the aforementioned fish food surveys, is of major commercial importance to the Gulf of Alaska groundfish fishery. Adult Pacific halibut consume mostly fishes (other flatfishes, walleye pollock, Pacific cod, rockfishes, and Pacific sand lance), squid, octopi, and king and Tanner crabs (Simenstad et al., 1977; Smith et al., 1978; IPHC, 1978). Juvenile halibut are also piscivorous but take a greater proportion of crustaceans. Cook Inlet populations fed mainly on shrimp (IPHC data in Smith et al., 1978).

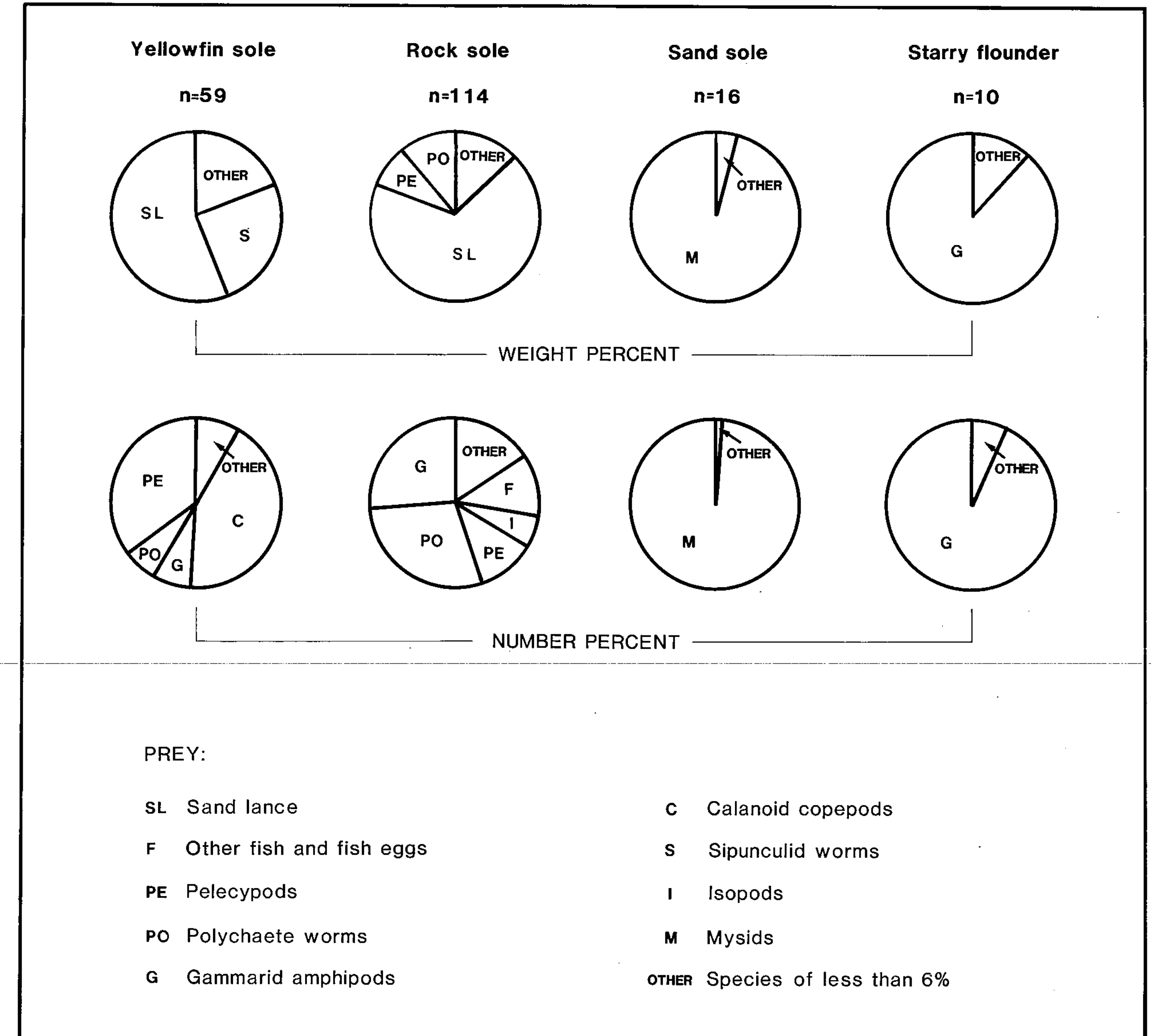


Figure 8.25 Dominant prey of four species of flatfishes in the Gulf of Alaska (Harris and Hartt, 1977).

Table 8.12 Principal prey of common fishes in NEGOA.

PREDATOR		Phytoplankton, Algae	PORIFERA: Sponges	CNIDARIA: Corals, hydroids	ANNELIDS: Polychaetes	MOLLUSCS: Chitons	MOLLUSCS: Gastropods	MOLLUSCS: Pelecypods	MOLLUSCS: Cephalopods	ARTHROPODS: Ostracods	ARTHROPODS: Copepods: Calanoids	ARTHROPODS: Copepods: Harpacticoids	ARTHROPODS: Barnacle larvae	ARTHROPODS: Mysids	ARTHROPODS: Cumaceans	ARTHROPODS: Isopods	ARTHROPODS: Amphipods	ARTHROPODS: Euphausiids	ARTHROPODS: Shrimp: Pandalids	ARTHROPODS: Shrimp: Crangonids	ARTHROPODS: Shrimp: Larvae	ARTHROPODS: Crabs: King & hermit	ARTHROPODS: Crabs: Tanner	ARTHROPODS: Crabs: Larvae	ARTHROPODS: Insects	ECHINODERMS: Ophiuroids	ECHINODERMS: Echinoids	VERTEBRATES: Eggs	VERTEBRATES: Larvae	VERTEBRATES: Fish: Clupeidae	VERTEBRATES: Fish: Salmonidae	VERTEBRATES: Fish: Osmeridae	VERTEBRATES: Fish: Gadidae	VERTEBRATES: Fish: Zoarcidae	VERTEBRATES: Fish: Trichodontidae	VERTEBRATES: Fish: Bathymasteridae	VERTEBRATES: Fish: Stichaeidae	VERTEBRATES: Fish: Pholidae	VERTEBRATES: Fish: Ammodytidae	VERTEBRATES: Fish: Scorpaenidae	VERTEBRATES: Fish: Anoplopomatidae	VERTEBRATES: Fish: Hexagrammidae	VERTEBRATES: Fish: Cottidae	VERTEBRATES: Fish: Agonidae	VERTEBRATES: Fish: Pleuronectidae	VERTEBRATES: Miscellaneous
Clupeidae	Pacific herring	E	.	.	.	.	.	.	.	.	AE	AE	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	AB	.	.	AB	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	.	AB	.	.	.	.	B	.	AB	AB	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	AB
	Chinook salmon	.	.	.	.	.	.	.	.	I	H	H	H	.	.	.	H	HI	I	.	.	.	.	HI	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	H
	Dolly Varden	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	AB	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	.	BC	.	.	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	AB	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Trichodontidae	Pacific sandfish (juvenile)	.	.	.	.	.	.	.	.	.	.	.	.	A	.	.	AB	B	AB	.	A	B	A	B	.	.	.	.	A	B	.	.	.	.	.	.	.	.	B	.	.	.	.	.	.	B
Ammodytidae	Pacific sand lance	.	.	A	.	.	AB	AB	.	B	AB	AB	AB	AB	B	.	AB	B	.	.	B	A	.	B	A	.	.	.	AB	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Scorpaenidae	Pacific ocean perch	.	.	.	.	.	.	.	.	.	FG	.	.	F	.	.	F	FG	G	.	G	.	.	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Anoplopomatidae	Sablefish	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	BK	B	.	.	.	.	B	.	.	.	.	.	B	.	B	.	.	.	.	.	.	K	.	.	.	.	.	.	B
Hexagrammidae	Kelp greenling	B	.	.	B	.	B	B	.	.	.	.	.	.	B	B	.	B	.	.	.	B	B	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	B
	*Rock greenling	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	AB	B	B	AB	AB	AB	AB	B	B	AB	B	B	AB	AB	B	B	AB	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	.	BK	.	BK	BK	BK	.	B	B	B	B	.	B	BK	BK	BK	BK	.	BK	BK	B	.	BK	.	.	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	ABK	.	B	ABK	B	B	ABK	B	B	B	B	BK	AB	AB	B	AB	BK	K	B	BK	B	B	B	B	BK	BK	AB	B	B	.	B	.	.	.	.	BK	B	ABK	.	.	B	B	B	B	AK
	*Yellowfin sole	AB	.	B	AB	.	B	AB	.	.	AB	AB	B	B	AB	B	AB	B	B	B	.	B	B	.	B	B	AB	B	B	.	.	B	.	.	.	.	B	.	AB	.	.	.	B	.	B	.
	Dover sole	.	.	.	C	.	C	C	C	.	.	.	.	.	C	.	C	C	C	.	.	.	C	.	.	C	C	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	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, 1963
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. 8.22 thru 8.25 and Table 8.11

8.4 EFFECTS OF OCS DEVELOPMENT ON FISH POPULATIONS

Knowledge of marine communities can be used to predict which species are most likely to be harmed by OCS development in NEGOA. By knowing the source, composition, and amount of contaminants together with the physical oceanography of the area, trajectory models can be constructed (see Chapter 3) 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 (see Chapter 3). Epipelagic fishes, many of which swim in dense schools (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 8.12). Pollutants ingested or adhering to herring could 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.

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; G. 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). Since 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.

CHAPTER 9 BIRDS

J. G. Strauch, Jr., SAI

9.1 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 below it. 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 NEGOA waters, but frequent mixing in the water column over the banks brings nutrients to the surface. Seasonal changes in plankton growth have not yet been 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 in 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 populations. Superimposed on this geographic trend are local year-to-year fluctuations in weather and in food supply. An unseasonably 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. Natural 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.

Although birds are believed to be important members of marine ecosystems, 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). Accordingly, the 260,000 breeding birds in NEGOA must consume about 8,000 metric tons of food during the breeding season.

Two to three thousand kcal/km^2/day flow through pelagic bird populations in NEGOA during April and May (Fig. 9.1; Wiens et al., 1978a). Shearwaters accounted for 62 to 89 percent of the total energy demand of the pelagic bird community in April and May.

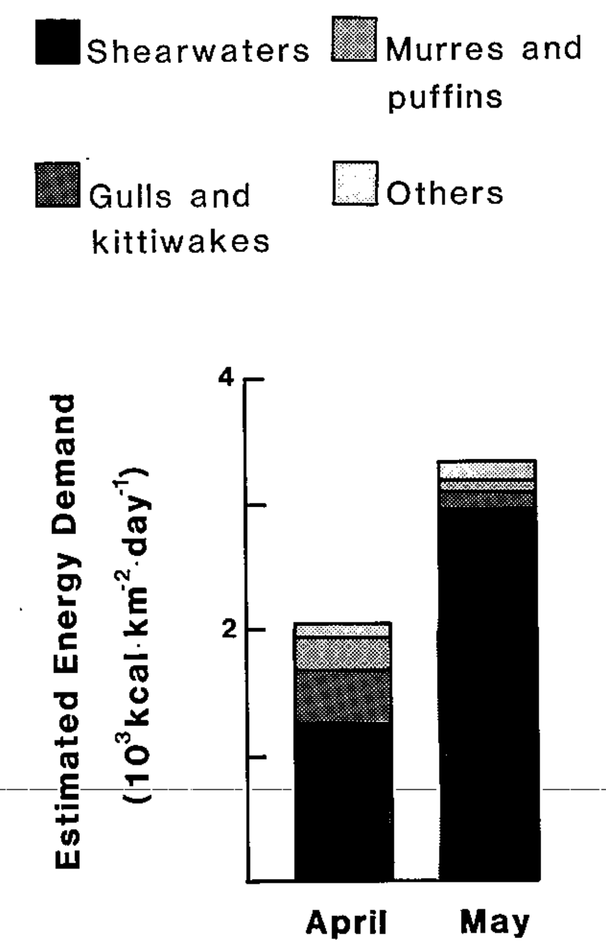


Figure 9.1 Temporal apportionment of total energy demand among the species groups recorded during transect censuses in NEGOA (Wiens et al., 1978a).

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. The murky, excrement-laden water flows continuously from murre colonies and 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).

9.2 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 waters (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, 1971), feeding by what Ashmole (1971) calls pursuit plunging (Fig. 9.2). 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. 9.2). They eat a variety of prey and are the smallest members of the generalist groups of tubenoses (Ainley and Sanger, 1979).

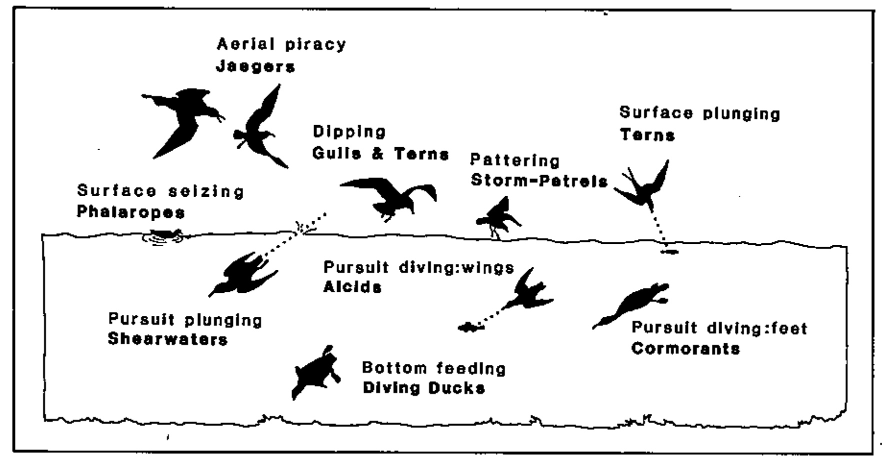


Figure 9.2 Seabird feeding methods (modified from Ashmole, 1971).

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, 1964). Although the young have functional nostrils, those of adults are almost completely closed, and the birds must breathe through their mouth. 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. 9.2), 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, can be placed in the second category 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 a 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. 9.2). Off the breeding grounds and at sea they are opportunistic, taking a variety of prey (Maher, 1974; Ainley and Sanger, 1979). They are common spring and fall migrants 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-legged 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 NEGOA. 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. 9.2) 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. 9.2). They do not pursue prey underwater, but 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. 9.2); they dive from the surface and actively pursue prey under water. 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 (Uria 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 trees or on the bare ground above timberline. 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, planktivorous 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 in NEGOA 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 winter in ice-free regions, mainly 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).

Three species of diving ducks, and four species of sea ducks are common or abundant wintering species on NEGOA waters. 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. 9.2), where they eat a variety of invertebrates. They 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 NEGOA ducks are discussed later.

Large numbers of breeding or staging shorebirds are found in NEGOA, which lies in a major shorebird migratory pathway (see Gill et al., 1979). The most important species are the Western Sandpiper (Calidris mauri) and the Dunlin (C. alpina), millions of which use mud flats in the area during migration. They probe in soft substrates for invertebrates. The importance of the Copper River Delta to migrant shorebirds is discussed in detail later. Other 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 NEGOA's rocky shores, and the Northern (Phalaropus lobatus) and Red (P. fulicarius) Phalaropes, which are found during migration in large flocks in NEGOA waters. Oystercatchers feed in rocky habitats on molluscs, primarily 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. 9.2) 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 NEGOA 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. Water Pipits (Anthus spinoletta) and Song Sparrows (Melospiza melodia) also forage frequently in intertidal areas.

9.3 DISTRIBUTION AND HABITAT USAGE BY NEGOA BIRDS

9.3.1 Pelagic distribution

Information on the distribution of marine birds on the waters in NEGOA is available from only a few aerial and shipboard transects for the Gulf of Alaska (Lensink and Bartonek, 1976; Guzman, 1976; Gould, 1977; Harrison, 1977; Myres and Guzman, 1977; Wiens et al., 1978b).

The results of the general Gulf of Alaska surveys are shown according to season for all birds in Figs. 9.3-9.6 and by month for several bird groups in Table 9.1. 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 NEGOA throughout the year. In winter (Feb-Mar) tubenoses, gulls, and alcids were the most common species recorded. Average densities per transect were between 5 and 57 birds/km^2. Highest densities were recorded along or near the shelf break, near Middleton Island, in Controller Bay, and in the eastern half of Prince William Sound. In spring (Apr-Jun) shearwaters were found in much higher numbers than any other species. Large numbers of terns were found in April in some areas, and northern phalaropes (Phalaropus lobatus) were abundant in May. High densities of gulls were reported from some stationary platforms but not from moving platforms. Average

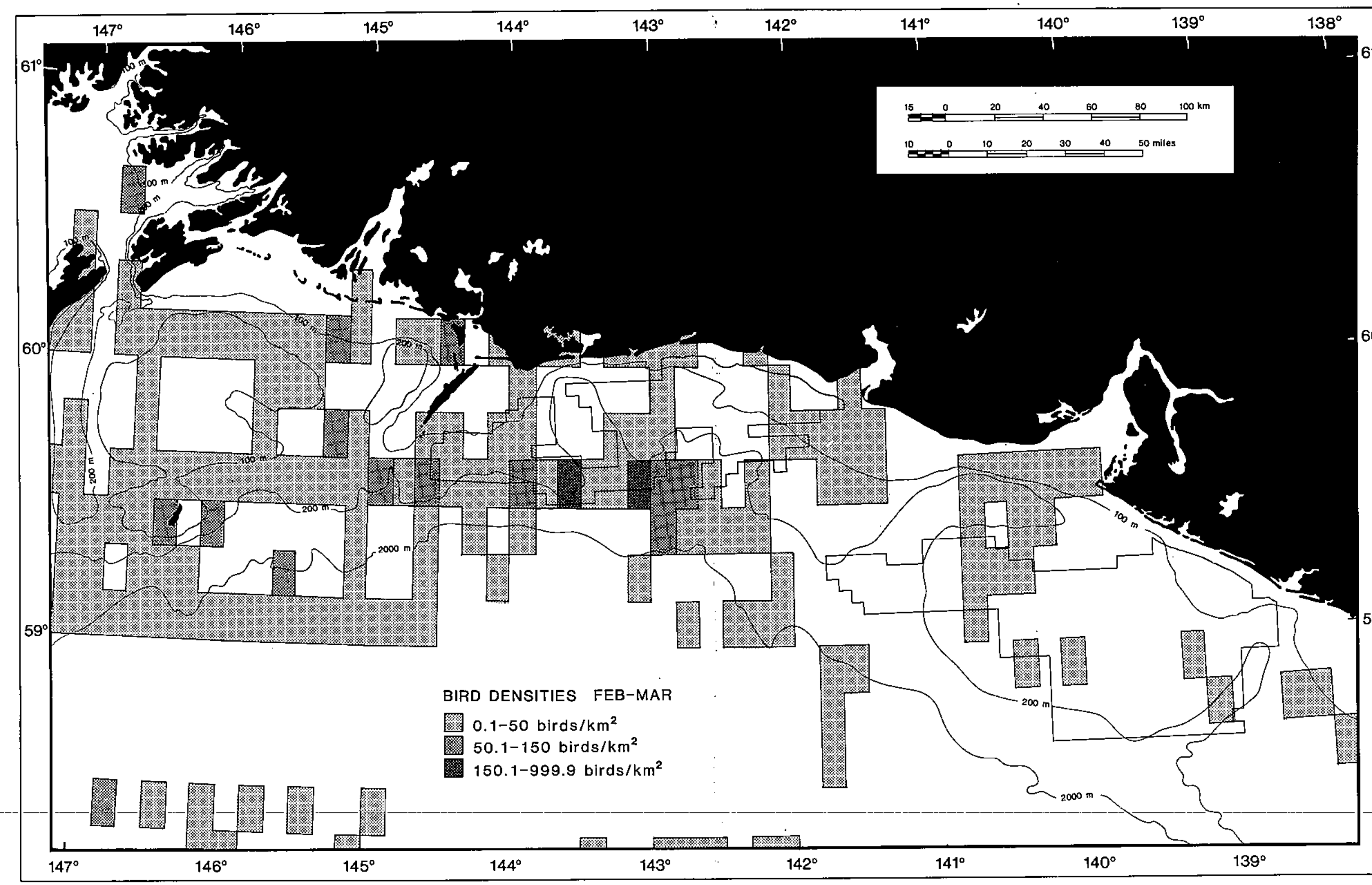


Figure 9.3 Winter pelagic distribution of birds (see text for data sources).

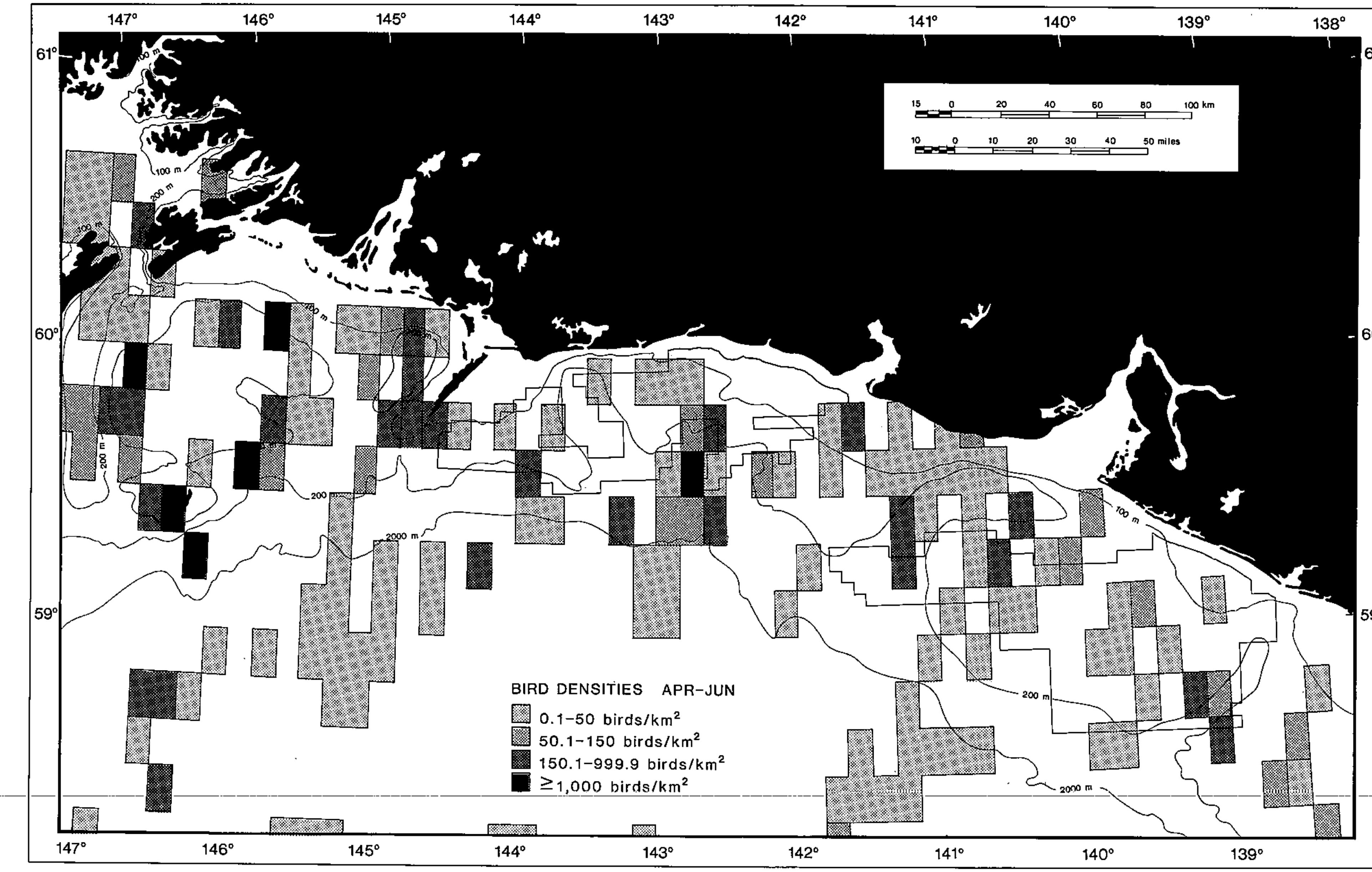


Figure 9.4 Spring pelagic distribution of birds (see text for data sources).

densities per transect were between 16 and 355 birds/km^2. Highest densities were reported along or near the shelf break, in the area west and southwest of Kayak Island, and in the area from Hinchinbrook Entrance south to the region southwest of Middleton Island. From July through September tubenoses, gulls, and alcids were the most common species. From October through December the average densities per transect were between 8 and 32 birds/km^2. Highest densities were recorded along or near the shelf break.

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.

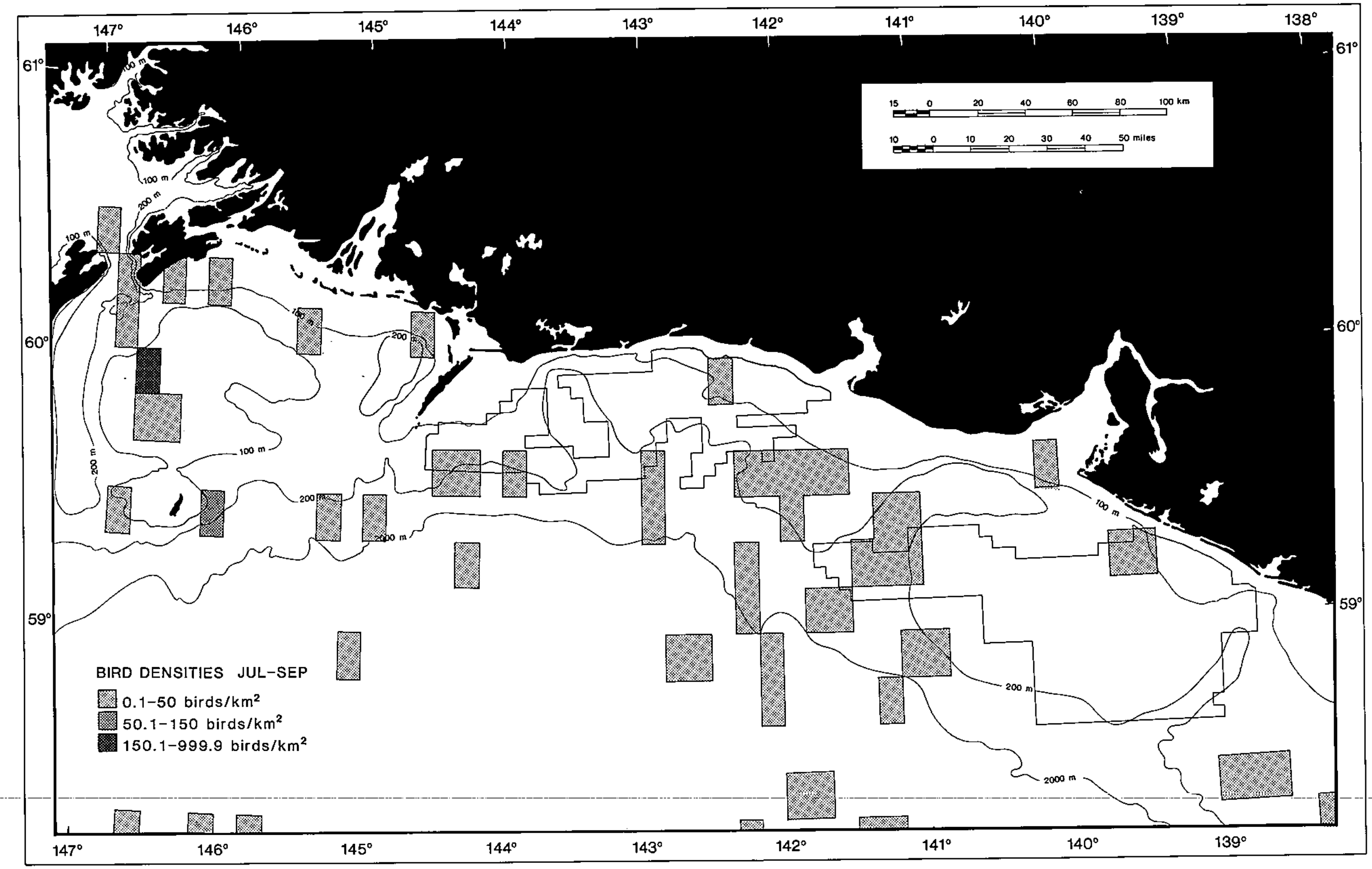


Figure 9.5 Summer pelagic distribution of birds (see text for data sources).

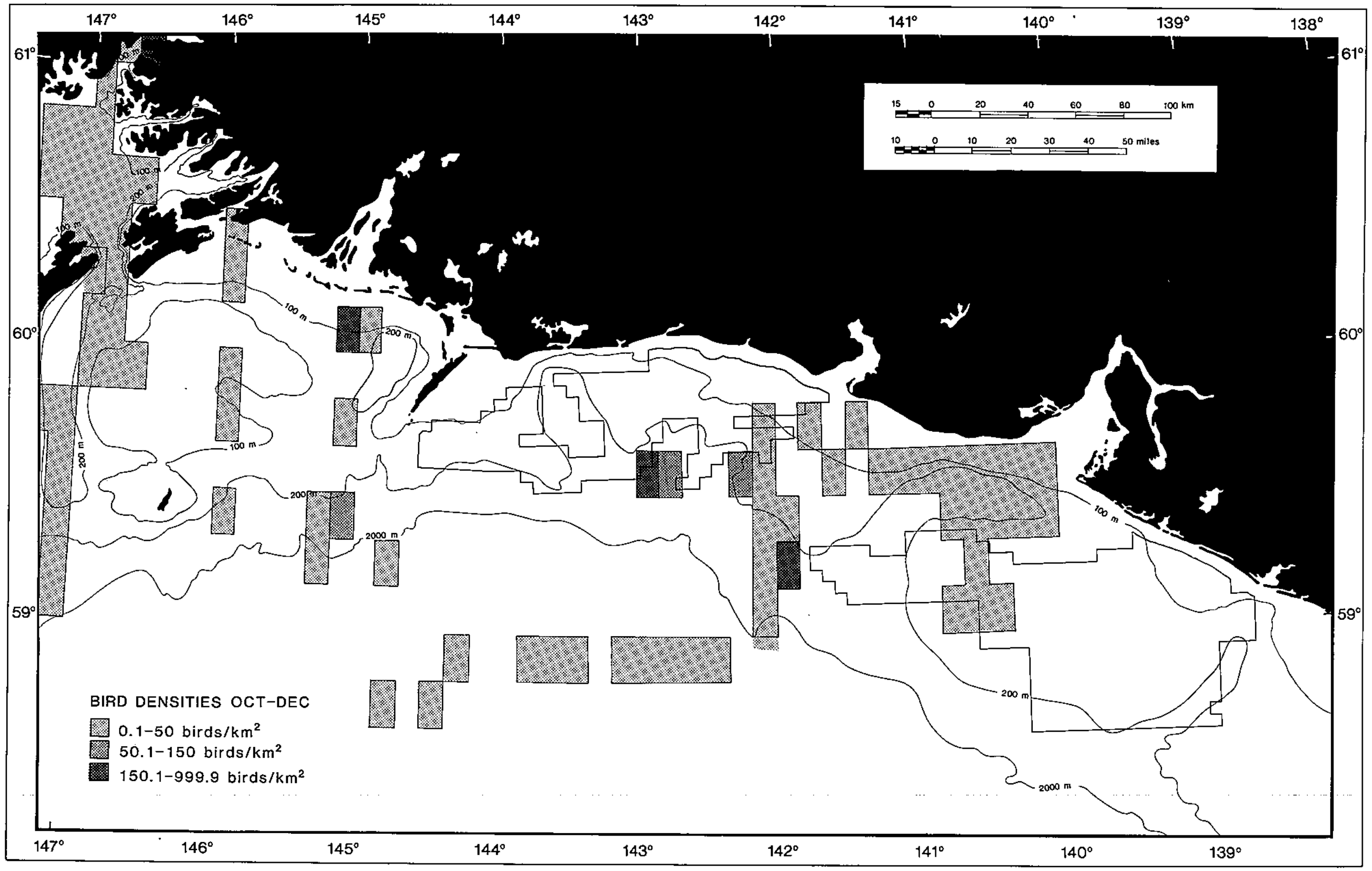


Figure 9.6 Fall pelagic distribution of birds (see text for data sources).

Table 9.1 Relative density of marine birds in NEGOA from shipboard and aerial transects in 1975-77 (Lensink and Bartonek, 1976, Gould, 1977; Wiens et al., 1978b).

Species	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Arctic Loon	o*	o	o	+	o	o	o	o	o	o
Common Loon	o	t	o	+	o	o	o	o	o	o
Yellow-billed Loon	o	o	o	t	o	o	o	o	o	o
Unidentified loon	+	o	+	+	t	o	o	t	t	t
Black-footed Albatross	o	o	+	+	+	+	t	t	t	t
Laysan Albatross	o	o	o	o	+	o	o	t	t	o
Northern Fulmar	+	+	+	+	+	+	+	+	+	+
Sooty Shearwater	o	o	++++	++++	++	+	o	+	+	t
Short-tailed Shearwater	+	o	+	+++	+	o	o	t	t	t
Unidentified shearwater	o	+	+	+++	+++	+	o	t	t	t
Scaled Petrel	o	o	o	+	o	+	o	o	o	o
Fork-tailed Storm-Petrel	+	+	+	+	+	+	+	t	+	+
Leach's Storm-Petrel	o	o	o	o	t	+	o	o	o	o
Unidentified storm-petrel	o	+	+	o	t	o	o	t	o	o
Double-crested Cormorant	o	o	o	t	t	o	o	o	t	o
Pelagic Cormorant	o	o	+	t	t	o	o	o	t	o
Red-faced Cormorant	o	o	o	o	o	o	o	o	o	t
Unidentified cormorant	+	+	+	t	t	o	o	t	t	t
Black Brant	o	o	+	t	o	o	o	o	o	o
Unidentified goose	o	o	o	+	o	o	o	o	o	o
Mallard	o	o	o	+	o	o	o	o	t	o
American Wigeon	o	o	o	t	o	o	o	o	o	o
Pintail	o	o	+	o	o	o	o	t	o	o
Greater Scaup	o	o	o	o	o	o	o	o	t	o
Oldsquaw	o	t	o	+	t	o	o	o	o	t
Black Scoter	o	t	o	o	o	o	o	o	o	o
White-winged Scoter	o	+	o	t	o	+	o	o	o	o
Surf Scoter	o	o	o	t	t	o	o	o	o	o
Red-breasted Merganser	o	t	o	o	o	o	o	o	t	o
Unidentified duck	+	+	+	+	o	o	o	o	t	o
Unidentified shorebird	o	t	o	+	+	+	o	t	o	o
Red Phalarope	o	o	o	+	+	o	o	+	o	o
Northern Phalarope	o	o	o	+	+	o	o	+	o	o
Unidentified phalarope	o	o	o	+	o	o	o	t	o	o
Pomarine Jaeger	o	o	o	+	+	o	o	t	t	o
Parasitic Jaeger	o	o	t	+	t	+	o	t	o	o
Long-tailed Jaeger	o	o	o	+	t	+	o	t	o	o
Skua	o	o	o	o	o	o	o	t	o	o
Unidentifed jaeger	o	o	o	t	t	o	t	t	t	o
Glaucous Gull	t	+	+	+	o	o	o	o	t	o
Glaucous-winged Gull	+	+	+	+	+	+	o	t	+	+
Herring Gull	+	+	+	+	+	+	o	t	t	t
Thayer's Gull	o	o	+	o	o	o	o	o	o	o
Mew Gull	t	+	+	+	o	o	o	o	t	t
Black-legged Kittiwake	+	+	+	+	+	+	o	t	t	+
Sabine's Gull	o	o	o	+	+	o	o	o	t	+
Unidentified gull	+	+	+	+	t	o	+	t	t	+
Arctic Tern	o	o	+	+	+	+	o	t	o	o
Aleutian Tern	o	o	o	+	+	o	o	o	o	o
Unidentified tern	+	o	++	+	o	o	o	o	o	o
Common Murre	+	o	+	+	+	+	o	t	o	o
Unidentified murre	+	+	+	+	+	o	o	o	o	+
Pigeon Guillemot	o	o	o	+	o	o	o	o	o	o
Marbled Murrelet	t	+	+	+	+	o	o	t	o	o
Kittlitz's Murrelet	o	o	+	+	+	o	o	o	o	o
Ancient Murrelet	o	+	+	o	t	+	o	o	t	o
Parakeet Auklet	o	o	o	o	+	+	o	t	o	o
Cassin's Auklet	o	+	+	o	t	+	o	t	o	t
Rhinoceros Auklet	o	t	+	o	t	+	o	t	o	o
Horned Puffin	+	+	o	+	+	o	o	o	o	o
Tufted Puffin	+	+	+	+	+	+	o	t	t	+
Unidentified alcid	+	+	+	+	o	+	o	+	+	+
Unidentified bird	+	t	o	+	+	o	o	o	o	o

* o = no birds; t = < 1 bird/km²; + = 1-9 birds/km²; ++ = 10-29 birds/km²; +++ = 30-99 birds/km²; ++++ = 100+ birds/km²

9.3.2 Coastal distribution

About 100 species of coastal birds are regularly found in NEGOA (Isleib and Kessel, 1973; Arneson, Gould, Hoffman, and Wohl, pers. comm.). Of these, about 43 species are usually found only in the littoral zone, and about 8 species are usually pelagic (Table 9.2). Although not every species fits the pattern, in general, loons, grebes, cormorants, raptors, gulls, some species of alcids, and passerines are residents. Geese and some species of shorebirds, terns, and some species of alcids are mainly summer residents. Diving ducks are chiefly winter residents, but some are non-breeding summer residents.

Table 9.2 Summary of habitat preference and seasonal abundance of common marine and coastal birds (Isleib and Kessel, 1973, Arneson, Gould, Hoffman and Wohl, pers. comm.).

Species	Littoral	Inshore	Shallow (<100 fath.)	Pelagic (100-1,000 fath.)	Epiabyssal
	W S S F	W S S F	W S S F	W S S F	W S S F
Common Loon		M M L M	L	L L	L L
Yellow-Billed Loon		M L V L	L V		
Arctic Loon		L M L M	L L	L L	L L
Red-throated Loon		L M M M	L L	L L	L L
Horned Grebe		M M L M	L L		
Red-necked Grebe		M M L M	L L		
Black-footed Albatross			V V V	L L L	L L L
Laysan Albatross			V V V	V V V	V V V
Northern Fulmar			M M M M	M M M M	M M M M
Sooty Shearwater			V A H H	V A H M	V H M M
Short-tailed Shearwater			V A H H	V A H M	V H M M
Scaled Petrel				V	L L L
Fork-tailed Storm-Petrel		V	L M M M	L M M M	L M M M
Leach's Storm-Petrel				L L L	L L L
Double-crested Cormorant	L M L M	L M L M			
Brandt's Cormorant	V V V V	V V V V			
Pelagic Cormorant	M M M M	M M M M	V V		
Red-faced Cormorant	M M M M	M M M N	V V		
Great Blue Heron	V V V V				
Trumpeter Swan	V H M H				
Whistling Swan	V H V H				
Black Brant	L L V V	L V V			
Canada Goose	V H M H				
Emperor Goose	V V V				
White-fronted Goose	- M V M				
Snow Goose	- H - H				
Mallard	L H M H	L			
Gadwall	V L V L				
Pintail	V A L A				
Teal	V M L M				
American Wigeon	V M L M				
Shoveler	- L V L				
Canvasback	- V V V	V V V			
Greater Scaup	L M L M	L M L M			
Common Goldeneye	L L V L	M L V L			
Barrow's Goldeneye	L L V L	M L V L			
Bufflehead		M M V M			
Oldsquaw		H M L M	L V L		
Harlequin Duck	M M M M	M M M M	L V L		
White-winged Scoter	L L L L	M H M H			
Surf Scoter	L L L L	M H M H			
Black Scoter		L L L L			
Common Merganser		L L V L			
Red-breasted Merganser	- - M -	L M V M	L L L L		
Bald Eagle	L L L L				
Peregrine Falcon	V L V L				
Sandhill Crane	- L V M				
Black Oystercatcher	L L L L				
Semipalmated Plover	- L L L				
Golden Plover	M H				
Black-bellied Plover	V M V M				
Whimbrel	- L V V				
Spotted Sandpiper	- L L L				
Wandering Tattler	- L L L				
Greater Yellowlegs	- M L M				
Lesser Yellowlegs	- L V L				
Black Turnstone	V H V H				
Ruddy Turnstone	H V M				
Surfbird	L M V M				
Knot	- M - V				
Rock Sandpiper	M M L M				
Pectoral Sandpiper	- L - L				
Baird's Sandpiper	- L - L				
Least Sandpiper	- H M H				
Dunlin	L A V A				
Semipalmated Sandpiper	- V V V				
Western Sandpiper	- A L A				
Sanderling	V H V H				
Short-billed Dowitcher	- M L M				
Long-billed Dowitcher	- M N				
Common Snipe	V M L M				
Red Phalarope		- L - L	- M - M	- L - L	- L - L
Northern Phalarope	- V - V	- A L A	- H L H	- H L H	- A L H
Pomarine Jaeger		- L L L	- L L L	- L L L	- L L L
Parasitic Jaeger		- L M L	- L M L	- L L L	- L L L
Long-tailed Jaeger		- V V V	- V V V	- V V V	- V V V
Glaucous Gull	L V V V	L V V V	L V V V	L V V V	L V V V
Glaucous-winged Gull	H H H H	H H H H	H H H H	M M L M	M M L M
Herring Gull	L L L L	L L L L	L L L L	L L L L	L L L L
Thayer's Gull		L L L	- L - L	- L - L	- V - V
Mew Gull	L H M H	L H M H	L L L L	L L L L	V V V V
Bonaparte's Gull	- M - M	- M - M	- V - V	- V - V	- V - V
Black-legged Kittiwake	L M M M	L M H M	L M H M	L M M M	L M M M
Sabine's Gull	L L L	- L L L	- L - L	- L - L	- L - L
Arctic Tern	- A H A	- A H A	- A H A	- A L A	- A L A
Aleutian Tern	- L M L	- L M L	- V - V	- V - V	- V - V
Common Murre		L L M L	M L M L	L L L L	
Pigeon Guillemot		M M M M	L L L L		
Marbled Murrelet		M M ?	M M ?		
Kittlitz's Murrelet		L L ?	L L ?		
Ancient Murrelet		L L L	L L L		
Cassin's Auklet		V V V	V V V	V V V	
Parakeet Auklet		V V V V	V V V V	V V V V	V V V V
Rhinoceros Auklet		L L L L	L L L L	L L L L	L L L L
Horned Puffin		- L L L	- L L L	- L L L	- L L L
Tufted Puffin		V M M M	L M M M	L L L L	L L L L
Black-billed Magpie	M M L M				
Northwestern Crow	M M M M				
Common Raven	M M M M				

V = Very low density
L = Low density
M = Moderate density
H = High density
A = Abundant density

An aerial survey of the NEGOA shoreline was made on 1-9 May 1976, and a partial survey (covering only exposed beaches) on 24 July 1976 (Arneson, ADF&G, pers. comm.; Table 9.3). In May the highest densities of birds (mainly shorebirds and gulls) were found between Cordova and Cape Suckling (Fig. 9.7a). In July the highest densities of birds in Icy Bay (mainly sea ducks) and in the area between Cape Suckling Bay and Icy Bay (mainly gulls) (Fig. 9.7b).

