OCS STUDY

MMS 85-0034

BEHAVIOR, DISTURBANCE RESPONSES AND DISTRIBUTION OF BOWHEAD WHALES *Balaena mysticetus* IN THE EASTERN BEAUFORT SEA, 1980-84

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TABLE OF CONTENTS

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OCS STUDY

MMS 85-0034

PROJECT RATIONALE AND DESIGN*

by

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TABLE OF CONTENTS

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INTRODUCTION

The bowhead whale, Balaena mysticetus, inhabits cold northern waters. All populations were exploited heavily by commercial whalers in the 18th or 19th centuries, and all were seriously reduced. Bowheads are considered endangered under U.S. legislation.

Bowheads of the Western Arctic (= Bering Sea) population, the one group occurring in U.S. waters, winter in the Bering Sea, summer in the eastern Beaufort Sea, and migrate around western and northern Alaska in spring and autumn (Fig. 1, inset). The size of this population was much reduced by intensive commercial whaling between 1848 and 1914 (Bockstoce and Botkin 1983). The extent of the summer range was apparently also much reduced (Dahlheim et al. 1980; Fraker and Bockstoce 1980). A subsistence harvest continues annually in Alaska. The International Whaling Commission's current 'best estimate' of the stock size is 3871 individuals (I.W.C. 1984).

The spring migration of Western Arctic bowheads is close to shore in the Chukchi Sea, but well offshore in the Alaskan Beaufort Sea (Braham et al. 1980, 1984; Ljungblad et al. 1982a). Thus, the eastward spring migration through the Alaskan Beaufort Sea in April-June is well north of the area of oil exploration near the coast. However, during the westward autumn migration in August - October, many bowheads occur close to shore, within or near some offshore oil leases (Braham et al. 1984; Ljungblad et al. 1984).

From June to early September, the great majority of the Western Arctic bowheads are in Canadian waters (Fraker 1979; Fraker and Bockstoce 1980; Davis et al. 1982). Intensive offshore oil exploration began several years earlier in the Canadian part of the Beaufort Sea than in the Alaskan portion. Nearshore drilling from artificial islands has been underway in the south-central part of the summering area since about 1972, with drillships in use farther offshore since 1976. Seismic exploration began there earlier and still continues. The main area of offshore drilling is north of the Mackenzie Delta and the western Tuktoyaktuk Peninsula (Fig. 1). Summering bowheads are sometimes common in and around that area (Fraker and Bockstoce 1980).

POTENTIAL FOR DISTURBANCE

The scientific literature contains few descriptions of the reactions of baleen whales to boats, aircraft, drillships, and other activities associated with offshore oil exploration. Until 1980 there had been few detailed or controlled studies of these reactions. Controlled studies are especially desirable because whale behavior is quite variable. In the absence of experimental control, it is difficult to determine whether a change in behavior is 'natural' or a response to some human activity. Long term effects of offshore industrial activities on whales are even more difficult to study. The literature on these topics has been reviewed recently by Fraker and Richardson (1980), Geraci and St. Aubin (1980), Acoustical Society of America (1981), Gales (1982), Malme et al. (1983), and Richardson et al. (1983).

Noise is one attribute of offshore oil exploration and development that may affect whales. Unlike major oil spills, noise is an ongoing component of normal offshore operations. Noise is introduced into the sea by most of the

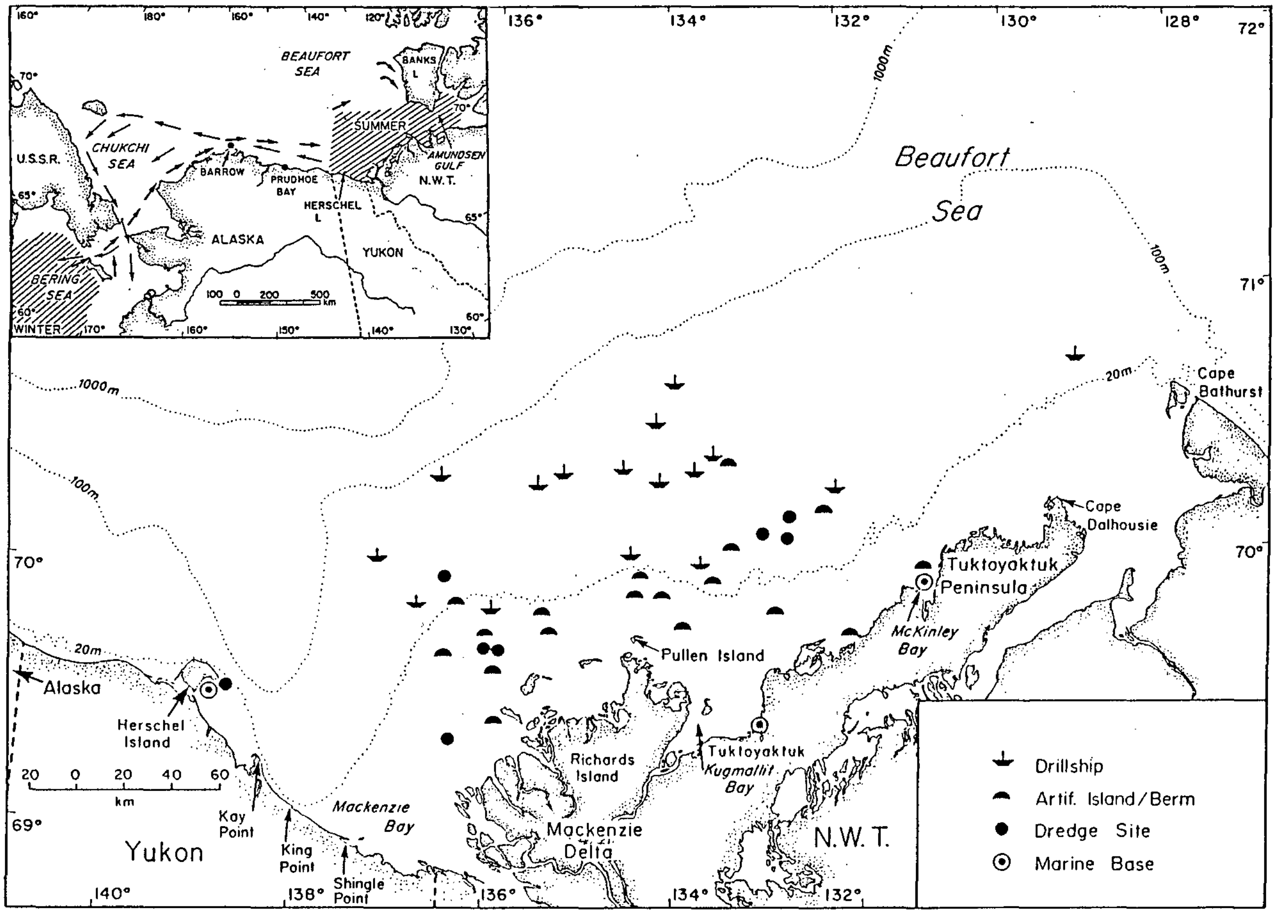

FIGURE 1. The eastern Beaufort Sea, study area for this project, showing the main sites of offshore industrial activity in August and early September, 1980-84. **Inset:** Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

offshore activities associated with the oil industry, including boat and aircraft traffic, seismic exploration, dredging and drilling (Acoustical Society of America 1981; Richardson et al. 1983). Many of the sounds produced are at rather low frequencies (below 1000 Hz). This is the frequency range of most bowhead calls (Ljungblad et al. 1982b; Clark and Johnson 1984). Hearing sensitivity of baleen whales has not been measured, but the predominance of low frequency calls (Thompson et al. 1979) plus anatomical evidence (Fleischer 1976) suggest specialization for detecting low frequencies.

Sound, unlike light, can propagate long distances through water (Payne and Webb 1971; Urick 1975). With calm to moderate sea states, noise from boats, dredging and drilling is readily detectable by instruments, and probably by bowheads, at ranges of several kilometres or more (Richardson et al. 1983). Noise from seismic exploration in open water is much more intense, and often detectable at ranges of several tens of kilometres (Ljungblad et al. 1980, 1982a; Richardson et al. 1983; Reeves et al. 1984). It is probable, therefore, that bowheads detect noise from offshore oil exploration and other offshore industrial operations at rather long distances--much longer than the distances to which vision or other sensory modalities could detect the industrial activity.

Within the often-large area around industrial activity where a bowhead could detect industrial noise, there is the potential for disturbance. This could take at least four interrelated forms: disruption of normal behavior, displacement (short- or long-term), physiological stress, or masking of natural sounds. The potential negative effects of these types of disturbance were discussed at length in the reviews cited above.

The importance of interference with detection of natural sounds is perhaps the least obvious of these types of potential disturbance. Increased noise levels reduce signal to noise ratios and, consequently, the range at which the sound signal becomes undetectable. Calls by baleen whales seem important for communication (Clark 1983), sometimes over distances of kilometres (Watkins 1981; Tyack and Whitehead 1983). Increased noise levels at frequencies similar to those of the calls will reduce the distances over which the calls can be detected. Detection of other environmental sounds may also be important to bowheads. For example, noise from ice or breaking waves may be important in finding open water within areas of heavy ice. Industrial noise may reduce the range to which bowheads can detect such noises, and consequently may delay whale movements in the presence of ice, or even increase the probability of entrapment by ice.

OBJECTIVES AND TASKS

Because of the endangered status of the bowhead whale, U.S. regulatory agencies were required, before permitting offshore hydrocarbon exploration in Alaskan waters, to assess whether that exploration would harm bowheads. After consultation among the responsible agencies, it was decided that there was insufficient information to determine the degree of jeopardy. Hence, research concerning the acoustic and non-acoustic effects of offshore hydrocarbon activities on bowheads was deemed necessary.

As part of its response, the U.S. Department of the Interior (USDI) awarded LGL Ecological Research Associates, Inc., a contract to investigate various aspects of potential industrial disturbance. The work was administered through USDI's Bureau of Land Management in 1980-81, and the Minerals Management Service in 1982-85. The general objectives were as follows:

1. "Identify and describe, qualitatively and quantitatively, the daily and seasonal behavior (e.g., feeding, breeding, calving) and activity patterns of the various age and sex classes of bowhead whales that occur in the eastern Beaufort Sea, and as it relates to the U.S. Beaufort Sea lease sale area.

2. "Determine, as possible, how and to what extent acoustic and [other] stimuli from oil and gas exploration/development activities may be expected to affect the distribution, movements, activities and activity patterns, and, ultimately, the survival and productivity of bowhead whales.

3. "Provide reliable baseline information which, in conjunction with long-term monitoring programs, can be used to detect changes in bowhead whale distribution, movements, activity patterns, etc. that may be caused by offshore oil and gas development in the Beaufort Sea.

4. "Assist ... (a) [in determining] the seasonal distribution and movements of bowhead whales in and adjacent to the Beaufort Sea Lease Sale Area; and (b) identify and characterize bowhead whale feeding areas, breeding/calving areas, or other areas of similar biological significance that may occur in or adjacent to the Beaufort Sea Lease Sale Area.

5. "Meet the study requirements of the Beaufort Sea, Endangered Species Act, Section 7 consultation..."

To address these objectives, four main tasks were defined at the start of the project, and a fifth task was defined in a subsequent contract modification:

<u>Task 1:</u> Prepare a literature review concerning (a) the distribution, movements, and activities, of bowhead whales; (b) the stimuli associated with offshore oil and gas exploration and development; and (c) present knowledge of the potential effects of those stimuli on bowheads. Task (1) was completed in 1980 (Fraker and Richardson 1980).

<u>Task 2:</u> Obtain baseline data on the activities and behavior of bowhead whales in the absence of sources of potential disturbance. This task was done because an understanding of the activities of bowheads in the absence of disturbance was necessary in order to interpret their behavior near industrial activities. There had been no previous study of the behavior of summering bowheads, and little previous study of behavior at any season. Task (2) was renewed for the entire 5-year duration of the project. However, in later years task (2) was a priority only when it provided specific control data needed for interpretation of disturbance responses.

<u>Task 3:</u> Conduct perturbation experiments and other studies to determine the behavioral reactions of bowhead whales to offshore oil and gas activities. Boat and aircraft traffic, seismic exploration, drilling, and construction activities were identified as the priority industrial activities. Both uncontrolled observational work and controlled experiments were required. Analysis of characteristics of waterborne sounds created by the industrial activities was considered to be part of the task. This task was renewed for all five years of the project, although priority activities changed from year to year as information accumulated about some topics.

<u>Task 4:</u> Determine the characteristics of bowhead feeding areas, with emphasis on zooplankton and the physical characteristics of the water masses. This task was limited in scope and was not continued after 1981. We

found that, in summer, bowheads tended to occur in areas with higher than average abundance of copepods, one of the known prey groups (Lowry and Burns 1980). The final report on this 1980-81 task was Griffiths and Buchanan (1982); the present volume does not cover this topic.

Task 5: Document occurrence and intensity of industrial activity in the Beaufort Sea during 1980-84 and, as possible, relate such patterns to recent trends in behavior and distribution of bowheads. This task was first identified in 1982; it included a retrospective analysis of existing 1980-81 data plus accumulation of additional data in 1982-84. The main intent was to assess whether there was any evidence of change in the distribution of summering bowheads with respect to the main area of offshore oil exploration in the eastern Beaufort Sea.

The present report summarizes the results pertaining to tasks (2), (3), and (5). Results from task (2) are covered in the 'Normal Behavior of Bowheads' section of this report (Würsig et al. 1985). Results from task (3) are covered in the 'Disturbance Responses of Bowheads' section (Richardson et al. 1985c) and in the 'Characteristics of Waterborne Industrial Noise' section (Greene 1985). Task (5) is covered in the 'Distribution of Bowheads and Industrial Activity' section (Richardson et al. 1985a). The present report is a self-contained account of the main results from all five years of the study, including previously unreported results from 1984. Additional details for 1980-81, 1982 and 1983 can be found in earlier reports (Richardson [ed.] 1982, 1983, 1984).

The present report excludes certain aspects of the project. Tasks (1) and (4) ended with the submission of the aforementioned reports by Fraker and Richardson (1980) and Griffiths and Buchanan (1982). A joint effort by Naval Ocean Systems Center and LGL to study bowhead behavior and reactions to seismic vessels in the Alaskan Beaufort Sea in autumn 1981 is reported separately (Fraker et al. in prep.). Plans to conduct spring sound propagation tests in Alaska in 1982, and artificial island noise measurements in Alaska or Canada in 1983, could not be implemented because of logistical constraints; funds allocated for these two efforts were redirected to task (3) in 1984.

APPROACH IN THIS STUDY

Study Area

The study area was the same in each year of the study: the southeastern Beaufort Sea, including the area of offshore oil exploration and surrounding waters to the west, north and east (Fig. 1). Observation sites were between 127°W and 141°W, and from the shore to 190 km offshore. The study period each year has been from late July or early August to late August or early September. This area and season were chosen (1) to take advantage of summer weather, light and ice conditions, (2) because bowheads travel less and thus are easier to study when feeding in summer than when migrating in spring or autumn, and (3) because this is the part of the bowheads' range where offshore oil exploration is furthest advanced. The presence of extensive offshore oil exploration provided opportunities for observation that did not exist in the Alaskan Beaufort Sea. Because this study was conducted in the eastern (Canadian) Beaufort Sea, site-specific information about reactions of bowheads to industrial activities in the Alaskan lease areas was not obtained. However, we believe that most data collected in the eastern Beaufort Sea are applicable to the Alaskan situation.

The eastern Beaufort Sea is largely ice covered from October to June, but by July there is usually open water south and east of a line from Herschel Island northeast to Banks Island (Fig. 1). However, wind shifts can blow much ice back into this area at any time. Most of our work was on whales in open water, but some was near or in pack ice. In most parts of the study area, water depths increase very gradually out to the shelf break near the 100 m contour, and then increase more rapidly to >1000 m (Fig. 1). The 100 m contour ranges from 15 to 150 km from shore.

Bowhead distribution in summer is variable within and between years. Whales occur in both open water and pack ice, both beyond the shelf break and in water as shallow as 10 m (Fraker and Bockstoce 1980; this study). August and early September are times of peak abundance in shallow areas. Feeding, socializing and travelling are the main activities.

Offshore drilling in the eastern Beaufort Sea began in 1972, initially from artificial islands built in a few metres of water off the Mackenzie River Delta, but after 1976 in deeper water. Each summer from 1976 to 1984, 3-5 drillships operated inside the 100 m contour, and artificial islands and caissons for drilling were completed in waters as deep as 31 m (Fig. 1). Dredges were widely used in constructing islands. By 1983-84, five drillships, 5-6 seagoing dredges, four icebreakers, 8-10 helicopters, and over 30 support vessels were in use offshore. Offshore seismic exploration occurs in the study area each summer. At most times in recent open water seasons, 2-4 seismic boats using airgun arrays or other high-energy noise sources have operated in the eastern Beaufort Sea. Each seismic boat produces an intense noise pulse every 6-15 s.

Approach and Logistics

Behavior of undisturbed bowheads (Task 2) was studied before and after disturbance experiments, thereby providing control data, and on other occasions when experiments were not possible. When logistical difficulties prevented us from conducting experiments, we collected data on undisturbed behavior.

Whenever possible in all years of the study, we conducted experimental tests of reactions of bowheads to industrial activities (Task 3). In these tests, we compared behavior of a specific group of bowheads before, during and after exposure. This method is more sensitive than uncontrolled observations of some whales in the presence of the industrial activity and others in its absence. Many factors aside from industrial activity may differ between groups of whales observed at different places and times. However, the uncontrolled observations were also of interest. For example, they showed that some bowheads approached full-scale industrial sites that could not be simulated adequately during experiments.

No field work specifically directed at determining bowhead distribution in relation to industrial activities (Task 5) was funded under this project. However, many distributional data were obtained incidental to our behavioral work. When task (5) was initiated in 1982, we compiled these distributional data, along with results from other studies of bowheads conducted in the same study area during 1980-84.

Our observations were obtained from three types of 'platforms'--aircraft, boats, and shore:

Aircraft: Most behavioral observations were from an aircraft circling high enough above whales to avoid aircraft disturbance. The aircraft crew had the advantages of great mobility and a good vantage point for observations. The aircraft crew could drop sonobuoys near bowheads to record the underwater sounds to which whales were exposed, as well as the calls that they emitted. An Islander aircraft was used in all years, although a Twin Otter was also used for part of the 1983 field season.

Boat: A boat, usually a 12.5-m fishing vessel, was chartered for at least part of each field season. The main functions of the boat were to conduct disturbance experiments, to record underwater sounds near whales and near industrial sites, and (in 1980-81 only) to conduct the 'characteristics of bowhead feeding areas' task.

Shore: Shore based observations were attempted at Herschel Island and King Point (Fig. 1) in 1980-81 but not in 1982-84. Many whales had been seen close to shore at these locations in some earlier years (Fraker and Bockstoce 1980). Virtually none were near King Point in 1980-81, and those near Herschel Island were too far offshore for effective shore-based observations or experiments. No shore based work was attempted in 1982-84. In 1983 and 1984 bowheads did occur close to shore at King Point, and much of our aircraft- and boat-based work in 1983 was in that area.

Results from the various tasks, platforms and years of the study were complementary. Detailed results from all five years are presented in the following four sections on normal behavior, disturbance responses, characteristics of waterborne industrial noise, and summer distribution relative to industrial activities. Results concerning zooplankton composition and biomass in some locations where bowheads were and were not observed in August 1980 and 1981 were presented in an earlier final report (Griffiths and Buchanan 1982). A summary of the entire study appears in a separate volume (Richardson, Greene and Würsig 1985b).

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NORMAL BEHAVIOR OF BOWHEADS, 1980-84*

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TABLE OF CONTENTS

ABSTRACT

Behavior of bowheads was observed during August and early September of 1980-84, mainly during 98.5 h while an observation aircraft circled at altitude $\geq$457 m above 'presumably undisturbed' whales. In 1980, 1983 and 1984, most whales studied were in waters 10-30 m deep, although not in the same areas during various years. In 1981 they were often in water about 50 m deep, and in 1982 most were in water >100 m deep. Year to year variation in distribution and behavior may have been attributable to changes in zooplankton availability, although this is unproven.

Surfacing, Respiration and Dive Cycles.--Intervals between successive blows were relatively stable, averaging 13.5 ± s.d. 8.88 s (n = 5161, calves excluded) over the five years. Number of blows per surfacing (4.34 ± 3.254, n = 626) and duration of surfacing (1.19 ± 1.137 min, n = 715) were positively correlated. Dives averaged 4.42 ± 6.319 min in duration (n = 333), with a skewed distribution and a maximum of 31 min. Blow rate, averaged over surface plus dive time, was 1.10 ± 0.873 blows/min (n = 156). Surfacing-respiration-dive variables were not strongly related to time of day or date in season but were different for mothers and calves than for other whales.

Feeding occupied much of the time of bowhead whales in summer. Whales sometimes skim fed at the surface either alone or in coordinated echelons of up to 14 animals. Bottom feeding was indicated when whales surfaced with mud emanating from their mouths, usually in water 6-24 m deep and with whales >75 m apart. Near bottom feeding was suspected on other occasions when mud streamed from the body but not the mouth. We suspected that whales fed in the water column on the many occasions when they dove repeatedly in an area without making forward progress, and did not surface with mud.

Social behavior, including nudging, chasing, or orienting toward one another when $\leq$½ body length apart, was more frequent in early August than later in summer. Apparent mating was seen only twice. Bowheads in groups often surfaced and dove in rough synchrony, and those within 3 km of one another did so at times.

Other behaviors.--On four occasions, we saw whales play with logs up to about 10 m long. Two cases of calf play consisted of orientation toward suspended or floating particles. Aerial activity consisted mainly of breaches, tail slaps, and flipper slaps. One whale breached 64 times, tailslapped 36 times, and flipperslapped 49 times in 75 min. Pre-dive flexes, consisting of a concave bending of the back, and raised flukes as the whale dove, were most common before long dives. Underwater blows occurred irregularly, but often during socializing.

INTRODUCTION

Several early authors--notably Scoresby (1820), Scammon (1874) and Bodfish (1936)--discussed behavior of bowheads, mainly of whales that were under stress during capture. Systematic observations of undisturbed behavior commenced only recently. Braham et al. (1979) and Rugh and Cubbage (1980) gathered information about durations of dives, surface times and swimming speeds for bowheads migrating past Cape Lisburne, Alaska, and Davis and Koski (1980) and Koski and Davis (1980) did similar work on bowheads migrating in the eastern Canadian arctic. Everitt and Krogman (1979) described six whales that were apparently involved in mating activity during the spring migration past Point Barrow, and there are other accounts of bowheads engaging in precopulatory behavior in the Bering and Chukchi Seas in spring. It has been known since commercial whaling days in the 19th century that feeding is the predominant activity of bowheads in the Beaufort Sea in summer.

Our study of behavior of undisturbed bowhead whales in the Canadian Beaufort Sea was conducted along with a study of disturbance responses (Richardson et al. 1985c) during the summers of 1980 through 1984. Results of these studies were described in yearly reports to the U.S. Minerals Management Service, and data for 1980-1982 are published in Würsig et al. (1984a, in press). The present report summarizes data for all five years of research. In 1982-84, a study similar to ours has been conducted on bowhead whales feeding and migrating in the Alaskan Beaufort Sea later in the season, in September. The behavioral findings of this Alaskan work for 1982 and 1983 are in Reeves et al. (1984) and Ljungblad et al. (1984b), respectively.

Objectives and Approach

The two main objectives of the 'Normal Behavior' task were (1) to provide a description of presumably undisturbed behavior immediately before and after experimental disturbance trials, against which the results of these trials could be compared, and (2) to provide general information on the normal behavior of bowhead whales. The first task is essential to an interpretation of how whales react to potential disturbance, and we attempted to obtain information on the behavior of the same individual animals immediately before and after the period of potential disturbance. The second main objective of the normal behavior study is also essential to a study of potential disturbance, because we must have a basic knowledge of undisturbed behavior patterns in order to properly assess disturbance reactions. There was considerable variability in behavior from year to year, and an ongoing study of normal behavior allows us to address whether whales might be more susceptible to disturbance in some situations or years than in others. Normal behavior studies were carried out (1) in association with experimental disturbance trials, and (2) when studies of disturbance effects were not possible.

Background information concerning the rationale and design of the study, and the choice of the eastern Beaufort Sea as the study area, is given in the previous section 'Project Rationale and Design' (Richardson et al. 1985b).

