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SYNTHESIS OF EFFECTS OF OIL ON MARINE MAMMALS

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FOREWORD

This manuscript summarizes the extensive and diverse data base on subjects dealing with oil effects to marine mammals and those aspects of an animal's life history vulnerable to exposure of spilled oil. The manuscript begins with a background chapter on the composition and fate of petroleum and spill treating agents in the marine environment and is followed by separate chapters describing the ecological perspective and the physiological and toxicological effects of petroleum and spill treating agents on pinnipeds. The same treatment is provided for cetaceans, sea otters, polar bears and manatees. A separate chapter describing modeling efforts to predict oil effects on marine mammals is also included for in recent years, several attempts have been made to predict population effects from oil spill events using quantitative methods.

By necessity and design, discussion of oil effects to marine mammals is a synthesis and evaluation of previous data and in some cases includes presentation of new data or reinterpretation of old data. In certain cases, synthesis of older data has led to new interpretations. Quite noticeable is the disparity between the content and complexity of discussion in the various chapters. This disparity represents differences in the availability of data. The fact that some animals are terrestrial vs. oceanic, occupy different environments, are easier to observe, or are more complex than other, are some of the reasons for this disparity.

Several authors contributed to this manuscript. J.M. Neff authored the chapters, Composition and Fate of Petroleum and Spill-Treating Agents in the Marine Environment, and Effects of Oil on Marine Mammal Populations: Results of Model Simulations; I.A. McLaren, Pinnipeds and Oil: Ecological Perspectives; B. Wursig, Cetaceans and Oil: Ecological Perspectives; K. Ralls and D.B. Siniff, Sea Otters and Oil: Ecological Perspectives; I. Stirling, Polar Bears and Oil: Ecological Perspectives; D.J. St. Aubin and V. Lounsbury, Oil Effects on Manatees, Evaluating the Risks; and D.J. St. Aubin and J.R. Geraci for the chapters describing the physiological and toxicological effects of oil for each of the marine mammal groups.

We thank the Minerals Management Service (MMS) for funding the preparation of this manuscript. R.E. Miller and W. Lang of the MMS were especially supportive in facilitating the project whenever necessary and without them, this manuscript would not have been possible. Finally, the manuscript is intended to be useful to the MMS and to readers involved with matters pertaining to oil and gas development on the outer continental shelf. For each animal group, separate discussions are provided for their natural history vs. physiological or toxicology effects. Separate reference sections are also provided for each chapter so readers may easily pursue additional literature on topics contained within each chapter.

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Eiji Imamura
Ventura, California

CHAPTER 1

COMPOSITION AND FATE OF PETROLEUM AND SPILL-TREATING AGENTS IN THE MARINE ENVIRONMENT

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Introduction

The chemical properties of oil ultimately determine its effects. Some compounds are actively toxic, and are damaging to delicate tissues, such as eyes, nasal cavities and other sensitive mucus membranes. Their noxious properties are balanced by rapid dissipation and removal from the environment. At the other end of the spectrum are the persistent forms, such as tar and weathered oil, which are not as toxic but have greater potential for environmental impact because of their resistance to weathering. To evaluate the consequences of oil exposure in marine mammals, it is important to understand these properties of petroleum: its composition, how it enters the marine environment, and what happens to it once it is there. This chapter addresses these issues.

Composition and Toxicity of Petroleum

Crude petroleum, a complex mobile mixture of fossil, biogenic origin (Speers and Whitehead 1969), contains thousands of organic and a few inorganic compounds. Included within the classification are natural gas, liquid petroleum oils, resins, and asphaltenes. A more precise definition of petroleum is impossible, because no two are identical. Most crude petroleums contain the same classes of compounds, but differ in the relative amounts of each constituent.

Crude petroleum may contain organic compounds ranging in molecular weight from methane to complex polymeric structures such as asphaltenes with molecular weights of 100,000 or more (Kallio 1976). Natural gas is separated from liquid petroleum at the time of production; the oil is then distilled to produce commercial products. Each fraction is collected at a different distillation temperature (Figure 1.1), and can be refined further into a product with more desirable properties. The residue after distillation contains much of the resin and asphaltene fractions of the crude oil. It is a thick tarry liquid or solid that may be used for fuel (Bunker C residual oil, Number 6 fuel oil), or paving (asphalt).

Hydrocarbons (compounds composed only of carbon and hydrogen atoms) are the most abundant components of crude and refined petroleum (Figure 1.2). They account for more than 90 percent of natural gas and from 50 to about 98 percent of liquid crude petroleum (Kallio 1976, National Academy of Sciences 1985). Other components include sulphur, oxygen, nitrogen and a variety of metallic elements which are complexed with organic compounds or exist as inorganic salts.

Alkanes, which contain single chemical bonds between carbon atoms, are the most abundant hydrocarbons in petroleum. There are three types: normal, branched, and cyclic. The normal and branched alkanes are usually present in about equal amounts. The n-alkanes range in size from methane (C_1) to about C_{60}, and possibly as high as C_{78}. A majority of the branched or iso-alkanes are simple 2-, 3-, and 4-methylalkanes. In addition, the branched alkanes include a series of isoprenoid hydrocarbons, based on isoprenoid buidling blocks, extending from

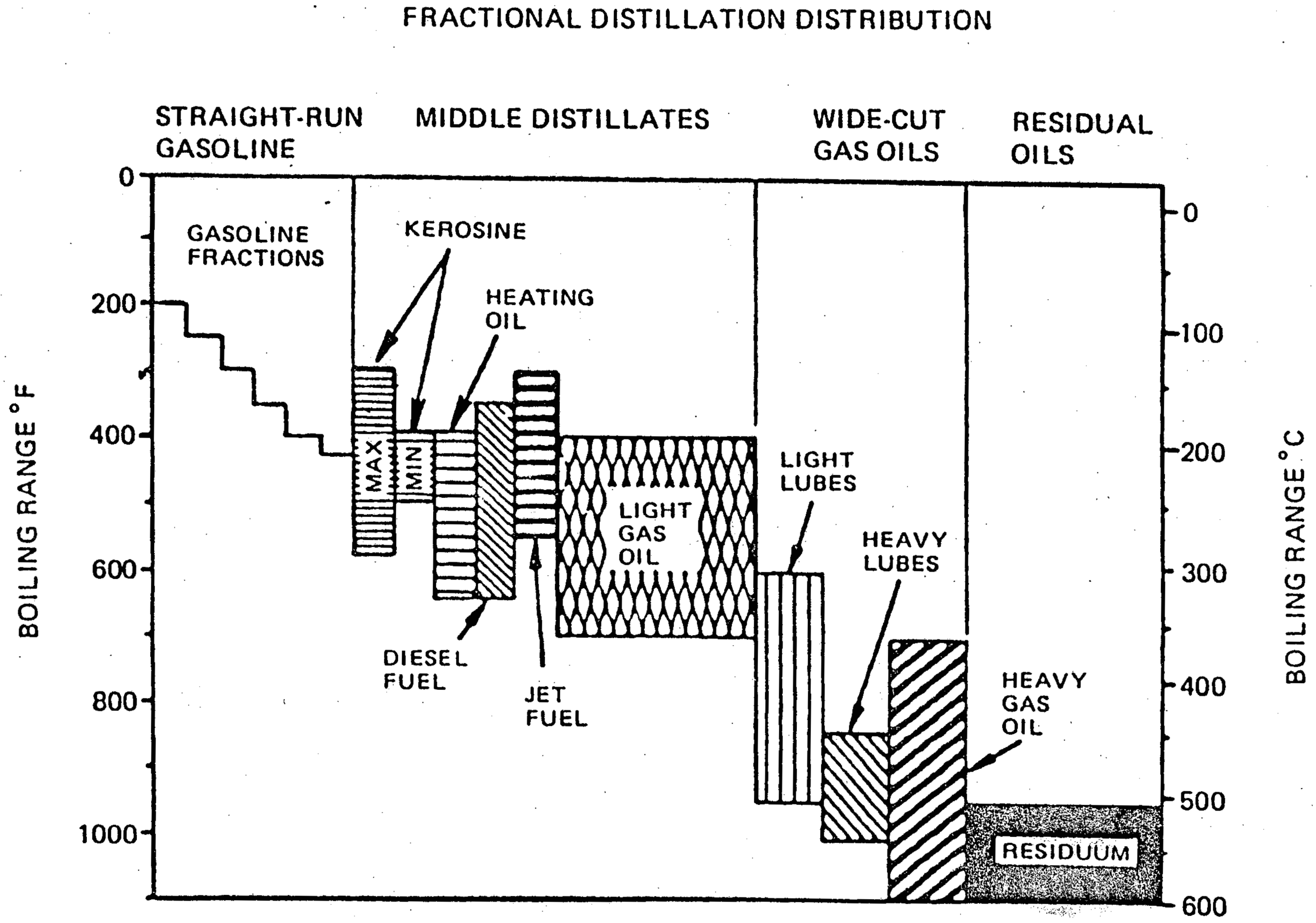
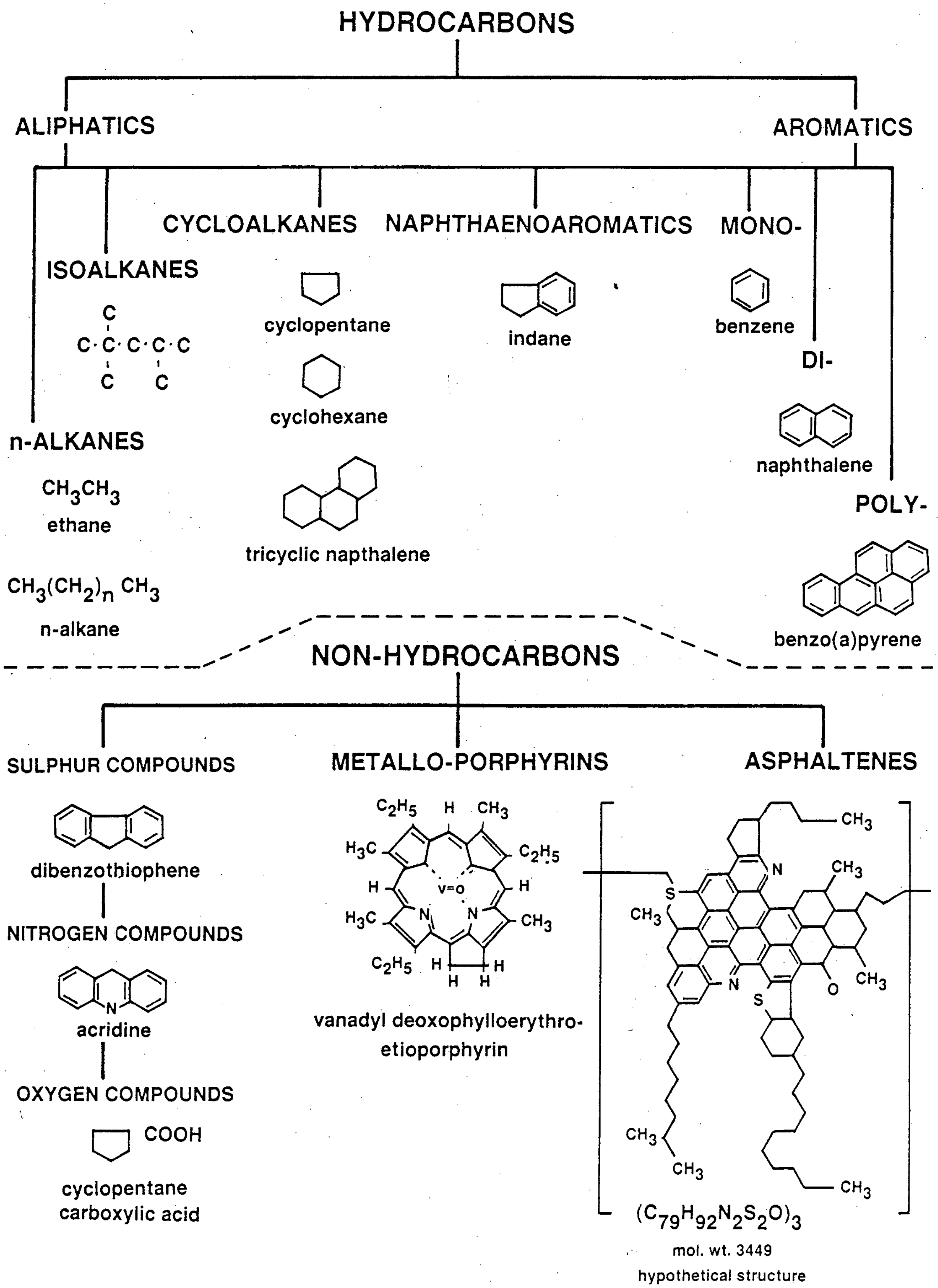


FIGURE 1.1: BOILING POINT RANGE OF FRACTIONS OF CRUDE PETROLEUM (National Academy of Sciences, 1985).

Figure 1.2

Examples of the chemical structure of some common components of crude petroleum (Miller and Connell 1982).


HYDROCARBONS
ALIPHATICS
AROMATICS
CYCLOALKANES
NAPHTHAENOAROMATICS
MONO-
ISOALKANES
C
C·C·C·C·C
C C
cyclopentane
indane
benzene
DI-
cyclohexane
n-ALKANES
CH_3CH_3
ethane
naphthalene
POLY-
tricyclic napthalene
$CH_3(CH_2)_n CH_3$
n-alkane
benzo(a)pyrene
NON-HYDROCARBONS
SULPHUR COMPOUNDS
METALLO-PORPHYRINS
ASPHALTENES
dibenzothiophene
NITROGEN COMPOUNDS
acridine
OXYGEN COMPOUNDS
COOH
cyclopentane carboxylic acid
C_2H_5 H CH_3
H_3C C_2H_5
H V=O H
H_3C N N CH_3
C_2H_5 H H H H
vanadyl deoxophylloerythro-etioporphyrin
CH_3 N CH_3 S CH_3 N O CH_3 S CH_3 CH_3 CH_3
$(C_{79}H_{92}N_2S_2O)_3$
mol. wt. 3449
hypothetical structure

C_{10} to about C_{40}. The most abundant isoprenoid alkanes in petroleum are pristane (C_{19}) and phytane (C_{20}).

Cycloalkanes, also called cycloparaffins or naphthenes, may account for as much as 50 percent of the total hydrocarbons in oil. Most are cyclopentane derivatives. They may contain aromatic ring structures, normal or branched alkane substituents, or non-hydrocarbon groups, such as one or more carboxylic acid moieties.

Aromatic hydrocarbons may account for about 20 percent of the total hydrocarbons in crude oil. The basic building block of an aromatic hydrocarbon is the benzene ring, a six-member carbon ring containing nine equally shared carbon-carbon covalent bonds. Benzene occurs in small amounts in natural gas, crude and particularly the lighter fractions of refined oil. It may be linked to another benzene ring through a single carbon-carbon bond to form biphenyl. Polycyclic aromatic hydrocarbons (PAH) are composed of two to nine or more fused benzene rings (Neff 1979). Naphthalene ($C_{10}H_8$), which consists of two fused rings, is the lowest molecular weight PAH. The abundance of aromatic hydrocarbons in petroleum usually decreases markedly with increasing molecular weight. In most cases, the one-ring (benzene) through three-ring (phenanthrene) compounds account for at least 90 percent of the aromatic hydrocarbons (Neff 1979). These may combine with cycloalkanes to form naphthenoaromatic compounds, and combine further to produce polymeric structures that are important components of the resin and asphaltene fractions of petroleum (Figure 1.2).

The resin and asphaltene fractions of crude oil have not been well characterized (Speers and Whitehead 1969, Kallio 1976). They presumably consist of high molecular weight hydrocarbons and hetero-compounds containing sulfur, oxygen or nitrogen and thermally-induced condensation products of lower molecular weight aromatics and heteroaromatics. Asphaltenes are thought to be present in colloidal suspension.

Refined Oil Products: Refined petroleum products contain all the chemical classes present in crude oil, but primarily those compounds boiling over a fairly narrow temperature range (Figure 1.1). For example, gasoline contains primarily low-boiling alkanes (C5 to C9) and monoaromatics, whereas residual oil contains high concentrations of high-boiling alkanes and polycyclic aromatic hydrocarbons, as well as most of the resins and asphaltenes originally present in the crude oil. In addition, catalytic cracking of the gasoline fraction produces a group of unsaturated compounds, alkenes and cycloalkenes, not ordinarily present at higher than trace concentrations in the original oil. The refining process may also increase the degree of alkylation of the alkane/alkene fraction. These changes improve the properties of the gasoline as a fuel.

Similar Compounds of Natural and Pyrogenic Origin: Combustion of organic material, including fossil fuels, is a major source of PAH containing three or more aromatic rings. Their formation is favored particularly if combustion takes place in an oxygen-deficient environment. Resulting PAH assemblages are complex and, unlike those in petroleum, are dominated by four-, five-, and six-ring aromatics. These differences are useful in distinguishing between petrogenic and pyrogenic hydrocarbon assemblages in environmental samples.

Toxicity of Petroleum Compounds: Composition of a crude or refined petroleum governs its behavior and ultimate fate when spilled in the marine environment. It also affects the responses of marine organisms, including mammals, that might come in contact with spilled oil. The different chemical components of petroleum vary tremendously in their acute and chronic toxicity.

Acute toxicity of alkanes to aquatic organisms tends to increase with molecular weight. However, acutely toxic concentrations for all but lowest molecular weight alkanes are higher than their solubility, and therefore cannot occur naturally in aquatic environments (Hutchinson *et al.* 1980). Low molecular weight cyclic alkanes (naphthene cyclohexane and several alkyl cyclohexanes) appear to be more toxic to aquatic organisms than n-alkanes and benzenes of similar molecular weight (Benville *et al.* 1985). Mixtures of higher molecular weight alkanes, such as paraffin oils, are considered inert. In fact, they are used by humans as laxatives. Low molecular weight alkanes (methane through octane) have mild anesthetic properties (Crisp *et al.* 1967), and, because of their volatility, may occur in a form which can be inhaled.

Aromatic hydrocarbons are the most toxic of the major classes of compounds in petroleum. The acute toxicity of crude and refined petroleums to aquatic organisms (Neff and Anderson 1981, National Academy of Sciences 1985) and mammals (EPA 1981) correlates directly with the concentration of light aromatic hydrocarbons (benzene through phenenthrene). Chronic effects of petroleum are attributed primarily to four- and five-ring aromatic and hetero-aromatic hydrocarbons, some of which are well-known carcinogens (Karcher *et al.* 1981, Oesch 1982, Grunbauer and Wegener 1983, Later *et al.* 1983). Benzene, though a known carcinogen (Fishbein 1984), is volatile and short-lived, and probably contributes more to acute than chronic toxicity.

The acute toxicity of aromatic hydrocarbons is inversely proportional to molecular weight (Neff 1979, Hutchinson *et al.* 1980). However, because of their low solubility, aromatic hydrocarbons with four or more rings rarely exist in acutely toxic concentrations. At the other extreme, the monocyclic aromatic hydrocarbons (benzene, toluene, and xylenes), are so volatile that they are lost rapidly from water. Thus, naphthalenes and phenanthrenes, which are slightly soluble and relatively persistent, contribute most to the toxicity of crude and refined petroleum (Neff 1979). Heterocyclic compounds can have a toxicity similar to the analogous aromatic hydrocarbons (Thomas *et al.* 1981). Dibenzothiophene and several of its alkyl homologues are abundant in many crude oils, and therefore probably contribute to their toxicity.

Sources of Petroleum in the Marine Environment

Petroleum enters the marine environment from various sources. Miller and Connell (1982) estimated that, of the 3100 million metric tons of oil produced in 1981, from 4.5 to 6.1 metric tons (0.15 to 0.20 percent of production) reached the oceans. The National Academy of Sciences (1985) gives a value of 3.2 million metric tons (more than 750 million gallons) of oil entering the ocean per year (Table 1.1).

These inputs are from a wide variety of natural and anthropogenic sources (Table 1.1). Natural sources such as marine oil seeps and erosion of oil-bearing rocks are the most difficult to estimate accurately. Wilson *et al.* (1974) compiled a list of 190 known submarine oil seeps. Several more have been identified since. In U.S. outer continental shelf (OCS) waters, 54 seeps have been identified off southern California, 28 off the south coast of Alaska, three along the coast of the Gulf of Mexico, and others scattered along the Bering and Beaufort Sea coasts of Alaska. Submarine seeps also occur in Mexican waters of the Gulf of Mexico, along the Caribbean coast of South America, and the northeast coast of Canada. The rate of discharge from different seeps varies widely, with as much as 30,000 tons each year from seeps in the Santa Barbara Channel alone (Fisher 1978). Total annual discharge from all marine seeps is estimated to be 200,000 metric tons (National Academy of Sciences 1985). Erosion of oil-bearing rocks accounts for about one-fourth the amount derived from seeps.

The most important source of petroleum entering the marine environment is that associated with marine transportation (1.47 million metric tons per year) and municipal and industrial wastes (1.0 million metric tons per year) (National Academy of Sciences 1985). Volumetrically less important sources include offshore oil production activities (50,000 metric tons per year), atmospheric deposition (300,000 metric tons per year), runoff from rivers and urban areas (160,000 metric tons per year), and ocean dumping, primarily of sewage sludge and industrial wastes (20,000 metric tons per year).

Tanker operations and accidents account for most of the oil entering the ocean from marine transportation activities. The major source is from discharges of ballast water and tank washing water. Such activities are regulated by the International Maritime Organization which allows discharge of oil from cargo areas of a tanker under way in international waters at a rate of no more than 60 liters per mile, not to exceed 1/15,000 of the total cargo of older tankers and 1/30,000 of the cargo of new tankers. No such discharges are allowed in territorial waters or certain low pollution areas, such as the Red and Mediterranean Seas.

When a tanker arrives in ballast at an oil terminal, the water in segregated or dedicated ballast tanks is not contaminated with oil and can be discharged to local waters. If ballast water is carried in the cargo tanks, which is the case for many supertankers and older tankers, it may be discharged to an onshore treatment facility. There the water is separated from the oil and discharged. The treatment facility in Valdez, Alaska, during its first two years of operation, discharged to Valdez Harbor a total of 33.4 billion liters of treated

Table 1.1: Input of petroleum hydrocarbons into the marine environment in millions of metric tons/year (National Academy of Sciences, 1985).

SOURCE	PROBABLE RANGE	BEST ESTIMATE[a]
Natural sources		
Marine seeps	0.02-2.0	0.2
Sediment erosion	0.005-0.5	0.05
(Total natural sources)	(0.025)-(2.5)	(0.25)
Offshore production	0.04-0.06	0.05
Transportation		
Tanker operations	0.4-1.5	0.7
Dry-docking	0.02-0.05	0.03
Marine terminals	0.01-0.03	0.02
Bilge and fuel oils	0.2-0.6	0.3
Tanker accidents	0.3-0.4	0.4
Nontanker accidents	0.02-0.04	0.02
(Total transportation)	(0.95)-(2.62)	(1.47)
Atmosphere	0.05-0.5	0.3
Municipal and industrial wastes and runoff		
Municipal wastes	0.4-1.5	0.7
Refineries	0.06-0.6	0.1
Nonrefining industrial wastes	0.1-0.3	0.2
Urban runoff	0.01-0.2	0.12
River runoff	0.01-0.5	0.04
Ocean dumping	0.005-0.2	0.02
(Total wastes and runoff)	(0.585)-(3.12)	(1.18)
TOTAL	1.7-8.8	3.2

[a] The total best estimate, 3.2 mta, is a sum of the individual best estimates. A value of 0.3 was used for the atmospheric inputs to obtain the total, although we well realize that this best estimate is only a center point between the range limits and cannot be supported rigorously by the data and calculation used for estimation of this input.

ballast water containing about 130 metric tons of particulate oil and 170 metric tons of volatile hydrocarbons (mainly benzenes) (Lysyj *et al.* 1981).

Tanker accidents are a dramatic source of spilled oil. In 1978, approximately 220,000 metric tons of crude oil was released and within a few weeks spread along 350 km of the Brittany coast of France after the Amoco Cadiz spill and in 1984, the Liberian tanker Nova spilled about 70,000 metric tons of Iranian crude oil, about 88 percent of the total spilled in tanker accidents that year. Less significant spills include those from accidents on oil platforms, pipeline breaks, and accidental spills at storage areas, terminals, and refineries.

Offshore oil exploration and production is viewed as a major source of spilled oil, and indeed it can be. The Ixtoc-I blowout in the Bay of Campeche in the Mexican Gulf of Mexico was the worst recorded oil spill of any kind. On June 3, 1979, an exploratory well about 80 km northwest of Cuidad de Carmen blew out. By the time the well was capped 290 days later on March 23, 1980, about 475,000 metric tons of oil had been lost (Jernelov and Linden 1981). Usually, platform spills are of a much smaller magnitude, on the order of 40,000 to 60,000 metric tons per year (National Academy of Sciences 1985).

In U.S. OCS waters, the performance record for offshore platforms has been quite good (Minerals Management Service 1986). Of the 5 billion barrels (690 million metric tons) of oil produced from the federal outer continental shelf in the last 15 years through 1985, about 61,000 barrels (8,400 metric tons) were spilled. This is 0.001 percent of production.

Recent spills of oil and hazardous substances from all sources have been documented for U.S. waters (U.S. Coast Guard 1987). In both 1983 and 1984, there were just over 10,000 incidents that resulted in spillage of about 87,000 and 57,000 metric tons, respectively, of oil. The largest volume of oil was spilled in the Pacific Ocean in 1983 and in the Atlantic Ocean in 1984. About 40 percent of the oil was spilled in ports and harbors and between 15 and 30 percent in territorial seas. Vessel accidents accounted for 9 percent in 1983, and 36 percent in 1984. Spillage from marine facilities was a mere one percent both years. Such accidents are the most variable source, in time, volume, and location, of oil in the marine environment.

Two types of discharges sometimes permitted by EPA from offshore exploration and production platforms may contain oil: drilling muds and produced water. Drilling muds are mixtures of clays, weighting agents and other ingredients in a water or oil-base (National Academy of Sciences 1983). They are used to lubricate the bit and offset pressure during the drilling of each well. In the North Sea and in Canadian waters, oil-base drilling muds containing up to 10 percent diesel oil have been discharged. This could represent up to about 100 tons of oil discharged for each drilled. Such practices are not permitted in U.S. OCS waters where only water-base drilling muds can be discharged. Even this form may contain small amounts of oil (usually less than about 100 mg/kg drilling mud).

Produced water is fossil water that emanates with the oil and gas from most wells. A well, during its life, yields approximately equal volumes of fossil fuel and produced water. The latter may be reinjected through another well to the reservoir, or treated to remove particulate oil and discharged. U.S. Federal standards not yet promulgated (EPA 1985) would set a maximum allowable concentration of petroleum in produced water at 59 mg/L.

The amount of produced water generated by a given well varies. A single production platform may discharge up to one million liters, and a large treatment facility up to ten million liters or more each day. The National Academy of Sciences (1985) estimated that approximately 50 billion liters of produced water are discharged to U.S. state and federal waters each year, carrying 1500 to 3000 metric tons of petroleum hydrocarbons.

Municipal and to a lesser extent industrial waste waters also deliver petroleum to the marine environment. The annual discharge of petroleum carried with sewage has been estimated to be about 13,000 tons in Hudson-Raritan Estuary (Connell 1982), 17,000 tons in the southern California Bight (Eganhouse and Kaplan 1982), and nearly 500 tons in central Puget Sound (Barrick 1982). The National Academy of Sciences (1985) estimated the total amount of petroleum discharged in municipal waste water each year to U.S. coastal waters to approach 200,000 metric tons. Industrial discharges, including those from oil refineries contribute smaller quantities of petroleum. These and several other less notable sources probably constitute little potential hazard to marine mammals.

Fate of Petroleum in the Marine Environment

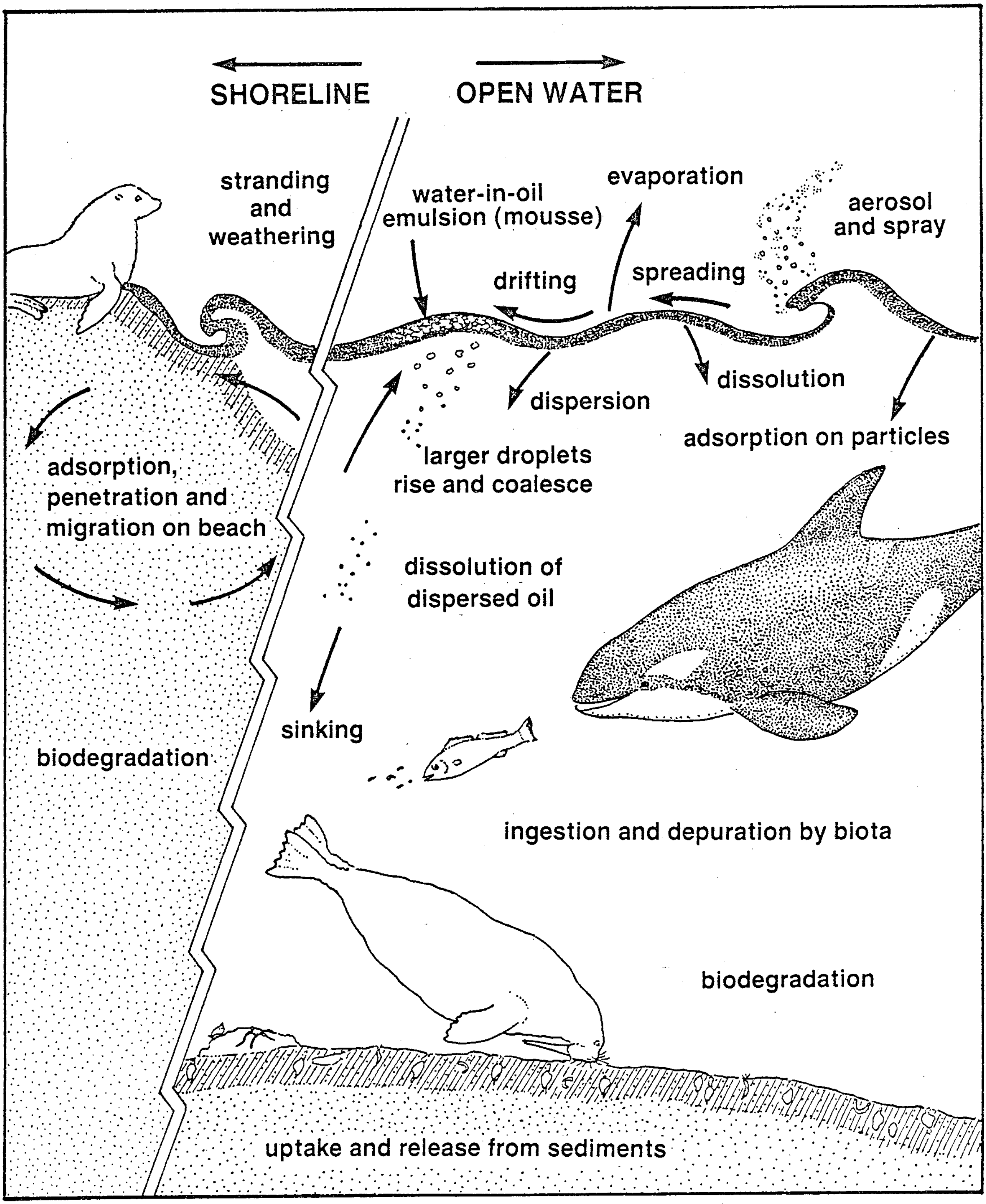
The timing and relative importance of physical, chemical, and biological processes affecting the fate of oil differ with each category of discharge and petroleum product. However, the types of processes are the same. Weathering plays the most important role in determining the fate of spilled oil. Weathering processes include spreading, evaporation, dissolution, dispersion into the water column, photochemical oxidation, formation of emulsions, microbial degradation, adsorption to suspended particulate matter, and stranding on shore or sedimentation to the sea floor (Payne and McNabb 1985, Payne *et al.* 1987, Boehm 1987) (Figures 1.3 and 1.4). Weathering changes the physical and chemical properties of spilled oil, and thereby influences its toxicity to marine organisms.

Spreading and Drifting: Oil released at or near the sea surface will first be affected by spreading (Figure 1.4). If discharged below the surface, it must rise through the water column before it can form an oil slick. Under such conditions, oil droplets form and disperse, and the lower molecular weight components dissolve (Boehm and Feist 1982). Most of the petroleum discharged as part of a complex mixture such as municipal sewage never reaches the sea surface, and so is not subjected to the same weathering forces.

When oil is released on the sea surface, it spreads horizontally in an elongated pattern oriented in the direction of the prevailing wind and surface water currents (Elliott 1986, Elliott *et al.* 1986). The center of the mass of the slick may move at a rate of approximately three percent of the wind speed with a 20 to 30 degree shift to the right (in the northern hemisphere) due to

Figure 1.3

Behavior and fate of oil spilled in the marine environment (Bobra and Fingas 1986).