Table 9.3 May and July densities of NEGOA coastal birds (Arneson, ADF&G, pers. comm.).

Group of birds	Densities (birds/km^2) in each section: May 1	2	3	4	5	6	7	8	9	10	11	Av.	July 1	4	5	6	Av.
Loons	t	2	t	t	1	t	t	1	1	1	t	1	t	t	0	t	t
Grebes	0	t	t	0	0	0	t	t	t	t	t	t	0	0	0	0	0
Cormorants	t	1	t	t	t	0	7	t	1	t	1	1	1	0	0	0	1
Swans and geese	2	t	t	2	2	3	2	2	t	4	1	2	0	0	0	0	0
Dabbling ducks	3	15	6	2	3	4	5	17	1	14	8	7	0	0	0	0	0
Diving ducks	2	3	23	1	15	1	6	15	1	11	15	7	0	0	0	0	0
Sea ducks	t	4	26	t	46	3	30	3	27	4	20	9	3	2	252	88	49
Mergansers	2	t	1	t	t	1	1	1	t	1	t	1	0	0	0	0	0
Raptors	t	t	t	t	t	1	t	t	1	t	t	t	t	t	t	t	t
Cranes	0	t	0	0	0	0	0	0	0	1	0	t	0	0	0	0	0
Shorebirds	24	4	22	2	38	24	98	138	7	222	316	67	t	13	0	14	7
Gulls and jaegers	7	7	20	38	55	81	163	12	774	32	76	45	106	4	59	677	284
Terns	7	4	2	23	34	5	t	2	t	4	t	7	33	4	19	48	32
Alcids	0	t	t	0	t	0	81	0	33	0	t	4	0	0	0	0	0
Corvids	t	0	t	0	t	t	t	0	t	t	0	t	0	t	0	0	t
Other passerines	t	0	0	0	t	0	t	t	t	t	t	t	0	0	0	0	0
Other birds	0	0	0	0	0	0	0	1	0	t	0	t	0	0	0	0	0
Totals	48	41	101	69	194	122	393	192	849	296	440	151	143	22	330	827	373

t = trace

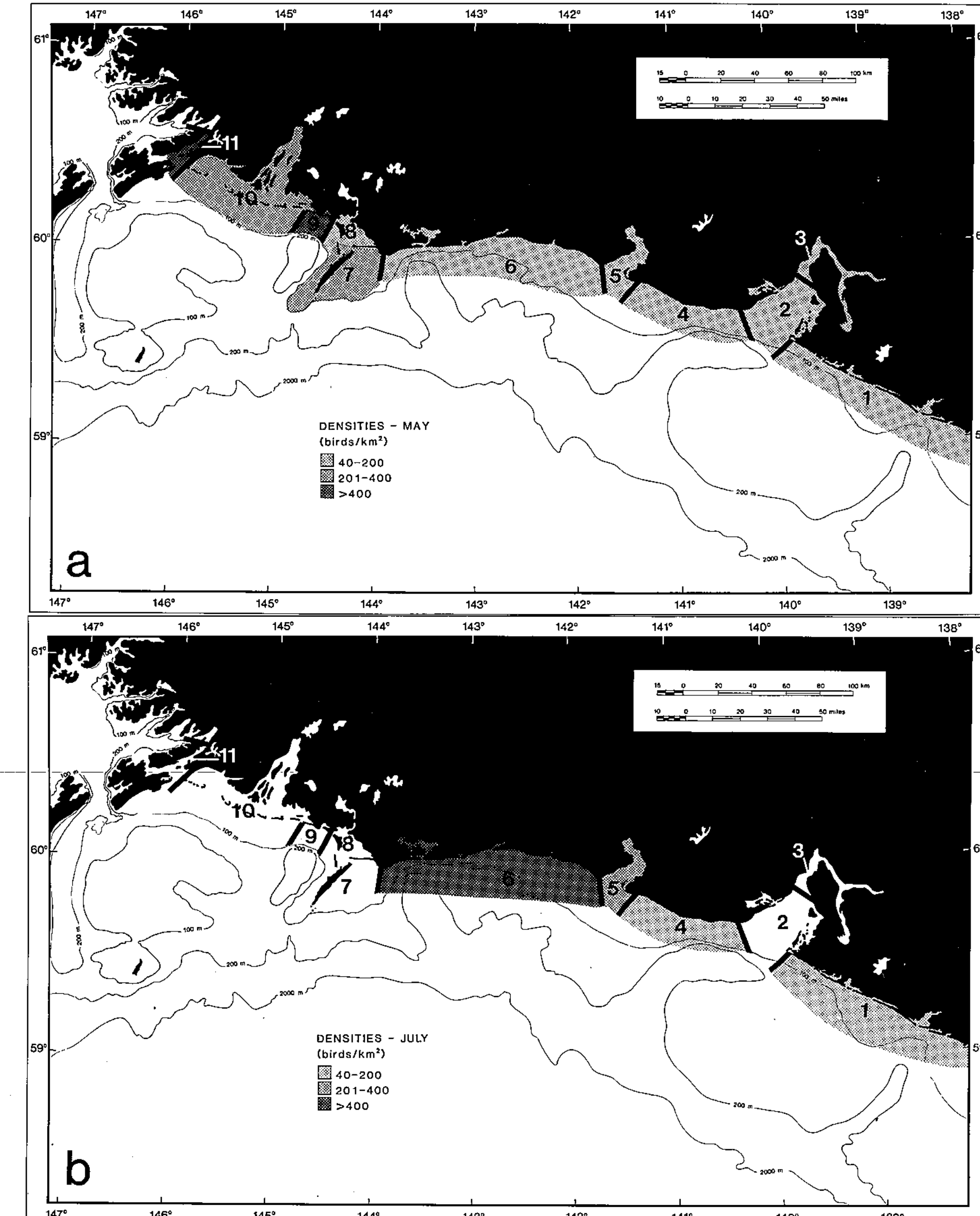


Figure 9.7 Spring (a) and summer (b) densities of NEGOA coastal birds (Arneson, ADF&G, pers. comm.).

Summaries of Arneson's (1977) May survey are shown in Figs. 9.7 and 9.8. Figure 9.7 shows the kinds of birds found in each habitat type, whereas Fig. 9.8 shows the types of habitats each kind of bird uses. Most kinds of birds show habitat specificity. One type of bird accounted for 50 percent or more of the usage of a type of habitat for 25 out of 30 habitats. One type of habitat accounted for over 50 percent of the usage of a type of bird for 8 out of 17 types of birds. Overall, about 26 percent of the birds were found on protected delta mud, 13 percent on exposed inshore waters, and about 9 percent each on bay rock and bay mudflats. Shorebirds accounted for 44 percent of all birds, gulls accounted for 30 percent, and total waterfowl for 17 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.

Copper-Bering River delta system

A large delta system about 120 km long extends from Orca Inlet in Prince William Sound to Controller Bay. This sandy and muddy intertidal zone (about 500 km^2) is a habitat island in the North Pacific region which is dominated by steep, fiord-like coastal topography with limited intertidal habitats. This delta system is the result of the deposition of immense amounts of sediments by the Copper River and, to a lesser extent, the Bering River. The area is extremely important for migrant and breeding birds (Norton and Senner, 1977).

More than 20 million waterfowl and shorebirds pass through the delta system each year in April and May (Isleib and Kessel, 1973). More than half of these birds are either Dunlin (<u>Calidris alpina</u>) or Western Sandpipers (<u>C. mauri</u>). The delta system is the first

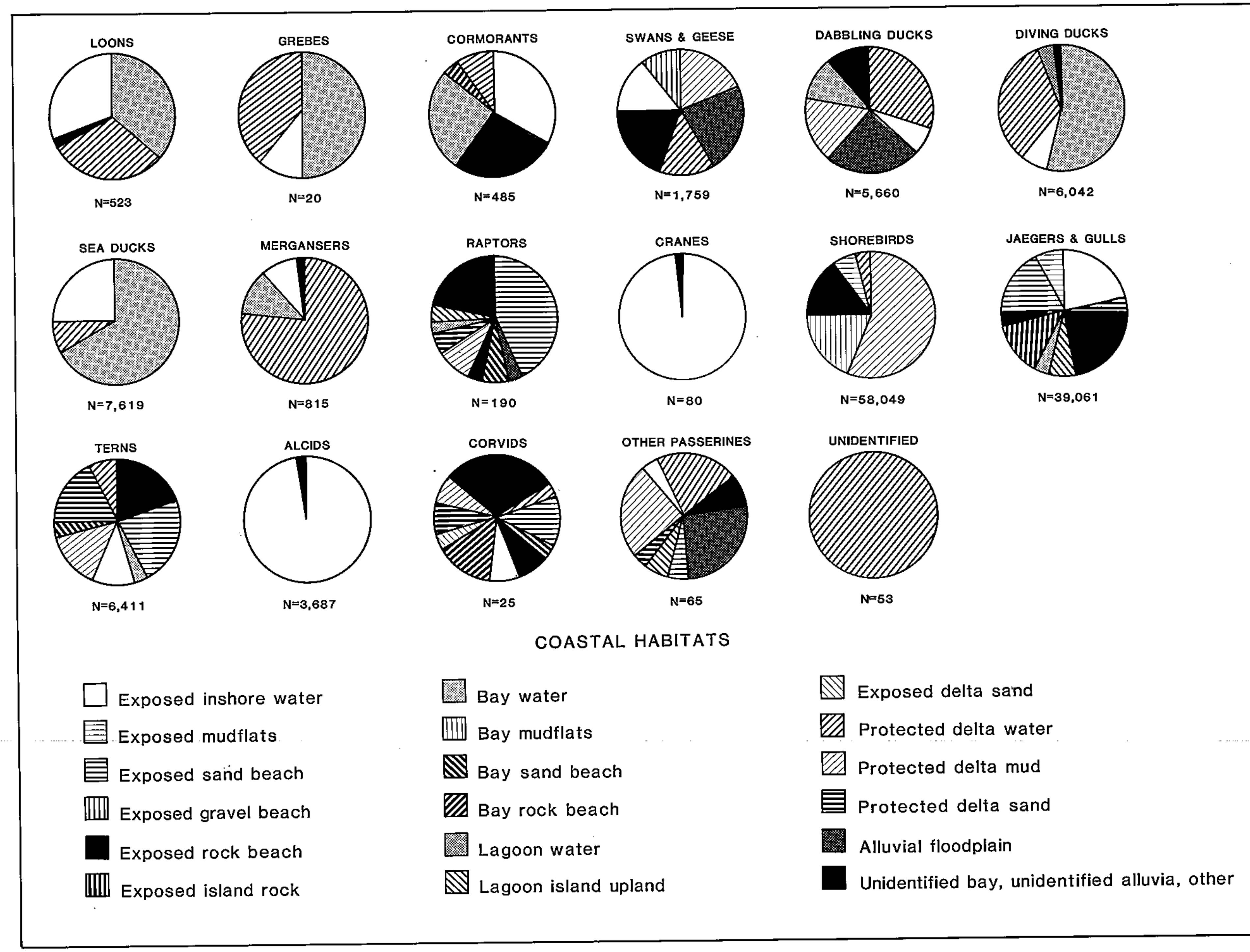
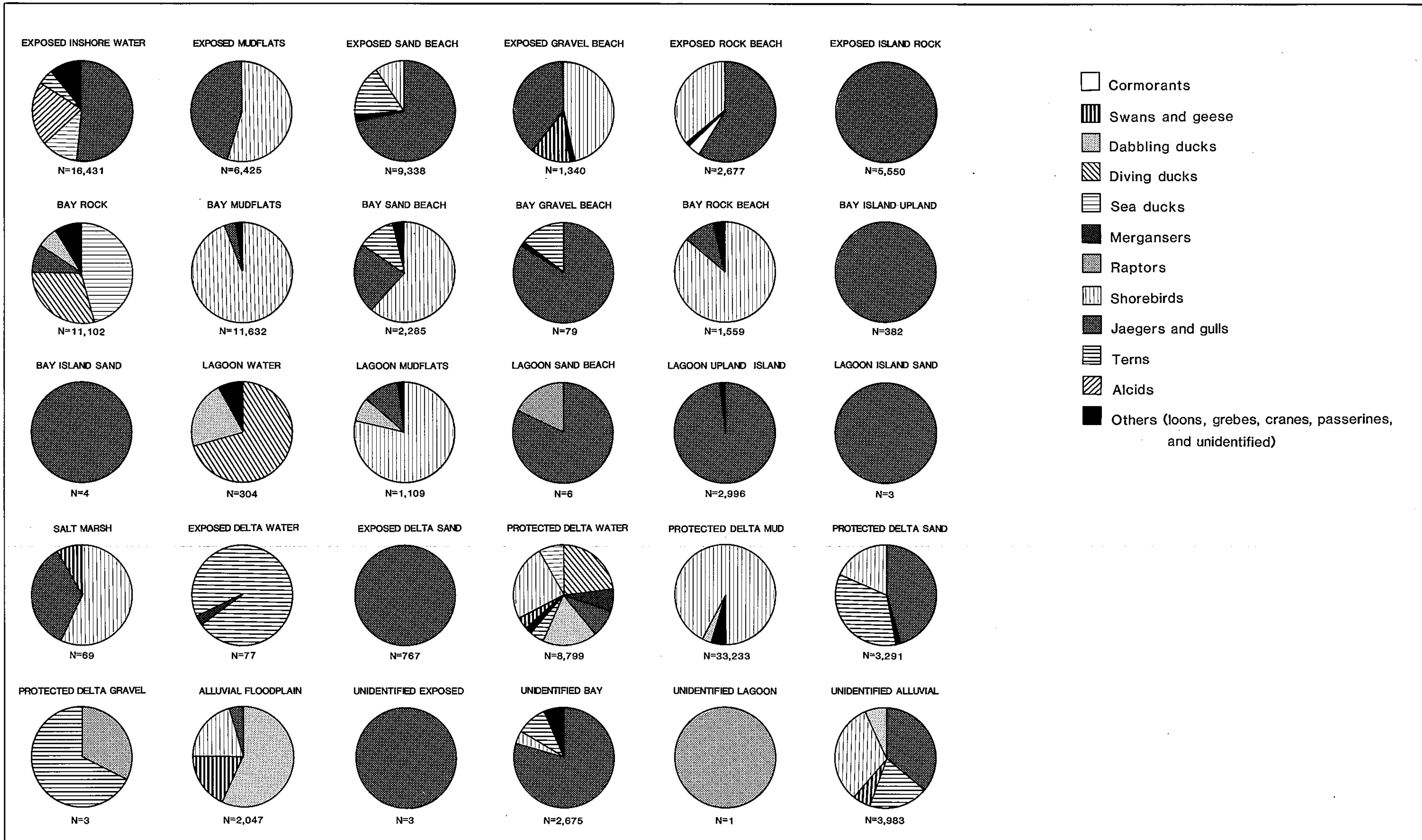


Figure 9.8 Types of NEGOA coastal habitats used by various types of birds, spring 1976 (Arneson, ADF&G, pers. comm.).

Figure 9.9 Distribution of birds among NEGOA coastal habitats, spring 1976 (Arneson, ADF&G, pers. comm.). →



EXPOSED INSHORE WATER
N=16,431
EXPOSED MUDFLATS
N=6,425
EXPOSED SAND BEACH
N=9,338
EXPOSED GRAVEL BEACH
N=1,340
EXPOSED ROCK BEACH
N=2,677
EXPOSED ISLAND ROCK
N=5,550
BAY ROCK
N=11,102
BAY MUDFLATS
N=11,632
BAY SAND BEACH
N=2,285
BAY GRAVEL BEACH
N=79
BAY ROCK BEACH
N=1,559
BAY ISLAND UPLAND
N=382
BAY ISLAND SAND
N=4
LAGOON WATER
N=304
LAGOON MUDFLATS
N=1,109
LAGOON SAND BEACH
N=6
LAGOON UPLAND ISLAND
N=2,996
LAGOON ISLAND SAND
N=3
SALT MARSH
N=69
EXPOSED DELTA WATER
N=77
EXPOSED DELTA SAND
N=767
PROTECTED DELTA WATER
N=8,799
PROTECTED DELTA MUD
N=33,233
PROTECTED DELTA SAND
N=3,291
PROTECTED DELTA GRAVEL
N=3
ALLUVIAL FLOODPLAIN
N=2,047
UNIDENTIFIED EXPOSED
N=3
UNIDENTIFIED BAY
N=2,675
UNIDENTIFIED LAGOON
N=1
UNIDENTIFIED ALLUVIAL
N=3,983
Cormorants
Swans and geese
Dabbling ducks
Diving ducks
Sea ducks
Mergansers
Raptors
Shorebirds
Jaegers and gulls
Terns
Alcids
Others (loons, grebes, cranes, passerines, and unidentified)

suitable landfall for these species north of Puget Sound and Southern British Columbia. Available evidence (Senner, 1977, 1979; Senner and Norton, 1976; Senner and West, 1978) indicates that the majority of these birds fly nonstop from the Puget Sound-Vancouver area and arrive in the eastern part of the delta system depleted of migratory fat reserves. Since the area's supratidal wetlands are usually covered with ice and snow in April and May, the birds are restricted to intertidal areas. Banding and color-marking experiments have shown that individual birds spend from about 30 hours to 4 days in the area (Senner, 1977, 1979; Senner and West, 1978). Both species feed on a wide variety of invertebrates, mainly bivalve molluscs, with *Macoma balthica* the principal prey of the Dunlin. Dunlin feed mostly on the tidal flats and loaf during high tide. Western Sandpipers, on the other hand, continue to feed during high tide. In 1977, when nearby terrestrial and aquatic habitats were free of snow and ice, Western Sandpipers also fed in those areas (Senner and West, 1978). In spring 1976 and 1977 Dunlin gained weight during their stay on the flats. In 1976 Western Sandpipers as a population showed no consistent weight gain while in the area, but in 1977, when supratidal areas were also available for foraging, they too gained weight (Senner and West, 1978). Dunlin fly directly from NEGOA to their breeding ground in western Alaska, while Western Sandpipers make at least one more stop in Kachemak Bay before proceeding to their breeding grounds (Gill et al., 1979; Senner and West, 1978). It appears that while most Dunlin rely on the Copper-Bering River delta system as their only refueling stop between the Puget Sound-Vancouver area and their breeding grounds, many Western Sandpipers cannot gain enough fat reserves at the delta system and must make at least one more stop before they reach the breeding grounds.

Millions of shorebirds, physiologically stressed from a nonstop migration of about 2,500 km, with little or no energy reserves and no suitable feeding habitat within 200 km, would probably suffer high mortality if they or their food supply became contaminated with oil. Since the entire western Alaska breeding population of the Dunlin (*C. alpina pacifica*) and nearly the world population of Western Sandpipers are believed to pass through the delta system each spring, such a diaster could be the worst ever inflicted on a large vigorous avian population.

The Copper River Delta is an important waterfowl breeding area. It has been estimated that about 20,000 ducks, about 20,000 Dusky Canada Geese (*Branta canadensis occidentalis*), and about 600 Trumpeter Swans (*Cygnus buccinator*) were breeding on the delta in 1976. About 3,000 Trumpeter Swans were estimated to have bred in Alaska in 1968, about 1,000 of them in the area from the Copper River Delta to Yakutat Bay (Hansen et al., 1971). The birds breeding on the delta probably represent at least 10 percent of the world population of this species. The entire population of the Dusky Canada Goose breeds along the Alaska coast between Cook Inlet and the Bering Glacier (Hansen, 1962). Almost the entire population of this subspecies breeds on the Copper River Delta. The highest concentrations of breeding Dusky Canada Geese are found near the coast between the Eyak and Copper Rivers (ADF&G, 1976b). Johnson et al. (1979) report that the subspecies of the Canada Goose that breeds in Prince William Sound is unknown but that individuals have some of the characteristics of the Vancouver Canada Goose (*B. canadensis fulva*).

9.3.3 NEGOA bird colonies

Approximately 260,000 birds nest in the colonies of NEGOA (Table 9.4, Sowls et al., 1978). Most of the colonies and about 97 percent of the total breeding population are located in the eastern part of Prince William Sound and on Middleton Island (Table 9.4, Fig. 9.10). The most abundant are the Glaucous-winged Gull (9 percent; Fig. 9.11a), Black-legged Kittiwake (74 percent; Fig. 9.11c), Common Murre (7 percent; Fig. 9.11f), and Tufted Puffin (6 percent; Fig. 9.11g).

No bird colonies have been found between Cape Suckling and Icy Cape. Just outside NEGOA another 47,000 birds are found in colonies in western Prince William Sound. The colonies in or near Icy, Yakutat, and Dry Bays are important for coastal nesting Mew Gulls (Fig. 9.11b) and Arctic (Fig. 9.11d) and Aleutian Terns (Fig. 9.11e). Colonies in NEGOA comprise more than 20 percent of the Gulf of Alaska breeding populations of Mew Gull, Black-legged Kittiwake, and Aleutian Tern. The only known Alaskan nesting colony of Brandt's Cormorant (11 birds) is located in eastern Prince William Sound.

Table 9.4 Estimates of breeding population at NEGOA bird colonies (Sowls et al., 1978).

Species	Region							
	Eastern Prince William Sound	(Total Prince** William Sound)	Middleton Island	Cape Suckling to Icy Cape	Icy Cape to Dry Bay	Dry Bay to Cape Spencer	Totals	Percent Gulf of Alaska population
Fork-tailed Storm-Petrel	?	(5,000)	-	-	-	-	?	?
Leach's Storm-Petrel	-	(400)	-	-	-	-	-	-
Cormorant (sp.)	-	(79)	-	-	-	-	-	-
Double-crested Cormorant	402	(421)	-	-	X	-	402	13.7*
Brandt's Cormorant	11	(11)	-	-	-	-	11	100
Pelagic Cormorant	430	(472)	4,682	-	X	80	5,192	33.7
Red-faced Cormorant	170	(320)	1	-	-	-	171	0.8
Harlequin Duck	3	(3)	-	-	2	-	5	?
Bald Eagle	8	(14)	-	-	-	-	8	?
Peregrine Falcon	2	(2)	-	-	-	-	2	?
Black Oystercatcher	26	(74)	-	-	18	-	44	?
Glaucous-winged Gull	16,894	(21,148)	1,140	-	4,400	40	22,474	13.1
Herring Gull	-	-	-	-	X	-	X	?
Mew Gull	60	(179)	-	-	725	-	785	25.1*
Bonaparte's Gull	-	(80)	-	-	-	-	-	-
Black-legged Kittiwake	39,496	(58,396)	150,494	-	250	1,600	191,840	20.3
Arctic Tern	462	(2,644)	-	-	1,110	-	1,552	14.6*
Aleutian Tern	-	-	-	-	350	-	350	31.0
Common Murre	12,510	(12,760)	6,596	-	-	46	19,152	9.5
Thick-billed Murre	X	(X)	207	-	-	-	207	13.4
Pigeon Guillemot	276	(1,582)	-	-	37	X	313	1.2
Marbled Murrelet	-	(X)	-	-	-	-	-	-
Ancient Murrelet	?	(X)	-	-	-	-	?	?
Parakeet Auklet	-	(451)	-	-	-	-	-	-
Rhinoceros Auklet	-	-	1,316	-	-	-	1,316	1.2
Horned Puffin	116	(1,284)	-	-	-	4	120	0.1
Tufted Puffin	13,070	(26,300)	3,500	-	2	80	16,652	1.4
Totals	83,936	(131,620)	167,936	-	6,894	1,850	260,616	7.8

X = present, * = coastal populations only, ** = Total Prince William Sound populations not included in NEGOA totals.

The Black-legged Kittiwake colony on Middleton Island is noteworthy for its rapid growth over the last two decades and for its use of nesting habitat atypical of the species (Hatch et al., 1979). Rausch (1958) estimated a breeding population there of 10,000 to 15,000 birds in 1956. Hatch et al. (1979) estimated 150,000 in 1978. The 1964 Prince William Sound earthquake raised the island about 5 m and exposed large areas of flat land previously under water. Kittiwakes usually nest on the faces of steep cliffs, but on Middleton they make extensive use of flat areas, both those exposed by the 1964 earthquake and those previously available. The causes of the growth of this colony are not fully understood. While the availability of new habitat has contributed to the population growth, the more intensive use of previously available habitat suggests that other factors are also important.

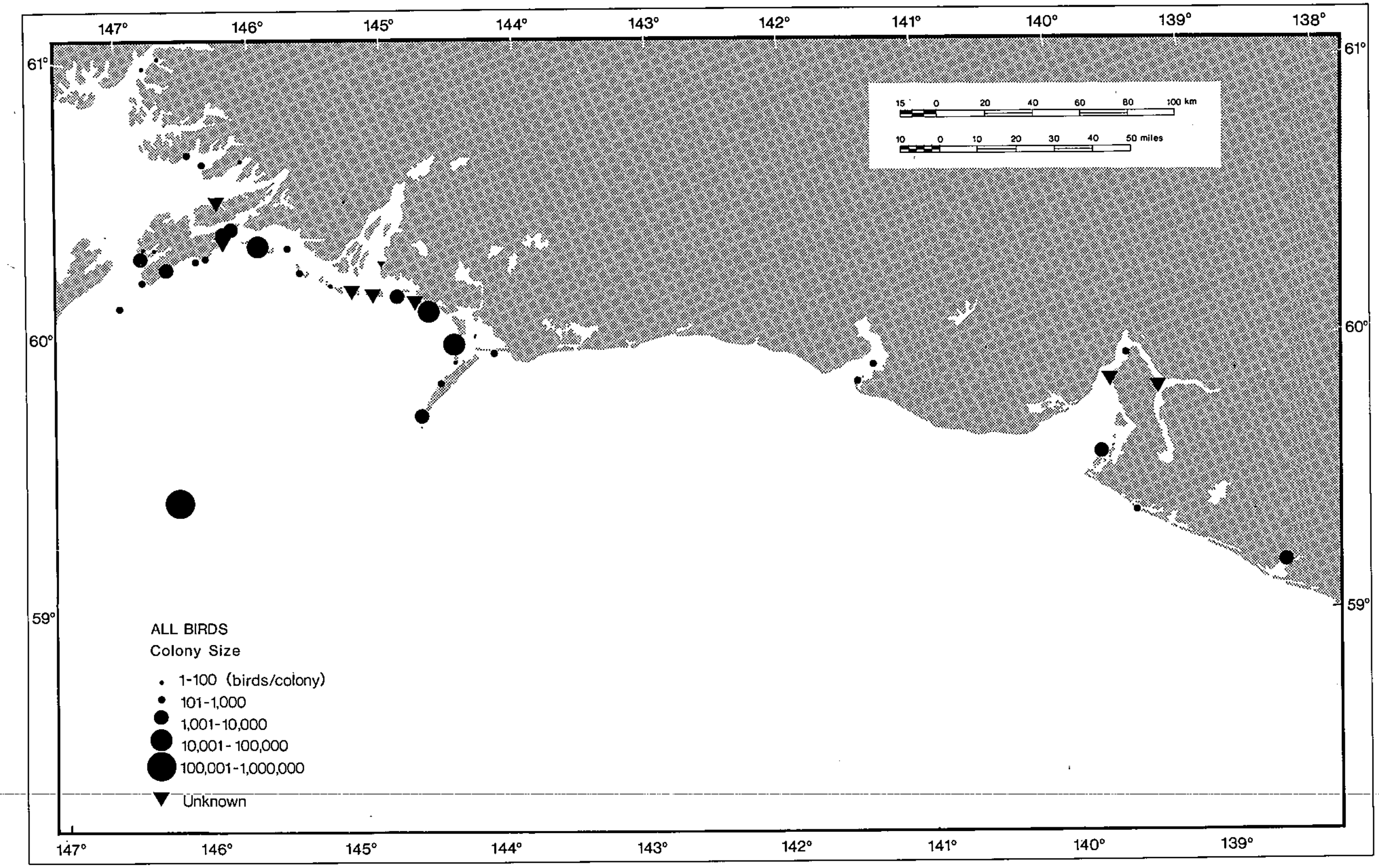


Figure 9.10 Distribution of NEGOA bird colonies (Sowls et al., 1978).

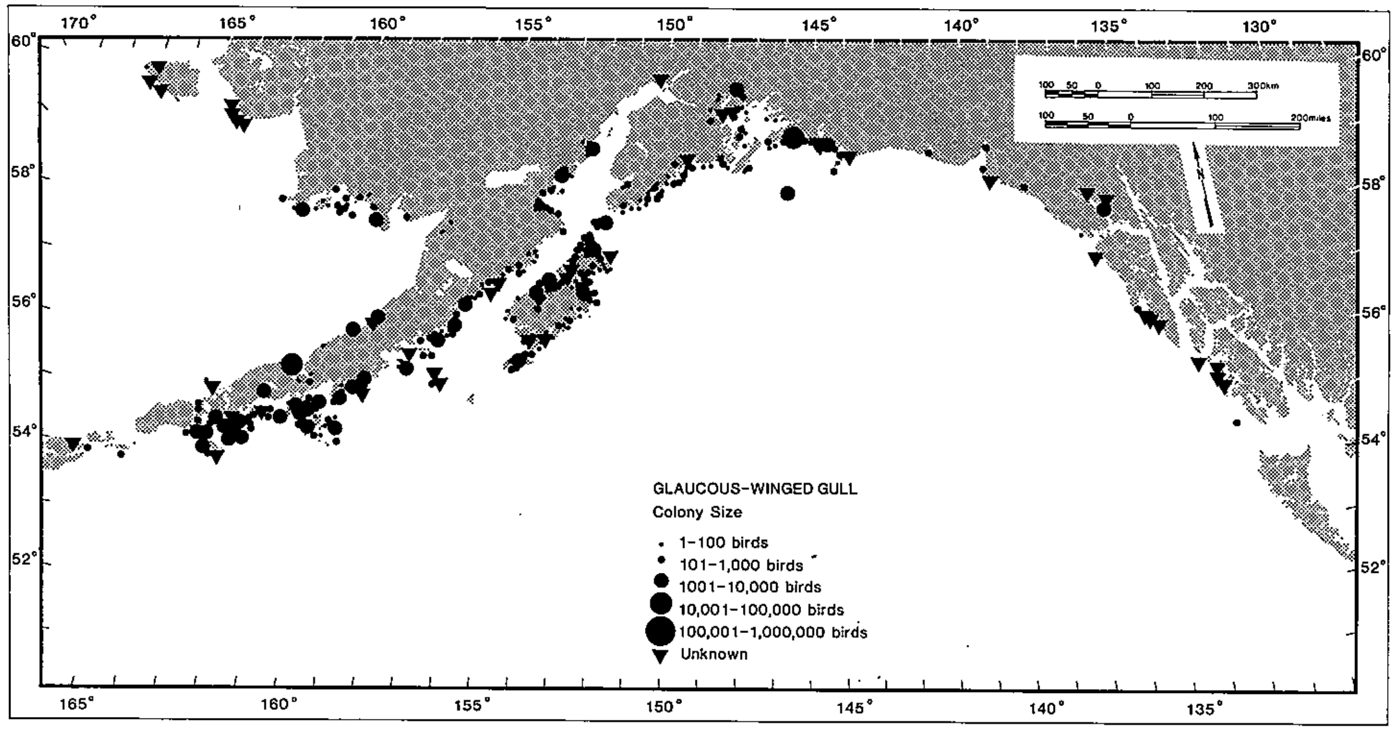


Figure 9.11a Distribution of Glaucous-winged Gull colonies (Sowls et al., 1978).

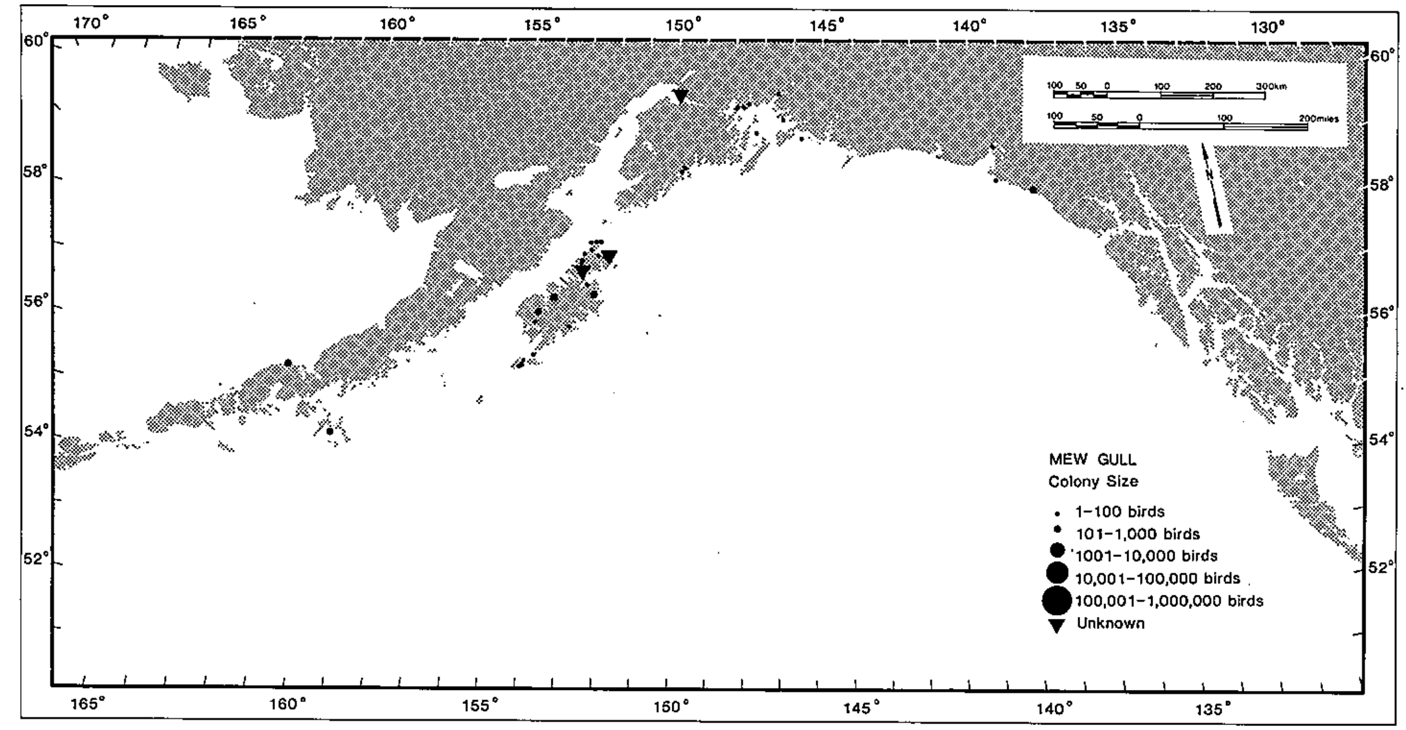


Figure 9.11b Distribution of Mew Gull colonies (Sowls et al., 1978).

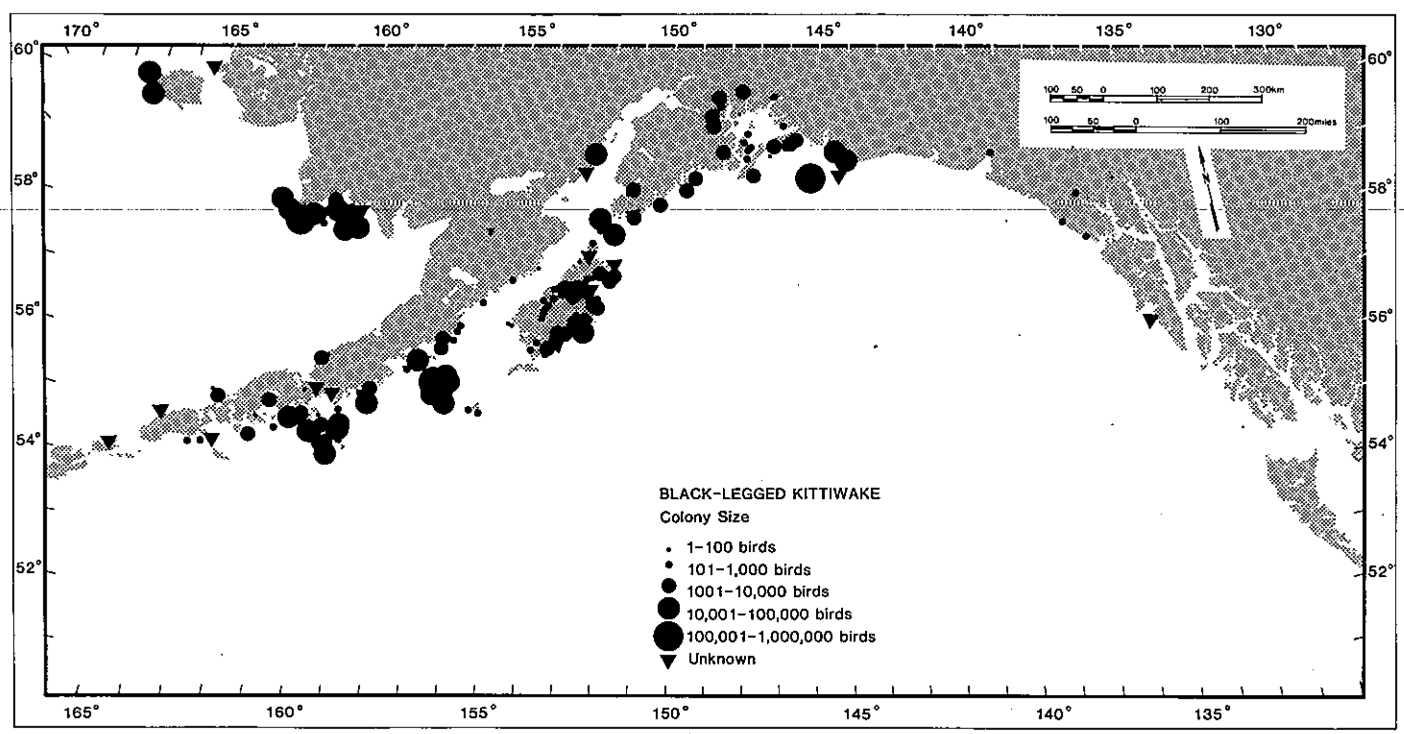


Figure 9.11c Distribution of Black-legged Kittiwake colonies (Sowls et al., 1978).