Field work occurred mainly in August, with some additional observations in late July and early September during certain years. Work was based at Tuktoyaktuk, Northwest Territories (Fig. 1). Observations of behavior were conducted from the air, from a boat, and--in 1980 and 1981 only--from shore

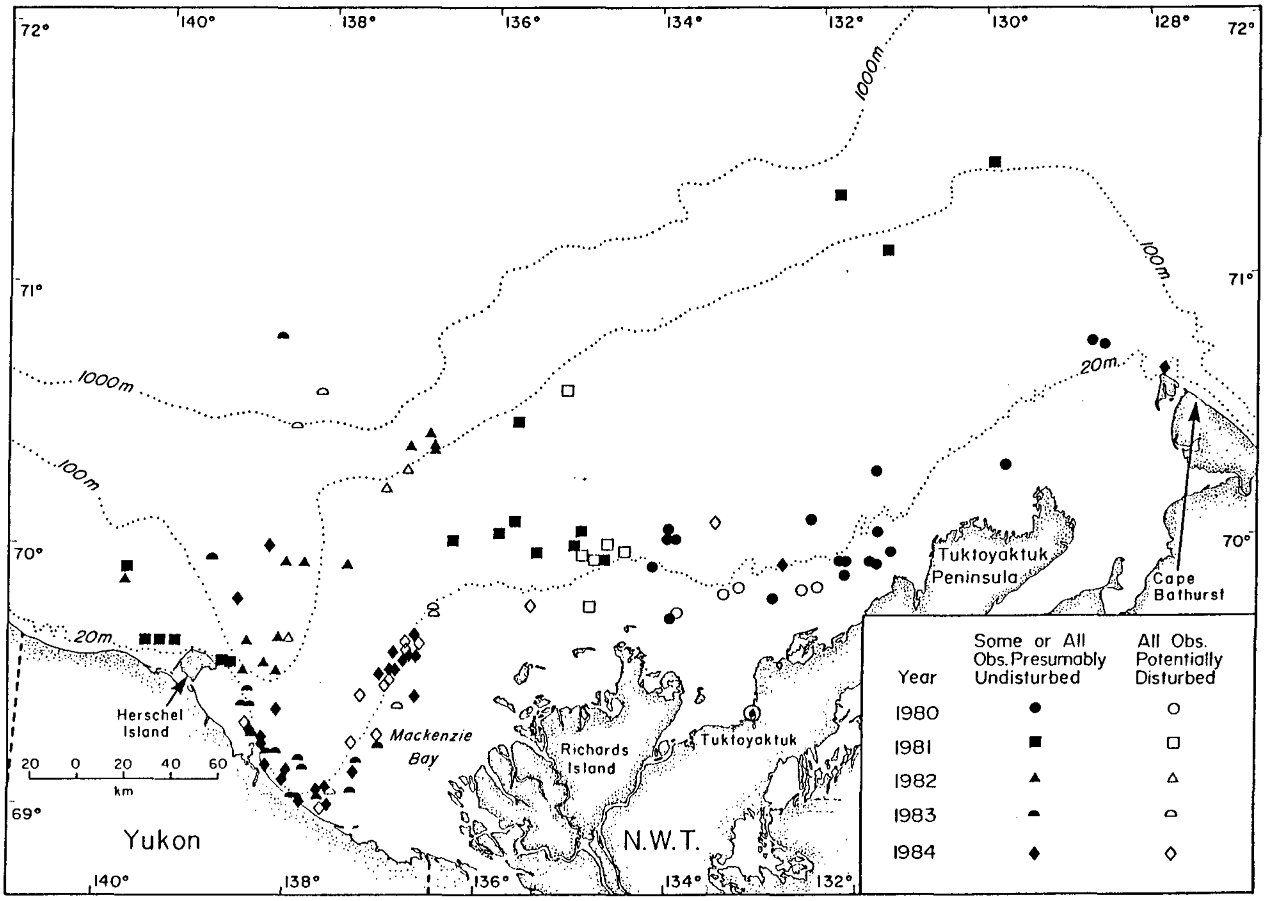

FIGURE 1. Eastern Beaufort Sea region showing bathymetry, locations mentioned in the text, and locations of behavioral observation sessions.

at Herschel Island, Yukon. Aircraft-based observers had the advantage of high mobility and a good vantage point and consequently collected most of the behavioral data. When whales were observed, sonobuoys were often dropped from the aircraft to allow us to hear and record bowhead sounds. Sonobuoys also allowed us to determine when industrial noises were present in the water. Boat-based observers used hydrophones for this purpose. Observations of bowheads in the presence of strong industrial noise may not represent undisturbed behavior, and were excluded from this section on 'Normal Behavior'.

METHODS AND DATA BASE

Aerial Observations

Most behavioral observations were made from a Britten-Norman Islander aircraft, although observations from 1-12 August 1983 were from a deHavilland Series 300 Twin Otter. These aircraft have twin engines, high wing configuration, and low stall speed. Both aircraft were equipped with radar altimeters and Very Low Frequency (VLF) navigation systems. Positions and flight tracks were recorded manually from the VLF systems. Both aircraft had an endurance of about 5.5-6.0 h plus reserves. The Islander had a forward-looking radar useful for determining distances to industrial sites, shore, etc. Sonobuoys (AN/SSQ-57A or AN/SSQ-41B) were deployed and monitored from both aircraft in order to record waterborne sounds from bowheads and industrial sources (details in Greene 1985). A hand-held color video camera (JVC-CV-0001 or Sony HVC-2000) connected to a portable videocassette recorder (Sony SLO-340 or SL-2000) was used through a side window to record oblique views of bowheads.

Our usual strategy was to search until we encountered bowheads and then circle over them as long as possible while making observations. Once contact was lost, we searched for another group. We created a fixed reference point about which to circle when bowheads were below the surface by deploying a dye marker (1-2 teaspoons of fluorescein dye in about 1 litre of water in a plastic 'freezer' bag, which burst on impact with the water). Near the start of most periods of circling above whales, a sonobuoy was deployed.

We made 132 offshore flights during the five seasons, and we gathered behavioral observations of bowheads during 85 of these flights. Most flights lasted 4 to 5.5 h, and we observed bowhead whales for a total of 186.3 h. We usually did not fly when wind speed exceeded 25 km/h; whales are difficult to detect and behavior is not reliably observable in more severe conditions. While searching for whales, we usually flew at 457 or 610 m (1500 or 2000 ft) above sea level (a.s.l.), and at 185 km/h. Bowheads rarely appeared to be disturbed by the aircraft when it remained at or above 457 m (Richardson et al. 1985c).

The aircraft crew usually consisted of four biologists and the pilot. In the Islander, from which most behavioral observations were obtained, three biologists were seated on the right side of the aircraft, which circled to the right when we were obtaining behavioral observations. Biologists seated in the right front (co-pilot's) seat and in the seat directly behind it were responsible for describing whale behavior. This information was recorded onto audiotape and also, on most occasions, onto the audio channel of the videotape recorder. A third biologist in the right rear seat operated the video camera during most periods while we circled above whales visible at the surface. That individual was also responsible for some record keeping, radar measurement of distances to industrial activities, and overall direction of the work. A fourth biologist, in the left rear seat, searched for bowheads outside of the area being circled, launched sonobuoys and dye markers, and operated sound recording equipment. The biologists and pilot were in constant communication via intercom. The Twin Otter circled to the left during behavioral observations; three biologists were seated on the left side behind the pilot and one in the right front (co-pilot's) seat.

We obtained consistent data of 15 types:

1. Location of sighting (and therefore approx. water depth from charts);
2. Time of day;
3. Number of individuals visible in area; number of calves;
4. Individually distinguishing features (if any) on whales;
5. Heading in degrees true, turns, and estimated swimming speed of each whale;

6. Distances between individuals (estimated in adult whale lengths);
7. Durations of time at surface and sometimes duration of dive;
8. Timing and number of respirations, or blows;
9. Indications of feeding: e.g., open mouth, defecation, mud streaming from mouth;
10. Socializing; probable mating;
11. Probable nursing;
12. Play with surface debris or logs;
13. Underwater blow (releasing a large burst of bubbles underwater);
14. Aerial activity: breaches, tailslaps, flipper slaps, lunges, rolls;
15. Behavior at start of dive: fluke out, peduncle arch, pre-dive flex.

Descriptions of these behaviors appear later in this report and, in more detail, in Würsig et al. (in press).

We were at times able to identify whales by sight, within an observation flight, based on distinctive chin patch shapes or white marks on the back or tail, and we were then able to determine dive durations for these individuals. Davis et al. (1983) showed that smaller bowheads tend to have fewer such white marks than do larger whales.

Water depths were determined by consulting Canadian Hydrographic Service chart #7650 (1980 printing) and Dome Petroleum Ltd. chart E-BFT-100-03. The distributions of behavioral observations by 10-day period, depth of water, and hour of day are presented in Figure 2. Most observations in 1980, 1983, and 1984 were in shallow water. Most observations in 1981 were in somewhat deeper water, and those in 1982 were in still deeper water, often near the edge of the continental shelf (Fig. 1).

In this section of the report, with rare exceptions that are specifically indicated, we describe only the behavior observed with no known potential disturbances. Data collected during periods of potential disturbance are described separately in the 'Disturbance' section (Richardson et al. 1985c). Whales were classified as 'presumably undisturbed' only if the observation aircraft was at an altitude of at least 457 m (1500 ft) a.s.l., no vessels were underway within 4 km, and no other industrial activities were close enough to create waterborne sounds prominent to the human ear. Observations in the presence of noise impulses from distant seismic vessels were treated as potentially disturbed and were excluded. Some observations were collected when our 12.5 m boat was nearby; the whales were considered to be presumably undisturbed if the boat had been anchored or drifting quietly with engine off for at least 30 min. Of 186.3 h spent observing bowheads, 98.5 h were during presumably undisturbed periods.

Behavioral observations were transcribed from audiotape onto data sheets during periods of poor weather between observation flights. The videotape was also examined at this time to provide additional details not noted in real time. After the field season, transcriptions were checked again with the audiotape and converted into a standardized numerical format with one record per surfacing or dive of each whale that was under detailed observation. These records were hand-checked by a different individual and entered into a microcomputer for subsequent computer validation, tabulation, and statistical analysis. The standardized data files contain the following:

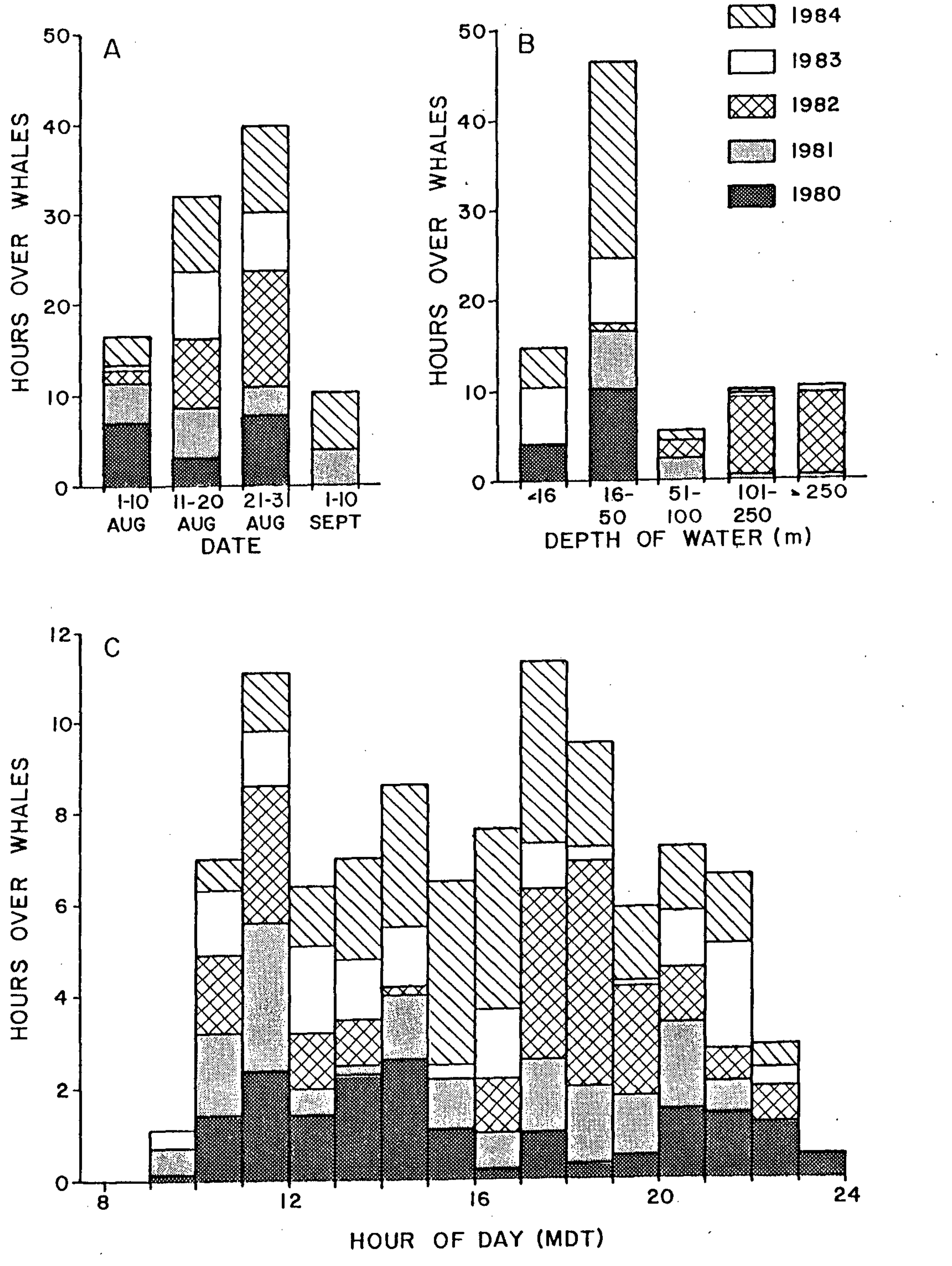

FIGURE 2. Distribution of behavioral observation time (98.5 h) from the air during presumably undisturbed periods, 1980-84, categorized by (A) date, (B) depth of water, and (C) time of day.

Year	Surfacing Records	Dive Records	Total Records
1980	563	223	786
1981	778	223	1001
1982	312	141	453
1983	1401	242	1643
1984	1283	129	1412
Total	4337	958	5295

Of these, 2129 surfacing and 475 dive records were from presumably undisturbed periods.

Methods of analysis of bowhead sounds recorded via sonobuoys are described in the 'Bowhead Sounds' section of the results, below.

Shore and Boat-Based Observations

Most behavioral observations were made from the air, but observations from shore and a boat at times helped us to understand activity patterns when the airplane was not present, and allowed us to obtain some data (precise speed information, for example) that we could not obtain from the air. Our limited theodolite tracking information appears in Würsig et al. (in press) and is not repeated here. Because our observations from boats pertain mostly to disturbance trials, these data are detailed in the 'Disturbance' section.

RESULTS

Respiration, Surfacing and Dive Characteristics

Four characteristics of a surfacing lend themselves to repeated quantitative sampling: the interval between blows in a surfacing (blow interval), the number of blows per surfacing, the duration of surfacing (surface time) and the duration of dive between surfacings (dive time). Because these variables are comparatively easy to assess quantitatively, they are suitable for use in analysis of responses to disturbances. A detailed understanding of respiration, surfacing and dive behavior under undisturbed conditions is a prerequisite for interpretation of disturbance responses.

Definition of Terms

The measurement of each of these four quantities depends on how a surfacing and dive are defined. Bowheads that are migrating or travelling for relatively long distances usually make two distinguishable types of dives--brief, shallow dives between successive respirations, and long, deeper dives between these groups of respirations. Rugh and Cubbage (1980) called the two types of dives series dives and sounding dives, respectively. Most bowheads observed in this study, however, remained at the surface between successive respirations. Moreover, from our aerial vantage point we could not always determine whether a whale was at the surface or slightly below it. As a result, we defined only one type of dive, the sounding dive, during which the whale was out of sight underwater. We defined a surfacing as the period of time during which the whale was at the surface or, from our aerial vantage point, visible just below the surface. Thus any shallow 'dives' that occurred for a few seconds between respirations were not counted as dives, or as interruptions of a surfacing.

Observers working from low vantage points on ice, shore or a boat would treat such shallow dives differently, because the whale would usually be out of their sight as soon as it went below the surface. Thus the definitions of surfacings and dives used in this study are in part a function of our aerial vantage point, and one must use caution when comparing our data with those collected from low vantage points.

On rare occasions a whale remained visible just under the surface of the water for periods of up to several minutes; these were considered dives if they exceeded an arbitrary minimum of 60 s. We used an additional convention in 1983 and 1984, when the water at observation sites was usually more turbid than in previous years; in these cases, whales were less easily visible while underwater. Periods of submergence lasting less than 15 s were not counted as dives in 1983-84 unless, before submerging, the whale lifted its flukes out of the water, arched strongly or performed a pre-dive flex.

A blow is an exhalation of air by a whale. It can occur either above or below the surface. Surface blows are usually visible as a misty white cloud. We calculated blow intervals only for successive blows within a single surfacing when our view of the whale was not interrupted between the blows. Underwater blows become visible at the surface as a white circular burst of bubbles that may grow to 15 m in diameter. They are discussed in a later section.

Calves, because of their small size, are much more difficult to observe when just under the surface of the water than are adults under similar conditions. We analyzed our observations of calves separately and will present that analysis following the non-calf observations. The remainder of this section considers undisturbed whales excluding calves, i.e. all adults and subadults that we observed.

Blow Interval

In 1980-84, we measured 5161 blow intervals for undisturbed non-calves. The frequency distributions were very similar in all five years; the modal category of blow intervals was 10-13 s in each year. The year 1984 had the shortest mean blow interval of the five years, and 1983 had the longest. Table 1 presents the summary statistics for blow intervals for the five years of this study. The overall mean blow interval for presumably undisturbed non-calves observed in 1980-84 was 13.5 ± 8.88 s (n = 5161, range = 1-173 s).

We wondered whether the first blow interval in a surfacing might be shorter than subsequent blow intervals, i.e., whether a whale tends to breathe more quickly at the start of a surfacing than for the remainder of a surfacing. For each year, we compared the first blow interval and the mean of the subsequent blow intervals in all surfacings that had three or more blows (two or more blow intervals) and for which all blows were timed. Only presumably undisturbed non-calves were considered. On average, the first blow interval was significantly shorter only in 1982 (paired t = 2.40, df = 43, $0.02<p<0.05$), which was the year with the longest dives and longest surfacings. In 1981 and 1983, the first blow interval averaged shorter than the mean of the subsequent blow intervals, but not significantly so, while in

Table 1. Summary statistics for the principal surfacing, respiration and dive variables in presumably undisturbed bowheads in 1980-84. Calves are excluded from every line except that labelled 'calves'.

		Blow interval (s)			Number of blows per surfacing			Length of surfacing (min)			Length of dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
All non-calves	1980	12.9	8.61	915	4.8	2.91	70	1.25	0.723	94	2.25	3.549	25
	1981	13.0	8.08	1113	4.2	2.91	194	1.06	0.764	204	3.80	4.986	80
	1982	14.9	8.66	795	7.4	5.11	58	2.05	1.320	70	12.08	9.153	51
	1983	17.0	13.49	866	3.2	2.37	229	1.05	1.484	248	1.88	2.357	140
	1984	11.6	4.66	1472	5.5	2.97	75	1.10	0.559	99	6.27	7.195	37
	1980-84	13.5	8.88	5161	4.3	3.25	626	1.19	1.137	715	4.42	6.319	333
Calves	1980	15.1	10.30	30	3.3	2.06	4	0.71	0.472	5	1.80	1.958	3
	1981	11.6	7.65	34	0.8	1.47	11	0.70	0.569	16	1.02	1.503	6
	1982	18.6	16.05	100	4.0	2.49	19	1.66	1.459	21	6.82	5.715	29
	1983	11.5	5.07	4	1.1	0.90	7	0.36	0.478	8	1.98	2.720	7
	1984	8.4	2.01	10	—	—	0	1.20	0	1	—	—	0
	1980-84	16.0	13.58	178	2.6	2.45	41	1.05	1.131	51	4.96	5.358	45
Adults with calf	1980	14.1	6.65	49	3.2	3.13	6	0.91	0.683	9	0.96	1.692	5
	1981	15.1	5.30	91	3.9	2.98	11	1.38	1.065	13	9.99	7.707	10
	1982	18.6	9.45	178	6.4	4.77	20	2.30	1.593	23	8.62	5.862	22
	1983	18.0	9.29	7	5.0	—	1	1.45	0.259	2	12.18	1.002	2
	1984	—	—	0	—	—	0	—	—	0	—	—	0
	1980-84	16.9	8.27	325	5.1	4.16	38	1.74	1.387	47	8.17	6.485	39
All other non-calves	1980	12.8	8.71	866	4.9	2.87	64	1.29	0.722	85	2.57	3.842	20
	1981	12.8	8.26	1022	4.2	2.91	183	1.04	0.738	191	2.92	3.791	70
	1982	13.8	8.11	617	8.0	5.25	38	1.93	1.164	47	14.70	10.361	29
	1983	17.0	13.52	859	3.2	2.37	228	1.05	1.489	246	1.73	2.015	138
	1984	11.6	4.66	1472	5.5	2.97	75	1.10	0.559	99	6.27	7.195	37
	1980-84	13.3	8.88	4836	4.3	3.19	588	1.15	1.108	668	3.92	6.138	294

Continued...

Table 1. Continued.

		Blow interval (s)			Number of blows per surfacing			Length of surfacing (min)			Length of dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
Skim-feeding whales	1980	13.7	11.36	30	—	—	0	—	—	0	—	—	0
	1981	16.4	12.90	48	2.8	2.05	13	0.70	0.702	12	3.34	4.258	9
	1982	—	—	0	—	—	0	—	—	0	—	—	0
	1983	31.7	23.79	120	6.9	3.99	10	5.20	3.636	15	0.93	1.001	16
	1984	—	—	0	—	—	0	—	—	0	—	—	0
	1980-84	25.3	21.58	198	4.6	3.63	23	3.19	3.549	27	1.80	2.840	25
Bottom-feeding whales	1980	—	—	0	—	—	0	—	—	0	—	—	0
	1981	—	—	0	—	—	0	—	—	0	—	—	0
	1982	—	—	0	—	—	0	—	—	0	—	—	0
	1983	11.5	5.39	6	3.0	2.65	3	0.13	0.130	2	0.42	0.024	2
	1984	11.9	5.13	133	7.0	3.42	7	1.43	0.480	10	12.31	14.555	2
	1980-84	11.9	5.12	139	5.8	3.61	10	1.21	0.668	12	6.36	10.851	4
All other non-calves (not skim or bottom feeding)	1980	12.8	8.51	885	4.8	2.91	70	1.25	0.723	94	2.25	3.549	25
	1981	12.8	7.77	1065	4.3	2.94	181	1.09	0.668	192	3.86	5.095	71
	1982	14.9	8.66	795	7.4	5.11	58	2.05	1.320	70	12.08	9.153	51
	1983	14.6	8.97	740	3.0	2.14	216	0.79	0.600	231	2.03	2.466	122
	1984	11.6	4.62	1339	5.3	2.91	68	1.06	0.557	89	5.93	6.806	35
	1980-84	13.1	7.66	4824	4.3	3.23	593	1.10	1.051	676	4.61	6.427	304
Socializing whales (including only whales that were actively interacting)	1980	13.6	9.10	127	4.7	2.08	3	1.40	0.488	10	0.25	0.186	3
	1981	14.2	11.60	223	3.8	2.17	41	1.15	0.868	43	3.07	3.195	24
	1982	14.2	8.01	74	3.8	2.75	4	1.34	0.796	5	0.58	0	1
	1983	15.6	9.70	85	4.3	2.46	13	1.22	0.711	14	0.62	0.235	3
	1984	14.0	5.56	44	—	—	0	1.42	0.309	4	8.35	0	1
	1980-84	14.2	9.93	553	3.9	2.23	61	1.22	0.766	76	2.66	3.139	32

Continued...

Table 1. Continued.