SHORELINE
OPEN WATER
stranding and weathering
water-in-oil emulsion (mousse)
evaporation
aerosol and spray
drifting
spreading
dispersion
dissolution
adsorption on particles
larger droplets rise and coalesce
adsorption, penetration and migration on beach
dissolution of dispersed oil
sinking
biodegradation
ingestion and depuration by biota
biodegradation
uptake and release from sediments

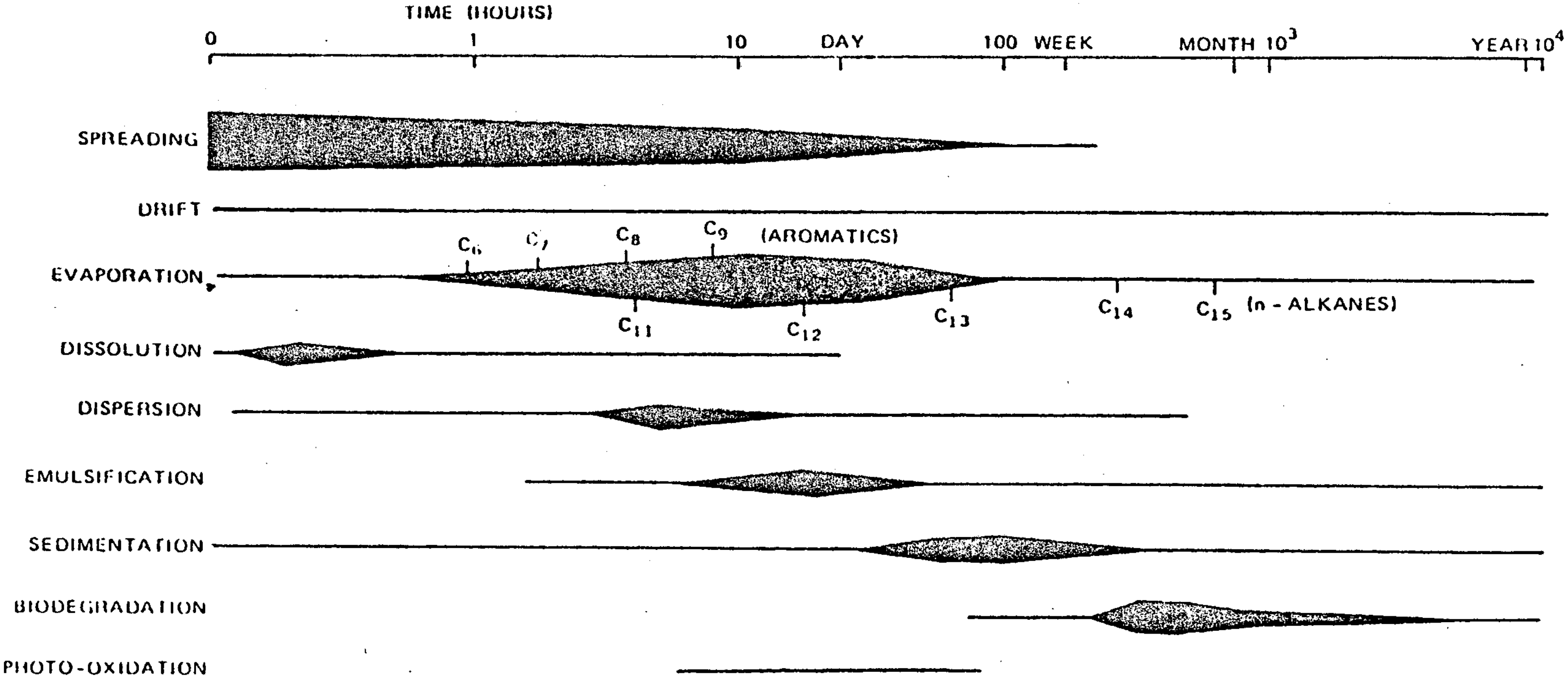


FIGURE 1.4: THE TIMING OF OIL WEATHERING PROCESSES FOLLOWING AN OIL SPILL ON THE SEA SURFACE. THE LENGTH OF THE LINE INDICATES THE PROBABLE TIMESPAN OF A PROCESS. THE WIDTH OF A LINE INDICATES THE RELATIVE MAGNITUDE OF THE PROCESS THROUGH TIME AND IN RELATION TO OTHER CONCURRENT WEATHERING PROCESSES (from Wheeler, 1978).

Coreolis force (Payne and McNabb 1985). Several mathematical models have been developed to predict the trajectories of oil slicks (Samuels *et al.* 1983). The major axis of the slick tends to elongate at a linear rate with time, whereas the width of the slick grows as a function of $t^{0.5}$. Spreading is more rapid on warm than on cold water due to differences in viscosity of the oil; moderate wave action also increases the rate of spread. Crude oils and heavy distillates form two phases during spreading: a thick phase (1-20 mm thick), consisting of viscous, partly emulsified oil, and a thin sheen 0.01 to 0.001 mm thick (Audunson *et al.* 1981). In addition, the leading edge of the slick tends to be thicker than the interior (Elliott 1986). The thick oil usually forms small patches, which subdivide as they continue to weather. These patches usually move downwind at a faster speed than the thinner slick, eventually leaving it behind.

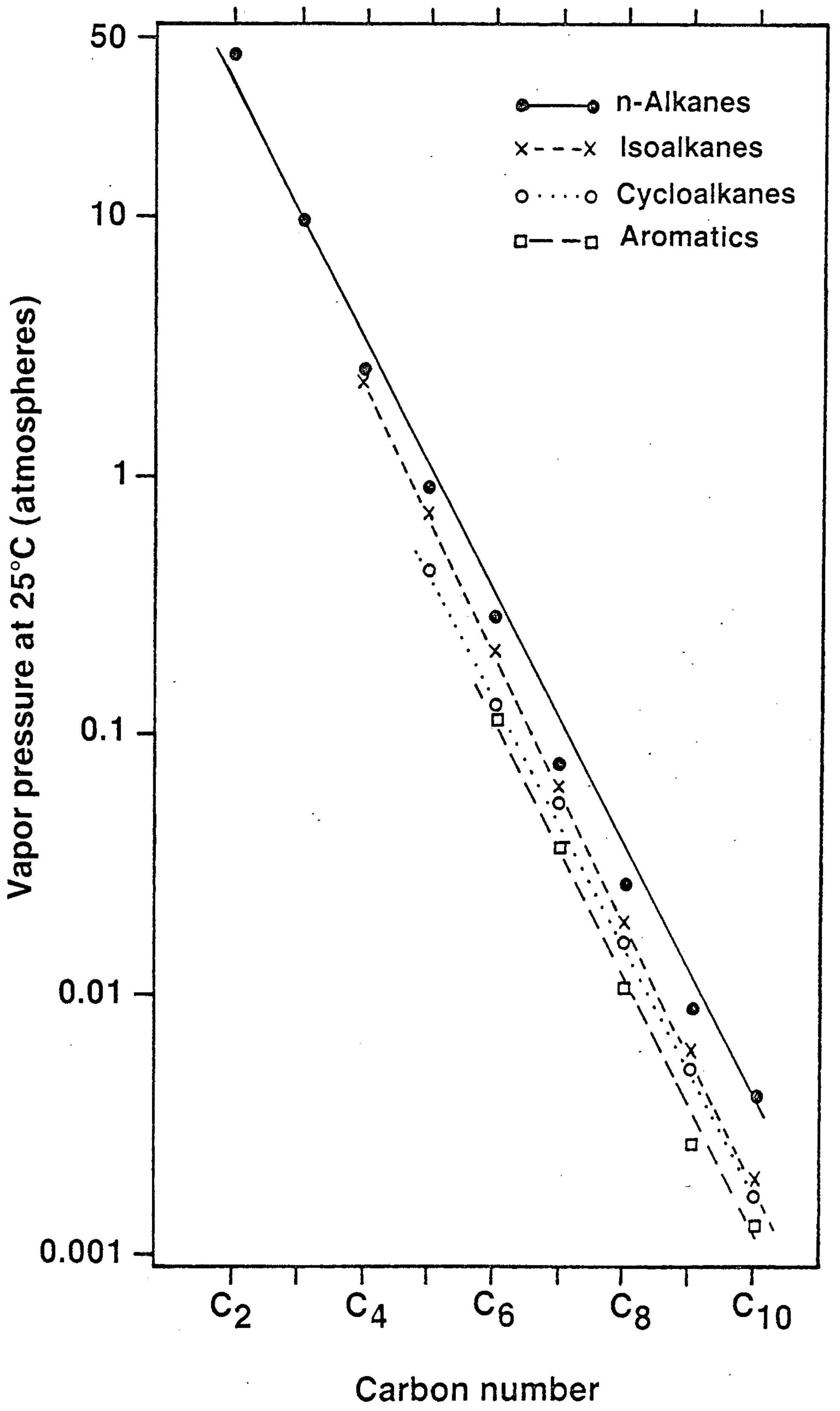
The area of the ocean surface covered by an oil slick cannot be calculated based on volume of oil alone. Composition of the oil, rate of discharge, and environmental conditions all affect the thickness, and thereby the area covered by the slick. A thin iridescent sheen is about 1 to 5 μm thick and has a concentration on the sea surface of about 1000 L/km^2 (National Academy of Sciences 1985), whereas the surface concentration of a 1 mm to 10 mm thick slick may be in the order of 10^6 to 10^7 L/km^2. Thus, the spill from the <u>Argo Merchant</u> on Nantucket Shoals, Massachusetts in December 1976 (29×10^6 L) could occupy initially as little as 2.9 km^2 or as much as 29,000 km^2, depending on thickness. A reasonable average thickness for a crude oil slick undergoing moderate weathering would be 0.1 to 1.0 mm; such a spill would occupy 0.1 to 1.0 km/metric ton of oil.

Evaporation: For the first few days after a spill, evaporation is the most important weathering process affecting the volume and composition of oil. The type of oil, surface area of the slick, and environmental conditions influence the rate of evaporation (Wheeler 1978), which for any given substance is directly proportional to its vapor pressure (Mackay and Leinonen 1975, Wheeler 1978) and inversely proportional to molecular weight (Figure 1.5). Aromatic hydrocarbons tend to evaporate more rapidly than alkanes of similar molecular weight (Figure 1.4), despite the lower vapor pressure of the former, apparently because aromatics have higher activity coefficient than alkanes in the oil phase (Harrison *et al.* 1975). Light distillate fractions, such as gasoline, kerosene, and jet fuel may evaporate completely (Figure 1.1), and as much as 60 percent of light crude oil may evaporate within a week or so after a spill (Wheeler 1978). Owing to the inverse relationship between temperature and vapor pressure, low molecular weight hydrocarbons evaporate more slowly in cold Arctic waters (Reijnhart and Rose 1982).

Evaporation profoundly effects physical and chemical properties of a slick. The loss of volatile components increases density and viscosity, and reduces in vapor pressure and toxicity (Bobra and Fingas 1986). Tarry resin and asphaltene fractions increase, promoting the formation of water-in-oil emulsions and tar balls. These in turn slow the rate of diffusion of remaining volatile hydrocarbons. Thus, emulsified oil, tar balls, and tar mats may develop a crust composed primarily of non-volatile oil components covering a core of less

Figure 1.5

Relation between carbon number and vapor pressure of four classes of hydrocarbons in petroleum (Wheeler 1978).


50
10
1
0.1
0.01
0.001
Vapor pressure at 25°C (atmospheres)
n-Alkanes
Isoalkanes
Cycloalkanes
Aromatics
C2
C4
C6
C8
C10
Carbon number

weathered oil containing high concentrations of light hydrocarbons (Butler 1975, Boehm and Feist 1982, Payne and Phillips 1985).

Dissolution: Usually, less than 2 to 5 percent of the oil is removed by dissolving into the water column (Harrison *et al.* 1975, McAuliff 1976, Payne *et al.* 1987). The process may nonetheless be significant because it brings the most toxic hydrocarbons into contact with marine organisms in a form that is readily available. In the Ixtoc-I blowout, significant fractions of the lighter hydrocarbons partitioned into the water as the oil rose through the water column; benzene under the slick reached concentrations greater than 100 μg/L (Payne *et al.* 1983). Both dissolved and dispersed hydrocarbons persisted in the water column for up to 40 km from the blowout site (Boehm and Feist 1982). Low concentrations of volatile aromatic hydrocarbons have also been detected in the water column 2 to 3 km from the treated ballast water discharge at Port Valdez, Alaska (Lysyj *et al.* 1981).

When a slick is subjected to turbulent mixing or wave action, there is a tendency for small droplets to break away from the main mass and become dispersed in the water column. If the droplets are small enough (less than 0.1 mm), they rise so slowly as to remain dispersed indefinitely (Payne and McNabb 1985), whereas larger droplets tend to coalesce, rise rapidly, and concentrate near the surface (Forester 1971).

Dispersion and Emulsion Formation: Dispersion is the most important process in the breakup and disappearance of a slick already reduced by evaporation. Dispersion begins soon after oil is discharged, reaches a peak within 10 hours (Figure 1.4), and within 100 hours overtakes spreading as the primary mechanism of transport of oil from the spill site (Wheeler 1978). The activity and effectiveness of the process is due in part to viscosity of the oil (Gordon *et al.* 1983) and to the presence of natural surfactants (Wheeler 1978) which facilitate droplet formation and inhibit coalescence.

Some oils, particularly after weathering, accumulate and retain dispersed water droplets within the oil phase (Mackay 1982). These water-in-oil emulsions, sometimes called chocolate mousse because of their appearance, may contain up to 75 percent water, and are more viscous than the parent oil. Their tendency to form depends on the concentration of heavy resin and asphaltene materials as well as endogenous surfactants (Payne and Phillips 1985). Stable emulsions form readily in the presence of sea ice (Payne and Phillips 1985). Those formed during ice breakup are not neutrally buoyant in the lower salinity water and tend to collect under the ice.

Formation of stable water-in-oil emulsions is important because it effects subsequent weathering of oil and also makes it less amenable to cleanup. Following emulsification, evaporation and dissolution of light fractions are inhibited, and photochemical and microbial degradation of the heavier fractions are slowed. Whether the slick forms a water-in-oil emulsion or an oil-in-water emulsion appears to depend on the viscosity, thickness, and chemical composition of the oil (Mackay 1982), and environmental factors.

Photochemical Reactions: Solar radiation acting on oil in the water generates photochemical reactions which yield new, mostly polar organic compounds. The compounds, although in low concentrations (Ducreux *et al.* 1986), affect toxicity and behavior of the spilled oil (Payne and Phillips 1985b). The primary mechanism of photodegradation is photo-oxygenation (Larson *et al.* 1976, 1977, Thominette and Verdu 1984a), yielding such reaction products as peroxides, aldehydes, ketones, alcohols, and fatty acids (Payne and McNabb 1985) which tend to be more water-soluble and toxic than the unoxidized parent compounds (Larson *et al.* 1979). The process also yields high molecular weight by-products that are not soluble in either oil or water (Thominette and Verdu 1984b).

Direct photolysis reactions, not requiring molecular oxygen, are quantitatively the most important mechanism of light-induced transformation (Zepp and Schlotzhauer 1979, Mill *et al.* 1981). The tendency toward direct photolysis increases with increasing molecular weight of polycyclic aromatic hydrocarbons. For example, the half-life of naphthalene (two rings) in surface fresh water in sunlight equivalent to 40° N latitude in mid-summer is 71 hours, compared to a half-life of eight hours for phenanthrene (three rings), and 0.54 hours for benzo(a)pyrene (five rings). Because light intensity decreases rapidly with depth, rate of photolysis of aromatic hydrocarbons in the water column also decreases with depth.

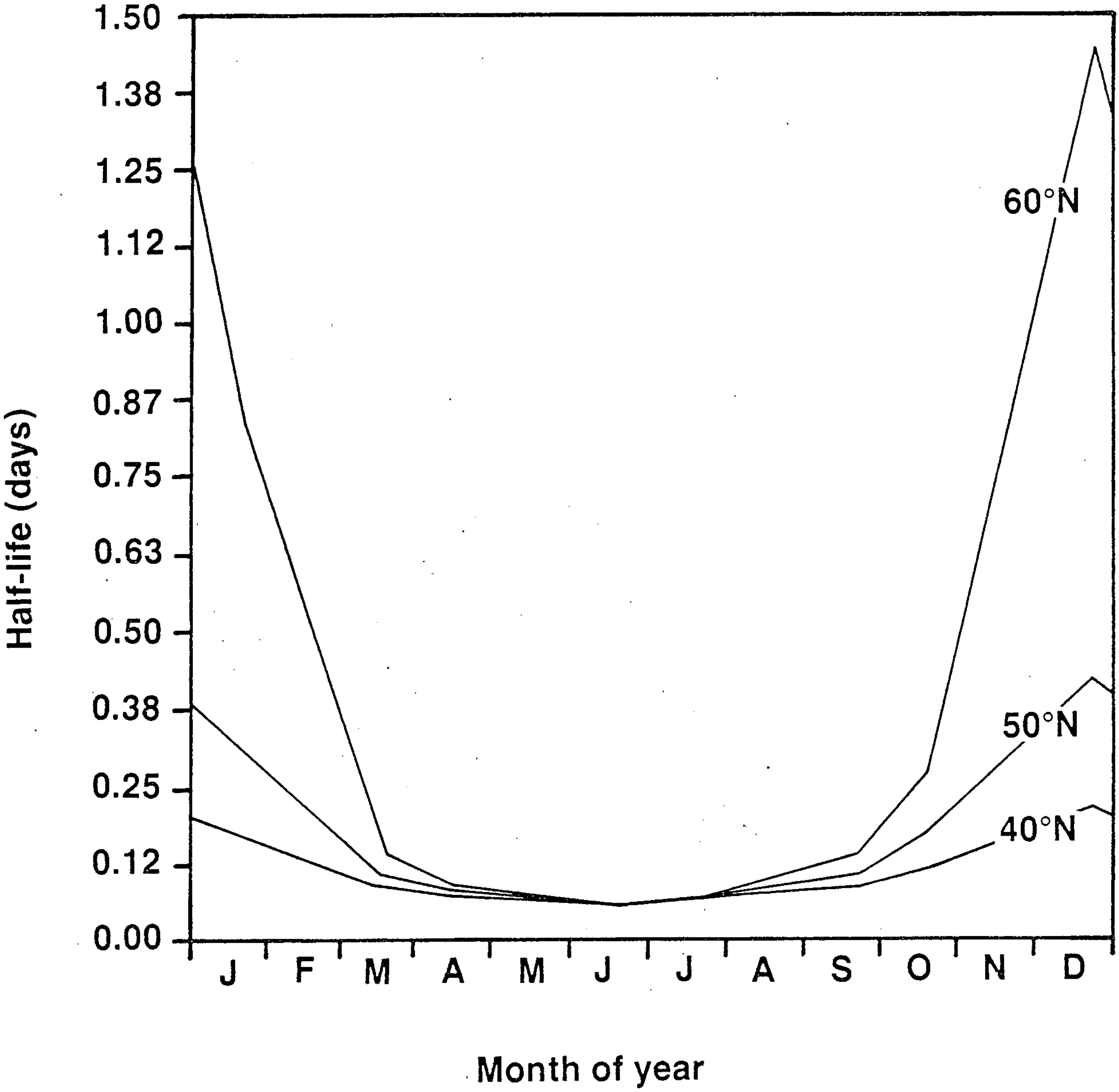
At high latitudes, the rate of photolysis is greatly diminished due primarily to the reduced intensity and daily duration of solar irradiance during the winter (Figure 1.6). At 60° N latitude, there is an approximately ten-fold decrease in the rate of photolysis of benzo(a)pyrene between June and December (Zepp and Baughman 1978). Photolysis rates of some compounds, such as benzo(b)thiophene and carbazole, are more sensitive to light intensity than others such as benz(a)anthracene and benzo(a)pyrene (Mill *et al.* 1981).

Biodegradation: Marine bacteria and fungi play an important role in degrading and removing petroleum hydrocarbons from surface slicks, the water column, and surficial sediments. Microbial degradation begins a day or so after the spill and continues as long as hydrocarbons persist (Wheeler 1978, Lee and Ryan 1983). Rate of degradation is related to oxygen concentration, temperature, nutrients (especially nitrogen and phosphorus), salinity, the physical state and chemical composition of the spilled oil, and previous history of oil pollution at the spill site (Atlas 1981, Bartha and Atlas 1987).

Following a spill, all hydrocarbon components and classes are degraded simultaneously, but at widely different rates by indigenous water column and sediment microbiota (Atlas *et al.* 1981, Bartha and Atlas 1987). Low molecular weight n-alkanes in the C10 to C22 chain length range are metabolized more rapidly, followed by iso-alkanes and higher molecular weight n-alkanes, olefins, monoaromatics, PAH, and finally, highly condensed cycloalkanes, resins and asphaltenes. Thus, as oil weathers through a combination of physical, photochemical, and biodegradative processes, it loses low molecular weight components and becomes enriched in higher molecular weight more complex saturates, naphtheno-aromatics, PAH, resins, and asphaltenes.

Figure 1.6

Annual variation in half-life (t_{50}) of benzo(a)pyrene dissolved in near-surface water at northern latitudes (Zepp and Baughman 1977).


1.50
1.38
1.25
1.12
1.00
0.87
0.75
0.63
0.50
0.38
0.25
0.12
0.00
Half-life (days)
60°N
50°N
40°N
J
F
M
A
M
J
J
A
S
O
N
D
Month of year

Temperature profoundly effects the process of degradation. The half-life for microbial degradation of phenanthrene at an initial concentration of 25 μg/L in seawater is 79 days at 18°C and 11,000 days at 2°C. Similarly, that for benz(a)anthracene at an initial concentration of 2.5 mg/kg in sediment is 1100 days at 15°C and 21,000 days at 4°C (Lee and Ryan 1983). The reliance on temperature was underscored by Wakeham *et al.* (1985, 1986) who showed that in summer conditions biodegradation was more important than volatilization in removing toluene, octadecane, and decane from the water column; under winter conditions, their contributions were reversed. Because both processes are markedly diminished at low environmental temperatures, the light fractions of crude and refined petroleum are very persistent in Arctic environments, especially in winter when low light intensity inhibits photo-oxidation.

Biodegradation is at best a slow process. Rates for hydrocarbons have been estimated to be 1 to 10 mg/m^3/day in open-ocean waters (Butler *et al.* 1976), 30 mg/m^3/day beneath the surface slick produced by the Amoco Cadiz spill (Aminot 1981), and 0.05 g/m^2/day in the upper 5 cm of intertidal sediments along the Brittany Coast of France, impacted by the Amoco Cadiz spill. Extrapolating to the length of coastline affected, Atlas and Bronner (1981) estimated that it would take more than 20 years to biodegrade the estimated 64,000 tons on the Brittany coast.

In Arctic environments, biodegradation is slower still, limited by nutrients (Bergstein and Vestal 1978, Atlas 1986) and low temperatures (Cundell and Traxler 1973, Gibbs *et al.* 1975). Nevertheless hydrocarbon-degrading bacteria abound (Atlas 1986), and can be coaxed into activity by exposure to petroleum (Button and Robertson 1985).

Deposition in Sediments: Heavier fractions of oil eventually deposit in bottom sediments and persist for a long time. Sedimentation may occur by 1) adsorption of droplets on suspended (including biological) particules and transport with them to the bottom, 2) stranding or beaching of oil, followed by adsorption onto sediments or erosion of hardened oil from substrates and subsequent transport to subtidal sediments, and 3) direct sinking of heavy or weathered oils (Anderson *et al.* 1986, Boehm 1987).

Suspended particles interact with spilled oil in two ways. They physically collide and adhere to dispersed droplets, and adsorb and partition dissolved hydrocarbons from the water phase (Payne *et al.* 1987). A key variable in adsorption appears to be the concentration of suspended particulate matter, especially clay, in the water column. The greater the suspended sediment load, the more oil may be adsorbed and transported to the bottom (Boehm 1987). Approximately 120 to 300 mg of petroleum may adsorb to each kilogram of suspended clay (Bassin and Ichiye 1977, Meyers and Oas 1978).

Weathered oil may become heavier than seawater and sink (Boehm 1987). The process is enhanced as the density of water is lowered by influx of freshwater as runoff or from melting ice. In areas of significant downwelling, as in a polynya at the edge of an ice sheet, sinking water may carry oil droplets to the bottom. Additional oil may be fixed onto biological particles, particularly zooplankton fecal pellets.

Beached oil can also contribute to the sediment load. Erosion of the beach by seasonal storms or ice-scouring results in transport of oil-laden sand into the subtidal zone. Studies of the Baffin Island experimental oil spill (Boehm *et al.* 1985) and the Amoco Cadiz oil spill (Gundlach *et al.* 1983) have shown that concentrations in excess of 100 ppm oil can deposit in subtidal sediments if oil comes ashore and subsequently erodes from the beach.

Interaction of Weathering Processes: The nature and extent of interactions between different weathering processes are difficult to ascertain. Some idea of the processes can be gleaned from an analysis of the fate of the 223,000 tons of oil spilled from the Amoco Cadiz (Gundlach *et al.* 1983). In this spill, there was a massive beaching of oil, a return of large amounts to sediments of bays and estuaries, and to anoxic intertidal and subtidal sediments where they persisted for several years. About 36 percent of the spilled oil was deposited on the shore or in subtidal sediments during the first months. Approximately 30 percent of the oil evaporated, and about 5 percent was degraded in the water column by bacteria. More than 20 percent of the oil was unaccounted for and probably was carried away as surface slicks or tar balls. The most persistent oil residues were those incorporated into subtidal sediments of estuaries or nearshore waters, and oil that washed onto beaches and was buried in the shifting sands. Most of the oil had disappeared from the water surface and water column within a few months after the spill.

Oil Dispersants

Between 1967 and 1979, chemical dispersants were used to combat at least 16 major oil spills. These substances promote the break-up of the slick into fine droplets that disperse in the water column and can be carried away and diluted by normal ocean mixing processes. Most dispersants are composed of surface active agents (surfactants), a solvent, and stabilizing agents (Tetra Tech 1985, Canevari 1986). A surfactant contains both a hydrophilic (water-compatible) and a hydrophobic (oil-compatible) group which allows it to concentrate at the boundary between oil and water (Figure 1.7). The effect is to reduce surface tension, thereby facilitating dispersion into the water column. There are three types of surfactants categorized according to the nature of the hydrophilic group: anionic, cationic, and nonionic. Nonionic surfactants are used most frequently in dispersants. They include ethoxylated alkylphols, such as nonyl phenol-ethylene oxide, ethoxylated linear alcohols, such as oleyl alcohol, and esters formed by the reaction of fatty acids with polyhydric alcohols.

A solvent is added to lower freezing point and reduce viscosity, making it easier to apply. These include aliphatic and aromatic hydrocarbon mixtures, water or alcohols in water, glycols, and glycol ethers. Dispersants containing

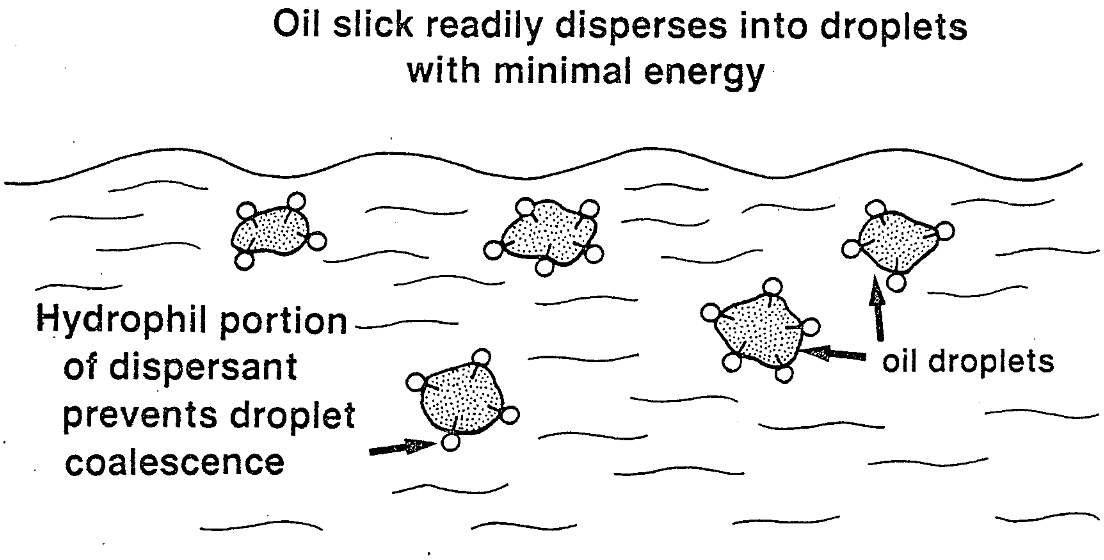


Figure 1.7 Dispersion of oil droplets resulting from application of a chemical dispersant

hydrocarbon solvents tend to be more effective in treating heavy, viscous oils. They are easier to mix and apply, but are more toxic than those containing water-soluble solvents. A stabilizer may also be added to adjust pH, reduce corrosiveness, help fix the dispersion after it is formed, or counteract adverse color or odor. Dispersant stabilizers may include alkalis, phosphates, silicates, nitrates, dyes and polymerized alkyl naphthalene sulfonates.

Other Methods of Treating Spills

A variety of other chemical agents has been proposed for treating marine oil spills. These include herding agents, demulsifiers, and gelling, wicking, and sinking agents. Most of these are in the conceptual or developmental stage, and their chemical compositions are proprietary.

Herding agents have a higher surface tension, and therefore, spreading force, than petroleum (Fickling and Hann 1980). When applied around a slick, they tend to compress it and prevent it from spreading. They reportedly have relatively low toxicity to marine organisms. Demulsifiers are mixtures of surfactants and wetting agents intended to facilitate the separation of the oil and water in emulsions (Canevari 1982). Once separated, the oil is recovered and the water discharged. The environmental properties and toxicity of demulsifiers should be similar to those of dispersants. Gelling agents transform spilled oil into a semisolid mass that can be handled easily with recovery equipment. By injecting them into the oil in cargo or fuel tanks of a sunken ship, they may slow or prevent release of oil. One such agent is a high molecular weight polymer of polyisobutylene (Waters and Hodermann 1987). These compounds, apparently have low toxicity to marine organisms (Tokuda 1979).

Spilled oil can be effectively burned, particularly if fire-proof booms are used (Buist *et al.* 1983). However, water serves as a heat sink making it difficult to sustain combustion. Not all the oil burns, and the residues and airborn particles may create added problems. Wicking agents are intended to lift the oil above the sea surface, enabling it to burn more efficiently. They have not been used successfully in open water, but may prove more beneficial on ice when oil gathers in relatively deep pools (Mackay 1982).

Sinking agents are dense particles (2.4 to 3.0 g/cc) with hydrophobic surfaces, that when applied to a spill, adsorb the oil and cause it to sink. They may include sand, fly ash, powdered cement, or other minerals coated with silicones, stearates, or waxes. They effectively remove oil from sight, but they may exacerbate the impact of the spill by rapidly depositing the oil on the bottom where it may persist.

Use of Chemical Dispersants and Cleaning Agents

Dispersants may be applied to an oil slick by hand, or from a suitably equipped boat or aircraft (Fickling and Hann 1980). Small to medium-sized boats with spray booms, usually about 7 to 10 meters long extending out from each side, are used most frequently. They apply water-based dispersants at a rate of about 100 to 150 gallons per minute; concentrates and hydrocarbon-based dispersants are applied at a lower rate. Aerial spraying has the advantage of covering large areas quickly. It requires that the dispersant be used full-strength and that the aircraft fly 30 to 50 feet above the surface.

The volume of dispersant required to treat a spill depends on sea state, nature of the oil, and the method of application. The rate of administration ranges from one liter for each 10 liters of spilled oil to a rate of one to one. Generally, the rougher the seas and the fresher the oil (less weathered), the less dispersant required to break up the slick. During the Ixtoc-I spill, several dispersants were used, most of which were applied by plane. Up to four spraying missions were flown per day, each applying about 135,000 liters of dispersant. Additional dispersant was applied from boats. Clearly, if the amount of dispersant discharged to the oceans would be very large if this method were adopted on a wide scale.

Dispersants have also been used to loosen oil on shore so that it can be removed more easily by cleaning devices or by wave action. This practice was discouraged after the Torrey Canyon oil spill in 1967 on the southwest coast of Cornwall, England, because the use of dispersant caused more damage to coastal ecosystems than did the oil itself (Nelson-Smith 1968, Southward and Southward 1978). Interest is now growing to evaluate the usefulness of less toxic dispersants for shoreline cleaning, but here too the advantages are questionable. Studies on rocky shores and intertidal mud flats reveal little difference in impact between raw crude oil and crude oil that was treated with a dispersant after stranding (Little *et al.* 1981, Rowland *et al.* 1981, Crothers 1983). Results from comparable studies in a salt marsh are somewhat more encouraging (Baker *et al.* 1980).

Fate of Dispersants in the Marine Environment

Chemical dispersants applied to oil spills undergo the same types of weathering processes as the spilled oil (Tetra Tech 1985). The most important processes affecting the fate of oil dispersants in seawter are evaporation, solubilization, diffusion, biodegradation, and possibly bioaccumulation (Wells *et al.* 1982).