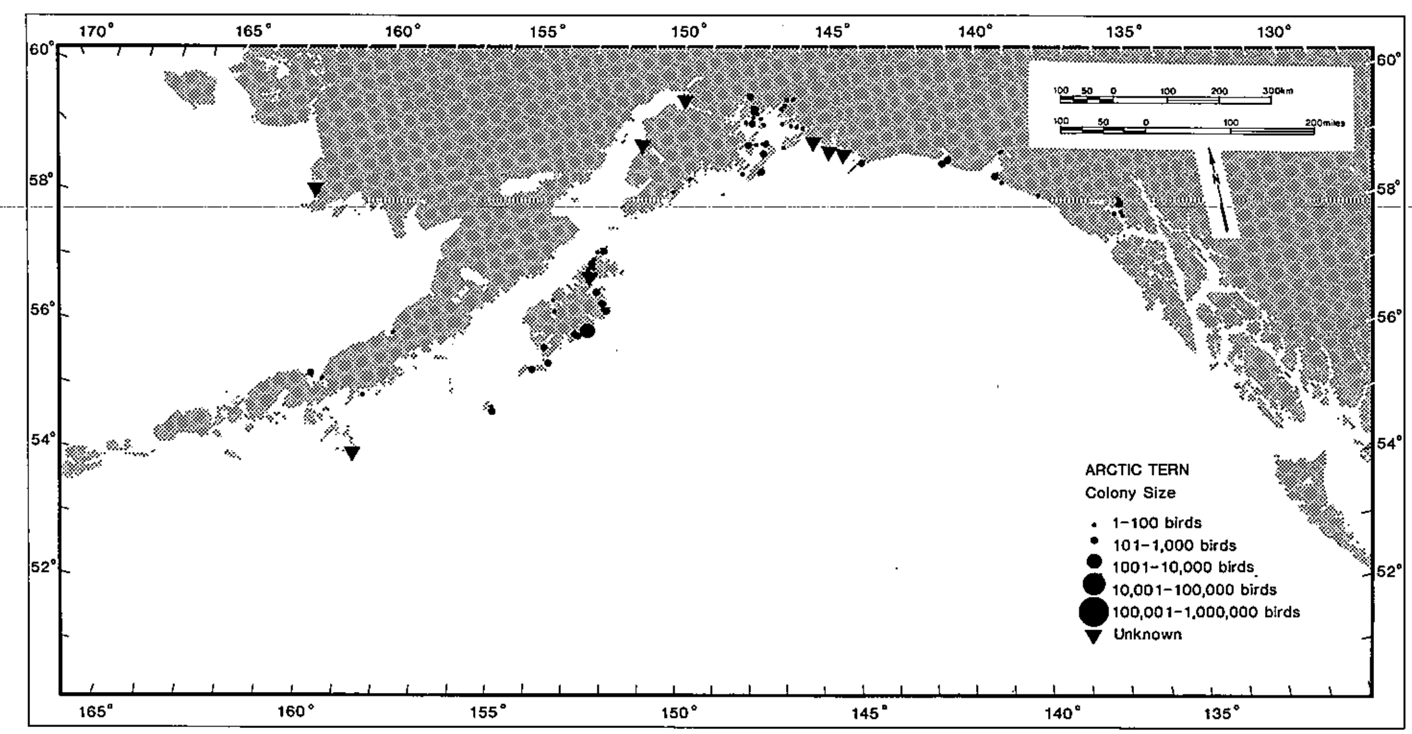


Figure 9.11d Distribution of Arctic Tern colonies (Sowls et al., 1978).

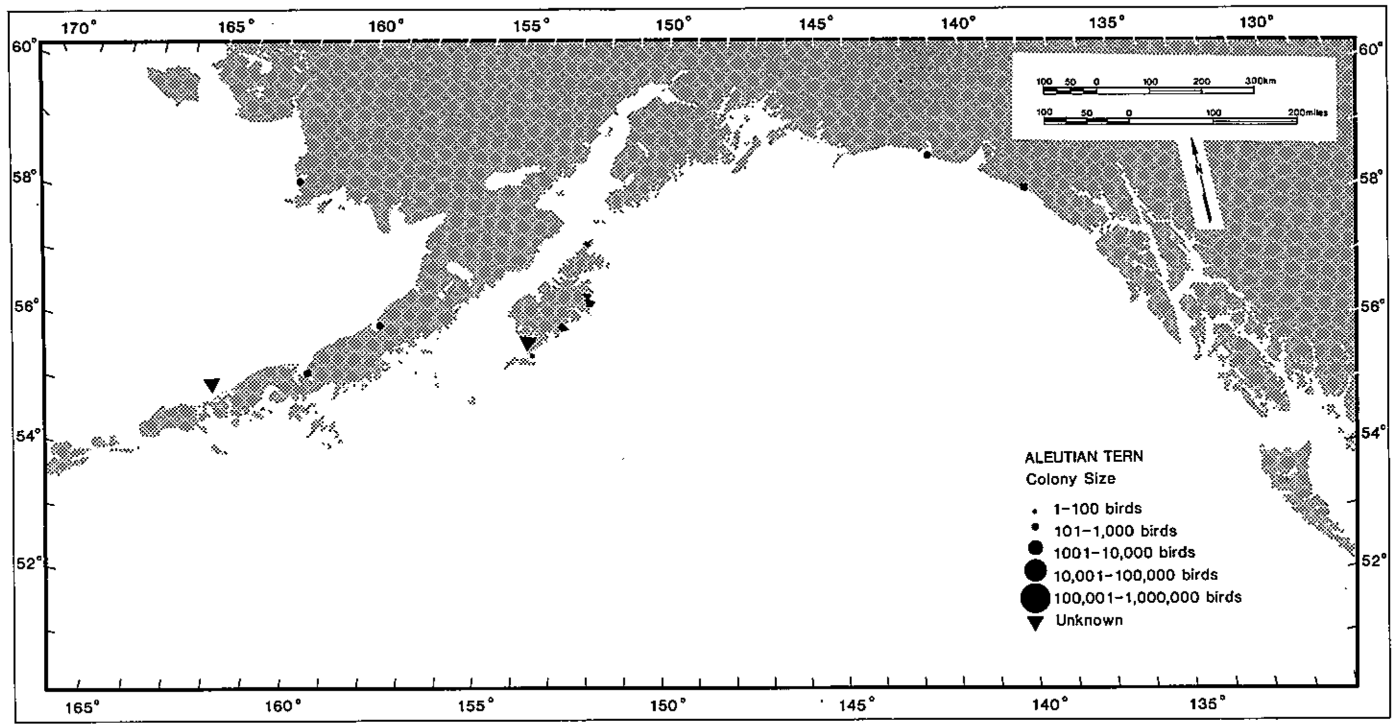


Figure 9.11e Distribution of Aleutian Tern colonies (Sowls et al., 1978).

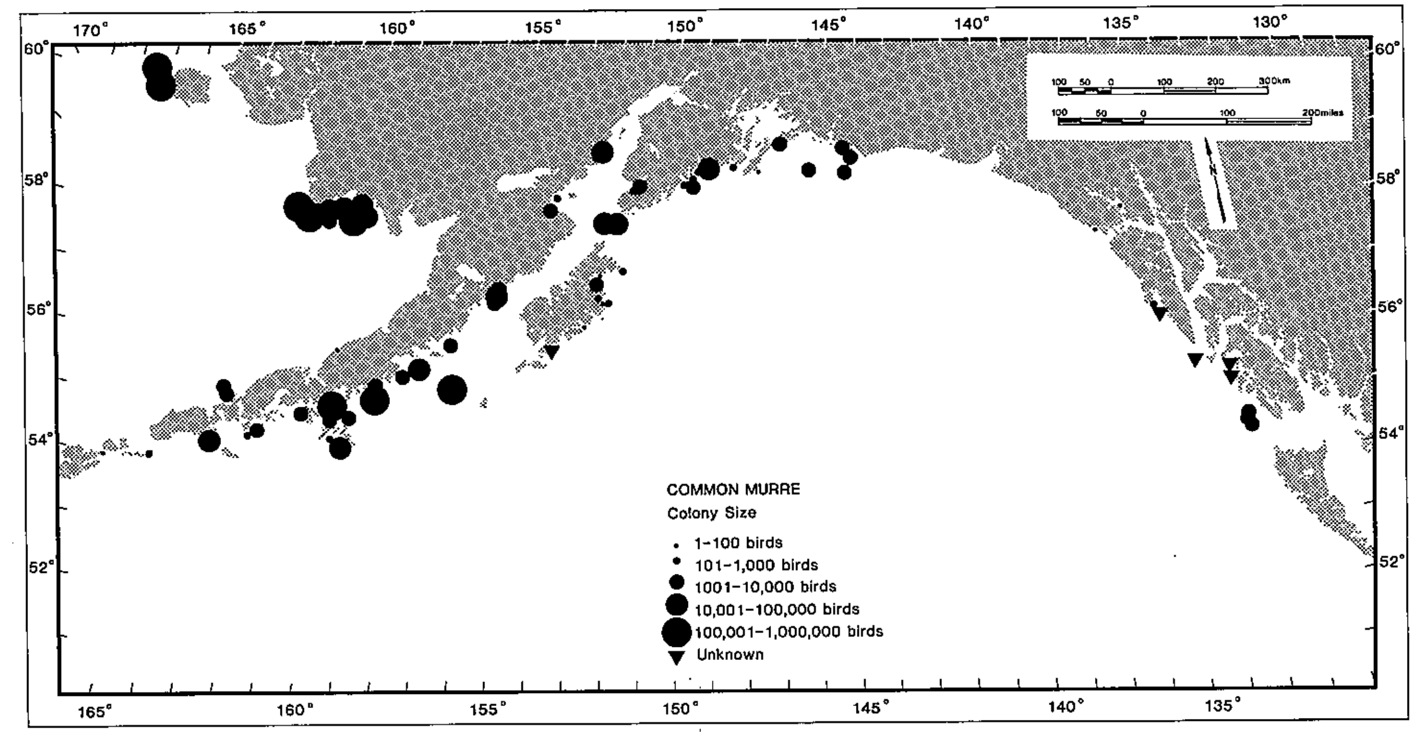


Figure 9.11f Distribution of Common Murre colonies (Sowls et al., 1978).

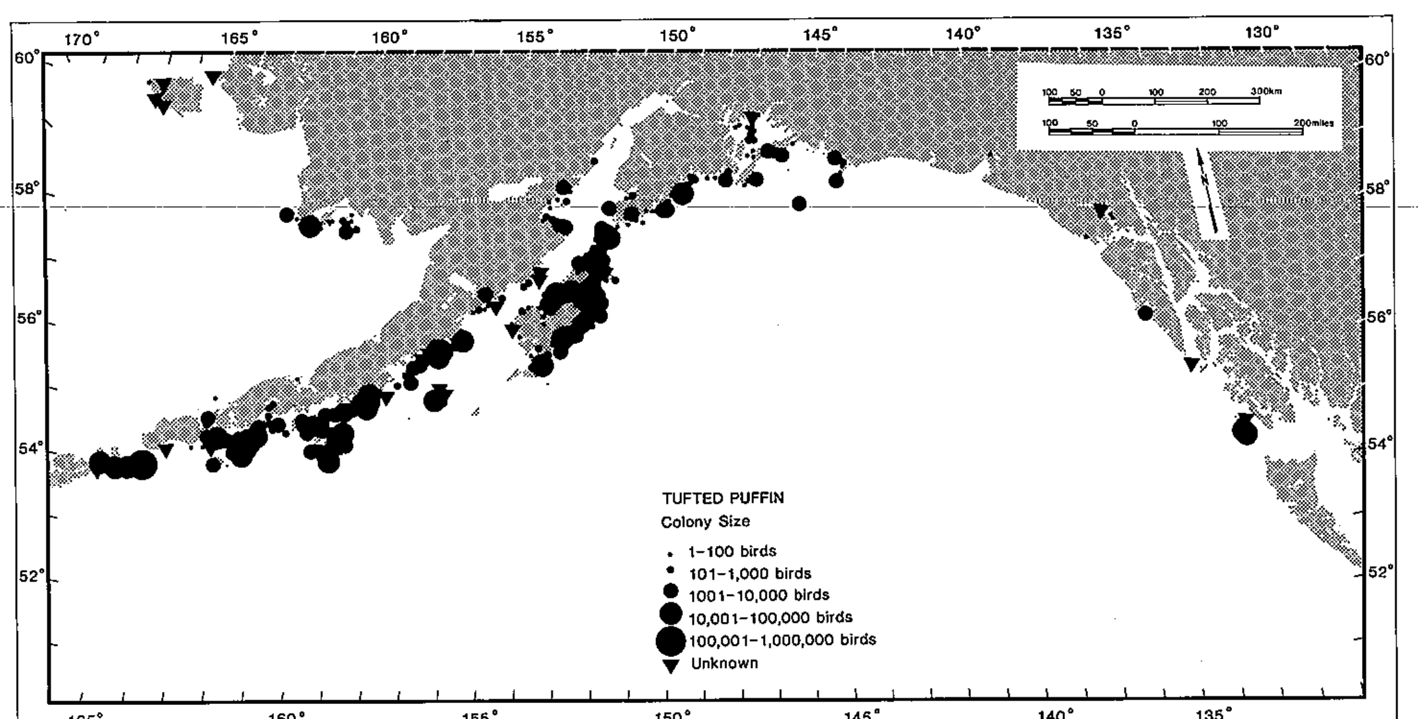


Figure 9.11g Distribution of Tufted Puffin colonies (Sowls et al., 1978).

9.3.4 Endangered species

The endangered Aleutian Canada Goose (Branta canadensis leucopareia) is not known to occur in the Gulf of Alaska (P. 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 Island and then fly across the Pacific to California (Fig. 9.12). In the spring they move north along the Oregon and Washington 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 (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 was marked. On the basis of current knowledge, it appears unlikely that development in NEGOA 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 NEGOA.

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 and 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. The current status of North American Peregrine Falcon populations has been reviewed by Schaeffer and Ehlers (1978).

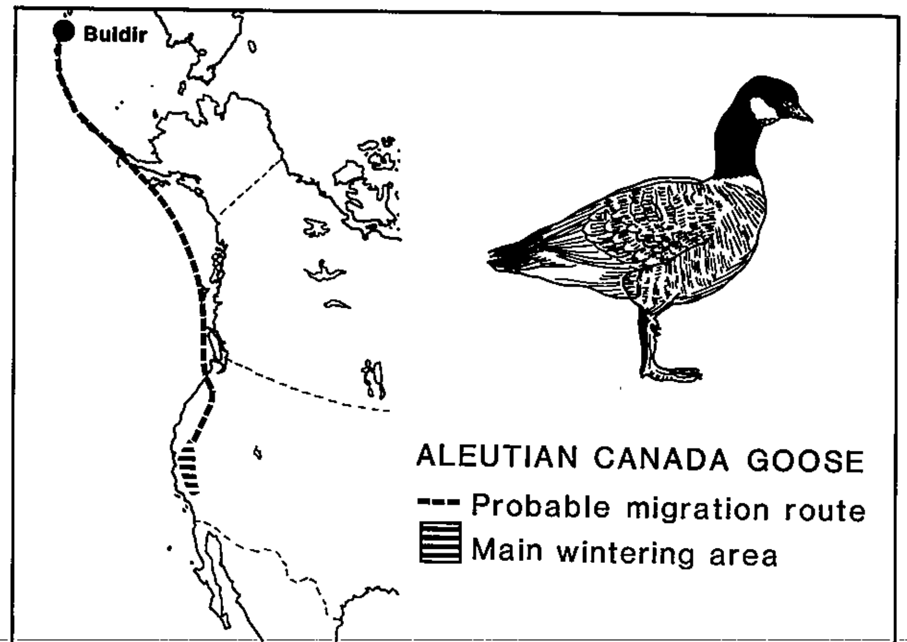


Figure 9.12 Distribution of the Aleutian Canada Goose (after Palmer, 1976). Only known breeding location is Buldir Island, but there is evidence that it may breed elsewhere (see text for details).

9.4 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 a clutch 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. However, many species will lay a second clutch if the first is lost early in the season.

The breeding phenologies for 10 species of marine and coastal birds on Middleton Island (Hatch et al., 1979) and the Wooded Islands (Mickelson et al., 1978) in 1976 and/or 1977 are shown in Fig. 9.13. Eggs of all species were laid between 23 April and 12 July. Leach's Storm-Petrel (Oceanodroma leucorhoa) began laying later than any other species in both years. Hatching began 20 May and continued to 27 August. The fledging period started on 3 July and continued to 14 August for most species. It continued into October for storm-petrels and puffins and was shortest for murres. Except for Leach's Storm-Petrel and Tufted Puffins, the species nesting on Middleton Island nested about two weeks earlier in 1978 than did the same species on the Wooded Islands and those in colonies in the Cook Inlet-Kodiak area in 1976 and 1977. For some species the entire breeding effort was protracted compared to other locations in the Gulf of Alaska. Hatch et al. (1979) suggest that the differences in breeding phenology found on Middleton Island could be attributed to age structure of the breeding birds or to prey fed to the young, which differs from that reported elsewhere in the Gulf (see below).

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 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.

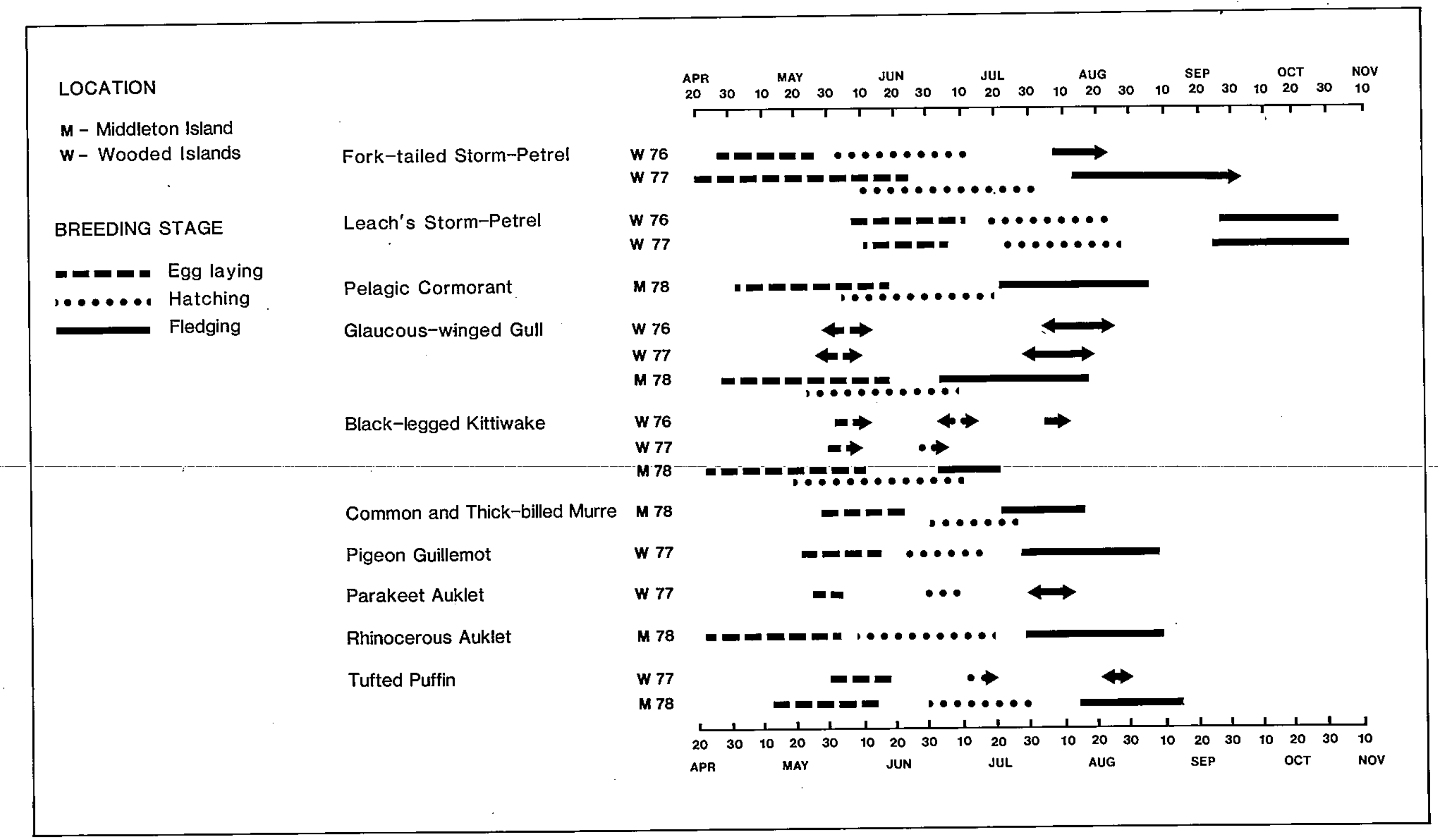


Figure 9.13 Breeding phenologies for 10 species of marine and coastal birds on Middleton Island and/or the Wooded Islands (Hatch et al., 1979; Mickelson et al., 1978).

Data on the breeding success of five species of marine and coastal birds for 1975 through 1978 on Dry Bay, Egg Island (Patten and Patten, 1978), Middleton Island (Hatch et al., 1979), or the Wooded Islands (Mickelson et al., 1978) are given in Table 9.5. The productivity (young fledged per breeding pair) ranged from 0.25 to 1.48. The data available do not suggest any significant differences among years or locations. The productivites reported for NEGOA are similar to those reported on the Barren Islands (Manuwal and Boersma, 1977, 1978) and around Kodiak Island (Nysewander and Hoberg, 1978; Baird and Moe, 1978).

The productivity of kittiwakes on Middleton Island reported in 1978 is only about 12 percent of that reported by Coulson and White (1958) for a rapidly growing kittiwake population in Britain. This is interesting, since the Middleton Island population has grown tremendously since 1964. Hatch et al. (1979) attribute the low production to the high proportion of young, inexperienced birds breeding in this population.

About 57 percent of the eggs laid in the colonies studied failed to produce fledged young. River otters (Lutra canadensis) killed about 23 percent of the breeding Fork-tailed Storm-Petrels nesting in soil on the Wooded Islands and an unknown number of chicks (Mickelson et al., 1978). On Middleton Island Glaucous-winged Gulls killed many young Black-legged Kittiwakes soon after they fledged. Hatch et al. (1979) found that "the flats below the cliffs became strewn with the remains of young kittiwakes which had been killed and eaten by gulls."

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

Table 9.5 Reproductive success in marine birds (see text for sources).

Species	Location[a]	Year	Number of[b] active nests observed	Clutch size	Eggs hatched/ eggs laid	Chicks fledged/ chicks hatched	Chicks fledged/ eggs laid	Productivity (young/pair)
Fork-tailed Storm-Petrel	WI	1976[c]	69	1.00	0.84	?	0.31	0.31
Fork-tailed Storm-Petrel	WI	1977[c]	?	1.00	?	?	0.25	0.25
Fork-tailed Storm-Petrel	WI	1977[d]	?	1.00	?	?	0.68	0.68
Fork-tailed Storm-Petrel	WI	1977[e]	?	1.00	?	?	0.64	0.64
Pelagic Cormorant	MI	1978	102	2.84	?	?	0.22	0.64
Glaucous-winged Gull	WI	1977	27	2.67	?	?	?	?
Glaucous-winged Gull	EI	1975	153	2.4	0.69	0.90	0.62	1.48
Glaucous-winged Gull	EI	1976	186	2.4	0.77	0.79	0.61	1.46
Glaucous-winged Gull	DB	1975	100	?	?	?	?	?
Glaucous-winged Gull	DB	1977	112	2.93	0.927	0.533	0.494	1.45
Black-legged Kittiwake	MI	1978	148	1.94	0.625	0.143	0.089	0.17
Black-legged Kittiwake	WI	1977	109	1.62	0.604	?	?	?
Tufted Puffin	WI	1977	56	1.00	0.464	"few"	"few"	?

a Locations: DB = Dry Bay
EI = Egg Island
MI = Middleton Island
WI = Wooded Islands

b An active nest contained at least one egg

c Nests in soil
d Nests in soil protected from predators
e Nests in rock

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 are low during their first winters but they increase to adult rates as the birds reach maturity (Ashmole, 1971; Ricklefs, 1973). The age at 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.

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 was 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. Small populations with unlimited resources have been found to grow exponentially. Most of the evidence concerning such populations comes from experiments, since natural populations in this stage are rarely available for study. The classic field 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 evidence that some seabird colonies do not produce enough young to maintain their numbers while others produce a surplus. 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 NEGOA, 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 nonbreeding 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.

The time to recover (defined as the time for a population to attain its original size) from a one-time imposed mortality for the five scenarios is shown in Fig. 9.14. 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 subadults has only about one-third the effect of mortality of the adults.

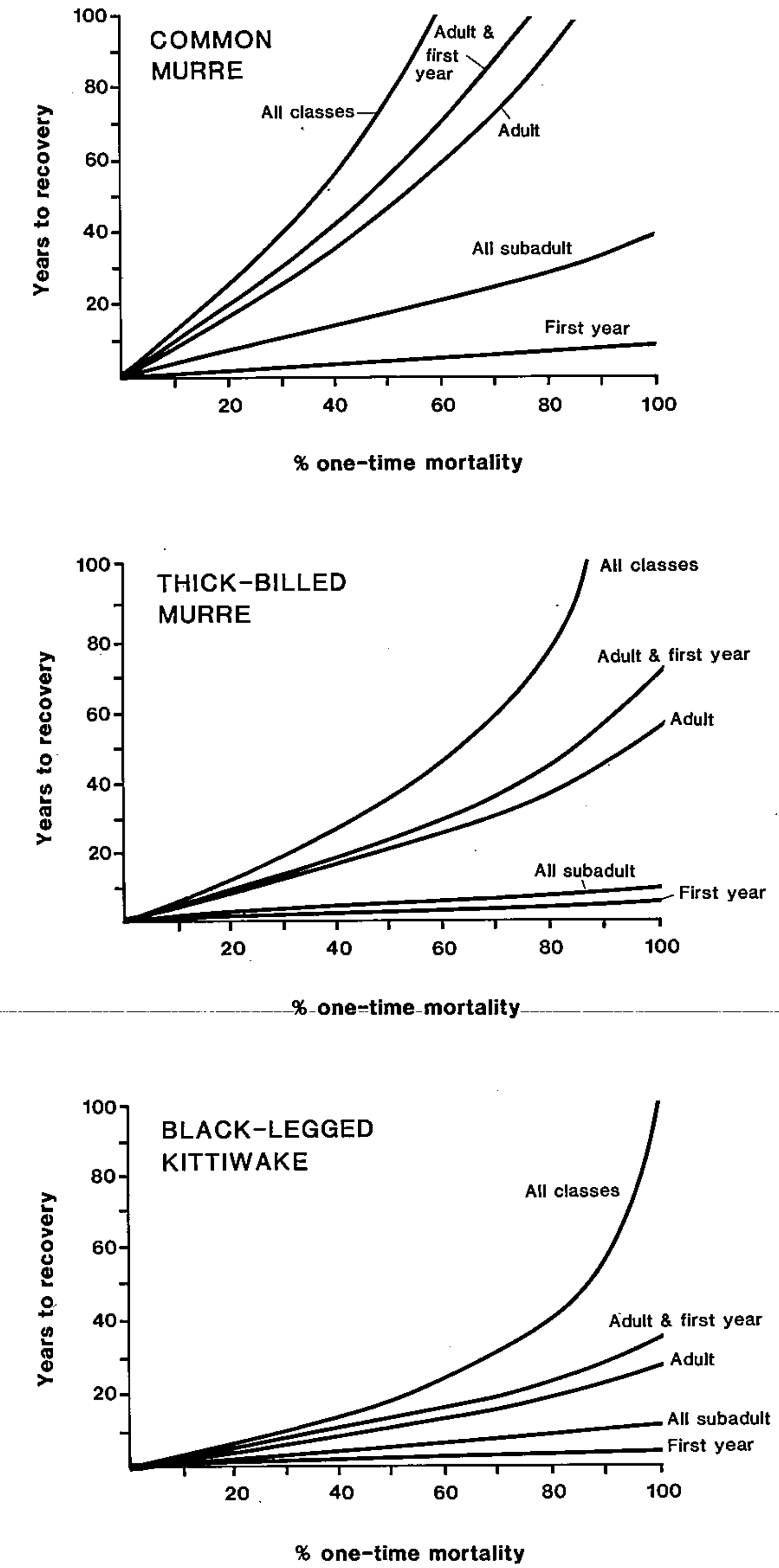


Figure 9.14 Time to recovery as a function of one-time mortality of various age-class combinations of Common Murres, Thick-billed Murres, and Black-legged Kittiwakes (Wiens et al., 1979).

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 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. 9.15). 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 and thus decrease recovery times.

The model predicts that the effects of long-term chronic sources of mortality could cause more damage to 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.

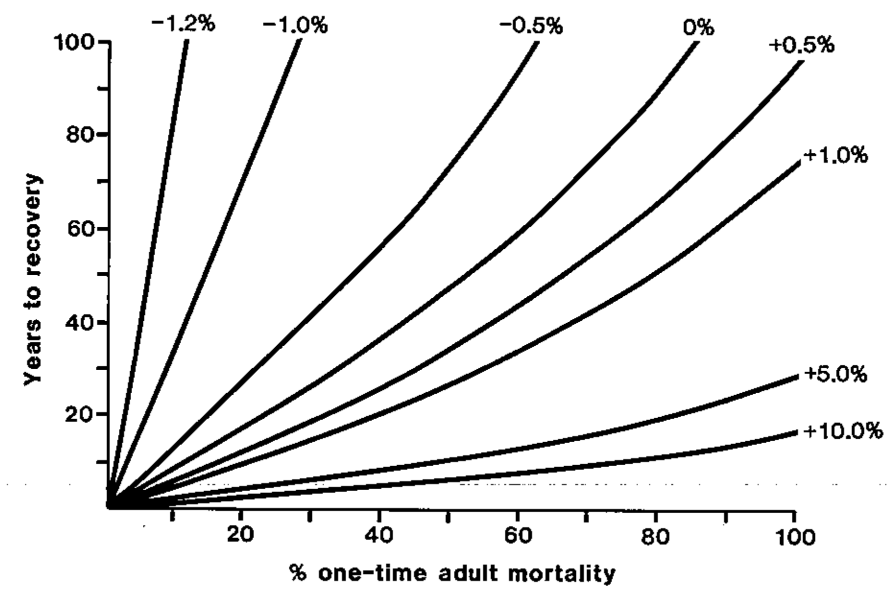


Figure 9.15 Time to recovery as a function of one-time mortality at different levels of change in the mean adult annual survival rate of Common Murres (Wiens et al., 1979).

9.5 TROPHICS

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.

9.5.1 Diet of adults

Data on the diets of adult marine birds from NEGOA are not currently available. Data from other areas in the Gulf of Alaska show that capelin (*Mallotus villosus*) and other fish are the major prey of Sooty Shearwaters, Black-legged Kittiwakes, Common Murres, and Horned and Tufted Puffins (Sanger et al., 1978; Sanger and Baird, 1977). Although capelin are not a major food item of Short-tailed Shearwaters, by their sheer numbers the amount this species consumes is second only to that taken by Sooty Shearwaters. Euphausiids are the major prey of Short-tailed Shearwaters, while squid are most important for Thick-billed Murres. Thus, fish support the majority of the species, but because Short-tailed Shearwaters are so numerous, euphausiids may actually 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 overall diets of diving ducks wintering in NEGOA are given in Table 9.6. Bottom-dwelling molluscs and crustaceans are the major food items of 11 of the 12 ducks listed. Molluscs and crustaceans were also

Table 9.6 Food habits of diving ducks (data from Cottam, 1939; Cottam and Knappen, 1939).

	Percent of volume of total diet						
Species	Pondweeds	Misc. plant	Molluscs	Insects	Crustaceans	Fishes	Misc. animals
Scaup (sp.)	19	25	39	7	7		
Goldeneye (sp.)	9	17	10	28	32	3	1
Bufflehead	7	14	16	41	17	4	1
Oldsquaw	2	10	16	11	48	10	3
Harlequin Duck		1.5	25	10	57	2.5	4
Steller's Eider	3	10	19	13	45	2	8
Common Eider		4	82	2	7		5
King Eider		5	46	5	19		25
Spectacled Eider	7	16	42	32	3		
White-winged Scoter		6	75	2	13	2	2
Common Scoter	5	5	65	3	17	3	3
Surf Scoter	3	9	61	10	10	3	4

found to be the major prey of Oldsquaws and White-winged Scoters collected in November through April in Kachemak Bay (Sanger et al., 1979). The dependence on these food resources is probably greater than indicated, because the data represent samples taken throughout the year and include birds taken on their inland breeding habitats (Cottam, 1939; Cottam and Knappen, 1939). Oil spills which destroyed the bottom fauna would be detrimental to wintering ducks, regardless of the time of year in which they occurred.

9.5.2 Diet of young

The diets of Black-legged Kittiwake, Rhinoceros Auklet, and Tufted Puffin chicks on Middleton Island are shown in Fig. 9.16. Kittiwake food samples were obtained from chicks which regurgitated when handled. Food samples were collected from Rhinoceros Auklet and Tufted Puffin chicks by taping their beak shut and collecting the food that adults left in the burrows over a 24-hour period. Kittiwake young were fed mostly fish (Pacific sand lance was the most common species identified) and euphausiids. Rhinoceros Auklet chicks were fed mostly Pacific sand lance, while Tufted Puffin chicks were fed mainly Pacific sand lance and cephalopods. These results are interesting, since the diets of chicks of the same or similar species in the Gulf of Alaska usually consist of high proportions of capelin, which were completely absent from the diets of chicks on Middleton Island. Harris and Hislop (1978) found that in Britain puffins obtained the best return for effort by feeding their young a few large oil-rich

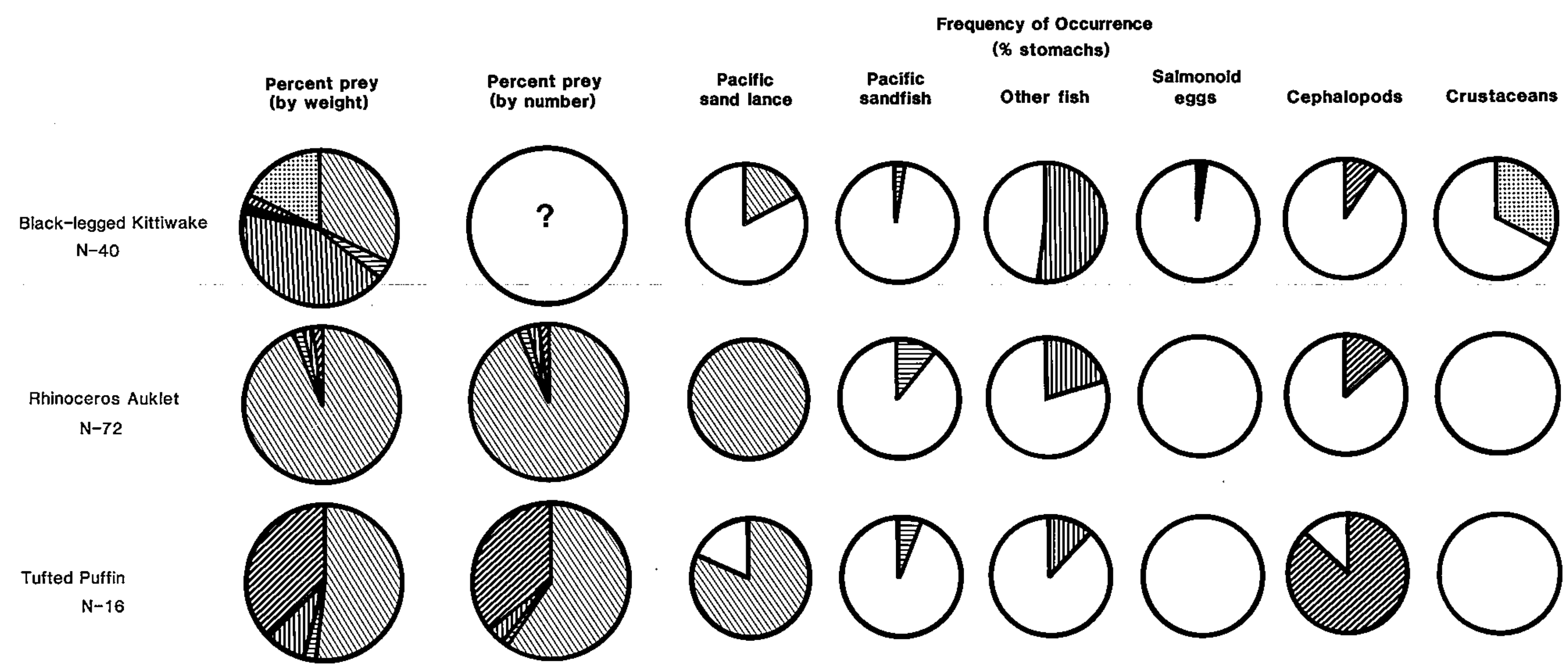


Figure 9.16 Diets of Black-legged Kittiwake, Rhinoceros Auklet, and Tufted Puffin chicks on Middleton Island (Hatch et al., 1979).

species. The heavy use of capelin by birds in other areas of the Gulf of Alaska seems to follow a pattern similar to that found by Harris and Hislop (1978). Hatch et al. (1979) report normal growth rates for kittiwakes and puffins on Middleton in spite of the lack of capelin in the chicks' diet.

9.5.3 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 9.7). 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 9.8) support this conclusion. They also present evidence that puffins have 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 9.7).

Table 9.7 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 9.8 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

9.6 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. Gorman and Simms (1978) asserted that the ingestion of crude oil had no effect on the growth of young chickens, ducks, and gulls. They suggest that Miller et al. used experimental animals which had completed their natural growth before the experiment began. Szaro (1977) suggested that oil ingestion, while perhaps not a major cause of seabird mortality, could affect the birds' physiology and reproduction.

Holmes and Cronshaw (1977) found that ducks maintained under laboratory conditions tolerated the chronic administration of oil-contaminated food. Those subjected to cold stress, however, showed increased mortality.

In addition to indirect effects on reproduction through ingestion of oil, breeding seabirds can transmit oil from their plumage to their eggs Experiments have shown that "minute quantities" of No. 2 fuel oil applied to eggs caused significant embryo mortality and reduced hatchability in the eggs of aquatic birds (White et al., 1979). Albers (1978) showed that oiling of eggs was most lethal when adult birds were in the early stages of incubation. Grau et al. (1978) studied effects of oil on eggs of Cassin's Auklets (Ptychoramphus aleuticus) on the Farallon Islands in California. They found a reduction in 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 include 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 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, because of the short food chains and lack of alternative food sources. An expected result would be a decrease in the carrying capacity of the habitat for marine birds (McKnight and Knoder, 1979). Other elements of the food chain would then be affected as well. The bird groups most likely to be affected by oil development are alcids, which constitute the majority of birds inhabiting coastal areas in winter, and the sea ducks, because of their diving and flocking habits and their flightless molt period (McKnight and Knoder, 1979).

King and Sanger (1979) have devised an Oil Vulnerability Index (OVI) for marine birds of the northeast Pacific. It is based on such characteristics of the species as range, population, habits, mortality, and exposure to oil development. Birds with high indices are more vulnerable to oil development than those with lower indices. King and Sanger (1979) confirm that alcids and sea ducks are the most vulnerable groups. Table 9.9 shows OVI's for water birds of NEGOA. They are arranged according to ranges of OVI. According to King and Sanger (1979), an OVI of 1-20 indicates species with low vulnerability; damage or future costs would not be expected. An OVI of 21-40 indicates species for which there is low concern. An OVI of 41-60 indicates species for which it would not be considered catastrophic if some birds were adversely affected. However, these species should 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 the number of species in NEGOA with a higher OVI is greater than the number in southeast Alaska, and similar to that in the Aleutian Islands. This indicates that the birds of NEGOA, as a whole, are more vulnerable to oil development than are those of southeast Alaska.

Table 9.9 Oil Vulnerability Indices of NEGOA marine birds.

OVI 1-20		OVI 21-40		OVI 41-60		OVI 61-80		OVI 81-100	
Scaled Petrel	1	Great Blue Heron	29	Common Loon	47	Yellow-billed Loon	65	Pigeon Guillemot	82
		Canada Goose	34	Arctic Loon	58	Fork-tailed Storm-Petrel	67	Marbled Murrelet	84
		White-fronted Goose	36	Red-throated Loon	49	Leach's Storm-Petrel	63	Kittlitz's Murrelet	88
		Snow Goose	32	Horned Grebe	48	Pelagic Cormorant	63	Cassin's Auklet	84
		Mallard	36	Red-necked Grebe	44	Red-faced Cormorant	67		
		Gadwall	38	Black-footed Albatross	50	Trumpeter Swan	63		
		Pintail	36	Laysan Albatross	52	Black Brant	70		
		Common Teal	34	Northern Fulmar	57	Emperor Goose	70		
		American Wigeon	36	Sooty Shearwater	51	White-winged Scoter	72		
		Northern Shoveler	34	Short-tailed Shearwater	53	Surf Scoter	72		
		Sandhill Crane	24	Double-crested Cormorant	52	Common Scoter	72		
		Semipalmated Plover	28	Brandt's Cormorant	57	Black Oystercatcher	65		
		American Golden Plover	35	Whistling Swan	50	Common Murre	70		
		Whimbrel	37	Canvasback	52	Ancient Murrelet	74		
		Spotted Sandpiper	24	Greater Scaup	52	Parakeet Auklet	80		
		Greater Yellowlegs	30	Common Goldeneye	48	Rhinoceros Auklet	74		
		Lesser Yellowlegs	30	Barrow's Goldeneye	56	Horned Puffin	72		
		Red Knot	39	Bufflehead	52	Tufted Puffin	72		
		Pectoral Sandpiper	32	Oldsquaw	66				
		Baird's Sandpiper	34	Harlequin Duck	60				
		Least Sandpiper	34	Common Merganser	56				
		Semipalmated Sandpiper	34	Red-breasted Merganser	56				
		Common Snipe	29	Bald Eagle	58				
		Long-tailed Jaeger	39	Peregrine Falcon	41				
		Herring Gull	38	Black-bellied Plover	43				
		Bonaparte's Gull	40	Wandering Tattler	48				
		Arctic Tern	32	Red Phalarope	58				
		Common Raven	21	Northern Phalarope	62				
				Black Turnstone	57				
				Ruddy Turnstone	44				
				Surfbird	54				
				Rock Sandpiper	59				
				Dunlin	41				
				Western Sandpiper	47				
				Sanderling	45				
				Short-billed Dowitcher	45				
				Long-billed Dowitcher	47				
				Pomarine Jaeger	41				
				Parasitic Jaeger	43				
				Glaucous Gull	45				
				Glaucous-winged Gull	56				
				Thayer's Gull	42				
				Mew Gull	44				
				Black-legged Kittiwake	49				
				Sabine's Gull	44				
				Aleutian Tern	53				
				Northwestern Crow	47				
TOTALS	1		903		2328		1251		338

Another hazard to birds living in NEGOA 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 NEGOA in winter.