		Blow interval (s)			Number of blows per surfacing			Length of surfacing (min)			Length of dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
Non-socializing whales (excluding whales <8 m apart that were not actively interacting)	1980	12.8	8.63	760	4.7	2.94	65	1.22	0.745	82	2.52	3.707	22
	1981	12.5	6.67	861	4.4	3.07	146	1.05	0.736	154	4.12	5.578	56
	1982	14.9	8.72	721	7.7	5.15	54	2.10	1.341	65	12.31	9.096	50
	1983	17.3	13.92	766	3.1	2.36	215	1.04	1.527	231	1.90	2.381	135
	1984	11.6	4.62	1428	5.5	2.97	75	1.10	0.557	93	6.51	7.399	34
	1980-84	13.4	8.75	4536	4.4	3.35	555	1.19	1.181	625	4.65	6.577	297
Single whales (excluding skim-feeders)	1980	13.3	10.20	324	5.2	3.20	32	1.32	0.955	33	1.26	2.154	7
	1981	12.1	5.08	394	5.4	3.07	51	1.24	0.684	56	3.89	4.709	20
	1982	13.7	8.22	530	8.6	5.09	31	2.10	1.190	40	15.82	9.844	27
	1983	14.0	7.89	521	3.0	2.15	151	0.71	0.540	151	2.12	2.466	74
	1984	11.6	4.66	1331	5.5	2.95	66	1.13	0.558	83	6.14	7.075	30
	1980-84	12.6	6.82	3100	4.6	3.40	331	1.10	0.822	363	5.41	7.474	158
Whales in groups (excluding skim-feeders)	1980	12.8	7.18	401	4.7	3.04	23	1.30	0.592	41	1.31	2.243	9
	1981	14.3	10.55	415	3.7	2.55	85	1.09	0.833	88	4.00	5.439	44
	1982	17.2	9.06	265	6.0	4.86	27	1.98	1.496	30	7.87	6.139	24
	1983	15.9	10.93	225	3.0	2.12	68	0.91	0.683	82	1.83	2.451	50
	1984	11.9	4.80	126	5.3	3.35	9	0.96	0.558	16	6.83	8.261	7
	1980-84	14.5	9.25	1432	4.0	3.05	212	1.16	0.904	257	3.85	5.200	134
Depth (m) <16	1980	12.6	7.13	89	2.7	1.67	19	0.70	0.403	24	0.76	1.236	9
	1981	—	—	0	—	—	0	—	—	0	—	—	0
	1982	—	—	0	—	—	0	—	—	0	—	—	0
	1983	19.4	16.58	459	3.4	2.66	111	1.32	1.934	131	1.69	1.757	87
	1984	11.0	4.11	221	6.0	2.77	13	1.07	0.469	15	12.44	7.809	10
	1980-84	16.2	13.79	769	3.5	2.67	143	1.21	1.722	170	2.62	4.251	106

Continued...

Table 1. Continued.

			Blow interval (s)			Number of blows per surfacing			Length of surfacing (min)			Length of dive (min)		
			mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
Depth (m)	16-50	1980	12.3	7.23	750	5.9	2.97	40	1.37	0.578	60	4.28	4.567	11
		1981	13.2	9.48	649	3.9	2.58	132	1.01	0.731	138	4.05	5.224	58
		1982	12.0	2.56	21	6.3	2.31	3	1.46	0.384	3	15.52	2.923	2
		1983	14.0	7.71	392	3.0	2.07	114	0.75	0.568	112	1.83	2.456	49
		1984	11.6	4.41	1191	5.5	3.19	52	1.12	0.596	74	4.64	6.622	17
		1980-84	12.5	6.97	3003	4.1	2.77	341	1.01	0.667	387	3.52	4.877	137
	51-100	1980	—	—	0	—	—	0	—	—	0	—	—	0
		1981	13.4	5.34	126	4.9	3.26	18	1.20	0.809	18	6.57	4.232	8
		1982	18.1	6.97	14	1.3	0.58	3	0.26	0.207	3	0.33	0.073	3
		1983	—	—	0	—	—	0	—	—	0	—	—	0
		1984	14.5	7.80	42	4.7	2.36	7	0.99	0.465	7	1.68	1.313	8
		1980-84	14.0	6.21	182	4.5	3.04	28	1.05	0.741	28	3.52	3.869	19
	101-250	1980	—	—	0	—	—	0	—	—	0	—	—	0
		1981	13.3	6.74	74	4.5	2.66	11	1.14	0.537	11	0.50	0.349	3
		1982	13.7	6.67	355	7.7	4.95	25	1.98	0.982	32	13.94	8.143	17
		1983	21.0	14.13	8	1.7	0.58	3	0.34	0.275	3	1.36	0.389	2
		1984	13.5	12.88	14	5.3	1.16	3	0.88	0.113	3	7.75	1.532	2
		1980-84	13.8	7.16	451	6.3	4.47	42	1.63	0.982	49	10.69	8.713	24
	>250	1980	—	—	0	—	—	0	—	—	0	—	—	0
		1981	11.5	4.95	19	—	—	0	—	—	0	—	—	0
		1982	15.9	10.18	405	8.0	5.42	27	2.34	1.572	32	11.96	9.679	29
		1983	18.0	9.29	7	5.0	0	1	1.45	0.259	2	12.18	1.002	2
		1984	—	—	0	—	—	0	—	—	0	—	—	0
		1980-84	15.7	10.02	431	7.9	5.35	28	2.29	1.539	34	11.98	9.353	31

Continued...

Table 1. Concluded.

		Blow interval (s)			Number of blows per surfacing			Length of surfacing (min)			Length of dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
Whales with flukes raised at end of surfacing/start of dive	1981	—	—	—	4.6	2.71	62	1.13	0.688	66	—	—	—
	1982	—	—	—	7.8	5.85	19	2.09	1.254	25	—	—	—
	1983	14.0	8.43	144	3.4	2.16	47	0.80	0.492	40	1.48	1.820	28
	1984	11.6	4.43	701	6.2	2.96	39	1.22	0.530	51	7.06	7.895	18
	1981-84	12.0	5.40	845	5.0	3.42	167	1.22	0.810	182	3.66	5.756	46
Whales with flukes not raised at end of surfacing/start of dive	1981	—	—	—	3.9	2.58	85	1.02	0.742	85	—	—	—
	1982	—	—	—	7.1	4.64	35	1.87	1.126	37	—	—	—
	1983	18.0	14.80	614	3.2	2.44	178	1.11	1.614	204	1.86	2.233	105
	1984	11.7	4.89	549	4.9	2.76	35	0.98	0.561	47	5.74	6.712	18
	1981-84	15.0	11.69	1163	4.0	3.05	333	1.15	1.329	373	2.43	3.524	123
Whales with pre-dive flex	1981	11.0	5.84	85	6.5	2.42	11	1.30	0.499	11	0.44	0.312	3
	1982	14.3	9.82	280	12.5	3.62	11	3.09	1.038	14	19.00	7.877	13
	1983	17.2	13.52	177	5.1	2.77	32	1.55	1.262	26	1.81	2.327	19
	1984	11.5	4.47	229	6.5	2.03	16	1.28	0.454	19	10.79	6.367	10
	1981-84	13.8	9.57	771	6.8	3.69	70	1.74	1.159	70	8.68	9.215	45
Whales without pre-dive flex	1981	13.2	8.59	534	4.3	2.73	105	1.07	0.723	109	5.05	4.970	40
	1982	15.4	8.12	473	6.2	4.68	44	1.79	1.284	52	10.15	7.465	36
	1983	18.2	14.73	517	2.9	2.19	177	1.04	1.624	186	1.75	2.088	97
	1984	11.9	4.83	841	5.2	3.14	59	0.99	0.582	63	5.68	7.796	19
	1981-84	14.3	9.55	2365	4.0	3.09	385	1.13	1.285	410	4.40	5.765	192

1980 and 1984 the first blow interval averaged slightly longer than the mean of the subsequent ones.

Blows per Surfacing and Duration of Surfacing

In 1980-84 we measured the number of blows per surfacing and the duration of surfacing in presumably undisturbed non-calves 626 and 715 times, respectively. The overall mean values were 4.34 ± s.d. 3.254 blows per surfacing (range = 0-19 blows) and 1.19 ± s.d. 1.137 min at the surface (range = 0.03-13.17 min). Table 1 presents the values for each year of this study. These two variables showed a highly significant positive correlation with each other in each year (Table 2B). This positive correlation is a result of the relative stability of blow intervals. The frequency distributions for number of blows per surfacing and duration of surfacing (Figs. 3B, 3C) show considerably more variation from year to year than do the frequency distributions for blow intervals.

Duration of Dives

Our estimates of mean dive duration are biased downward to a degree that has varied somewhat from year to year. The reason for this bias is that it is more difficult to find and recognize a whale when it resurfaces after a long dive than after a short dive. In 1982, the conditions for measuring durations of long dives were better than in any other year because many of the whales were recognizable and we often circled over only one or two whales and could be certain that we had not missed any surfacings. Table 1 presents the mean duration of dive measured for each year. The substantially higher mean dive time for 1982 is only in part the result of the reduced bias against long dives, however, for in that year it was obvious that most whales were in fact making proportionally more long dives and fewer short dives than in any other year. In 1983, we obtained the lowest mean dive time for the study, but there was an especially strong sampling bias against long dives: most whales we circled in 1983 had few or no distinguishing marks and were in relatively large groups. The overall mean dive time for presumably undisturbed non-calves for all five years of this study was 4.42 ± s.d. 6.319 min (n = 333, range = 0.03-30.98 min).

Figure 3D presents the frequency distributions for duration of dive. In all years except 1982 there was marked skewing of the frequency distributions. For this reason, all statistical comparisons of dive times were done non-parametrically.

In 4 of 5 years there was a significant positive correlation between dive times before and after a surfacing; in 1980 the correlation was strong (0.659) but only marginally significant due to low sample size (Table 2A). Thus, a whale tends to make a series of dives of similar length rather than alternating short and long dives.

In most years, the duration of the dive preceding a surfacing was better correlated with both the duration of that surfacing and the number of blows in it than was the duration of the dive following the surfacing. The number of blows per surfacing showed a positive correlation with previous dive time that was significant in all five years and highly significant in most of them (Table 2D). The duration of surfacing similarly showed a highly significant positive correlation with the duration of the previous dive in all years

Table 2. Degree of correlation between all pairs of the following four variables: number of blows per surfacing, duration of surfacing, duration of previous dive, and duration of subsequent dive. Only presumably undisturbed non-calves are included. r_s is the Spearman rank correlation.

A. Previous dive vs. subsequent dive[a]

	r_s	n	sign. level
1980	0.659	8	(*)
1981	0.371	35	*
1982	0.695	29	***
1983	0.313	80	**
1984	0.682	11	*

B. Number of blows vs. surface time[a]

	r_s	n	sign. level
1980	0.801	65	***
1981	0.852	193	***
1982	0.936	56	***
1983	0.829	218	***
1984	0.875	75	***

C. Previous dive vs. surface time[a]

	r_s	n	sign. level
1980	0.757	15	**
1981	0.509	73	***
1982	0.734	35	***
1983	0.033	116	ns
1984	0.613	26	**

D. Previous dive vs. number of blows

	r_s	n	sign. level
1980	0.859	13	***
1981	0.550	70	***
1982	0.677	32	***
1983	0.225	98	*
1984	0.607	24	**

E. Subsequent dive vs. surface time[a]

	r_s	n	sign. level
1980	0.150	14	ns
1981	0.149	59	ns
1982	0.448	31	*
1983	0.101	110	ns
1984	0.460	21	*

F. Subsequent dive vs. number of blows

	r_s	n	sign. level
1980	0.415	13	ns
1981	0.205	58	ns
1982	0.591	26	**
1983	0.114	100	ns
1984	0.612	19	**

significance levels:

ns :	$p>0.10$
(*):	$0.05<p\leq 0.10$
* :	$0.01<p\leq 0.05$
** :	$0.001<p\leq 0.01$
*** :	$p\leq 0.001$

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[a] See Würsig et al. (1984a) for scatter diagrams.

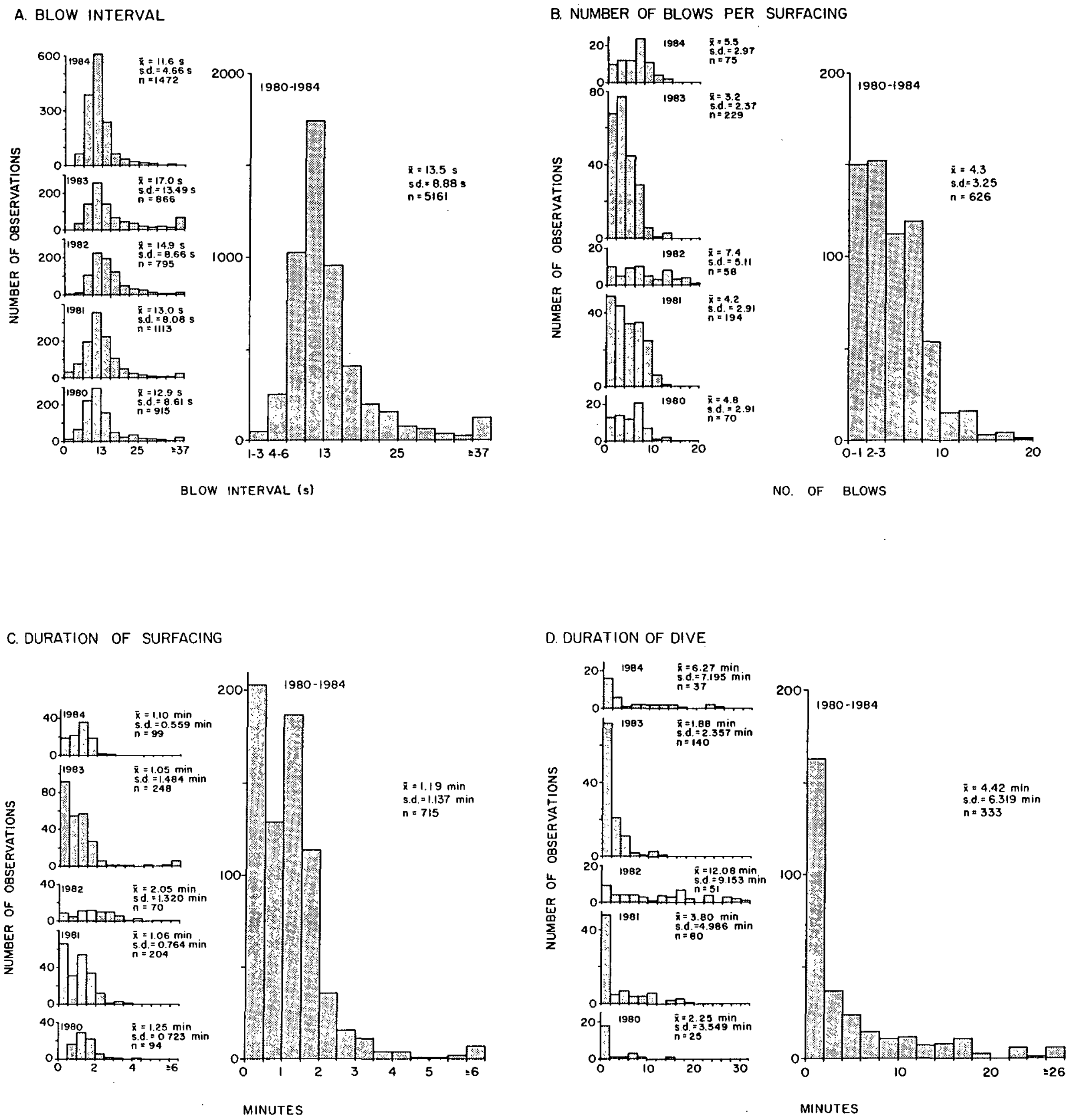


FIGURE 3. Frequency distribution of each of the four principal respiration, surfacing and dive characteristics for presumably undisturbed non-calves, 1980-84.

except 1983 (Table 2C). In contrast, number of blows per surfacing and surface time were significantly correlated with the subsequent dive time only in 1982 and 1984 (Table 2E, F). This suggests that the respiration and surfacing behavior of bowhead whales is determined more by the duration of the dive that has just ended than it is by the duration of the dive that is about to begin.

Blow Rate

The blow rate was calculated by dividing the number of blows during a complete surfacing by the sum of the durations of that surfacing and the subsequent dive (surface-dive cycles in which the dive was <30 s long were excluded from this analysis as too short to be meaningful). The resulting number of blows per minute is a function of the surface time, dive time, and number of blows per surfacing, and describes the respiratory activity of the whale during a longer period of time than any of the constituent variables considered separately. We measured the blow rate for presumably undisturbed non-calves 156 times in 1980-84 and obtained an overall mean value of 1.10 ± s.d. 0.873 blows per min (range = 0-4.36). The frequency distributions for blow rates (Fig. 4A) show considerable variability from year to year; the mean value for 1982 was the lowest observed.

Proportion of Time at the Surface

The proportion of time that a whale was at the surface was calculated from all surfacings of known duration that were followed by dives of known duration. As explained above, if a whale made shallow submergences between blows in the middle of a surfacing, it was considered to be at the surface the whole time. We measured the proportion of time at the surface for 235 surface-dive cycles for presumably undisturbed non-calves in 1980-84 and obtained an overall mean value of 0.38 ± s.d. 0.284 (range = 0.01-0.98). The frequency distributions for proportion of time at surface (Fig. 4B) vary considerably from year to year. The mean values in 1982 and 1984 were lower than in other years.

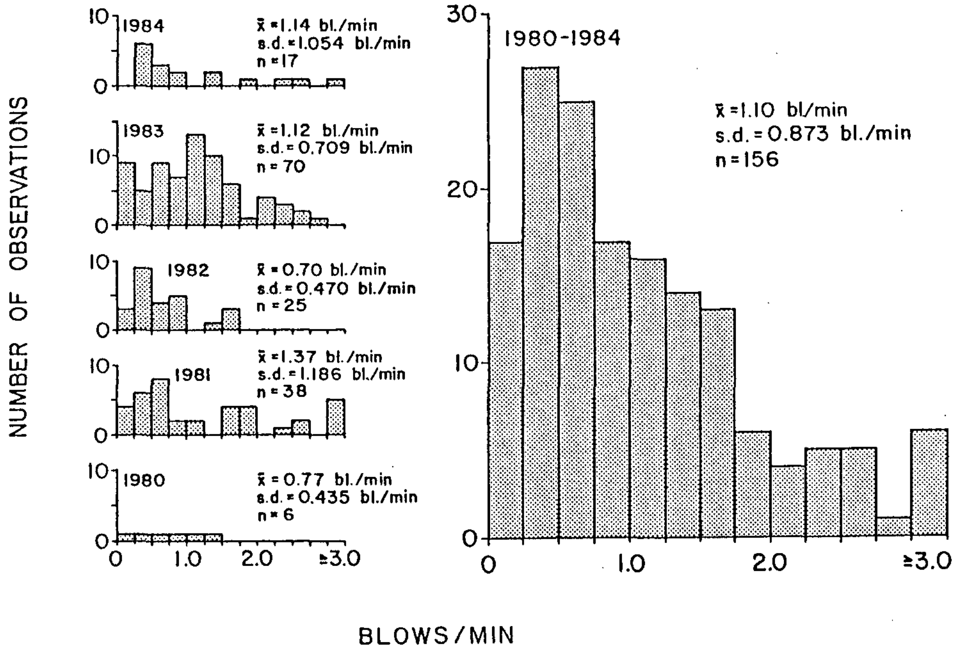
The data in Figure 4B weight each surfacing/dive cycle equally, regardless of its total duration. For purposes of evaluating sighting probability during aerial surveys, each cycle should be weighted proportional to its duration (Davis et al. 1982). Based on this method, the overall mean proportion of time at the surface was 0.27; values for 1980-84 were 0.28, 0.25, 0.19, 0.43 and 0.11, respectively.

Calves and Mothers

Behavior of Mother-Calf Pairs

Calves of the year are light tan in color, distinct from the black or gray of non-calf bowhead whales. An adult whale close to a calf was assumed to be its mother unless there was ambiguity due to the close proximity of a second adult. In 1980, 1981 and 1982, calves were sighted 12, 16, and 16 times, respectively. In 1983 they were only sighted 5 times, and in 1984 only 2 times, despite the fact that we spent more time circling over whales in these two years than in earlier years (Table 3).

A. BLOW RATE



B. PROPORTION OF TIME AT SURFACE

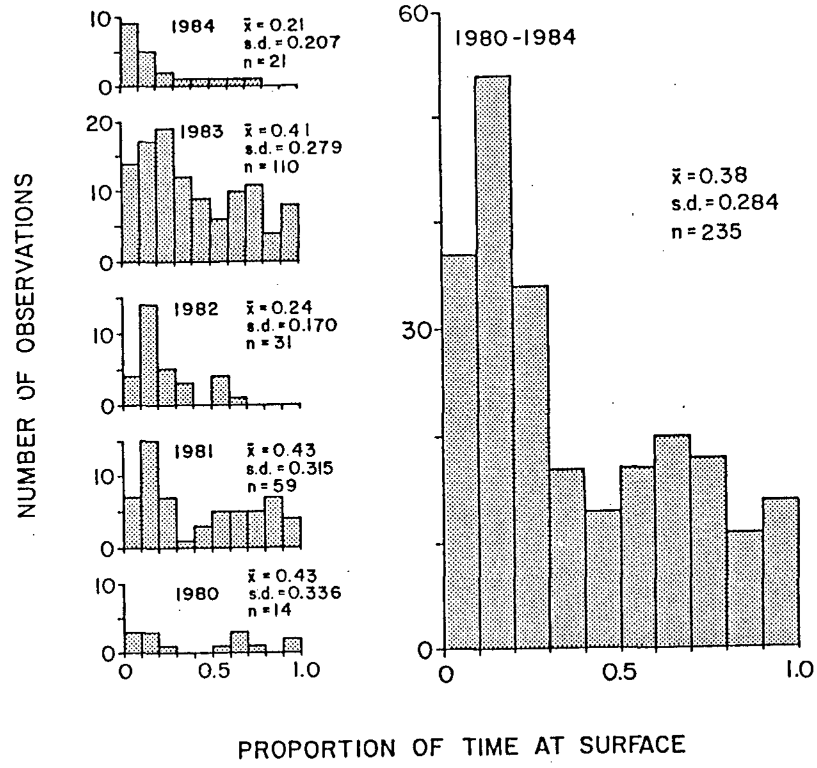


FIGURE 4. Frequency distributions of (A) blow rate and (B) proportion of time at surface for presumably undisturbed non-calves, 1980-84. See text for definitions.

Table 3. Calf sightings and observation time in 1980-84. Both presumably undisturbed and potentially disturbed periods are included. The number of sightings of calves is approximate because multiple counts of the same calf were possible where the calf and its mother were not recognizable.

	1980	1981	1982	1983	1984
Number of calf sightings	12	16	16	5	2
Number of flights[a]	14	18	14	15	24
Calf sightings per flight	0.86	0.89	1.14	0.33	0.08
Hours in plane over whales	30.4	30.8	36.5	38.4	50.2
Calf sightings per hour	0.39	0.52	0.44	0.13	0.04
Total calf time at surface (min)	22.0	30.2	101.3	20.1	2.15
% of calf surface time unaccompanied by mother	7.3%	42.1%	37.7%	57.2%	100%

[a] Only flights with behavioral observations are considered.

In 1981, 1982, and 1983, calves spent about 40-60% of their time at the surface unaccompanied by an adult, and during the two short observations of 1984, calves were alone 100% of the time. In 1980, however, they were seen most of the time with the presumed mother. At times, mothers will dive--presumably to feed in the water column--while the calf remains at the surface; at other times the calf dives with the mother but surfaces before the mother surfaces. We have seen lone calves and presumed mothers rejoin on several occasions, once from as far apart as 1.6 km. Details of rejoining are presented in Würsig et al. (in press).

We suspected that nursing was taking place when a calf dove toward the teat region of the mother. During apparent nursing, the mother was usually quite inactive at the surface. The longest nursing bout that we observed occurred on 23 August 1982, and involved a calf that had been separated from its mother (who was probably feeding nearby in the water column) for at least 71 min. The calf dove towards the mother's teat region six times, for submergences lasting 18, 11, 27, 17, 12, and 10 s (mean = 15.8 ± s.d. 6.37 s). Brief surfacings between the nursing dives lasted 6, 6, 9, 11, 23, and 17 s (mean = 12.0 ± s.d. 6.75 s), and there was only one detectable blow in each short surfacing. Although most bouts of nursing were shorter and involved only one to two nursing dives, the number of blows per surfacing, duration of surfacing, and duration of dive were all considerably reduced for calves whenever they were nursing. The blow rates of calves while nursing were higher than while with their mothers but not nursing (nursing blow rate: 2.8 ± s.d. 0.93 blows/min, n = 5; non-nursing blow rate: 0.5 ± s.d. 0.28

blows/min, n = 10; $t' = 5.40$, df = 4.5, $p<0.01$)[a]. We have detailed data on blow rates for one mother calf pair: during 1.7 h on 24 August 1982, while a pair was diving, travelling, and nursing, there was a significant positive correlation between the blow rates of the two animals ($r = 0.87$, $n = 10$, $p = 0.001$). Further details on mother and calf behaviors are in Würsig et al. (1984a, in press).

Segregation by Age Class

In all years, we noticed some clumping of mother-calf sightings, with usually more than one calf sighted in a particular area during a flight in which a calf was seen, interspersed with some flights or areas with no calves. We also had the impression that subadults, that is, non-calves that were not full grown, were often sighted together. Our ability to detect such segregation was weak, however, because we usually did not have length measurements for the specific whales that we observed. Davis et al. (1982, 1983, in prep.) and Cubbage et al. (1984) measured bowhead whales photogrammetrically in the eastern Beaufort Sea in the summers of 1981-84. In each year they found geographic variation in the distribution of length classes over several hundred kilometres. In 1982 they also had evidence that the distribution of length classes within a single area varied over time on a scale of days or weeks.