Much of the hydrocarbon or water-soluble solvent fraction of the dispersant is lost by evaporation during and immediately after application of the dispersant to the oil slick. Evaporation of the solvent is most rapid when the dispersant is applied as a fine spray from an airplane.

When applied to a spill on the water surface, the dispersant immediately dissolves in the partitions between the oil and water phases. Mackay and Hossian (1982) estimated that the oil-water partition coefficient for the types of surfactants most frequently used in oil dispersants is about 10. Because the ratio of oil to water in nearly all spills is very low, most of the dispersant (up to about 99 percent) partitions into the water phase. Once in aqueous solution, the dispersant is diluted by diffusion and convective mixing, but surfactant components are detectable in concentrations of 1-3 ppm for over 6 hours after application to an oil spill (Bocard *et al.* 1984).

The complex fatty acid ester mixtures usually used as surfactants in modern oil dispersants are readily degraded by marine bacteria and fungi. Several types of marine water column and sediment bacteria are capable of rapid and sustained growth with oil dispersant as the sole source of carbon and energy (Liu 1983). More than 55 percent of the dispersant BP1100X was degraded in 8 days by a mixed population of microbes isolated from oil-contaminated sediments (Bhosle and Row 1983). Microbial degradation probably is the most important mechanism quantitatively for removing dispersants from the marine environment.

Although surfactants from oil dispersants are readily accumulated from the water by marine animals (Kikuchi *et al.* 1980), they are also readily metabolized by freshwater and marine animals (Payne 1982). The animals enzymatically hydrolize the surfactant to hydrophilic and hydrophobic components. Hydrophilic components probably are excreted via the gills and kidneys, whereas hydrophobic components accumulate in the gall bladder of fish and are excreted very slowly. Because of the rapid metabolism of surfactants by marine animals, there is little likelihood of food chain transfer of surfactant chemicals from marine invertebrates and fish to consumers, including marine mammals.

Overview of Possible Interactions between Petroleum and Marine Mammals

Many of the properties of petroleum and its behavior and fate when spilled in the marine environment make it likely that marine mammals will come in contact with oil in some form. There is some concern that such encounters will be harmful (Geraci and St. Aubin 1980).

Physical Contact with Oil: All marine mammals spend considerable time at the surface, swimming, breathing, feeding, or resting, thereby enhancing the possibility of contact with a surface slick, water-in-oil emulsion, or tar balls. In species with heavy pelage, such as fur seals, sea otters, and polar bears, contact may lead to fouling. Polar bears and otters groom themselves regularly as a means of maintaining the insulating properties of the fur, and may thereby ingest oil. Oil would have less tendency to adhere to the surface of animals with relatively little or no pelage, such as whales, dolphins, manatees, and most seals.

Some baleen whales forage at the surface, a behavior called skim-feeding (Wursig *et al.* 1985). It affords the potential, when in an area of a slick or tar balls, to foul the feeding apparatus. Tarry residues in particular could coat the baleen plates.

In polar regions, spilled oil tends to accumulate at the ice edge, in leads, polynyas, and breathing holes (Figure 1.8), where animals such as narwhals, belugas, ringed seals, walruses, and polar bears spend much of their time. The oil tends to persist, thus setting the stage for unavoidable contact.

Oil that comes ashore is likely to foul pinnipeds that require such areas for haul-outs or nursery areas, and to lesser extent, otters and bears. Some of the oil is eventually returned in subtidal sediments, where it may transfer to species, such as the gray whale, walrus, and some seals, which feed heavily on benthic animals.

Accumulation of Oil from Air and Water: Marine mammals encountering fresh oil are likely to inhale volatile hydrocarbons evaporating from the surface slick. Such fractions contain toxic monoaromatic hydrocarbons (benzene, toluene, xylenes) and low molecular weight aliphatics with anaesthetic properties. Inhalation of these compounds is potentially dangerous (Carpenter *et al.* 1975, 1976).

Inhalation of concentrated petroleum vapors may cause inflammation of and damage to the mucus membranes of airways, lung congestion, or even pneumonia (Hansen 1985). Volatile hydrocarbons, such as benzene and toluene, that are inhaled are transferred rapidly into the bloodstream in the lungs. They may accumulate from the blood in such tissues as brain and liver, causing neurological disorders and liver damage (Geraci and St. Aubin 1982).

Marine mammals probably will not accumulate much oil directly from solution or dispersion in the water column. The skin of cetaceans seems relatively impermeable to oil (Geraci and St. Aubin 1980). Most marine mammals do not drink large volumes of seawater, so significant accumulation of hydrocarbons by this route is unlikely.

Fur-bearing marine mammals such as fur seals, polar bears, and sea otters may ingest oil during grooming. The limited data avilable indicate tht oil is not particularly toxic at least to pinnipeds when taken in by this route. Geraci and Smith (1976) showed that seals experienced no acute damage when they ingested 75mL of oil over a short period of time. However, ingestion of oil during grooming may have contributed to the death of heavily oiled polar bears (Oritsland *et al.* 1981).

Ingestion of Oil-Contaminated Food: Marine mammals, except the manatee, are carnivores that rely on invertebrates or fish for sustenance. Their feeding strategies could lead to ingestion of oil-contaminated food, because most of the prey organisms can accumulate petroleum hydrocarbons in their tissues (Neff 1979, Capuzzo 1987).

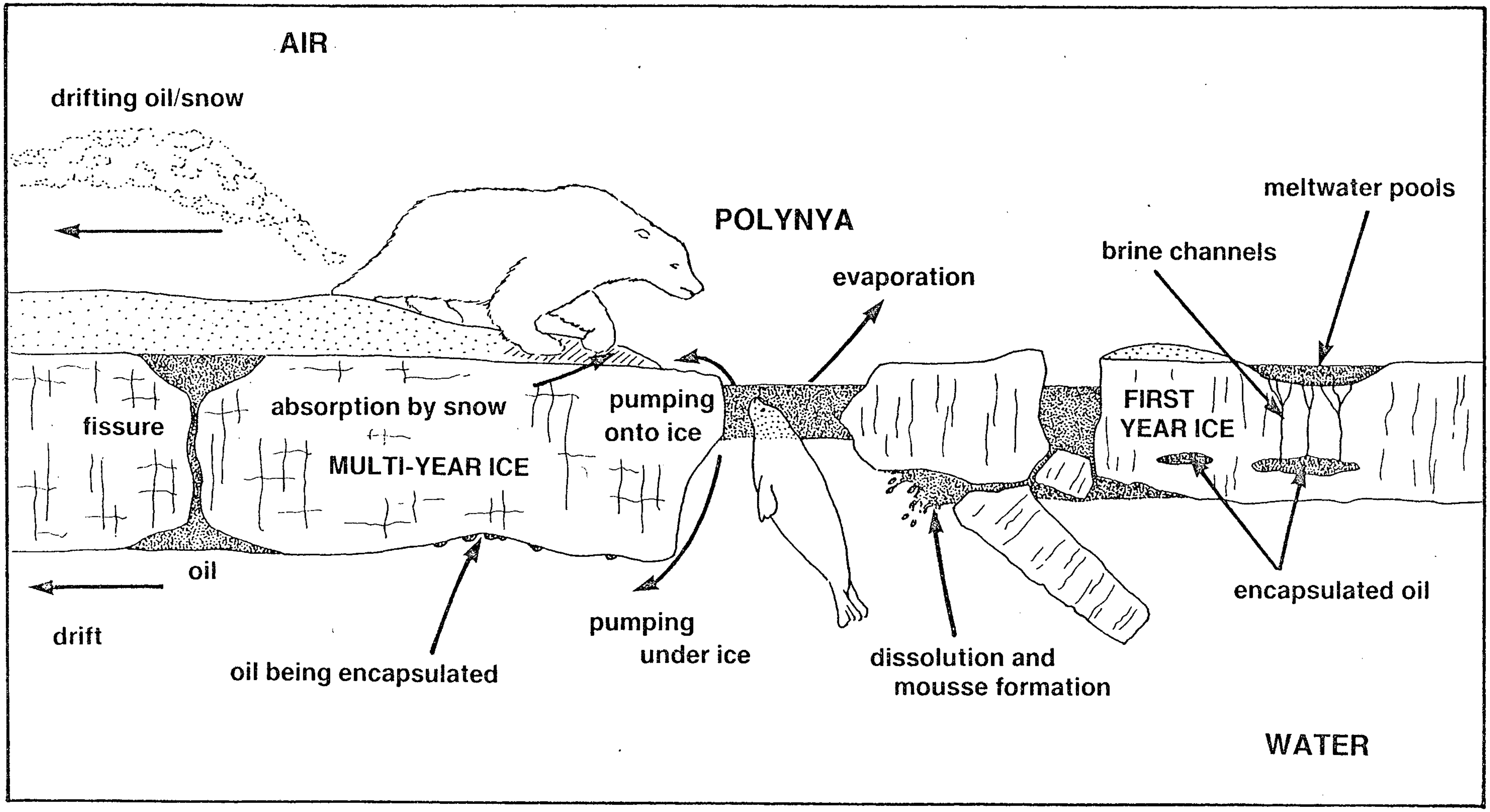


Figure 1.8 Behavior of oil in a polar environment

Zooplankton are a particularly important food resource, particularly for baleen whales. Some, such as copepods, euphausiids, and mysids, assimilate hydrocarbons directly from seawater and by ingesting oil droplets and oil-contaminated food (Corner 1978). Copepods are one of the few taxa in which hydrocarbon uptake appears to be more efficient from food than from water (Corner *et al.* 1976). There is an inverse relationship between ambient temperature and rate of accumulation of petroleum hydrocarbons by copepods (Harris *et al.* 1977); polar and boreal species store more lipids, and therefore hydrocarbons than those from warm environments. Planktonic crustaceans can transform aromatic hydrocarbons to polar metabolites that may be excreted or bound to tissues (Malins 1977). A fraction of hydrocarbons is also retained for days or weeks in unmetabolized or metabolized form in zooplankton (Corner *et al.* 1976). During this time, the hydrocarbons could be transferred to consumers of zooplankton.

Benthic invertebrates and higher forms such as the sand eel, Ammodytes americanus (an important food item of Atlantic humpback whales) (Payne *et al.* 1986), may accumulate petroleum hydrocarbons from contaminated sediments and food, and to a greater extent, from water (Neff 1984). Bivalve mollusks tend to accumulate petroleum hydrocarbons to higher concentrations and retain them longer than other taxa (Neff and Anderson 1981, Capuzzo 1987). This is due in part to their limited ability to metabolize the compounds to excretable polar metabolites; they essentially lack the mixed function oxygenase (MFO) system to do so (Lee 1981). Thus, marine mammals that rely heavily on bivalve mollusks for food, such as the walrus (Oliver *et al.* 1983), and otter share a higher risk of ingesting petroleum hydocarbons.

Benthic crustaceans, the major food of gray whales in the northern Bering Sea and the Chukchi Sea (Nerini and Oliver 1983), also accumulate oil from water, sediment and food (Neff 1979, Capuzzo 1987). However, most marine crustaceans have a well-developed MFO system (Lee 1981), and so are able to metabolize and excrete accumulated hydrocarbons quite rapidly. Thus, benthic crustaceans would provide a source of hydrocarbons to feeding gray whales for only a short period of time after a spill. However, benthic amphipods are quite sensitive to spilled oil; they are among the first marine animals killed and the slowest to recover (Spies 1987). Thus, a major spill in the northern Bering Sea in summer could affect the whales' main food resource.

Marine fish also take up petroleum hydrocarbons from water and food. The compounds induce the hepatic MFO system in liver (Stegeman 1981); within a few days after exposure, aromatic hydrocarbons are oxygenated to polar metabolites and excreted. For this reason, most fish, even in heavily oil-contaminated environments, do not accumulate and retain high concentrations of petroleum hydrocarbons, and so are not likely to transfer them to predators.

Fish may nevertheless be tainted with metabolites bound to tissue macromolecules including DNA. The metabolites are so reactive, it is unlikely that they would be released in a toxic form during digestion and absorption by the consumer, and so would not pose a serious threat.

In general, marine carnivores are inefficient assimilators of petroleum compounds in food. For this reason, and because all prey species are able to release hydrocarbons from their tissues (Neff and Anderson 1981), marine food chain biomagnification does not occur. Thus, there is no direct correlation between a marine mammal's trophic level and the concentration of residues that it might consume. In fact, top carnivores such as polar bears and killer whales that feed on large pelagic fish and seals are less likely to be exposed to petroleum in their food, than are species such as baleen whales and walrus that feed on zooplankton and benthic invertebrates.

Effects of Oil Dispersants

Excepting their use to clean oil-fouled sea otters, virtually nothing is known about the effects of oil dispersants on marine mammals. By removing spilled oil from the sea surface, dispersants obviously reduce the risk of contact. The oil remaining would be less sticky, and therefore less likely to adhere to fur, skin, baleen plates, or other body surfaces. On the other hand, the surfactants in dispersants may remove natural oils from marine mammal fur, thereby decreasing its insulating properties. Cleaning oiled beaches and rocky shores with dispersants may be an effective means of preventing oiling of pinnipeds that may wish to haul out there. More work needs to be done before we can adequately weigh the advantages or disadvantages of using dispersants in such habitats.

Distribution of Oil Inputs and Marine Mammals

The distribution of oil production and transportation activities is very uneven in U.S. coastal and outer continental shelf waters. Major tanker routes worldwide are concentrated in the Indian Ocean and South and North Atlantic, reflecting the massive export of petroleum to western Europe and the United States. In U.S. waters, there is significant tanker traffic in the Gulf of Mexico along the Texas coast, along the Pacific coast from Alaska to southern California (the main tanker route for Alaskan Prudhoe Bay oil to refineries in Washington and California), and the Atlantic coast from refineries to major urban markets. Approximately 95 percent of offshore production in U.S. waters is in the Gulf of Mexico, especially off Louisiana. The remainder is off southern California, in Alaska at Cook Inlet, and in the Beaufort Sea. Oil production is also taking place off the east coast of Canada on the Grand Banks, in the Canadian Beaufort Sea off the MacKenzie River delta, and along the Gulf coast of Mexico. In addition, virtually all major coastal cities discharge oil to local waters.

A variety of marine mammals have been reported from the Gulf of Mexico. The one most familiar along the coast of Texas is the bottlenose dolphin which frequents passes and coastal bays. A total of 20 species of marine mammals have been sited at least once in the central and western Gulf, the areas of most intense oil activities. These included the endangered fin, humpback, right, sei, and sperm whales (Wursig, Chapter 4). The West Indian manatee occurs along the Gulf coast of Florida and has been sighted occasionally along the south Texas coast.

By comparison, 29 species of cetaceans and two species of seals have been recorded off the northeast coast of the United States and Canada, 26 in the Bering Sea, and 21, including the sea otter, in Lower Cook inlet, Shelikof Strait, and the northern Gulf of Alaska (McLaren, Chapter 2; Wursig, Chapter 4). Coastal waters off California also support a rich fauna which includes 29 species of cetaceans, 5 of pinnipeds, and the sea otter.

Based on these distributions, the most likely locations of the most frequent encounters between marine mammals and potential oil spills are along the California coast, in the Gulf of Alaska, and on the Grand Banks of eastern Canada. If substantial development of offshore oil resources continues in the Beaufort Sea and tankers are used to transport the oil south, or if commercial reservoirs of oil are found and developed in the Bering Sea, then the northern Bering Sea could also become a major area of interaction between oil and marine animals.

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CHAPTER 2

PINNIPEDS AND OIL:
ECOLOGIC PERSPECTIVES

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Introduction

Pinnipeds share many characteristics with other marine mammals, and indeed with large mammals in general, especially in demographic features (Fowler and Smith 1981), energetics (Lavigne *et al.* 1986) and social behavior (Eisenberg and Kleiman 1983). This allows us to draw on a wide range of empirical and theoretical literature to assess possible responses of pinnipeds to an environmental impact. Their amphibious nature poses special circumstances under which they face such threats.

The familiar fusiform bodies, with limbs modified as flippers, clearly reflect the pinniped's aquatic mode of life. They evolved from advanced terrestrial carnivores, related to the canid-ursid-mustelid line, perhaps from a common ancestral species. They are sufficiently coherent in most characteristics to be treated as a taxon. An excellent general account is by King (1983).

The three major kinds of pinnipeds are the hair seals (family Phocidae), the otariid seals (fur seals and sea lions; family Otariidae) and the walrus (family Odobenidae). Although intermediate in some respects, the walrus more closely resembles otariids in certain important ways. A prominent distinguishing feature of hair seals is their inability to rotate the hindflipper forward - theirs are fixed as "sculling" organs, while those of otariids and walruses can be turned forward in a more-or-less plantigrade position. The otariids and odobenids are accordingly more mobile on rough substrates. Although hair seals can "slither" quite rapidly on sand, smooth rock or, especially, ice, they must "hump" awkwardly over obstructions. When swimming, otariids use their large, propulsive foreflippers, placed close to mid-body, while hair seals and walruses rely on their hindflippers, using the foreflippers for steering. Hair seals, walruses and sea lions have short hair coats, especially sparse in the walrus. They are protected from excessive heat loss in part by a thick layer of blubber. Fur seals, have a particularly dense underfur to trap air for insulation. Both blubber and thick fur are disadvantageous at high temperatures; with a few notable exceptions, pinnipeds are found in temperate-to-polar regions.

There is general agreement that there are 34 living species of pinnipeds. The North American species are grouped in taxonomic categories on Table 2.1, which includes broad information on ranges and population status. Clearly, except for the Guadalupe fur seal, none is either very rare or excessively localized.

Distribution: Geographic distribution is a primary determinant of the probability of encounter with oil. In coastal and shelf waters of North America, pinnipeds occur from Mexico in the Pacific, up along the west coast through the Arctic Ocean and south to New England. At present only relatively small fractions of their ranges are at present leased or proposed for hydrocarbon exploration or production. Yet, because oil transport, even via the Canadian Arctic, is pervasive, I map the distributions of pinnipeds

Table 2.1: Pinnipeds of North America, with estimates of populations within areas of interest.

SPECIES	BREEDING RANGE	POPULATION[1]	STATUS[2]	SOURCES[3]
Family Odobenidae				
Walrus	E. Canadian Arctic	25,000?	s?	Davis et al. (1980)
	Bering-Chukchi Seas	160,000	s?	Estes and Gol'tsev (1984)
Family Otariidae				
Steller Sea Lion	California	7,000	-	Mate and Gentry (1979)
	Oregon and Washington	3,000	s?	Everitt and Beach (1982)
	British Columbia	5,000 (p)	s?	Obee (1984)
	Gulf of Alaska	103,000	s?	Loughlin et al. (1984)
	Aleutians, Bering Sea	93,000	-	Loughlin et al. (1984)
California Sea Lion	California	62,000+	+	Le Boeuf et al. (1983) Bonnell and Ford (1987)
	Mexico	83,000	+	Le Boeuf et al. (1983)
Guadalupe Fur Seal Mexico		1,000+	+	Fleischer (1978)
Northern Fur Seal	Pribilof Islands	1,300,000	-	Lander (1981)
	San Miguel Is., Ca.	7,000 (p)	+	Cooper & Stewart (1982)

Table 2.1 cont'd.

SPECIES	BREEDING RANGE	POPULATION[1]	STATUS[2]	SOURCES[3]
Family Phocidae				
N. Elephant Seal	California, Mexico	60,000+	+	LeBoeuf (1981)
Bearded Seal	E. Canadian Arctic	100,000?	s?	McLaren (1958b)
	W. Canadian Arctic	3,000+	s?	Stirling et al. (1977)
	Bering-Chukchi Seas	300,000?	s?	Burns (1981a)
Hooded Seal	E. Canada, Davis Str.	366,000 (p)	+	Bowen et al. (1987)
Ringed Seal	E. Canadian Arctic	1,000,000?	s?	McLaren (1958c)
	Beaufort-Chukchi Seas	40,000+	s?	Frost and Lowry (1984) Stirling et al. (1977)
	Bering Sea	1,250,000?	s?	Lowry and Frost (1981)
Spotted Seal	Bering-Chukchi Seas	225,000?	s?	Lowry and Frost (1981)
Harbor Seal	New England	10,000+	+	Payne and Schneider (1984)
	E. Canada	13,000+	+?	Boulva and McLaren (1979)
	Labrabor	?	?	Mansfield and Sergeant (1960)
	E. Canadian Arctic	100s?	-?	Mansfield (1967)
	S. Alaska	67,0000+	s?	Everitt and Braham (1980) Calkins and Pitcher (1977)

Table 2.1 cont'd.

SPECIES	BREEDING RANGE	POPULATION[1]	STATUS[2]	SOURCES[3]
Harbor Seal cont'd.	Aleutians	?	?	Burns and Gol'tsev (1984)
	British Columbia	35,000?	s?	Bigg (1969)
	Washington	8,000+	+?	Washington State Dept. Game (1980)
	Oregon	3,000+	s?	Everitt and Beach (1982)
	California	X,000+	s?	Stewart (1980)
Harp Seal	Eastern Canada	2,250,000 (p)	+	Roff and Bowen (1983, 1986)
Ribbon Seal	Bering-Chukchi Seas	100,000?	s?	Burns (1971)
Gray Seal	E. Canada	70,000	+	Zwanenburg et al. (198)

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[1] A lack of symbol indicates that the estimate is a mean based on actual counts with attempts at statistical analysis, etc.; + indicates that such mean estimates were believed by the source to be minimal; ? after a number indicates that the estimate is considered by the source to be highly approximate, or is not based on stated sampling procedures or statistical analyses; a ? without number indicates that no estimates have been found, although some information on the population is given in the source publications; (p) indicates that the estimate is based on counts of young, here multiplied by 4.5 as estimates of total populations.

[2] The symbol s indicates that the source publications imply that the population is thought to be more or less stationary; + indicates that the population is thought to be increasing, and - that it is decreasing; ? indicates that uncertainty is expressed about status.

[3] The source populations are generally the latest original references to population size and status. Secondary sources are used where original estimates are qualified or where the primary sources are relatively inaccessible.

4. Probably largely non-breeding migrants from Atlantic Canada.

throughout North American waters, with emphasis on areas within the U.S. Offshore Continental Shelf and regions of present or future hydrocarbon transport (Figures 2.1-2.18).

Life Histories

General Patterns: There is a common pattern to the annual cycles and habitat use of pinnipeds; they spend much of their lives at sea, but occupy land or ice to reproduce and often to molt (Table 2.2, Figure 2.19). The timing and duration of haul-out behavior varies considerably. In species like the walrus, birth, mating and molting are spread out in various segments of the population for more than half the year (Figure 2.19). Some species are almost never "hauled out", while others spend much time ashore between feeding forays at all times of year.

A solid substrate is vital for the nurturing of young, except for pups of harbor seals (Lawson and Renouf 1987), and perhaps the walrus (Fay 1982) and the bearded seal (Burns 1978), which are able to enter water soon after birth. Many species are selective in their choice of substrate, and for that reason, entire life histories feature seasonally synchronous reproductive activities at well-established sites. This may involve long-distance homing from feeding grounds to massive breeding colonies, much in the manner of seabirds, and with the same amplified risks of exposure to pollutants. Added to this is the likelihood that some individuals with strong site fidelity, may refuse to abandon an area that has been impacted.

Birth and Care of Young: There is a dichotomy between maternal behavior of phocids, and that of otariids and walruses (Oftedal *et al.* 1987). Attendance of young hair seals may be punctuated by brief departures of females, or continuous during lactation periods that range from 4 days (Bowen *et al.* 1985) to about a month. Walruses attend their young more-or-less continuously for much longer periods, while female sea lions and fur seals undertake lengthy feeding trips between suckling bouts (Gentry and Kooyman 1986).

Growth and Maturation: Growth rates and body sizes of pinnipeds (Table 2.3) are presumably adapted to environmental circumstances, but no obvious biogeographical rules are evident. For example, the huge walrus and the much smaller ringed seal occur together in polar waters; the even larger elephant seal is found in subtropical Mexico, and the small harbor seal ranges without obvious differences in body size from the high Arctic to Baja California. As a rule, females double their length, and therefore increase their core weight about 8-fold, between birth and full size (Table 2.2). The relative weights of fully grown animals, often inaccurately recorded in the literature, can also be approximated from the cubes of lengths given on Table 2.3. Rate of growth and final body size of males are probably driven by the advantages of large size for threat and combat during breeding. This sexual dimorphism is

Figure 2.1

Distribution of the gray seal in the western North Atlantic (after Mansfield and Beck 1977).

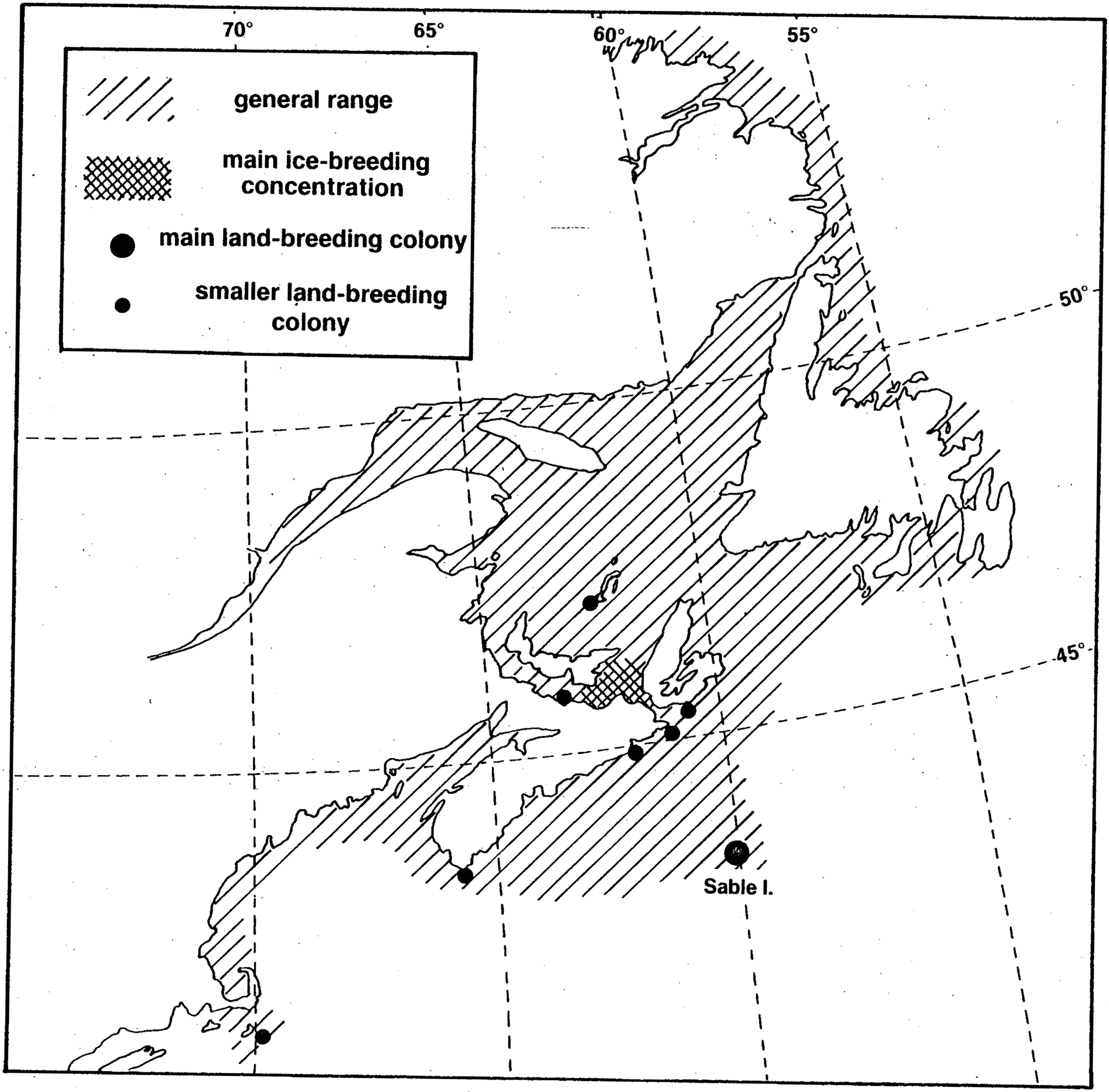

general range
main ice-breeding concentration
main land-breeding colony
smaller land-breeding colony
70°
65°
60°
55°
50°
45°
Sable I.

Figure 2.2

Distribution of the harbor seal in the western North Atlantic (after Mansfield 1967).

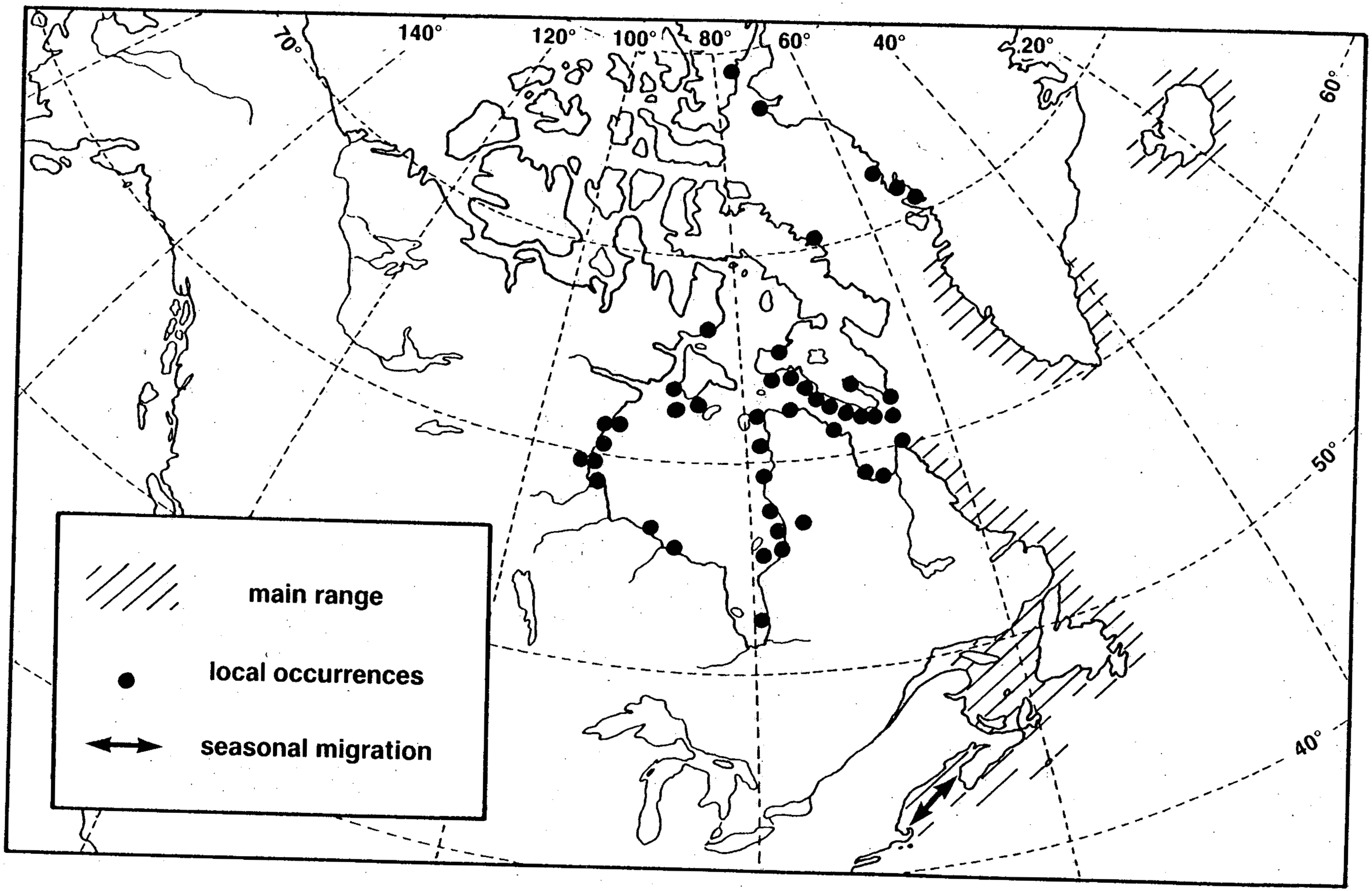

70°
140°
120°
100°
80°
60°
40°
20°
60°
50°
40°
main range
local occurrences
seasonal migration

Figure 2.3

Distribution of the harp seal (after Sergeant 1965, Davis *et al*. 1980).