CHAPTER 10 MAMMALS

Bruce R. Mate, SAI

10.1 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 the regulation of subsistence harvests, walrus management was returned to the federal government. As a result, virtually all marine mammal management is regulated by 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). Several populations of each of the species of large cetaceans have been so depleted that they have been designated as endangered or threatened by the Endangered Species Act of 1973 and by the International Whaling Commission. Northern fur seals are harvested by the U.S. under the Convention on Conservation of North Pacific Fur Seals (CNPFS), signed by Japan, the U.S.S.R., 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.

Little is known about most marine mammal species. Even enumeration of the populations can be difficult. Most current studies are basic, emphasizing descriptive natural history. Comprehensive data may never be available, even for a single tract. Thus, data collected from other areas may have to be used for planning of development. Although a site may be of only seasonal importance to these highly migratory mammals, lease decisions may require examination of the status of a species over its entire range.

All marine mammals are modified for living in the sea, and they share many characteristics. As they spend much of their time in cold waters, most have adaptations to maintain body temperature, such as thick layers of subcutaneous fat and countercurrent heat exchangers in the circulation to the 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. Thus, they may be affected by changes in the abundance and quality of organisms lower in the web.

Current knowledge of the marine mammals which occur in NEGOA is discussed below according to their dependency on the sea. The discussion begins with the cetaceans, which spend their entire lives in the water, and ends with species which venture into marine environments only occasionally.

10.2 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. The fastest animals in the sea are cetaceans; 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) entangled in a cable at 1,134 m. Sperm whales have been tracked on sonar to nearly 1,828 m and by hydrophone to 2,427 m. Inferential evidence suggests diving capability in excess of 3,150 m, and there is speculation that 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).

10.2.1 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 take food-rich water into their mouth and pass it 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

Baleen whales are thought to migrate to productive polar waters in summer for feeding and then to temperate or subtropical waters in winter to give birth and to mate. Most information regarding movements of individual whales and the identification of discrete populations has come from "discovery" tags. These are numbered shafts shot into whales which are subsequently recovered by commercial whalers.

Seven of the nine known species of baleen whales occur in the Gulf of Alaska (Table 10.1): gray whale (Eschrichtius robustus), minke whale (Balaenoptera acutorostrata), sei whale (B. borealis), fin whale (B. physalus), blue whale (B. musculus), humpback whale

Table 10.1 Seasonal presence, habitat type, and areas of peak occurrence of baleen whales most commonly reported in NEGOA (Braham, pers. comm.).

Species	Season* Winter	Spring	Summer	Fall	Habitat type	Areas of probable peak occurrence
Gray whale**	M+F?	M+F?	F	FM+	Coastal	All coastal waters
Minke whale		F	F	M	Coastal	All coastal waters and shelf
Sei whale**		F	F		Shelf/offshore	Portlock and Albatross Banks
Fin whale**			F?		Nearshore/shelf	"
Blue whale			F	M	Offshore	?
Humpback whale**		FM	F	M	Coastal	Prince William Sound & Entrance
Right whale**			F		Shelf	?

* Winter = Dec-Feb, Spring = Mar-May, Summer = June-Aug, Fall = Sep-Nov
F = feeding grounds
M = migration route
\+ = nearshore waters appear to be critical during annual life cycles
** = endangered species

(*Megaptera novaeangliae*), and right whale (*Balaena glacialis*). All 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, might possibly stray into the gulf, although this is unlikely and there are no records of its occurrence.

The migration of the gray whale is the best known of the large whales because of the nearshore movements of this species along the eastern Pacific. The gray whale calves and breeds from December through April in three major lagoon areas on the Pacific side of Baja California and migrates north in the spring through shallow waters to its summer foraging areas in the Bering, Chukchi, and Beaufort Seas (Rice and Wolman, 1971). This is the longest known mammalian migration, a round trip of 10,000 to 22,000 km (Vaughan, 1972). Observations of gray whales made during the northbound spring migration through NEGOA are shown in Fig. 10.1.

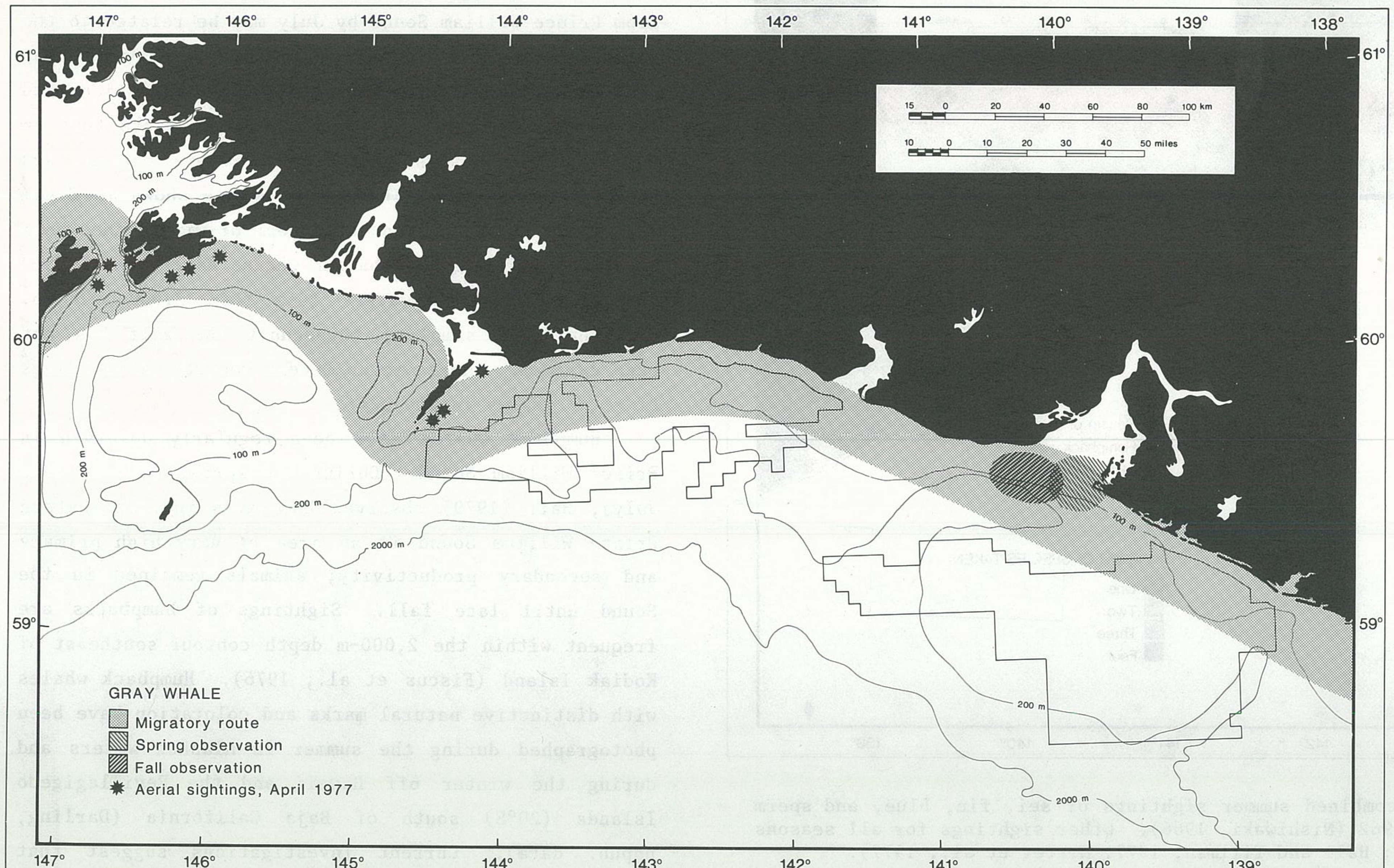


Figure 10.1 Probable migratory route of the gray whale (Braham, National Marine Mammal Laboratory, unpub. data; Hall, 1979; Hall and Tillman, 1977).

Southbound migration in the fall is probably similar. Both migrations are very close to shore, although migrating gray whales have occasionally been sighted offshore (Braham, 1977; Braham et al., 1977; Hall, 1979). In some areas, during good weather in autumn, about 70 percent of the migrants are found within 700 m of the shore (Rugh and Braham, 1978; Hall, 1979). Most of the sightings in NEGOA are in waters less than 200 m deep.

Observations at Unimak Pass (the closest navigable channel of the Aleutian chain to the Alaska mainland), off central Oregon, and off southern California have documented the timing of the fall and spring migrations and also have produced the first accurate population estimates by season through direct observation for any of the large whales. Recent radio tagging of a gray whale indicates that the northbound migration speed is approximately 110 km/day (Mate, unpub. data).

While more is known of the seasonal movements of this species than of those of any other large whale, little is known of its offshore distribution in its shallow arctic and subarctic feeding areas. Although previously thought to feed only in the latter areas, gray whales have been observed feeding during the migration and in summer in more temperate areas (Darling, unpub. data; Sumich and Mate, unpub. data).

Whaling records show that the entire Gulf of Alaska 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 in and near Prince William Sound and in the region south of Montague Island (Fiscus et al., 1976; Hall, 1979). Figure 10.2 shows the distribution of sightings of minke, sei, blue, and humpback whales in NEGOA by whalers from 1945 to 1962 (Nishiwaki, 1966) and for all seasons from 1958 through 1976 (Fiscus et al., 1976).

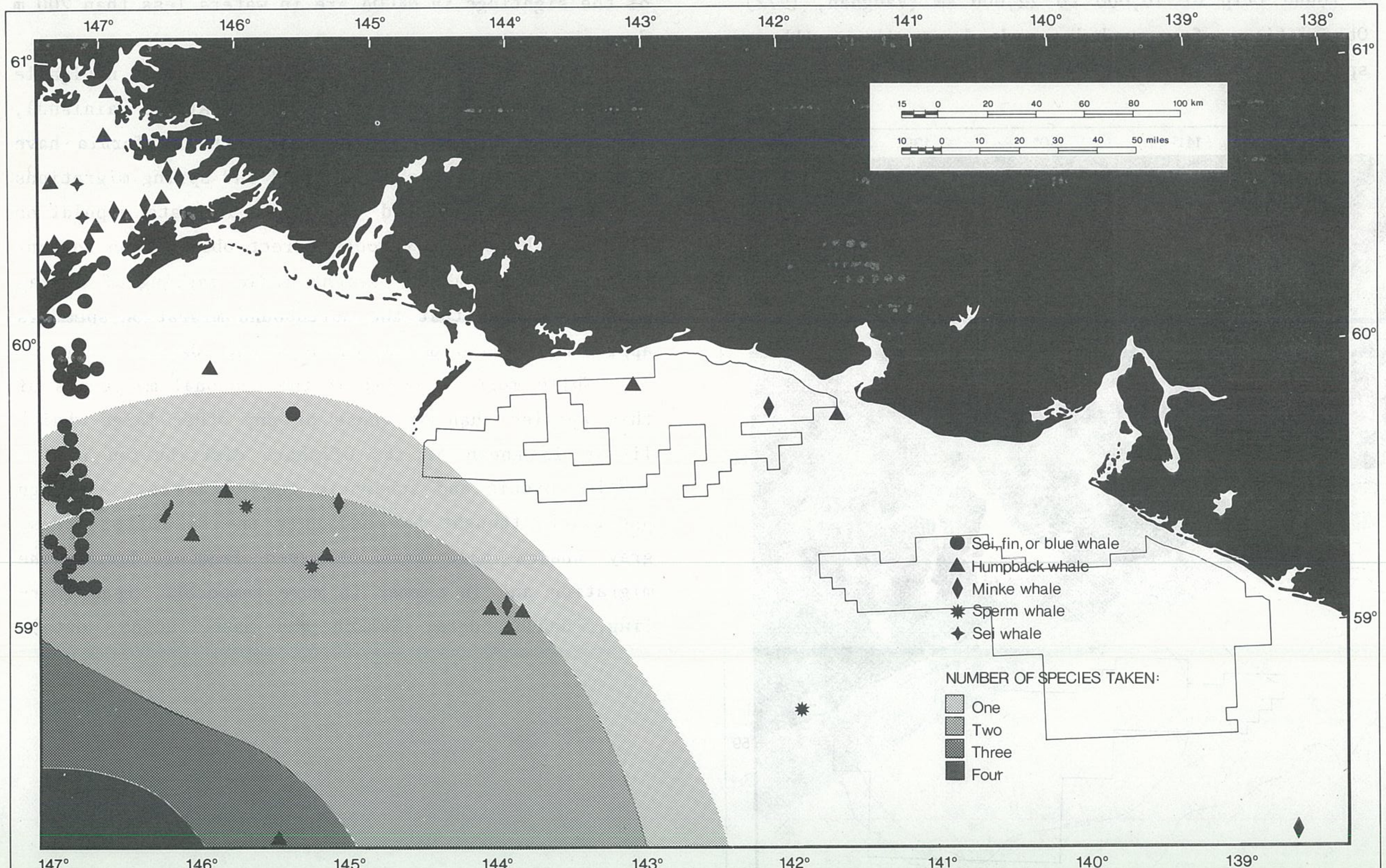
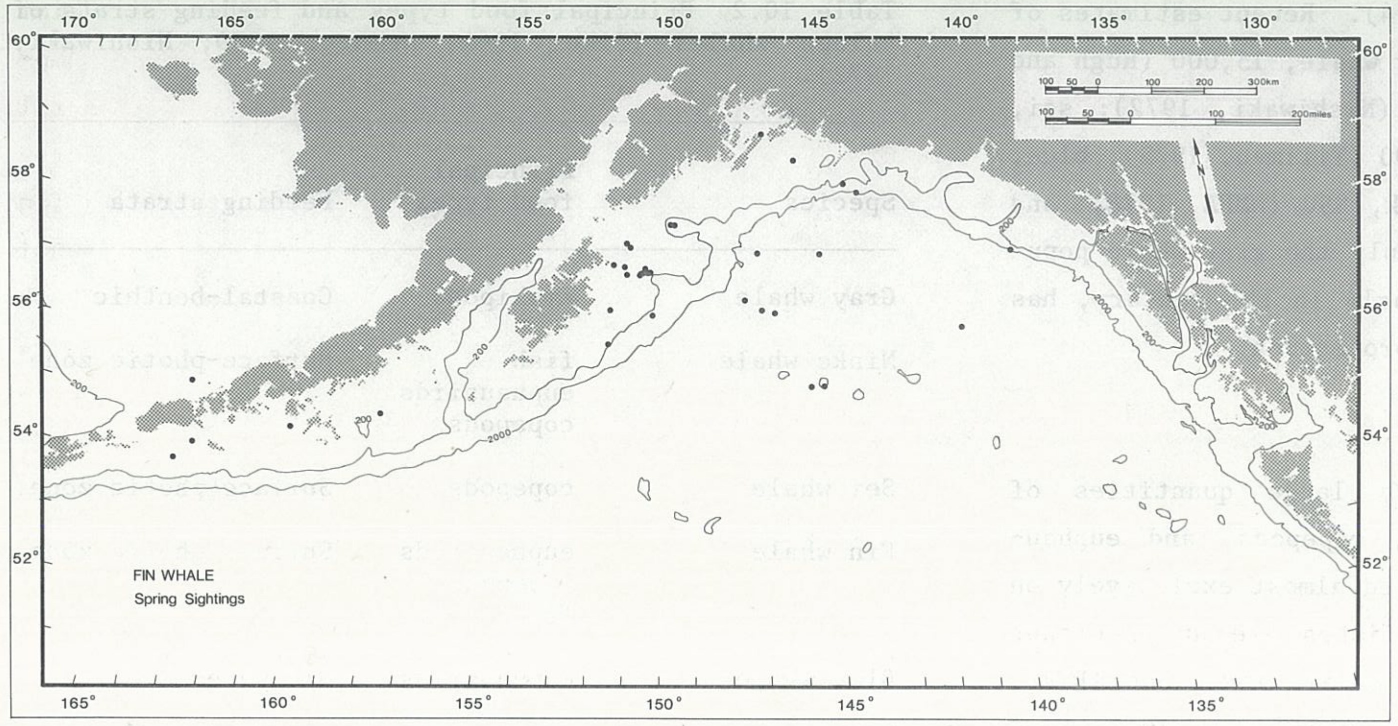
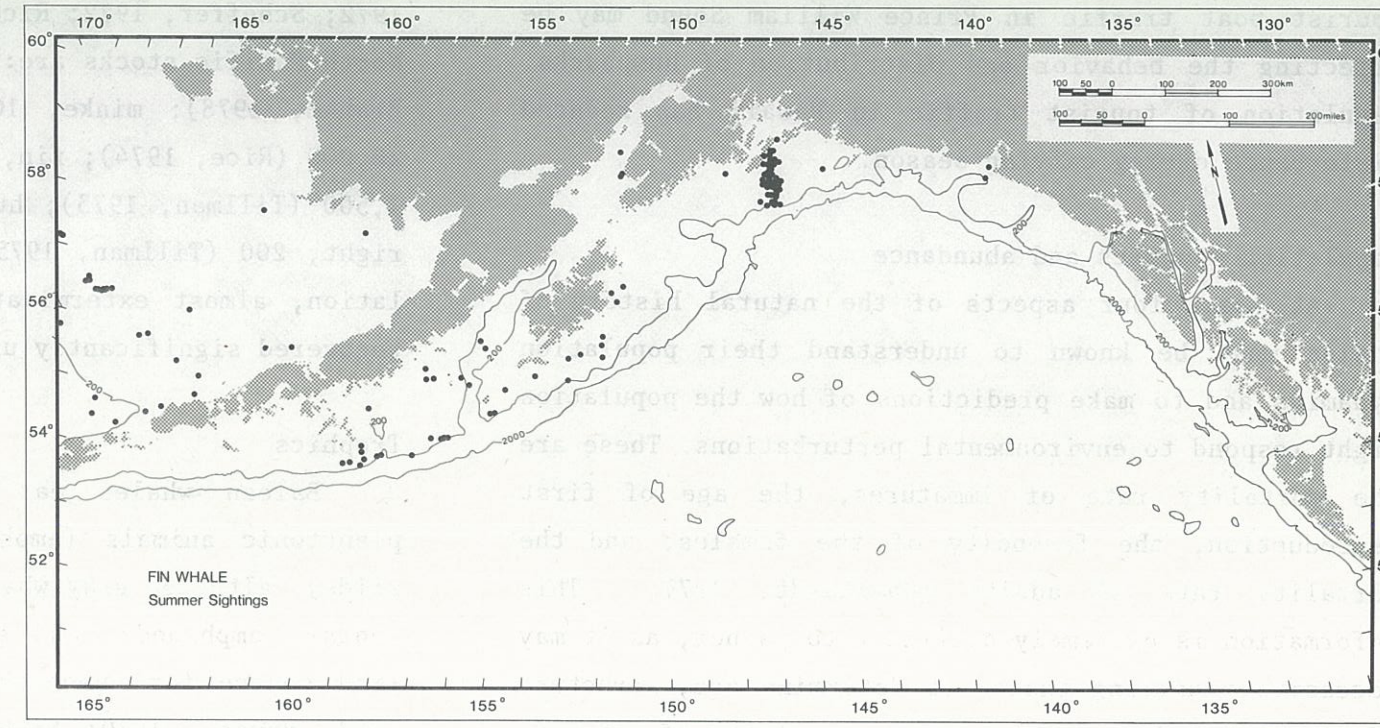


Figure 10.2 Sightings of whales. Shaded areas represent combined summer sightings of sei, fin, blue, and sperm whales based on Japanese whaling results from 1945 through 1962 (Nishiwaki, 1966). Other sightings for all seasons 1958 through 1974 are shown individually (Fiscus et al., 1976; Hall and Tillman, 1977; Mercer et al., 1977).

In population studies of cetaceans in Prince William Sound and its adjacent waters, Hall (1979) found humpback whales from May to November, fin whales from April through June, and minke whales from May through October. 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. 10.3. It demonstrates that this species occurs in NEGOA primarily in the spring, although some individuals occur throughout the year in the western gulf. Hall (1979) suggests that the departure of fin whales from Prince William Sound by July may be related to the concurrent decline in secondary productivity in that area and a continuation of the fin whale migration into the western Bering Sea. Nasu (1974) suggests that in summer baleen whales prefer areas where coastal and oceanic waters mix. The distributions shown in Figs. 10.2 and 10.3 are concentrated near or within the shelf break and indicate that baleen whales have been sighted most frequently in waters less than 2,000 m deep. Unfortunately, sampling throughout the gulf has not been uniform. There are no recent reports of sightings of right whales in the gulf.

Humpback whales have been regularly observed in Prince William Sound. During the spring (May to late July), Hall (1979) observed humpbacks in northeastern Prince William Sound in an area of very high primary and secondary productivity; animals remained in the Sound until late fall. Sightings of humpbacks are frequent within the 2,000-m depth contour southeast of Kodiak Island (Fiscus et al., 1976). Humpback whales with distinctive natural marks and coloration have been photographed during the summer in Alaskan waters and during the winter off Hawaii and the Revillagigedo Islands (20°S) south of Baja California (Darling, unpub. data). Current investigations suggest that





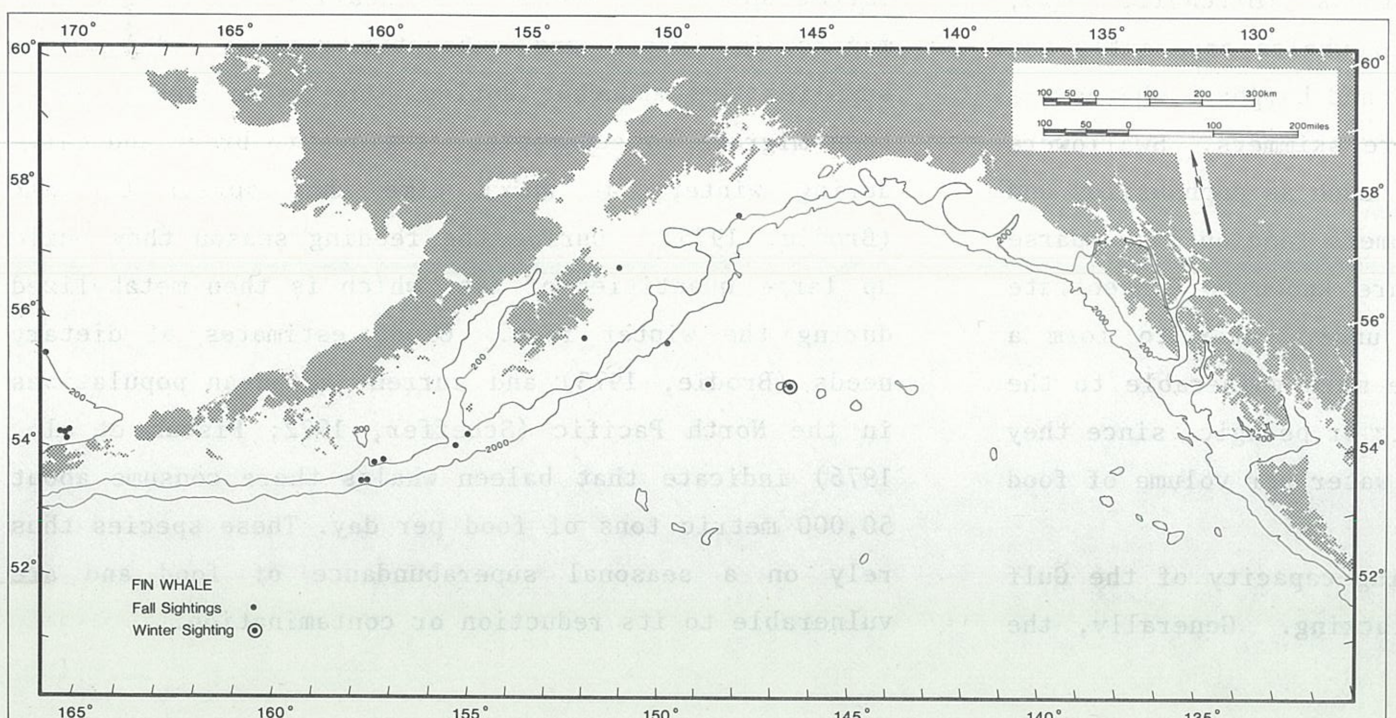


Figure 10.3 Seasonal distribution of sightings of fin whales (Braham, National Marine Mammal Laboratory, unpub. data).

tourist boat traffic in Prince William Sound may be affecting the behavior and distribution of humpbacks. Regulation of tourist traffic in Hawaii has reduced disturbance during calving season.

Population dynamics and abundance

At least four 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 mortality rate of immatures, the age of first reproduction, the fecundity of the females, and the mortality rate of adults (Eberhardt, 1977). This information is extremely difficult to gather, as it may necessitate killing whales to determine age, structure of the population, and reproductive status of individuals. Even population estimates are difficult to obtain due to the short periods that cetaceans are at the surface. Small and/or widely distributed populations are especially difficult to estimate. Direct counts of all baleen whale populations, except possibly those of gray whales, are impossible.

Reproductive rates are usually low for large, long-lived animals. The gestation period for baleen whales is 10 to 12 months. Females probably breed only once every two years (Nishiwaki, 1972; Vaughan, 1972), but they may breed as infrequently as once in four years, as is 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 so declined that most are now believed to be endangered (Nishiwaki, 1972; Scheffer, 1972; Rice, 1974). Recent estimates of North Pacific stocks are: gray whale, 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, almost exterminated early in the century, has recovered significantly under protection.

Trophics

Baleen whales eat mainly large quantities of planktonic animals (amphipods, copepods, and euphausiids), although gray whales feed almost exclusively on benthic amphipods, and small fishes are an important food source for humpbacks in certain locations (Pike, 1962; Nemoto, 1970; Nishiwaki, 1972; Table 10.2; Fig. 10.4). Baleen whales have two typical pelagic feeding patterns: swallowing, in which large patches of clumped prey are ingested all at once, 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 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 using exhaled air under water 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, at which time they appear to fast (Brodie, 1975). During the feeding season they build up large quantities of fat, which is then metabolized during the winter fast. 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.

Table 10.2 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

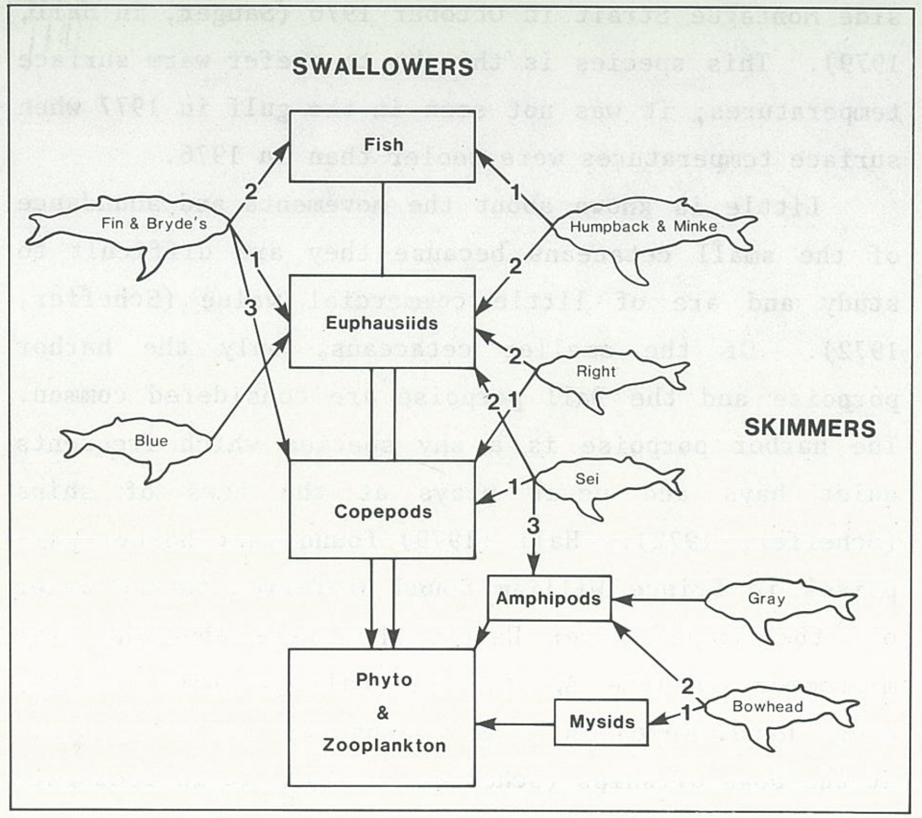


Figure 10.4 Generalized food web showing predation by swallowing and skimming baleen whales on main food sources. "Skimmers" strain a long column of water with the mouth continuously open, whereas "swallowers" gulp a mouthful at a time, then close the mouth, squeeze the water out, and retain the food (modified from Mitchell, 1978).

10.2.2 Toothed whales, dolphins, and porpoises (Odontoceti)

Odontoceti are distinguished from other cetaceans 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 (Table 10.3): 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 occur casually or hypothetically in the gulf. It is likely that other Pacific species 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, and harbor porpoise in NEGOA (Fiscus et al., 1976; Mercer et al., 1977) for all seasons 1958 through 1976 is shown in Fig. 10.5. The distribution of these sightings, like those of baleen whales, suggests that these species prefer areas within the shelf break.

Table 10.3 Seasonal presence, habitat type, and areas of peak occurrence of toothed cetaceans most commonly reported in NEGOA (Braham, pers. comm.).

Species	Season* Winter	Spring	Summer	Fall	Habitat type	Areas of probable peak occurrence
Killer whale		FM	FM	M?	Coastal/pelagic	?
Harbor porpoise	F?+	C?+	CF	F	Shallow bays/rivers/ estuaries	coastal waters
Dall porpoise	F?	C?FM?	FM?	F	Deeper bays/shelf/ slope	common pelagically
Beluga	F?	C?F	F+	F	Bays/rivers/estuaries	Cook Inlet, winter?
Sperm whale**			F?		Offshore	?

*Winter = Dec-Feb, Spring = Mar-May, Summer = Jun-Aug, Fall = Sep-Nov
C = suspected calving area
F = feeding grounds
M = migration route
\+ = nearshore waters appear to be critical during annual life cycles
** = endangered species

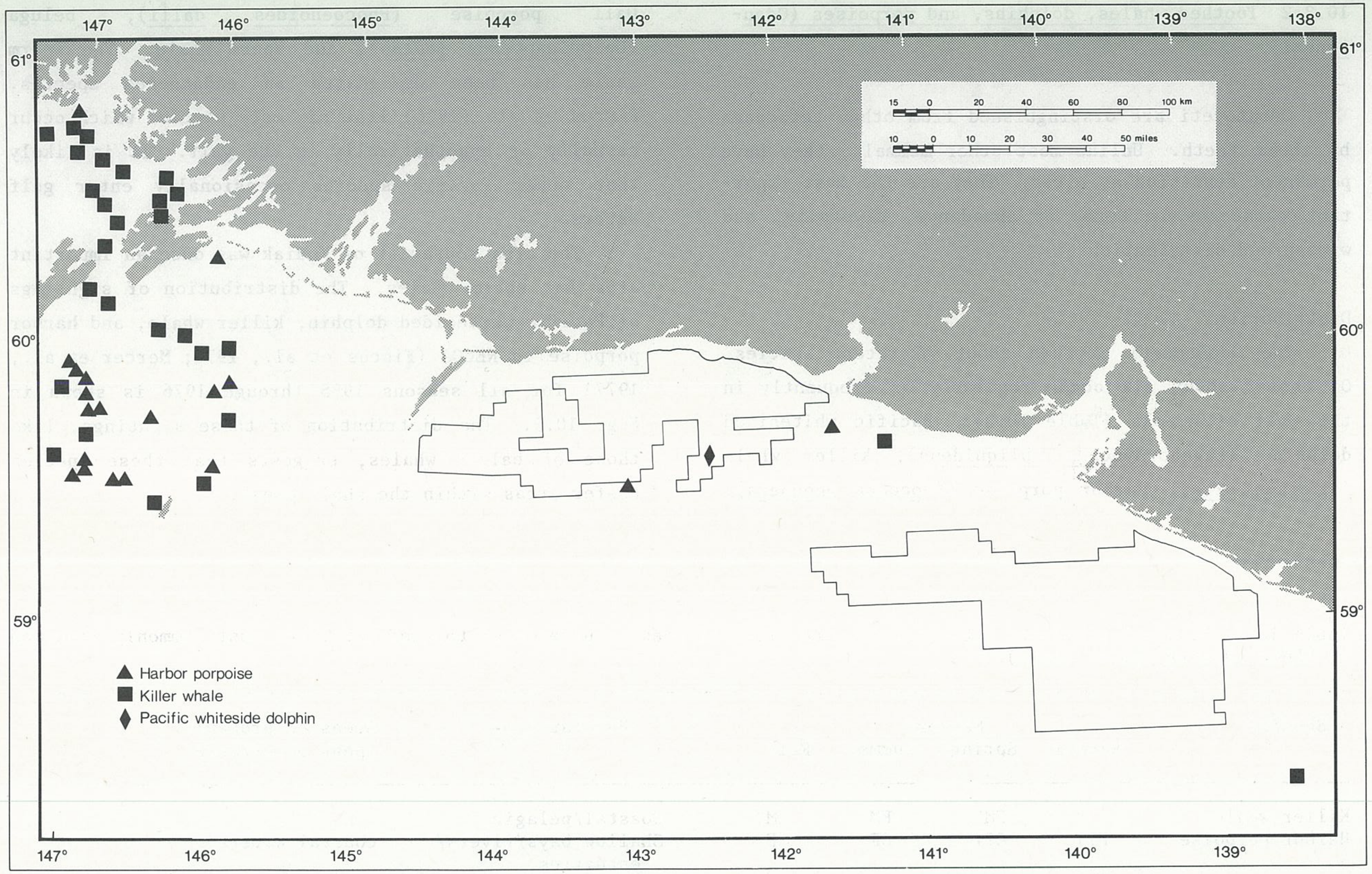


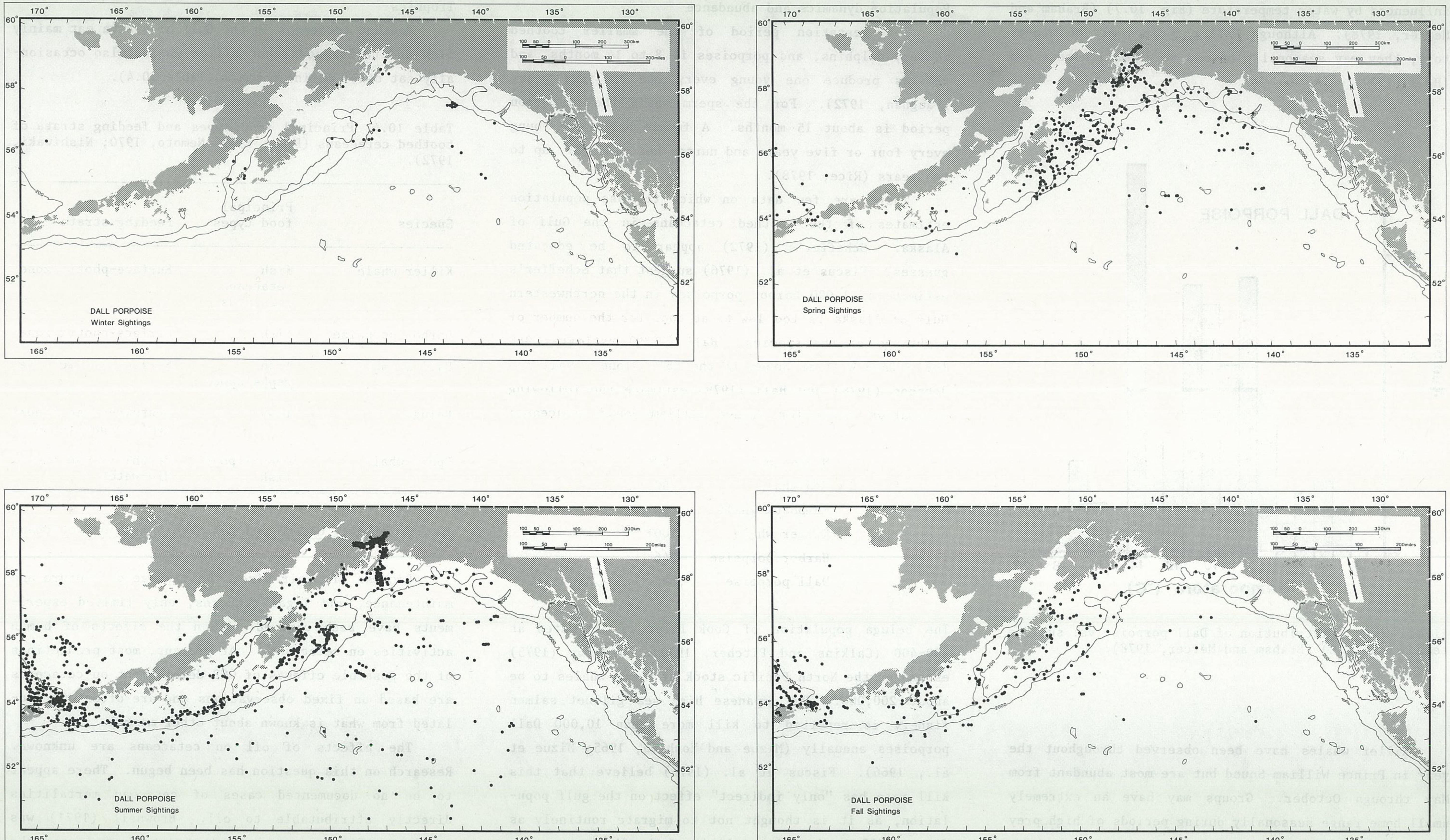
Figure 10.5 Sightings of Pacific whiteside dolphin, killer whale, and harbor porpoise, all seasons 1958-77 (Fiscus et al., 1976; Hall and Tillman, 1977; Mercer et al., 1977).

Beluga whales are observed all year in Lower Cook Inlet, with largest number occurring in the summer (Murray, in Calkins and Pitcher, 1979). The Lower Cook population is thought to be geographically isolated (Sergeant and Brodie, 1969), and thus it may be genetically distinct from the year-round Bering Sea population. The wintering population varies with ice concentrations and in years of heavy ice, the Cook Inlet population is low, perhaps explaining sightings in Yakutat Bay. Harrison and Hall (1978) saw belugas near Kodiak only twice (one in March and two in July) in 40,000 km of aerial surveys in the gulf.

Although the Pacific whitesided dolphin is rarely seen in the gulf, several hundred were seen just outside Montague Strait in October 1976 (Sanger, in Hall, 1979). This species is thought to prefer warm surface temperatures; it was not seen in the gulf in 1977 when surface temperatures were cooler than in 1976.

Little is known about the movements and abundance of the small cetaceans because they are difficult to study and are of little commercial value (Scheffer, 1972). Of the smaller cetaceans, only the harbor porpoise and the Dall porpoise are considered common. The harbor porpoise is a shy species which frequents quiet bays and never plays at the bows of ships (Scheffer, 1972). Hall (1979) found that harbor porpoises in Prince William Sound preferred turbid water off the Copper River Delta; they were abundant from midsummer to late April. The Dall porpoise, on the other hand, feeds in large groups and and often plays at the bows of ships (Scheffer, 1972). It is frequently reported from shipboard surveys. The seasonal distribution of sightings of Dall porpoise is shown in Fig. 10.6. These sightings show that Dall porpoise occur throughout the Gulf of Alaska in all seasons, with an apparent concentration from Kodiak waters to Prince William Sound in the spring and summer (Braham and Mercer, 1978). In Prince William Sound, Dall porpoise are most abundant in summer and fall (an estimated 6,756 individuals) and are rarely found in water less than 20 m deep (Hall, 1979). The presence of the species in the Gulf of Alaska may be strongly

Figure 10.6 Seasonal distribution of sightings of Dall porpoise (Braham, National Marine Mammal Laboratory, unpub. data).