In 1983 we sighted calves with mothers only during the first two observation flights of the season, both on 7 August. These calf sightings occurred in deep water far offshore from our main area of observations in 1983, which was in shallow water in Mackenzie Bay, along the Yukon coast (Fig. 1). In the latter area most whales appeared smaller than full grown adults, and lacked the large white chin patches and pigmented tailstocks common in larger whales (<u>cf</u>. Davis et al. 1983). We obtained a few photogrammetric measurements using the techniques of Davis et al. (1983); these confirmed that, indeed, most whales in the Mackenzie Bay area were only 7-12 m long, i.e. shorter than the 13-m length at maturity:

Length category (m)	7-8	8-9	9-10	10-11	11-12	12-13
Number of whales	4	2	2	8	4	2

Thus, most of our 1983 data came from a major concentration of subadult whales that included few adults.

Simultaneous with our 1983 study, Cubbage et al. (1984) measured a larger sample of whales over a wider area. They found that bowheads west of Tuktoyaktuk tended to be <13 m long, a higher proportion of those off the Tuktoyaktuk Peninsula were >13 m long, and virtually all those whales farther east in Franklin Bay were >13 m.

In 1984 we observed only two calves, both on 17 August in Mackenzie Bay close to the Yukon shore. They were within an area where whales appeared to us to be mainly poorly-marked subadults, as in 1983. Extensive

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[a] t' is the t-statistic calculated assuming that the population variances are unequal.

photogrammetric data confirmed that most whales in Mackenzie Bay in August 1984 were again subadults (Davis et al. in prep.).

Mothers and Calves Compared to Other Bowheads

The respiration, surfacing and dive variables for calves, mothers, and all other non-calves are presented in Table 1 (all years) and in Figure 5 (overall 1980-84 values only). Due to the strong segregation by age class in 1983 and 1984, it is likely that many or most whales in the "all other non-calf" category were not fully mature animals, at least in those two years. Mothers with calves (labelled as 'adults with calves' in Fig. 5) were the only bowheads whose maturity we could ascertain. The overall mean blow intervals both of calves and of mothers were significantly longer than the mean for all other whales. For mothers, the mean blow interval was higher than that for other non-calves within every year as well as over all years, but for calves, the mean blow interval was higher than that for other non-calves only within two of the five years (Table 1). Since over half of the 1980-84 blow intervals for calves came from the year with the highest mean (1982), it is possible that our somewhat unexpected finding of longer blow intervals in calves than in other non-calves is not representative. The mean blow intervals of mothers and calves were not significantly different from each other.

For number of blows per surfacing, the overall mean for mothers was not significantly higher than that for other non-calves; but the mean for calves was significantly lower than that either for mothers or for other non-calves. For duration of surfacing, relative values of the three means were the same as for number of blows, with calves lowest and mothers highest. However, the difference between calves and other whales was not significant, whereas the mean surface time for mothers was significantly longer than the mean for either other category. Multivariate analysis, however, showed that the longer surface times for mothers may have been an artefact of depth or year effects (see below).

Mothers with calves showed the longest overall mean dive time of these three categories of whales; the mean dive time of mothers was significantly longer than that for other non-calves, but was not significantly longer than the mean for calves (Fig. 5). The calves' mean dive time was significantly longer than the mean for other non-calves. This latter difference may be an artefact of year-to-year differences in sample size and in mean dive time, however. Within any one year, calves had a shorter mean dive time than other whales, except in 1983 when the two means were quite close. But over 60% of the 1980-84 sample for calves came from 1982 when dives for all categories of whales were very long, whereas less than 10% of the 1980-84 sample for other whales came from 1982 and almost 50% came from 1983 when most measured dives were very short (Table 1).

There was no significant difference between the blow rates of mothers and calves, but the mean blow rates for both mothers and calves were significantly lower than for other non-calves. There was likewise no significant difference between the proportion of time at the surface for mothers and calves, but the mean value of each of these categories was lower than the mean for other non-calves.

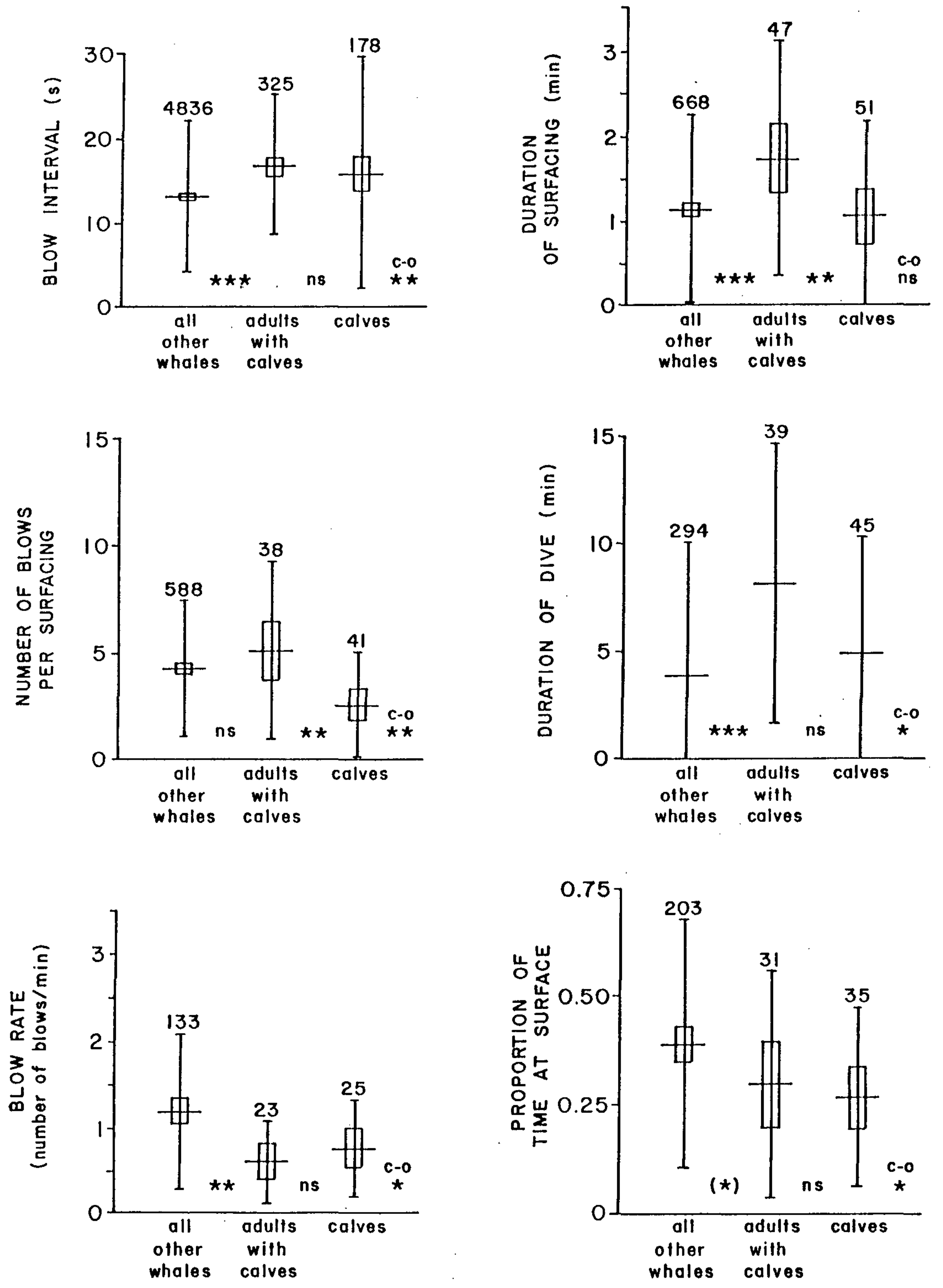

FIGURE 5. Comparison of respiration, surfacing, and dive variables for calves, mothers and all other whales during presumably undisturbed periods, 1980-84. Means ± s.d. (vertical line), ± 95% confidence intervals (rectangles), and sample sizes are shown. Significance levels for 'Other-Mother', 'Mother-Calf' and 'Calf-Other' (C-O) comparisons are shown, coded as in Table 2 (p. 29). The statistical tests used were Dunn's multiple comparison for duration of dive and Newman-Keul's test for all other variables.

Feeding Behavior

During the five years of this study we obtained data on several types of feeding by bowheads: feeding at or just below the surface, at or near the bottom, and probably in the water column (see Würsig et al. in press for more details).

Types of Feeding

Skim feeding occurred when whales moved forward with mouths open at or just under the surface. At times, whales skim fed alone; under such circumstances they were separated >75 m from other whales and were oriented in various directions. At other times, skim feeding occurred in coordinated echelons of up to 14 whales. Whales skim feeding in echelon were staggered to the side and behind the whale at the apex, with each whale separated by 5 to 50 m from the next whale. We suspect that echelon feeding increases the feeding efficiency of these whales, perhaps by helping them to catch prey that escape or spill from the mouth of an adjacent whale, or by reducing the ability of prey to escape to the side. We saw skim feeding only for several days in 1980, 1981, and 1983.

Bottom feeding had apparently occurred when whales surfaced with mud emanating from their mouths. We saw whales coming up with mud on two days in 1980, on one day in 1981, on three days in 1983, and on 12 days in 1984 (including observations near industrial activities). In 1984, when by far the greatest amount of probable bottom feeding was seen, we observed 96 incidents of whales with mud, from 13 August through 2 September, in water 6-24 m deep. Bottom feeding whales were usually >75 m from each other and did not appear to be cooperating while feeding. Interestingly, mud did not always emanate from the mouths of bottom feeding whales when they first surfaced. Of 14 complete surfacings when mud emanated directly from the mouth, it did so at the start of the surfacing only 5 times, and came from the mouth 10 to 83 s after surfacing during the remaining 9 surfacings (mean time after surfacing was 31 ± s.d. 28.1 s). This indicates that the mouth may stay closed for a considerable period after surfacing.

The baleen whale that is best known for feeding on organisms in bottom sediment is the gray whale, *Eschrichtius robustus* (Nerini 1984). The relatively short and coarsely fringed baleen of that species probably is particularly adapted to bottom feeding. In contrast, bowhead whales have very long, finely fringed baleen well suited for skimming through clouds of prey and seemingly not well suited for bottom feeding. Nevertheless, the amounts of mud that we have occasionally seen pouring from the mouths of bowheads appeared too great to have been picked up incidentally while bowheads fed on water column organisms near the bottom. Therefore, bowheads at times take in considerable quantities of sediment or suspended particulates while feeding near the bottom.

Pebbles and bottom dwelling species have been found in bowhead stomachs (Johnson et al. 1966; Durham 1972; Lowry and Burns 1980; Hazard and Lowry 1984; Lowry and Frost 1984). Lowry and Burns (1980) found that most species in the stomachs of five bowhead whales killed off Kaktovik, Alaska, in fall were benthic amphipods. However, the benthic amphipods were an insignificant part of the overall volume of stomach contents; pelagic prey such as calanoid copepods and euphausiids were predominant. Lowry and Burns suggested that a feeding dive probably involves swimming obliquely from surface to bottom and back, feeding the entire time. This is possible, but we suspect that bowheads usually concentrate their feeding at depths where prey is most abundant.

Stomachs of small, subadult bowheads have been found to contain some benthic prey, whereas stomachs of large adult bowheads contained only plankton (Lowry and Frost 1984). Interestingly, photogrammetric data showed that the area where we observed bottom feeding in 1983 and 1984 was occupied mainly by small, subadult bowheads (this study; Davis et al. in prep.). Thus, it is possible that bottom feeding is primarily or even exclusively an activity of young bowheads.

Water-column feeding probably occurs often in the Beaufort Sea in summer, but because it occurs below the surface and is not associated with mud, we have not been able to ascertain its frequency. We believe that water-column feeding occurred in most years and was the major feeding mode during 1982, when bowhead whales were generally encountered in deep water and dove for up to 0.5 h at a time. We suspect that feeding in the water column is generally not done cooperatively, unlike skim feeding in echelon. Whales believed to be water-column feeding were usually separated from each other by several hundred metres.

We saw reddish-brown feces near bowhead whales only sporadically (23, 11, 1, 11, and 5 times during 1980-84, respectively). We assume that much defecation occurred out of our sight below the surface of the water. It therefore does not appear possible to use incidence of defecation as an indication of relative amount of feeding.

Respiration and Surfacing Characteristics of Feeding Bowheads

Figure 6 and Table 1 summarize the principal respiration, surfacing and dive variables for skim feeders, bottom feeders, and other bowheads. Many of the 'other' whales were probably feeding in the water column.

There were no significant differences in the respiration, surfacing and dive characteristics of bottom feeding whales compared to other whales. The sample sizes were low for bottom feeding whales, because all bottom feeders observed in 1980 and 1981 and most of those observed in 1983 were near industrial activities and were therefore excluded from this consideration. Skim-feeding whales, on the other hand, had a significantly longer overall mean blow interval than either bottom feeding whales or non-feeding whales. Skim-feeding whales also tended to remain at the surface significantly longer per surfacing than either other category of whale. The mean number of blows per surfacing for skim-feeding whales was not significantly different from the mean for either other category of whales, probably because of the long blow intervals for skim-feeders. The dives of skim-feeding whales were shorter than for either other category of whales, but the differences were not statistically significant.

Social Behavior

Behavior was termed social when whales appeared to be nudging or pushing one another, orienting toward each other when <1/2 whale length apart, or chasing each other. We observed apparent mating--consisting of two whales rolling ventrum to ventrum and stroking each other with their flippers--on

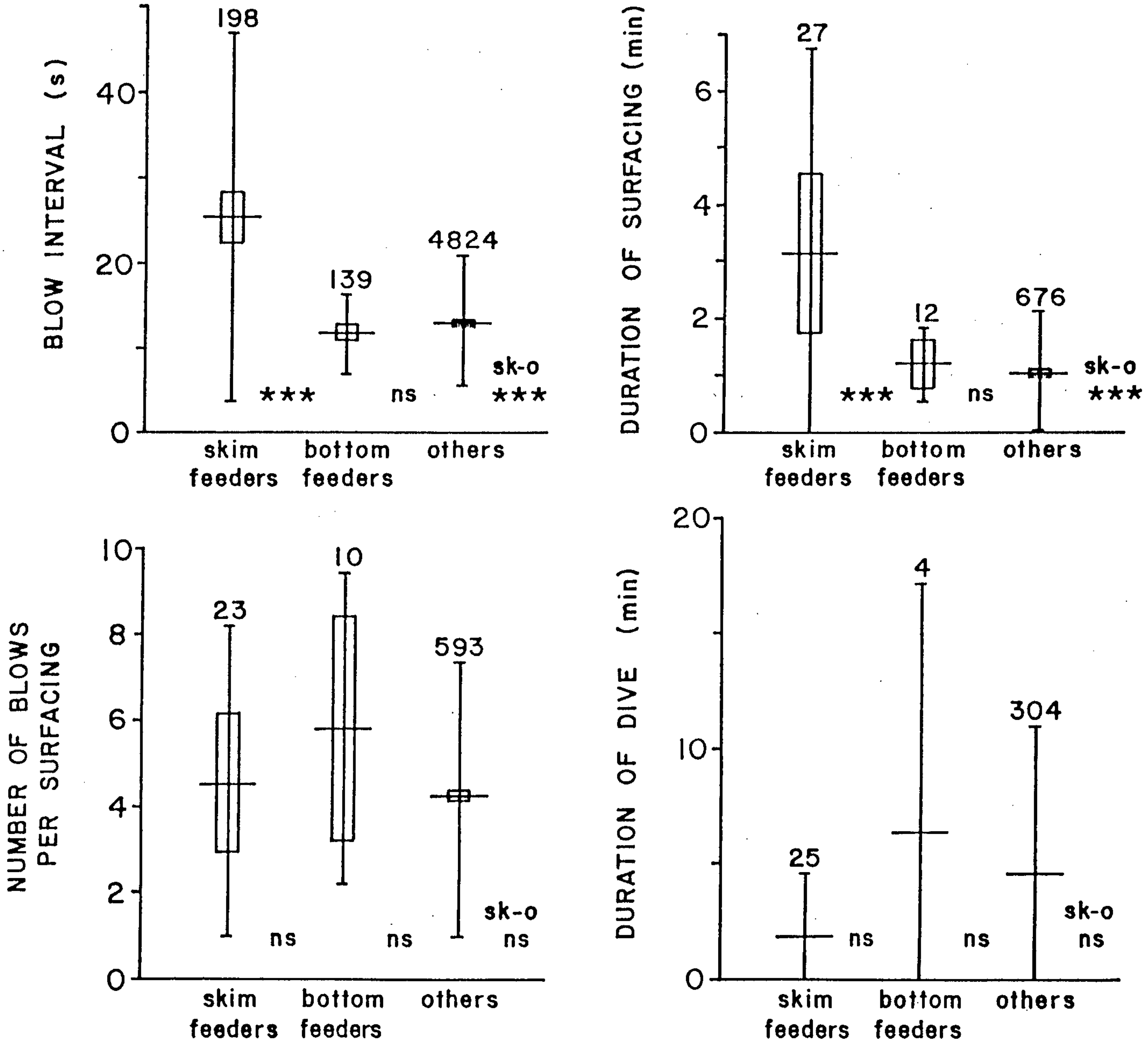

FIGURE 6. Comparison of respiration, surfacing and dive variables for skim feeding, bottom feeding, and other bowheads, 1980-84. Only presumably undisturbed non-calves are included. *** means $p \leq 0.001$; ns means $p > 0.1$. The statistical tests used were Dunn's multiple comparison for duration of dive and Newman-Keul's test for all other variables.

only two occasions, both in 1981. Würsig et al. (in press) provide further descriptions of social interactions. Interactions between mothers and calves, between whales skim feeding in close proximity, and between whales lying close together but not actively interacting were not included as social interactions in this analysis. Whales may, of course, communicate by sound and thus may socialize over far greater distances than those described here. Because groups of whales usually could not be reidentified positively from one dive to the next, we treated observations of social behavior at intervals >5 min as independent for the purpose of counting numbers of interactions. Conversely, we did not score social behavior in the same area more than once in 5 min when counting its frequency unless separate groups were identifiable. We observed socializing that involved calves on only one occasion, on 7 August 1983, when two calves interacted quite boisterously for about 5 min. This case occurred in the presence of seismic noise, so it is not included in the analysis below.

Social behavior occurred with rather low frequency in all years. We calculated rates of socializing by dividing the number of instances of socializing by the number of whale-hours at the surface (the sum of the durations of all observed surfacings including those of calves). In 1980, there were approximately 30 social incidents, but data on them were too incomplete to allow calculation of a precise socializing rate. In 1981-84, the socializing rate varied from year to year by as much as a factor of five. The highest and lowest rates were observed in 1981 and 1982, respectively (Table 4).

Table 4. Rate of active socializing among presumably undisturbed bowhead whales, 1981-1984.

Year	1981	1982	1983	1984
Number of instances of socializing	36	7	20	14
Whale-hours of observation	6.7	6.3	7.9	7.6
Socializing rate (instances/wh.-h.)	5.4	1.1	2.5	1.8

More socializing took place in early August than at the end of August and beginning of September (Fig. 7A, chi-square = 19.42, df = 3, p<0.001). This trend was evident every year. There seemed to be more social activity in water 16-50 m deep than in other depths (Fig. 7B), but the socializing data in the 16-50 m category come mainly from several days in 1981, and may not be representative. There was no consistent trend in the rate of socializing with respect to time of day (Fig. 7C), contrary to our earlier suggestion based on fewer data (Würsig et al. in press).

Socializing Whales Compared to Non-Socializing Whales

The mean blow interval for socializing whales was slightly but significantly longer than for non-socializing whales (Fig. 8 and Table 1). Duration of surfacing and number of blows per surfacing were similar for socializing and non-socializing whales, but multivariate analysis (below) revealed a tendency for surfacings to be longer in socializing whales, after

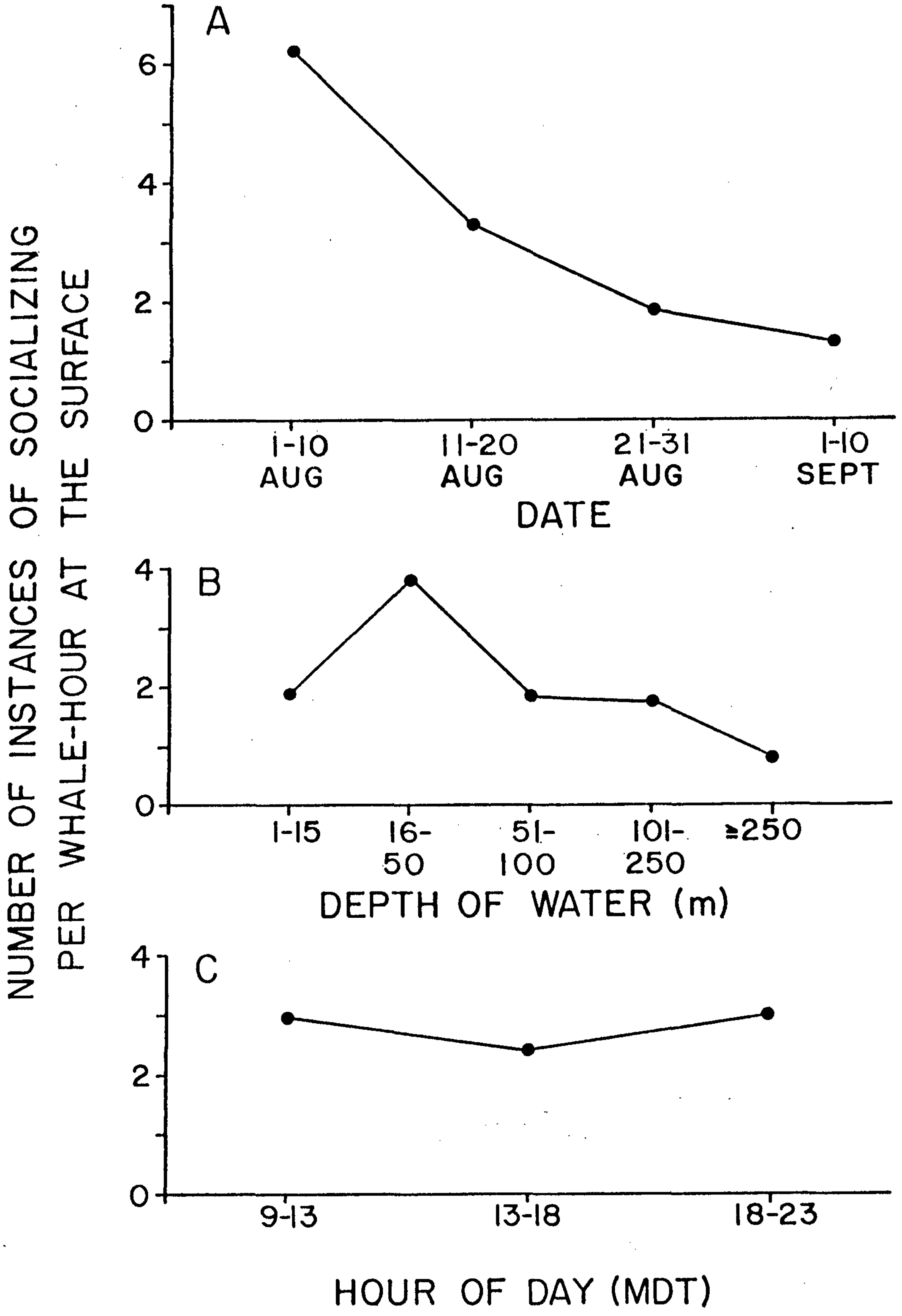

FIGURE 7. Rate of socializing by presumably undisturbed bowheads in relation to (A) date, (B) depth of water, and (C) time of day, 1981-84.