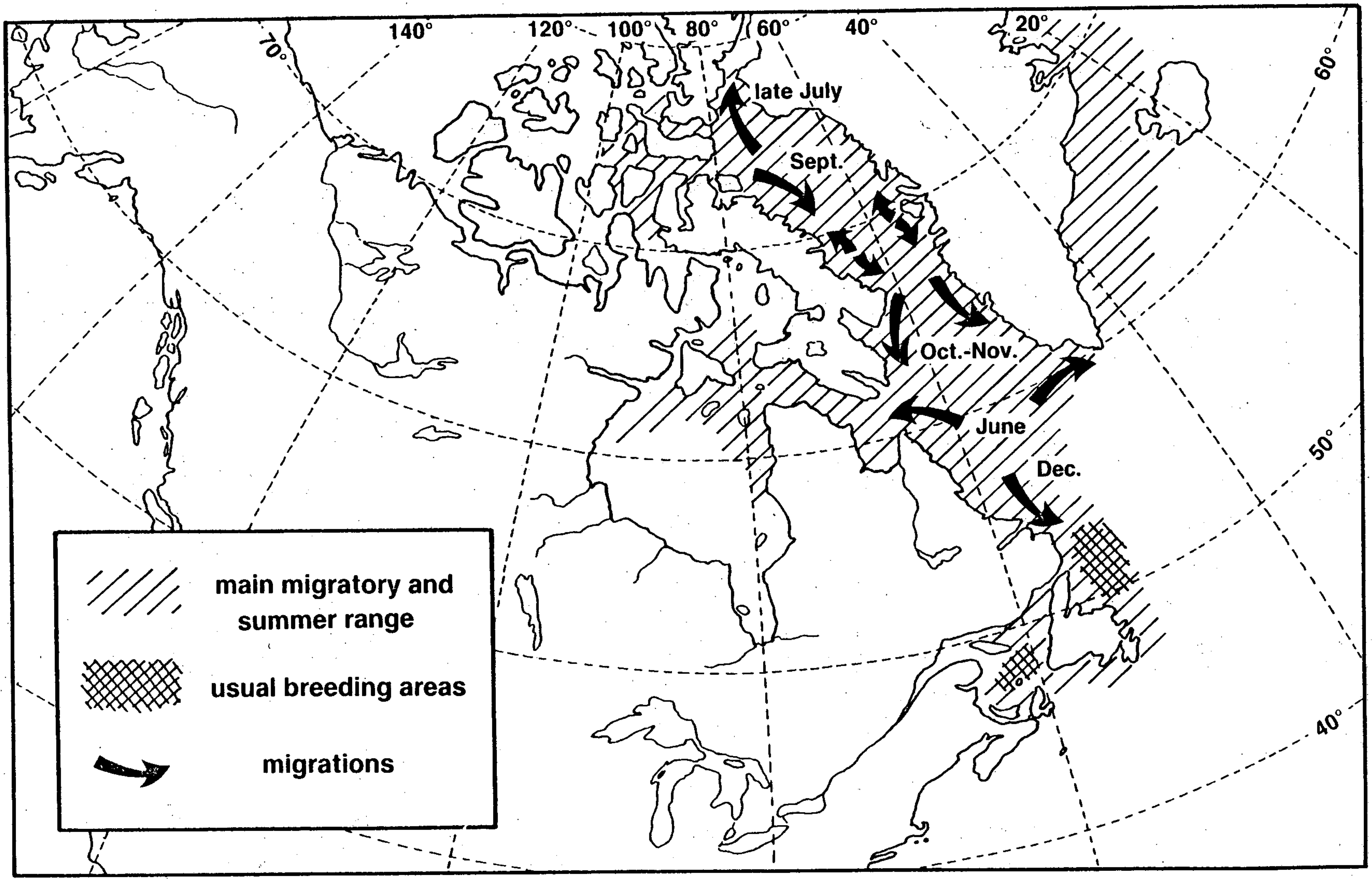

140°
120°
100°
80°
60°
40°
20°
70°
60°
50°
40°
late July
Sept.
Oct.-Nov.
June
Dec.
▨ main migratory and summer range
▩ usual breeding areas
migrations

Figure 2.4

Distribution of the hooded seal. Many extralimital records, as far as Alaska and Florida, have been omitted (after Davis *et al*. 1980, Reeves and Ling 1981).

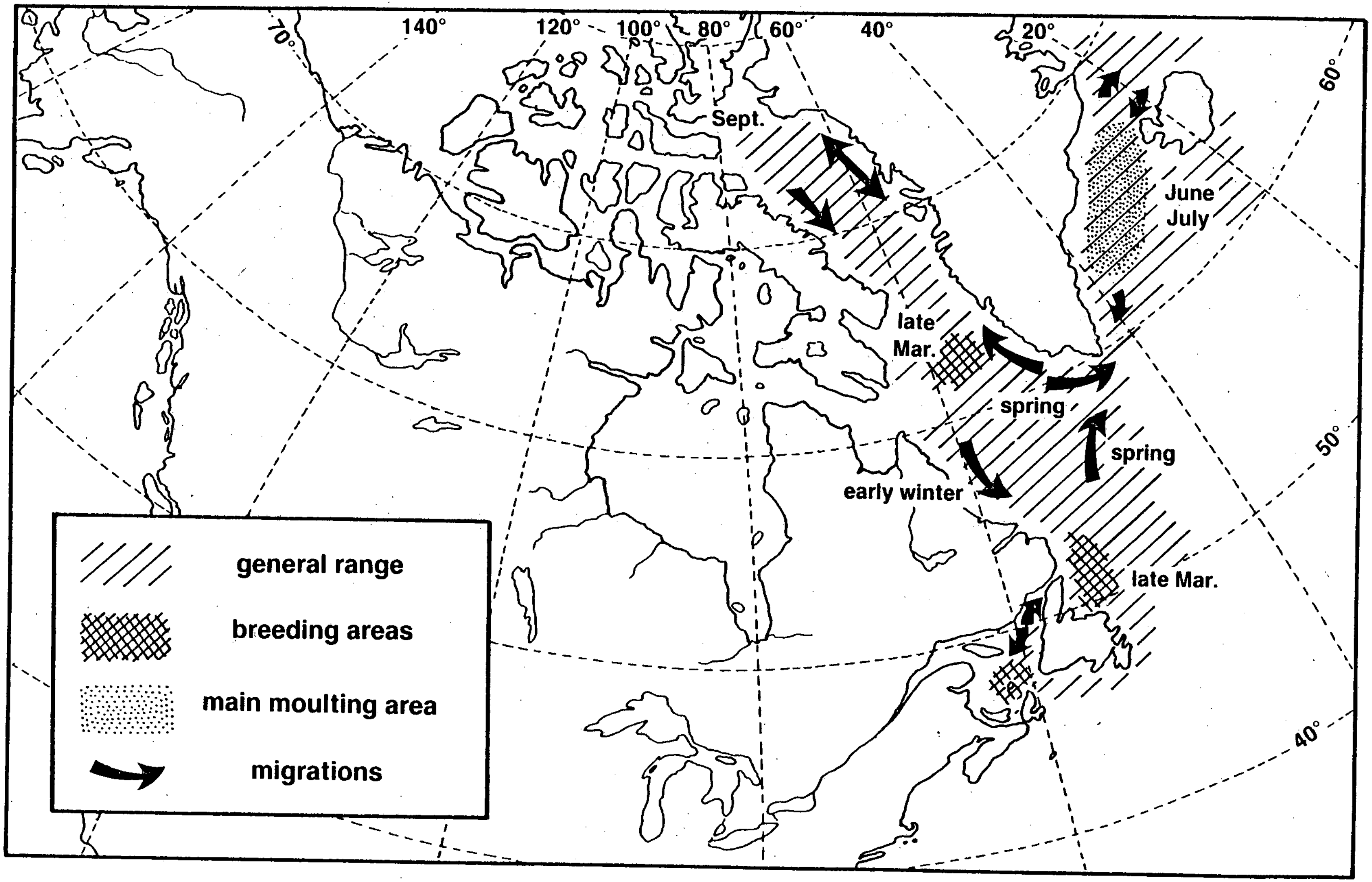

140°
120°
100°
80°
60°
40°
20°
70°
60°
50°
40°
Sept.
June
July
late
Mar.
spring
spring
early winter
late Mar.
general range
breeding areas
main moulting area
migrations

Figure 2.5

Distribution of the ringed seal in northern Canada (after McLaren 1958c, Smith 1975, Davis *et al.* 1980, Finley *et al.* 1983).

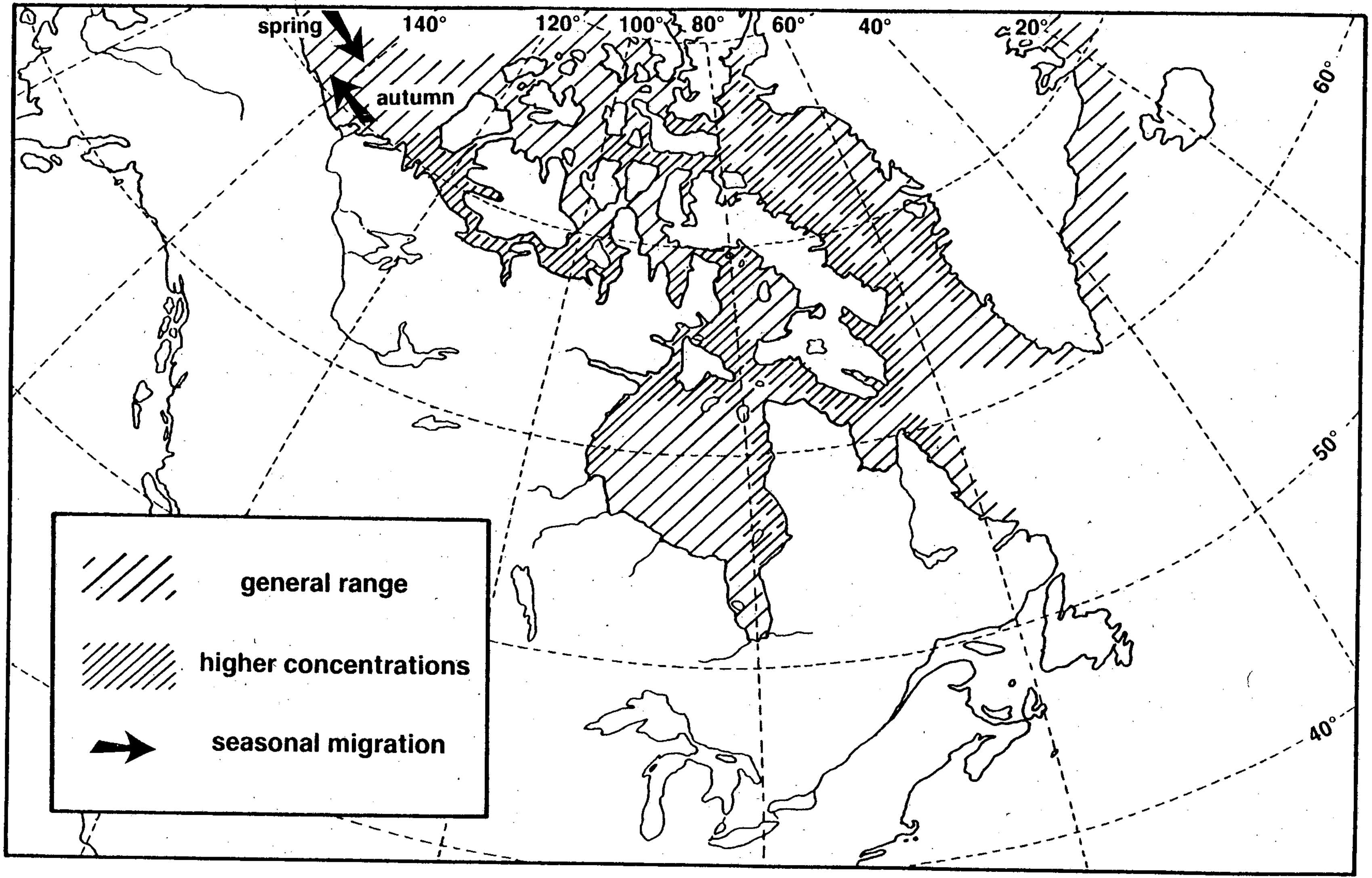

spring
autumn
140°
120°
100°
80°
60°
40°
20°
60°
50°
40°
general range
higher concentrations
seasonal migration

Figure 2.6

Distribution of the bearded seal in the Canadian Arctic (after Mansfield 1967a, Davis *et al.* 1980).

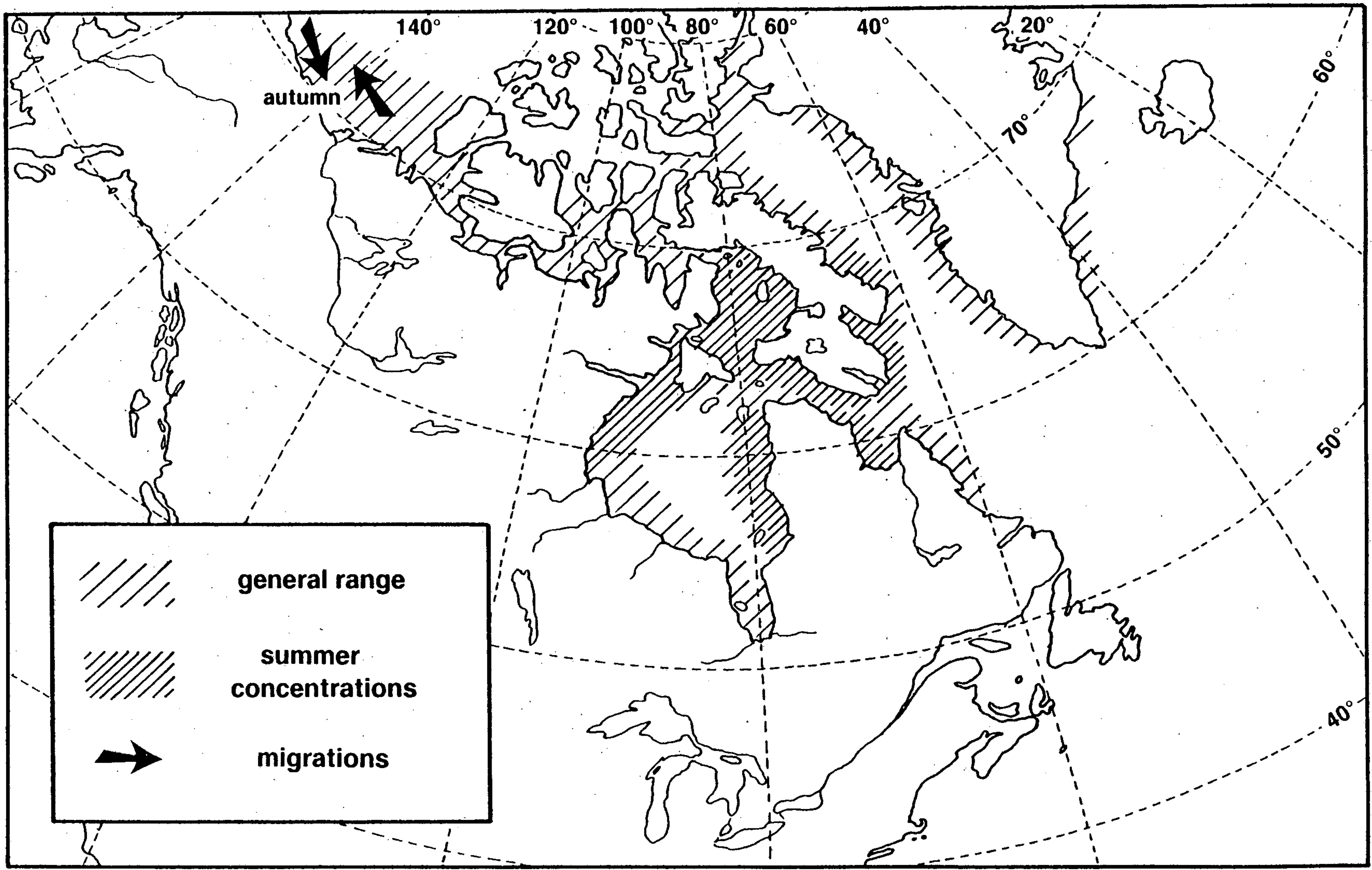
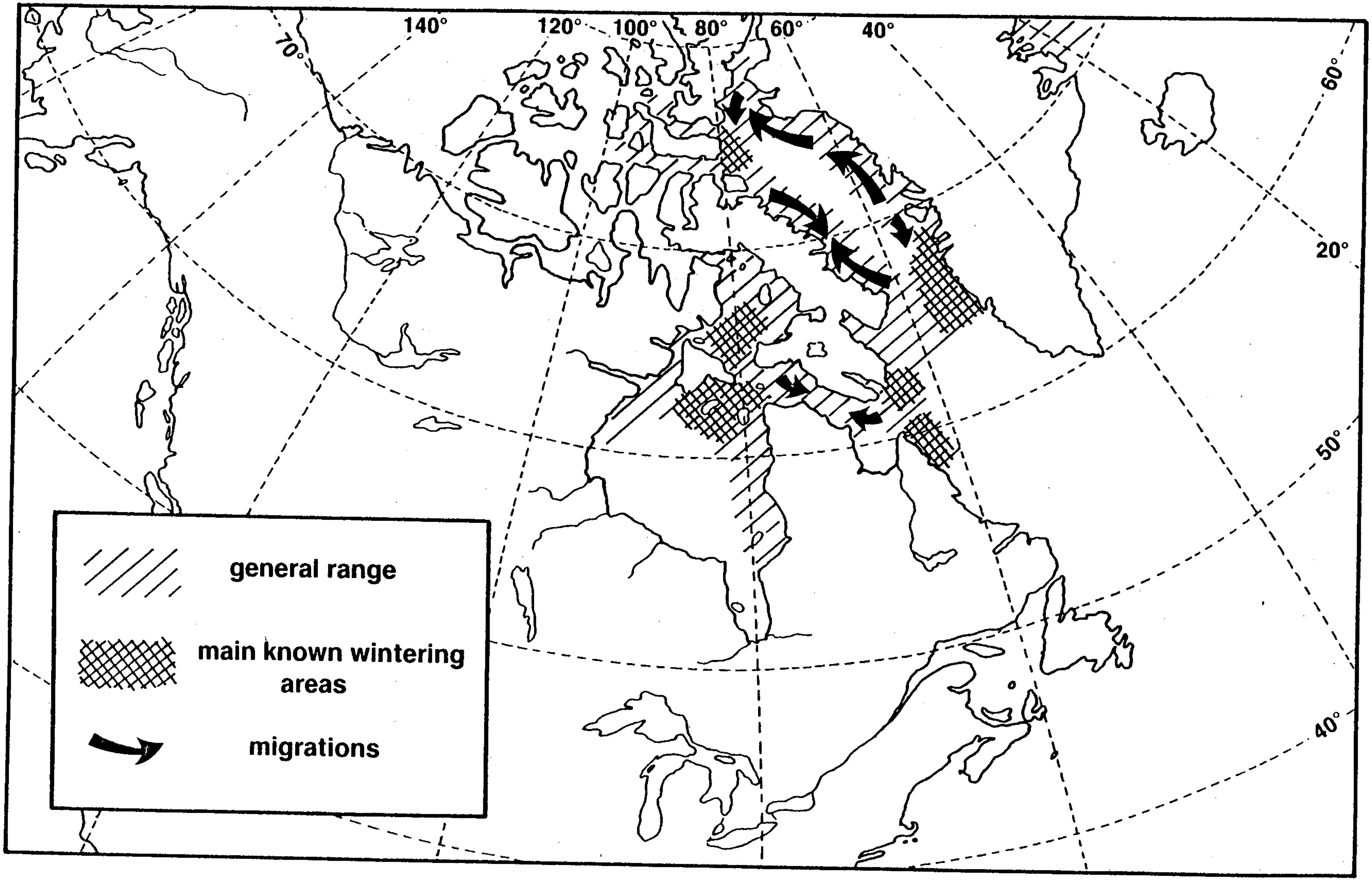

140°
120°
100°
80°
60°
40°
20°
70°
60°
50°
40°
autumn
general range
summer concentrations
migrations

Figure 2.7

Distribution of the Atlantic walrus (after Davis *et al.* 1980).



140°
120°
100°
80°
60°
40°
70°
60°
20°
50°
40°
general range
main known wintering areas
migrations

Figure 2.8

Distribution of the Pacific walrus in the Bering and Chukchi Seas (after Fay 1982, Frost *et al.* 1983).

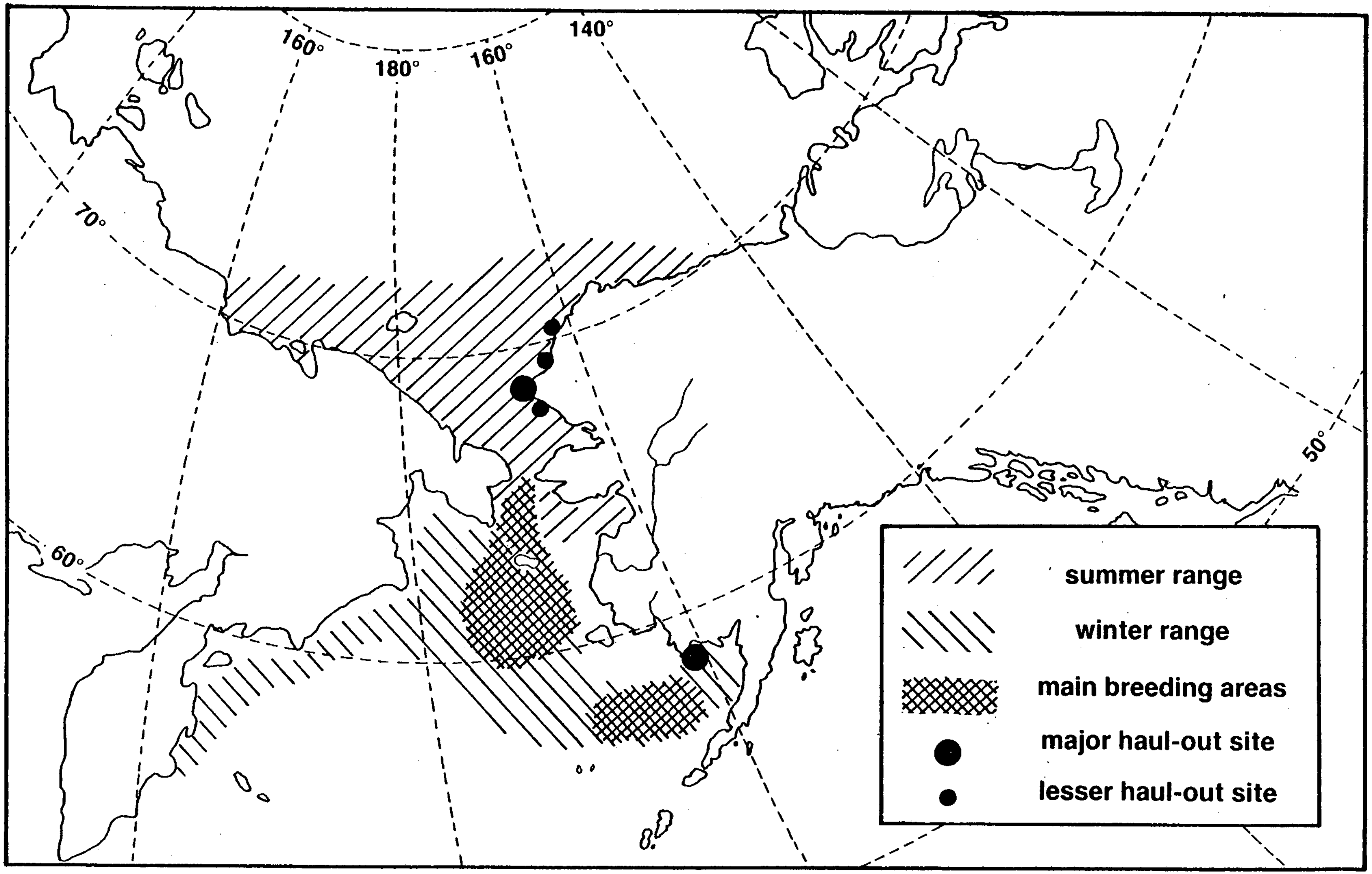

160°
180°
160°
140°
70°
60°
50°
summer range
winter range
main breeding areas
major haul-out site
lesser haul-out site

Figure 2.9

Distribution of the ribbon seal (after Burns 1981a, Braham *et al.* 1982, Frost *et al.* 1983).

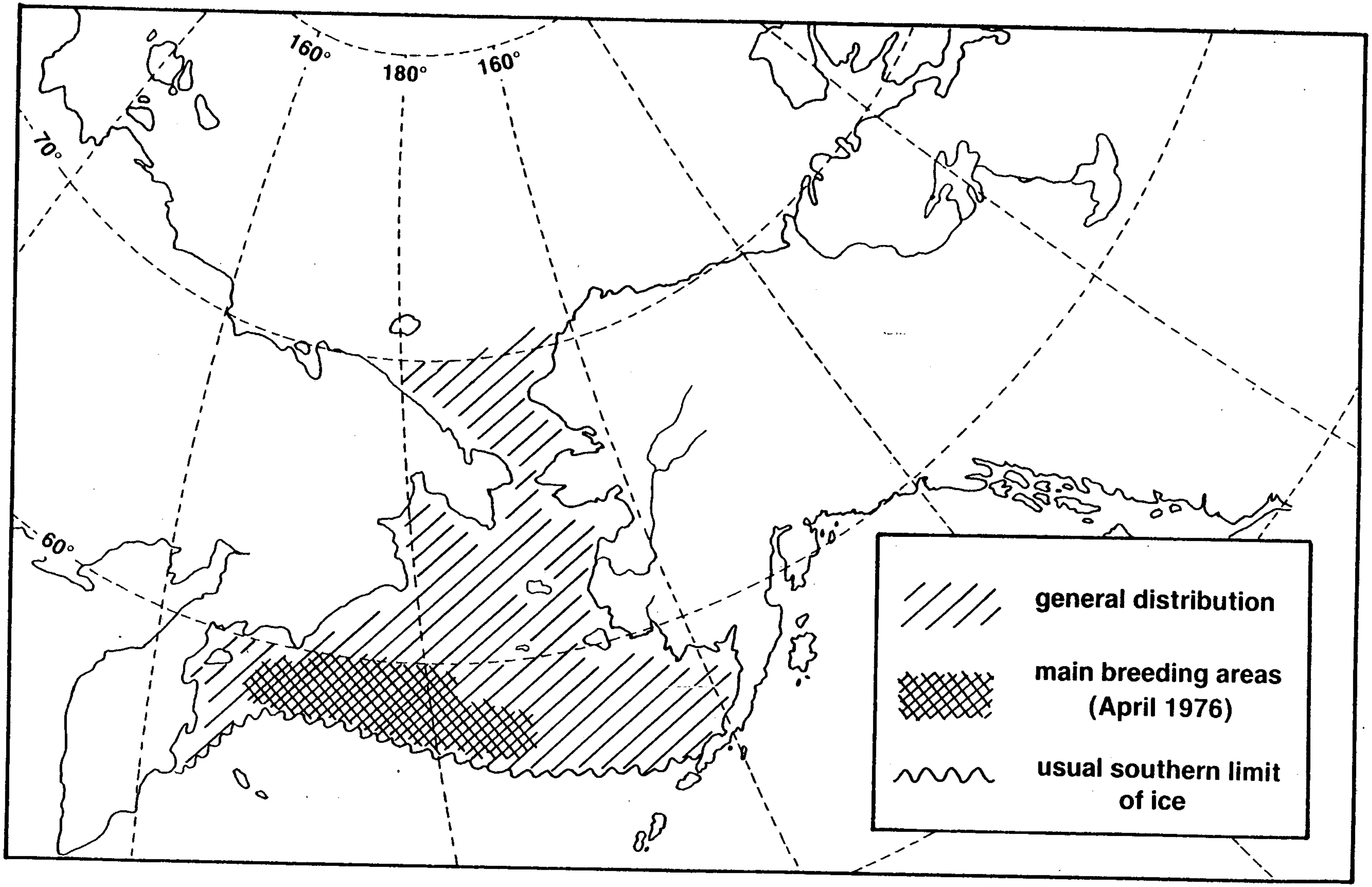

160°
180°
160°
70°
60°
general distribution
main breeding areas (April 1976)
usual southern limit of ice

Figure 2.10

Distribution of the ringed seal in the Bering, Beaufort and Chukchi Seas (after Burns 1978).

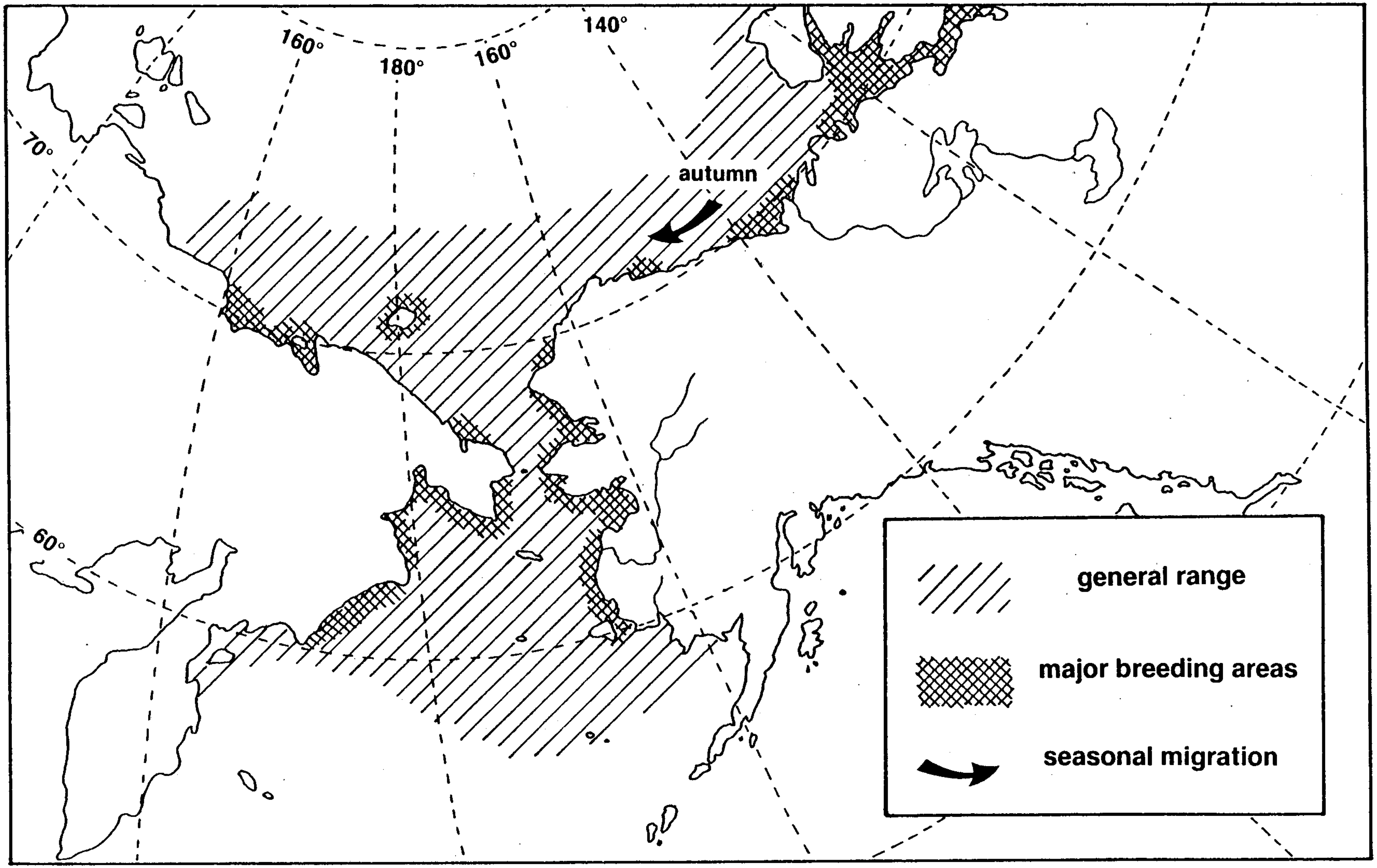

160°
180°
160°
140°
70°
60°
autumn
general range
major breeding areas
seasonal migration

Figure 2.11

Distribution of the bearded seal in the Bering, Chukchi and Beaufort Seas (after Burns 1978, Braham et al. 1982).