DALL PORPOISE
Winter Sightings
DALL PORPOISE
Spring Sightings
DALL PORPOISE
Summer Sightings
DALL PORPOISE
Fall Sightings
170° 165° 160° 155° 150° 145° 140° 135° 130°
60° 58° 56° 54° 52°
100 50 0 100 200 300km
100 50 0 100 200miles
2000

influenced by water temperature (Fig. 10.7) (Braham and Mercer, 1978). Although Dall porpoises may be migratory, they may seasonally have a very small home range (Hall, 1979).

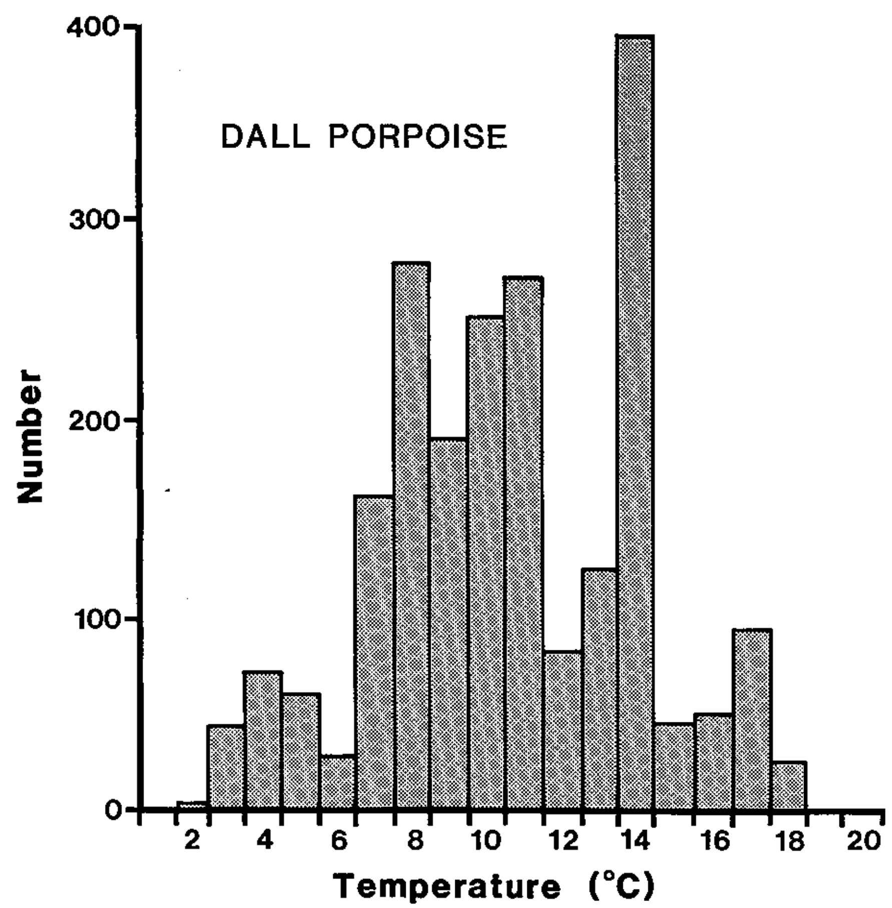


Figure 10.7 Distribution of Dall porpoise vs. surface temperature (°C) (Braham and Mercer, 1978).

Killer whales have been observed throughout the year in Prince William Sound but are most abundant from May through October. Groups may have an extremely small home range seasonally during periods of high prey abundance (Hall, 1979).

Population dynamics and abundance

The gestation period of the smaller toothed whales, dolphins, and porpoises is 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. A female bears one young every four or five years and nurses her calf for up to two years (Rice, 1978).

There are few data on which to base population estimates of the toothed cetaceans in the Gulf of Alaska. Scheffer's (1972) appear to be educated guesses. Fiscus et al. (1976) suggest that Scheffer's estimate of 1,000 harbor porpoises in the northwestern Gulf of Alaska is too low to account for the number of sightings of the species. Hall (1979) estimates 946 for Prince William Sound in the fall alone. Hall and Johnson (1978) and Hall (1979) estimate the following population sizes for Prince William Sound cetaceans:

Minke whale	50+
Fin whale	50
Humpback whale	50+
Killer whale	100+
Harbor porpoise	946
Dall porpoise	7,328

The beluga population of Cook Inlet is estimated at 300-400 (Calkins and Pitcher, 1979). 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 Dall 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 as 175° W, the eastern limit of the fishery.

Trophics

Toothed cetaceans in the Gulf of Alaska eat mainly fish and cephalopods, but killer whales also occasionally eat other marine mammals (Table 10.4).

Table 10.4 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
Dall porpoise	fish cephalopods	Surface-photic zone
Beluga	fish	Benthic-ocean floor Surface-photic zone
Sperm whale	cephalopods fish	Benthic-ocean floor Mid-water

10.2.3 Effects of oil and gas development on cetaceans

Because of their size, the expense of capture and maintenance, and legal concerns, only limited experiments have been carried out on the effects of human activities on cetaceans. At present, most predictions of the possible effects of OCS development on cetaceans are based on fixed observations and are often extrapolated from what is known about other mammals.

The effects of oil on cetaceans are unknown. Research on this question has been begun. 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 on the fouling of baleen by oil are under way. 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.

Cetaceans produce a wide variety of sounds which are believed to be important in their communication and navigation (Caldwell and Caldwell, 1972; Thompson et al., 1979). Background noise from human activities could cause social disruption or echo-confusion. The effects of noise on cetaceans are under study.

10.3 PINNIPEDS

Pinniped morphology and behavior have been modified for an amphibious marine life. All species use the land (or ice) to breed, give birth, and molt. 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 (Callorhinus ursinus) is believed to have the longest migratory path of all pinnipeds and may travel 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 of pinnipeds is enveloped in a thick layer of fat, which provides insulation and an energy reserve during lactation and fasting. The eyes are large, 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 seal, 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 the 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 have 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 females in estrus. Pups may be suckled for over eight months in some species.

Phocids swim primarily with their hind flippers and 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 are usually weaned within six weeks (Pitcher and Calkins, 1980).

Distribution and abundance

The northern sea lion is distinctive in its use of a few specific locations along the coast as rookeries (for breeding and pupping) and hauling grounds. In early May the adults gather on the 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. Many of the areas used as rookeries are also used as hauling areas throughout the rest of the year. Some locations are used exclusively as rookeries or for hauling.

Northern sea lion haulout areas and rookeries occur throughout the Gulf of Alaska (Fig. 10.8) (Calkins and Pitcher, 1979). The size of the adult population is in excess of 52,000 during the breeding

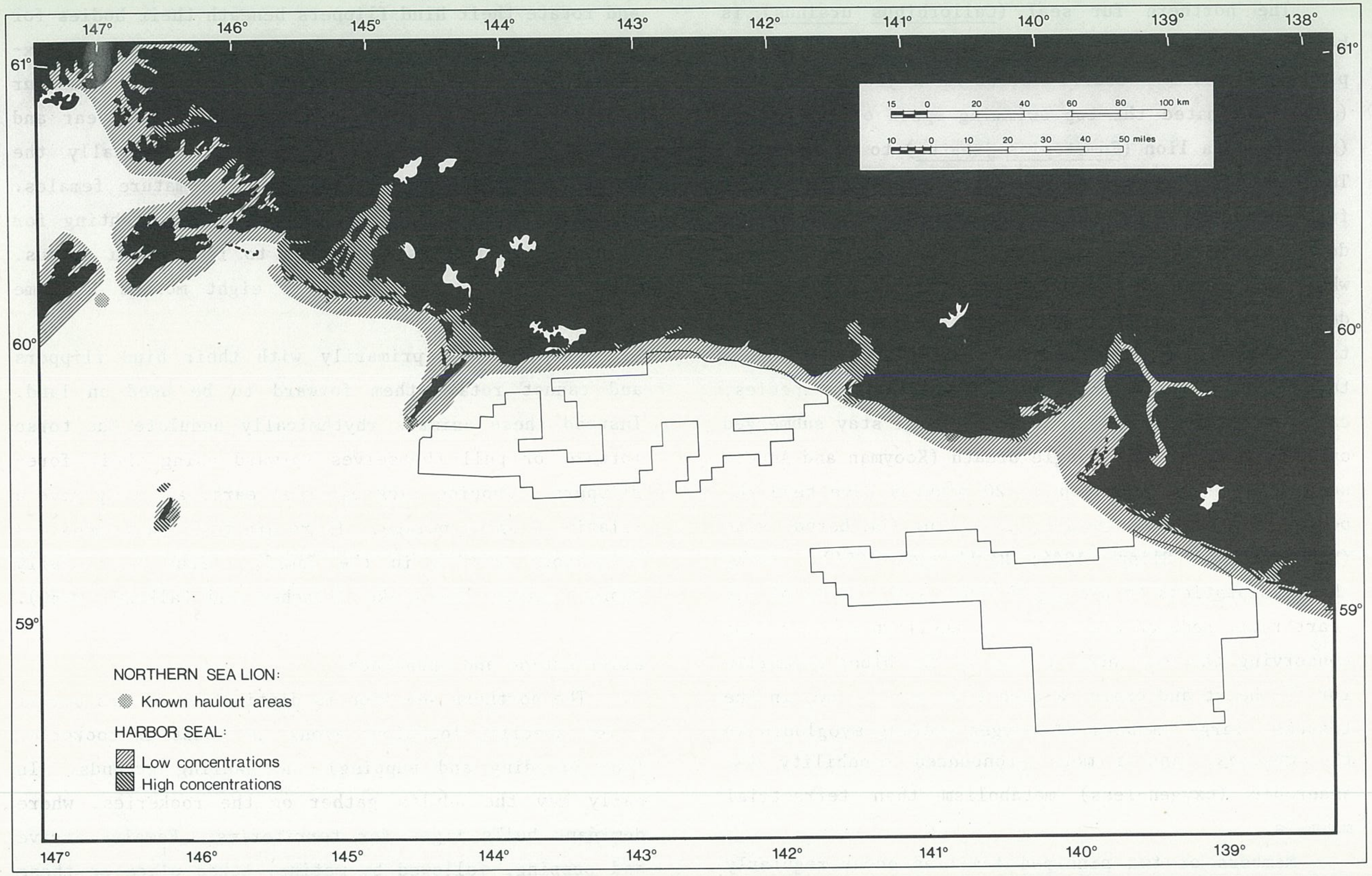


Figure 10.8 Distribution of northern sea lions and harbor seals (ADF&G, 1973; Calkins and Pitcher, 1977; Calkins et al., 1975; Pitcher, 1975).

season. 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 occurring in the Gulf. Major rookeries in or near NEGOA are Seal Rocks (Fig. 10.8), Chiswell Island, and Outer Island. In 1978 7,082 adults and approximately 1,000 pups (4 percent of the pups produced in the Gulf of Alaska) occupied these three rookeries. Sitkagi Bluffs and Middleton Island are hauling areas in NEGOA. During winter and spring as many as 3,000 sea lions (mostly at Middleton) may haul out here. These may represent a redistribution from the rookeries (Calkins and Pitcher, 1977).

Observations indicate that sea lions range out to the shelf break throughout the year (Mercer et al., 1977).

Considerable movement of sea lions in the Gulf of Alaska has been detected by observing individuals branded on their natal rookeries in 1975 and 1976 (Calkins and Pitcher, 1979). Fig. 10.9 illustrates the dispersion of some branded animals. These movements appear to represent 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), 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 had largely moved away from their natal rookeries and were sighted at haulouts from Chirikof and the Semidi Islands in the southwest to Cape St. Elias in the northeast. Studies at Cape St. Elias and Sugarloaf Island indicate differences in haulout patterns for branded sea lions. Branding studies thus yield considerable information on the dispersal and seasonal movements of sea lions. This information may be extremely important in predicting the long-term effects of spills or blowouts on this species (Calkins and Pitcher, 1979).

Northern fur seals occur in open water throughout the Gulf of Alaska, with high concentrations reported around Middleton Island off Cape St. Elias, and just east of NEGOA on the Fairweather Grounds (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 also occur (Fig. 10.10). Almost all of the approximately 1,400,000 animals in the Pribilof Islands breeding

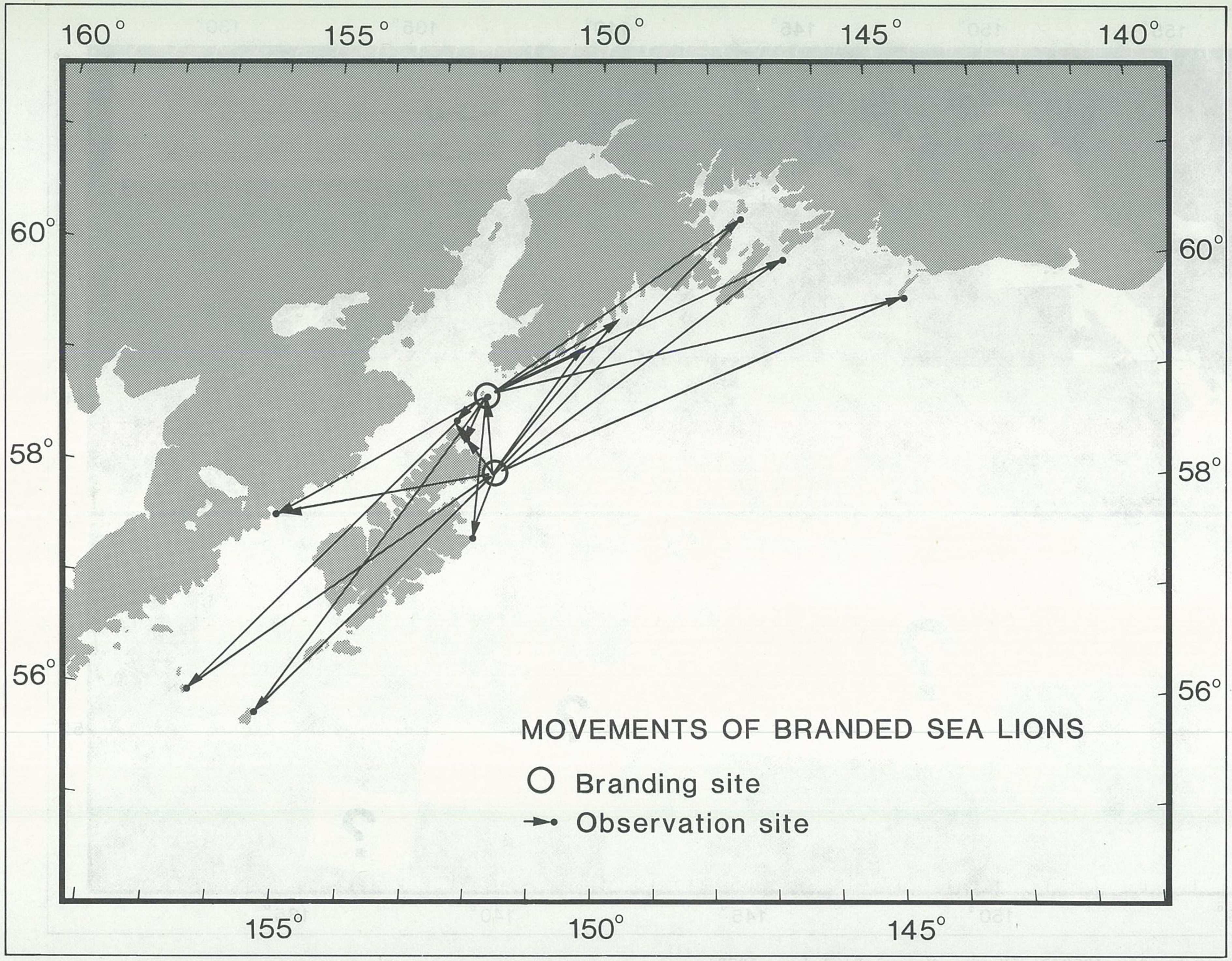


Figure 10.9 Movements of branded northern (Steller) sea lions. Site of banding and site of relocation are connected with straight lines; actual paths taken by the sea lions are unknown (Calkins and Pitcher, 1979).

population migrate through NEGOA (Baker et al., 1963). Immature animals begin the southward migration in August, 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. Northern fur seal movements through the Gulf of Alaska are complex, with seasonal variation 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 could be exposed year round to the effects of petroleum development but would be less vulnerable during August through October.

Calkins (ADF&G, pers. comm.) reported 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. Each year about 26,000 sub-adult males are harvested under the auspices of The Interim Convention on Conservation of North Pacific Fur Seals (USDC, 1980). The harvest and initial skin processing employs around 80 resident Aleuts and provides them with their major source of income. The cost of the harvest is about $440,000 annually while the value of pelts brings about $800,000 to the Federal Treasury (W. Kirkness, National Marine Fisheries Service, in litt.).

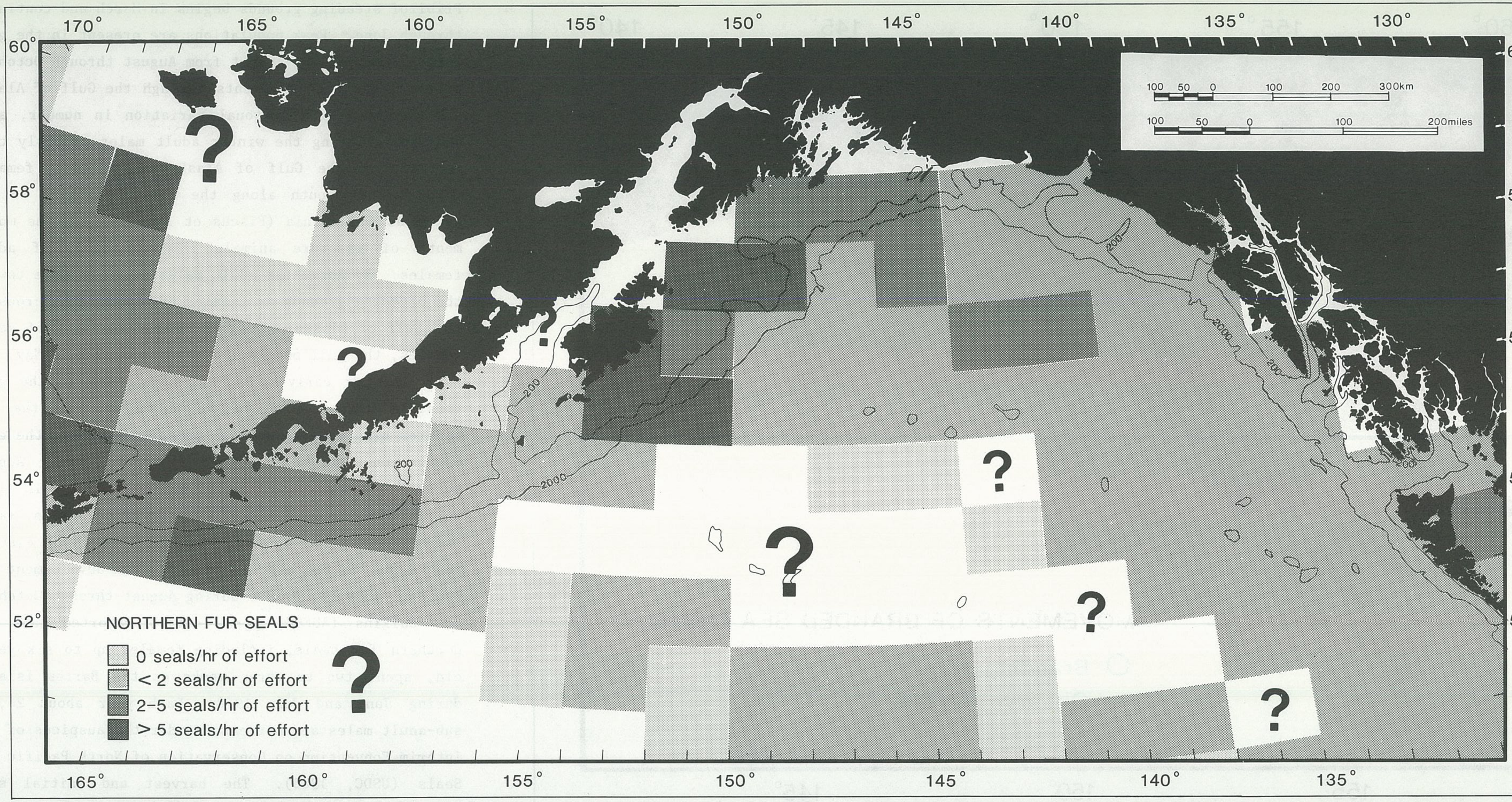


Figure 10.10 Sightings of northern fur seals in the Gulf of Alaska, 1958-74 (Marine Mammal Division, 1978).

The land-breeding harbor seal, Phoca vitulina richardsi, 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. Common residents 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, beaches of remote islands and floating ice pans calved from glaciers, when available. In winter, ice shelves which form at the heads of bays are frequently used as hauling platforms.

Harbor seals have a continuous distribution along the shoreline of NEGOA (ADF&G, 1973; Pitcher and Calkins, 1980; Fig. 10.8). Several traditional hauling areas are well populated in NEGOA (Table 10.5). There is no total estimate for the NEGOA populations, as only a fraction of the animals haul out at a time. In the Copper River Delta seals have been in conflict with the commercial gillnet fishery for 30 years. As a result, 30,000 seals were killed from 1951 to 1958, but the population is thought to have nearly recovered. Seals were reported as abundant on floating ice in Yakutat Bay, where 300 were harvested in 1969. One of the most spectacular concentrations of harbor seals was reported from Icy Bay, where floating ice is used extensively in the summer for pupping and hauling out. More than 1000 seals per year were harvested there for several years, and several thousands were estimated to be present in 1973. Calkins et al. (1975) estimated the population in excess of 5,000. When areas freeze in the winter, harbor seals apparently disperse to other, unknown areas. Calkins et al. (1975) estimated the Prince William Sound population at more than 13,000. Pitcher and Calkins (1980) counted 8,100 harbor seals scattered throughout NEGOA. Thus it is possible that the NEGOA harbor seal population exceeds 25,000. East of NEGOA the species has been reported to concentrate on icebergs in Lituya Bay.

Table 10.5 Observed harbor seal populations with more than 125 individuals (Pitcher and Calkins, 1980).

Location	Maximum Number of Seals Observed	Date
Disenchantment Bay	331	31 May 1976
Icy Bay	5,000	Summer 1975
Kaliakh River	200	28 May 1976
Controller Bay	186	26 Jul 1973
Cape St. Elias	350	Mar-Jun 1977-78
Copper River Delta	1,571	Aug 1975
Middleton Island	125	26 May 1976

The highest population counts frequently occur during the pupping and molting seasons, suggesting that the species needs to haul out at these times. Thus, harbor seals are probably particularly sensitive to human disturbance during pupping and molt periods (B. W. Johnson, 1977).

Harbor seals are usually found in water less than 200 m deep; however, individuals have been sighted up to 100 km offshore, and one radio-tagged seal moved 74 km from Tugidak Island and returned (Pitcher and Calkins, 1980).

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 compete successfully for breeding territories and access to females in estrus. Eighty-one percent of all females collected 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 copulation occurs on the territories of the bulls. Some males have semi-aquatic territories, which could result in an increased exposure to oil. Mortality of a large fraction of the population of breeding males, even though it represented only a small part of the total male population, could have long-term genetic effects on the population, as reproduction would then 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.

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 are also manipulated for maximum harvest (Marine Mammal Division, 1978).

Most of the Pribilof population migrate through or winter in the Gulf of Alaska.

The population of the northern fur seal on the Pribilofs was probably 2-3 million when first discovered in 1786. After a century of heavy harvesting fur seals had declined to an estimated low of 300,000 individuals in 1912. Under controlled management the population increased to approximately 2.2 million by the mid-1950's. It is presently estimated at 1.4 million and produces approximately 300,000 pups a year. The population worldwide is about 1.9 million. The annual harvest is approximately 35,000 subadult males.

Male fur seals must reach sexual maturity before they can compete successfully for territory. Males may be successful by age 10 and few live longer than age 15. Female fur seals may be sexually mature by age 3, although 5-7 is more common. Females give birth to single pups between late June and mid-July and breed approximately six days later. Females nurse pups on shore between progressively longer trips to sea to feed (USDC, 1979).

Harbor seal females in NEGOA ovulate for the first time between five and seven years of age (average five), while males become sexually mature at about six. The average age at first ovulation is lower in Prince William Sound and British Columbia. As the age of sexual maturity drops in many species when the population is reduced, the higher age at first ovulation in NEGOA may be a sign of a healthy population. Ninety-two percent of all collected females eight years or older were pregnant. Pupping takes place from mid-May to late June, with a peak in mid-June. Pups suckle for five to six weeks. Ovulation occurs shortly after weaning. There is an apparent 11-week delay in implantation (Pitcher and Calkins, 1980). Estimated average annual mortality rates from birth to four years is 74 percent for females and 79 percent for males, after which the rate drops to 11 percent per year for females to age 19 and 13 percent per year for males to age 17 (Pitcher and Calkins, 1980).

Trophics

Pinnipeds eat a variety of invertebrates and fish. Small schooling fish such as herring (Clupeidae) are usually swallowed whole under water; larger prey are consumed at the surface, where they are reduced to small pieces by violent shaking (Spalding, 1964).

In examining the stomach contents of 193 northern sea lions collected in the Gulf of Alaska, Calkins and Pitcher (1978) 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 fishes most commonly eaten. Seventy-one sea lions collected from the Kodiak area took about 54 percent by number capelin and 25 percent walleye pollock (Table 10.6). The remains of a harbor seal were found in one of the stomachs. Spalding (1964) reports that sea lions feed mostly during darkness.

The diet of the northern fur seal in the Gulf of Alaska includes about 32 percent cephalopods and 68 percent fish (North Pacific Fur Seal Commission, 1975). Pacific sand lance (about 25 percent) and walleye pollock (18 percent) are the most common fishes (Table 10.6). 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 coasts of Washington and British Columbia 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 each of rockfish (*Sebastes* spp.) and squid (Teuthoidea), and 6 percent capelin (North Pacific Fur Seal Commission, 1975). Fur seals collected over the continental shelf fed mainly on fishes, while those collected beyond the shelf fed mostly on squid. Like northern sea lions, fur seals feed mainly at night (Spalding, 1964).

Harbor seals feed during daylight, mostly in

Table 10.6 Identification of the prey from the stomachs of northern sea lions (N = 71), northern fur seals (N = 172), and harbor seals (N = 225).*

Prey species	Northern sea lion (percent total)	Northern fur seal (percent volume)	Harbor seal (percent total)
Invertebrates			
Cephalopods	1.4	32.5	22.2
Crustaceans	0.4	tr	4.1
Fishes			
Skates	6.6	-	0.7
Salmon	1.7	5.2	1.8
Smelt	-	-	1.1
Herring	-	1.5	6.7
Capelin	54.0	12.3	9.2
Eulachon	-	-	1.8
Walleye pollock	24.8	18.0	21.6
Other gadids	8.1	3.7	9.1
Eelpouts	0.1	-	1.4
Rockfish	-	-	0.9
Greenlings	-	-	0.5
Cottids	0.1	-	2.3
Pacific sandfish	-	0.1	2.3
Pacific sand lance	-	25.0	4.4
Pleuronectids	0.7	-	5.3
Unidentified fish	0.3	1.4	3.9
Mammals			
Harbor seal	1.7	-	-

* Data on northern sea lions are from animals collected in the Kodiak Area (Calkins and Pitcher,1978); data on harbor seals are from animals collected in the Gulf of Alaska (Pitcher and Calkins, 1980); data on northern fur seals are from animals collected in the Gulf of Alaska (North Pacific Fur Seal Commission, 1975).

nearshore waters (Spalding, 1964). Their diet in the Gulf of Alaska is about 22 percent cephalopods and 74 percent fish (Pitcher and Calkins, 1980). In NEGOA walleye pollock is the most important food species (Table 10.6).

10.3.1 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. When adults return to colonies after such panics there may be an unusually high level of territorial aggression, which could be injurious to pups and adults. Intentional repeated harassment in British Columbia caused the 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 attribute mortality directly to oil (Simpson and Gilmartin, 1970; Brownell and LeBoeuf, 1971; LeBoeuf, 1971; Spooner, 1967; Warner, 1969; Davis and Anderson, 1976).

Kooyman et al. (1976, 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 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.

In another experiment, three captive ringed seals immersed in water covered with light crude oil under conditions similar to an experiment carried out "in the field", died within 71 minutes. The field test had resulted in no mortality, leading the investigators to surmise that the added stress of captivity was the principal difference in the second experiment (Geraci and Smith, 1976). Extrapolation of these results suggests that normally sublethal effects might become lethal with the added stress of disease, parasitic infection, reproduction, molt, or inadequate food. The blubber layer of seals is thinnest during the molt. Haulout during molt may be an important strategy to avoid cold, and some evidence suggests that the warm skin surface promotes the growth of new epidermal cells.

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 cytotoxicity 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, excreting them via the bile and urine. Harp seals fed 75 ml of crude oil showed evidence of tissue damage. While the 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 placed 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.

During their pupping, suckling, and molting periods pinnipeds are probably most easily disturbed by OCS development activities. Disturbance by aircraft and boat traffic may be the most immediate problem. While little is known of direct effects of oil on pinnipeds, their position near the top of the food chain makes them particularly vulnerable to a reduction in numbers of their prey, which could be much more sensitive to the direct effects of oil pollution.

10.4 SEA OTTER

The sea otter is the only member of the family Mustelidae that is exclusively marine. Wild sea otters have not been observed to enter fresh water (Kenyon, 1972). The species prefers rocky coasts where inshore waters are rich in bottom fauna.

The sea otter 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. 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. They spend much time in grooming their fur.

The species is unique in that it sleeps, eats, and carries and nurses its young while resting or swimming on its back. 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 and abundance

At the turn of the century sea otter populations in NEGOA had been reduced to remnants in Prince William Sound. The recovery of these populations was slow until the 1960s, when observations indicated rapid population increases followed by the spread to new areas (Schneider, 1976). The Prince William Sound population was estimated at 5,000 in 1973 (Pitcher, 1975). In 1966 ten sea otters were transplanted to Yakutat Bay; 15 were sighted there in 1970 (Calkins et al., 1975). Population estimates for the rest of NEGOA do not exist. Figure 10.11 presents a recent estimate (Schneider, pers. comm.) of sea otter distribution in NEGOA.

Population dynamics

Sea otters breed throughout the year, with a peak in breeding activity and births in the fall and winter.

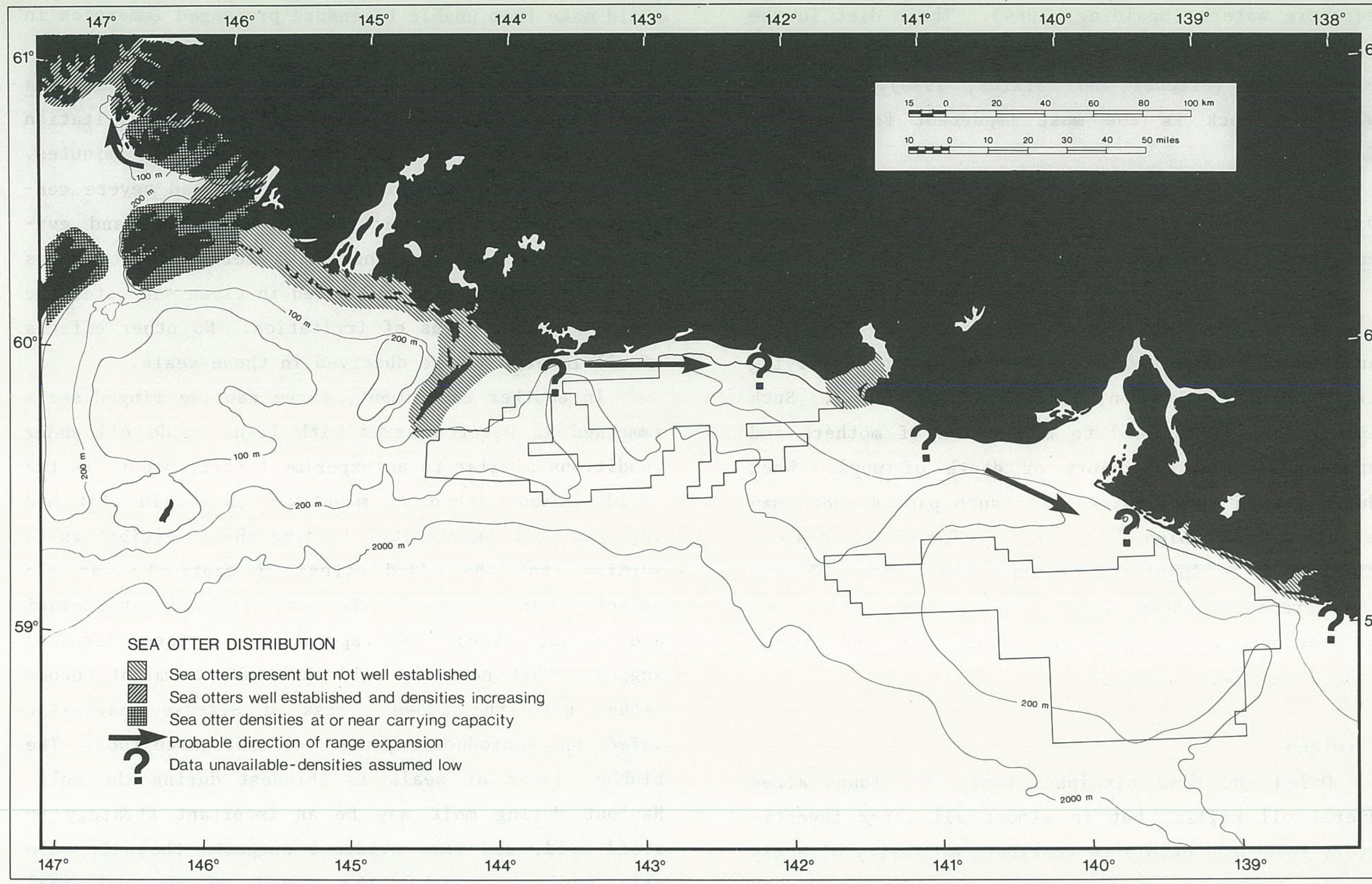


Figure 10.11 Distribution of sea otters (Schneider, ADF&G, pers. comm.).

Trophics

Kenyon (1969) found that sea otters off Amchitka Island fed only in the intertidal and sublittoral regions within the 60-m depth contour. In examining the stomachs of 309 sea otters he found that molluscs, echinoderms, and fish constituted about 98 percent of their diet (Table 10.7). The sea otter has a high metabolic rate (about 2.5 times that of other mammals of its size) (Morrison et al., 1977). It consumes from one-fifth to one-fourth of its body weight daily. Estes and Palmisano (1974) estimated that sea otters eat about 35,000 $kg/km^2/yr$ of animal biomass off Amchitka. Sea otters thus are key members of nearshore marine communities and are important in determining community structure.

Table 10.7 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 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 communities. Sea otters control herbivorous invertebrate populations and indirectly affect wave exposure and the composition of the rocky intertidal community (Fig. 10.12). In areas with dense sea otter populations, sea urchins, limpets, and chitons are reduced to sparse populations of small individuals; macroalgae flourish, providing food and shelter for a variety of organisms, especially crustaceans; wave exposure is reduced, siltation increases, and overall productivity is high. In contrast, similar areas with few or no sea otters have dense populations of large herbivores, macroalgae are severely overgrazed, bare rocky substrates are exposed to wave action, and overall productivity is low.

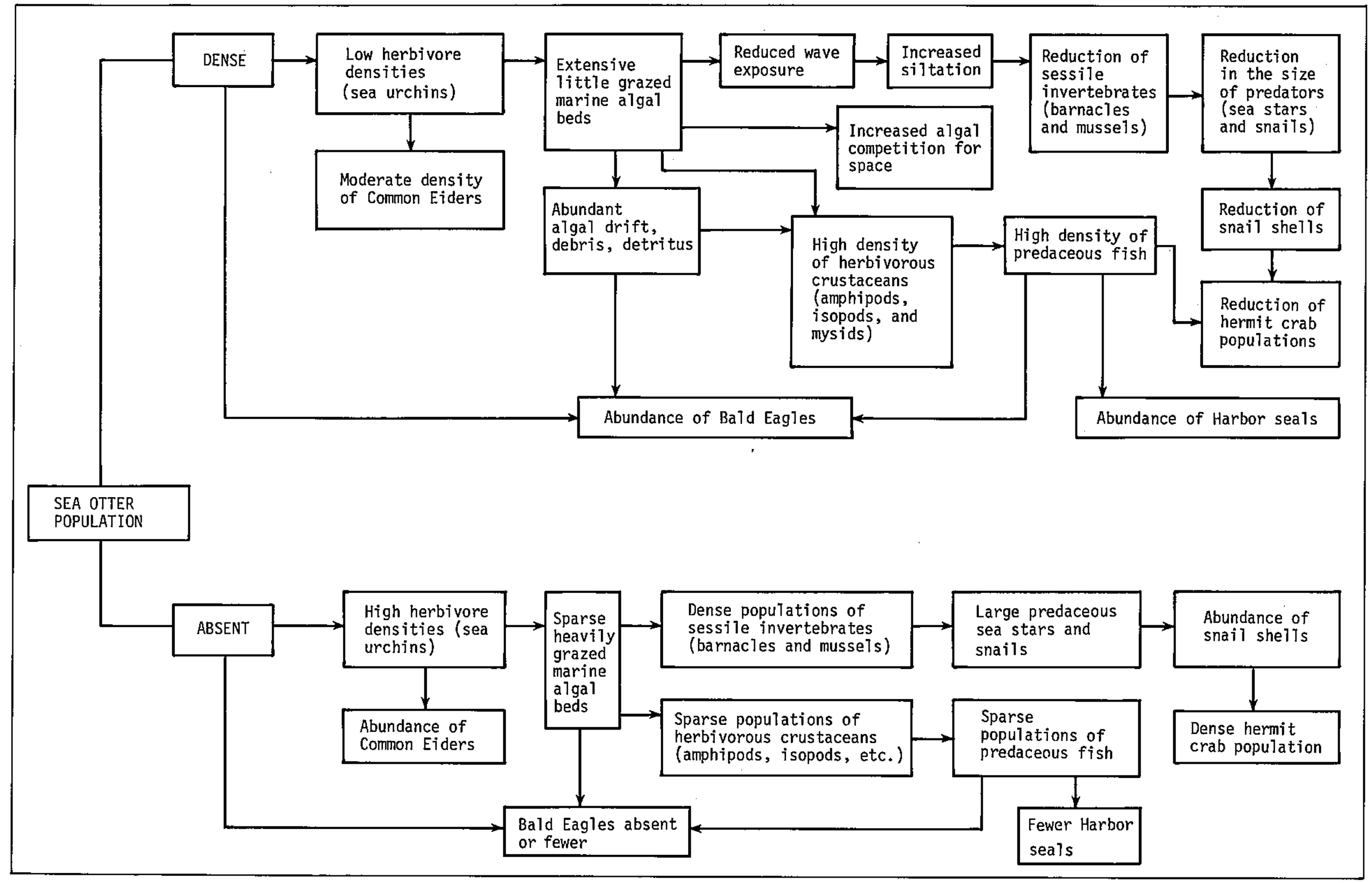


Figure 10.12 Diagram of interactions within nearshore communities with and without sea otter populations (Palmisano and Estes, 1977).

Effects of petroleum development

Sea otters are especially vulnerable to the effects of petroleum development. 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 caused death and severe stress (Kooyman and Costa, 1979). It has been predicted that mortality among wild oiled sea otters would be high. However, during the summer of 1979 several wild sea otters were partially 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 this time there was no known mortality nor evidence that the oiling affected the health of any of the otters.

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). This could be a particular problem for the marginal populations found within NEGOA.

10.5 TERRESTRIAL MAMMALS

The brown bear (Ursus arctos) and the black bear (U. americanus) are both widely distributed along the NEGOA shoreline (ADF&G, 1973). The areas where they are most abundant are shown in Fig. 10.13. Both species use the shoreline most intensively in early spring, when they rely on grass flats in estuarine areas, and in late summer and fall, when they concentrate on salmon streams. Of the two species, the brown bear appears to be the more dependent on coastal areas, since it is absent or scarce where grass flats and salmon streams do not occur.

The Sitka black-tailed deer (Odocoileus hemionus sitkensis) was introduced to Yakutat Bay in 1934, where it has done well on a few islands, and to several islands in Prince William Sound, where it is now fairly abundant (Fig. 10.13b) (ADF&G, 1973). During the winter these populations are forced into a narrow strip along the beach where forage is usually of poor quality. 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.