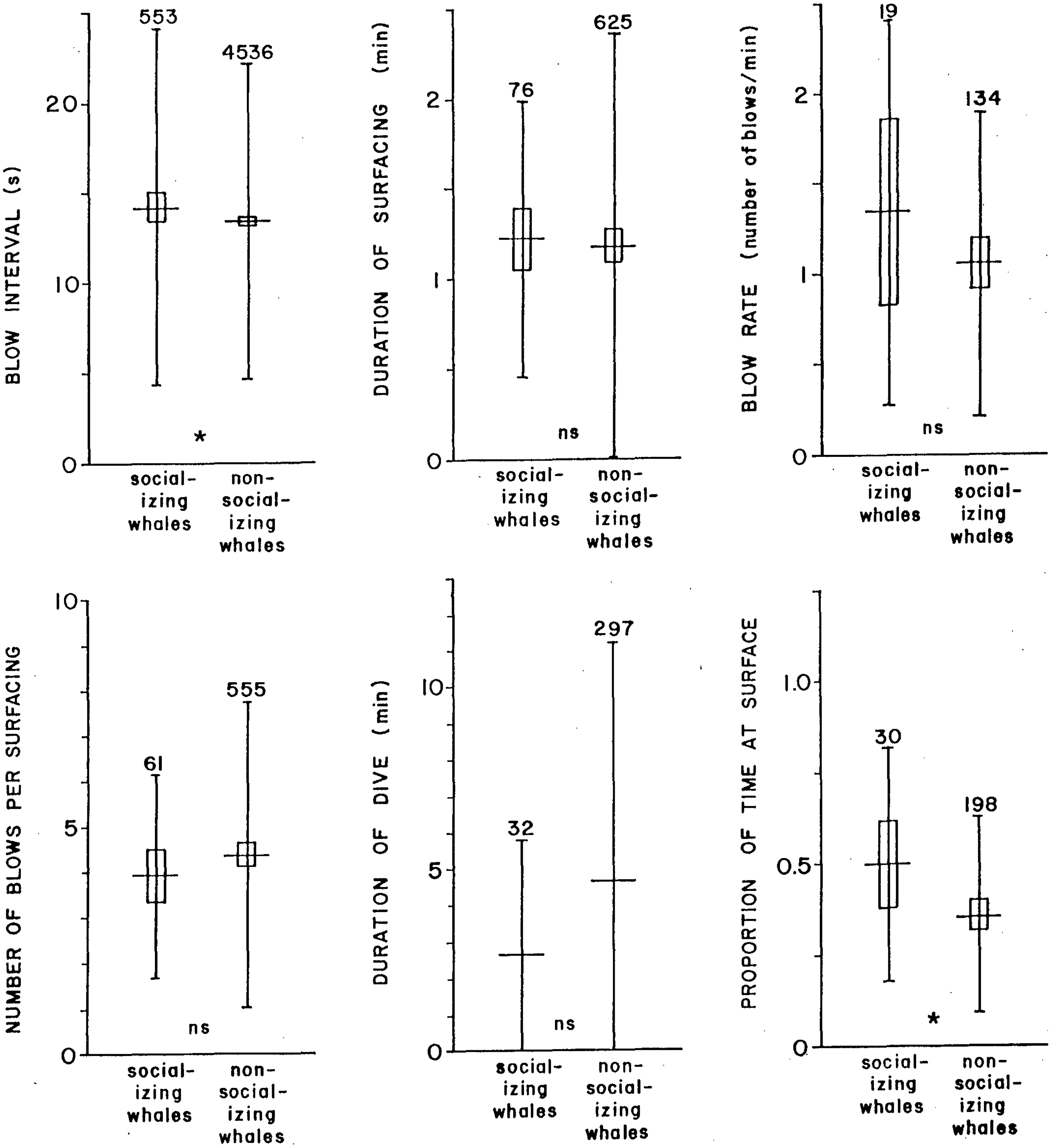

FIGURE 8. Comparison of respiration, surfacing and dive characteristics for socializing and non-socializing bowheads, 1980-84. Only presumably undisturbed non-calves are included. * means 0.05>p>0.01; ns means p>0.1. The statistical tests used were Mann-Whitney U test for duration of dive and t-test for all other variables.

allowing for other factors. Dives by socializing whales tended to be shorter than dives by whales that were not socializing, but not significantly shorter. Both the mean blow rate and the mean proportion of time at the surface were higher in socializing whales, but the difference was significant only for the latter variable.

In the process of interacting with nearby whales, socializing whales often make turns while at the surface. In contrast, non-socializing whales often come to the surface and dive again without changing direction. The difference in frequency of turns between these categories of whales was very highly significant (chi-square = 21.68, df = 1, p<<0.001; see Table 5).

Table 5. Frequency of turns during complete surfacings of actively socializing and non-socializing bowheads, 1980-1984. Only presumably undisturbed non-calves are included.

	Socializing Whales	Non-socializing Whales
Surfacings with turns	35	171
Surfacings without turns	30	477
Total surfacings	65	648
% surfacings with turns	53.8%	26.4%

Whales in Groups vs. Lone Whales

We also analyzed the effect of group size on the main surfacing, respiration, and dive variables by comparing lone whales to whales in groups of two or more. A group was defined as all whales within five body lengths of each other. Whales in a group are not necessarily interacting socially in the way that we have defined for socializing above. However, the proximity required for whales to be classified as being in a group normally must represent at least a minimum level of social interaction. For this analysis of lone whales vs. whales in groups, we excluded skim-feeding whales from both categories in order not to confuse the effect of skim-feeding, which often occurred in groups, with any effect of group size.

Trends in respiration, surfacing and dive variables for lone whales vs. whales in groups were, for the most part, consistent with trends for non-socializing vs. socializing whales (Table 1; Fig. 9 vs. 8). The overall mean blow interval for whales in groups was significantly higher than that for lone whales, and the overall mean number of blows per surfacing for whales in groups was significantly lower. There was no significant difference in the mean surface time or mean dive time. The overall mean blow rates were not significantly different, but the whales in groups spent a significantly higher mean proportion of their time at the surface than did the lone whales.

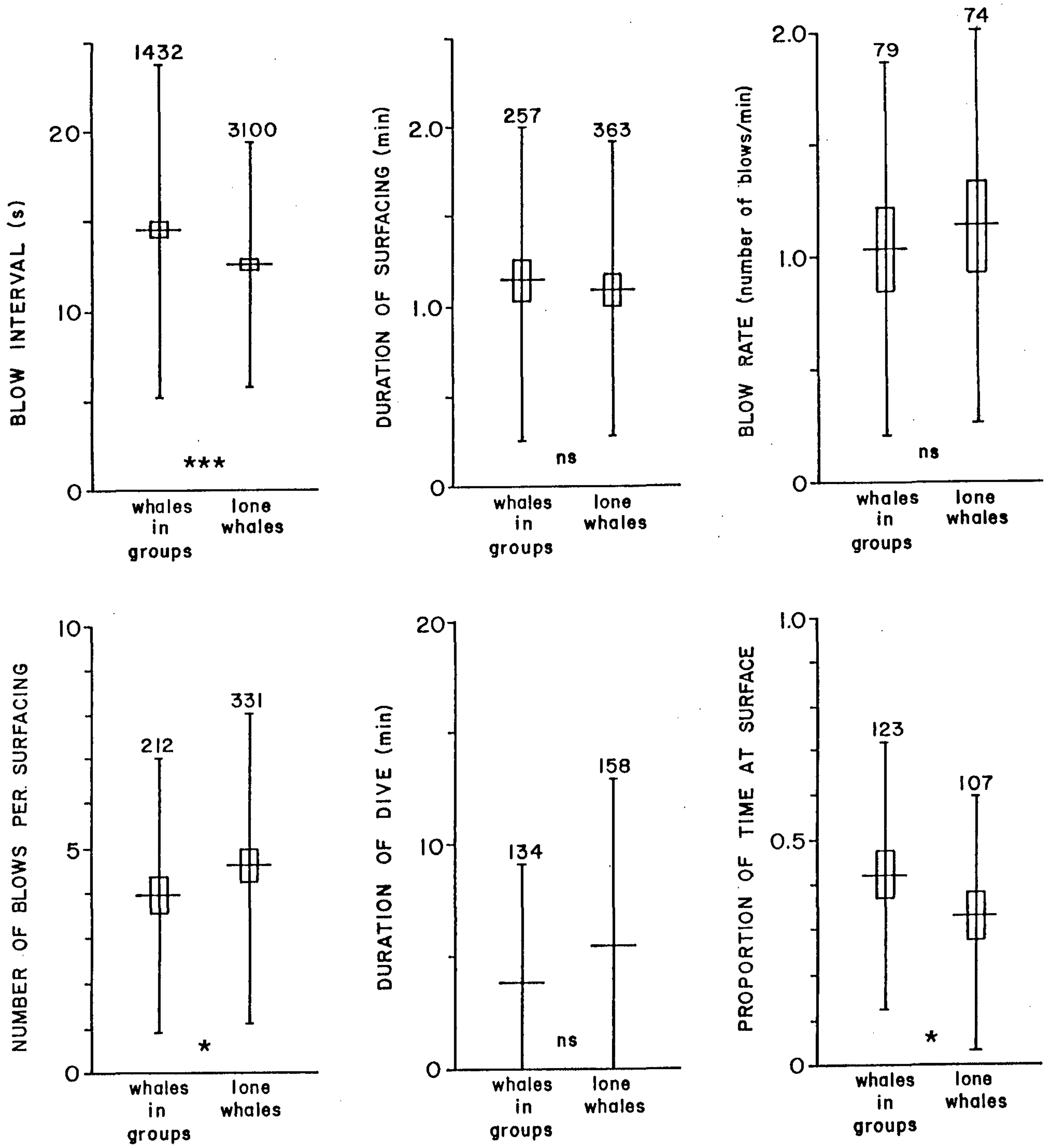

FIGURE 9. Comparison of respiration, surfacing and dive characteristics for lone whales and whales in groups, 1980-84. Calves and skim feeding whales are excluded from both categories, and only presumably undisturbed periods are considered. Significance levels coded as in Table 2 (p. 29). The statistical tests used were Mann-Whitney U test for duration of dive and t-test for all other variables.

Environmental Factors

Depth of Water

Blow intervals did not show any consistent trend with depth (Fig. 10; Table 1). Therefore, although there were statistically significant differences between means for various depth categories, we suspect that these differences were due to factors other than depth. The other three variables--number of blows per surfacing, surface time, and dive time--all showed more or less clear tendencies to increase with increasing depth.

Number of blows per surfacing showed the increasing trend most clearly (Fig. 10). The means for the shallowest three categories ($\leq$100 m) were not significantly different from each other, but the means for each of the two deepest categories were significantly different from the means for each of the three shallower depths ($p<0.05$ in each case, Newman-Keuls tests). Subsequent multivariate analysis, however, showed that this apparent effect of water depth may be an artefact of year-to-year effects (see below).

For duration of surfacing, as for number of blows per surfacing, the means for the three shallowest depth categories did not differ significantly. The mean for the deepest category, >250 m, was significantly higher than any of the other means ($p<0.001$ in each case, Newman-Keuls tests). The mean for 101-250 m was significantly higher than the means for <16 m and for 16-50 m ($p<0.025$ in each case).

For duration of dive, means for the two deepest categories were significantly greater than means for the three shallowest categories (Dunn's multiple comparisons, $p<0.05$ in each case). Means for the two deepest categories were similar, as were means for the three shallowest categories.

In general, number of blows per surfacing, duration of surfacing and duration of dive tended to be greater in deep (>100 m) water than in shallow ($\leq$100 m) water. These trends were largely attributable to the high values of these variables in 1982, a year when most observations were in deep water (Figs. 1,2). There was only very limited evidence that the trends existed within single years (see Würsig et al. 1984a and Table 1). Thus, it is difficult to determine whether the trends were attributable to depth or year effects (see 'Multivariate Analysis' section below).

Time of Day and Date in Season

For each of the four principal surfacing, respiration, and dive variables, we looked at the mean value for presumably undisturbed non-calves by hour of day. We failed to find any apparent trend by hour of day for any of the variables in any of the five years or in all five years combined. The only exception was for blow intervals in 1983 when mean values were considerably longer in the hours 16:00 to 18:00 MDT. These were hours when much skim feeding was observed; skim feeding whales in 1983 had particularly long blow intervals, and the long mean blow intervals at this time probably were due to the activity of the whales rather than the time of day. We conclude that time of day had no consistent effect on any of the four principal variables.

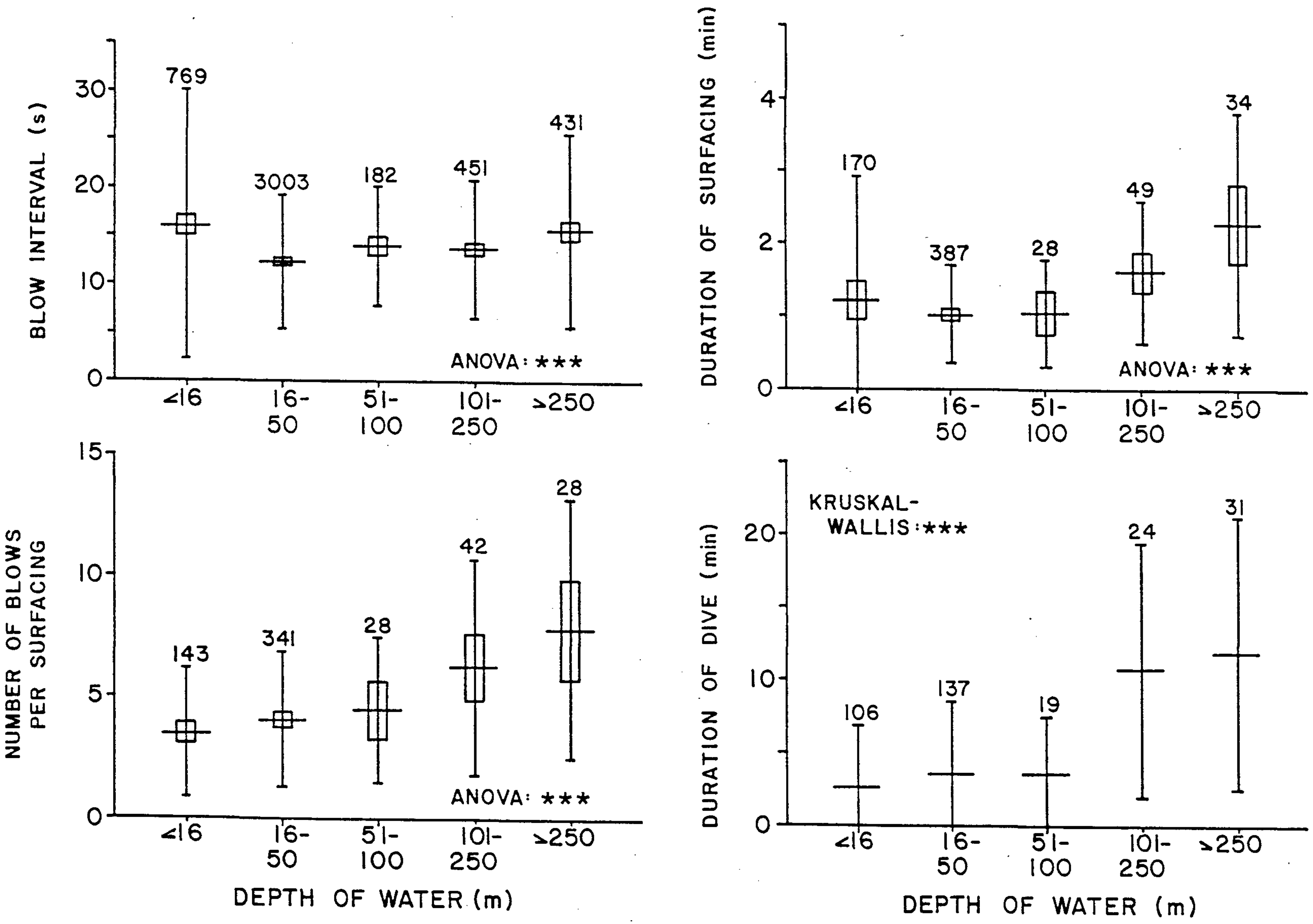

FIGURE 10. Comparison of respiration, surfacing and dive characteristics for bowheads in five categories of water depth, 1980-84. Only presumably undisturbed non-calves are included. *** means $p \leq 0.001$.

We also looked for seasonal trends in the four principal surfacing, respiration, and dive variables over the period of our study, from 1 August to 10 September. We divided this period into four 10- or 11-day periods (1-10 Aug, 11-20 Aug, 21-31 Aug, and 1-10 Sep); in the last period we collected data only in 1981 and 1984 (Fig. 2A). Blow interval, number of blows per surfacing, duration of surfacing and duration of dive all showed no consistent trend across these 10-day periods. As previously noted, frequency of active socializing did decline over the period (Fig. 7A).

Multivariate Analysis

Introduction

In preceding sections, we analyzed relationships of the principal surfacing, respiration and dive variables (for presumably undisturbed bowhead whales) to environmental factors and whale activities. Factors that appeared to have a statistically significant effect on at least one of the variables were the following: status of whale (mother, calf or other), behavior of whale (skim feeding or not feeding; socializing or not), group size, depth of water, and year of observation. We found no evidence that surfacing, respiration and dive variables were affected by occurrence of bottom feeding, time of day, or date within our short field season. In some cases we partitioned the data by year, activity of whale, etc., in an attempt to allow for the multiplicity of factors that might simultaneously affect the variable in question. In all cases we separated calves from older whales. With these exceptions, however, all preceding analyses examined one factor at a time. We knew that some factors were interrelated, like year and depth of water, and suspected that others might be. Hence we used multiple regression analysis to try to sort out the relative importance of each factor.

Three dependent variables were considered in separate multiple regression analyses: number of blows per surfacing, duration of surfacing, and mean blow interval. The last of the variables was the sum of all blow intervals in a surfacing divided by the number of blow intervals. Thus, each surfacing was represented by one case in each multiple regression analysis. Data from 1980 were excluded because too many of the necessary predictor variables were unknown. Data from calves were excluded because of the considerably different behavior of calves. Because of rightward skew in the distributions of all three dependent variables (Fig. 3A-C), logarithmic transformations were used:

$$\mathrm{LOGNBL} = \log_{10}(\mathrm{NBLOWS} + 1), \text{ where NBLOWS} = 0 \text{ to } 19;$$
$$\mathrm{LOGSFC} = \log_{10}(\mathrm{LENSFC}), \text{ where LENSFC is in seconds;}$$
$$\mathrm{LOGMBI} = \log_{10}(\mathrm{MEANBI}), \text{ where MEANBI is in seconds.}$$

Test runs with the dependent variable not transformed gave very similar results as those on the transformed data, showing that the results were not sensitive to the type of transformation chosen.

Seventeen variables were considered as potential predictors of the three dependent variables:

YEAR.82	1 if year = 1982; 0 if not.
YEAR.83	1 if year = 1983; 0 if not.
YEAR.84	1 if year = 1984; 0 if not.

(Note: No 'dummy variable' for 1981 was needed; 1981 was treated as the standard year against which others were compared.)

DATE & DATE.SQ - Date, in days after 31 July, and its square (to test for non-linear relationship).
TIME & TIME.SQ - Hour + Min/60 (0-24 scale) and its square (to test for non-linear relationship).
LOG.DEPTH - log (Water depth in metres); transformed because of extreme skewness.
SEA.STATE - Sea state, 0-5 scale.
ICE.% - Percent ice cover.
GT.5%.ICE - Greater than 5% ice cover = 1; otherwise 0.
ALT.AIRCR - Aircraft altitude, in hundreds of feet (cases with ALT<15 excluded because they were considered potentially disturbed).
MOTHER - 1 if recognized as mother because of presence of calf; 0 if not.
BOTTOM.FEED - 1 if whale brought mud to surface during this surfacing, indicative of bottom feeding; 0 if not.
SKIM.FEED - 1 if skim feeding during this surfacing; 0 if not.
ACT.SOCIAL - 1 if active socializing; 0 if not.
GT.ONE - 1 if group size>1 (i.e., if another whale within 5 whale lengths); 0 if not.

Only those cases for which all 17 predictors were known were used in the analyses. The resulting sample sizes were 479 for NBLOWS, 538 for LENSFC, and 966 for MEANBI. The ratio of variables to cases was low in each analysis, so the results are comparatively reliable.

Several multiple regression equations were calculated for each of the three dependent variables. These included equations containing

- all 17 predictor variables,
- all 14 predictors exclusive of year variables,
- the 3 year variables only, and
- the 'backwards elimination' equation, including all variables that were of significant value as predictors (nominal $p \leq 0.05$).

Equations including various other combinations of variables were also examined to assess the effects of intercorrelations among predictors on the results. We used an interactive stepwise multiple regression program, ELF version 5 (Winchendon Group 1983), with enhancements by LGL. The accuracy of this microcomputer program was confirmed by duplicating similar analyses previously done with BMDP (Dixon and Brown 1977).

Because of the large sample sizes, simple and partial correlations were statistically significant even when the degree of correlation was very low. Most of the 'highly significant' correlations noted below ($p \leq 0.001$) involved correlation coefficients in the 0.15 to 0.25 (or -0.15 to -0.25) range. Most correlations significant at the 1% ($0.01 \geq p > 0.001$) level were in the ± 0.10 to ± 0.15 range. We have not placed much emphasis on variables significant only at the 5% level.

Number of Blows per Surfacing (LOGNBL)

The univariate analyses described in earlier sections showed that number of blows per surfacing tended to be high in 1982 (Fig. 3), marginally higher for single whales than for whales in groups (Fig. 9), and higher for whales in deep water (Fig. 10). There was nothing unusual about the number of blows per surfacing by mothers, socializers, or skim- or bottom feeders; and there was no obvious relationship to date or time of day (see Table 6A, univariate column). The simple correlations of the variables used in the multiple regression analyses showed that LOGNBL tended to be high in 1982 and 1984, and low in 1983, relative to other years (Table 6A, simple correlation column). The only other strong simple correlations were with water depth ($r = 0.226$) and aircraft altitude ($r = -0.153$, all altitudes at least 457 m). There were also significant intercorrelations between many predictor variables. For example, water depth and aircraft altitude were strongly correlated with year.

When all 17 predictor variables were included in a multiple regression equation (Table 6A), the only variables significant at the nominal 1% level were the years 1982 and 1984, in both of which LOGNBL tended to be high. Water depth and aircraft altitude were no longer significant as predictors of LOGNBL after year effects were taken into account. If year variables were excluded, depth was positively related to LOGNBL ($r_{partial} = 0.190$). The backwards elimination procedure resulted in an equation including only three predictor variables, all of which were year variables (Table 6A, 'optimum' column).

In summary, year to year variation was the most conspicuous contributor to variation in number of blows per surfacing. Once year effects were taken into account, there was no clear evidence that any other variable affected LOGNBL. However, water depth and (to a lesser degree) group size, average aircraft altitude and average ice cover at observation sites differed among years. It is possible, but unprovable, that depth or perhaps some of these other variables affected LOGNBL. The most important conclusion is that the apparent effect of water depth on number of blows per surfacing, as suggested by Fig. 10, cannot be distinguished from a generalized year effect.

Duration of Surfacing (LOGSFC)

The earlier univariate analyses showed that duration of surfacing tended to be high in 1982 (Fig. 3), higher for mothers and skim-feeders than for others (Figs. 5,6), and higher for whales in deep water (Fig. 10). There was nothing unusual about durations of surfacing by bottom feeders, socializers or whales in groups, and there was no obvious relationship to time or date (Table 6B, univariate column). The simple correlations of the variables used in the multiple regression analyses provided very similar results (Table 6B, simple correl. column).

When all 17 predictors were considered together, five predictors were positively related (at $p<0.01$) to LOGSFC: 1982, 1984, aircraft altitude, skim feeding, and socializing. The backwards elimination procedure resulted in an equation that included these same five variables at similar significance levels, plus three additional variables that were also positively related to LOGSFC--date, water depth and sea state (Table 6B, 'optimum' column). Note that the multiple regression analysis revealed apparent relationships between

Table 6. Summary of univariate and multiple regression analyses of relationships between (a) environmental and activity variables and (b) surfacing and respiration variables.