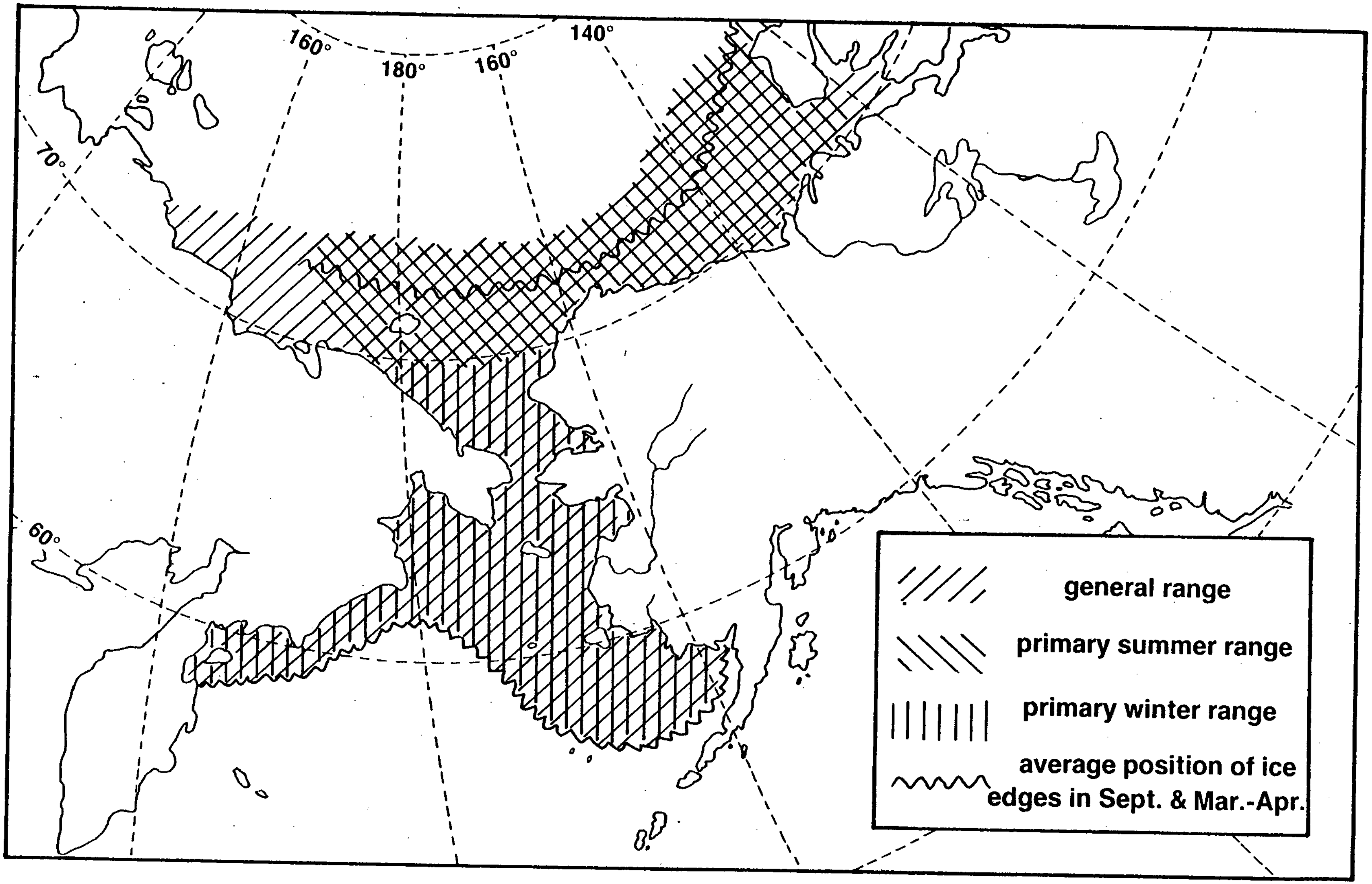

160°
180°
160°
140°
70°
60°
general range
primary summer range
primary winter range
average position of ice edges in Sept. & Mar.-Apr.

Figure 2.12

Distribution of the spotted seal (after Bigg 1981, Braham *et al*. 1982, Davis *et al*. 1984).

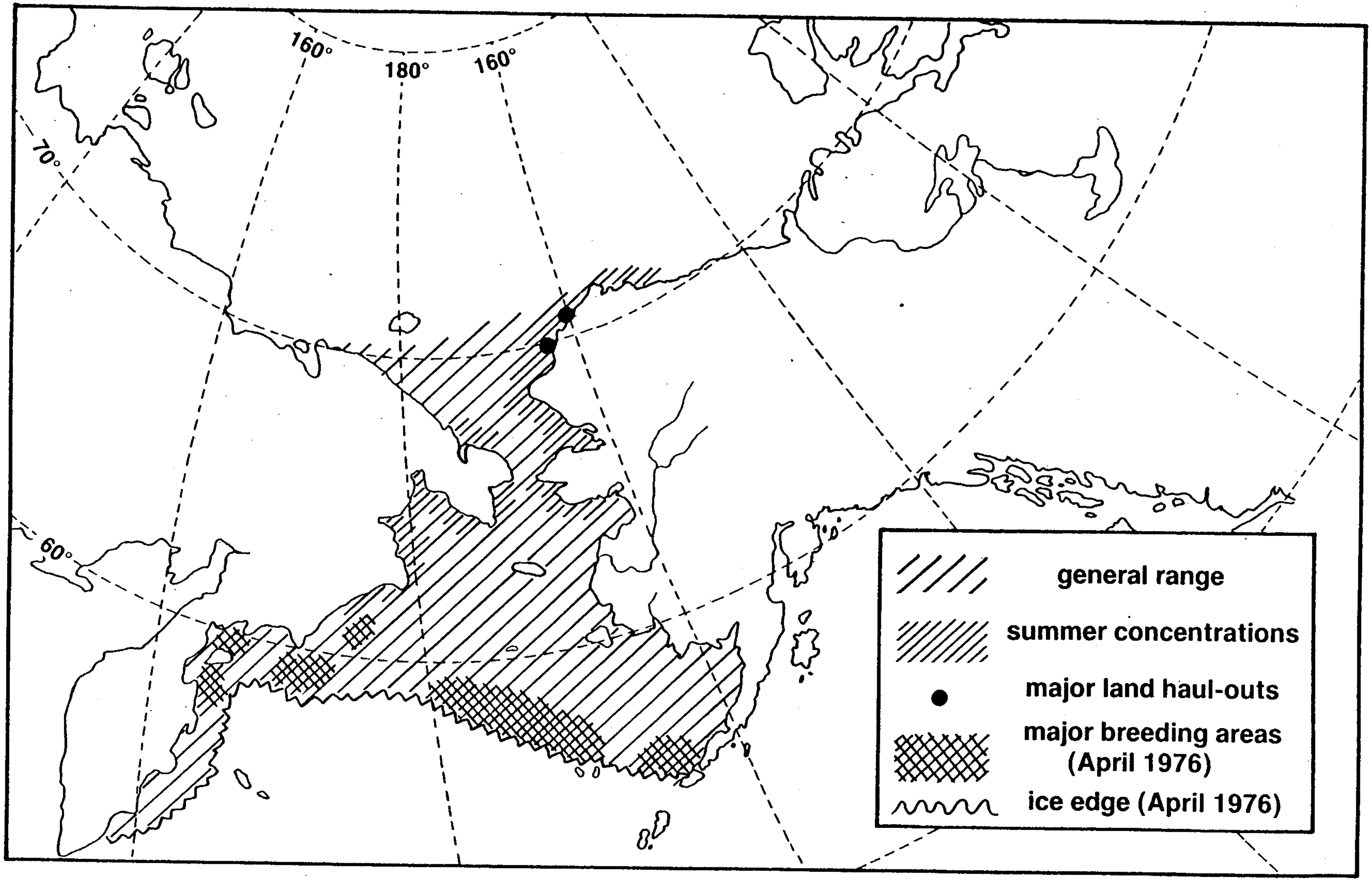

160°
180°
160°
70°
60°
general range
summer concentrations
major land haul-outs
major breeding areas (April 1976)
ice edge (April 1976)

Figure 2.13

Distribution of the northern fur seal (after Fiscus 1978, Braham *et al*. 1982).

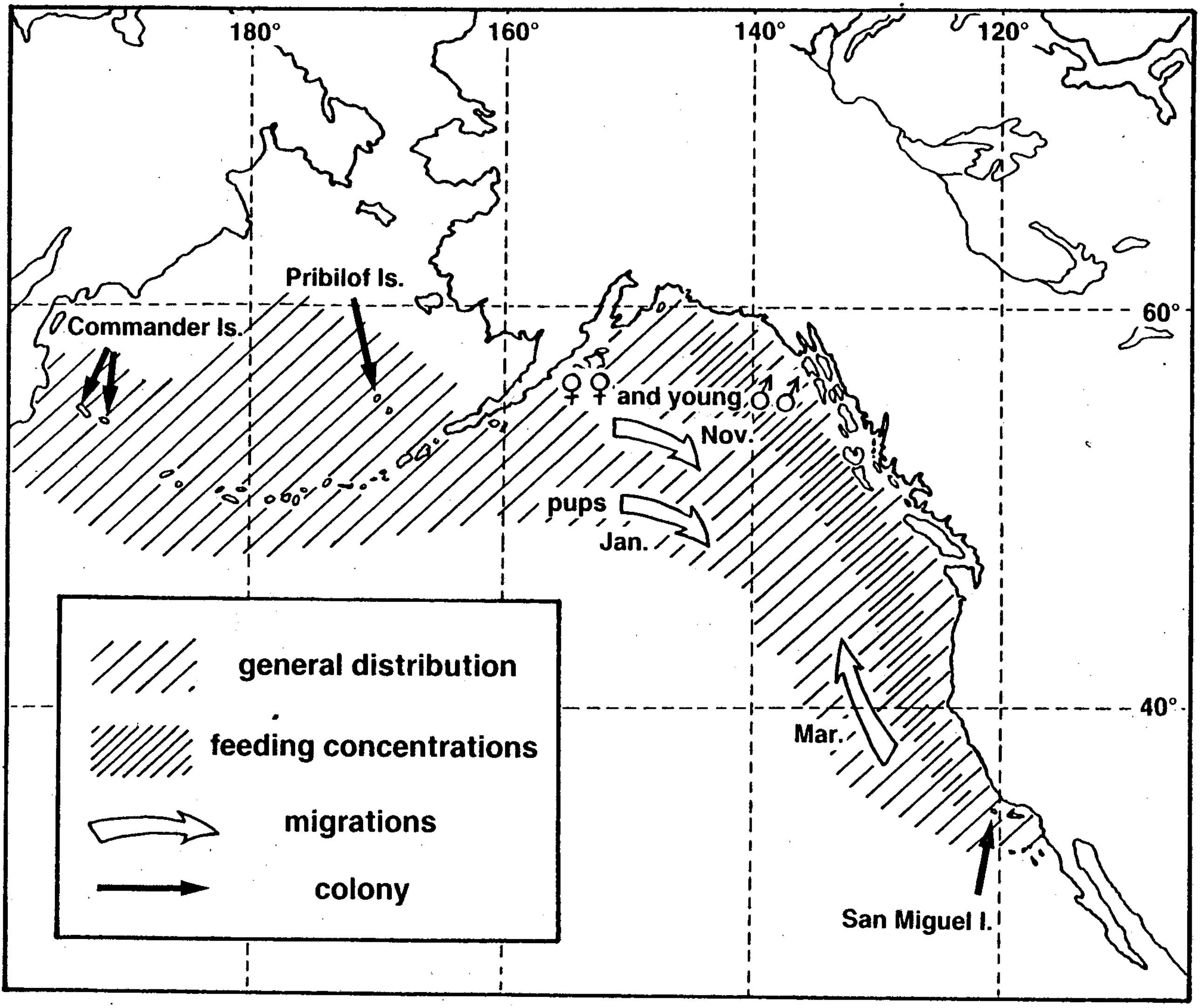

180°
160°
140°
120°
60°
40°
Pribilof Is.
Commander Is.
♀ ♀ and young ♂ ♂
Nov.
pups
Jan.
Mar.
San Miguel I.
general distribution
feeding concentrations
migrations
colony

Figure 2.14

Distribution of the harbor seal in the Pacific (after Bigg 1981, Burns and Gol'tsev 1984).

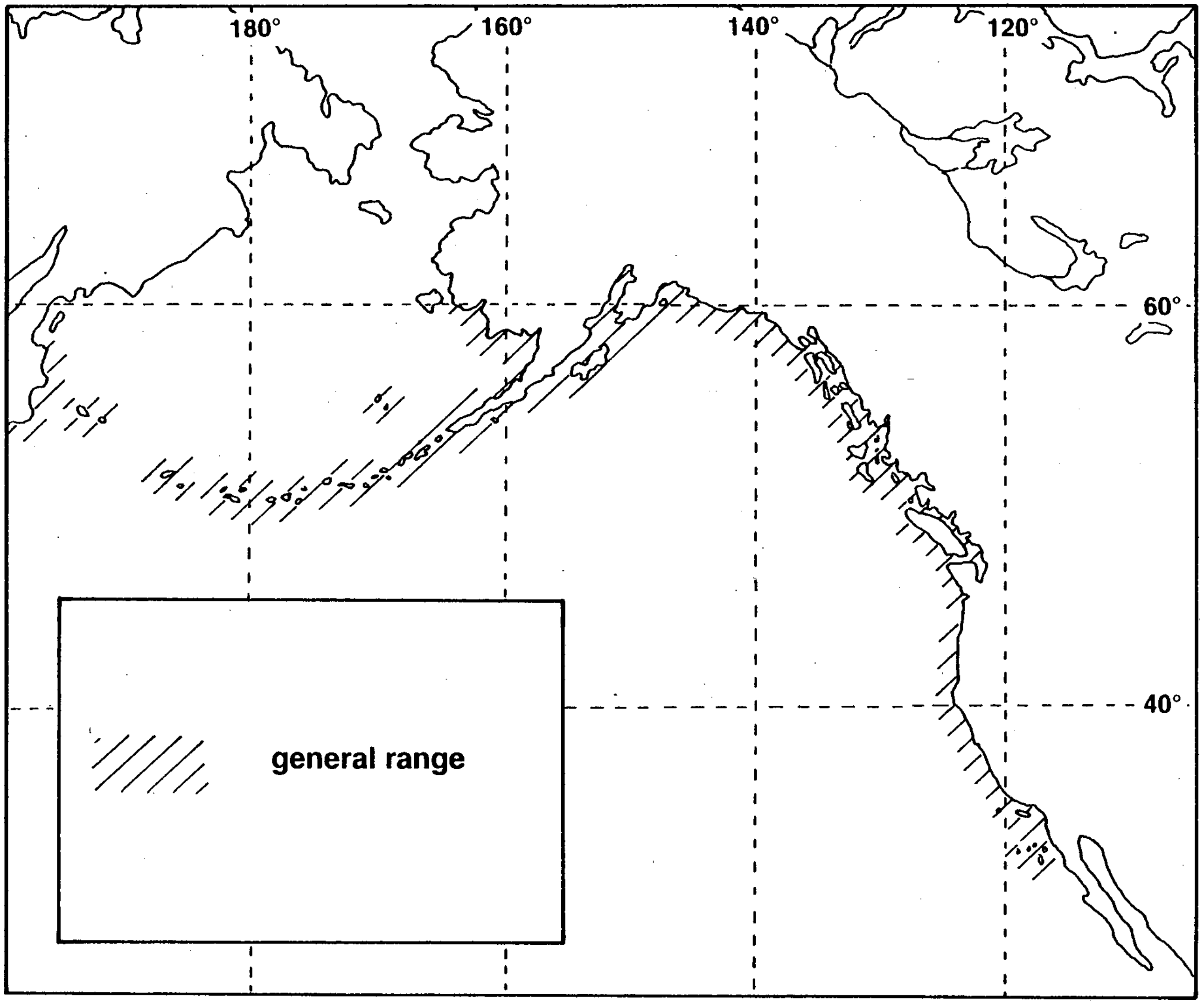

180°
160°
140°
120°
60°
40°
general range

Figure 2.15

Distribution of the Steller sea lion (after Shusterman 1981).

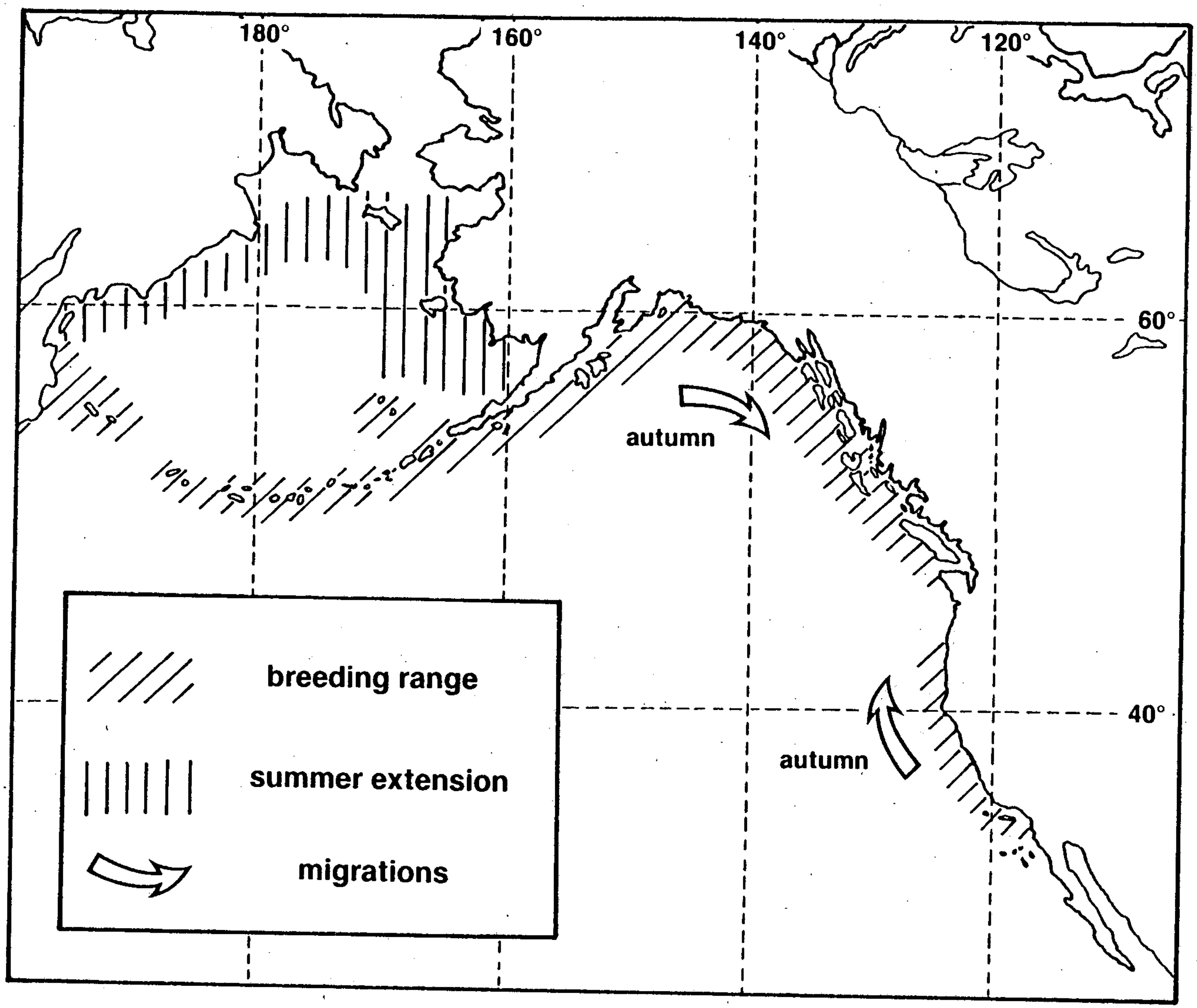

180°
160°
140°
120°
60°
40°
autumn
autumn
breeding range
summer extension
migrations

Figure 2.16

Distribution of the California sea lion (after Odell 1981, DeMaster *et al.* 1982, Le Boeuf *et al.* 1983).

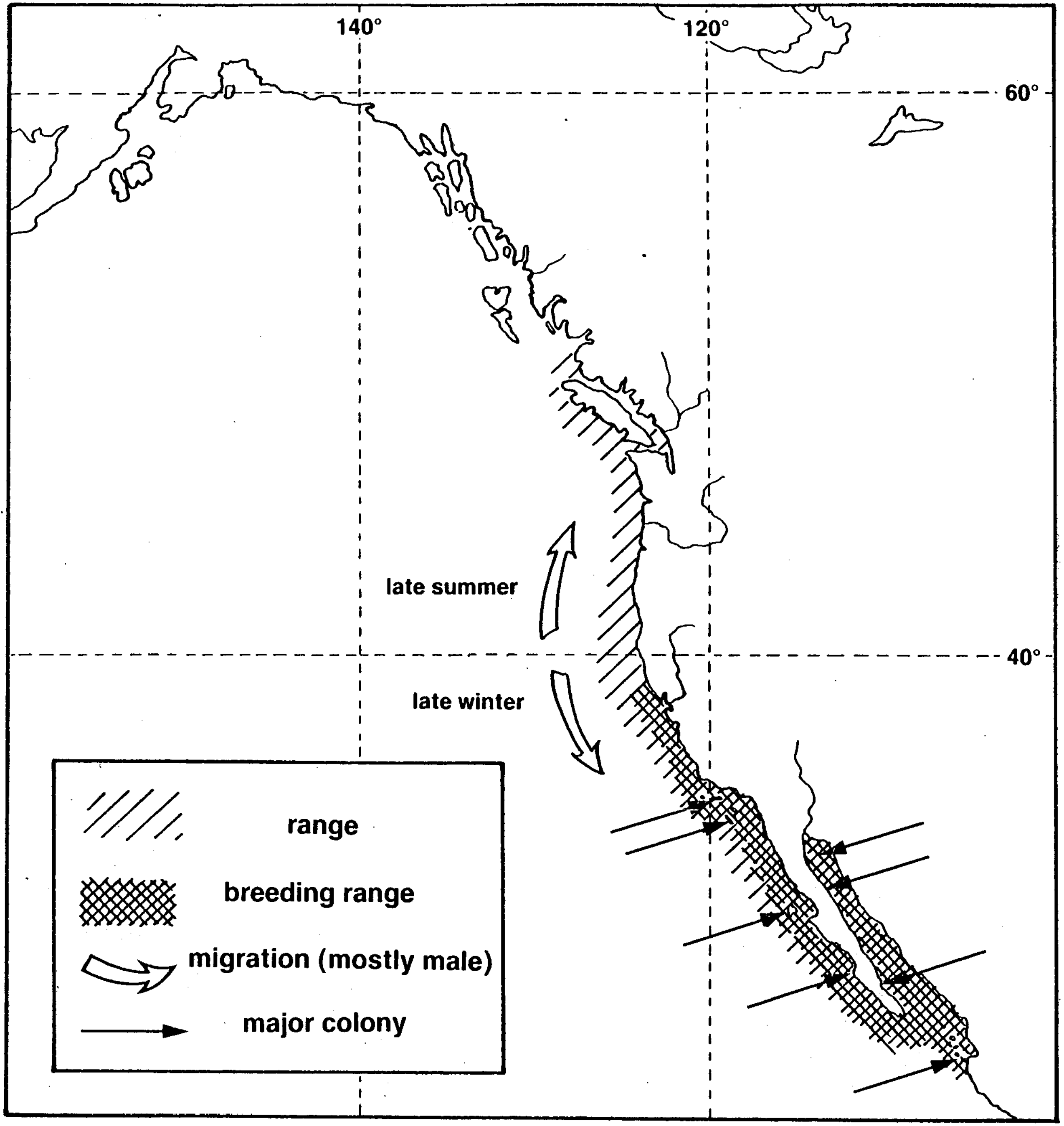

140°
120°
60°
40°
late summer
late winter
range
breeding range
migration (mostly male)
major colony

Figure 2.17

Distribution of the northern elephant seal (after DeLong 1978).

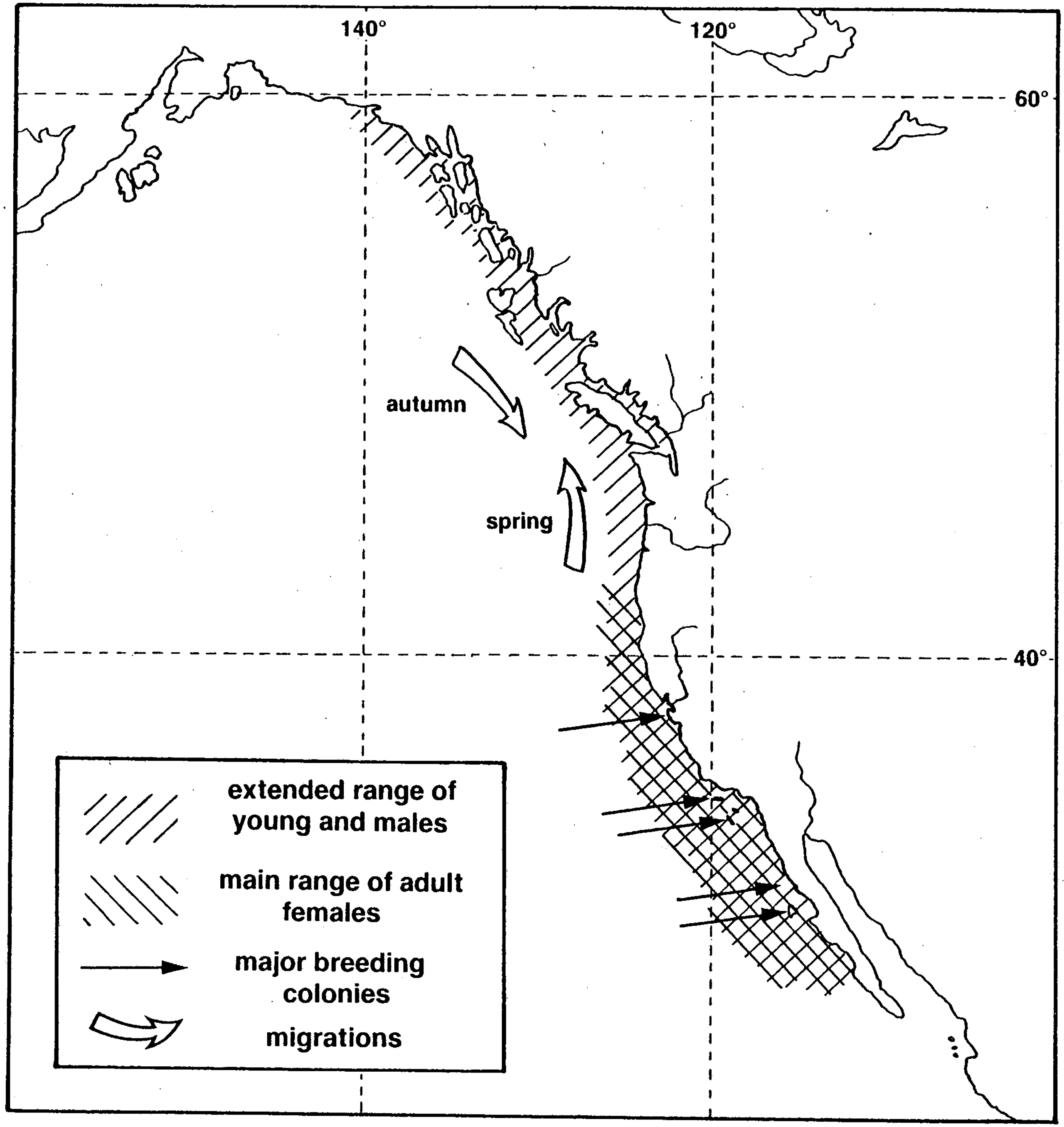

140°
120°
60°
40°
autumn
spring
extended range of young and males
main range of adult females
major breeding colonies
migrations

Figure 2.18

Distribution of the Guadalupe fur seal (after Fleischer 1978).

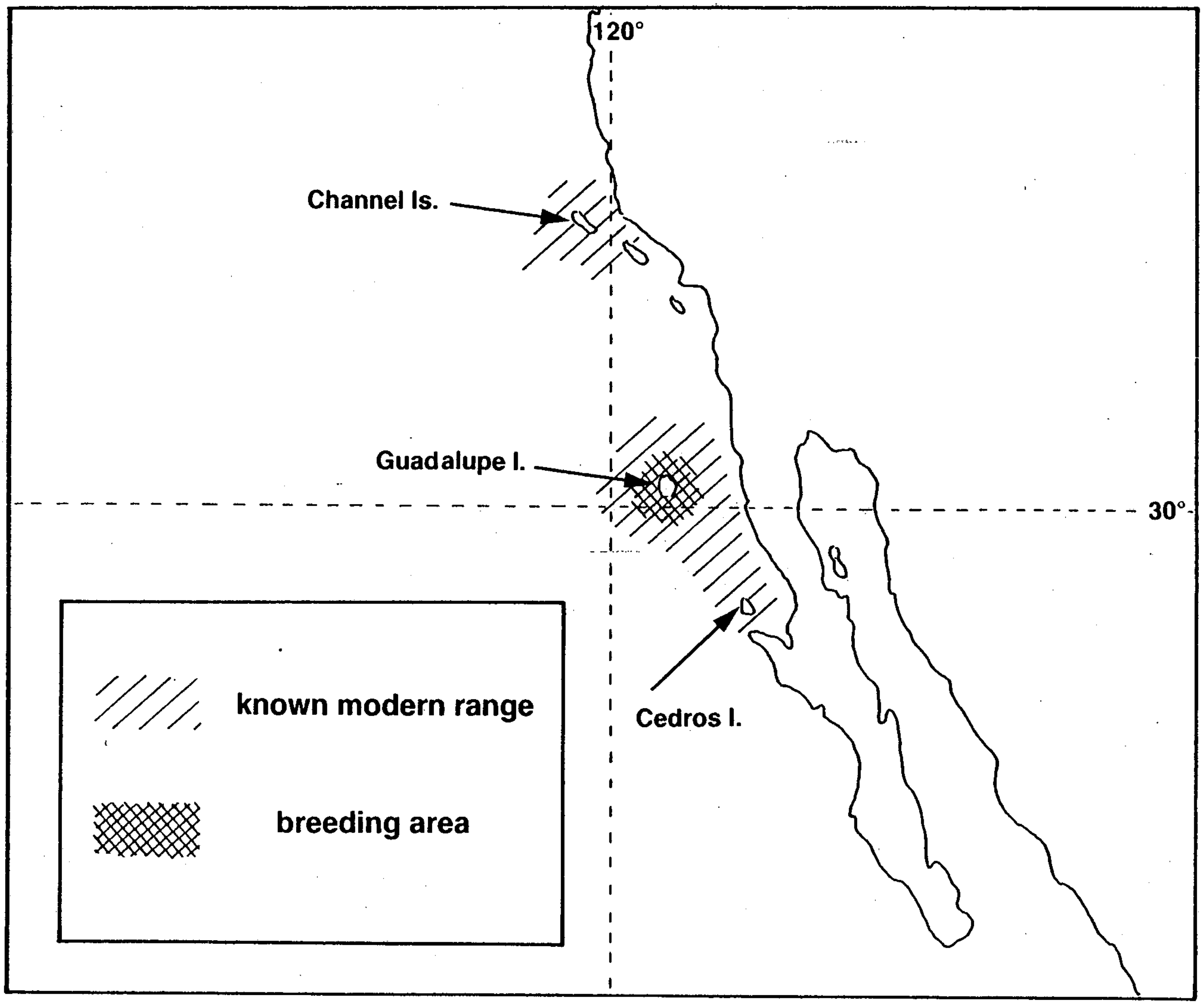

120°
Channel Is.
Guadalupe I.
30°
Cedros I.
known modern range
breeding area

Table 2.2: Broad patterns of habitat use by North American pinnipeds. From various routine accounts.

SPECIES	BREEDING HAULOUTS	MOLTING HAULOUTS	HAULOUTS AT OTHER TIMES	AQUATIC HABITATS-RANGES[1]
Walrus	pack ice	pack ice or land	pack ice or land	coastal <--> pelagic (shelf)
Steller Sea Lion	land	not needed?	land	coastal <--> pelagic
California Sea Lion	land	not needed?	land	coastal
Northern Fur Seal	land	not needed?	land, rarely	coastal --> pelagic
Guadelupe Fur Seal	land	not needed?	land	coastal
Northern Elephant Seal	land	land	land, uncommonly	coastal <--> pelagic
Bearded Seal	pack ice	pack ice	pack ice, if available	coastal <--> pelagic (shelf)
Hooded Seal	pack ice	pack ice	pack ice, if available	coastal <--> pelagic
Ringed Seal	fast & pack ice	fast & pack ice	pack ice, if available	coastal
Spotted Seal	pack ice	pack ice	pack ice and land	pelagic --> coastal
Harbor Seal	land	land	land	coastal
Harp Seal	pack ice	pack ice	pack ice, if available	coastal <--> pelagic
Ribbon Seal	pack ice	pack ice	pack ice, if available	pelagic
Gray Seal	pack ice, land	land	land	coastal <--> pelagic

[1] Migratory movements after reproduction indicated by directional arrows. Localized or short-term exchanges by double-ended arrows.