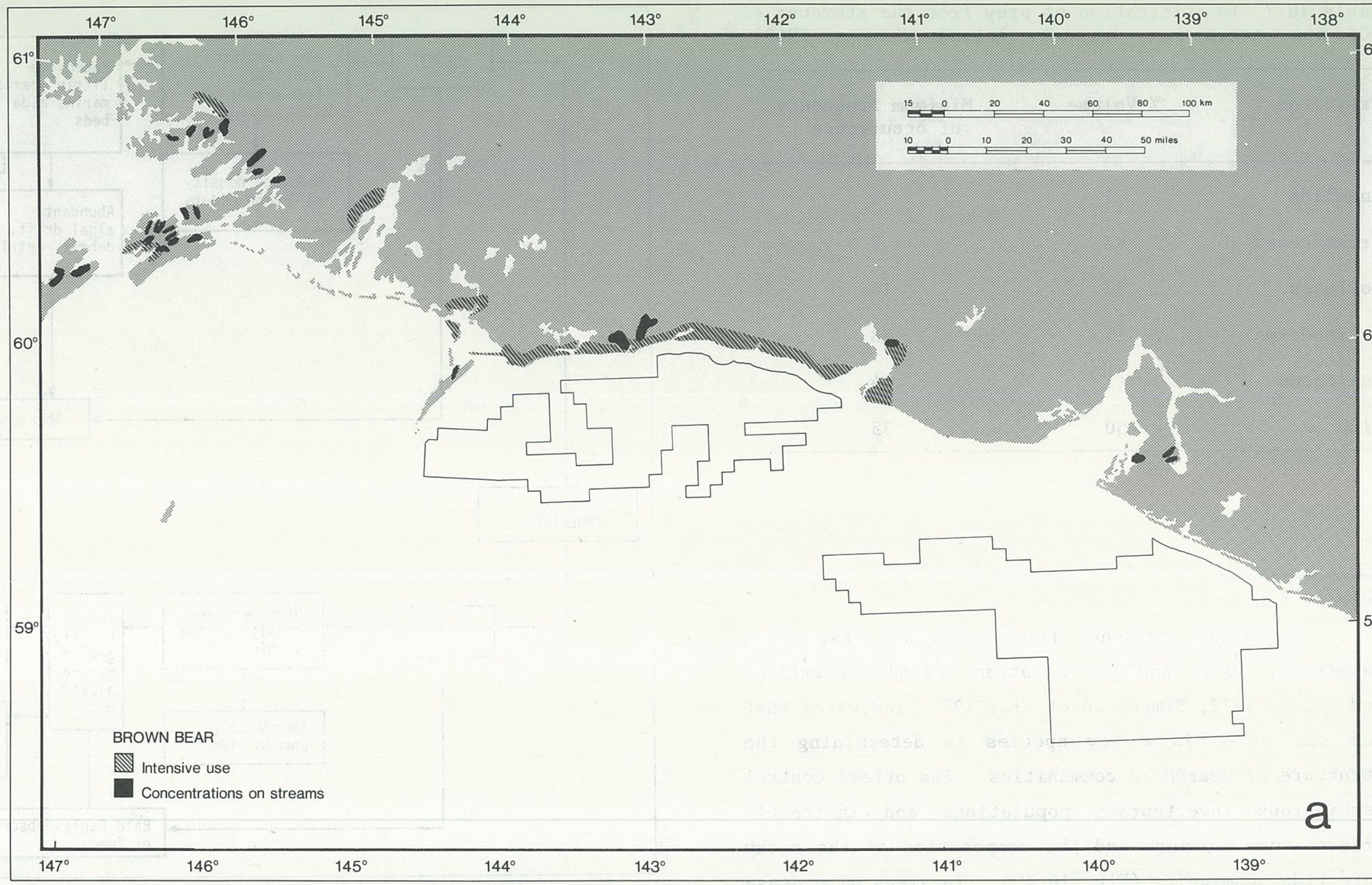


Figure 10.13 Areas of intensive use by bear (a, b) and high-density winter range of deer (b) (ADF&G, 1973).

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.

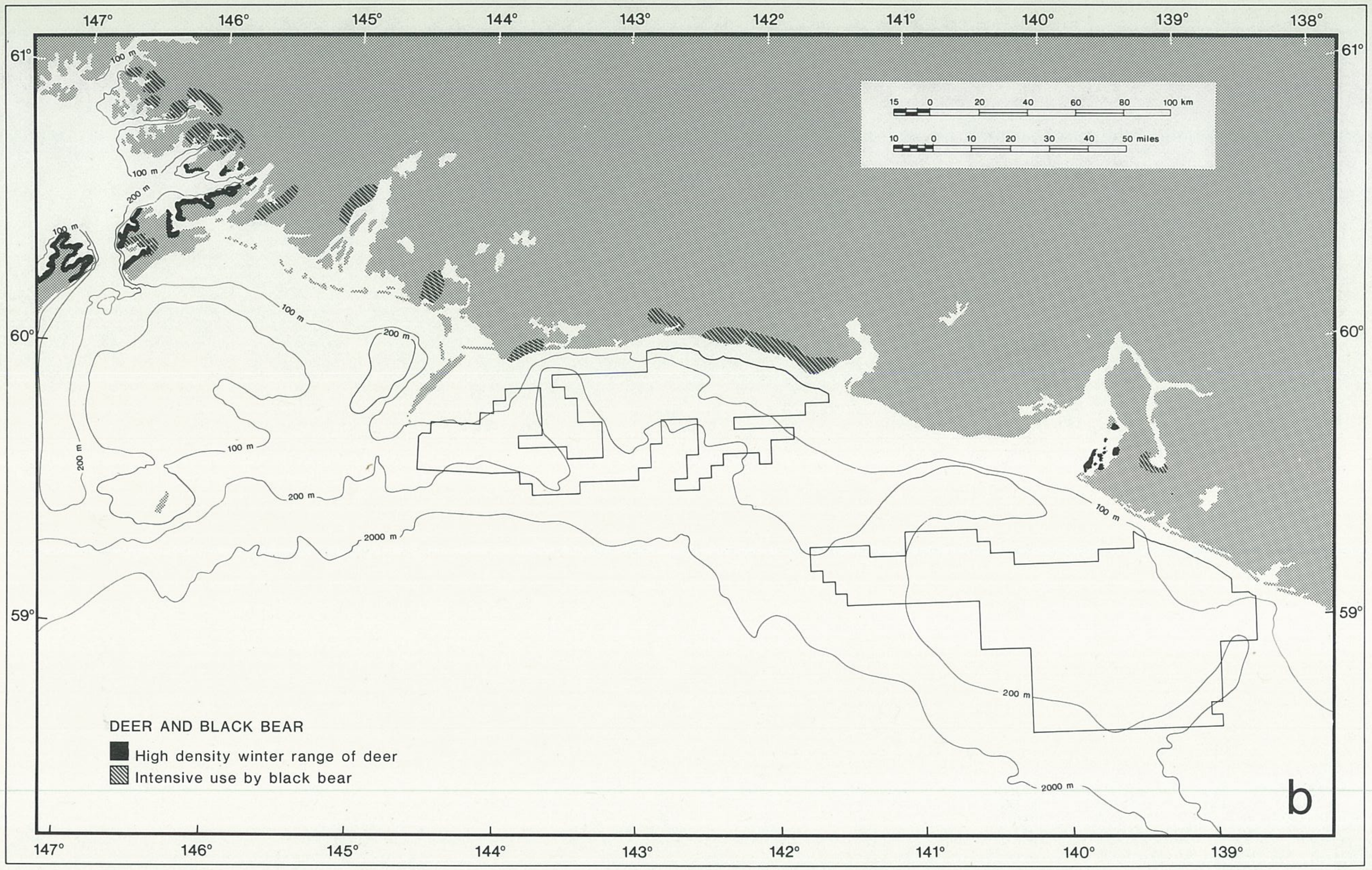


Figure 10.13 continued

CHAPTER 11 PETROLEUM INDUSTRY DEVELOPMENT

L. Jarvela, OCSEAP

11.1 RELEVANCE

The social, economic, and environmental consequences of OCS oil gas and development cannot be adequately assessed without information on the scope and nature of industry's involvement. OCSEAP's immediate concerns lie with environmental issues, principally those affected by

- o the locations of offshore platforms, pipelines, and onshore facilities and the nature and timing of their development,
- o the quantities and physico-chemical properties of contaminants anticipated from various sources,
- o qualitative and quantitative aspects of environmental disturbance accompanying OCS exploration and development.

BLM is OCSEAP's major source of information on offshore oil and gas development. Other important sources are the USGS, the petroleum industry, and state agencies such as the Departments of Community and Regional Affairs, Environmental Conservation, and Natural Resources.

The applications of this information to environmental issues are diverse. Data on types and locations of structures are used to assess potential hazards arising from extreme natural events such as storms and earthquakes. Knowledge of the sources, types, and quantities of contaminants, together with bioassay and transport data, permit evaluation of their effects on organisms at individual, population, and community levels. The potential for disturbance of the biota or habitats as a consequence of OCS oil activities can be predicted when the nature and extent of the activities are specified.

Initially, the projections may be largely speculative, as in the case of NEGOA, where there is no history of offshore production. If gas or oil is discovered, knowledge of the extent of the resource and formulation of development plans will lead to more specific projections.

11.2 PETROLEUM EXPLORATION AND PRODUCTION IN NEGOA

The presence of numerous onshore oil seeps between the Copper River Delta and Yakutat stimulated interest in the petroleum potential of NEGOA in the late 1800's and resulted in the discovery of the Katalla field in 1896. Only some 154,000 barrels were produced between 1901 and 1933, when the field was abandoned (USDI, 1976). Between 1954 and 1963, 25 other onshore exploratory wells and coreholes were drilled near Yakutat, Icy Bay, and Yakataga. None had commercial quantities of petroleum hydrocarbon, and all were abandoned (Fig. 11.1).

The State of Alaska held six competitive offshore sales in state waters between Yakutat and the Copper River between 1960 and 1967 (Table 11.1). Texaco did the only exploratory drilling about two miles east of Kayak Island (USDI, 1976), but that well was also abandoned after drilling to a depth of 3700 m.

NEGOA was the first OCS frontier area in Alaska to be offered for offshore leasing by the federal government. The prospect of large quantities of petroleum appeared good. In April 1976, 24 companies nominated 1,350 tracts covering approximately 2.9 million hectares. A total of 189 tracts covering 408,134 hectares was offered at Sale 39. Seventy-six high bids, totaling $571.9 million, were accepted by the Department of Interior (Plamondon, 1976). Figure 11.2 shows the tracts awarded to the high bidders.

Table 11.1 State of Alaska competitive offshore lease sales in NEGOA (USDI, 1976).

Map reference	Sale no.	Sale date	Areas offered (thousands of hectares)	Areas leased (thousands of hectares)	Percent leased	Bonus Paid ($ thousand)
Yakutat/ Controller Bay	3	12/07/60	5.0	2.1	44	6
Controller Bay/ Copper River	5	5/23/61	9.5	9.5	100	66
Controller Bay/ Icy Bay	6	8/04/61	5.4	5.4	100	111
Yakutat Bay/ Icy Bay	7	12/19/61	20.4	15.9	78	269
Middleton Island	16	7/19/66	12.5	11.0	88	4,457
Controller Bay	18	1/24/67	4.1	1.9	47	9
Totals			56.9	45.8	80	4,918

Source: Alaska Dept. Nat. Res. 1975

One stratigraphic (C.O.S.T.) well and 11 exploratory wells have been drilled thus far in the Sale 39 area. The consortium-sponsored C.O.S.T. well was abandoned after it reached a depth of 1,525 m because of difficulty in setting casings and because of intense fall storms (Atkinson, 1975). Shell, Atlantic Richfield, Exxon, Gulf, and Texaco drilled the exploratory wells on high bid tracts between January 1977 and July 1978 (Table 11.2). Although Texaco reportedly found gas at its Icy Bay test well, that well and the other 10 drilled were not commercially exploitable. Further drilling by industry on Sale 39 tracts is unlikely. ARCO's attempt to relinquish some of its Sale 39 tracts is an example of industry's pessimism on the subject (Anon., 1979a).

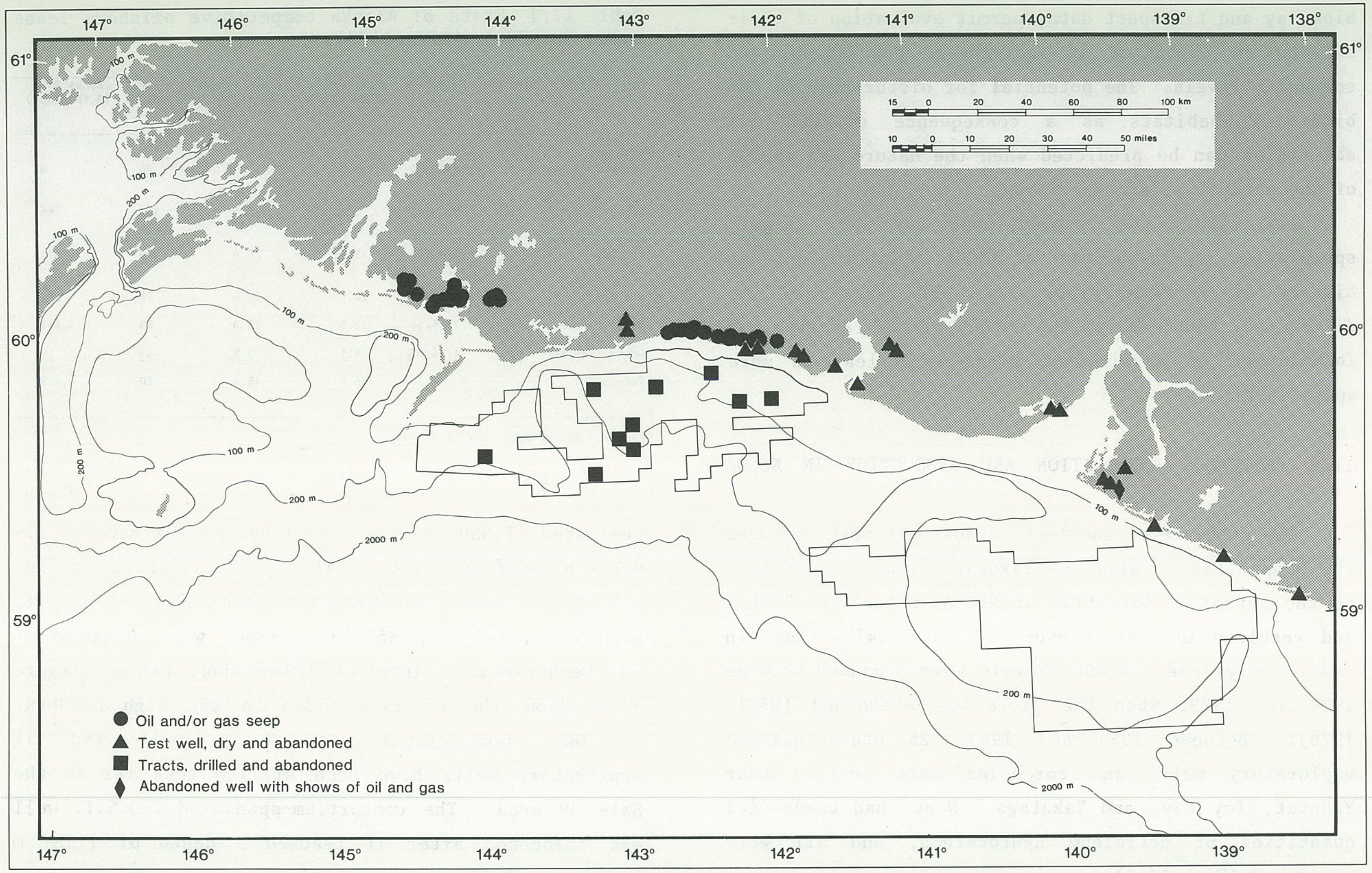


Figure 11.1 Distribution of oil and gas seeps and previous petroleum exploration in NEGOA.

Table 11.2 Wells drilled for petroleum, Outer Continental Shelf, NEGOA (Alaska Consultants, 1979).

Company	Well	Drilling rig	Completion date	Total depth(m)	Location
Shell	OCS Y-0011 #1	Sedco 706	1/25/77	4,100	OCS Block 106 Tract 42 35 km east of Cape Suckling
ARCO	Salome #1	Ocean Ranger	5/24/77	5,500	OCS Block 72 Tract 39-30 37 km west of Icy Cape
Shell	OCS Y-0014 #1	Sedco 706	6/20/77	4,100	OCS Block 111 Track 47 32 km SW of Cape Yakataga
Exxon	OCS Y-0050 #1	Alaskan Star	7/05/77	4,000	OCS Block 284 Track 126 58 km SW of Cape Yakataga
Texaco	OCS Y-0046 #1	Ocean Bounty	7/15/77	4,600	OCS Block 241 Tract 116 185 km W of Yakutat
Gulf	OCS Y-0059 #1	Aleutian Key	8/17/77	3,700	OCS Block 329 Tract 142 190 km W of of Yakutat
Shell	OCS Y-0014 #2	Sedco 706	9/06/77	4,700	OCS Block 111 Tract 47 60 km SE of Cape Suckling
Exxon	OCS Y-0080 #1	Alaskan Star	1/04/78	4,100	OCS Block 343 32 km SE of Kayak Island
Texaco	OCS Y-0032 #1	Ocean Bounty	2/20/78	4,800	OCS Block 162 Tract 39-78 137 km W of Yakutat
Exxon	OCS Y-0072 #1	Alaskan Star	3/14/78	3,000	OCS Block 414 55 km SE of Cape Suckling
Exxon	OCS Y-0035 #1	Alaskan Star	7/01/78	3,600	OCS Block 165 24 km SW of Icy Cape

In May 1978, the U.S. Department of the Interior called for tract nominations for a second lease sale, OCS Sale 55, to take place in October 1980 (Anon., 1978b). The area of call extended about 450 miles from the western end of Montague Island eastward to Cape Fairweather and consisted of 1,873 blocks (excluding those previously leased in Sale 39) totaling 4.2 million hectares (BLM, 1978). Three companies nominated 389 blocks to be considered for leasing. Of these, USDI selected 350 for intensive environmental study (Anon., 1978c). The tracts form a single area of about 800,000 hectares in the eastern end of the call area. By June 1980 140 tracts had been eliminated at the request of state and Yakutat officials. The remaining 210 tracts are shown in Fig. 11.2.

In anticipation of the sale, ARCO attempted to form a consortium to drill a stratigraphic well in the Yakutat Shelf region (Anon., 1978d). Although the proposed stratigraphic test was abandoned because of lack of support by other companies, some geophysical surveys were being made in the area in July 1980 (Anon., 1979c, 1980).

11.3 LOCATION, NATURE, AND TIMING OF DEVELOPMENT OF PLATFORMS, PIPELINES, AND SHORE FACILITIES

OCS petroleum extraction operations include reconnaissance, exploration, development, production, and shutdown. The character, timing, and duration of activities during the various phases depend on market conditions, resource potential and location, proximity of logistical support and shore facilities, environmental conditions, federal, state, and local policies, and availability of suitable land and harbor facilities. Often the phases overlap. For example, exploration drilling may be going on while a production platform is being installed.

Reconnaissance surveys normally precede a lease sale. The information obtained is necessary to evaluate the potential of an area for petroleum hydrocarbon production and to guide company bidding for tracts. Shipboard geophysical surveys and C.O.S.T. wells are employed to obtain data on sedimentary structures.

After a sale, successful bidders drill exploratory wells using mobile rigs; these may be semisubmersibles, jack-ups, or drilling ships. Supply vessels, aircraft, and shoreside service bases are needed to supply the rigs with drilling materials and to transfer personnel. The amount and duration of exploration depends on resource potential, the depth of the structures being drilled, and water depth. In the event of a major discovery, additional exploratory wells are required to delineate the extent of the resource.

When the economic potential of the field has been evaluated and a plan for production has been outlined, the development phase begins. Development includes the design, fabrication, and installation of production platforms, the construction of onshore structures, and installation of gas or oil collection systems. It is the phase that uses the most manpower. The scope and character of development depends on the amount of oil or gas present, the location of the fields,

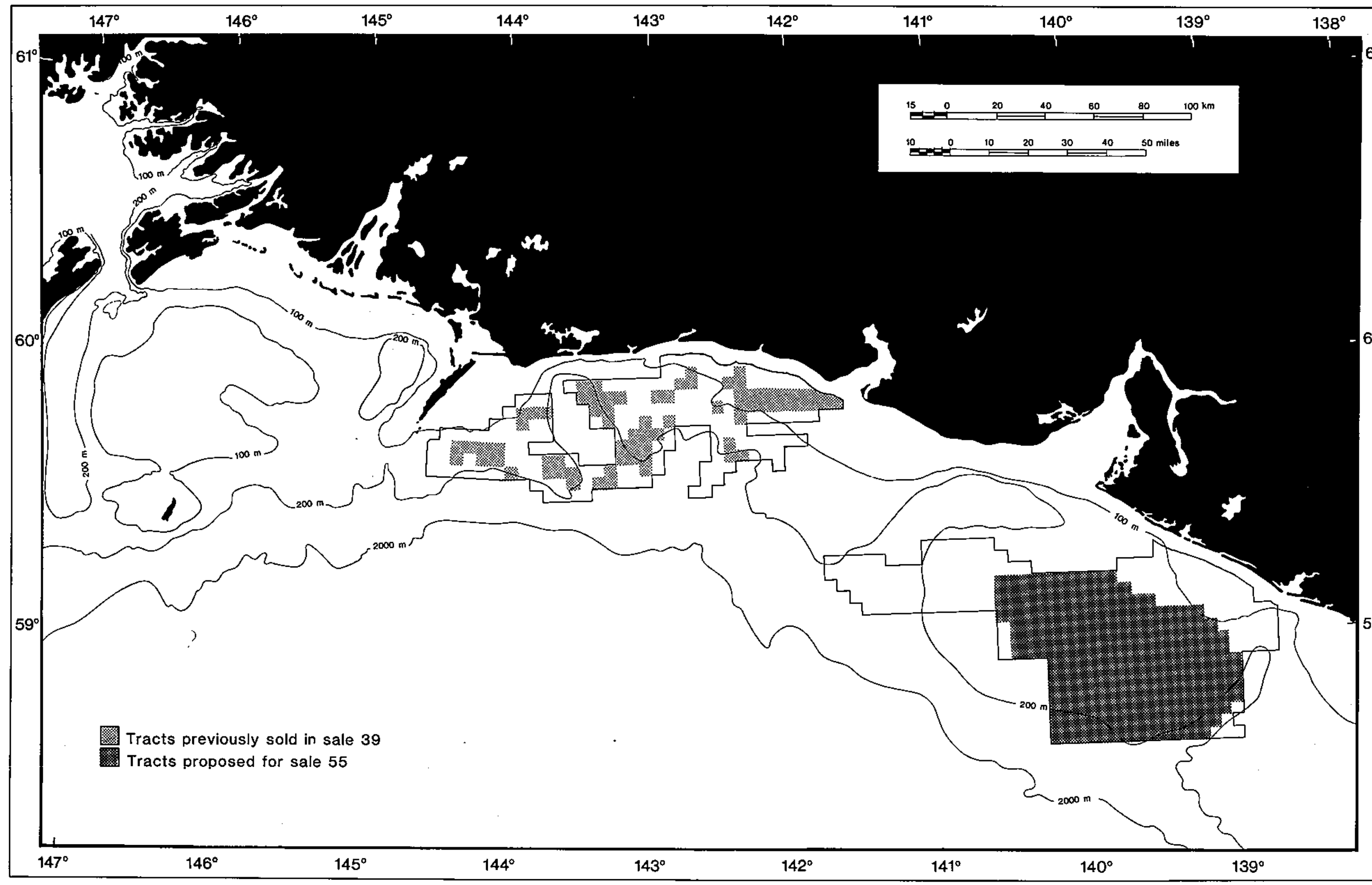


Figure 11.2 Distribution of tracts sold in OCS Sale No. 39 and tracts selected for OCS Sale No. 55 (USDI, 1976, 1980b).

environmental conditions, and proximity to onshore support facilities. For example, if a field of moderate size is found, it may be more economical to collect the petroleum at the production platform and load it directly on tankers than to pipe it to a storage area on shore. In short, the details of production facilities cannot be specified until the resources have been discovered and defined. Even though oil is discovered shortly after exploration begins, the shortest time interval between a sale and the onset of development is approximately four years.

The production phase commences when all facilities are in place and ready to receive petroleum. Manpower requirements decline sharply (although they are still higher than in later stages of production because numerous wells are usually drilled from each production platform). Construction crews depart and the labor force remaining consists of those involved in routine operational tasks. Activity at service bases decreases, as does the need for supply vessels and helicopters to transport personnel and materials between the platforms and shore. The duration of the production phase depends on the size of the producing field and on the rate of extraction. Typically, it is 15 to 20 years, but the lifetime of a large field could extend to 40 years.

The shutdown phase follows exhaustion of the extractable oil or gas reserves. It includes the removal of production platforms and dismantling of equipment and structures.

11.4 OCS ACTIVITIES ASSOCIATED WITH SALE 55

Projections of Sale 55 activities are speculative, since the sale is proposed for October 1980. The following discussion relies heavily on previous activities during NEGOA Sale 39, planning information developed by the State of Alaska for NEGOA, and materials presented in BLM environmental impact statements for Sale 39 and the Beaufort Sea.

11.4.1 Reconnaissance activities

Sale 55 reconnaissance activities near Yakutat have been confined to offshore geophysical shipboard surveys. They include the collection of data on seismic reflection and refraction, magnetic intensity, and bottom sediment properties along closely spred tracklines. The data are used to identify geological structures likely to contain hydrocarbons. Little, if any, shoreside logistical support is required for these surveys.

11.4.2 Exploration activities

Both Seward and Yakutat were used as rig support bases during the drilling of Sale 39 lease tracts. Exxon, Gulf, and Texaco based their operations in Seward, while ARCO and Shell based theirs primarily at Yakutat but occasionally operated out of Seward (Alaska Consultants, 1979). These ports were used because the lease area was located midway between them on a remote section of the coast. In contrast, the Sale 55 area is close to Yakutat and an excellent harbor, Monti Bay (Fig. 11.2). Most of the onshore support facilities and activity associated with exploration on Yakutat Shelf tracts will probably be in the Monti Bay-Yakutat area.

Semisubmersible drilling rigs were employed during Sale 39 drilling. Table 11.3 lists them and some of their characteristics. As the severe environmental conditions on the NEGOA shelf largely exclude other types of mobile rigs such as jack-ups and drill-ships, semisubmersibles probably will also be used off Yakutat. The number of rigs depends on activities in other OCS areas and the industry's prediction of exploitable quantities of oil or gas in the sale area. The Gulf of Alaska recently ranked 17th among 22 OCS areas in the U.S. in resource potential (USDI, 1979). Probably no more than four exploratory rigs will be present in the Sale 55 area at a given time.

Table 11.3 Characteristics of semisubmersible drill rigs used in NEGOA (Anon., 1975; 1976a, 1976b, 1976c).

Characteristics	<u>Ocean Ranger</u>	<u>Sedco 706</u>	<u>Alaskan Star</u>
Dimensions (m)	120x80x79	90x75x40	84x66x33
Depth capabilities (m)			
Water	900	-	450
Drilling	7600	-	9100
Mooring system	12 20,000 kg anchors 8.3-cm chain & cable w/ 3.2-cm MM breaking strength	-	8 14,000 kg anchors; 1200 m 7.6-cm chain
Sea state capabilities			
Drilling	-	-	-
Survival	-	-	30 m
Towing/propulsion system	Self-propelled; four 3,500 hp motors	Self-propelled four 2,000 hp thrusters	-
Storage capacity			
Liquid mud	2,450 bbls	-	2,058 bbls
Bulk mud & cement	625 m^2	-	350 m^3
Sacked mud	20,000 bbls	-	6,000
Fuel	22,000 bbls	-	10,136 bbls
Potable water	48,800 bbls	-	1,227 bbls
Drill water	20,500 bbls	-	12,230 bbls
Quarters	100 men	96 men	100 men
Cost	$50 million	$46 million	$48.5 million

Exploration will probably begin within a year after Sale 55 and last about two years if no discovery occurs. In the event of a discovery, exploration activity would continue to delineate the size, shape, and depth of the reservoir. At the peak of activity four exploratory rigs could be in use.

The number of boats needed to supply exploratory rigs depends on the distance between the service base and the rig, rate of use of drilling material, and vessel speeds. About 10 trips per month per rig are required to transfer drill pipe, fresh water, muds, and other materials (Kramer et al., 1978). During the peak of Sale 39 exploratory activity, 13 supply vessels used the Seward service base, although no more than six were in port at a given time (Alaska Consultants, 1979). The typical supply vessel used for offshore operations is 50 to 65 m long and has a cruising speed of 14 to 17 kts and a range of 320 to 480 km (Kramer et al., 1978).

Fewer vessels will be required for Sale 55 exploration because the sale area is closer to the service base and because fewer exploratory rigs are predicted. The farthest reaches of the nominated area are within 145 km of Yakutat. If four rigs are present during peak activity, 40 vessel trips per month are predicted. The vessels could reach the most distant part of the sale area in about six hours as compared, for example, to the 12 to 14 hours required to reach the <u>Ocean Ranger</u> from Seward when it was drilling off Yakataga. No more than eight supply vessels will be needed.

Helicopters are used to transport personnel and some supplies between drilling rigs and shore. During Sale 39 exploratory activities, one or two helicopter trips to each rig were made from Yakutat each day (Kramer et al., 1978). Large helicopters are used (e.g., the 10-place Bell 222) in order to reduce the frequency of flights and because the larger helicopters are safer in inclement weather. The number of helicopter flights from the Yakutat Airport during Sale 55 exploratory drilling probably will be comparable to that during Sale 39 drilling.

11.4.3 Development and production activities

Offshore oil development is guided by economics. Producers attempt to minimize production costs through technology coupled with consideration of field location, water depth, weather and sea conditions, governmental regulations, exploratory data, and production goals. (See, for example, Reeds et al., 1976, and Fig. 11.3.) Exploratory data dictate to a large extent the selection of drilling sites and the means to extract, process, and transport oil or gas. The number of fields discovered, their size and location relative to one another and to shore, determine how many platforms will be needed, as well as requirements for storage capacity and transshipment (Kramer et al., 1978). In the case of the Yakutat Shelf, where "hard" information is lacking, one must employ scenarios based on assumed resource sizes and field development in similar settings.

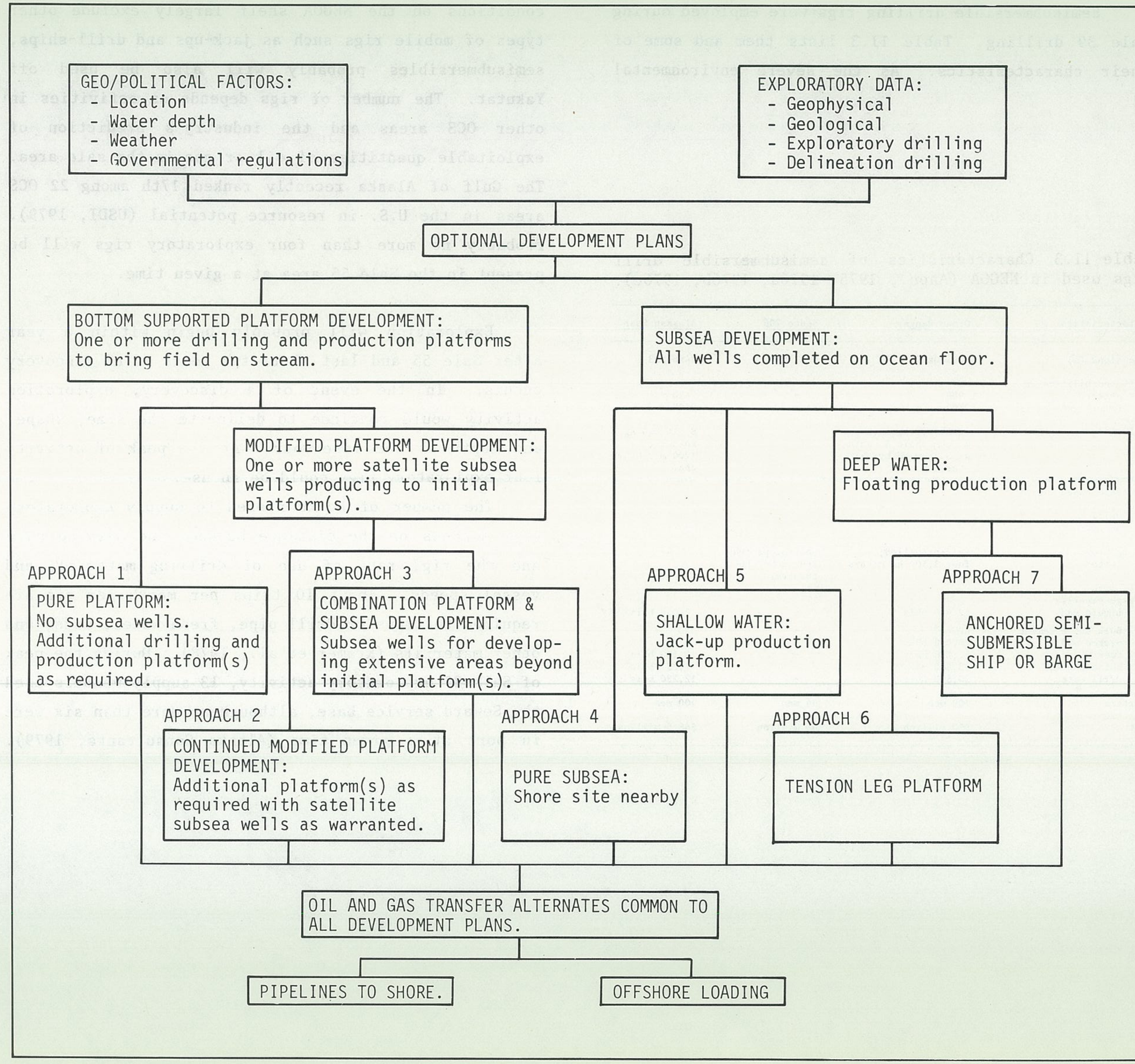


Figure 11.3 Economic criteria leading to field development (Reeds and Trammell, 1976).

11.4.4 Resource estimates

Several estimates of the amounts of oil and natural gas in the Gulf of Alaska are available. For Sale 39, the USDI's 95 and 5 percent probability estimates were 100 million and 2.8 billion barrels of oil and 8.5 billion and 25 million m^3 of gas, respectively (USDI, 1976). The USGS estimated that the area of call for Sale 55 contains up to 4.4 billion barrels of oil and 37 billion m^3 of gas (Anon., 1978b). More recently, their 50 percent probability estimates were 0.5 billion barrels of oil and 5.7 billion m^3 of gas (Anon., 1978b). USDI (1980b), however, estimates that the undiscovered reserves off Yakutat may be as much as 800 million barrels of oil and 6.4 billion m^3 of gas.

11.4.5 Development possibilities

The moderate (1.25 billion barrels) and high (2.2 billion barrels) find scenarios developed by Kramer et al. (1978) for NEGOA illustrate three possible courses of development following a commercial discovery. Table 11.4 summarizes the development needs arising from the three options. As pipelines are very expensive to install, they will probably be used only in the case of an undispersed moderate find or of a high find. Installation of pipelines will necessitate expanding service base pipe storage facilities; lay and bury barges will be needed to install the pipe. Shoreside oil storage and loading facilities and possibly treatment facilities will also be needed. All shoreside facilities will probably be located on or near Monti Bay.

The exact timing of development activities cannot be predicted. In the Scottish North Sea, the interval between discovery of a field and production ranged from three to seven years for nine fields discovered between 1969 and 1974, the average being 5.4 years (Busemann, 1978). The rapid production was possible partly because British government policy allowed production to begin before development drilling and pipelaying were completed. Differing U.S. federal and state government policies and the remoteness from platform fabrication yards suggest that production will be slower in NEGOA. If a commercial discovery is made immediately after exploration begins, a minimum timetable can be set forth for construction and operation of the industrial facilities (Table 11.5). Service bases would be in operation before the sale, but they might have to be expanded to meet the demands for additional supply boat berthing and pipe storage during the period of platform installation, pipelaying, and construction of shore facilities. Other facilities would be designed and constructed so that production could begin eight or more years after the lease sale. The period of about four to eight years after a commercial discovery would be characterized by intense local activity, including the installation of platforms, laying of pipe, and construction of treatment facilities and oil terminals. This activity would decrease sharply as soon as production began.

Table 11.4 Development needs (Kramer et al., 1978).

Development needs	Moderate find: No pipeline	Moderate find: Pipeline	High find
Supply boat berths	3	5	10
Supply boats	~8 hectares	~8-10 hectares	~25-36 hectares
Oil terminal	Offshore loading	1 (small)	1(650k bbl/day)
Pipelines	None	1(120-160km)	1(190-240 km)
Lay barge	None	1	1-2
Production platforms	4	4	7
LNG plant	None	None	1

Table 11.5 Minimum time frame for facilities and activities (Kramer et al., 1978).

Industrial facility	Years from sale: Planning	Construction	Operation
Service base	-2 to -1	-1 to 0	0 to 47
Production	1 to 2	2 to 7	7 to 47
Treatment facility	3 to 4	4 to 8	8 to 47
Pipelines	3 to 4	4 to 8	8 to 47
Oil terminal	3 to 4	4 to 8	8 to 47
LNG plant	5 to 7	7 to 9	9 to 47

11.4.6 Offshore platforms

The type of wellhead system that will be used is not known. Kramer et al. (1978) predict that large steel jacket production platforms will probably be used, as they can reach depths of about 165 m in the Gulf of Alaska. More efficient extraction systems may be developed soon, however. (See Dames and Moore, 1979, for a discussion of platforms.) If steel jacket platforms are used, as many as 20 to 40 wells could be drilled from each platform. Deviated (or slant) drilling will permit a single platform to cover up to three lease tracts (about 52 km²) (Kramer et al., 1978).

11.4.7 Offshore oil storage

If moderate-level fields are dispersed, crude oil probably will be treated, stored, and loaded offshore. Few onshore facilities will be required. Offshore storage will be in floating or bottom-mounted underwater structures; the floating structure is less vulnerable to earthquakes (USDI, 1976). The size of the storage structure will be determined by anticipated production rates, tanker size, and rates of tanker arrivals. Offshore storage structures with capacities up to 1.4 million barrels are currently in service in the North Sea (Kramer et al., 1978). Some representative values based on 10-day production storage capacity and various combinations of production rates and tanker sizes are given in Table 11.6 to indicate the potential requirements.

11.4.8 Pipelines

Marine pipeline systems typically consist of a pressure source, gathering lines, transmission lines, and booster stations. The pipeline may go directly to an onshore treatment or storage facility, or it may be connected by an onshore pipeline to such facilities (Kramer et al., 1978). The steps in designing an offshore pipeline are shown in Fig. 11.4 (Powers, 1978). Oceanographic and route surveys are needed to obtain bottom profile, sub-bottom profile, side-scan sonar, bottom current, and sediment sample data. These are used to determine possible hazards to pipelaying or burial, active faults, and pipeline stability. As pipelines may cost up to $2.5 million per km, considerable effort is made to minimize the length of pipe needed (Kramer et al., 1978).

While the lay barge is laying the pipelines it is attended by supply boats which reset anchors used by the barge to pull itself forward. Pipelines in less than 60 m of water must be buried at least one meter deep except in shipping fairways or anchorage areas, where the minimum depth is three meters (Kramer et al., 1978). Bury barges bury the pipe; a commonly used method is to jet sediments out of the way with high-pressure nozzles. Perhaps 80 km of pipeline can be laid during the summer season in NEGOA (Kramer et al., 1978). One or two summers would probably be required to lay and bury a pipeline in the Yakutat area.

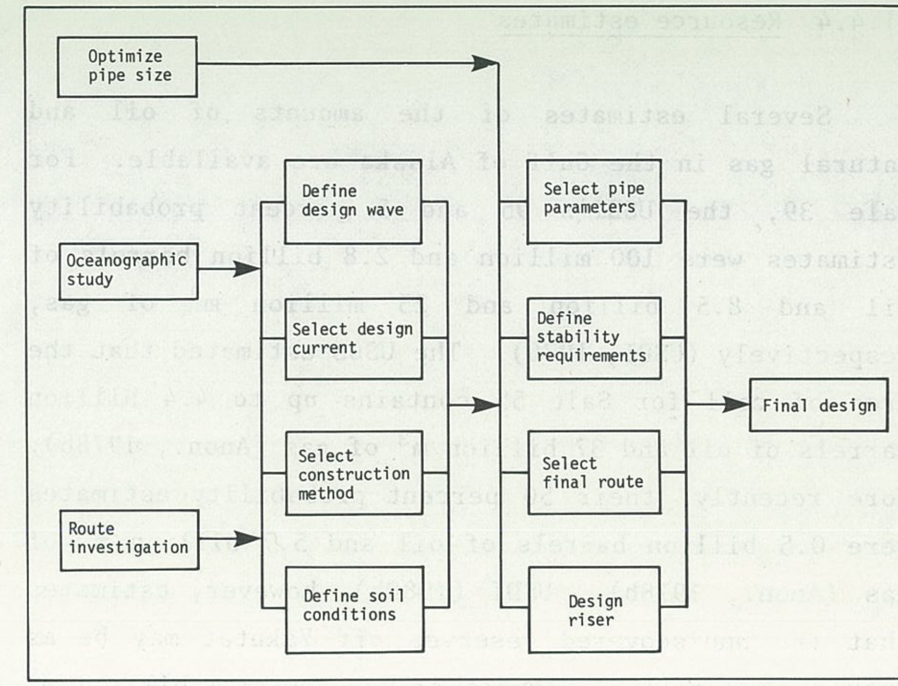


Figure 11.4 Steps in designing an offshore pipeline (Powers, 1978).