Predictor Variable	A. No. Blows per Surfacing					B. Duration of Surfacing					C. Blow Intervals				
	Uni-variate[a]	Simple Correl.	All 17 Variables	Year Excluded	'Optimum'	Uni-variate[a]	Simple Correl.	All 17 Variables	Year Excluded	'Optimum'	Uni-variate[a]	Simple Correl.	All 17 Variables	Year Excluded	'Optimum'
YEAR.81	Fewer					Shorter					Intermed.				
YEAR.82	High	+++[c]	++		+++	Long	+++	+++		+++	Intermed.	+++	++		+++
YEAR.83	Fewest	---	ns		-	Shorter	---	ns			Long	+++	+++		+++
YEAR.84	Fewer	+++	+++		+++	Shorter	ns	++		+++	Shortest	---	ns		
DATE	No trend	(+)	ns	ns		No trend	+	ns	ns	+	No trend	ns	ns	ns	++
DATE.SQ	[b]	+	ns	ns			+	ns	ns			ns	ns	ns	
TIME	No trend	ns	ns	ns		No trend	ns	ns	+		No trend	ns	ns	ns	-
TIME.SQ		ns	ns	ns			ns	ns	-			ns	ns	ns	
LOG.DEPTH	+++	+++	(+)	+++		+++	+++	+	+++	++	No trend	+	ns	+	
SEA.STATE		ns	ns	ns			ns	+	ns	+		--	ns	ns	
ICE.%		ns	-	--			ns	ns	-			ns	ns	ns	
GT.5%.ICE		+	+	++			ns	ns	(+)			ns	ns	ns	
ALT.AIRCR		---	ns	ns			ns	+++	(+)	+++		(+)	ns	ns	
MOTHER	ns	+	ns	ns		+++	+++	(+)	+		+++	+++	ns	ns	
BOTTOM.FEED	ns	ns	ns	ns		ns	ns	ns	ns		ns	ns	ns	ns	
SKIM.FEED	ns	ns	+	ns		+++	++	+++	+++	+++	+++	+++	+++	+++	+++
ACT.SOCIAL	ns	ns	(+)	ns		ns	(+)	+++	+++	+++	+	(+)	ns	ns	
GT.ONE	-	ns	ns	-		ns	ns	ns	ns		+++	+++	++	+++	+++
% Var. Expl.			16.8	11.4	13.3			17.6	14.1	16.2			12.7	9.3	12.1
# Cases		479					538					966			

---

[a] Summary of univariate results is based on Figure 3 (year effects), Figure 5 (mother vs. other), Figure 6 (skim- and bottom-feeders vs. other), Figure 8 (active socializers vs. other), Figure 9 (whales in groups vs. singles), Figure 10 (depth), and the text (time and date).

[b] Blanks in the table denote variables that were not analyzed, or not included in the multiple regression equation.

[c] Pluses indicate positive and significant correlations or partial correlations; minuses indicate negative relationships;
+++ or --- means $p \leq 0.001$
++ or -- means $0.01 \geq p > 0.001$
+ or - means $0.05 \geq p > 0.01$
(+) or (-) means $0.1 \geq p > 0.05$
ns means $p > 0.1$

LOGSFC and both socializing and aircraft altitude even though there was no significant simple correlation with either variable. Conversely, there was no evidence that mothers had longer surface times after other factors were taken into account. Skim feeding and socializing remained significant as predictors of LOGSFC regardless what other variables were dropped from the equation. This indicates that the higher surface times for these two groups of whales were real and not spurious indirect effects. However, the removal of any one of depth, altitude and year from the equation affected the apparent significance of one or more of the others. Hence their effects on LOGSFC could not be separated.

In summary, skim-feeding and socializing bowheads tended to remain at the surface for unusually prolonged periods. The latter effect was not recognizable from univariate analyses. In contrast, the relatively long surface times displayed by mothers and by whales in deep water might be spurious results of intercorrelated factors, most notably the fact that many sightings of mothers and most sightings in deep water occurred in 1982, a year with long surface times. The depth effect did not disappear entirely when year and other variables were taken into account (Table 6B), and it is possible that much of the apparent year effect was actually a depth effect.

Blow Interval (LOGMBI)

Univariate analyses showed that blow intervals tended to be shortest in 1984 and longest in 1983 (Fig. 3). Blow intervals averaged longer for mothers (Fig. 5), skim feeders (Fig. 6), socializers (Fig. 8) and whales in groups (Fig. 9) than for other whales. There was nothing unusual about blow intervals of bottom feeders, and no clear trends with respect to water depth, time or date. The simple correlations of the variables used in the multiple regression analyses provided very similar results, and also showed a negative correlation between LOGMBI and sea state (Table 6C).

A multiple regression equation including all 17 predictors explained only 12.7% of the variance in LOGMBI, lower than for either of the other two dependent variables (Table 6). Four of the 17 predictors were significantly and positively related to LOGMBI: 1982, 1983, skim feeding and group size>1 (Table 6C). With years removed from the equation, the partial correlations with skim feeding and group size remained about as before, and only one additional variable--depth--acquired marginal significance (Table 6C). This suggests that, for blow intervals, the effects of years and other variables are less seriously confounded than was true in the analyses of LOGNBL and LOGSFC. The backwards elimination procedure produced an equation with six predictor variables, including 1982, 1983, date, time, skim feeding, and group size. All partial correlations, except the marginal one with time, were positive. The negative relationship to time suggests that LOGMBI had a slight tendency to decrease late in the day after effects of other variables were taken into account.

These results confirm the univariate evidence that blow intervals tended to be long in 1983, for skim feeders, and for whales in groups. The partial correlations do not confirm the univariate trends for longer blow intervals in the cases of mothers or socializers. However, the relationships of LOGMBI to group size, mothers, and socializing were confounded. Socializing, by our definition, occurs only in groups, and mothers are almost always identified by close proximity of a calf. When group size was excluded from the regression equations, positive partial correlations ($p<0.05$ or better) with mothers and socializing became evident.

Synchrony of Behaviors

Bowheads within groups often surfaced and dove in rough synchrony. At times we also had the strong impression that whales of different groups, greater than five whale lengths from each other, had partially synchronized surfacing-dive patterns. However, because we usually did not know exactly how many whales were in an area, and we could not identify all whales, our analysis of potential synchrony is incomplete. We investigated the possibility of synchronized surfacing-dive patterns during five observation sessions for which we believed we had nearly complete records of the surfacings of whales in our observation circle. We compared the observed number of 3-min intervals with 0, 1, 2, etc. single whales or groups at the surface against the expected number if there were no synchrony, i.e., assuming a Poisson distribution.

During 4 of 5 tests, we found no significant deviation in surfacing pattern from that of a Poisson distribution, although the data were suggestive of possible synchrony during two tests. On 2 September 1984, however, synchrony was strongly indicated. The session involved approximately three lone whales within a 3 km diameter circle, each whale about 250-1000 m from the others. Surfacings and dives were monitored for 42 3-min intervals. There were fewer intervals with one whale and more intervals with two whales than expected (Table 7), indicating that two of the separated whales tended to surface together (chi-square = 7.83, df = 2, $p<0.025$); however, we do not know whether these were always the same two whales.

Table 7. Data for analysis of surfacing synchrony in three lone whales on 2 September 1984. Expected values were derived from the observed mean of 1.2 whales at the surface per 3-min interval ($\pm$ s.d. 0.98, n = 42). See text for discussion.

Maximum number of whales at surface during 3-min interval	Observed number of intervals	Expected number of intervals[a]
0	13	12.7
1	10	15.2
2	16	9.1
≥ 3	3	5.1

[a] Assuming a Poisson distribution with mean 1.2

Potential synchrony in surfacings and dives is especially difficult to analyze because number of whales involved is not known, whales may move into or out of the area while under observation, and whales may move into or out of groups. The apparent synchrony on 2 September 1984 occurred while lone whales were possibly feeding in the water column; during other times when synchrony has been suspected (but has remained unsubstantiated by analysis), subsurface feeding has also usually been indicated. We do not know why whales some distance apart from each other would wish to be at or below the surface at the same time, but it is possible that in this manner they remain in better acoustic contact. Donald Ljungblad (Naval Ocean Systems Center, San Diego, pers. comm.) believes that bowheads sometimes make more sounds just before they surface, and they may stay in contact and synchronize surfacings in this manner. We attempted to correlate sounds and surface-dive behavior in this study, but our limited data do not substantiate the suggestion that sounds are more frequent at any particular part of the dive cycle.

Miscellaneous Behaviors

Play

Although whales may engage in play during various social interactions, we could not separate play from possible mating activity or aggression. Therefore, we considered whales to be playing only when they associated with an object other than another whale. We saw such associations in 1981, 1982, and 1984. Play behavior during 1981 and 1982 is summarized in Würsig et al. (in press), and we present only a brief overview here.

Log Play.--We observed whales playing with logs up to about 10 m long on two occasions in 1981, and once each in 1982 and 1984, for 5 s, 10 min, at least 1.5 h, and 5 min, respectively. Most contact with the log consisted of the whale nudging or pushing the log with the head or body. Sometimes the log was clasped by the flippers while the whale was belly-up underneath the log, or was lifted up by the back or tailstock.

Association with objects other than conspecifics has been described for at least four other species of large whales (a humpback whale, Couch 1930; a sperm whale, Nishiwaki 1962; right whales, Payne 1972; and gray whales, Swartz 1977). Some specific elements of log play in bowheads were strikingly similar to play with seaweed observed in southern right whales (Payne 1972); both involved lifting the object with the head, moving the object along the back, and patting it with the flippers. Attempts to submerge the log with the head are also reminiscent of a motion made by male right whales when attempting to mate with uncooperative females (Payne, in review).

Calf Play.--Calves were seen alone at the surface on about ten occasions, apparently 'waiting' for their mothers to come up from a dive. Usually calves were rather inactive at those times; however, on two occasions in 1982 they interacted with debris in the water. On 19 August 1982, a calf swam in a meandering line of surface debris approximately 2 m wide and probably composed mainly of invertebrates. The calf associated with the line for 12.3 min, with rapid and often jerky movements, reminiscent of any uncoordinated young mammal. We do not believe that the calf was feeding on the debris in a concerted manner, although its mouth was open slightly for brief periods. It is possible that the calf was practicing skills required for skim feeding.

The second incident, on 23 August 1982, involved a calf moving within an area about 40 m wide and 100 m long marked by dispersed fluorescein dye from one of our dye markers. The calf actively rolled and twisted within the dye, reorienting itself at the edge of the dye in order to stay within the dyed area for 22.3 min. The association with this area ended when the calf left the dye and oriented toward its mother, which was approaching the calf at 120 m distance. When the two joined, the calf began nursing. It is possible that, as in the previous account, the calf may have oriented toward suspended matter while practicing skills used to feed on clouds of invertebrate prey. If so, some play may be of functional value.

Aerial Activity

Aerial activity, consisting mainly of breaches, tailslaps, and flipper slaps, occurred sporadically throughout our five field seasons. General descriptions of these activities are presented in Würsig et al. (in press), and the frequency of aerial activity each summer is shown in Table 8.

Table 8. Frequency of aerial activity, 1980-84, based on whale-hours of observation at the surface. Both presumably undisturbed and potentially disturbed periods are included. Rates are probably overestimated because we occasionally observed bowheads specifically to document aerial behavior.

	1980	1981	1982	1983	1984
Bouts of aerial activity	6	14	9	19	7
Whale-hours at the surface	10.03	14.98	10.95	17.91	13.67
Rate of aerial activity (bouts/whale-hour at surface)	0.60	0.93	0.82	1.06	0.51

Breaches were usually performed by whales that were >100 m from other whales, and occurred both as single breaches and in series of up to 19 breaches with no interruptions by other surface activity. The mean interval between breaches within a series was 0.53 ± s.d. 0.154 min (n = 66). Tailslaps onto the surface of the water included single slaps and uninterrupted series of up to 148 slaps. The mean of 266 measured intervals between successive tailslaps was 4.9 s (± s.d. 1.94 s). Flipper slaps onto the surface of the water also included single slaps and up to 10 slaps in an uninterrupted series, with the mean of 43 measured intervals within a series being 2.9 s (± s.d. 1.62 s). Thus, breach intervals are longest, tailslap intervals are much shorter, and flipper slap intervals are the shortest. This ordering corresponds roughly to the amount of body mass the whale lifts above the surface of the water.

The longest bouts of aerial behavior that we observed were by lone whales and usually consisted of alternating series of tailslaps, flipper slaps, and breaches. A particularly dramatic series involving two whales occurred on 22 Aug 1983. A lone whale that was aerially active before we began circling it interspersed 49 tailslaps with 6 breaches during 11.8 min of observation. Its blow rate was 1.61 blows/min if it did not blow during the breaches or 2.12 blows/min if it blew during every breach. A second whale began breaching 300 m away as the first whale surfaced after its last breach series. The second whale made 64 breaches, 36 tailslaps and 48 flipper slaps during the 75 min that we observed it. During that time, its blow rate was between 1.19 and 2.04 blows/min, depending on whether or not it blew during the breaches. The first whale moved away from the second as the second began breaching, and we soon lost sight of it. We left the area about 9 min after we last saw the second whale submerge, and we do not know whether it resumed aerial activity on its next surfacing.

Some tailslaps and flipper slaps occurred in groups of whales, either as single slaps or in short series of up to 10 slaps, sometimes while the whales were actively socializing. On one occasion in 1981, the socializing appeared to include copulation between two animals, in addition to numerous tailslaps and flipper slaps by both animals. On three occasions we have seen a bowhead whale strike another with its tail flukes or a flipper in an apparently aggressive manner: once each in 1980 and 1981, one whale slapped its tail onto the head of another, and in 1983, a whale slapped a flipper three times onto the back of another whale, which responded by hitting the first whale on the back with its flukes six times.

We have observed only five spyhops, where a bowhead lifted its head more or less vertically out of the water, up to the level of its flippers at the highest, and sank back into the water tail first. All spyhops were quite brief. Four of the spyhops were performed by whales that were socializing, and one was interspersed with many other aerial behaviors.

We observed calves aerially active on only two occasions in five field seasons. One involved a single tail slap and the second, seen from shore on Herschel Island, was of a calf aerially active for 29 min during which it made 37 breaches or partial breaches, with up to three-quarters of the body remaining in the water. The calf breached back and forth, changing direction often, and therefore stayed within 1 km of the presumed mother, although it covered a distance of at least 3 km in its meandering course. This kind of meandering is similar to right whale calves breaching in 'circles' near their mothers (Thomas and Taber 1984). When the calf stopped breaching, it rapidly headed back toward the adult. Further detail on the breaching of this calf is supplied in Thomas (1982).

Aerial activity probably has several functions. Single tailslaps or flipper slaps may indicate disturbance or aggression, as when possibly precipitated by the approach of an airplane (see Richardson et al. 1985c) or when directed against a conspecific. Bouts of aerial activity may signal 'arousal' of some type, and may also serve to communicate to nearby conspecifics. Our sonobuoy recordings showed that many breaches and tailslaps produce pulses of low-frequency underwater noise (see 'Bowhead Sounds' below). Breaches, tailslaps and flipper slaps may also represent play behavior and may not always have a function beyond play.

In other species of large whales, the function of breaching and other aerial behavior remains uncertain. Whitehead (1985), in reviewing current hypotheses about functions of breaching, noted that breaching is most common in species that have many close-range social interactions. In humpback whales, Megaptera novaeangliae, breaching is more common on winter mating and calving grounds than on summer feeding grounds. Whitehead suggested that a breach might be a display of strength in male humpbacks (directed at receptive females and/or competing males) and that play might be the main function of breaching in calves. Payne (in review) argued that breaching by southern right whales in winter functions at times as an acoustic signal to maintain contact between animals. Both authors reported that tail slaps and flipper slaps are often associated with breaching, and both felt that breaching likely has more than one function. However, breach sounds may not be especially suitable as long-distance contact signals; they are created at the surface and, at a distance, are no stronger than calls.

Behaviors Associated with Dive

Several seconds before some (but not all) dives, bowhead whales make a pre-dive flex--a distinctive concave bending of the back, with the back about 0.5 to 1 m below the level of the tail and rostrum. Rostrum and tail usually lift slightly out of the water during the flex, and considerable white water may be created near these two points. The whale then straightens its back and lies momentarily still before arching the back convexly as it pitches forward and down. During 25 timed observations in 1983, pre-dive flexes occurred a mean of 15.4 ± s.d. 12.00 s before the dive. On rare occasions we saw two or even three flexes before a dive.

We collected consistent data on occurrence of pre-dive flexes in 1981-84. Within specific years, the proportion of dives preceded by flexes ranged from about 1/10 to 1/4 (Table 9). Dives preceded by a flex were longer than those not preceded by a flex (Table 1; for 1981-84, Mann-Whitney $U = 3302$, $0.01<p<0.02$). Surfacings with flexes were longer and had more blows than surfacings without flexes (see Table 1; $p<0.001$ for both variables in 1981-84). There was no significant difference in the mean blow interval for surfacings with and without a pre-dive flex.

Table 9. Percent of dives preceded by a pre-dive flex or by raised flukes in presumably undisturbed non-calves.

	1981	1982	1983	1984
% of dives preceded by pre-dive flex	10.1%	24.4%	15.5%	20.4%
Number of dives scored for pre-dive flex	178	131	277	269
% of dives preceded by raised flukes	46.7%	48.8%	19.5%	51.3%
Number of dives scored for raised flukes	214	125	390	448

During the dive, the whale arches (makes its back convex) and pitches forward and down. During 51 timed arches in 1983, the arch began a mean of 5.1 ± s.d. 8.36 s before the final disappearance of the whale's body. If the angle of the dive is steep, the tail is usually raised above the surface; if not, the tail may remain below or just touch the surface. Data on the presence or absence of raised flukes during dives were tabulated for 1981-84. Flukes were raised out of the water on about half of the dives in every year, except in 1983, when only about one fifth of the dives were preceded by raised flukes (Table 9). We had information on the presence or absence of both raised flukes and pre-dive flexes for 803 surfacings in

1981-84. A flex occurred during 137 of these surfacings, and flukes were raised at the end of 321 of the surfacings. These two pre-dive behaviors occurred together during 84 surfacings, much more frequently than the 55 times expected by chance (chi-square = 31.3, df = 1, $p \ll 0.001$).

In 1981-84, the mean duration of dives that started with raised flukes was longer than that for dives that started with flukes not raised, but the difference was not statistically significant (Table 1). There was no significant difference in the durations of surfacings that ended with and without raised flukes. The mean number of blows per surfacing was, however, significantly higher for surfacings that ended with flukes raised ($t = 5.21$, $df = 498$, $p<0.001$). In addition, the mean blow interval was significantly lower for surfacings that ended with flukes raised ($t = 7.79$, $df = 2006$, $p<0.001$).

Underwater Blows

The number of underwater blows that we observed varied widely from year to year. Considering both disturbed and undisturbed periods, the number of underwater blows seen per year was as follows:

1980	1981	1982	1983	1984
158	66	6	347	5

We have been uncertain how to interpret underwater blows ever since we first observed them in 1980. We tentatively classified them as a potential type of feeding behavior in that first year, because of their similarity to some bursts of bubbles associated with feeding in humpback whales (Hain et al. 1982). We did not see any direct evidence of feeding in connection with underwater blowing in 1980, but in that year the incidence of underwater blows seemed correlated with the incidence of various feeding behaviors. In 1981, there were again some indications that high numbers of underwater blows occurred on occasions with much feeding behavior, but we again failed to see any specific feeding behavior associated with any underwater blow. In 1983 we observed a very high number of underwater blows, and many of them occurred near socializing whales.

We observed the whales that made (or probably made) 43 of the 131 underwater blows seen during presumably undisturbed periods in 1983. Those 43 underwater blows were produced as or just after the whale dove out of sight. Of those 43 blows, 14 were produced by whales that were actively interacting with another whale just before the underwater blow, and 23 blows (including the 14) were produced by whales within five body lengths of one or more other whales. In at least one case it appeared that the interaction continued underwater after the whales dove. Of the 88 underwater blows produced by unseen whales in 1983, 23 blows were within five body lengths of one or more whales at the surface. The remaining 65 underwater blows appeared at the surface with no whales visible nearby.

To quantify the relationship between underwater blowing and socializing, we calculated underwater blow rates by dividing the number of underwater blows seen by the total whale-hours of observation, including periods both at the surface and underwater. (The resulting rates somewhat underestimate the actual underwater blow rate because underwater blows cannot occur while whales are at the surface. We felt that our estimates of whale-hours of observation while whales were underwater were too imprecise to be useful, however, especially when large numbers of whales were under observation.) For 1982 and 1984, the underwater blow rate was too low for meaningful analysis, and for 1980, adequate data were not available often enough for reliable quantification. Based on behavioral observation sessions in 1981 and 1983, there was a positive correlation between rate of underwater blows and rate of socializing (for 1981, Spearman $r_s = 0.53$, $n = 17$ sessions, $0.02<p<0.05$; for 1983, $r_s = 0.92$, $n = 15$, $p<0.001$).

The correlation of underwater blows with socializing, plus observations of underwater blows within actively socializing groups in 1983, indicates that underwater blows sometimes were part of the repertoire of behaviors involved in social interactions. Clark (1983) reported frequent underwater blow sounds in interacting groups of southern right whales. One of us (RP) has noted that forceful underwater blows in these right whales often occur during aggressive social interactions. For humpback whales in apparently aggressive social contexts, both forceful underwater blows and curtains of bubbles (produced by whales exhaling underwater while moving forward) have been reported (Darling et al. 1983; Tyack and Whitehead 1983; Baker and Herman 1984). We do not know whether the underwater blows by socializing bowheads in 1983 were likewise of an aggressive nature, or whether at times underwater blows in bowheads have functions unrelated to socializing.

Bowhead Sounds

There is now considerable information about the acoustic behavior of the bowhead whale (Ljungblad et al. 1980, 1982, 1983, 1984a; Clark and Johnson 1984; this study). Most of these efforts have concentrated on describing the calls of the bowhead and their associations with various observed behaviors. Interpretation of the biological significance of calls has relied heavily on a comparison between bowhead and southern right whale calls. The two species show remarkable similarities in their call repertoires, and more is known about the functions of calls of the southern right whale (Clark 1982, 1983). In general, the majority of bowhead vocalizations are low (<400 Hz) frequency-modulated (FM) calls. Bowheads also produce a variety of other sound types that are acoustically more complex, sometimes with energy up to 3-4 kHz, but less common than the simple FM sounds.

In this section we first summarize the methods used to obtain, analyze and categorize our field recordings of bowhead sounds. This is followed by descriptions of the different sound types and the contexts, both social and environmental, in which they were heard. To clarify factors that affect bowhead acoustic behavior under presumably undisturbed conditions, we searched for associations between these acoustic data and other relevant conditions. These associations are important for the proper interpretation of results obtained during potentially disturbed conditions.

Methods

All sound recordings were obtained via 68 sonobuoys (AN/SSQ-57A or AN/SSQ-41B) deployed near bowheads in the eastern Beaufort Sea (128° to 140°W longitude, Fig. 1) during the 1 August to 8 September periods in 1980-1984. Most sonobuoys were dropped 0.5-1.0 km from bowheads that were under observation from the aircraft circling at 457-610 m altitude. Later in the recording sessions, whales could either be closer or farther away. The hydrophone was deployed to 18 m below the surface (occasionally 9 m in 1981) in water depths ranging from 11 m to 950 m. In a few cases water depth was so shallow that the hydrophone was on the bottom. Sonobuoy signals were recorded with calibrated equipment aboard the observation aircraft (Greene 1985).

The procedure for analyzing tape recordings was slightly different in 1980-81 than in 1982-84. For 1980-81, tapes were listened to at normal speed and a general description of each sound and its time of occurrence were noted. Sounds judged to be of sufficient intensity were converted into hard copy spectrograms using a Spectral Dynamics SD 301C real-time analyzer or a Kay 6019A spectrograph. From each spectrogram, CWC measured the sound's initial, final, lowest and highest frequencies (± 10 Hz) and its duration (± 0.1 s). From these analyses and ongoing analyses of bowhead calls recorded during the spring migrations of 1979 and 1980 (Clark and Johnson 1984), eight general categories of sound types were recognized (see Table 11, below). In later analyses the number of categories was reduced to seven, with any occurrences of the rare double call type pooled with the inflected call type.

All 1982-84 recordings were listened to at normal speed while a continuous spectrographic output was displayed on a memory oscilloscope. This spectrographic visual image was obtained by playing the taped analog signal into the Spectral Dynamics SD 301C real-time analyzer, which was coupled to a Tektronix 5111 memory oscilloscope. By this procedure the analyst (CWC) could simultaneously hear the sounds and see their spectrographic image. This procedure greatly facilitated both the detection of faint signals and the categorization of the sounds as one of the seven call type categories. In 1982-84 the analyst also judged the relative intensity of each call, subjectively, as either loud or faint. Loud calls represented whales near the sonobuoy; these whales were the ones being observed visually, counted, and sometimes subjected to simulated industrial disturbance.

In all years, sounds associated with respiration, referred to as blow sounds, and sounds associated with aerial displays (breaching, tail slapping, flipper slapping), referred to as slap sounds, were noted. All call data were tabulated by the aforementioned seven call types and, in 1982-84, by relative intensity. All data were also categorized according to presence and type of potential disturbance. In this section, we present results obtained under presumably undisturbed conditions. The results obtained during potentially disturbed conditions are presented in the disturbance section (Richardson et al. 1985c).

Over all five summers, there were 129.2 h of recordings during 64 different recording sessions on 49 days, considering both presumably undisturbed and potentially disturbed conditions. Under the presumably undisturbed conditions there were 56.5 h of recordings during 42 different recording sessions on 34 days. These 56.5 h of data from presumably undisturbed conditions are the basis of all further discussion in this section. In some cases, however, we deal with <56.5 h of data since there were periods of acoustic recording when either the number of whales in the observation area and/or their behavior was unknown.