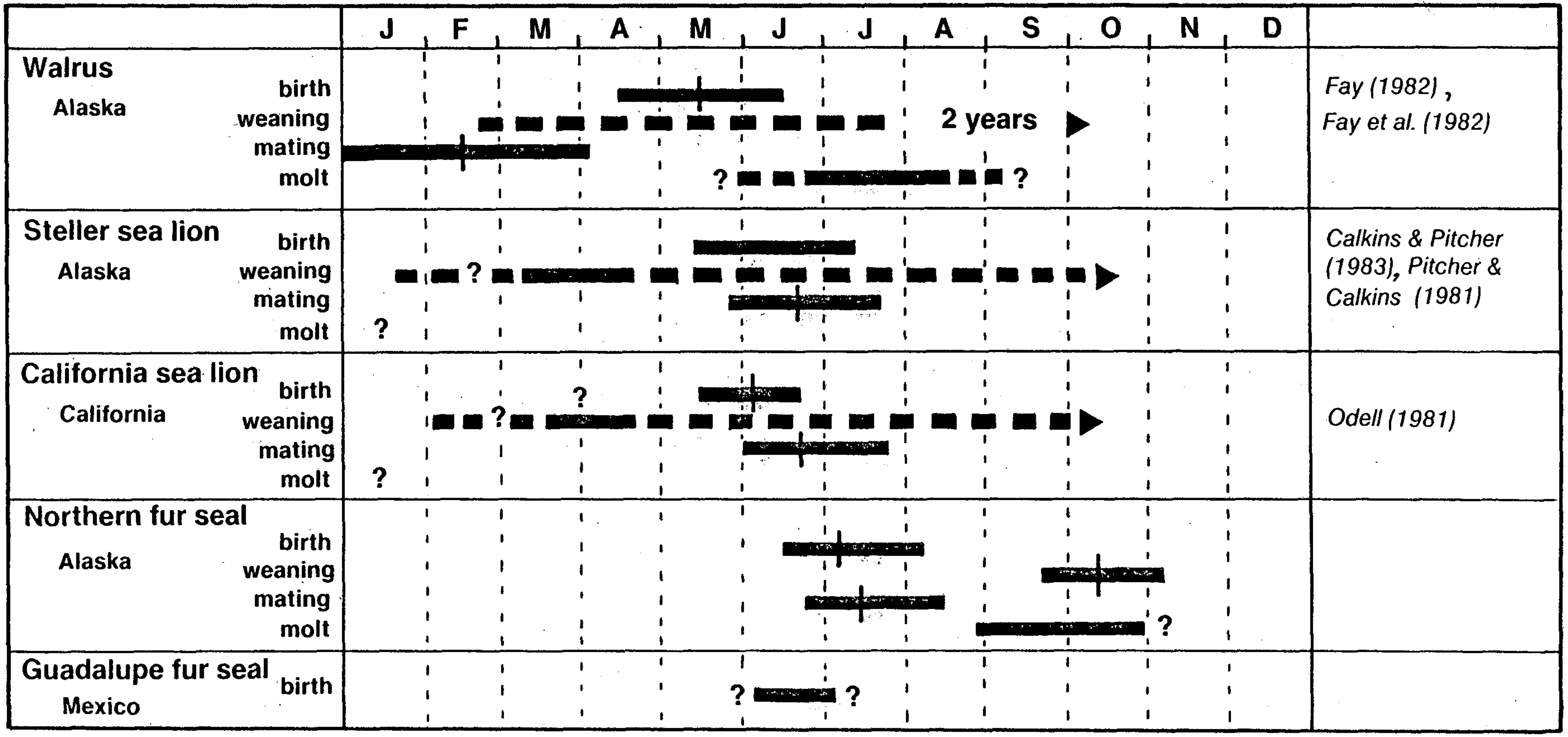


Figure 2.19: Life history tables for pinnipeds occurring in North American OCS waters.

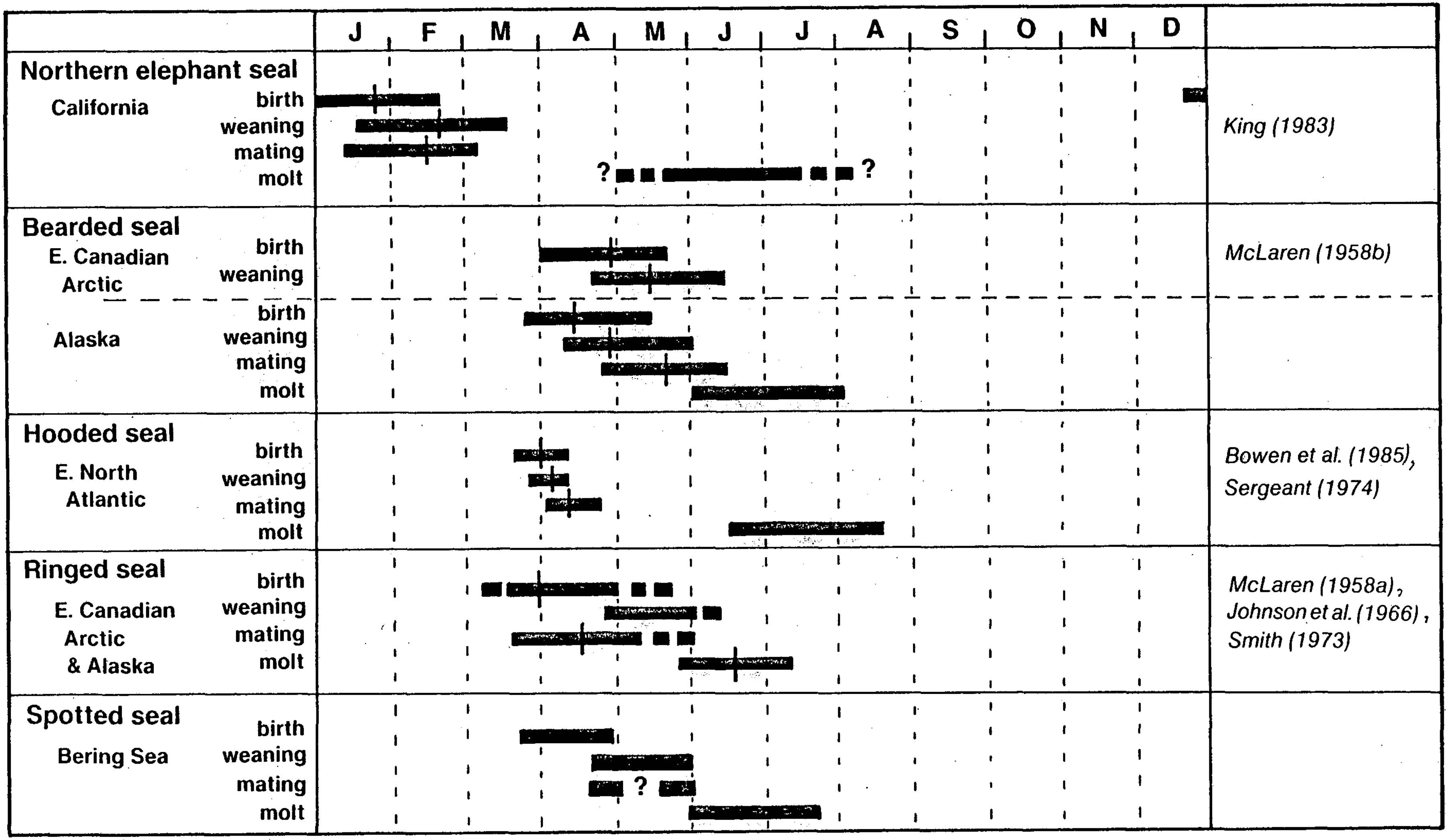


Figure 2.19 (cont'd.): Life history tables for pinnipeds occurring in North American OCS waters.

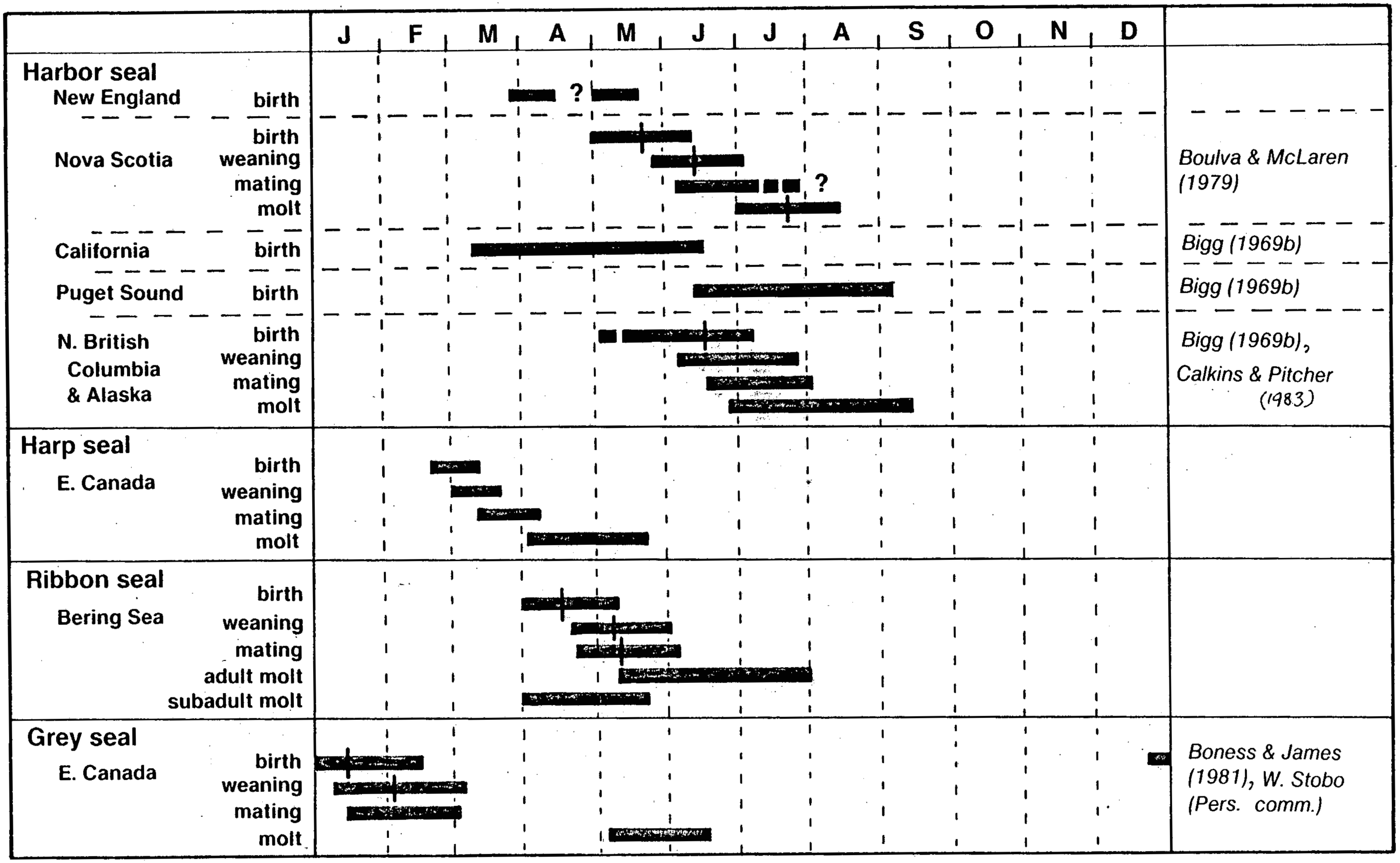


Figure 2.19 (cont'd.): Life history tables for pinnipeds occurring in North American OCS waters.

Table 2.3: Sizes of North American pinnipeds. Lengths measured in a variety of ways in some original sources have been converted to standard lengths and asymptotic (not maximum) lengths determined by fitted growth curves by McLaren (in preparation) using methods given by McLaren and Smith (1986). Those qualified by ca. are unreliable, usually largest rather than asymptotic lengths.

SPECIES	REGION	NEWBORN LENGTH	ASYMPTOTIC LENGTH MALE	ASYMPTOTIC LENGTH FEMALE	SOURCES
Walrus	Alaska	115	311	256	Fay (1982)
Steller Sea Lion	Alaska	106	331	241	Fiscus (1961), Calkins and Pitcher (1982)
Calif. Sea Lion	California, Mexico	73	ca.225	ca.180	Gilmartin et al. (1976), Lluch B. (1969b)
N. Fur Seal	E. North Pacific	63	190	129	McLaren and Smith (1985)
N. Elephant Seal	California	ca.150	ca.450	ca.360	Le Boeuf (1979)
Bearded Seal	Bering-Chukchi Seas	131	223	223	Burns and Frost (1979)
Hooded Seal	Greenland-E. Canada	93	197	229	Wiig (1985), Beloborodov and Potelev (1966)
Ringed Seal	Bering Sea	63	139	132	Fedoseev (1965)
	Chukchi Sea	61	121	117	Fedoseev (1965), Johnson et al. (1966)
	Beaufort Sea	71	127	131	Smith (1987)
	S. Baffin Island	68	121	122	McLaren (1958a)

Table 2.3 cont'd.

SPECIES	REGION	NEWBORN LENGTH	ASYMPTOTIC LENGTH MALE	ASYMPTOTIC LENGTH FEMALE	SOURCES
Spotted Seal	Bering-Okhotsk Seas	81	170	160	Tikhomirov (1968)
Harbor Seal	E. Canada	78	161	150	Boulva and McLaren (1979)
	British Columbia	82	170	156	Bigg (1969)
	S. Alaska	82	162	150	Pitcher (1977), Pitcher and Calkins (1983)
Harp Seal	E. Canada	85	165	165	Innes et al.(1981), Stewart and Lavigne (1980)
Ribbon Seal	Bering-Okhotsk Seas	81	156	156	Shustov and Yablokov (1967), Fedoseev (1973)
Gray Seal	E. Canada	108	202	228	Mansfield (1978)

pronounced among otariids and elephant seals, in which males may weigh 2.5-5 times as much as females, and less so in the gray seal, in which full-grown bulls weigh about 1.5 times as much. Males of highly polygynous species may be potent when quite young (Spotte and Schneider 1982), but have a sharp growth-spurt at puberty and mate effectively only after reaching much greater body size. Males of "monogamous" species are generally the same size as or even smaller than females, even those which defend underwater or under-ice breeding territories. The male hooded seal seems anomalous, weighing some 1.6 times as much as a female. Though it defends individual females on pack ice, it is not strictly monogamous; aggressive males may be capable of mating with several females sequentially.

Size differences among individuals and species could influence their response to an environmental impact. Large individuals with favorable surface-to-volume ratios might be more resilient. However, when large size is driven by sexual selection to the detriment of other components of fitness, some advantage might be lost. This is perhaps reflected in the reduced lifespans of large, polygynous species.

Diet and Feeding Tactics: Pinnipeds generally have broad opportunistic diets. The majority are piscivorous, but many also take feed on of cephalopods, planktonic crustaceans, and epibenthic organisms. Only the walrus and to a lesser extent the bearded seal feed primarily on burrowing bottom animals. Some North American pinnipeds consume seals or birds from time to time, though none is as voracious a top carnivore as the Antarctic leopard seal. Lowry and Fay (1984) document the remains of seals, mostly pups, in 8 of 645 stomachs of walruses from the Bering Strait and western Chukchi Sea. Steller sea lions sometimes prey on harbor seals (Pitcher and Fay 1982) and, perhaps regularly, on northern fur seal pups (Gentry and Johnson 1981). The literature on apparently casual predation on seabirds by pinnipeds is summarized by Lucas and McLaren (MS submitted).

In conclusion, significant amounts of hydrocarbons would probably not be consumed by pinnipeds in their food, since none of the prey is likely to accumulate residues. Exceptions are bearded seals and walruses foraging in heavily contaminated benthos and individuals of a number of species that might specialize in eating seals or birds (Lucas and McLaren, manuscript submitted), thereby consuming raw oil entrained in pelage or plumage. The probability of the latter would be enhanced if contamination rendered the prey more vulnerable to capture, as Lucas and McLaren observed with gray seals.

Habitat Use

Major Patterns of Distribution: The marine ranges of pinnipeds during the non-breeding season can be discussed in four somewhat overlapping categories: coastal versus pelagic, and ice-using (pagophilic) versus ice-shunning (pagophobic). Each category presents specific circumstances under which a species would encounter oil.

Some coastal species migrate regularly, others disperse somewhat offshore or alongshore during the non-breeding season, while still others remain in the vicinity of breeding sites. Most species that stay inshore through the year are generalized, even opportunistic, predators, and their distributions are probably more influenced by availability of suitable hauling-out sites than by food requirements. On a local scale, Boulva and McLaren (1979) found a strong correlation between abundance of harbor seals in Nova Scotia and the number of islets along the coastline. On a regional scale, the abundance and species richness of pinnpeds around such places as the southern California islands have much to do with their suitability for safe hauling out. Of course coastlines with many islands, islets and bars also pose greater risks of oil spills through marine accidents. Furthermore, the enclosed topographies of bays, estuaries and passages used by coastal pinnipeds can lead to oil concentrations.

Among coexisting coastal species, there are some indications of niche differences. Thus, on the West Coast, the two major coastal otariids are generalized, nocturnal feeders, but the Steller sea lion ranges further offshore than the California sea lion (Fiscus and Baines 1966), and the latter is seen increasingly in estuaries (Bayer 1981). The harbor seal is also a generalist in diet, seldom ranges seaward, and is not notably nocturnal. Elephant seals evidently feed more frequently in deeper water on larger and more bottom-dwelling fishes than do the other coexisting pinnipeds (McGinnis and Schusterman 1981). On the East Coast, the gray and harbor seals are piscivores, but the former ranges over the Scotian Shelf and central Gulf of St. Lawrence, while the latter is rarely seen far out at sea. The general trend among these examples is that the larger species range farther offshore.

Pelagic species by definition spend the non-breeding seasons in offshore waters where hauling out is possible only on ice. The distribution and movements of such species are more likely to be controlled by availability of food, in turn influenced by hydrography and submarine topography. For example, the northern fur seal is concentrated in winter along the outer continental shelf from British Columbia to California, where it feeds on schooling fishes and squids (Kajimura 1984). The ribbon seal evidently summers largely near the edge of the Bering Sea shelf (Burns 1981a). These distributions may be related to high productivity, and are generally remote from oil exploration activity or concentrated oil-shipment routes. The distributions of the two benthic feeders, walrus and bearded seal, are constrained within the continental shelves, but can range quite far offshore, especially in the Bering Sea.

Species that produce young on ice are accordingly limited in distribution, in spite of occasional anomalies such as the parturition of a hooded seal on land (Richardson 1975). Among North American species (Tables 2.2 and 2.4), only the ringed seal breeds on fast ice; it also uses pack ice (Finley *et al.* 1983). Post-reproductive hauling out by ice-using species is also variable (Tables 2.2 and 2.4). Some, like the hooded, bearded (with some exceptions (Burns 1981b)), ringed, and ribbon seals, haul out only on ice. They may follow and use retreating ice over long distances. Others reside in areas where the ice disappears seasonally. This independence of ice is

Table 2.4: Social organization of North American pinnipeds. These summaries are categorical, from a number of general sources and do not include many qualifications and exceptions.

SPECIES	BREEDING STRUCTURES	NON-BREEDING HAUL-OUTS	BEHAVIOR AT SEA
Walrus	Extensive mobile aquatic leks of displaying adult males attracting estrous females from pack ice.	On land, ice. Segregation of females, adult and sub-adult males.	Gregarious, groupings as in non-breeding haulouts.
Steller sea lion	Stable male territories on land before peak of arrival of gregarious females within them.	Often daily on land, gregarious, sexes and ages mixed.	Often gregarious, possible cooperative foraging.
California sea lion	Labile or stable male territories on land after peak arrival of gregarious females.	Often daily on land, gregarious, sexes and ages mixed.	Often gregarious, possible cooperative feeding.
Northern fur seal	Stable male territories on land before arrival of gregarious females. Some restraint by males.	Rare (pathological?)	Non-gregarious, casual associations.
Guadelupe fur seal	Females in male territories on land.	Gregarious on land. Daily(?)	(?)

Table 2.4 cont'd.

SPECIES	BREEDING STRUCTURES	NON-BREEDING HAUL-OUTS	BEHAVIOR AT SEA
Bearded seal	Solitary females and pups on ice. Females later attracted by "singing" males in under-ice territories(?) or leks(?).	Non-gregarious and opportunistic on ice.	Non-gregarious, casual associations.
Hooded seal	Scattered in extensive "patches" on pack ice.	Large "molting patches" on female guarded by sequentially polygymous male.	Non-gregarious, casual associations?
Ringed seal	Scattered females with pupping lairs in fast (sometimes pack) ice. Mating within under-ice male territories covering one or more lairs (?).	Non-gregarious during molt and casually later, on ice.	Non-gregarious, casual associations.
Spotted seal	Scattered females pup on pack ice. Female guarded by male on mating in water. Sequentially polygymous(?).	Non-gregarious (?) molt on ice? Casual groups on land.	Non-gregarious, casual associations.
Harbor seal	Scattered females pup on land, mating in underwater male territories (?) off shorelines.	Solitary or "vigilence groups" on rocks, etc.	Non-gregarious, casual associations.

Table 2.4 cont'd.

SPECIES	BREEDING STRUCTURES	NON-BREEDING HAUL-OUTS	BEHAVIOR AT SEA
Harp seal	Females with pups, scattered or in large "patches" on pack ice, mating with males in under-ice territories(?).	Large molting assemblages near breeding ice. Casual on ice later, usually in groups.	Gregarious, herd behavior in migration.
Ribbon seal	Scattered females with pups on pack ice, mating with males in under-ice territories(?).	Non-gregarious, casually in groups on ice during molt, opportunistically later.	Non-gregarious, casual associations.

pronounced in the ribbon seal (Burns 1981a). The walrus and the spotted seal, although dependent on ice for reproduction, may haul out on land during the ice-free season.

Habitat Features: Physical characteristics of a habitat could influence the way in which a pinniped contacts oil. Habitat features will be examined in the context of seven major categories: sandy shores, rocky shores, fast ice, pack ice, shore leads, polynyas and ocean fronts.

Oil on a <u>sandy shore</u> is readily rubbed into the pelage of a pinniped. Balancing that, I have observed on Sable Island, Nova Scotia, that clean sand can cleanse oil from pelage by adsorbance and abrasion. On open coasts, sand can also "process" beached oil rather rapidly by adsorption and dispersion, and often by burying it. Temporary burial may spread out the period of potential exposure of pinnipeds, but presumably lessens its intensity.

While completely smooth <u>rocky shores</u> might receive only a thin coating of oil during a major spill, depressions and tide pools could accumulate near-smothering amounts. On the other hand, crevices and finer scale relief on such shores, may sequester oil away from contact by pinnipeds. In less dynamic environments, oil on rocky shores may long persist to form a hard, tarry coating.

<u>Fast ice</u> rarely extends beyond headlands; its distribution in Arctic waters in North America has been mapped by McLaren (1958c), Smith and Rigby (1981), Finley *et al.* (1983) and Frost *et al.* (1985). The way in which oil is incorporated into fast ice and subsequently appears in melt-pools on the surface has been outlined by Neff (Chapter 1). Some pinnipeds, notably the ringed seal, depend on fast ice at the mouths of bays and inlets (Kingsley *et al.* 1985) for a breeding habitat; other northern species such as the bearded seal and walrus only occasionally maintain breathing holes in fast ice (Stirling *et al.* 1981). There has been some concern that oil may concentrate in these breathing holes (Johnson 1983, Engelhardt 1985). Yet unless the oil were released directly under the ice or swept under by strong currents, it would not likely spread beyond the barrier presented by the edge of the ice. Instead, oil would accumulate in leads and tide cracks which penetrate into frozen bays and inlets.

<u>Pack ice</u> forms annually to fill virtually all seasonally open water from the Bering Sea, across the Canadian Arctic, to the coasts of Atlantic Canada. Old or multi-year ice, which is often very thick, predominates in the Arctic Ocean, drifting into the Bering Sea and Canadian Arctic Archipelago. The southern limits of pack ice in the Bering Sea are sketched on Figures 2.9, 2.11 and 2.12. In eastern Canada, heavy drift ice of the Labrador current is augmented further south by the outpouring of the Gulf of St. Lawrence, from which extensive ice sometimes (as in spring 1987) reaches Sable Island and Halifax, Nova Scotia. Ice from the Bay of Fundy region rarely intrudes significantly on pinniped habitat.

More than half the pinniped species in North America reproduce on pack ice and use it in other ways (Tables 2.2 and 2.4). Pack ice concentrates oil between the floes (Ayers *et al.* 1974), where it could reach smothering levels. This might be especially so in thick, old pack ice. Wind, currents and proximity to land will also influence the distribution and concentration of oil within the pack, and also at the floe edge, where pinnipeds often reside (McLaren 1958a). In the Bering Sea, spotted and ribbon seals are concentrated along the southern ice front during the winter (Burns 1978). During migration and summer, young harp seals may actively seek pack ice (Sergeant 1976) and thus frequently occur along ice edges, perhaps to exploit prey (Wells and Percy 1985).

Two other ice configurations influence the distribution and activities of pinnipeds - <u>shore leads</u> and <u>polynyas</u>. Common to both are enhanced productivity because of ice-edge effects (Dunbar 1981) and the propensity to accumulate or confine oil. Also, both settings are likely to be used as lanes for shipping oil.

Depending on tides, winds and season, <u>shore leads</u> may open to varying extents at the boundary between fast ice and pack ice. Some are sufficiently recurrent and persistent in winter to qualify as polynyas. Many shore leads in the Canadian Arctic are described and discussed by Smith and Rigby (1981) and Stirling *et al.* (1981). The great spring shore lead off northwest Alaska is depicted by Davis and Thomson (1984). The distribution of polynyas in the Canadian Arctic is mapped and analyzed by Smith and Rigby (1981) and Stirling (1981) and their pattern along the Alaskan coast is depicted in Shapiro and Burns (1975).

Whenever and wherever there is any loosening of the pack ice, pinnipeds literally take advantage of the breathing space. Polynyas have important wintering concentrations of pinnipeds, especially bearded seals, immature ringed seals and walruses (Stirling *et al.* 1981) and in the eastern Canadian Arctic, harbor seals (Mansfield 1967b). The most important shore leads may be recurrent ones that facilitate traditional migration by pinnipeds into summering areas. The open-water lead off northwest Alaska is a major migration corridor for walruses and ringed, spotted and bearded seals entering the Chukchi sea in spring (Davis and Thomson 1984). Shore leads in Hudson Strait may serve the same function for walruses and harp seals (Stirling *et al.* 1981).

<u>Oceanic fronts</u> occur at the boundary between stable and vertically mixed water masses (Le Fèvre 1986). It has long been recognized that upwelling water can bring nutrients to phytoplankton in surface waters. It is now understood more generally that when waters are too stable, nutrients become exhausted, whereas with too much vertical mixing, phytoplankton are denied sufficient residence time in sunlit waters. Thus ideal circumstances for high production develop seasonally when mixed waters begin to stabilize, and also in persistent fronts. These may occur at the margins of major oceanic currents, where river plumes contact coastal waters, where currents round headlands, at the edges of underwater banks and most notably along margins of continental shelves. There is some dispute about the extent to which these systems physically concentrate zooplankton as opposed to enhancing its

phytoplankton food (Le Fèvre 1986). However, there is no doubt that both zooplankton and the pelagic (and larval benthic) fishes that feed on it are abundant in such frontal zones.

Among North American pinnipeds, only the northern fur seal seems closely tied to such large-scale frontal production systems. It is most common during winter along the edges of the continental shelf from British Columbia to California (Fiscus 1978), where prevailing westerlies cause upwelling of deep water. The ribbon seal may also take advantage of upwelling along the southern edge of the Bering Sea shelf in summer (Burns 1981a). It is possible that harp and hooded seals follow the Labrador shelf edge during their seasonal migrations, but the former at least is taken by inshore hunters on the southward migration (Sergeant 1965). They have also been seen in schools along the edge of ice off Labrador, where they may take advantage of upwelling.

On an ephemeral or local scale, upwelling and downwelling may occur in estuaries, with currents or tidal mixing, off points and along small reefs and ridges, and everywhere in response to the Langmuir circulation of winds. At sea, areas of upwelling (marked by slicks) and downwelling (marked by flotsam) are often frequented by seabirds and mammals (Buckley *et al.* 1979). In upwellings some pinnipeds (e.g. ringed and harp seals) may feed directly on macrozooplankton (euphausiids, hyperiid amphipods) brought to the surface. Others may use the fishes that feed on such macrozooplankton or that "shelter" under seaweed and flotsam which gather in downwelling zones. Local upwelling would act to disperse surface oil, but there may be some concentration in the downwelling zones. Fresh oil and old tar balls are known to accumulate in such flotsam (Le Fèvre 1986), posing risk of ingestion by foraging pinnipeds.

Movements and Migration Patterns: Almost all pinnipeds show regular movements to and from traditional areas or sites (Table 2.2, Figures 2.1-2.19). In fact, some return repeatedly to precise locations (Pitcher and Calkins 1983). Even relatively sedentary species that haul out on land make daily forays to feed at sea. Others make coherent, far-flung migrations. All such movements complicate assessment of the probabilities that they may encounter oil.

Harbor seals (Boulva and McLaren 1979) and females and young of two west-coast sea lion species (Fiscus and Baines 1966) may have regular, once-a-day foraging schedules off their hauling out sites. Others that undertake more extensive seasonal movements may show such daily forays at times of the year. Lactating otariid females make periodic forays to feeding grounds lasting some days (Gentry and Kooyman 1986).

Some species or populations of pinnipeds (Table 2.2) show seasonal movements, but not large-scale migrations, from their coastal breeding or haul-out areas to feeding grounds further offshore. A recent study of the California sea lion in the Southern California Bight (Bonnell and Ford 1987) found about 18% of the population at sea around the breeding islands during the breeding season, compared with about 54% a month later. Most gray seals in eastern Canada are at sea from summer through early winter (Mansfield and Beck 1977). Adult ringed seals in the eastern Canadian Arctic inhabit fast ice in winter, and move offshore in summer. Immatures spend the winter offshore, and move into the ice to molt in spring (McLaren 1958a). Animals offshore are highly dispersed and large numbers are not likely to contact a spill at sea.

Some populations that disperse offshore seasonally have considerable latitudinal movement that qualifies as migration. Harbor seals seem to move from Maritime Canada to southern New England during winter (Rosenfeld and George 1985). On the west coast, there are major northward movements of northern elephant seals (Condit and LeBoeuf 1981) and male California and Steller sea lions (Mate 1975) after the breeding seasons. Alaskan populations of Steller sea lions may move south in winter (Schusterman 1981).

Some populations of Arctic pinnipeds show seasonal migrations related to ice conditions. During autumn many immature ringed seals appear to vacate the western Canadian Arctic and spend the winter in less icebound parts of the northern Bering Sea (Burns and Eley 1977, Smith 1987). Bering Sea stocks of walruses and bearded seals move to the Chukchi Sea in summer (Figures 2.8 and 2.11). While migrating, these populations traverse a variety of environments where oil might be encountered. Except for the large herds of walrus that may move synchronously through areas subject to oil exploration (Figure 2.8), these migrations do not appear to concentrate large fractions of the total population of any particular species in localized areas. In general, such populations appear to be less at risk than are sedentary ones, given equal probabilities of an oil spill in any given area.

Large-scale, long-distance, synchronous migrations are undertaken by three north American pinnipeds. Northern fur seals move through oil-exploration areas in the southeastern Bering Sea (Figure 2.13); harp and hooded seals migrate through potential oil-production areas off Labrador (Figures 2.3-2.4). The harp seal might be particularly vulnerable because it migrates in large groups (Sergeant 1965).

Habitat Aspects of Reproduction: Characteristics of the habitat where pinnipeds mate, and produce and nurture their young may lead them to encounter oil. Pinnipeds are born on solid substrates with ready access to the sea; it is precisely at such boundaries where oil is likely to be spilled and to accumulate. Species or populations that reproduce on offshore islands (e.g. northern fur seals) or pack ice (spotted and ribbon seals) might be less subject to casual encounters with oil than those favoring inshore sheltered localities (harbor and ringed seals). Young pinnipeds, such as gray seals, born and nurtured away from the water's edge (Boness and James 1979) are less likely to encounter oil than harbor seals produced on small, sometimes tidally covered bars (Lawson and Renouf 1987). Young harp seals born near the leading margins of the ice pack (Sergeant 1976) might more likely encounter oil than would young hooded seals in the thicker, older floes (Bowen *et al.* 1987b).

Population Size and Habitat Quality: The rate of recovery of a population from a catastrophic event might depend on how close the population was to the environmental carrying capacity at the time of the event. Other than the effects of crowding in colonies of highly polygynous species, the density-dependent mechanisms involved in the regulation of pinniped populations are poorly understood (McLaren and Smith 1985). There are hints of mechanisms involving resource use in a few cases. Evidence suggests that the stable or declining population of Pacific walruses consumes approximately the net productivity of its preferred benthic prey from the Bering-Chukchi shelf (Fay 1982). The declines in recent years of the Steller sea lion in California (Cooper and Stewart 1982) and Alaska (Merrick *et al.* 1987) and the northern fur seal on the Pribilofs (Fowler 1982) are not understood, but can be taken as prima faciae evidence for deterioration of their habitats, whether due to natural changes in their food base, interactions with fisheries, or competition from other pinnipeds.

From the apparently higher frequency of pathological conditions among pinnipeds from the Bering Sea compared with those from the Gulf of Alaska, Fay *et al.* (1979) conclude "that life in the Gulf may be less precarious than in the pack ice, or that populations in the Gulf are in better equilibrium with their environment than are those in the Bering Sea." The Beaufort Sea may be an even more marginal environment, judging from large-scale, long-term secular variations in reproductive rate and body condition in ringed seals, the only pinniped that lives there in numbers all year. As noted by Geraci and Smith (1976) during "poorer" years "the effects of an environmental disturbance (on ringed seals) would presumably be more widespread, affecting entire year classes and weakened segments within the population."