11.4.9 Treatment plants

Crude oil must be treated before transport, either on the production platform or ashore. Water, gas, and other constituents may be removed and reinjected at the well instead of piping them to shore. If treatment is to take place ashore, the size of the plant will be determined by production rates. The 170,000 bbl-per-day Trading Bay facility in Cook Inlet requires 12 hectares for the physical plant. The plant at Granite Point, which produces only 7,000 to 8,000 bbl per day, is situated on 0.8 hectares. Onshore treatment facilities would probably be located near Monti Bay.

11.4.10 Oil terminals

At oil terminals crude oil is stored and loaded onto tankers for shipment to refineries. If oil is to be piped ashore, an oil terminal will probably be constructed near Monti Bay. It probably will consist of conventional above-ground steel tanks surrounded by earth dikes. The number and/or size of the tanks will be determined by production rates (see Table 11.6 for representative storage capacities). The placement of tanks is dictated by topography, greater acreage being required in sloping areas than on flat terrain. From 7 to 88 hectares would be required for a NEGOA oil terminal, based on a maximum terminal throughput of 650,000 bbl per day (Kramer et al., 1978).

Table 11.6 Hypothetical crude oil storage and transport requirements for various production rates (Kramer et al., 1978).

	Crude oil production (1000's bbl/day) 250	450	650
10-day storage capacity (million barrels)	2.5	4.5	6.5
Tanker arrivals			
Small (60,000 dwt) vessel	every 2 days	daily	every 16 hrs
Medium (120,000 dwt) vessel	twice a wk	every 2 days	every 36 hrs

Note: 1 dwt approx. equal to 7 bbls

(To put the above production rates in perspective, the flow of Prudhoe Bay crude by the Trans-Alaska Oil Pipeline was about 1.16 million barrels per day in May 1978 (Anon., 1978a).

11.4.11 Liquefied natural gas plants

Natural gas may occur with oil (associated gas) or alone (dry gas). The gas may be flared, reinjected, processed for local use, transported by pipeline, or liquefied for shipment by ship. The lack of a large market near Yakutat and regulations limiting flaring suggest that any gas found there would be reinjected or liquefied for shipment elsewhere. Because of the large capital investment needed, an LNG plant would be constructed only in the event of a major find. Reserves of at least 42 to 56 billion m^3 would be required to justify a plant (Kramer et al., 1978).

The basic elements of an LNG plant consist of a liquefaction train, storage tanks, marine loading facility, and support structures (Kramer et al., 1978). The design capacity of such a plant is based on gas production rates over the anticipated lifetime of the field. The Phillips Facility at Nikiski produces about 5.6 million m^3 per day, while the proposed Pacific Alaska LNG Company and El Paso Natural Gas Company facilities have design capacities of 11 million and 87 million m^3 per day, respectively (Kramer et al., 1978). The site requirements for the three facilities are about 10, 24, and 200 hectares, respectively. The Yak-Tat-Kwaan, Inc. reserved 160 hectares for an LNG plant on the south side of Monti Bay in anticipation of a commercial gas find on Sale 39 leases; that site presumably will be used if gas is discovered on the Yakutat Shelf.

11.4.12 Loading oil and gas

Tankers can be loaded at a shoreside fixed pier, at an offshore loading dock (sea island), or at a single buoy mooring system (SBM). The latter two systems require underwater pipelines from the storage facility. SBM's are used for offshore oil loading. Shoreside piers are the most commonly used for loading. A sea island is used at the Drift River terminal in Cook Inlet because of shallow water and large tides. SBM's are lower in cost and relatively insensitive to earthquakes and heavy seas (Kramer et al., 1978; USDI, 1976). Deep water close to shore, excellent shelter under all weather conditions, and other siting factors (Kramer et al., 1978) indicate that either an SBM or shoreside loading facility could be used in Monti Bay.

11.4.13 Crude oil and LNG carriers

Tankers used to transport oil from the Gulf of Alaska to refineries will probably range from 40,000 to 165,000 deadweight tons (dwt) (Kramer et al., 1978). A 165,000-dwt tanker is approximately 300 m long and has a draft of about 18 m, thus requiring deep water and considerable room for maneuvering. A 165,000-dwt LNG carrier is about 320 m long; however, because of the lighter weight of its cargo, it draws less water--about 12 m.

The frequency of visits of LNG or crude oil carriers to marine terminals depends on production rates and ship size. Some representative values of crude oil loading frequency are given in Table 11.6. For LNG, Kramer et al. (1978) give a range of from one ship visit per day to one visit every eight to nine days for three operational or proposed LNG plants. Since LNG production, in contrast to crude oil production, can be decreased or stopped in the event of shipping delays, less storage capacity is required.

11.5 QUANTITIES AND PHYSICOCHEMICAL NATURE OF CONTAMINANTS ANTICIPATED FROM VARIOUS SOURCES

Contaminants as defined here are substances which, by their presence, are detrimental to living organisms. They need not be toxic (e.g., mud that smothers sessile benthic organisms), and they may occur as gases, liquids, solids, or any combination thereof. Atmospheric contaminants are called emissions, whereas those in water are called effluents. Emissions and effluents are often quickly and widely dispersed. Examples include radioactive fallout from nuclear testing and acid rain from industrial activities. Such ubiquitous contamination with no identifiable specific origin is often termed non-point source pollution. The focus here, however, is point source contamination, i.e., contamination from sources which produce levels and effects distinguishable from "background" contamination. Potential sources include offshore platforms, pipelines, shore facilities, and tankers. The types and quantities of contaminants which they may produce are discussed below.

11.5.1 Offshore platforms

Gaseous, liquid, and solid wastes are produced by exploratory and production drilling platforms. They include (1) flare gas, (2) treated sewage, (3) brines from distillation and ballast systems, (4) deck washings, (5) drilling muds and cuttings, (6) refuse, and (7) formation waters. The disposal of these wastes is permitted and monitored by governmental agencies according to laws, regulations, and OCS stipulations and operating orders.

Treated sewage and brines are usually released at the platform; noncombustible refuse and waste oils are returned to shore for disposal. Flaring of produced gas was widespread in the past, but it is less common now in accordance with concern about air pollution and conservation. It is unlikely that gas will be flared in NEGOA.

11.5.2 Drilling muds

Drilling muds carry drill cuttings, lubricate the drill bit, and control formation pressures. Their composition is determined by the particular conditions at the drill site. Mud constituents are shown in Table 11.7. 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 of muds, while caustic soda and lignosulfonates are considered their most toxic components (Dames and Moore, 1978). Normally the muds are reused after separating them from drill cuttings. The cuttings, along with a small fraction of the muds, are discharged from the platform. The amount of mud that may be discarded depends on the formation being drilled, and in addition, on regulations pertaining to methods of discharge and quantities of allowable discharges. According to USDI (1979), about 20 m^3 of cuttings would be discharged from a typical Beaufort Sea well. From 4,500 to 5,800 barrels of mud would be discharged per well.

Contamination of organisms by poisoning or smothering depends on discharge rates of drilling fluids and cuttings, the rate of dilution of waters at and near the discharge point, and the sensitivity of the organisms present to the muds and cuttings. The turbulence created by the semisubmersible drilling rig <u>Ocean Ranger</u>, when currents were above 0.1 kt, produced discharge dilutions of at least 10,000:1 within 100 m of the rig (Dames and Moore, 1978). Within the water column, total suspended solids from drilling fluids ranged from 0.001 to 0.01 mg/l at 100 m from the rig during normal drilling to 8.1 mg/l at the end of drilling operations. The former values typify the more

Table 11.7 Drilling mud constituents (USDI, 1976; 1979).

Component class	Typical compounds used
Weighting agents and viscosifiers	Barite, calcium carbonate, bentonite, attapulgite
Dispersants	Tannin; various lignites, lignosulfonates;
Fluid loss reducers	Pregelatinized starch, sodium carboxymethyl cellulose
Lubricants, detergents, and emulsifiers	Processed hydrocarbons, detergent, anionic surfactant blends
Defoamers, flocculants, and bactericides	Aluminum stearate, flocculating agent, paraformaldehyde, sodium carbamate
Lost circulation materials	Fibrous material, walnut shell bits, ground mica
Commercial chemicals	Sodium chromate, sodium hydroxide, sodium carbonate, sodium bicarbonate, calcium hydroxide
Oil base invert emulsion muds	Oil base mud, water in diesel oil
Emulsifiers for invert emulsions	Primary emulsifier, viscosity and gel builder, high temperature stabilizer
Specialty products	Shale control reagent, bentonite extender, nonionic surfactant

prevalent continuous discharge rates while the latter is characteristic of maximum discharge conditions. No significant changes in benthic populations or accumulations of mud or cuttings in the vicinity of the rig were found (Dames and Moore, 1978). Strong tidal currents (up to 2 kts) near the rig rapidly dispersed the discharged effluent.

Current meters off Icy Bay show that currents on the Yakutat Shelf average about 15 cm/sec and are directed westward. They vary widely both in mean speed and direction, especially during the summer. Speeds in excess of 2 kts sometimes occur (Muench et al., 1978). Although the currents in the Sale 55 area are probably similar to those found near the Ocean Ranger and would be sufficient to dilute drilling fluids, confirmation at the platform site will be required.

11.5.3 Drill cuttings

About 0.1 m^3 of cuttings is produced for every meter of well drilled (USDI, 1979). Thus, for a 4,000-m well (typical of those drilled during Sale 39) some 370 m^3 of cuttings would be produced. After separation from muds, the cuttings are diluted with sea water and discharged. The dispersal of cuttings after disposal depends on particle size composition, density, water depth, current speed, and turbulence. These will affect sinking rates and horizontal distances to which an individual particle may be carried.

As cuttings from the Ocean Ranger C.O.S.T. well in Lower Cook Inlet had a specific gravity of 2.6 and size range of 0.1 to 10 mm (Dames and Moore, 1978), they settled out rapidly and separated from the finer, lighter drilling muds. In the high-energy environment at the C.O.S.T. well site, drill cuttings were rapidly dispersed. The percentage of cuttings larger than 0.85 mm found at any sampling site was less than 3 percent by sample weight (Dames and Moore, 1978). Cuttings were incorporated into the bottom sediments to about 9 cm. Simulations indicated that currents will carry 0.1 to 0.2 mm cuttings up to 5.6 km from the drill site 10 percent of the time (Dames and Moore, 1978). When currents are weaker, much greater accumulations of drill cuttings can be anticipated around the base of a drilling platform. At production platforms, production and localized accumulation of drill cuttings would be higher due to the drilling of numerous wells from a single platform.

11.5.4 Formation waters

Some water accompanies each barrel of crude oil produced. For example, in the Beaufort Sea, BLM estimates that from 0.5 to 5 barrels of formation water will be produced per barrel of oil (USDI, 1979). The water may be separated from the oil at the production platform or at a shoreside treatment plant. In the former case, formation water may be reinjected, injected into disposal wells, or discharged into the sea. The latter alternative raises concerns about possible biological damage. Formation waters may be anoxic, highly saline, and may contain dissolved aromatic hydrocarbons, heavy metals and hydrogen sulfide. Any of the above conditions could be detrimental to the biota. Formation waters may be diluted with seawater to reduce contaminant concentrations to acceptable levels before discharge.

For the Beaufort sale area, at oil concentrations of 30 ppm, the discharge of one-half of the produced formation waters could result in the introduction of up to 1,000 or 10,000 barrels of oil annually into the environment (based on the 0.5:1 and 5:1 formation water:oil ratios noted above) (USDI, 1979). These values represent about 25 and 70 percent, respectively, of the estimated maximum volume of crude oil released annually from all Beaufort Sea field sources. Similar calculations for NEGOA based on extractable reserves of 0.5 billion barrels and a 30-year field life produce maximum annual rates of 250 and 2,500 barrels of oil discharged with formation waters.

11.5.5 Accidental oil spills

Oil spills from platforms can be either operational or phenomenological. The former can be predicted with confidence, based on abundant data from OCS oil operations elsewhere. Spills caused by natural phenomena, such as great storms and earthquakes, are more problematical. First, since OCS oil activities in hostile northern environments are of recent origin, few data are available on spills there. Second, great storms and earthquakes occur so seldom that there is little information on which to base predictions.

Accidents resulting in oil spills can be caused by blowouts during drilling, platform fires, equipment failures, and operator errors. Representative statistics on the frequencies of operational spills are presented in Table 11.8. The data are based mainly on operations in the Gulf of Mexico and may not be applicable to NEGOA due to improvements in technology, differing operating conditions, and other factors. Annual maximum oil spillage from platform fires, overflow, malfunction or rupture of equipment, and minor spills (all sources) during peak production from Sale 39 tracts was estimated at 6,450 barrels per year (USDI, 1976). In addition one blowout, which would release 2,100 barrels of oil sometime during the production period of the lease area, was projected.

Table 11.8 Operational oil spill statistics (USDI, 1976; 1979).

Source	Spill rate	Average amt. spilled (bbl)
Platform		
Blowout	1/2860 wells drilled	2,100
Fire	0.0029% of production	-
Equipment failure	0.000054% of production	130
Pipeline	0.0017% of production	-
Tanker	0.013-0.016% of transport	-
Miscellaneous minor	9.4% of total production spillage	less than 50

Oil spills from platform collapses attributable to storms or earthquakes were predicted in BLM's Sale 39 risk analysis (USDI, 1976). It was assumed that the blowout protector valve was 96 percent reliable and that a 1.5 or 2.0 safety factor was used in the platform design. Table 11.9, extracted from the BLM analysis, presents representative probabilities. Salient points of the analysis are that the probability of collapse from a 100-year or 200-year storm or earthquake of large magnitude (Richter 7.2 to 8.6) increases linearly as the age of the field increases and decreases linearly as design criteria are made more stringent. Also, probabilities of platform collapse due to earthquakes are 3 to 7 times higher than those of severe storms. Moreover, the probability of an oil spill at a production platform would be greater than the values shown in Table 11.9 due to the presence of more than one well. As the number of production wells increases, the likelihood of a valve failure at the platform increases.

Table 11.9 Estimates of platform collapse and well blowout assuming blowout preventer valve 96 percent reliable (USDI, 1976).

Event	Probability of platform collapse 20-yr field life	30-yr field life	40-yr field life
Severe Storms			
100-yr storm			
1.5 safety margin	0.0036	0.0056	0.0076
1.0 safety margin	0.0016	0.0024	0.0032
200-yr storm			
1.5 safety margin	0.002	0.0028	0.0036
2.0 safety margin	0.008	0.0012	0.0016
Earthquakes			
Richter 7.2			
1.5 safety margin	0.13	0.20	0.26
2.0 safety margin	0.11	0.179	0.22

The physical and chemical characteristics of spilled petroleum influence its subsequent fate and its possible effects on the biota. The properties of crude oil have been under intensive investigation in recent years. A comprehensive review (Malins, 1977) emphasizing the subarctic and arctic regions is applicable to the NEGOA Sale Area. Little information on petroleum in NEGOA, other than that on natural seeps by Blasko (1975, cited in USDI, 1976), exists.

11.5.6 Pipelines

Contaminants associated with pipelines include sediments from pipelaying and burial and oil or gas released during operations. OCS regulations require burial of pipelines in waters shallower than 60 m. Consequently, it is probable that only a small amount of pipeline will be buried in NEGOA, but burial may be required for pipeline laid near Yakutat. Submarine pipelines require a swath of seafloor about five feet wide. A somewhat wider area is disturbed where pipe is buried (Kramer et al., 1978) because of the displacement of bottom sediments, but the disturbance is short-lived. The strong currents in the Yakutat area can be expected to flush out quickly any turbidity arising from pipeline burial.

Contamination from oil leaks or pipeline breaks during operations may be more serious than that resulting from pipelaying. Data from actual spills (Table 11.8) and an annual field production rate of 16.7 million barrels of oil suggest that 284 barrels of oil per year could be spilled through pipeline accidents in the Sale 55 area. However, that projection is an annual average based on data from another region, and it combines all categories of spillage (leaks, rupture, valve failures). More likely are low annual levels of chronic spillage punctuated by sporadic large discharges. The large discharges are of interest in view of their potential for widespread damage. A worldwide summary of oil spills in 1978 that exceeded 20,000 gallons (Anon., 1979b) indicates that of 12 accidental pipeline ruptures and leaks reported, most resulted in spills of less than 1,000 barrels; a few exceeded 2,500 barrels and one discharged over 17,000 barrels. Because of serious risks to pipelines from possible soil slumping in the Sale 39 area, USDI

(1976) recommended special attention to the selection and design of pipeline routes. This will probably be true for the Sale 55 area also.

11.5.7 Shore facilities

Contaminants at shore facilities may occur as emissions, effluents, and solid wastes. Sewage and refuse would probably be disposed of by the municipality.

The processing, storage, and loading of petroleum results in the release of hydrocarbon vapors and spillage; 317 kg of hydrocarbons typically are lost per thousand m^3 of crude oil transferred from tank to tanker (Kramer et al., 1978). For a 65,000 dwt tanker this would amount to about 25 metric tons of hydrocarbons lost through evaporation. Evaporation losses from tanks during storage are about 18 kg and 3.4 kg per thousand m^3 stored for fixed and floating roof tanks, respectively (Kramer et al., 1978). Vapor losses during tank filling may be 87 kg per thousand m^3 (Kramer et al., 1978).

Emissions from treatment plants are generally within allowable levels, according to Kramer et al. (1978); treatment plants also generate potentially harmful liquid and solid wastes. Formation waters separated from crude oil must be disposed of; existing regulations permit a maximum daily average of 72 mg of oil per liter of water discharged (Kramer et al., 1978). Varying quantities of sands and other solids also are separated from the wellstream and are disposed of in landfills. Designated landfills are used for solid wastes which contain significant quantities of oil (Kramer et al., 1978).

Inevitably, some crude oil is spilled during transferring or loading. The spillage rate has been low in recent years. During a nine-year period, spillage accounted for only 0.0011 percent of all oil moved at the Milford Haven terminal (Brummage, 1973). This information suggests that for a projected annual production of 16.7 million barrels from the Sale 55 Area, about 184 barrels might be spilled per year. The reported spillage at the new Valdez terminal is even lower: 0.5 barrels per million barrels shipped (Purdy et al., 1979), identical with the current standard estimate for oil pollution from discharges and terminal operations in port areas given by Bright (1979). If this rate were achieved in the Sale 55 Area terminal operations, the annual spillage from the projected production would be only about eight barrels.

A source of chronic contamination of waters near oil terminals is the effluent from ballast water treatment. Rather than discharging ballast water at sea as was the past practice, tankers now discharge ballast water at oil terminals (e.g., Valdez). As these waters may contain considerable quantities of hydrocarbons, they must be treated before release. The treatment may include gravity separation, flocculation, and air flotation, followed by dilution to reduce contaminant concentrations in the final effluent to allowable levels. The final effluent at the Valdez facility contains about 11 mg carbon per liter; it consists of 48 percent volatile aromatic hydrocarbons, 36 percent nonvolatile water-soluble organics, and 16 percent suspended organic matter (Lysyj et al., 1979). Although concentrations of hydrocarbons may be low, the total amount discharged may be high due to the large volume of ballast water treated. At the Valdez facility, for example, about 10 million gallons of ballast waters are discharged per day with about 80 gallons of aromatic hydrocarbons and 45 gallons of dissolved organics (Lysyj et al., 1979). The implication is that in the absence of adequate dilution of the effluent by tidal mixing and currents, localized accumulations of hydrocarbons may occur.

11.5.8 Tankers

The two major contaminants from tankers are stack emissions and spilled oil resulting from accidents or structural failures. (Ballast water and spillage during oil loading were considered earlier.) Tanker emissions are a major issue in areas having air quality problems, such as Southern California. The Santa Barbara County Air Pollution Control District estimated that, at a crude oil production rate of 200,000 barrels per day, tanker loadings of processed oil would add over 1,800 metric tons of hydrocarbons per year to the air basin (Chorich, 1978). A 150,000-dwt tanker emits from 2.9 to 3.6 metric tons of sulfur dioxide per day while burning heavy residual diesel oils; the amount of discharge can be reduced by burning low-sulfur fuel while in port (Kramer et al., 1978).

The worldwide accident rate for oil tankers is 4.4 accidents per 1,000 voyages (Bright, 1979). About 20 percent of the accidents result in oil spills, but 90 percent of the spills are of less than 25 barrels. Thus oil spills from tankers are rare, most spills are small, and most of the spillage results from a few large spills. A consequence of this is that "average" spill statistics are not very meaningful. Worldwide data indicate a two-percent probability that a 60,000-barrel or larger spill will occur within 50 miles of land because of a tanker casualty (Bright, 1979). The CEQ reported a tanker spillage rate of 0.016 percent of oil transported, including operational spillage (USDI, 1976). That rate and an annual production of 16,700,000 barrels of crude oil in the

Sale 55 Area suggest that tanker spillage could amount to 2,670 barrels per year.

The locations of tanker routes are important determinants in potential oil spill consequences. In the Sale 55 Area, tanker loading sites and shipping routes have not yet been designated. Either an offshore SPM or a terminal in Yakutat Bay could be built. However, the coastal configuration and bottom topography near Yakutat are such that tankers would not have to remain near shore for any appreciable distance. The major shoal in the region is the Fairweather Ground, about 110 km SSE of Yakutat Bay; minimal depths there are 24 m.

11.6 ENVIRONMENTAL DISTURBANCE LIKELY TO ACCOMPANY DEVELOPMENT

Disturbance may take the form of human activities that cause organisms to alter their usual behavioral patterns, or it may consist of the physical preemption of habitat through direct removal or alterations that make it unattractive to the biota.

11.6.1 Increases in turbidity

Localized increases in turbidity from the disposal of drill muds and cuttings and from pipe trenching and burial are expected to be of limited significance in the Yakutat region. Furthermore, the biota of this area are routinely subjected to high natural levels of suspended matter. Rock flour originating from numerous streams and glaciers and bottom sediments resuspended by wave action produce suspended particulate concentrations in excess of 2 mg/l over wide areas of the inner shelf near Yakutat. The highest values at the sea surface occur during river runoff in summer, while the highest values near the seafloor occur during winter storms (Feely et al., 1979). In comparison, maximum suspended solids concentrations in the effluent of the Lower Cook Inlet C.O.S.T. well were about 6 mg/l (Dames and Moore, 1978).

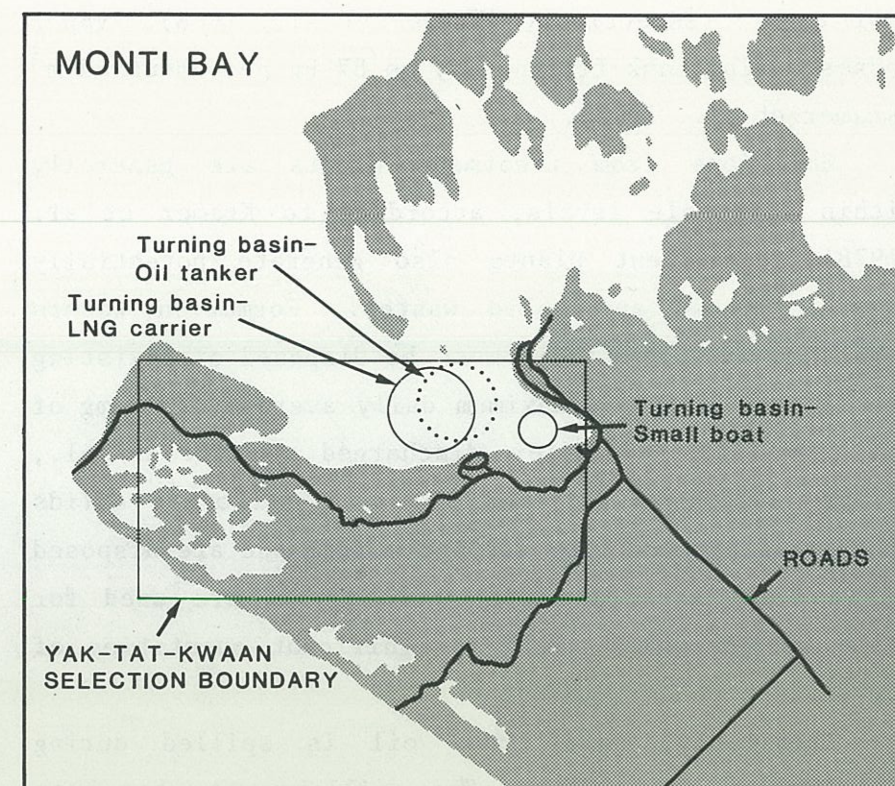
11.6.2 Habitat removal

The construction of shoreside facilities constitutes a long-term, if not permanent, removal of habitat. The consequences of such removals may differ widely, depending on the location and type of the habitat and its importance to the biota. Habitats believed to be of particular importance are designated "critical habitats."

The number of development options conceivable in the Sale 55 Area is too great to detail all the alternatives and their concomitant land requirements. Instead, the requirements for various kinds of facilities (Table 11.10) are shown to indicate the kinds and amounts of land that might be needed. Sites adjacent to a suitable harbor and as close as possible to the producing field are desirable in all cases. Development in the Sale 55 area would be concentrated on or near Monti Bay, as the harbor is suitable for supply vessels, LNG tankers, and large crude carriers; it is close to the sale area, sheltered, has adequate level land along its south side, and is close to transportation and shipping facilities (cf. Kramer et al., 1978, pp. 185-187, and Fig. 11.5). The village of Yakutat lies at the eastern end of the bay; thus the concentration of oil facilities nearby would localize the geographical effects of habitat removal in an area that has already experienced some disturbance from man's activities. In the event of an oil discovery, a site-specific environmental survey of the proposed locations of the facilities should be performed to identify problems which may arise from development and to furnish data that can be used to minimize environmental contamination through proper facility siting and design.

Table 11.10 Representative onshore land requirements for OCS oil activities (Kramer et al., 1978).

Activity	Size/ capacity	Site Area (hectares)	General needs
Service base	1 berth	2 to 5	Harbor location, 61 m frontage
	4 berths	11 to 15	Harbor location, 230 m frontage
	10 berths	26 to 36	Harbor location, 600 m frontage
Onshore pipeline	to 91.4 cm dia.	15 to 30 m right-of-way enroute	About 900 m^3 gravel/km req'd for pipe bedding
Treatment plant	7 k bbl/day	1	Location relatively flexible
	170 k bbl/day	12	
Oil terminal	250 k bbl/day	28	Usually located on closest suitable harbor to platforms. Acreage needed affected by slope; less needed if flat.
	650 k bbl/day	200	
LNG plant	200 million ft/day	16	Usually sited near production
	2.9 million ft/day	200	Usually sited near producing field. Requires marine facility to load LNG vessels.



11.6.3 Direct disturbance

Human activities often cause changes in the behavior of animals. These may include attraction or repulsion, alteration of feeding habits, and disturbance of breeding activities. Human activities that are detrimental to some species may benefit others. Furthermore, the location and time of the disturbance must be considered as well as the behavior of individual species, species interactions, and the nature of the disturbing agent. There are many potential sources of disturbance from OCS oil and gas activities; among the most important in NEGOA are aircraft and boat traffic, the physical presence of structures, and increased density of human population.

Low-flying aircraft can cause high mortality of young at seal rookeries and seabird colonies, and possible desertion by nesting waterfowl (Hunt, 1976; OCSEAP, 1978). Disturbance of harbor seals is especially critical during the period of mother-pup bond formation. At seabird colonies the highest mortality probably occurs when adults flushed by aircraft leave young and eggs unprotected from predators. Similar damage occurs when vessels come close to bird or mammal rookeries. In addition, vessel traffic may cause marine mammals to be temporarily displaced from or to desert areas traditionally used for foraging, migration, and other activities. The usual way of minimizing aircraft or vessel disturbances of animals is to regulate traffic patterns and periods that the patterns must be used.

← Figure 11.5 Proposed development, Monti Bay (Kramer et al., 1978).

Shoreside and offshore structures, utility corridors, and the activities associated with them may repel or attract animals. They may be beneficial to some species (e.g., scavengers such as gulls and crows) but fatal to others (e.g., migrating birds attracted to lights). Death may occur through collisions or entrapment. Other possible effects are restructuring of biological communities, increased vulnerability of organisms to predation (e.g., by commensal species such as foxes or gulls), alteration of feeding patterns, and avoidance of the area due to increased noise levels. If shoreside development is concentrated near Monti Bay, the disturbing effects of structures in the Sale 55 Area would be confined to relatively small areas.

Recreational activity is a potentially large source of disturbance of animals. Kramer et al. (1978) estimated that in the case of a bonanza oil and gas discovery in NEGOA, up to 10,000 people could be directly employed. Estimated employment in the no-find case was about 700. As noted earlier, the largest number would be present during construction of oil terminals and other facilities, but only 40 percent of that number would be needed during production.

If persons indirectly employed because of OCS development and dependents of both groups are also considered, it becomes apparent that recreation in the Yakutat region resulting from development could exert considerable pressure on fish and wildlife resources. Total additional population increases in NEGOA could range from 1,366 to 24,924 people (no-find and bonanza cases, respectively) (Kramer et al., 1978). Demand for consumptive and nonconsumptive uses of fish and wildlife (e.g., hunting, fishing, birdwatching, photography) could increase by orders of magnitude, producing significant pressure on local animal resources and probably requiring much more restricted use than is currently allowed.

11.7 EVALUATION OF DATA

The available data are limited and come mostly from other areas. Technical aspects of present exploration and production systems are known. However, rapidly evolving technology might result in the use of yet untried equipment or techniques. Furthermore, in the absence of a discovery or development plan, one can only speculate about the geographic disposition and characteristics of the system that might be employed to extract, treat, store, and load crude oil or LNG.

The only available information on the composition of petroleum in NEGOA is from oil seeps and oil from the Katalla Field, which could differ markedly from that found near Yakutat. Speculations about quantities of contaminants that might be released from various sources are based mainly on data from less hostile environments and may not reflect currently achievable standards. Data from North Sea oil fields are probably most similar to those expected in NEGOA. There are few, if any, precedents from which to evaluate the probability of earthquake-caused platform collapses and oil spills from deepwater production platforms.

The environmental disturbances likely to result from OCS activities can be predicted. Some activities, such as ship and aircraft traffic, can be controlled through stipulations. Other activities will vary according to the character of development and locale, and their effects cannot be predicted with certainty until development plans become available.

11.5.3 Direct disturbance

Human activities often cause changes in the behavior of animals. These may include attraction or repulsion, alteration of feeding habits, and disturbance of breeding activities. Human activities that are detrimental to some species may benefit others. Furthermore, the location and time of the disturbance must be considered as well as the behavior of individual species, and the nature of the disturbing agent. There are many potential sources of disturbance from OCS [illegible]

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[illegible] young and easy vulnerable to predators. Similar damage occurs when vessels [illegible] birds or animal [illegible] displaced from [illegible] foraging, migrations, and other activities. The usual way of minimizing aircraft or vessel disturbance of animals is to regulate traffic patterns and periods that the patterns must be used.

Figure 11.3. Proposed development, [illegible] (Kramer et al., 1978).

Shoreside and offshore structures, utility corridors, and the activities associated with them may repel or attract animals. They may be beneficial to some species (e.g., scavengers such as gulls and crows) but fatal to others (e.g., migrating birds attracted to lights). Death may occur through collisions or entrapment. Other possible effects are restructuring of biological communities, increased vulnerability of organisms to predation (e.g., by commensal species such as foxes or gulls), alteration of feeding patterns, and avoidance of the area due to increased noise levels. If shoreside development is concentrated near Nome, [illegible] the disturbing effects of structures in the [illegible] be con[illegible] small [illegible] large [illegible]

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The environmental disturbances likely to result from OCS activities can be predicted. Some activities, such as ship and aircraft traffic, can be controlled through stipulations. Other activities will vary according to the character of development and locale, and their effects cannot be predicted with certainty until development plans become available.

CHAPTER 12 ENVIRONMENTAL HIGHLIGHTS AND ISSUES OF THE NEGOA REGION

L. Jarvela, OCSEAP

12.1 INTRODUCTION

The following pages give a description of the dominant physical and biological characteristics of NEGOA, including unique environments, key species and their habitats, natural hazards to OCS oil and gas activities, and information gaps. Some issues pertinent to the forthcoming Sale 55 are then considered in light of the above and possible development activities.

12.2 PHYSICAL SETTING

Physiography has a dominant influence on biological, physical, and man-induced interactions in the environment. Much of the following description of the physiography of NEGOA is drawn from regional profiles prepared for the State of Alaska by AEIDC (Selkregg, 1974). NEGOA abuts one of the most rugged and spectacular coasts in the world. Spanning an arc of roughly 1,000 km from Gore Point on the Kenai Peninsula eastward to Cape Spencer near the southeastern Alaska Panhandle, NEGOA is ringed by the high coastal Fairweather, St. Elias, and Chugach ranges. Many peaks higher than 4,000 m, topped by Mt. St. Elias at about 5,500 m, rise close behind the narrow (1 to 40 km wide) coastal plain between Icy Point and the western edge of the Copper River Delta. The coastline here is, for the most part, unprotected from oceanic storms and offers little shelter for vessels. Yakutat, Lituya, and Icy Bays are the principal embayments, the others being shallow river estuaries. West of the Copper River Delta, Hinchinbrook and Montague Islands form the seaward boundaries of Prince William Sound, a complex of islands and fiords. The waters of the Sound are relatively protected, as only a few passages--the largest being Hinchinbrook Entrance and Montague Strait--connect the Sound with the Gulf of Alaska. The coastline of the Kenai Peninsula, to the west of Montague Island, is indented by numerous fiords and dominated by steep mountains.

Compared with the broad continental shelves of the Bering and Beaufort Seas, the shelf in NEGOA is narrow. It is about 100 km across near the Fairweather Ground, but only 10 km wide off Bering Glacier. West of Kayak Island, an elongated island that projects offshore just west of Cape Suckling, the shelf again becomes 80 to 100 km wide. The shelf is dissected by numerous sea valleys. The most prominent include those off the Alsek River, Yakutat Bay, Bering Glacier, and Hinchinbrook Entrance. The major topographic highs on the shelf in NEGOA include the Fairweather Ground, off Cape Fairweather; Tarr Bank, south of Hinchinbrook Entrance; and Middleton Platform, from which Middleton Island rises. The island is the only major emergent feature lying a considerable distance offshore in NEGOA.

The climate of NEGOA is maritime. The cool summers and mild winters are caused by the moderating influence of the counterclockwise-flowing Alaska Current. Ice forms only in protected inshore waters. Frequent storm systems from the western Pacific move eastward, encounter the high coastal mountains and stagnate, causing much precipitation. Precipitation occurs throughout the year, ranging from 147 cm (annually) at Middleton Island to 460 cm at Latouche (Brower et al., 1977). During winter and at higher elevations during much of the year, considerable precipitation occurs as snow. The annual average is 5.8 m at Yakutat and perhaps 20 m in the St. Elias range. Coastal temperatures vary little, ranging from mean annual maxima of 7-8°C in summer to minima of 0-3°C in winter. Farther offshore at Middleton Island, summer temperatures are warmer, and mean annual maxima reach 17.6°C.

The copious precipitation feeds icefields, piedmont glaciers, and valley glaciers that are among the largest in the world (e.g., the huge Bering and Malaspina Glaciers between Yakutat and Kayak Island). Some of the glaciers reach tidewater. Streams that enter NEGOA are typically short and steep; they carry large sediment loads. Many are braided, as is typical of glacial outwash streams, and along the eastern Gulf coast their estuaries are usually fronted by barrier spits. The Alsek and Copper Rivers are the only streams that penetrate the coastal ranges and drain watersheds of the interior.

12.3 DEMOGRAPHY

The human population of NEGOA consists of only a few thousand people. Few live on the outer coast. Yakutat is the largest coastal village and had a population of 405 people in 1977 (Alaska Consultants, 1979). Most of the inhabitants live in the Prince William Sound communities of Whittier, Cordova, and Valdez, and in the Kenai Peninsula community of Seward. The populations of those communities in 1970 were 130, 1,164, 1,005, and 1,587, respectively (Selkregg, 1974). In 1978 the population of Cordova had grown to 3,220, while the population of Seward has declined to 1,187 (Bennett et al., 1979).

As road or rail access to the interior is possible only from Valdez, Seward, or Whittier, travelers rely heavily on air or marine transport. All communities but Whittier are served by regularly scheduled flights. Yakutat, Valdez, Cordova, Whittier, and Seward have port facilities, and the latter three communities have regular ferry service. Much of the port activity in NEGOA is related to commercial fishing or fish processing.

12.4 LAND OWNERSHIP

The federal government controls most of the land along the NEGOA coast. Among the current federal landholdings are the Tongass National Forest, which includes much of the coastal plain east of Yakutat and most of the coast from Cape Suckling west through Prince William Sound to Seward; the Glacier Bay National Monument; and D-2 lands (recently placed in abeyance under the Antiquities Act). Most of the remaining land is owned or has been selected by the State of Alaska. Native corporations have selected lands at Yakutat, Cordova, Tatitlek, and Chenega. The transfer of ownership of the state and native land selections is in progress.

12.5 GEOLOGY

NEGOA is one of the most tectonically active regions in the world, being situated at the boundary between the active Pacific and stationary North American crustal plates (see Chapter 3 for details). The region is in a transition zone between two types of tectonic activity resulting from crustal plate interaction. In the eastern part of NEGOA, slippage along the plate junction forms wrench faults such as the Fairweather Fault, whereas in the western part the principal tectonic activity is subduction. The Pacific plate there is moving northward and being subducted under the North American plate, forming the Aleutian Trench (Perez and Jacob, 1980). The dramatic effect of relative motion along the Fairweather Fault can be seen in the northerly offset of glacial valleys that cross the Desolation Valley near Lituya Bay; the average relative movement along that part of the fault has been 4-5.8 cm/yr during the past 1,000 years (Molnia and Wheeler, 1978).

Earthquakes result from the periodic release of accumulated stress between the crustal plates and are frequent in NEGOA. Many have exceeded 7.5 on the Richter scale. Patterns of earthquake activity in the region strongly indicate that a major earthquake is imminent in the Yakataga "seismic gap" (Perez and Jacob, 1980). While seismic activity is less on the outer shelf, the shelf edge portion of Yakutat wedge, a segment of the continental shelf between Cross Sound and Icy Bay, could be the locus of a major earthquake (Perez and Jacob, 1980).

Tectonic uplift often accompanies earthquakes. During the 1964 Great Alaska and the 1899 Yakutat earthquakes localized increases in elevation of 9 and 14 m, respectively, occurred. The elevated wave-cut benches in many areas also suggest tectonism, although some investigators (e.g. Derksen, 1975; cited in Molnia and Wheeler, 1978) believe that some terraces resulted from eustatic lowering of sea level and isostatic rebound following glacial retreat.

In addition to the major fault systems associated with the crustal plate junctions, numerous subsidiary surface and near-surface faults have been identified in NEGOA. They tend to parallel onshore faults and often are uplifted on the northern or northwestern side. Most of the reported offshore faults are in the Icy Bay area, near Kayak Island, and scattered across Tarr Bank and Middleton Platform. Few have been found in the eastern part of the region, possibly because this area has been little studied. Some of the faults near Tarr Bank may be active, as suggested by seismic activity in the area (see Chapter 3).

Forces resulting from the collision of the plates formed the young (Mesozoic-Cenozoic) mountains that surround the gulf. In concert with other natural events such as the Pleistocene glaciations, they produced numerous glacial-fluvial coastal landforms. Much of the coast which is now exposed was covered by glaciers in historic times. At Icy Bay, which was completely covered by a glacier 70 years ago, the ice front has retreated 42 km in less than 50 years (Cannon, 1976). The mountains are being rapidly eroded by glacial processes, precipitation, and freeze-thaw cycles. The steep slopes speed erosion and the transport of eroded materials. One result of these processes is a coastal landscape typified by a mosaic of bedrock exposures, morainal deposits, alluvial fans, and till deposits.

Sea valleys, such as those off Yakutat and Icy Bays and Bering Glacier, are the submerged counterparts of glacial valleys on land. During the peak of the Pleistocene glaciation the continental ice sheet extended offshore. The sediment found today on the outer shelf was laid down by glacial marine processes. As the ice retreated onshore, the principal contribution of sediments from the deposition of fine rock flour by outwash streams. The fine sediments are rapidly covering the older deposits on the inner shelf. Major contributors of contemporary sediments in NEGOA are the Alsek, Bering, and Copper Rivers. All of these have deltas, of which the Copper River's is the most extensive. The major repositories of the sediments carried westward on the shelf are sea valleys and other depressions such as Kayak Trough and Prince William Sound. Rapid submarine accumulation of sediment also occurs in numerous fiords and fiord embayments.

Rapid erosion and accretion of coastal beaches are common in NEGOA. The retreat of the glaciers in the region with the consequent reduction in sedimentation has caused widespread coastal erosion, exemplified by the Malaspina Foreland and Yakataga areas. In some areas sediments are insufficient to replace land eroded by the high surf common in the gulf. Instead of gently sloping beaches backed by low foreshores, beaches in these areas are backed by wavecut bluffs, often with large accumulations of trees eroded out of the bluffs.