To standardize for observation periods of varying duration and with different numbers of animals, call counts were expressed as calls per whale-hour (calls/wh-h). This call rate was computed by dividing the number of sounds by the duration of the recording session and by the estimated number of whales within about 5 km of the sonobuoy. To compare acoustic behavior under various conditions, we often determined the proportions of calls that were complex. The complex call proportion was the sum of the high, pulsed tone and pulsive calls divided by the total number of calls.

Blow and Slap Sounds

A total of 396 blow sounds were recorded in 1980-84 during presumably undisturbed periods. There were dramatic year-to-year variations in the number of blow sounds recorded, and in the rate per whale-hour (Table 10). Especially large numbers of blows were heard in 1983. Figure 11a,b illustrates a normal above-water blow sound and an underwater blow sound.

Changes in number of blow sounds appeared to be associated with the amount of feeding or socializing. On average there were a third more blow sounds during feeding or socializing (1.2 blow sounds/wh-h) than during other behaviors (0.8 blow sounds/wh-h). This general association was possibly a result of a higher level of physical exertion, which may have caused the whales to respire more deeply or forcefully during feeding or socializing than during other behaviors. However, blow sounds were not always associated with feeding and socializing. In 1980-81, 36 blow sounds were heard during 17.8 wh-h of feeding, while in 1984 no blow sounds were heard in 28.5 wh-h of feeding. In 1982, 22 blow sounds were heard in 53.3 wh-h of socializing, while in 1983 there were 161 blow sounds in only 48.3 wh-h of socializing. Many of the social blow sounds in 1983 were coincident with visible underwater blows, which were probably heard at greater distances than surface blows due to better energy coupling with the water. Another factor confounding the general association between blow sounds and feeding or socializing is that the number of blow sounds recorded was strongly affected by the proximity of the hydrophones to the animals. For example, 35 blow sounds were heard on 17 August 1984 between 15:24 and 17:04 h when several different whales (not feeding or socializing) were within several hundred metres of the hydrophones. Their blow sounds were extremely clear in their aural detail, and we were able to hear an unusually large number of these animals' respirations.

Bowhead slap sounds, which are best described as short (<0.2 s) broadband signals with sharp onsets, were difficult to identify because of their similarity to certain ship noises. Therefore slap sounds were noted only if they were loud and relatively undistorted and occurred when ships were absent or quiet. Figure 11c,d illustrates breach and tailslap sounds. Of the 64 slap sounds recorded, 21 were during a flight on 22 August 1983, when a whale was engaged in a prolonged bout of breaching, tail slapping and pectoral flipper slapping. These were our clearest examples of bowhead slap sounds associated with specific visual aerial behaviors that were observed. At a range of several hundred metres, peak received levels of slap sounds from these breaches and tail slaps were 115-118 dB and 107-118 dB//1 μPa, respectively (Greene 1984). Interestingly, not all aerial behaviors produced audible slap sounds. For example, during one 2.4 min period on 22 August 1983, we saw six breaches by one whale; only the first three breaches were clearly audible. Similar results were found for tail slaps and pectoral

Table 10. Number and rates of blow sounds recorded in different years, subdivided by activity of nearby bowheads.

	No. of Recording Periods	No. Blow Sounds Recorded	Hours of Recording	Whale-h of Recording	Rate, Blows per Whale-h
1980-81					
Feeding	2	36	2.2	17.8	2.0
Soc. & Feed.	1	43	1.5	36.7	1.2
Socializing	5	13	6.5	54.7	0.2
Other Behav.	2	18	0.7	4.2	4.3
Sub-Total	10	110	10.9	113.4	1.0
1982					
Feeding	0	0	0.0	0.0	0.0
Socializing	3	22	5.3	53.3	0.4
Other Behav.	8	7	9.0	48.2	0.1
Sub-Total	11	29	14.3	101.5	0.3
1983					
Feeding	2	35	1.5	9.1	3.8
Socializing	5	161	4.2	48.3	3.3
Other Behav.	3	6	1.2	9.5	0.6
Sub-Total	10	202	6.9	66.9	3.0
1984					
Feeding	4	0	5.1	28.5	0.0
Socializing	3	2	2.6	16.9	0.1
Other Behav.	10	39	5.1	29.5	1.3
Sub-Total	17	41	12.8	74.9	0.5
1980-84					
Feeding	8	71	8.8	55.4	1.3
Soc. & Feed.	1	43	1.5	36.7	1.2
Socializing	16	198	18.6	173.2	1.1
Other Behav.	23	70	16.0	91.4	0.8
Total	48	382	44.9	356.7	1.1

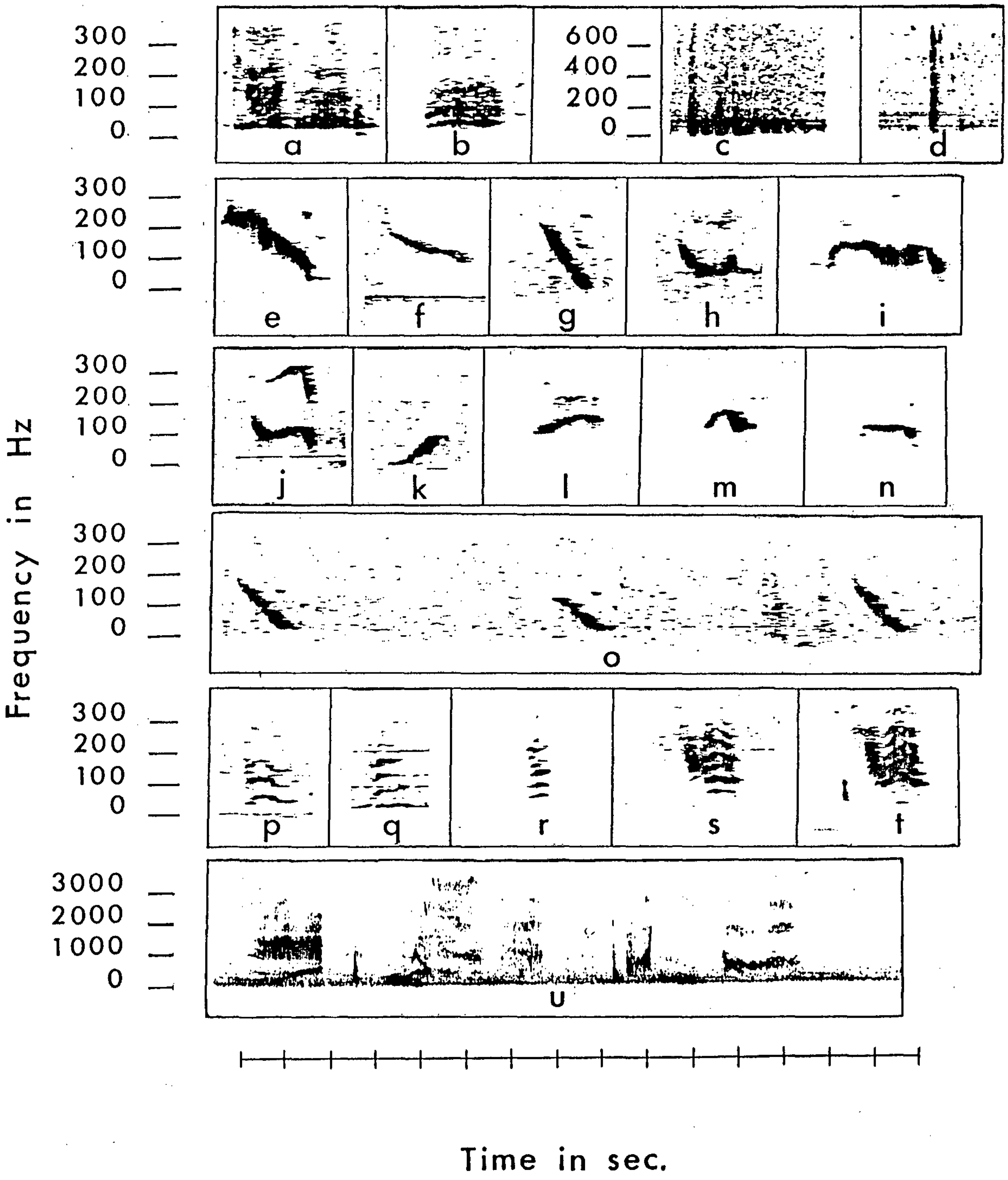

FIGURE 11. Sounds produced by bowhead whales: (a) normal blow sound; the first half is the expiration and the second half is the inhalation; (b) underwater blow sound; (c) breach slap sound with several echoes; (d) tailslap sound with single echo; (e-n) examples of simple FM calls; (o) three calls from a series containing a total of 26 nearly identical FM downsweeps; (p-t) examples of pulsed tonal calls; and (u) series of pulsive screams. See Würsig et al. (1982, p. 117) for additional examples.

flipper slaps. Apparently, there is considerable variation in the acoustic level of different breaches, tail slaps and flipper slaps. Breach sounds were concentrated at lower frequencies than were tailslap sounds (Fig. 11c vs. 11 d; Greene 1984).

Call Types and Their Characteristics

Not including blow and slap sounds, the majority (86%) of sounds recorded in 1980-84 were tonal, frequency-modulated calls lasting 1-2 s. All of the types of calls previously reported for migrating bowheads (Ljungblad et al. 1982; Clark and Johnson 1984) were also recorded here. Figure 11 illustrates a variety of the common, low tonal FM calls as well as the rarer pulsed tonal and pulsive scream calls. The pulsed tone call was called a harmonic call in our earlier reports. Table 11 is a summary of some of the acoustic characteristics for these call types in 1980-81. Although no quantitative comparisons were made between seasons, visual inspection of spectrograms and aural judgements indicated that there were no differences between the general characteristics of sounds in the summers of 1980-84.

Variations in Acoustic Behavior

In 1980-81, calls were not coded as either loud or faint, and therefore call rates were computed using the total number of sounds heard. In 1982-84 when the loud/faint distinction was made, call rates were computed using either the total number of calls or the total number of loud calls. Because of the subjective nature of the loud vs. faint distinction, and the fact that the number of whales within audible range of the sonobuoy was only estimated, the calculated call rates are only estimates.

Call production may be influenced by environmental factors such as water depth, sea state and percent ice cover, all of which affect detectability of calls and may also affect the whales' acoustic behavior. Other factors that may affect rates of vocalization include the density, ages and activities of the whales, abundance of food, etc.

Effects of Environmental Conditions.--Recorded call rates in 1982 were much higher than in other years:

	1980-81	1982	1983	1984
Total call rate (calls/wh-h)	2.2	45.3	2.8	2.6
Loud call rate (calls/wh-h)	-	8.3	0.9	0.9
Whale-h	114.1	108.8	91.6	82.0
Average depth (m)	29	260	24	31

The high apparent call rates in 1982 were probably related to a greater range of detectability in deep water. In 1982 most sonobuoys were in deep water (260 m on average); in all other years most were in shallow water (28 m average). The calculated call rates per whale-hour consider only the whales within about 5 km. In 1982 we probably underestimated the number of whales whose calls were detected, thereby resulting in inflated call rates. In fact, there was a significant correlation ($n = 50$, $r = 0.31$, $0.01<p<0.05$)

Table 11. Acoustic parameters of bowhead call types during presumably undisturbed conditions, 1980-81. Mean ± s.d. are shown.

	Call Type							
Acoustic Parameter	Up	Down	Constant	Inflected	Double	High	Pulsed Tone	Pulsive
Initial frequency (Hz)	146 ± 62	200 ± 53	230 ± 24	249 ± 41	210 ± 45	720 ± 295	68 ± 16	-
Final frequency (Hz)	174 ± 80	133 ± 40	229 ± 23	255 ± 25	250 ± 115	666 ± 216	65 ± 16	-
Lowest frequency (Hz)	146 ± 62	200 ± 53	230 ± 24	156 ± 29	146 ± 50	590 ± 160	-	1006 ± 387
Highest frequency (Hz)	174 ± 80	133 ± 40	230 ± 24	254 ± 40	256 ± 82	793 ± 182	-	1470 ± 405
Duration (s)	1.5 ± 0.4	1.3 ± 0.4	1.2 ± 0.4	1.2 ± 0.6	2.1 ± 0.2	0.7 ± 0.3	1.5 ± 0.4	1.3 ± 0.5
Sample size	75	26	14	11	9	15	47	57

between water depth and total call rate when all five years were considered. There were no significant correlations between call rates and sea state or ice conditions.

Effects of Social and Behavioral Context.--In the following discussion we compare the call types recorded near socializing and non-socializing whales, feeding and non-feeding whales, whales with and without calves, and situations when most whales were subadults (1983, 1984 Yukon Coast) or adults (1982 Herschel Island). The variable compared was the proportion of calls that were complex. Proportions rather than actual rates were used since 1982 rates were extremely high regardless of whale activity; this year effect might mask any possible relationship between social context and acoustic behavior if call rates were considered. The Mann-Whitney U test was used to test for the significance of differences between call proportions under these various conditions.

Socializing vs. Non-socializing -- Types and rates of bowhead calls may be related to the social context according to preliminary analysis of (a) our 1980-81 summer data, and (b) spring and fall data from Alaska (Ljungblad et al. 1983, 1984a). In both of these studies, there were several cases when high proportions of complex calls clearly were associated with high levels of social activity. These analyses suggested that swimming and resting bowheads produce mostly low FM tonal calls, whereas bowheads in active social groups produce a variety of complex sounds. To test this hypothesis, we compared the proportion of calls that were complex during periods when at least some of the whales near the sonobuoy were socializing vs. periods when no socializing was observed. We found a higher proportion of complex calls during periods with socializing, but the difference was not statistically significant. This was true both for all calls in 1980-84 (U = 252,; n = 17 social periods vs. n = 23 non-social periods) and for loud calls in 1982-84 (U = 105; n = 11 vs. 16). The lack of a significant association between socializing and complex calls is similar to results reported by Ljungblad et al. (1984a). Our failure to observe a significant association between socializing and complex calls may be the result of our inability to isolate the sounds of socializing whales. During periods with socializing, there were almost always other whales in the area that were not socializing but may have been vocalizing. In addition, we could not tell whether socializing continued underwater after we observed it occurring at the surface. We scored a whole recording session as "social" if any socializing was seen; however, socializing may not have lasted for the entire session, further diluting the sounds of socializing whales with sounds of non-socializers.

Feeding vs. Non-feeding -- There was no significant difference between the proportions of loud calls that were complex on occasions with and without skim- or bottom feeding (U = 33; n = 2 feeding vs. 25 other occasions). There was a tendency for loud tonal call rates to be lower for skim- or bottom feeding whales as compared with other whales (1983-84 data only, 0.58 vs. 0.95 tonal calls/wh-h).

Calves Present vs. Absent -- When a calf was present, the presumed mother was sometimes very near the calf, but at other times they were separated either horizontally or vertically. We suspected that calls were involved in the process of rejoining. To compare calls in the presence and absence of calves, we analyzed the proportions of loud calls that were complex. There was no significant difference (U = 81; n = 9 occasions with calves vs. 18 without). Altogether, loud tonal call rates were higher for periods with calves than for periods without calves but this result is a consequence of the fact that 8 of 9 'with-calf' periods were in 1982 when call rates were exceptionally high.

Subadults vs. Adults -- In 1982 not only were most observations made over deep water but the majority of animals were estimated to be adults (large, well-marked animals, cf. Davis et al. 1983). This contrasts with the 1983 and 1984 data taken in shallow water when most of the animals were subadults (small, poorly-marked animals, cf. Davis et al. in prep.). To compare calls in 1982 with 1983-84, the proportions of loud calls that were complex were examined. There was no significant difference between results from 1982 and 1983-84 (U = 90.5; n = 12 occasions in 1982 vs. 15 in 1983-84).

Comparison with Acoustic Behavior During Migration

The types of sounds recorded during the summers of 1980-84 in the eastern Beaufort Sea are qualitatively very similar to those reported during the spring and fall migrations (Ljungblad et al. 1980, 1982; Clark and Johnson 1984). Comparisons can be made, in terms of proportions and rates (calls/h), between our summer data and the data from the 1984 spring migration past Barrow (Clark et al. 1985) since the two data sets have been analyzed similarly.

The relative proportions of tonal and complex calls were very similar at the two times of year; 85% of springtime calls were tonal as compared to 83% in summer. Correspondingly, 15% of the springtime calls were complex as compared to 17% in summer. However, considering the seven recognized types of calls, there were differences in the proportions of the different call types depending on the season:

	Percent of Calls of Each Type						
	Up	Down	Constant	Inflected	High	Pulsed Tone	Pulsive
Spring 1984	37.3	19.3	11.7	16.9	0.1	11.7	3.0
(n = 15876 calls, 321.5 h)							
Summer 1980-84	34.9	21.5	18.7	8.2	4.1	6.2	6.3
(n = 6537 calls, 56.6 h)							

There were proportionately twice as many inflected and pulsed tone calls in spring as in summer. There were, proportionally, only one-fortieth as many high calls and half as many pulsive calls in the spring as in the summer. The results concerning high and pulsive calls must be qualified by the consideration that these two call types are often very difficult to identify in the spring because of their similarity to some sounds produced by white whales (Delphinapterus leucas), which were sometimes numerous near the hydrophones. However, this problem did not exist for either the inflected or pulsed tone call types, which were certainly more prevalent in the spring than in the summer. The reason for this seasonal difference is not clear.

Overall, apparent calling rates in calls/h were greater in the summer (115.5 calls/h) than in the spring (49.4 calls/h). However, the importance of these rate differences is not clear since we do not know the number of whales nearby during each period of observation in spring, and therefore the spring rates cannot be standardized in terms of calls per whale-hour. Also, depths at recording sites in spring were shallower (20-25 m) than the average depth in summer (113 m). Spring recording sessions lasted for many days, including periods when few or no whales were nearby, whereas summer sessions were for several hours and were always near whales.

Ljungblad et al. (1983, 1984a) report relative proportions of tonal and complex calls for spring and fall that are quite different from those reported here (in spring, 57% complex in 1982 and 41% complex in 1983; in fall 28% complex in 1982 and 37% complex in 1983). These higher proportions of complex calls are probably a result of sonobuoys being dropped more often near socializing groups. The difference is not a result of discrepancies in procedures for call categorization since the different analysts have conferred and agreed on this method.

Associations of Bowheads with Other Species

During the 5 years of this study, we occasionally observed a few other animal species near bowheads: glaucous gulls (Larus hyperboreus), arctic terns (Sterna paradisaea), phalaropes (probably red-necked phalaropes, Phalaropus lobatus), gray whales (Eschrichtius robustus), ringed seals (Phoca hispida), and white whales (Delphinapterus leucas).

During this study, birds were seen near bowheads on at least 30 occasions. Flocks of up to 50 phalaropes were often present near skim-feeding bowheads. At times, phalaropes appeared to follow the whales, alighting on water disturbed by the whales. The birds probably fed on some of the same plankton species that the bowheads were eating. MacIver (1984) reported red-necked phalaropes associating with feeding humpback whales. Whalers often used the presence of phalaropes to indicate presence of 'whale feed' and, therefore, where whales were likely to be found (Bockstoce in press). Glaucous gulls and arctic terns were also seen circling and passing over skim-feeding bowheads on a few occasions, presumably foraging on the plankton brought to the surface or perhaps bowhead feces. The number of gulls and terns in any one incident ranged from 1 to 8. In Baffin Bay, northern fulmars (Fulmarus glacialis) have been seen feeding on bowhead feces (C.R. Evans, LGL, pers. comm.).

White whales were observed in the same general area as bowheads on at least 15 occasions in 1980-84. The closest approach seen was on 17 August 1983 when two white whales were 45 m from a bowhead and oriented toward it. On 22 August 1983 we observed a white whale within 100 m of a bowhead whale. In neither case did we see any obvious interaction between the two species. The sounds made by white whales underwater are at higher frequencies than most bowhead sounds, but are often intense (e.g., Ford 1977; Wood and Evans 1980). It is likely, therefore, that bowhead whales and white whales knew of each other's presence on several occasions, but we do not know what effects their sounds may have had on each other.

Ringed seals were seen near bowheads on at least five occasions, once within 15 m (24 Aug 1981). No obvious interactions were noted. However, the seals may have been feeding on some of the same organisms as the whales, or on other organisms (e.g., fish) that were feeding on the same species as the bowheads. Lowry et al. (1978) found large zooplankton--euphausiids and amphipods--in the stomachs of both ringed seals and bowhead whales that had been taken in Alaskan waters.

Lone gray whales were seen in the general vicinity of bowheads on two occasions. On 29 August 1980, a gray whale was seen very briefly at 70°42'N, 128°58'W; it was about 800 m from a bowhead whale. On 18 August 1982, a gray whale was seen with muddy water streaming from its mouth, indicative of bottom feeding. The whale was at 69°37'N, 138°30'W in an area with approximately six bowheads, none of which appeared to be bottom feeding. The gray whale was about 500 m from the closest bowhead, and there was no apparent interaction between them. Rugh and Fraker (1981) reviewed earlier sightings of gray whales in the Canadian Beaufort Sea.

DISCUSSION

Year-to-Year Variations in Behavior of Bowheads

Of the year-to-year variations in behavior that we observed during the five years of this study, one of the more dramatic has been the considerable differences in the locations where we encountered bowhead whales each year (Richardson et al. 1985a). In 1980, many bowheads came close to shore off the Mackenzie Delta and Tuktoyaktuk Peninsula. From 1980 to 1982 there was a progressive increase in the depth of water in which bowheads were observed. In 1983 and 1984 we again found bowheads in very shallow water close to shore, but in a different part of the study area. In 1983 and 1984, the nearshore whales were along the Yukon coast in a region from which they were absent in 1980 and 1981, west of the area where they were so common in 1980.

Another difference between 1983-84 and 1980 was the age composition of nearshore whales. In 1980 these whales included calves and mothers and other presumably mature whales, as indicated by large white chin patches and white areas on the tailstock and flukes. In 1983, mothers with calves were encountered only in deep water >100 km north of the immature group (this study) and in offshore areas much farther east (McLaren and Davis 1985; J. Cubbage pers. comm.). In 1984, calves were sighted near shore during only one flight. Most whales near shore in 1983 and 1984 were subadults, based on length measurements and the rarity of white markings on the tail. Because of age-class segregation and because we rarely flew far offshore in 1983 and 1984, our calf sighting rate was lower in 1983-84 than in 1980-82 (Table 3).

Feeding is presumed to be the predominant activity of bowheads summering in the Beaufort Sea. Observed frequencies of various types of feeding varied from year to year; in 1980 we saw indications of bottom feeding, skim-feeding, and water-column feeding; in 1981 we saw skim-feeding and water-column feeding; and in 1982 we presumed that most whales were water-column feeding but had little direct evidence for this aside from observations of long dives. Feeding activity in 1983 was probably most like that in 1980, as the feeding behavior observed near shore was bottom feeding and skim-feeding. In contrast to 1980 and 1981, none of the skim-feeding observed in 1983 was by whales in echelon formation. In 1984, bottom feeding but no skim feeding was observed; water column feeding probably also occurred.

We saw variable amounts of social behavior over the years, with the rate of socializing lowest in 1982, when whales were in the deepest water, and highest in 1981 (Table 4). In all years the rate of socializing was lower in late August and early September than in early August. We presume that this seasonal decrease is part of a longer term seasonal decline in frequency of socializing from spring migration, when mating and boisterous interactions appear to occur (cf. Rugh and Cubbage 1980), to fall migration, when there is little social behavior.

There was considerable variation in the number of underwater blows, with by far the highest number in 1983. In 1981 and 1983, there was a positive correlation between rates of underwater blowing and of socializing, and in 1983 we observed many underwater blows near actively socializing whales.

The rate of aerial activity has not varied very much from year to year. It is interesting that the rate of aerial activity should have been so stable over five years when so many other activities have varied to a much greater extent.

The types of sounds recorded underwater in the presence of bowheads have been the same in all five years of this study. Measured call rates, however, varied considerably among years. There were indications that changes in depth of water and social context were related to the variations in apparent call rates. For example, in 1982, when there was a six-fold increase in average water depth during recording sessions compared to 1980-81, total number of calls recorded was much higher. Calls from whales far away are more likely to be detected in deep than in shallow water. In 1982, the majority of the calls were low, frequency-modulated calls and the rate of socializing was less than in 1980-81. Associated with this drop in socializing was a decrease in the proportion of complex harmonic or pulsive sounds from 56% in 1980-81 to 10% in 1982. In 1983, this value increased to 15%, concurrent with an increase in socializing. Complex pulsive sounds are believed to be associated with socializing in southern right whales as well as bowheads (Clark 1982, 1983).

We wondered whether there might be some cyclicity to the year-to-year changes in behavior of bowhead whales. In the southern right whale, most mature females bear calves every third year and are absent from the calving grounds in Argentina during the two years between calves (except for a brief stay early in the winter by some females the year after giving birth to a calf--Taber and Thomas 1982). There is, therefore, a different population of mature females on the calving grounds each year for three years, after which the pattern is repeated. It is possible that the breeding cycle in bowhead whales is similar to that of southern right whales (Davis et al. 1983; Nerini et al. 1984), but, after five years of study, we have no consistent evidence that the considerable year-to-year variation in behavior of bowheads forms a repeating pattern.