Social Organization and Behavior

Among pinnipeds, social organization is not so elaborate as it is in cetaceans, and pinniped groups are often site-dependent and ephemeral. Nevertheless, bonds among individual pinnipeds may lead to multiple exposures to oil.

Although pinnipeds do exhibit elements of courtship display (even group solicitations by females, Heath 1985) and pair bonding, pre-copulation gatherings of land-breeding polygynous species seem to develop more through site fidelity and cohesiveness among females (e.g. California sea lion, Odell 1981; northern elephant seal, Schusterman 1981) than through sexual attachment to individual males. Females would therefore be unlikely to remain in a hazardous situation because of pair-bonding.

Bonding between mothers and their pups is vital when females must discriminate among masses of young (Bartholomew 1959) or when following-behavior is important (Lawson and Renouf 1987). Even the mother ringed seal, which might only need to recognize a fixed birth site, presumably has the usual mammalian bonding with its dependent pup. The bond is broken during weaning by departure of the female from the breeding site (most species) or by increasing indifference to the pup (Lawson and Renouf 1987). It is possible that an oiled pup would be unrecognizable to its mother and prematurely abandoned. A more serious problem might arise if females, as the demographically most important segment of the population, were loathe to abandon pups when threatened by major oil pollution.

Sea lions sometimes nurse older individuals along with the current year's pup (Odell 1981, Schusterman 1981). Francis and Heath (1985) determined that most of these older sucklings are female, which might compound the seriousness of an oil spill at a breeding colony.

Non-reproductive Groups: Many pinniped species are gregarious at times other than during breeding. Time spent on ice or ashore saves energy and permits restorative sleep. Even species that form unstructured groups may gain some advantage in surveillance (Krieber and Barrette 1984). Other species have socially structured groups that benefit individuals. For example, Harestad and Fisher (1975) found that, in a non-pupping colony, adult male Steller sea lions maintained tranquil areas within which females were free from harassment by subadult males. Disruption of such arrangements could increase energy loss and stress individuals.

Normally "solitary" species such as bearded, ringed and harbor seals form non-interactive groups at sea, usually in response to localized resources. Without cohesive ties, they might disperse from a spill. Less predictable would be the reaction of harp seals (Sergeant 1971) and sea lions (Fiscus and Baines 1966) which dive and swim synchronously, in a display of group cohesion.

Walruses are among the most gregarious of mammals. They occur as small groups at sea, and haul out in groups of up to several thousand. After suckling for two years, weaned calves form unisexual herds, particularly in the Pacific walrus (Fay 1982). Groups of young females determine the reproductive potential of the population, and hence an effect on them would far outweigh an equivalent exposure on a herd of males.

Reproductive Behavior: In some species breeding males posture and fight tenaciously to maintain status or territory. The behavior persists over long periods of time at the expense of feeding, the minimum cost of such reproductive effort is debilitation. Moreover, fighting among highly polygynous species that breed on land (LeBoeuf 1974) and in the water (Boulva and McLaren 1979) can result in severe wounding. These elements combine to heighten the level of stress, and thereby affect an animal's reaction to an environmental disturbance.

The period devoted to nurturing young varies greatly among species (Figure 2.19), from as little as 4 days in the hooded seal (Bowen *et al.* 1985) to a year or more in the walrus and sea lion. Females with shorter periods are less restrained to the breeding habitats, and because of efficient transfer of nutrients are more robust at the time of weaning (Bowen *et al.* 1987b). Such females should be more resilient to an oil-pollution event.

Attendance pattern of nursing females will determine the frequency of exposure to oil on the water or at the ice edge. Some female phocids, for example the northern elephant seal (LeBoeuf 1981) and some land-breeding gray seals (Boness and James 1979), attend their young throughout lactation, thus lessening the risk of repeated exposure. Otariid females, in contrast, make extensive foraging trips to sea during lactation (Gentry and Kooyman 1986). Harbor seals and most ice-breeding species may return to the water several times a day between suckling bouts (Oftedal *et al.* 1987). The opportunity for repeated contact would be greater in these animals.

Circumstances surrounding weaning affect survivorship of pups. Sea lions (Odell 1981, Pitcher and Calkins 1981) and walruses (Fay 1982) continue to suckle their young after they have learned to eat other foods. Phocids and the northern fur seal are left to develop their own skills in foraging and consequently have higher mortality rates during this critcal period. Oil may compound the difficulty in establishing successful foraging patterns if it results in exclusion from favorable areas, impairs mobility or sensory capability of the pups, or redistributes suitable prey.

Grooming: Pinnipeds scratch themselves vigorously with their flippers, but do not seem to mouth or lick themselves. Although mammalian mothers routinely lick and mouth-groom their young, this seems to be almost unrecorded among pinnipeds (one example is the California sea lion on the Galapagos, Eibl-Eisenfeldt 1955). Steller sea lions may lift and carry their pups by mouth (Schusterman 1981). Play among young pinnipeds may involve the mouthing of beach debris (Schusterman 1981). None of these behaviors is likely to contribute to ingestion of significant quantities of oil.

Commensalism with Humans: Like other animals, pinnipeds can become tame when unmolested. Thus harbor seals are reappearing in numbers in harbors in eastern Canada and the west coast. Shaughnessy and Chapman (1984) document the dependence of South African fur seals on food around Cape Town docks, and their increased vulnerability to harbor pollutants.

Demography

A significant effect of oil pollution should be measurable as a population change. Therefore it is important to consider the demography of pinnipeds as a guide to understanding or even predicting such changes.

Life-history Parameters: Pinnipeds have many attributes of K-selected species (Eberhart 1977). That is, they are late-maturing, slow-reproducing, long-lived animals that are thought to exist in numbers close to the limits set by resources. Females do not mature until at least 3 years old, produce at most one young per year (twins rarely), and live well over 20 years (Table 2.5). There are exceptions. In some species, population limits may be set by mortality of young in dense breeding aggregations as a byproduct of sexual selection. This in turn can select for accelerated maturation rate and reduced length of adult life (McLaren 1967, Reiter 1984).

There are important differences among species in age of maturity, age-specific fertility rate, and lifespan. However, there are no simple allometric or biogeographic rules relating these parameters to body size (Tables 2.3 and 2.5). Thus, at one extreme females of the northern elephant seal, the largest and one of the more polygynous species, may produce first offspring when less than 4 years old, and annually thereafter for a rather limited lifespan. Northern fur seals, equally polygynous, live longer and do not mature as quickly, perhaps because of the more elaborate requirements of mothering. Sea lions, also highly polygynous but with lengthier periods of parental investment by females (Pitcher and Calkins 1981), mature later still and live even longer. McLaren (1967) thought that the late maturation and long lives of such "solitary" species as ringed and harbor seals were related to their need for considerable learning about specific environments and circumstances to ensure successful breeding. Mass ice-breeders such as harp and ribbon seals, with less need for such knowledge, mature earlier and have shorter lives. The walrus, and to a lesser extent the bearded seal, are interestingly anomalous: females are very late maturing, yet not very long-lived (Table 2.3). There are records of much older male walruses (34 to 38 years in Krylov 1970, 30+ years in Mansfield 1958). Is it possible that exploitation of benthic resources or life on the arctic pack ice are particularly stressful, especially to females? In this context, it is noteworthy that the walrus has a unique biennial cycle of reproduction, driven by exceptionally long devotion to the young (Fay 1982). This, along with late maturity, would make the walrus demographically the most vulnerable of all pinnipeds to population catastrophes.

The Possibility of Local Extinction: The large populations (Table 2.1) and wide geographic distributions (Figures 2.1 to 2.18) of most pinnipeds insulate them from extinction by any conceivable effect of oil pollution. However, local populations may be less secure. There is a developing empirical and theoretical literature on the subject of extinction, particularly in the context of rare, localized populations or species and the design of biological reserves.

Life-history parameters of pinniped species would determine their potential responses to negative anthropogenic influences. In general, adults of such long-lived animals are "designed" to be resilient. Furthermore, the loss of a year's reproductive output may be of little consequence in a population with many year classes and overlapping generations. However, <u>sustained</u> decreases in survival or fertility rates can lead to inexorable population declines. In late maturing, low-fertility species, decreases in

Table 2.5: Reproductive parameters of females of North American pinnipeds.

SPECIES	GEOGRAPHICAL REGION	MEAN AGE FIRST YOUNG[1]	ADULT PREG. RATE[2]	MAXIMUM AGE	SOURCES
Walrus	Bering-Chukchi Seas	7.2-7.8	0.44	28	Fay (1982), Krylov 1967, 1970)
	E. Candian Arctic	8.5	0.34	20+	Mansfield (1958)
Steller Sea Lion	Gulf of Alaska	5.9	0.87	30	Pitcher and Calkins (1983)
Calif. Sea Lion	California, Mexico	ca.8	ca.1.0	31	Lluch B. (1969), Maser et al. (1981)
N. Fur Seal	E. North Pacific	4.8	0.85	26	Lander (1980), York (1980)
N. Elephant Seal	California	2.7	ca.1.0	14+	LeBoeuf an Reiter (198)
Bearded Seal	Bering-Chukchi Seas	6.4	0.88	23	Burns and Frost (1979)
Hooded Seal	Newfoundland	3.8	0.95	30+	Oritsland (1975), Oristland and Benjaminsen (1975), Kapel (1981)
Ringed Seal	E. Canadian Arctic	7.9-8.1	0.85-0.93	43	McLaren (1958), Smith (1973)
	Beaufort Sea	7.7	0.88	36+	Smith (1987)
	Bering-Chukchi Seas	7.9-8.3	0.93	29	Fedoseev (1965), Burns and Eley (1977)

Table 2.5 cont'd.

SPECIES	GEOGRAPHICAL REGION	MEAN AGE FIRST YOUNG[1]	ADULT PREG. RATE[2]	MAXIMUM AGE	SOURCES
Spotted Seal	Bering-Okhotsk Seas	5.1+	ca.1.0	35	Tikhomirov (1966, 1968)
Harbor Seal	Atlantic Canada	5.2	0.95	32	Boulva and McLaren (1979)
	Alaska	5.4-6.2	ca.1.0	36	Calkins (1977), Pitcher and Calkins (1979)
Harp Seal	Atlantic Canada	4.4	0.94	30+	Bowen et al. (1981), Nazarenko and Timoshenko (1974)
Ribbon Seal	Bering Sea	3.5-4.0	0.95	26	Burns (19), Shustov (1965), Tikhomirov (1966)
Gray Seal	Atlantic Canada	5.0	0.86	44	Mansfield (1977), Mansfield and Beck (1977)

[1] where two values are given, they come from the two sources; a + sign indicates that the the estimate is based on ovulations rather than pregnancies.

[2] ca. 1.0 implies that most females are give birth annually, but that success rates have not been established.

[3] a + indicates that the source indicates that older animals were suspected.

adult survival rate can be more dangerous than a comparable decrease in fertility rate, or equivalent decrease in survival rate of young. This is exemplified using the gray seal as a model species (Figure 2.20). In a population well below equilibrium, a doubling of mortality will thwart population increase. The same result can only be achieved by reducing fertility rates to about 25% of normal. However, suspected pollution-related population declines of harbor seals (Reijnders 1986), and ringed and gray seals (Bergman and Olsson 1986) in Europe have implicated impaired reproduction rather than increased mortality.

A different kind of threat comes from the remote chance of catastrophic accident with direct, acute mortalities. This could be particularly serious in small, localized populations, already close to the level where "chance" might settle their fate. The role of chance in extinction has long attracted theoretical enquiry. Earlier models assumed that population birth and death rates were on average equal, but with variation among individuals. Under these conditions, extinction is inevitable, although large populations with reasonably small variances may persist for a long time. Recently it has become clear that it is not the "built in" variance among individuals, but variance in environmental conditions that leads rapidly to dangerously low populations.

Though pinnipeds do show attributes of K-selected species, McLaren and Smith (1985) argued that pinnipeds of extreme environments in particular may be considerably influenced by density-independent environmental factors. Thus the ringed seal in the Canadian Beaufort Sea showed a substantial drop in numbers, body condition, and reproductive success during the years 1972-1976 (Smith 1987). Coincident long-term variations in ringed seal densities have been noted along the Alaskan coast (Frost *et al.* 1985). Though not fully understood, causes of such population changes may be caused by variation in the marine "climate" and attendant changes in ice cover and food supply.

Clearly, pollution can contribute to the variance of environments in which pinnipeds live. According to Johnson (1983), the accumulation of small environmental perturbations in the Arctic is capable of generating "noise" in energy flow paths, increasing variability and possibly eliminating important stocks, among which he singles out the walrus as particularly vulnerable. His rather abstract view resists quantitative treatment at present. However, there have been some recent advances relating environmental variance to the probability of local extinctions. Strebel (1985) demonstrated formally that there is a greater probability of extinction when there is resonance between species generation length and the average interval between environmental (or resource) fluctuations. In other words, there is great resilience of long-lived species like pinnipeds to normal seasonal or other short-term fluctuations. However, long-term, lower-amplitude fluctuations, whether natural or anthropogenic, might be more "attuned" to the life-cycle characteristics of pinnipeds. Goodman (1987a) has shown that, with purely individual variation, expected persistence time of a population increases as the power of the assumed population "ceiling", whereas with purely environmental variation the time increases somewhat less than linearly with the ceiling. This is a formal

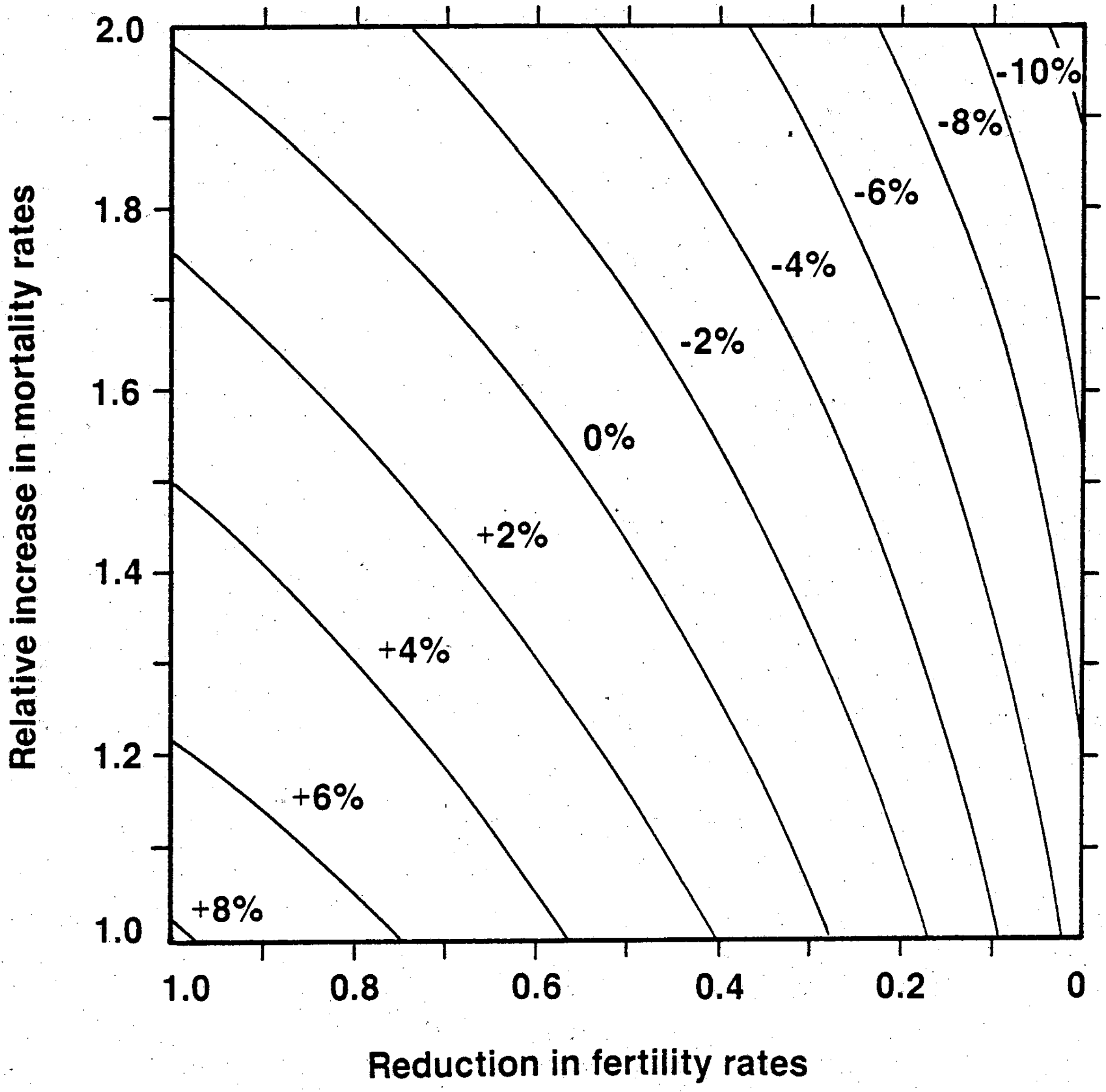


Figure 2.20

Theoretical population response to changes in mortality and fertility rates. The gray seal has been used as the model species, a population well below equilibrium increasing at a rate of 8% per year. If mortality rate doubles or fertility rate decreases by 75%, there will be no net increase in population size.

analysis of the commonsense view that, if some environmental event is bad for the whole population, large numbers will not be a protection.

Another determinant of persistence of a population is the extent of immigration, which obviously can counteract local tendencies toward extinction. Goodman (1987b) demonstrates theoretically, as might be expected, that scattered subpopulations, each experiencing its own environmental variation, with sufficiently high interchanges will persist longer than a single, isolated population with the same overall ceiling. Species of pinnipeds with well-developed homing or patrophilic tendencies would thus be more prone to local extinction than are those that wander unpredictably.

Another recurrent concern about rare and diminishing populations is the reduction of genetic variation that occurs from inbreeding, with its supposed consequences for individual fitness. Earlier work seemed to indicate that the northern elephant seal had indeed already experienced such genetic depauperation as a result of earlier overexploitation (Bonnell and Selander 1974). It was speculated that this would make them more vulnerable to such influences as pollution. However, it is now clear that pinnipeds are naturally homozygous at most enzyme loci (Lidicker *et al.* 1981), so that reduced genetic variance is probably not a potentially dangerous consequence of local population reductions. This conclusion may be revised with current technology for studying nuclear and mitochondrial DNA.

An excellent consideration of the above theoretical possibilities for pinnipeds is found in the study of the isolated ringed seals in Lake Saima, Finland (Jarvinen and Varvio 1986). The population is clearly endangered, with only some 130-150 individuals remaining. Thus, it is tempting to apply models of stochastic extinction. However, as Jarvinen and Varvio (1986) argue, "when one traces the history of endangered or extinct species, it is not stochastic extinction that one typically finds, but rather a tragedy of persecution and habitat deterioration" and "the absolute rule of chance in a small population is only the final stage of a long process leading to extinction." They conclude that the reduction of the seal stock is not a result of stochastic fluctuations, even amplified, in environmental conditions; but rather stems from <u>persistent</u> pressures. Previously high hunting mortality in adults has been succeeded by heightened mortality of pups due to artificial water-level changes, entanglement in fishing gear, and possibly pollutants.

The theoretical literature on the demography of extinction thus may not offer too many insights into processes that could lead to local extinction of populations of seals because of impacts from oil. It does seem, however, that catastrophes are likely to be less important than small, but sustained, reductions in survival and fertility. Chronic oil pollution could contribute to such effects.

Population Recovery After Catastrophe: If we take as a premise that an oil-pollution catastrophe has produced a large kill of pinnipeds, it is important to consider the rate at which the population is restored to its original level. Indeed, rate of return to "normality" is often an explicit component of environmental impact statements. The rate of recovery will of course depend on the species and circumstances; a handful of direct estimates is (Table 2.6). Clearly pinnipeds populations could recover at rates of 7-17% per year, provided they were well below equilibrium levels before the catastrophe. Those closer to equilibrium should show an enhanced rate of increase following substantial reduction of numbers. However, individuals raised under the stress of overcrowding may not be capable of producing an immediate population response. Some species, such as the northern fur seal and Steller sea lion (Table 2.1), are indeed declining locally, presumably because the carrying capacity of their environments is in some way deteriorating. For these, a catastrophic kill might not be followed by population recovery even in the long term.

The rate of recovery of a seal population will also depend on the segments of the population that are killed. Table 2.7 illustrates, using the British gray seal as a demographic model, that loss of a year's offspring is more quickly compensated than is an equivalent loss of all age groups from the population, or particularly of adults. Yet even the long time for near-recovery of populations that were at equilibrium before a catastrophe (Table 2.7) might be optimistic if individuals raised in a crowded environment fail to respond to population reduction.

Table 2.6: Direct estimates of rates of increase of unexploited or lightly exploited pinniped populations thought to be recovering at high rates following earlier overexploitation, and believed to be uncomplicated by immigration. Rates of increase (X) are multiples per year.

SPECIES	LOCALITY	YEARS	INCREASE (X)	SOURCES
California sea lion	S. California	1927-1946	1.091	Chapman (1981)
N. Fur seal	Pribilof Islands, Alaska	1912-1924	1.085	Chapman (1981)
Antarctic fur seal	South Georgia	1958-1972	1.168	Payne (1977)
Subantarctic fur seal	Gough Island	1955-1977	1.149	Bester (1980)
N. elephant seal	California, various islands	1964-1981	1.146-1.793	Cooper and Stewart (1983)
Gray seal	Farnes and Outer Hebrides, Britain	1950-1976	1.067-1.073	Summers (1978)

Table 2.7: Recovery times of hypothetical seal populations after various catastrophic reductions, assumed to occur immediately after the young are born. The population is based on the same model gray seal population used for Figure 2.21.

SCENARIO	% POPULATION REMOVED	TIME TO 95% RECOVERY (YR)
Population initially at equilibrium size		
All newborns killed	23	2
Equal proportions all age classes killed	23	37
Equal proportions mature age classes killed	23	43
Population initially at one-half equilibrium size		
All newborns killed	20	1
Equal proportions of all age classes killed	23	6
Equal proportions of mature age classes killed	23	7

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CHAPTER 3

PHYSIOLOGIC AND TOXICOLOGIC EFFECTS ON PINNIPEDS

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Historical Notes

The record of encounters between pinnipeds and oil spans four decades and comprises at least 27 events, covering Europe, the Antarctic and the Pacific, Atlantic and Arctic coasts of North America. Armed with information from such diverse habitats, we should have little difficulty in predicting the consequences of oil exposure for most pinniped species. Yet the quality of the reports is variable. Early accounts are often vague or brief, and some of the more recent efforts, undertaken in an emotionally charged atmosphere, are less than objective. Though incomplete, the record provides a clear indication of selective vulnerability to oil.

Well blow-outs and tanker accidents attract considerable attention, while more insidious sources such as vessels that intentionally discharge fuel can in fact be as damaging. During the late 1940's, there were two instances in which seals were affected by petroleum presumed to have been deliberately released from ships. In the Antarctic, Lillie (1954) observed "half-grown seals covered in a sticky, tarry mess, their eyes bloodshot with irritation". Davies (1949) reported that two seal pups encased in oil drowned when washed out to sea near Ramsay Island off the coast of Wales; other oiled pups were apparently unaffected. Waste oil dumped from vessels may account for other incidents of fouling (Table 3.1), when there has been no reason to suspect a well blow-out or a tanker accident as the source of contamination. Generally, reports of these events are limited to recovery of 2 or 3 oil-stained animals, with little evidence to determine whether the seals were fouled before or after death.

A systematic study was performed following one such event along the coast of Wales in 1974 (Davis and Anderson 1976). Oil from an unknown source fouled gray seal rookeries at the onset of pupping season, when the animals are considered to be most vulnerable. On Skomer Island, 25 pups and 23 adults were wholly or partly oiled, and pup mortality was higher than at other less affected sites. However, there was no significant difference in mortality rate between oiled and clean pups on Skomer Is., and necropsy examinations did not reveal gross evidence of ingested petroleum. Cows continued to nurse oiled pups, though these had lower average peak weights at weaning than their unoiled counterparts. Attempts to clean fouled animals met with limited success, since cleaned pups were often recontaminated by their mothers. Furthermore, the disturbance associated with cleaning operations may have interfered with nursing, and contributed to the lower peak weights of these seals. The only deaths directly attributed to fouling were those of two pups so encased with oil which they drowned when washed off the beach.

Tanker groundings have resulted in major oil spills that have affected pinnipeds. The first such event was the sinking of the Torrey Canyon off the coast of England in 1967. Two or three gray seals were observed surfacing in the oil slick, and three oiled animals were recovered dead or dying (Gill *et al.* 1967); Spooner (1967) reported that as many as 12 seals (species not indicated) had died. In view of the magnitude of the spill and the extent of clean-up activities which involved the use of over 10 million liters of relatively toxic dispersants, the impact of this event on pinnipeds was minor.

Table 3.1: Reports of pinnipeds associated with oil.

Date	Location & Source	Oil Type & Quantity	Species	Impact	Reference
late 1940's	Antarctic Ship discharge	Fuel oil Quan. ?	unspecified seals	bloodshot eyes; surface fouling with tarry oil	Lillie 1954
1949	Ramsay Island, Wales Source unknown	Fuel oil Quan. ?	gray seal	Pups largely unaffected by thick coating of oil. Two fouled pups drowned.	Davies 1949
Mar. 1967	English Channel *Torrey Canyon*	Crude oil >100,000 tons	gray seal	Seals observed surfacing through slick. 3 oiled seals found dead or dying. Up to 12 confirmed deaths.	Gill *et al.* 1967, Spooner 1967
Jan. 1969	Gulf of St.Lawrence Storage tank	Bunker C 4,000 gal.	harp seal	10-15,000 seals coated. Unspecified number of dead seals recovered.	Warner 1969 Sergeant 1987
Feb. 1969	Santa Barbara,CA Union Oil well	Crude oil >100,000 tons	harbor seal elephant seal Calif. sea lion	Oiled seals observed on Channel Islands and along mainland coast. Mortalities not conclusively linked to oil.	LeBoeuf 1971, Brownell and LeBoeuf 1971, Simpson 1970, and others.
Nov. 1969	N. Dyfed, Wales Source unknown	Type ? Quan. ?	gray seal	14 oiled, dead pups found. No causal relationship.	Anon. 1970b
Feb. 1970	Chedabucto Bay, Sable Is., N.S. *Arrow*	Bunker C $16x10^6$ L	gray seal harbor seal	50-60 harbor seals and 100 gray seals oiled on Sable Is. 500 oiled seals in Chedabucto Bay. 24 found dead, some with oil in mouth or stomach.	Anon. 1970a, 1971b

Table 3.1 (cont'd.): Reports of pinnipeds associated with oil.

Date	Location & Source	Oil Type & Quantity	Species	Impact	Reference
Aug. 1974	Strait of Magellan *Metula*	Crude oil, 47,000 tons Bunker C, 3-4000 tons	S. sea lion S. Am. fur seal	Sea lions and fur seals in the area apparently unaffected.	Baker 1976
Aug. 1974	Coast of France Source unknown	Fuel oil Quan. ?	harbor seal gray seal	Oil in intestine of 1 harbor seal. 3 oiled gray seals, 1 ingested oil.	Duguy and Babin 1975
Sept. 1974	Pembrokeshire, Wales. Source unknown	Type ? Quan. ?	gray seal	2 heavily oiled pups drowned when washed off beach. 25 pups and 23 adults fouled.	Davis and Anderson 1974
Jan. 1975	Ireland *African Zodiac*	Bunker C 2700 barrels	seals	Seals in the area were apparently unaffected.	ESL 1981
Aug. 1977	Greenland USNS *Potomac*	Bunker C 380 tons	ringed seal other seals	16 oiled seals observed 1 month after spill.	Grose *et al*. 1979
Mar. 1978	France *Amoco Cadiz*	Crude oil 200,000 tons	gray seals	2 of 4 dead seals coated with oil. No causal relatinship.	Prieur and Hussenot 1978

Table 3.1 (cont'd.): Reports of pinnipeds associated with oil.

Date	Location & Source	Oil Type & Quantity	Species	Impact	Reference
Feb.- Mar. 1970	Kodiak Is., AK Ship discharge	Slop oil or oily ballast	hair seals sea lions	Est. 500 mammals contacted; No mortality.	Hess and Trobaugh 1971
Apr. 1970	Alaska Peninsula Source unknown	Diesel fuel Quan. ?	hair seals	400 seals exhibited unusual behavior. No mortalities.	Anon. 1971a
Nov. 1970	Farne Islands Source unknown	Type ? Quan. ?	gray seal	Yearling seal found oil-stained pelt and crusting around mouth. Otherwise healthy.	Bonner and Hickling 1971
Mar. 1972	British Columbia Vanlene	Bunker B 2400 barrels	seals	Seal herds in area unaffected	ESL 1981
Sept. 1973	Repulse Bay, NWT Ship discharge	Refuse oil Quan. ?	ringed seal	Hunters killed 5 oil-covered seals.	Muller-Willie 1974
1973	Dutch coast Source unknown	Type ? Quan. ?	harbor seal	Patches of oil inconclusively associated with skin lesions.	Van Haaften 1973
1974-1979	Cape Town, S.A. Ships and industry	Chronic discharge	Cape fur seals	Fur seals lingering in polluted harbor without obvious effect.	Shaughnessy and Chapman 1984

Table 3.1 (cont'd.): Reports of pinnipeds associated with oil.

Date	Location & Source	Oil Type & Quantity	Species	Impact	Reference
May 1978	Great Yarmouth, U.K. *Eleni V*	Heavy fuel oil. 24000 barrels	seals	20 oiled seals observed.	ESL 1981
Oct. 1978	South Wales *Christos Bitas*	Crude oil 20,000 barrels	seals	Mortality of 16 of 23 oiled	Bourne 1979
Dec. 1978	Shetland Is., Scotland *Esso Bernicia*	Bunker C 8800 barrels	seals	Some seals oiled. No deaths reported.	Anderson 1981
Feb. 1979	Latvia *Antonio Gramsci*	Crude oil 36,500 gallons	seal	One seal killed by oil.	ESL 1981
Mar. 1979	Cabot Str., N.S. *Kurdistan*	Bunker C 7500 tons	gray seal harbor seal	At least 4 gray and 6 harbor seals found dead coated with oil. No causal relationship. Oiled seals on Sable Is.	Parsons *et al.* 1980. Marston (pers. comm.)
Nov. 1979	Pribiloff Is., AK F/V *Ryuyo Maru*	Fuel oil 290,000 gallons	northern fur seal	Some oiled, dead pups found. Causal relationship not demonstrated.	Reiter 1981
Feb. 1984	Sable Is., N.S. Well blow-out	Gas condensate	gray seal	4 oiled seals observed on Sable Is. No mortality.	Anon. 1984

Subsequently, major spills from the Arrow, Amoco Cadiz, Christos Bitas and Kurdistan had similar consequences. Harbor and gray seals were fouled in Chedabucto Bay, Nova Scotia, where the tanker Arrow released 16 million liters of Bunker C fuel oil in February, 1970 (Figure 3.1). On Sable Island, 200 km to the south, most of the 50-60 harbor and 100 gray seals occupying the beaches were fouled to some degree. A few animals were thought to have suffocated because vital orifices had been plugged (Anon. 1970a). Nine years later, the tanker Kurdistan sank in Cabot Strait, 200 km northeast of the wreck of the Arrow, and oiled gray and harbor seals were again observed on Sable Island (Parsons *et al.* 1980) (Figure 3.1). Investigators found no evidence of mortality or physical impairment despite the fact that some seals were heavily oiled. Along the nearby coast of Nova Scotia, however, 4 dead gray seals and 6 dead harbor seals were found coated with oil.

Following the sinking of the Amoco Cadiz in March 1977, two of four dead gray seals recovered were fouled with oil; autopsies were not performed to confirm the cause of death (Prieur and Hussenot 1978). In October 1978, the grounded Christos Bitas discharged over 2 million liters of Iranian crude oil in the same area where Davis and Anderson had investigated a spill five years earlier. Reports that 16 gray seal pups died acutely were not confirmed, and subsequent necropsy examinations of a limited number of specimens (Bourne 1979).

Oiled seals have been observed following the breakup of at least seven other vessels, with mortalities reported in two of the events. An unspecified number of oil-fouled dead fur seal pups were recovered in the Pribiloff Islands after the grounding of the fishing vessel F/V Ryuyo Maru (Reiter 1981), and a single seal (species not identified) presumably died after contacting crude oil spilled from the Antonio Gramsci in the Baltic Sea (ESL 1981). In neither instance was a detailed examination performed on an animal.