Sediments are being deposited along a small proportion of the coastline, most notably in the Copper River Delta. The most striking example of rapid deposition is at Point Riou in Icy Bay. Since 1904 the point has grown 6.6 km at the expense of the Malaspina Foreland, which is retreating at 37 m/yr (Molnia, 1977). Although in the short term, coastal erosion is more prevalent than deposition along the NEGOA coast, in a longer geological time period even in erosional areas the coastal plain is accreting due to episodic uplifts (Ruby, 1977).

Rapid sedimentation is probably the major cause of slope instability on the continental shelf in NEGOA (see Fig. 2.17). The high rate of sedimentation and high water content of the sediment results in under-consolidation. Slumping is not confined to steep slopes. Slumps on slopes of less than one degree have been reported (Molnia et al., 1977; Carlson et al., 1978). Major slump features have been observed off the Copper River Delta, in Kayak Trough, and seaward of Icy Bay. Numerous areas which are likely to slump have also been identified. Mass movement of sediments may be initiated by hydrostatic loading resulting from storm waves, but earthquakes are probably the principal cause. The amount of material set in motion can be large. Molnia et al. (1977) estimated the Kayak Trough slump at 5.9 km^3; this slump is believed to have occurred during the past 70 years (see Chapter 3).

Another cause of sediment instability in NEGOA is gas-charging. The gas-charged sediments found thus far appear to be the result of decomposition of buried organic matter rather than seepage from petroleum reservoirs.

Earthquake activity and glaciation in NEGOA are also the cause of tsunamis and glacial outburst floods. The major cause of death in the 1964 Prince William Sound earthquake was the tsunamis generated by the quake (Selkregg, 1974). In addition to tsunamis resulting from tectonism, large waves and seiches have been caused by landslides and icefalls into confined bodies of water, e.g., the 1958 Lituya Bay and 1845 Yakutat Bay waves, the latter of which caused 100 deaths. Outburst floods have occurred or could occur at numerous locations around the gulf. Cannon (1976) describes a large outburst flood from Harlequin Lake east of Yakutat. Berg Lake, formed by an ice dam from Bering Glacier, could cause a major flood with peak flows over 30,000 m^3/s, should the dam burst (Carlson, 1977). That peak flow rate is roughly ten times that of the Copper River during peak runoff in July (Ingraham et al., 1976). There are other potential outburst flood hazards near Icy Bay (See Chapter 3).

Other features of the glaciated terrain could cause problems for onshore activities or structures. Among these are glacier surges, buried ice blocks and stagnant ice masses, unstable ground, delta front slumping in the intertidal zone, and drift ice from glaciers. Buried ice may also occur in the gulf. Molnia (1976) found evidence of buried ice in submarine sedimentary deposits at the head of Bering Trough. The bathymetry there echoed the kame and kettle topography associated with terrestrial buried ice.

12.6 OCEANOGRAPHY

NEGOA is part of the subarctic region of the North Pacific. High precipitation, seasonal heating and cooling, and seasonal mixing by winds and convection produce distinctive structural features in the upper waters of the region (Tully, 1964). A dilute surface layer overlies a zone of rapidly increasing salinity that begins at about 100 m depth. The halocline causes a pronounced increase of density between 120 and 200 m. As vertical mixing between surface and deeper waters is thus inhibited, most of the seasonal cycles of water properties occur near the surface. There is a shoreward decrease of salinity from oceanic to coastal waters. Because of these features, the region has been termed an estuarine analog (Tully and Barber, 1960).

Recent physical oceanographic and meteorological studies have added much detail to the previous knowledge of currents in NEGOA and the processes driving them. The net flow is westward and usually parallels bottom contours. Currents are more complex and variable west of Kayak Island than to the east. An apparently permanent eddy or gyre is present just west of Kayak Island; it is probably caused by the interaction of topography and currents. The strongest flows occur near the continental slope and in a narrow band along the coast. The former current is the well-known Alaska Current; the latter has no name, but has been called a coastal jet by Royer (1979b).

Considerable seasonal and shorter-term variation occurs in the current field due to annual cycles in winds and freshwater inflow, storms, and mesoscale turbulent features such as eddies, which occasionally traverse the shelf.

The Alaska Current is a narrow, intense flow near the shelf break. Mean surface speeds in the Alaska Current have been estimated at 60 cm/s, with peak speeds of up to 120 cm/s (Royer, 1979b). Flow appears to increase in winter, and speeds then may be double those during summer. Most of the transport by the current takes place in a 50- to 100-km-wide band, mainly in the upper 500 m. The volume of transport is comparable to that of the California Current. Seasonal fluctuations in transport are the subject of debate; some investigators believe that there is no significant seasonal signal, while others suggest that maximum transport occurs in May and minimum transport about November (Royer, 1979b). In the latter case, the five-month lag between the period of maximum winds and that of maximum transport is attributed to the averaging effects of wind stress (assuming that wind stress is a dominant forcing mechanism). The Alaska Current acts as a dynamic boundary separating oceanic waters from those on the shelf.

The width of the shelf in NEGOA affects circulation patterns. East of Kayak Island, where the shelf is narrow, the Alaska Current and the coastal jet are juxtaposed, while west of the island they are separated by a mid-shelf zone of more variable, sluggish flow. Mid-shelf waters have weaker vertical density gradients than waters farther inshore or offshore; thus vertical mixing can extend to greater depths. Cyclonic eddies 70-100 km in diameter are common in the mid-shelf region. As in the Alaska Current, the westerly transport in the mid-shelf region varies seasonally, being greatest in October-November and smallest during summer. The introduction of fresh water into the system in autumn probably causes the increased speeds and transport then.

The distinctive westward-flowing coastal jet in NEGOA averages 30 km in width, has surface speeds of at least 50 cm/s, and is believed to exceed 80 cm/s occasionally. Its maximum transport is thought to occur in January, four to five months after the periods of maximum precipitation and runoff. Strong January winds intensify the flow.

Winds, freshwater runoff, eddies, and bathymetry are major driving mechanisms of NEGOA currents. In addition to direct effects of stress on the sea surface, winds also cause barotropic and baroclinic responses. Regional forcing results from the curl of the wind stress and contributes to the broad-scale cyclonic movement of water in the gulf. Local winds are also important in the generation of currents; they include those that accompany storms and katabatic flows. Storms produce short-term (up to two weeks) current pulses that often equal or exceed mean current speeds. Although they may occur at any time of year, they are most prevalent during winter. In nearshore waters, responses to wind stress are rapid and reflect local events. Since local winds may not be related to the synoptic-scale field (e.g., katabatic flows), such responses must be considered individually.

The influx of fresh water into NEGOA is a major driving force of currents in the coastal waters. It produces the baroclinicity that results in the coastal jet. Freshwater runoff peaks in autumn. In winter baroclinicity is heightened by prevailing easterly winds that constrain the fresh water nearshore. Further augmentation of the coastal current at that time comes from concurrent wind drift and barotrophic effects.

Bathymetry directs flow and causes current fields to largely parallel bottom contours. Eddies that break off the Alaska Current and move shoreward are thought to transfer momentum onto the continental shelf in NEGOA.

While having negligible effects on net flow in the region, tides are important dispersive agents. Off Icy Bay tides comprise about 60 percent of the variance of currents in summer and 25 percent in winter. The lower percentage in winter is due to the greater proportion of low-frequency energy generated by storms during that season (Muench et al., 1978).

The wind field in NEGOA varies greatly because of the alternate domination of the Aleutian Low in winter and the North Pacific High in summer. In winter the intensification of high pressure in the interior of Alaska causes mean winds twice as strong as those in summer. Along the NEGOA coast winter winds are predominantly easterly, whereas in summer they are more variable and occasionally may be westerly. Coastal winds are modified by three major processes: orographic steering, land-sea temperature differences, and katabatic winds. Because of the high mountains adjacent to the gulf, coastal winds are mostly alongshore as far as 100 km offshore (see Chapter 2). Katabatic winds occur intermittently near piedmont glaciers and passes through the coastal mountains.

These winds are most prevalent and strongest in winter and sometimes exceed 165 km/hr; their effects may result in offshore winds that extend as far as 25-30 km offshore.

NEGOA is one of the stormiest areas on Earth. Winds of 37-38 m/s and waves up to 23 m are likely to occur every few years, while a 100-year storm could produce sustained winds of 52 to 53 m/s and waves of 38 m (Table 12.1). Under certain conditions of winds, tides, and waves, storms may cause flooding of coastal beaches. Past storm surge floods have extended up to several kilometers inland of presently active beach faces (Ruby, 1977; Molnia and Wheeler, 1978). Areas most vulnerable to flooding are beaches backed by low beach scarps and the mouths of outwash streams; however, severe storms may cause damage even where no flooding occurs. Single storms have eroded as much as 50 m from beach faces (Hayes, in Ruby, 1977).

Table 12.1 Annual maximum winds and waves for selected return periods in NEGOA (Brower et al., 1977).

	Return period (yrs)[1]			
	5	25	50	100
Max. sustained wind (m/s)	38	45	49	53
Max. significant wave (m)	13	17	19	22
Extreme wave (m)	23	30	34	38

[1] Ranges represent different values estimated for Marine Areas D & E, upon which this table is based.

Levels of hydrocarbon and heavy metal contaminants in NEGOA waters and sediments are comparable to those in other unpolluted areas of the world's oceans. Some petroleum enters the gulf from natural seeps, notably those near Katalla. The Katalla hydrocarbons seem to be rapidly dispersed, as no oil is detectable in nearby waters (Shaw, 1978). Concentrations of floating tar in NEGOA are as low as those of pristine areas. Seasonal increases in hydrocarbons in the water column in spring are attributable to biological activity. A submarine oil seep in Yakutat Bay is suspected from anomalously high methane concentrations observed at the bay's entrance (Cline et al., 1978). Levels of heavy metals are low in NEGOA. Concentrations of particulate heavy metals are somewhat higher near shore and at depth than they are offshore or at the surface, a reflection of the distribution of sediments. In Yakutat Bay manganese levels increased near bottom, suggesting a flux from the sediments.

12.7 LIVING RESOURCES AND HABITATS

The prevention or minimization of adverse effects of OCS oil and gas development on marine ecosystems and their components is a major goal of the BLM/OCSEAP study plan. To obtain information on marine ecosystems, OCSEAP has made reconnaissance surveys to determine species density distributions, inventory habitats and identify key species; trophics studies of selected species and communities; and studies of the population dynamics of key species. Other studies have addressed contaminants, transport patterns, and the vulnerability of organisms to contamination. Most of the OCSEAP studies were made in the western half of NEGOA because that area was believed to be more likely to be affected by oil and gas development in Sale 39 tracts and because of important organisms and habitats at risk there. The forthcoming sale in the Yakutat area and the lack of discoveries on Sale 39 tracts have shifted the focus of research to the eastern part of NEGOA.

The likelihood of damage by OCS oil and gas activities to organisms and habitats appears to be less in the Yakutat region than in the western part of NEGOA. This is due at least in part to the more hostile physical conditions of the eastern part of the region. Except for a few locations such as Yakutat Bay, Icy Bay, Dangerous River, and Dry Bay, protected littoral habitats east of Kayak Island are few. Furthermore, the high wave energy and substrates along most of the coastline east of Kayak Island indicate that spilled oil would not persist long there. Such is not the case for much of the coastline west of the island.

12.7.1 Marine mammals

Harbor seals and northern sea lions are common and conspicuous; they are the only resident pinnipeds of NEGOA. Both species prefer coastal waters and are uncommon beyond the shelf break. The largest rookeries of both species are outside NEGOA; however, hundreds of harbor seal pups are born annually in Icy Bay, while a few hundred sea lions are born every year at rookeries at Cape St. Elias and Seal Rocks. The Copper River Delta is another area where harbor seals concentrate.

Sea otter numbers probably approach the carrying capacity of the habitat in the outer parts of Prince William Sound, and this species is well established in the inner sound and eastward to Cape Suckling. Farther east, small numbers are present around Icy Bay and along the coastline between Yakutat and Dry Bay.

Large numbers of fur seals move through NEGOA in spring en route to the Pribilofs and again in fall during their return to more southerly waters. It is not known how many are present in each season. High densities of fur seals have been observed in the western part of NEGOA near Cape St. Elias and Middleton Island and east of the region on the Fairweather Ground.

Information on cetaceans in NEGOA is sketchy. The small harbor porpoise and the wide-ranging Dall porpoise are two of the more abundant resident species. Prince William Sound and nearby waters attract numbers of larger whales during summer. Large numbers of gray whales migrate through coastal waters during spring and fall; humpback whales concentrate in late winter and early spring between Yakutat Bay and Cape Spencer.

12.7.2 Marine birds

In total numbers of colonies and breeding birds in the Gulf of Alaska, NEGOA is a minor seabird nesting area. The Middleton Island colony is the only one exceeding 100,000 birds. Most of the colonies in NEGOA are west of Kayak Island. The region does support large seasonal concentrations of seabirds. In spring millions of Southern Hemisphere shearwaters migrate westward through the region, mostly offshore along the outer shelf and shelf break. Glaucous-winged Gulls, Black-legged Kittiwakes, Common Murres, and Tufted Puffins are the most abundant breeding species. One quarter or more of the Gulf of Alaska breeding populations of Pelagic Cormorants, Mew Gulls, and Aleutian Terns nest in NEGOA.

Migrating shorebirds are abundant in spring and fall at coastal estuaries between Kayak Island and eastern Prince William Sound. Western Sandpipers and Dunlin frequently number in the millions. Most of the world's population of Western Sandpipers and the entire western Alaska breeding population of Dunlin are believed to pass through NEGOA during their migration.

NEGOA is a major migration corridor for waterfowl. In spring and fall millions of swans, geese, and ducks stop to feed, rest, and stage in the Copper-Bering delta system in the western part of the region. The total number of waterfowl that breed in NEGOA is small compared with those in major breeding areas elsewhere in Alaska; those that do breed in NEGOA include a large percentage of the Trumpeter Swans breeding in Alaska and almost the entire population of the Dusky Canada Goose.

12.7.3 Fishes

Numerous species of anadromous and marine fishes in NEGOA form the basis of significant domestic and foreign fisheries. Fisheries are a dominant element of the economic base of NEGOA. Salmon are present throughout the region. Pink and chum salmon are the dominant species in the Prince William Sound region, where hundreds of small streams and their intertidal reaches are used for spawning. The salmon fishery of the sound is by far the largest in NEGOA; it was worth about $14 million in 1973. In the eastern half of the area, sockeye and coho salmon are the important species in the net fisheries in estuaries. Yakutat area salmon earnings in 1974 were about $2 million. Coho and chinook salmon on the Fairweather Ground and waters inshore of that area are the target of the largest offshore troll fishery in the gulf. The coastal waters of NEGOA are a migratory route for hundreds of millions of young salmon moving northward from spring through fall; these fish come from local streams and waters as far south as Washington and Oregon and are believed to concentrate near shore.

Halibut are another major commercial species in NEGOA. They occur throughout the region and spawn along the continental slope. American and Canadian longliners take the bulk of the catch, but significant numbers are captured incidentally by foreign trawlers; the latter fish must be returned to the water. The average annual halibut catch from 1973 to 1977 was about 3.5 million pounds from the region from Cape Spencer to Hinchinbrook Entrance. That is equivalent to about $7 million annually at today's ex-vessel prices.

Herring occur throughout NEGOA; they are locally abundant and spawn in Yakutat Bay and inner Prince William Sound. Major fisheries for herring roe on kelp and sac roe have been developed in the Prince William Sound region in recent years. In the past, the herring fishery was principally a reduction fishery. No commercial fishery for this species currently exists elsewhere in NEGOA.

Groundfish, which include rockfish, roundfish, and flatfish that occur at or near the sea bottom, have been fished extensively by Russian, Japanese, and other foreign fleets in NEGOA in recent years. With the passage of the Fisheries Conservation Act of 1976, however, the groundfish fisheries are in transition. The State of Alaska has set forth a 20-year program to develop the bottomfish industry (Anon., 1979c). Included are plans for a competitive domestic fishery, markets for the products, regional processing facilities and labor forces, and management based on sustained yields.

Since the early 1960's the Japanese have taken large catches of sablefish along the outer continental shelf and slope. Sablefish are taken principally by longline and secondarily by trawling and pot fishing. Soviet trawl fisheries initially sought Pacific Ocean perch but have shifted to other species in recent years due to overfishing of those stocks. Walleye pollock have become a major target species of all foreign trawl fisheries in NEGOA, but significant effort also is directed toward fishes such as arrowtooth flounder and Pacific cod, which are abundant in the region. Areas off Cape Suckling and Yakutat are among the most productive groundfish areas in the Gulf of Alaska. The contribution of NEGOA to the Gulf of Alaska groundfish catch has fallen in recent years. In 1977 the total catch was about 12,500 metric tons.

Little is known of the pre-recruit life stages of groundfishes in NEGOA. Russian research (Lisovenko, 1964) indicates that the continental slope off Yakutat is the major spawning ground for Pacific ocean perch in NEGOA. It is likely that important spawning areas of other species also occur in NEGOA.

Several forage species that occur in the Gulf of Alaska are not now commercially exploited, but are prey for numerous species of fish, seabirds, and marine mammals. Capelin and Pacific sand lance appear to be most important; they occur throughout NEGOA and are major prey species of many seabirds, seals, sea lions, salmon, Pacific cod, halibut, and numerous commercially exploited fishes. Little is known of the distribution and abundance of these species in NEGOA. Sand lance and capelin have been shown to be important to higher-level consumers in the Kodiak and Lower Cook Inlet regions, and it seems reasonable to assume that they are also important in NEGOA.

12.7.4 Commercial shellfish

The Tanner crab ecosystem and fishery are important in NEGOA. OCSEAP investigations indicate that the species constitutes about two-thirds of the epibenthic biomass and is distributed throughout the region. The major fisheries for Tanner crabs are on the continental shelf in depths of 60-220 m; most of the fishing effort in recent years has been between Yakutat and Cape Spencer and in the western part of NEGOA off Prince William Sound. Tanner crab stocks have fluctuated widely in NEGOA; the Prince William region fisheries have supplanted those in the Fairweather region in recent years. Dungeness crab, an inshore species commercially fished throughout NEGOA is second in importance in shellfish catches. The Dungeness crab fishery is particularly productive in the Icy Bay area, between Yakutat and Dry Bay, and off the Copper River Delta.

Unlike in other regions of the Gulf of Alaska, king crab and shrimp are of negligible economic importance in NEGOA. A minor commercial king crab fishery occurs in the Prince William Sound area, and both king crab and shrimp are utilized for subsistence throughout the region.

Weathervane scallops are present in the shelf waters between Cape Fairweather and Cape St. Elias. They support a moderate fishery that has annually accounted for about one-quarter of the Gulf of Alaska catch.

Other shellfish of current or potential economic importance include razor clams, butter clams, surf clams, and cockles. Only the razor clam has been commercially harvested to any extent in NEGOA. Razor clams occur along much of the outer coast on sandy beaches, but they have been harvested only in the vicinity of Cordova. The exploitation of NEGOA's clams and cockles has been restricted by the requirement to certify that clam beaches are free of paralytic shellfish poisoning, together with the lack of transport, processing, and marketing facilities.

12.7.5 Benthic invertebrates

OCSEAP and earlier studies have inventoried benthic invertebrates in NEGOA. Over 450 species have been collected from the shelf region between Yakutat and Montague Island. While the ecology of NEGOA benthos remains poorly understood, it appears that benthic community structure is determined largely by sedimentation patterns (Feder, 1979). The inner shelf areas have high loads of suspended sediment and mobile detritus-feeders predominate. Though these areas are high in biomass, they are low in species diversity. On the outer shelf and south of Hinchinbrook Entrance, where suspended sediment levels are lower, greater numbers of species are present and sessile filter-feeding organisms are more common.

Important benthic organisms in the NEGOA shelf region include polychaetes, clams, cockles, snails, amphipods, cumaceans, brittle stars, sea stars, and sea cucumbers. Polychaetes are represented by the greatest number of species (132), followed by molluscs (69), arthropods (66), and echinoderms (24). Common infaunal and epifaunal species which are important in terms of biomass are the clams *Axinopsida serricata*, *Nucula tenuis*, *Nuculana pernula*; the polychaete *Sternaspis scutata*; the box crab *Lopholithodes foraminatus*; the sunstar *Pycnopodia helianthoides*; the basket star *Gorgonocephalus* sp.; the sea star *Ctenodiscus crispatus*; the brittle star *Ophiura sarsi*; and the sea cucumber *Molpadia* sp. (Feder and Mueller, 1975).

12.7.6 Intertidal communities

Substrate, disturbance, and exposure are important physical determinants of intertidal community composition in NEGOA. Four general classes of intertidal substrates are present: bedrock, gravel/cobble, sand, and mud. More than one substrate may be present at a given location as, for example, a sandy beach with boulders. The NEGOA intertidal zone is predominantly sandy east of Kayak Island, except for the eastern shore of Yakutat Bay, which is rocky (bedrock, boulder gravel); it is sandy in the outer part of the Copper River Delta and muddy inshore, and is rocky around Kayak Island and from Hinchinbrook Island westward (O'Clair et al., 1978). Species diversity and biomass are typically highest on bedrock. Muddy substrates have fewer species and sand beaches the least. The diversity and biomass of gravel or cobble beaches depend on exposure; they range from almost nil where disturbance is frequent to high values in more sheltered locations.

Exposed intertidal locations along the outer coast east of Kayak Island usually have low diversity even on rocky substrates; frequent disturbance appears to inhibit plant and animal growth and settlement. In more sheltered sand and mud areas in the Copper River Delta region diversity is higher; intertidal communities are composed mainly of annelids, molluscs, and crustaceans. The greatest number of species and highest biomass occur west of the Copper River Delta, where rocky substrate is common. This region offers ideal conditions for many macrophyte and invertebrate species. Large kelp beds occur along the coasts of Hinchinbrook and Montague Islands. Well-developed invertebrate communities are associated with the macrophytes, and the intertidal and subtidal zones are used by many species of fish.

12.7.7 Major habitats

OCSEAP has not yet made a systematic classification and inventory of marine habitats in NEGOA. More is known about the supralittoral and littoral zones because they are more accessible than deeper waters. Studies of the littoral zone have yielded information on the gross physical characteristics of the coastline and on the communities associated with major intertidal substrate types. Information on subtidal habitats is limited to some investigations near Hinchinbrook Entrance prompted by evidence that the area would be vulnerable to oil spills originating at Sale 39 tracts. The results of reconnaissance surveys of benthos, fish, plankton, and surficial sediment distributions in offshore shelf waters indicate some biotic associations reflecting differences in habitats. However, the physical and biological boundaries are indistinct, and the extent of their temporal and spatial variability is unknown.

The following is a summary of some of the characteristics and resource values of parts of the NEGOA area.

I. Coastal waters

A. Montague and Hinchinbrook Islands

- Bedrock/cobble/gravel substrates dominate shoreline.
- Outer coasts exposed, inner coast more protected.
- Intertidal communities well-developed, diversity and biomass high. Detrital contributions to food webs possibly significant.
- Subtidal communities well-developed, macrophyte communities with large resident fish populations in areas exposed to oceanic conditions.
- Hinchinbrook Entrance and Montague Strait are major migratory corridors for marine mammals and salmon.
- Sea otters key species in intertidal-subtidal communities; present in numbers at or near carrying capacity of habitat.
- Many small salmon streams characterize the region, with no one stream dominant in productivity; intertidal spawning of pinks is widespread.

B. Copper River - Controller Bay region

- Predominantly a depositional environment inside the barrier islands; probable long oil retention times in coastal marshes.
- Barrier islands unstable, sandy.
- The Copper-Bering delta is one of the world's major water-fowl and shorebird concentration areas during migration periods; contains the bulk of the wetlands in NEGOA; important nesting area for Trumpeter Swan and Dusky Canada Goose.
- Thousands of harbor seals present on barrier islands during summer.
- Major fisheries for Dungeness crab; sockeye and coho salmon off the Copper River Delta.
- Sea otters present in large numbers along the Copper-Bering coast eastward to Cape Suckling.

C. Kayak Island

- .Bedrock/cobble substrate dominant in the littoral and sub-littoral zones.
- .One of the largest sea lion rookeries and hauling areas in NEGOA at Cape St. Elias.
- .Sea otters abundant in nearshore waters; the eastern boundary of the species' established range in NEGOA.

D. Cape Suckling - Cape Fairweather region

1. Beaches

- .Predominantly sand; some gravel, cobble, bedrock. High energy environment, unstable, with erosion common. Low oil spill vulnerability.
- .Littoral biota impoverished, with low diversity and biomass. Macrophytes insignificant.
- .Razor clams present where substrate suitable; potential for commercial harvest.

2. Embayments with fiord circulation

a. Icy Bay

- .Hauling and pupping grounds for thousands of harbor seals.
- .Dynamic environment undergoing rapid alteration due to recession of glacier and sedimentation from littoral drift.
- .Important Dungeness crab fishery.

b. Yakutat Bay

- .Major deepwater bay in NEGOA. East side of bay protected, stable, with gravel/cobble beaches which could retain oil for long periods.
- .Local subsistence fisheries for halibut, chinook and coho salmon, shrimp, crabs.
- .Some commercial trolling, set netting in bay.
- .Possibly significant seabird wintering area.

3. Outwash streams and lagoons

- .Situk River, Alsek River, and other streams support major runs of coho and sockeye salmon; chinook, pink and chum salmon stocks much less important.
- .Most coastal streams with protected tidewater lagoons fronted by sandspits, which may be radically altered by floods and storms.
- .Estuaries probably important for migratory waterfowl and shorebirds.
- .Lagoons important set gillnet sites for coastal salmon fishery.
- .Oil entering lagoons possibly retained for long periods.

II. Shelf waters

A. Benthic habitats

- .Substrate commonly sandy inshore due to resuspension, winnowing by waves and currents; fine sediments dominant on mid-shelf and in topographic lows such as sea valleys, troughs; coarser, poorly sorted sediments at shelf edge and on topographic highs.
- .Mobile detritus-feeders dominant inshore; more sessile filter feeders offshore where suspended sediment concentrations lower.
- .Tanner crabs common; estimated to constitute about two-thirds of the biomass of epibenthos in 1975-76.
- .Dungeness crab fisheries inshore; Tanner crab and scallop fisheries farther offshore.
- .Major groundfish and halibut fisheries on the continental slope, outer shelf and in sea valleys such as Alsek Trough, Yakutat Sea Valley and Hinchinbrook Sea Valley. The outer shelf and slope off Yakutat, the Fairweather Ground, and the Bering Trough consistently high production areas for groundfish.

B. Pelagic habitats

- .Coastal surface waters fresher and more sediment-laden than outer shelf waters. Influx of fresh water and sediment are highly seasonal, occurring mainly during the spring-fall period.
- .A 30- to 40-km-wide zone along coast is migration corridor of young salmon from spring through fall; higher concentrations of fish are near the sea surface and near shore.

- .Nearshore zone a probable corridor of gray whale migration between summer and winter ranges.
- .Large numbers of eggs and larvae of Dungeness crab, Tanner crab, weathervane scallop, numerous flatfish species, walleye pollock, and other commercial species possibly present in surface waters over the continental shelf from spring through fall.
- .Yakutat-Fairweather region appears to be concentration area for humpback whales in late winter and early spring.
- .Major troll fisheries for chinook and coho salmon on Fairweather Ground and waters inshore of that area from spring through autumn; nursery areas for those species in same area.
- .Major spawning grounds of halibut and perhaps Pacific ocean perch along the continental slope off Yakutat.

12.8 ISSUES

Because of differences in geography, the environment, and its biota, the issues pertinent to Sale 55 differ from those related to Sale 39. Furthermore, the fading prospects for development in the latter area make the Sale 39 issues largely moot. Thus the following discussion will be restricted to Sale 55 issues.

Nine generic OCS oil and gas development issues have been identified by USDI (1979): (1) subsistence lifestyles, (2) commercial fishing, (3) recreation and tourism, (4) social infrastructure, (5) coastal and marine ecosystems, (6) air and water quality, (7) archeological and cultural resources, (8) shipping conflicts, and (9) environmental hazards. The applicability and relative importance of each of the above vary among OCS regions--and even within a region, in the case of NEGOA--due to regional differences in social, cultural, economic, and environmental factors. We consider here mainly environmental aspects of the issues, touching lightly or not at all on several issues that may be of local significance. Some issues, while perhaps of minor importance to the Yakutat region, have broader geographical implications and thus must be included.

ISSUE: Potential effects of OCS oil and gas development on commercial fisheries and fur seals.

- .Competition for labor and dock space.
- .Loss of fishing gear due to OCS transportation activities and structures.
- .Preemption of fishing space by platforms and pipelines.
- .Contamination of commercial fish, shellfish and their prey.
- .Oiling of fur seals.

Regional fisheries form the basis of Yakutat's economy (Alaska Consultants, 1979). Furthermore, they contribute to other economies within and outside Alaska. In addition to domestic salmon, halibut, and shellfish fisheries, a major domestic fishery to utilize groundfish now harvested mainly by foreign distant water fleets may develop. The groundfish industry could include a processing plant in Yakutat.

There is concern for the potential effects of OCS oil and gas development on these fisheries. Millions of young salmon and the eggs and larvae of many groundfish species are seasonally abundant in the surface waters, where they would be vulnerable to spilled oil. Besides locally produced fry, hundreds of millions of juvenile salmon from southeastern Alaska, British Columbia, and Pacific Coast states migrate westward through the nominations area from spring through fall (Sakagawa, 1972).

Competition for labor and dock space could occur in the event of an oil discovery. A major oil discovery could shift the work force from fishing and fish processing due to the high pay available from OCS construction and operation activities. The labor shortage could be exacerbated if there is coincidental development of a bottomfish industry in Yakutat. Also, at least temporary shortages of dock space could occur during early stages of oil field development.

Conflicts between fishing and OCS transportation activities center around the loss of fishing gear. In Lower Cook Inlet, large vessels have cut crab pot lines, with the consequent loss of the expensive pots and earnings. As Tanner and Dungeness crab fishing are major seasonal activities in the nominations area, the potential for pot losses around Yakutat is great. In addition, trawl gear could be damaged or lost through fouling on anchors or other obstructions around production platforms and pipelines.

The loss of fishing gear can be reduced or eliminated by designating fairways for tankers and supply vessels and by providing fishermen with maps of obstructions to gear.

Preemption of fishing space probably is a minor concern. Even in the event of a major oil discovery, it is likely that only a few production platforms would be installed. Of 14 producing fields in the Scottish North Sea, all but the largest two have only one platform. The one-billion-barrel Brent and Forties fields have four platforms each (Busemann, 1978).

Preemption of fishing space by pipelines would be negligible. A pipeline would be laid only if a large find occurred; at most only one or two pipelines would be needed. Furthermore, pipeline corridors would be only a few feet wide.

Adverse effects on fisheries such as tainting of fish flesh or heightened mortality of commercial species from chronic contamination are possible in the Yakutat area, but the likelihood of either seems remote. Contamination from dissolved hydrocarbons in treated ballast water effluents and those in formation waters should be negligible if attention is paid to location of outfalls and effluent concentrations. Small oil spills (less than 100 barrels) would have localized effects which would depend on location, season, and species present. The greatest potential for oil spill damage would appear to be in enclosed areas such as Monti Bay. However, spillage in such protected locations would also be more easily controlled and cleaned up than offshore. Small offshore spills would probably be dispersed quickly.

Large oil spills (over 1,000 barrels) in coastal waters during periods when the young of commercially important fish and shellfish are abundant in the surface waters are of major concern because of the possibility of decreased recruitment of stocks in subsequent years. As noted in Chapter 6, large spills are comparatively rare. Furthermore, evidence suggests that the effects would vary considerably with season, being greater from spring through fall, when young of the species of interest are more abundant in the surface waters. The spill's location and subsequent movement would also be important factors in determining the amount of damage. Little information is available from the nominations area on the seasonal numbers and density distributions of epipelagic early life history stages of fish and shellfish. Therefore, it is impossible to describe the temporal and spatial abundance of the various species and to predict the risk posed by spills at various times and locations.

The determination of possible effects of oil spill-caused mortalities of pre-recruits on subsequent recruitment of stocks to fisheries is confounded by other factors. First, year-classes of commercial stocks usually fluctuate markedly in abundance due to large natural variations in spawning success, predation, and other factors. Second, for many species (e.g., salmon), the stocks in question are mixed, highly migratory, and enter fisheries over a huge geographical area. Thus, even if reasonably accurate estimates of the mortality of young fish and shellfish due to oil are available, for some species it will be highly unlikely that subsequent decreases in fishermen's catches can be conclusively attributed to oil spillage.

Local stocks appear to be more vulnerable to oil spills than transient stocks under certain circumstances. Large mortalities of planktonic eggs and larvae of groundfish and shellfish could occur if an oil spill passed into a spawning ground during or shortly after spawning, before currents had dispersed the eggs and larvae. Similarly, a spill at a stream mouth from which large numbers of salmon smolts were entering salt water could kill the smolts and thus affect subsequent runs to that stream. Spills in other locations would probably be less critical for a particular stock. Assuming that the aggregations of the species present comprise diverse stocks, the effects would be more widely distributed.

Because of the economic importance of the stocks, the seasonal density distributions of pre-recruits need to be determined. This information will help to identify particularly sensitive areas and time periods, and from these, strategies to minimize damage from oil spills can be developed.

Northern fur seals are not commercially harvested in the Yakutat area but are important to the economy of the Pribilof Islands. They are potentially at risk because oiling of their pelage causes a loss of insulation and may bring about a thermoregulatory imbalance (Kooyman et al., 1976). Some fur seals remain in NEGOA throughout the year; however, the greatest numbers occur during fall and spring migrations through the region. The scanty systematic census data near Yakutat indicate that fur seals concentrate on the Fairweather Ground just south of the Sale 55 area in spring. Due to prevailing currents, these animals probably would not be affected by oil spills in the area. The species' widespread pelagic distribution suggests that only a negligible fraction of the eastern Pacific population could be affected by spills on the Yakutat shelf. However, it is desirable to determine the extent to which the species uses the region to better assess the degree of risk to the population.

ISSUE: Potential for loss of life, destruction of OCS oil and gas facilities, and oil spillage due to environmental hazards in the Yakutat area.

- .Earthquakes and ground shaking.
- .Active faulting.
- .Unstable sediments.
- .Tsunamis.
- .Storm surges.
- .Outburst floods, erosion, and other coastal hazards.
- .Storm waves and swells.

Environmental hazards have been emphasized in NEGOA since the inception of OCSEAP. Until 1979 efforts were focused on the Sale 39 area; however, the forthcoming Sale 55 prompted a shift of emphasis to fill data gaps. Although some of the results of ongoing studies will be available before the proposed sale, many studies will not be completed until 1981.

The seismicity of the Sale 55 area has been monitored by the USGS-NOAA seismic network installed for the Sale 39 area. OCSEAP will add some additional instruments in 1980 to improve the resolution of the network in the Yakutat region. As this region is seismically very active, the likelihood of a large earthquake occurring west of Yakutat in the Yakataga seismic gap in the next decade or two is high. Accelerometers have been installed to obtain data on strong ground motions accompanying earthquakes. This information will influence the design specifications of production platforms near Yakutat and elsewhere in the Gulf of Alaska. Active faults were indicated by shipboard reconnaissance data obtained near Yakutat in 1975. A cluster of shallow, low-magnitude earthquakes south of Yakutat detected in 1974 also suggests possibly active surface faulting. Data obtained from shipboard geophysical surveys and ocean bottom seismometers during the summer of 1979 should provide a much improved information base to evaluate the hazards presented by faulting in the Sale 55 area.

Unstable sediments are widespread throughout NEGOA, as evidenced by the large slumps in Kayak Trough and off the Icy Bay-Malaspina Glacier coastline. Just west of the nominations area, massive blocks of sediments have moved downslope on slopes of less than one degree. The results of intensive investigations during the summer of 1979 are not yet available; however, observations in the Sale 39 area suggest that areas of unstable sediments are also present off Yakutat. The forthcoming results will indicate the potential for slumping in the nominations area, as well as other causes of instability, such as gas charging of sediments. Geotechnical sampling and more site-specific studies proposed for 1981 will quantitatively measure sediment instability.

The likelihood of tsunamis in the Sale 55 area is high. In addition to tsunamis generated by nearby or distant earthquakes, localized tsunamis have occurred in Yakutat and Lituya Bays as a consequence of ice falls and landslides. Careful siting of shore facilities should prevent damage to onshore structures. The likelihood of major damage to offshore structures is remote, according to CEQ estimates presented in the Sale 39 EIS (USDI, 1976).

Storm surges are common along the coast of NEGOA from Icy Bay southward beyond Yakutat Bay (see Molnia and Wheeler, 1978; Ruby, 1977). If proper attention is paid to setbacks of structures, these events should not pose any hazard to OCS activities.

Numerous onshore phenomena, such as outburst floods and rapid erosion, that pose hazards to onshore structures have been identified and mapped by OCSEAP investigators. The eastern shore of Yakutat Bay appears to be the most stable segment of coastline in NEGOA (Ruby, 1977). Any onshore development in the bay probably would occur there.

Great storms in NEGOA constitute a major hazard to exploratory rigs and production platforms. The large data base generated by the oil industry's study of wave and wind climatology in NEGOA will aid in the design of offshore structures. The results of the study are to be made public in 1981-82 (McLeod, 1979).

ISSUE: Coastal and marine ecosystems at risk from OCS development in the Yakutat area.

- .Contamination of benthic communities by spilled oil.
- .Contamination and alteration of waterfowl and seabird habitats.
- .Harm to threatened or endangered whales.

The benthos could be damaged by rapid incorporation of oil into sediments, given the high loads of suspended sediment and rapid sedimentation in the Yakutat and Icy Bay areas. Experiments by Shaw (1978) and Feely et al. (1978) indicate that the adsorption of hydrocarbons by glacial flour is much greater for oil in a dispersed state than for dissolved fractions. Estimated maximum concentrations due to sedimentation of dissolved hydrocarbons from treated ballast water effluent are 13 ppb for the Port Valdez area and below 240 ppt for the more vigorously mixed central Lower Cook Inlet (Malinky and Shaw, 1979). This suggests that chronic releases of dissolved hydrocarbons in formation waters and treated ballast waters should not cause harmful accumulations of hydrocarbons in bottom sediments if mixing and dispersion are sufficient. If a major spill occurred in the turbid nearshore zone, however, large amounts of oil could be rapidly deposited in surficial sediments. The amount of oil held by suspended material is a function of the petroleum's concentration, its chemical nature and viscosity, the mineralogical and size characteristics of the suspended particulate matter, temperature and degree of mixing (Feely et al., 1978). The potential effects of oil in sediments on the benthos or the Yakutat region are unknown, since they depend to a large degree on the amount and concentration of oil deposited, the tolerance of organisms to oil, persistence and toxicity of the oil, and local sedimentary regime. It is probable, however, that large quantities of oil would enter the sediments only rarely because major spills are infrequent.

The coast of NEGOA is dominated by a steep fiord-like topography and there are few resting and feeding areas for shorebirds and waterfowl between Prince William Sound and Cape Spencer. Similarly, there is little protected habitat for wintering seabirds. The east side of Yakutat Bay is probably, a wintering area for seabirds, and the estuaries are used by large numbers of waterfowl, but the relative importance of the habitats for the various species and the times they are used is not known. Such information can be used to evaluate possible effects of disturbances or a major oil spill in the lease area and to develop stipulations to minimize disturbance in these areas.

Patterns of surface currents and results of oil spill trajectory simulations indicate that a spill originating in the lease area would probably be carried westward and would contaminate first the segment of coastline from Dry Bay west to Point Manby. It is not clear whether oil would enter coastal lagoons or Yakutat Bay, where it could persist for long periods (Hayes and Ruby, 1977b). The coastal jet and circulation patterns in the nearshore zone and in Yakutat Bay have not yet been studied. Some satellite images show evidence of predominantly along-shore drift to the west along the coast and outflow from the west side of Yakutat Bay, but the orientation of sand bars on the west side of the bay indicates at least periodic alongshore drift into the bay's west side.

Gray and humpback whales are two of the most common endangered species which occur in NEGOA. The grays migrate close to shore. Humpbacks have been seen on the coastal shelf between Yakutat Bay and Cape Spencer during late winter and early spring. Information is presently inadequate to evaluate the importance of the region to these animals or to speculate on effects of OCS activities or oil spills. There is even less information on other species of cetaceans.

ISSUE: Effects of OCS activities on subsistence lifestyles.

The consumption of waterfowl, terrestrial and marine mammals, fish, and shellfish are traditional among NEGOA residents. Most subsistence activities occur on shore or in the bays and estuaries. Several species of salmon, Tanner, Dungeness, and king crabs, razor clams, halibut, and ducks and geese are harvested, as well as some larger mammals, such as harbor seals, moose, deer, and brown bear.

The primary effects of OCS development on subsistence lifestyles could include increased competition for the living resources between residents and the imported workforce, disturbances of the resources, and destruction of habitat, all of which would decrease harvests. Perhaps the biggest changes would result from the establishment of an oil terminal at Monti Bay through concomitant growth of the human population. The effects of increased demands on subsistence species can be regulated to some degree; in practice this often means shortened seasons, decreased bag limits and smaller harvests of fish and game. Opportunities to harvest large terrestrial mammals such as moose and brown bear probably would be most changed, as their numbers are low in comparison to the other animals.

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: greenlings, 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 (M_L) 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 under 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 gm/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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