No incident involving marine mammals and spilled oil has sparked as much controversy as the blowout of Union Oil's A-21 well in the Santa Barbara Channel (Figure 3.2) on January 28, 1969 (Easton 1972). The magnitude and duration of the spill and its occurrence near a densely populated coast drew national attention for several months. Residents who perceived the spill as an irreversible blow to the economic and aesthetic value of the coastal environment confronted industry and federal representatives, as conflicting reports of the extent of the spill and its impact on marine life were presented and challenged. Studies that found minimal effects were dismissed by the public as inadequate, whereas media reports were often overstated and sensational, and found little favor with the scientific community. From this large body of diverse and often conflicting documentation, some attempt has been made to evaluate the impact on pinnipeds.

Along the mainland coast, there was little evidence of impact. Ten days after the blowout, the Santa Barbara News-Press published a photograph of an oiled harbor seal that had been "rescued" and presented for cleaning. By February 21, Time (Anon. 1969a) reported that six dead seals had washed up on California beaches. Seven more were recovered during the following month.

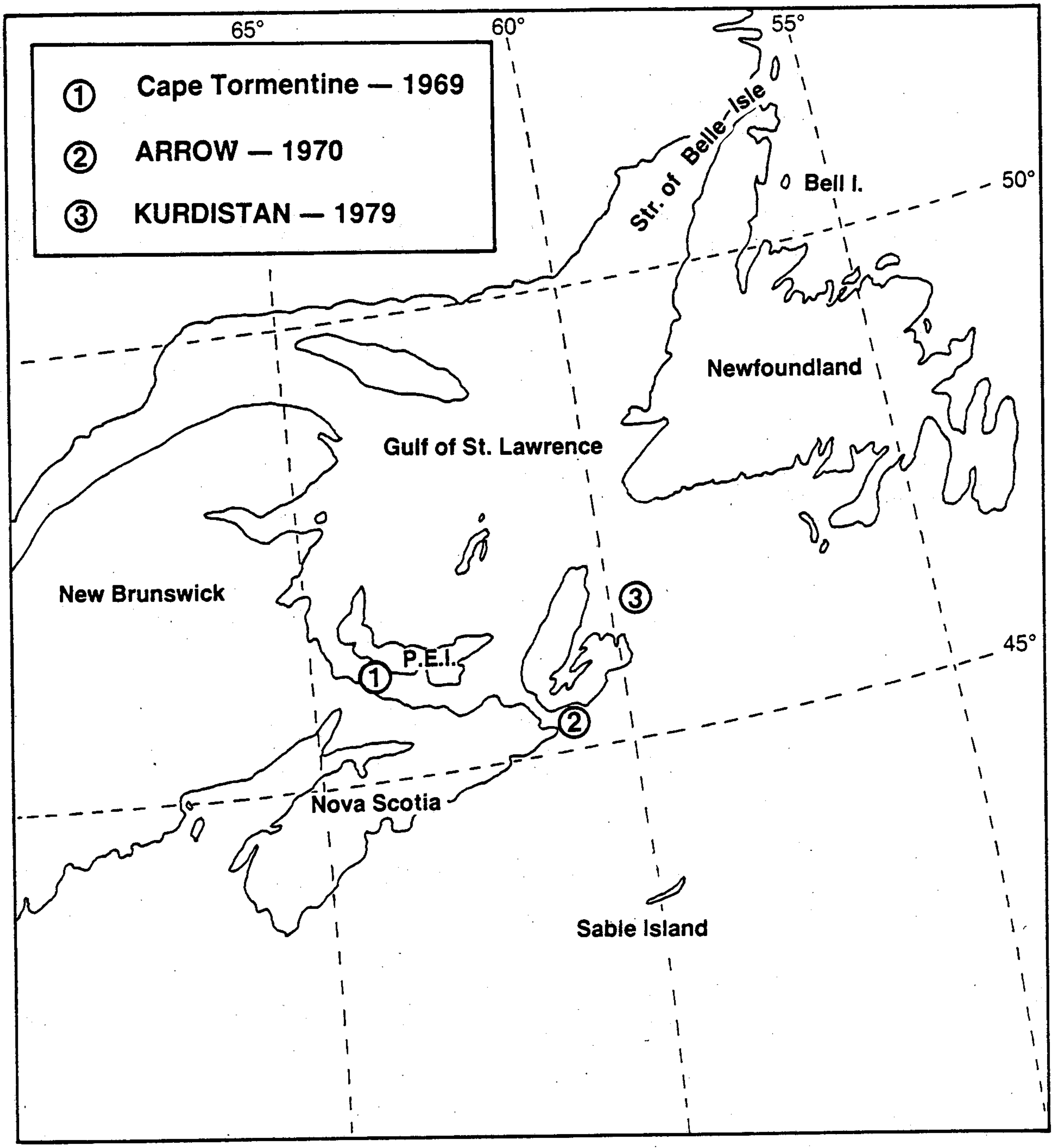

Figure 3.1 Location of three oil spills in Northeast Canada

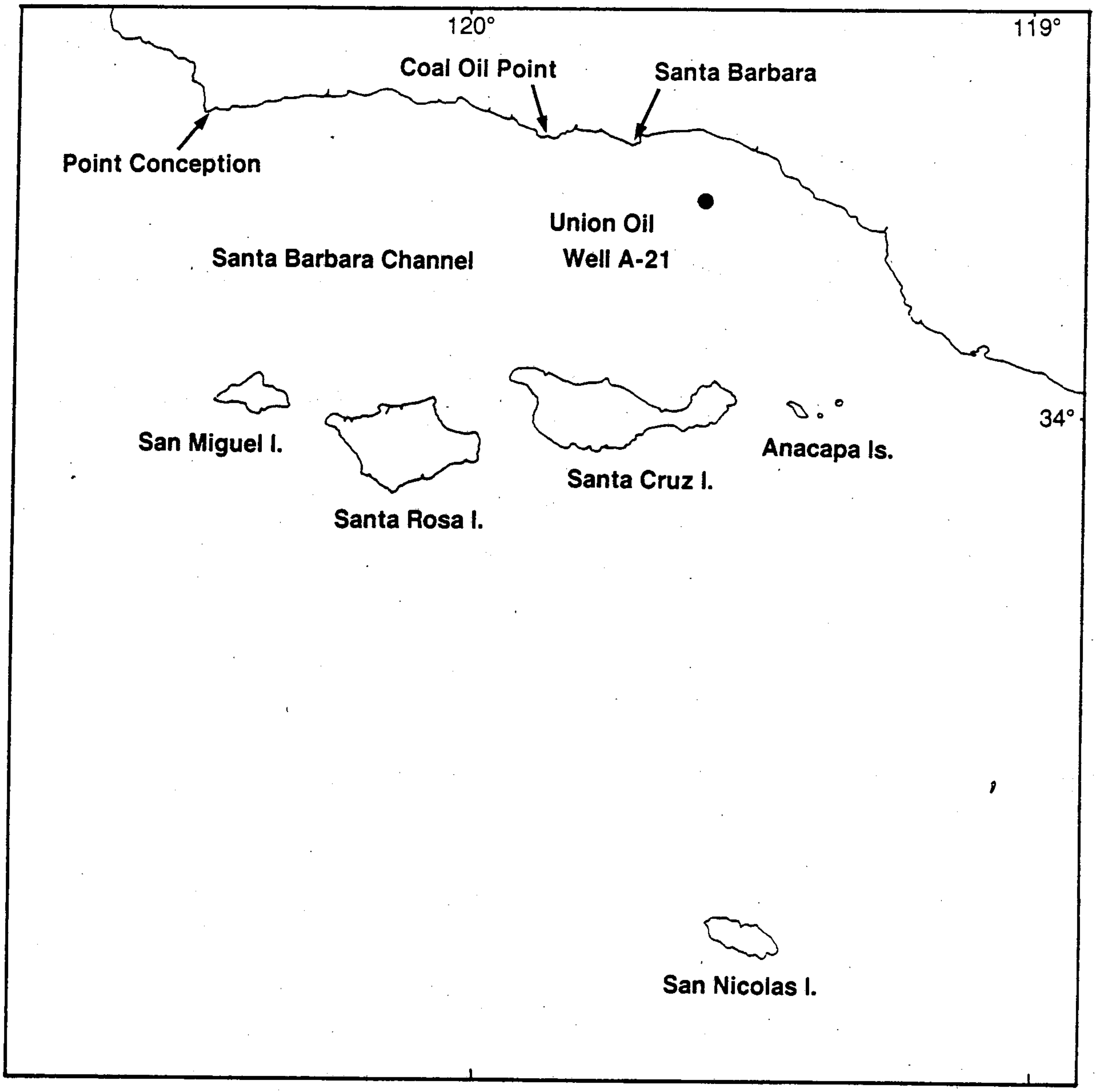

Figure 3.2 Location of the Santa Barbara Channel oil spill

Most of the attention and controversy centered around rookeries on the channel islands - San Miguel, San Nicholas, Santa Cruz, and Anacapa (Figure 3.2) - that are occupied throughout the year by several species of pinnipeds. From early February until the end of June, the islands were surveyed on at least 15 occasions by groups representing the California Department of Fish and Game, the University of California (Santa Barbara and Santa Cruz), the Defenders of Wildlife, the Santa Barbara Museum of Natural History and various press agencies, including Time magazine. Their observations and interpretation of the events form the basis of the controversy.

The principal inhabitants of the islands are California sea lions and elephant seals, both of which use the islands for breeding. Elephant seal pups are born in early January and most were weaned when oil reached the islands one week after the blowout. On March 17, LeBoeuf (1971) observed over 100 elephant seal pups coated with oil, sand and detritus. Fifty-eight of these were tagged, along with an equal number of unoiled animals. During the next 15 months, 40% of the oiled group and 25% of the controls were resighted. Conclusions about survivorship are tenuous, since there was no assurance that seals that were clean when tagged did not subsequently encounter oil. Later, LeBoeuf and Peterson reported that they had also observed four dead elephant seals lying in pools of oil (Anon. 1969b). During the first two weeks in April, Simpson and Gilmartin (1970) surveyed the rookery on four occasions and found three dead seals, with no evidence of oil contamination. No hydrocarbon residues were detected in tissues collected from two of these, nor in blood samples from two live seals.

The effect on California sea lions was the subject of particular concern and disagreement. Though peak pupping season for the sea lions does not occur until late May through June (McLaren, Chapter 2), observers were confounded by an apparently large number of premature births, beginning in February. Counts ranged from 25 in late March (Brownell and LeBoeuf 1971) to 200 in mid-May (Snell 1969), just before the onset of the normal parturition season. Arguments arose over whether the incidence of abortions was representative of normal mortality. No hydrocarbon residues were detected in tissue samples from aborted fetuses (Simpson and Gilmartin 1970, Simpson 1970), and the association between pup mortality and the oil spill remained circumstantial. Subsequent investigations of premature births among sea lions show that the incidence observed in 1969 was not unusual. DeLong *et al.* (1973) counted 242 dead pups on April 25, 1970 and 348 on May 18, 1971 on San Miguel Island; Odell (1970) reported 442 on San Nicholas Island between January 17 and May 3, 1970. More recent studies have shown possible associations with infectious organisms and organochlorine residues (Gilmartin *et al.* 1976), and it is possible that the stress of oil exposure may have had an additive effect. To summarize, there was no clear evidence directly implicating oil as the principle cause of mortality among sea lion pups.

Concurrent with the Santa Barbara spill, a much less publicized incident in Canadian waters had a far greater impact on pinnipeds. A ruptured storage tank on Cape Tormentine, New Brunswick, discharged 18,000 L of Bunker C oil into the Gulf of St. Lawrence (Figure 3.1), fouling the sea ice where harp seals were about to begin pupping. During March and early April, observers reported 10-15,000 oil-fouled adults and pups so heavily contaminated that they were almost unrecognizable (Sergeant 1987). Hundreds of pups were tagged as part of an annual effort by Canadian Fisheries biologists, and the relatively high tag return during this season suggested an increase in mortality rate. An unspecified number of dead seals were found on the ice floes, in the water and along the beaches of Bell Island (Warner 1969). Oil-fouled pups migrated normally towards the Strait of Belle Isle, despite the heavy coating which observers felt would impede swimming (Sergeant 1987). A telling clue to their condition, however, was that the pups were easily taken weeks later by seal hunters who reported that the animals uncharacteristically would not leave the ice floes (Sergeant 1987). This incident represents the worst possible combination of viscous residual oil in an ice-infested, cold water environment at a particularly vulnerable period in the life of a pinniped.

Detection and Avoidance of Oil

Pinnipeds are physiologically and anatomically well-equipped to detect the presence of oil, though no study has addressed this question experimentally. They have reasonably acute vision (Nachtigall 1986), particularly underwater over a wide range of light intensities. A large pupil and extensive summation of rod-type receptors facilitate discrimination under such low light conditions (Jamieson and Fisher 1972), and a well-developed tapetum further enhances this ability. Pinnipeds take advantage of these adaptations to feed at night (Renouf *et al.* 1980) or at great depths. In ice-covered seas, where ambient light is further reduced, Arctic seals readily travel between breathing holes, and are able to detect incongruities at the surface.

Pinnipeds appear to have a good sense of smell. They use olfaction to identify their young (Sandegren 1970, Fogden 1971, Renouf *et al.* 1983), and seals basking on ice floes test the air while maintaining their vigil against predators. We might expect that their olfactory sense is keen enough to detect hydrocarbon vapors.

It is unlikely that any pinniped has an acoustic sense as sophisticated as that found in some odontocetes. Studies on the ability of seals to echolocate (Renouf *et al.* 1980, Renouf and Davis 1982) have been challenged (Wartzok *et al.* 1984). Blind pinnipeds can survive for some time in the wild, presumably by taking maximum advantage of acoustic cues. However this provides no insight as to whether a seal can detect oil beyond its ability to see or smell it.

If they can detect it, why do some pinnipeds remain within its reaches long enough to become fouled? Perhaps they were unable or unwilling to avoid it, or that they did eventually, but only after coming in contact with it. We can judge the relative strength of the avoidance response in pinnipeds from observations following some of the major oil spills.

Most of the several thousand resident gray and harbor seals apparently left Chedabucto Bay, Nova Scotia, after the grounding of the Arrow (Mansfield 1970), though their response may have beeen as much to the marked increase in human activity as to the oil itself. Harbor seals temporarily abandoned Yell Sound in the Shetland Islands, Scotland, when Bunker C oil from the Esso Bernicia escaped from containment booms (Anderson 1981). The seals returned several weeks later, after most of the oil had beached. Native hunters from Wainwright, Alaska, reported that a chronic fuel spill which resulted in a 5 km-long slick was responsible for low numbers of seals in the area (Cowles *et al.* 1981), though their absence may have related more to changes in food distribution and abundance. Relatively few seals were observed in the vicinity of oil spilled from the USS Potomac, due more to the lack of sea ice than to presence of oil (Grose *et al.* 1979).

Such indirect and inconclusive evidence for oil avoidance behavior in pinnipeds is balanced by observations of seals, sea lions and fur seals swimming in the midst of oil slicks. After the Torrey Canyon spill, two gray seals were seen "deliberately" diving and surfacing in a patch of oil (Spooner 1967). Seals and sea lions did not abandon rookeries fouled after the oil well blowout in the Santa Barbara Channel, and showed no reluctance to enter oiled waters surrounding Anacapa and Santa Cruz Islands when disturbed by personnel from the California Department of Fish and Game (Battelle Memorial Institute 1969). In Alaskan waters, fur seals were apparently indifferent to small slicks of oil and mousse released from the Ryuyo Maru (Reiter 1981). Under confined laboratory conditions, three ringed seals placed in a pen containing seawater with a 1-cm thick slick made no attempt to use a haul-out platform. However, the platform was not provided until the animals had been in the pen for 20 minutes, and by then the seals may have been too excited or disoriented to notice its presence (Geraci and Smith 1976a).

A most intriguing account of the response of pinnipeds to oil comes from observations made over a five year period in Table Bay Harbour, Cape Town, South Africa (Shaughnessy and Chapman 1984). There, in inner reaches of the harbor where petroleum residues accumulate at the surface and in the water column, Cape fur seals regularly come to feed on fish inadvertently discharged from trawlers. The authors could not determine how long individuals remained within the harbor, or whether more seals would have been present if pollution levels were lower. Nevertheless, their observations demonstrate that a pinniped intent on a ready meal is not discouraged by the mere presence of oil.

Behavioral Effects

Oil spills could have a disruptive effect on individuals or populations by interfering with normal behavior patterns. Of particular concern is the effect on maternal behavior. Pinnipeds appear to rely on scent to establish a mother-pup bond (Sandegren 1970, Fogden 1971), and oil-coated pups may not be recognizeable. On San Miguel Island, media representatives reported that female sea lions were biting and tossing pups which might have been their own (McMillan 1969). J. Bennett of the University of California, Santa Barbara, Museum of Zoology, observed in a limited survey that females appeared to ignore pups that attempted to suckle (Santa Barbara News-Press, June 29, 1969). In a systematic study of nursing behavior in oiled gray seals, Davis and Anderson (1976) concluded that mother-pup interactions were normal, though oiled pups had lower peak weights at weaning. Frequent attempts by the researchers to clean the pups likely disturbed nursing behavior more than did the oil itself. Earlier, Davies (1949) had noted that gray seals continued to nurse pups that were heavily contaminated with fuel oil.

Cape fur seals feeding within the heavily polluted Table Bay Harbour were observed to behave normally (Shaughnessy and Chapman 1984). An unusual behavior, noted on four occasions during the five-year observation period, was an uncharacteristic swimming posture in which a seal carried its head, neck and trunk above water for extended periods of time. No conclusion could be made as to whether these animals were responding to irritating substances in the water.

Fouled seals may be reluctant to enter the water, according to observers in the Gulf of St.Lawrence (Sergeant 1987) and Alaska (Anon. 1971). The seals in Alaskan waters had "a glazed look in their eyes", and were possibly disoriented after contacting a spill of light diesel fuel. The young harp seals in the Gulf, though weaned and mature enough to swim, were impeded by a heavy coating of Bunker C which stuck their flippers to their sides.

Surface Contact - Eyes and Mucous Membranes

The most sensitive tissues exposed to the environment are the mucous membranes that surround the eyes and line the oral cavity, respiratory surfaces, and anal and urogenital orifices. Petroleum hydrocarbons, particularly volatile aromatics and short-chain fractions, are irritating to these and other delicate tissues such as the cornea. People exposed to hydrocarbon vapors report irritation of eyes and respiratory epithelium at relatively low concentrations (Davis *et al.* 1960).

Ringed seals experimentally placed in crude oil-covered water showed a similar reaction (Smith and Geraci 1975). Within minutes after exposure to oil, the seals began to lacrimate profusely, and eventually had difficulty keeping their eyes open. By 24 hours, they developed severe conjunctivitis, swollen nictitating membranes, and corneal abrasions and ulcers. The inflammation subsided soon after the seals were placed in clean water. It is reasonable to assume that continued exposure could have resulted in permanent damage.

Similar effects have been observed in the natural setting (Lillie 1954). In addition, pinnipeds contacting highly weathered petroleum face persistent contamination of periocular tissues because of the tenacity of these viscous substances. Further compounding the problem is the tendency for tar to entrap debris, such as sand and sticks, to the point where some animals may have difficulty opening their eyes (Anon. 1969a). We can conclude that pinnipeds, with their relatively large, often protruding, eyes would be particularly vulnerable to such effects.

Surface Contact - Integument

Though not as sensitive as mucous membranes, epidermis can also be damaged by petroleum, particularly the low-molecular weight fractions (Walsh *et al.* 1974, Hansbrough *et al.* 1985). These components remove protective lipids from the skin surface, penetrate between epidermal cells, disrupt cellular membranes, and elicit an inflammatory response in the dermis (Lupulescu *et al.* 1973). Necrotic epidermis is generally sloughed, leaving ulcers. In humans, this can occur after contact for less than an hour (Klauder and Brille 1947, Tagami and Ogino 1973).

Despite the potential for cutaneous damage, such lesions have rarely been noted on oil-fouled seals. Van Haaften (1973) supposed that skin lesions on harbor seals recovered in Dutch waters resulted from contact with oil, but acknowledged that similar lesions occur without evidence of oil contamination. In a controlled experiment, Geraci and Smith (1976b) found no indication of skin damage in ringed seals immmersed in oil-covered water for 24 hours. Perhaps their dense wetable underfur prevented much of the oil from contacting the epidermis. Without evidence, we can only speculate that there would be a greater opportunity for contact and perhaps greater risk in species with relatively sparse pelage, such as the California sea lion and the walrus.

Of greater concern is the potential effect of surface fouling on thermoregulation. The marine environment is particularly demanding energetically, due to low temperatures and high specific heat of the medium. Pinnipeds are highly adapted to withstand immersion in near-freezing seas, using anatomic features and physiological mechanisms to maintain core body temperature. For insulation, they rely on a thick layer of subcutaneous fat (blubber), dense fur, or both. In an <u>in vitro</u> experiment, Kooyman *et al.* (1976, 1977) compared thermal conductance through pelts from northern fur seals, bearded and Weddell seals and California sea lions. The dense pelage of the northern fur seal provided the greatest resistance to heat transfer, whereas specimens from bearded seals and the sea lion had much higher conductance values.

Fur is an effective thermal barrier because it traps air and repels water. Petroleum reduces its insulative value by removing natural oils that waterproof the pelage. The rate of heat transfer through fur seal pelts can double after oiling (Kooyman *et al.* 1976, 1977), adding an energetic burden to the animal. In fact, fouling of approximately one-third of the body surface resulted in 50% greater heat loss in fur seals immersed in water at various temperatures (Kooyman *et al.* 1976).

Pinnipeds other than fur seals are less threatened by thermal effects of fouling, if at all. Oil has no effect on the relatively poor insulative capacity of sea lion and bearded and ringed seal pelts; oiled Weddell seal samples show some increase in conductance (Oritsland 1975, Kooyman *et al.* 1976, 1977). In oil-fouled ringed seals and weaned harp seal pups, core body temperature remained within the normal range, though it was not determined whether there was a compensatory increase in the animals' metabolic rate (Smith and Geraci 1975, Geraci and Smith 1976a). If we presume that blubber provides sufficient insulation in these species, we need only be concerned about the thermal effects of oil fouling of newborn phocids, which have little subcutaneous fat and are thought to rely on their lanugo, or birth coat, for insulation. Yet these animals are metabolically equipped to survive birth under rigorous Arctic or sub-Arctic conditions. By utilizing brown fat stores, newborn phocid seals can compensate for the relative ineffectiveness of lanugo made wet by amnionic fluid (Blix *et al.* 1979). It would be important to know whether these adaptations might offset the potentially deleterious effects of oil fouling until the pups establish adequate blubber.

A coating of oil may have other more obvious effects. Fouling can interfere with locomotion, particularly in young animals. Davis and Anderson (1976) observed two gray seal pups drowning, their "flippers stuck to the sides of their bodies such that they were unable to swim". Similar observations were made following a spill of heavy Bunker C oil in the Gulf of St. Lawrence, where the effect was compounded by low ambient temperatures. A larger stronger seal should be able to resist drowning, but may endure other effects of increased buoyancy due to a tarry coat. Oil might also impair the movements of more delicate structures such as eyelids and vibrissae.

Oil Ingestion

Petroleum is composed of a wide variety of hydrocarbons, some of which are toxic if ingested (Neff, Chapter 1). Aromatics and other low molecular weight fractions can be absorbed from the intestine and transported via the bloodstream to various target organs. Depending on the amount and composition of the ingested oil, the effects can range from acute death to subtle, progressive organ damage. Ingested hydrocarbons can irritate or destroy epithelial cells that line the stomach and intestine, thereby affecting motility, digestion and absorption. The effect might be compounded by pre-existing lesions or ulcerations, which frequently occur in pinnipeds infected with gastric nematodes (Geraci and St. Aubin 1987). Disruptions in the integrity of the mucosa could also facilitate the direct movement of petroleum fractions into the bloodstream. Effects on pinnipeds would presumably parallel those in other mammals.

Ingestion of petroleum hydrocarbons has been implicated in the deaths of a number of stranded gray and harbor seals along the coast of France (Duguy and Babin 1975, Babin and Duguy 1985). On post mortem examination, oil was grossly evident within discolored loops of intestine, and its presence was confirmed by gas chromatography in three of seven specimens analysed. Histopathologic changes in liver and intestine were seemingly correlated with the presence of oil in the gut. Yet, the authors admitted that carcasses were autolyzed, and their diagnosis might have been obscured.

The effects of crude oil ingestion have been examined in three studies on two species of phocid seals (Smith and Geraci 1975, Geraci and Smith 1976a, Engelhardt 1982). In all three experiments, relatively small doses of oil were used to duplicate conditions that might realistically occur in the wild; no attempt was made to establish lethal thresholds. Sensitive biochemical tests were used to monitor organ function and detect subtle changes in metabolic processes.

No overtly deleterious effect was noted in harp seal pups given a single dose of up to 75 mL (1-3 mL/kg) of crude oil or in ringed seals given 5 mL of crude oil daily for up to five days. Harp seal pups ingesting oil vocalized more than control seals, and remained active for several hours after control pups had fallen asleep. Within 1.5 hours, oil was apparent in their feces, suggesting increased gastrointestinal motility. Analysis of tissue-specific enzyme activity in blood revealed mild liver damage in one of six seals given 75 mL of crude oil. The seals were killed and examined at scheduled intervals over a ten-day period following ingestion; no relevant lesions were noted.

Two similar studies on ringed seals focused on absorption, tissue distribution and clearance of petroleum hydrocarbons. Isotope-labelled benzene (Engelhardt *et al.* 1977) or naphthalene (Engelhardt 1982) was added to the oil, and tissues and body fluids were analyzed for levels of radioactivity. Labelled fractions were readily absorbed into the blood stream, and were detected in liver, blubber and muscle biopsies first collected two days after the initial dose of oil. Hepatic and renal enzyme systems were presumably responsible for the conversion of the labelled fractions to polar metabolites detectable in plasma and urine (Engelhardt 1982). In the liver of one of four seals tested, activity of aryl hydrocarbon hydroxylase (AHH) was apparently induced to levels four to five times higher than in the other seals; AHH activity was elevated in the kidneys of the other three. Tissue levels of radioactivity declined rapidly within two weeks (Engelhardt *et al.* 1977), but were still present in trace amounts after four weeks.

Plasma activity of tissue-specific enzymes in the seals remained within normal ranges throughout the ten-day monitoring period after oil ingestion (Smith and Geraci 1975). After four daily doses of crude oil, plasma cortisol levels were markedly increased (Engelhardt 1982), though without adequate controls it is not possible to ascertain whether this was a consequence of oil ingestion or the stress of repeated handling as the oil was administered. Similarly, the apparent increase in cortisol turnover evident in two of three seals cannot be interpreted as a direct consequence of oil ingestion, since there were no controls for the superimposed stresses of handling.

These limited studies demonstrated that phocid seals can tolerate small quantities of ingested oil. To predict the amount of petroleum which might potentially be toxic, we must extrapolate from data derived for terrestrial species. In rats, the LD_{50} for ingested fuel oils ranges between 5 and 25 mL/kg (Elars 1980 a-d). Thus, a small phocid such as a ringed or harbor seal weighing 50 kg might have to ingest approximately 1 L of fuel oil to be at risk; for an adult male elephant seal, the quantity would be 30 L or more. It is unrealistic to assume that pinnipeds would consume such large volumes of oil during the course of normal feeding. Nor would grooming present a potential route for ingestion; this activity is relatively uncommon in pinnipeds (McLaren, Chapter 2). Davis and Anderson (1976) found no evidence of ingested oil in the stomachs of heavily oiled gray seal pups, and no hydrocarbon residues were detected in blood and tissues collected from seals and sea lions at the time of the Santa Barbara spill (Simpson and Gilmartin 1970). Viscous oil and tar have been noted in the mouths of seals (Anon 1970a) and sea lions (Calkins 1979), though in these instances the effect would more likely be mechanical interference with feeding than metabolic toxicity.

Chronic ingestion of sub-toxic quantities of petroleum may have subtle effects which would only become apparent through long-term monitoring. All pinnipeds examined to date have the enzyme systems necessary to convert absorbed hydrocarbons into polar metabolites which can be excreted in urine (Engelhardt 1982, Addison and Brodie 1984, Addison *et al.* 1986). However, some proportion of the non-polar fractions will be deposited in lipid-rich tissues, particulary blubber. The occurrence of petroleum residues has been noted in several species of pinniped (Risebrough *et al.* 1978, Geraci and St. Aubin 1985), though there is no direct evidence of associated pathologic or metabolic effects. Nor is there evidence that such compounds will accumulate with repeated exposure. Other pollutants that do, including PCB's and DDT, have been implicated in reproductive disorders affecting ringed seals in the Baltic Sea (Helle *et al.* 1976) and California sea lions (DeLong *et al.* 1973, Gilmartin *et al.* 1976), and petroleum hydrocarbon residues might enhance this effect. Mobilization of fat stores during annual molting and reproductive periods could lead to release of residues, and possibly enhance toxicity at those times. Transfer of petroleum fractions via lipid-rich milk is also a potential route of exposure to pups, which have significantly lower levels of some of the detoxifying enzymes (Addison *et al.* 1986).

Inhalation

There has been no study to assess the effects of inhaled hydrocarbon vapors in pinnipeds. However, indirect evidence from immersion studies and data extrapolated from terrestrial mammals can be used to predict possible consequences in these species. We begin with the basic assumption, for which evidence is accumulating, that pinnipeds have metabolic systems similar to those in other mammals for detoxifying absorbed hydrocarbons.

Ringed seals placed in a pen containing oil-covered water for 24 hours had levels of petroleum hydrocarbons up to several ppm in blood and tissues (Engelhardt *et al.* 1977). Since there was no postmortem evidence of ingested oil, the investigators concluded that uptake of hydrocarbons had occured across the respiratory epithelium. One of the six seals had histological evidence of renal tubular necrosis and fatty degeneration in the liver; a second seal had kidney lesions only (Smith and Geraci 1975). The occurence of these lesions correlated with tissue concentrations of petroleum hydrocarbons; the nature of the damage was similar to that observed in laboratory species (Nau *et al.* 1966). Plasma levels of a liver-specific enzyme, alanine aminotransferase, were mildly elevated in three of the seals, including the one with morphologic evidence of liver damage; there was no consistent pattern in any of the other plasma chemical constituents analyzed.

Vapor concentrations in the experimental setting were not measured. However, exposure conditions were intensified to some degree by the design of the pen, which had plywood walls extending 60-70 cm above water, thereby retarding the dissipation of volatile fractions. Yet the absence of pathologic changes in the lungs of the seals would suggest that the levels were less than 500 ppm. Twenty-four hour exposure to more concentrated vapors generally results in hemorrhage, inflammation and congestion in the lungs of a variety of laboratory species (Carpenter *et al.* 1975, 1976).

In a subsequent immersion study, three ringed seals acclimated to captivity for two months died within 71 minutes after oil was introduced to their pool (Geraci and Smith 1976a). Exposure to gasoline vapor concentrations in excess of 10,000 ppm is rapidly fatal in humans (Machle 1941), yet it was highly unlikely that such levels could have been attained in the open setting of this experiment. The seals' death was interpreted as the cumulative effect of a variety of stresses associated with transportation, captivity and the experimental regime. The proximate cause of death was likely cardiac fibrillation triggered by the synergistic effects of high circulating levels of epinephrine and hydrocarbons. Similar occurrences have been noted occasionally in humans who have been chased after intentionally sniffing gasoline (Bass 1986).

This observation has significant implications for free-ranging pinnipeds stressed by parasitism or other pre-existing metabolic disorders. In such animals, brief exposure to relatively low concentrations of hydrocarbon vapors might be fatal if combined with other stimuli eliciting a major adrenal response. Parasitic lung disease, a relatively common finding in pinnipeds (Geraci and St. Aubin 1987), would further complicate the effects of even mild irritation of respiratory tissues. For most pinnipeds, particularly in northern habitats, it is unlikely that petroleum vapors could become sufficiently concentrated to represent a threat. However, selected individuals within a given population may be particularly sensitive and thus be predisposed to the deleterious effects of inhaled hydrocarbon vapors.

Summary

Oil fouling has been implicated in the deaths of pinnipeds, though much of the evidence has been circumstantial. Large-scale mortality has occurred rarely, even after some of the more catastrophic spills. In general, the prediction that spilled oil would have its greatest impact on young pinnipeds in cold, ice-bound waters has been borne out following the discharge of residual oil in the Gulf of St. Lawrence in 1969.

Pinnipeds are not unduly sensitive to the noxious characteristics of oil. Incidental ingestion during feeding, exposure to vapor concentrations that might be expected under natural conditions at sea, and surface fouling with relatively fresh oil do not appear to cause significant distress. Pinnipeds trapped near the source of a spill, or forced to emerge in heavy accumulations of oil in leads and around rookeries will undoubtedly exhibit the most severe effects. For fur seals, experimental studies indicate that surface fouling will decrease the insulative value of the pelt, possibly leading to thermal and energetic stress. Individuals of all species and groups that are compromised by pre-existing disease, or stressed by pressures of an unfavorable habitat, intra-specific competition, or unusual environmental conditions may be the most sensitive to the effects of oil exposure.

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