Year-to-Year Variations in Behavior of Other Cetaceans

In our study, two of the main attributes that varied from year to year were (a) bowhead distribution within the eastern Beaufort Sea, and (b) the frequency and type of feeding. Both might reflect changes in prey distribution, abundance, or species composition. We do not have sufficient data on the prey of these bowheads to test such a relationship. Stomach contents of bowheads from the eastern (i.e. Canadian) Beaufort Sea have not been collected, and factors affecting zooplankton dynamics in that area have not been studied in any detail. There are indications, however, that some of the variability in bowhead distribution is related to variability in water mass characteristics, which are presumed to reflect differences in prey availability (Borstad 1984; LGL, ESL and ESSA 1984). In addition, the most impressive case of near-surface skim feeding that we observed (18 Aug 1981) was at a location where copepod abundance in near-surface waters was unusually high (Griffiths and Buchanan 1982).

Studies of other baleen whales provide quite direct evidence for changes in geographic distribution in response to changes in their prey. Humpback whales are a good example of this because they feed on different kinds of prey in different areas and they have been studied intensively in recent years. On Stellwagen Bank near Cape Cod, where sand lance (Ammodytes americanus) were present in large concentrations, individual humpback whales returned in consecutive years (Mayo 1982, 1983). Their movements within each summer were quite predictable even to the extent of which points on the bank (separated by only 25 km) they occupied early and late in the season. In contrast, humpback whales that feed farther north near Newfoundland utilize mainly capelin (Mallotus villosus). Sighting rates for humpbacks in one small nearshore area roughly quadrupled over three years, while humpbacks disappeared from a second area farther offshore (Whitehead 1981). Capelin stocks offshore collapsed at the same time that humpbacks and spawning schools of capelin became plentiful inshore. Whitehead concluded that summer distribution of humpbacks changed in direct response to the failure of offshore capelin stocks. Similarly, Bryant et al. (1981) found evidence that the disappearance of humpbacks from Glacier Bay, Alaska, in 1980 was attributable to a low krill population in that year. Thus, when the prey species remained in the same place in high abundance, humpback whales returned each year to the same area. When the prey moved dramatically, the whales also moved.

The above examples are from humpback whales that summer and feed nearshore, but the same kinds of conclusions have been drawn from studies of whales feeding farther from shore, in open ocean areas in the Antarctic and in the North Pacific. Data obtained from the 'Discovery' expeditions showed that changing distributions of rorquals in the Antarctic Ocean were related to the variable distribution of their principal prey, the krill Euphausia superba (Mackintosh 1965). Mauchline and Fisher (1969) demonstrated that major concentrations of krill in the Antarctic may occur in different places in different years, appearing unpredictably in any given year at new locations often hundreds of kilometres away from the concentration centers of a previous year. Meteorological factors, specifically the tracks of major storms, may be partly responsible for the variable distribution of krill and, hence, whales (Beklemishev 1960).

In rorquals feeding in the open North Pacific ocean, there is great year-to-year variability in food availability, whale diet, whale distribution, and time of occurrence on the feeding grounds (Nemoto 1959). Over 6 years, the principal prey of fin whales alternated each year between euphausiids and Calanus copepods. Plankton tows demonstrated that this reflected alternating abundance of these prey items in the area (Nemoto 1957). Nemoto also noted that blue whales do not migrate to an area southeast of the Kamchatka Peninsula when euphausiids are not abundant. However, when euphausiids are abundant, blue whales arrive there early in summer. The entire migration route of blue whales in the North Pacific may be determined by annual fluctuations in the distribution of the main centers of euphausiid concentration (Nemoto 1957).

It is not surprising that annual changes in prey distribution can cause changes in whale distribution. Baleen whales apparently cannot obtain enough food by feeding in areas of average prey abundance; they must feed selectively in areas of concentrated prey (Nemoto 1970; Brodie et al. 1978; Brodie 1981; Griffiths and Buchanan 1982). Year-to-year or other variations in the types and vertical distribution of prey could presumably affect the relative frequencies of surface, water-column, and near-bottom feeding.

Changes in prey availability probably affect other aspects of behavior, such as social and aerial behavior. Gray whales on the north side of the Alaska Peninsula in spring apparently feed on both inbenthic and epibenthic prey (Gill and Hall 1983). While feeding on the bottom, gray whales are usually solitary, but while feeding on patchily distributed prey in the water column, they tend to aggregate. This aggregation gives a greater chance for social interactions (BW, pers. observ.). As well, low-intensity aerial behavior, consisting of flippers and fluke tips raised above the water surface, often occurs while gray whales feed on epibenthic prey in shallow water, but does not occur during bottom feeding. This variation in behaviors exists on a regional basis and a day to day temporal basis, and probably is related to different relative abundances of food types. Humpback whales in the Frederick Sound area of southeast Alaska also feed near the surface and below it, and the relative frequencies of different feeding modes change between years (C.S. Baker, Univ. Hawaii, pers. comm.). Surface feeding involves lunges through the prey, often resulting in half-breaches and other forms of aerial activity. Feeding in the water column involves little surface activity. Surface lunge feeding often occurs in concert with other whales; non-surface feeding is more often solitary (Jurasz and Jurasz 1979).

Given the above, we suspect that the observed annual variation in bowhead behavior is also in large part a reflection of varying horizontal and vertical distribution of their prey. For example, we saw little socializing in 1982, when bowheads appeared to feed mainly in the water column, and more social activity while many whales fed close to the surface near shore. To understand for any given year where bowheads are likely to concentrate and how they are likely to feed, it will be necessary to understand factors affecting prey distribution. It is not known to what extent the distribution of the prey of bowheads in the eastern Beaufort Sea is affected by factors like (1) timing and amount of spring run off from the Mackenzie River, (2) distribution of ice during spring and summer, (3) wind patterns and paths of major storms, and (4) the variable distribution of the plume of turbid brackish water from the Mackenzie River. Any or all of these interrelated factors could affect prey distribution and therefore the distribution and behavior of bowheads (Borstad 1984; LGL Ltd. in prep.).

A further uncertainty is the degree to which the present Western Arctic bowhead stock is food-limited. The total size of this stock is clearly lower than before commercial exploitation, so the present stock might not be food-limited. If so, details of summer distribution of bowheads might not be predictable even with a detailed understanding of prey distribution. However, the number of bowheads now summering in the eastern Beaufort Sea may be a high proportion of the number that summered there before commercial exploitation (Fraker 1983). Also, populations of potential food competitors (e.g., arctic cod, Boreogadus saida; Lowry and Frost 1981; Frost and Lowry 1984) may have increased since the beginning of commercial whaling. Thus, bowheads summering in the eastern Beaufort Sea may be food-limited at present. Also, the important limitation is probably not the total amount of food available. Bowheads apparently must concentrate their feeding in areas with dense patches of zooplankton (Brodie 1981; Griffiths and Buchanan 1982). If patch locations vary, as is likely, then bowhead distribution is also likely to vary. Thus, an understanding of prey variability would be especially important in understanding the variable activities and distributions of bowhead whales.

Comparisons with Bowhead Whales in the Alaskan Beaufort Sea

During both spring and fall migration into and out of the Beaufort Sea, bowhead whales engage in all of the major behaviors observed on the summering grounds, but with different relative frequencies. Thus, while travelling is the predominant activity during migration, socializing and mating also occur, more often in spring than in summer or fall. Feeding has been reported in fall, and (rarely) in spring, as well as summer. Aerial activity occurs in spring, summer and fall, and young-of-the-year are closely associated with their mothers, probably nursing, in all three seasons. We will review the evidence for each of these types of activity in turn.

During spring migration, bowhead whales appear to do little feeding before they reach the Canadian Beaufort Sea. Bowheads taken in Alaskan waters in spring usually have nearly empty stomachs (see Marquette et al. 1982 for review). Some, however, do contain food (e.g., Hazard and Lowry 1984).

Bowheads seen off northern Alaska in September as well as October are often described as migrating, but it is clear that many are feeding, loitering, and exhibiting behavior very similar to that in the Canadian Beaufort Sea in summer. Bowheads may loiter for considerable periods in the eastern portion of the Alaskan Beaufort Sea during late August through early October, and considerable feeding occurs at these times between Kaktovik, Alaska, and the Alaska-Yukon border (Ljungblad et al. 1980, 1983, 1984a; Lowry and Burns 1980; Ljungblad 1981; Lowry and Frost 1984). Bowheads seen in this area in late August and September typically dive repeatedly in the same locations, and do not begin to travel rapidly westward until later in September or early October when freeze-up accelerates. Nine bowheads killed and examined near Kaktovik in autumn had been feeding recently, mainly on copepods or euphausiids (Lowry and Frost 1984). The eastern part of the Alaskan Beaufort apparently is a part of the main summer feeding range.

Later in autumn, bowheads tend to travel more consistently and rapidly toward the west. However, feeding has also been reported just east of Point Barrow during several autumns, and also off the Soviet coast (e.g., Braham and Krogman 1977; Braham et al. 1977; Lowry et al. 1978; Johnson et al. 1981; Marquette et al. 1982). The rate and consistency of feeding during fall migration probably are lower than in summer, but quantitative data are lacking.

The primary mating period of bowhead whales is in early spring and includes the spring migration (Everitt and Krogman 1979; Carroll and Smithhisler 1980; Johnson et al. 1981; Ljungblad 1981). Everitt and Krogman (1979) described a particularly active mating group of six whales seen on 8 May 1976 near Point Barrow, Alaska. We saw some evidence for mating in the Canadian Beaufort Sea in August of both 1980 and 1981, but not in later years. Even the active rolling at the surface that we observed in 1981, however, was not as boisterously active as the large mating group described by Everitt and Krogman. Mating probably is more common during spring migration than during summer in the Beaufort Sea. Non-mating social activity also appears to be more common during the spring migration, but quantitative data for spring are lacking. There is a waning of social activity during the summer, and by late fall it does not occur often (Ljungblad et al. 1984a,b).

Aerial activity similar to what we observed in the eastern Beaufort Sea--breaches, tail slaps, flipper slaps, spy hops and rolls--has been observed in bowheads during spring migration (Carroll and Smithhisler 1980; Rugh and Cubbage 1980). Rugh and Cubbage recorded breaches by 23% of 280 bowheads observed in 1978 from Cape Lisburne, Alaska, a rate far above what we observed, but also higher than the reports from other spring observation sites (Pt. Barrow and Pt. Hope, Alaska). Although quantitative comparisons are not possible among the various observation sites, our impression is that aerial behavior is more frequent during spring migration than on the summer feeding grounds. This is consistent with the fact that Rugh and Cubbage (1980) observed the rate of breaching to decline through the spring season. Aerial activity in fall appears to occur at about the same frequency as in summer (B. Würsig, pers. obs.).

Travelling is clearly more pronounced in spring and late autumn than in summer but bowheads sometimes move long distances within the July-early September period. Carroll and Smithhisler (1980) estimated that 95% of the time that bowheads were observed migrating past Point Barrow and Point Hope in the spring, from 1975 through 1978, animals 'exhibited the normally expected migratory surfacing patterns', i.e. were travelling. Similarly, Davis and Koski (1980) and Koski and Davis (1980) found that eastern arctic bowheads migrating along the coast of Baffin Island in fall travelled consistently to the southeast. Ljungblad et al. (1984a) have found that, after a certain year-specific date in late September, most bowheads seen in the Alaskan Beaufort Sea are travelling strongly westward, whereas before that date most are feeding and loitering. We have no estimate for the percent of time that bowheads summering in the eastern Beaufort Sea were actively travelling; it was low but not zero. Although direct observations of rapid travel during summer were infrequent, changes in distribution from week to week and month to month provided proof that large numbers of whales often travel long distances within the eastern Beaufort Sea and Amundsen Gulf during summer (Renaud and Davis 1981; Davis et al. 1982; Richardson et al.

1985a). Within-season resightings of individually-recognizable bowheads also show considerable movement within the summer (Davis et al. 1983, in prep.). One identifiable whale was photographed near Herschel Island on 18 August 1982, 154 km to the northeast on 23 August 1982, and again near Herschel Island on 5 September 1982 (Davis et al. 1983).

Because the predominant activity of bowheads during spring and late fall is travelling, their surfacing pattern is slightly different from that usually seen in summer. During the intervals between blows within a surfacing sequence, migrating bowheads usually make brief shallow dives called 'series' dives (Rugh and Cubbage 1980). Series dives may occur because of the hydrodynamic advantage to a moving whale of avoiding wave generation at the air-water interface. Summering bowheads, on the other hand, often remain at the surface between blows, probably because it is easier to breathe if the whale remains at the surface and because submerging provides no hydrodynamic advantage if the whale is not trying to make forward progress.

The behavior of bowhead calves during autumn migration is very similar to behavior seen in summer. It includes nursing and 'waiting at the surface' while mothers are diving (B. Würsig, pers. obs.). Most calves are apparently born in late winter or spring; nursing presumably occurs during spring migration as well as summer and autumn. Many bowhead calves remain with their mothers for at least the first part of the fall migration (Davis and Koski 1980; Ljungblad et al. 1984a). The age of weaning of bowhead calves is not known, but some southern right whale calves remain with their mothers for one year and ultimately separate from their mothers after returning to the wintering area (Taber and Thomas 1982).

In comparing the quantitative data on surfacing, respiration and dives that we have gathered for summering bowheads with similar data for migrating bowheads, we must use caution. Different investigators have gathered their information and defined their variables in somewhat different ways, because of differences in vantage point and in surfacing behavior of the whales. The comparisons that seem valid are presented here.

In comparison with our results, Koski and Davis (1980) found longer blow intervals for eastern arctic bowheads migrating along the coast of Baffin Island in the autumn of 1979 (our data for non-calves 1980-84: 13.5 ± s.d. 8.88 s, n = 5161; Koski and Davis: 16.1 ± s.d. 8.29 s, n = 399; t = -5.66, $p<0.001$).

The overall mean number of blows per surfacing that we recorded for non-calves in the eastern Beaufort Sea from 1980 through 1984 was 4.3 ± s.d. 3.25 (n = 626), less than the values reported for bowheads on their spring migration off Alaska by Carroll and Smithhisler (1980; mean = 6.5 ± s.d. 2.84 blows per surfacing, n = 41; t = 4.23 $p<0.001$) and by Rugh and Cubbage (1980; a mean of approximately 6.4 blows per surfacing). The overall mean duration of surfacing that we observed in non-calves during 1980-84 was 1.2 ± s.d. 1.14 min (n = 715). This was slightly shorter than the approximate mean of 1.52 min that we derived from data collected by Carroll and Smithhisler (1980) from bowheads during spring migration. Our value was also shorter than the mean reported for bowheads during fall migration in the eastern arctic by Koski and Davis (1980): 1.69 ± 1.01 min, n = 93; in comparison with our data, t = 4.03, df = 806, $p<0.001$.

During summer, durations of dives by undisturbed non-calf bowheads varied more from year to year than did the aforementioned variables. The overall mean dive duration for 1980-84 was 4.4 ± s.d. 6.32 min (n = 333, range = 0.03 to 31.0 min). Braham et al. (1979) reported that dives of whales migrating past Cape Lisburne, Alaska, in spring ranged from 1.7 to 28 min, but those authors did not give a mean. Carroll and Smithhisler (1980) found long dives, 15.6 ± s.d. 5.0 min (n = 63), during spring migration; and Koski and Davis (1980) found somewhat shorter dives of duration 8.65 ± s.d. 2.73 min (n = 88) during autumn migration in the eastern arctic. Both of these mean dive times for migrating bowheads exceed our overall 1980-84 mean for summering whales. However, our results from the summer of 1982 (12.08 ± s.d. 9.15 min, n = 51) are more similar to observations during migration.

On 6-30 September 1983, behavior of bowheads was studied in the Alaskan Beaufort Sea, between Prudhoe Bay and the Alaska-Yukon border (Ljungblad et al. 1984b). These data were gathered from a circling Twin Otter aircraft; techniques were similar to those during our study. Blow intervals, number of blows per surfacing, duration of surfacing and duration of dives for non-calves all averaged somewhat higher in the Alaskan study than in our five-year study. However, there was a great deal of overlap, and for each variable, some of our annual means were higher than the mean value in Alaska in 1983. In the autumn of 1983, Ljungblad et al. (1984b) found more travelling and less socializing than we found one month earlier in the Canadian Beaufort Sea. They found no skim- or bottom feeding in Alaskan waters in 1983, although both have been observed there in other autumns.

Calls recorded in spring and fall were similar to those recorded in summer but occurred in different proportions. The most common call types in all seasons were tonal FM sounds. The proportions of complex calls were greater in summer than in spring recordings from ice camps (Clark et al. 1985, Clark pers. obs.) but less than in spring or fall recordings via sonobuoys dropped from aircraft (Ljungblad et al. 1983, 1984a). This difference resulted from the different sampling methods, perhaps including a tendency to drop sonobuoys near interacting groups of whales during spring and fall. The higher proportion of complex calls in spring relative to fall (Ljungblad et al. 1984a) appears to reflect the greater amount of social activity in spring.

Bowhead whales on their summering grounds, including the eastern part of the Alaskan Beaufort Sea up to mid or late September, appear to have the same basic repertoire of behaviors as do migrating bowheads. However, summering and migrating bowheads differ in the relative amounts of time spent in different activities--feeding, socializing, breaching and other aerial behavior, and travelling. At least some of the differences appear to occur as a continuum between seasons rather than an abrupt change. Travelling is the predominant activity during spring and fall migrations, while feeding is the predominant activity during summer. The average length of stay in any one area is therefore longer in summer, but considerable travelling occurs in summer and some feeding occurs during migration, especially in fall. Although quantitative comparisons of surfacing, respiration, dive and acoustic characteristics are not always possible and need to be treated with caution, there appear to be some significant quantitative differences between the seasons, but few qualitative differences.

Comparisons with Other Baleen Whales

Bowhead whales spend their entire lives in arctic and near-arctic waters, apparently never moving far from the ice edge. This habit separates them from all other baleen whales, which may move into temperate or subtropical waters (see, for example, review by Lockyer and Brown 1981). This may be the reason that parturition occurs mainly in spring in bowheads, but in early winter for other species (Nerini et al. 1984). But behavior is in large part determined by feeding mode and related ecological factors, and here similarities between bowhead whales and several other species are evident.

Gray, bowhead, and right whales are often found in shallow water, and all of these species feed on small invertebrates. While gray whales usually feed near the bottom (e.g., Bogoslovskaya et al. 1981; Nerini 1984), both right and bowhead whales may skim their food at or near the surface (Watkins and Schevill 1976, 1979; Payne in review, for right whales; Würsig et al. in press for bowheads). But all three species are also adaptable in feeding behavior. Gray whales will feed on mysids associated with kelp (Darling 1977) for example, and apparently feed on <u>Pleuroncodes</u> sp. in the water column (Norris et al. 1983). Right whales also feed below the surface, probably straining swarms of copepods and other small invertebrates in the water column (Pivorunas 1979; Payne in review). While it has long been known that bowhead whales feed at the surface and in the water column (Scoresby 1820), it was recently established from stomach content analyses (Durham 1972; Lowry and Burns 1980; Hazard and Lowry 1984), and from our observations of bowhead whales surfacing with muddy water streaming from their mouths, that bowheads sometimes feed near or at the bottom. It is not surprising that we found many similarities in the behavior of these species. Bowhead and right whales, in particular, are morphologically and taxonomically quite similar, and appear to obtain their food in very much the same ways. In fact, Rice (1977), mainly relying on a detailed comparison of morphology of bowhead and right whales, suggested that the two species be put in the same genus, <u>Balaena</u>.

The sleeker rorquals (Balaenopterid whales) generally gather their food more actively by lunging through concentrations of prey, and at least in the case of humpback whales, have developed complicated behavioral strategies for confining and concentrating their prey (Jurasz and Jurasz 1979; Hain et al. 1982). In general, the behavior of bowhead whales is more similar to that of gray and right whales than it is to the behavior of rorquals.

Gray whales spend part of the winter in warm water, near the shores of Baja California, and most of the summer feed in the northern Bering and southern Chukchi seas. Western Arctic bowheads make much shorter migrations, spending their winters in the pack ice of the Bering Sea and their summers predominantly in the Beaufort Sea. The two species thus use the Bering Sea at different seasons--gray whales to feed in summer and bowhead whales apparently to mate and calve in winter. However, the summer and autumn habitats overlap in part. Both gray and bowhead whales feed in the southern Chukchi Sea in autumn, and in the 19th century bowheads as well as gray whales occurred there in summer (Townsend 1935; Dahlheim et al. 1980). We have seen single gray whales in the Canadian Beaufort Sea during four of our five years of bowhead whale work, but this represents the outer fringe of the gray whale's summer range (Rugh and Fraker 1981).

Like bowhead whales summering in the Beaufort Sea, gray whales summering in the Bering Sea spend most of their time feeding. However, both bowheads and gray whales (Sauer 1963; Fay 1963) occasionally socialize during the summer. The blow rate of gray whales feeding near St. Lawrence Island in July 1982 was similar to that of non-calf bowhead whales in 1980-84 (gray whale mean = 0.93 ± s.d. 0.229 blows/min, n = 67 whales; bowhead whale mean = 1.10 ± s.d. 0.873 blows/min, n = 156 blow rates; gray whale data from Würsig et al. 1984b). The basic pattern of diving for several minutes and then surfacing, generally for 2-10 respirations, is also similar for the two species on their summer feeding grounds.

Right whales, like bowhead whales, often appear to feed in the water column and to stay in the same general area for days. Right whales, like bowheads, also skim feed at the surface (Watkins and Schevill 1976, 1979), and they at times aggregate into echelons while skim feeding (Payne in review). In right whales, these echelons usually consist of only 3 to 6 whales, while we saw up to 14 bowhead whales skim feeding in echelon. However, Payne's observations of right whales have been obtained during the late winter and early spring, which is not the period of maximum feeding intensity for right whales. Bowhead and right whales have both been observed making the same kinds of nudges and pushes during socializing, but the winter-spring social activity of right whales is much more boisterous than the summer social activity of bowheads. Observations of bowhead whales in spring indicate that their social-sexual activity at that season can be every bit as boisterous as is seen in mating groups of right whales (Everitt and Krogman 1979; Carroll and Smithhisler 1980; Rugh and Cubbage 1980; Johnson et al. 1981; Ljungblad 1981). The belly-up position of a female bowhead photographed in spring in the Alaskan Beaufort (Everitt and Krogman 1979) indicates that females may attempt to evade potential mates who pursue them in large mating aggregations in the same way that female right whales evade males in Argentine waters (Payne in review). A photograph showing a remarkably similar mating group of right whales is shown in Payne (1976). The fact that similar-looking social aggregations are seen in both species argues for a similar social system, although it does not show that the social systems are similar in all details.

The acoustic behavior of right whales and bowheads is remarkably similar. Their low tonal FM calls are essentially identical, and the up call is their most common call type. In right whales, Clark (1982, 1983) has shown that up calls are contact calls, and that complex calls are associated with highly active social groups, many of which were sexually active. For the two cases in 1981 when bowheads were highly active, the proportions of complex calls were unusually high (72 and 85%). Ljungblad et al. (1983, 1984a) also observed highly active, often mating, whales that were apparently producing complex calls at high rates. In this study, we were not able to show an overall correlation between proportions of complex calls and social activity. Our definition of socializing included groups that were only mildly active. We were also not able to determine which specific whales were responsible for the sounds being recorded. Thus, our results are consistent with the idea that socializing bowheads tend to produce many complex calls, although our data do not specifically show this.

Relevance to Studies of Disturbance Responses

This study was planned primarily to assist the interpretation of the simultaneous study of responses of bowheads to potential disturbance. The results confirm that data on normal behavior are essential as a basis for recognizing and evaluating reactions to disturbance. We found that undisturbed behavior of summering bowheads varies considerably from day to day and from year to year, both in terms of general activities and distribution and in terms of surfacing, respiration and dive characteristics. Consequently, no observed variations in bowhead behavior that appear to be caused by disturbance can be properly attributed to the disturbance until natural variability has been taken into account.

Data on surfacing, respiration and dive characteristics are useful for assessing disturbance responses because these characteristics can be measured repeatedly with relative ease and because it is clear that they change in the situation where immediate disturbance reactions are most dramatically obvious, i.e. when a boat travels through a group of whales (Richardson et al. 1985c). Among the obvious reactions of bowheads to this situation are shortened surfacings with fewer blows per surfacing. It is reasonable to expect that milder forms of disturbance might cause similar but less dramatic changes in surfacing and respiration patterns, and the disturbance portion of this overall study has found suggestions of such changes in the presence of several different forms of industrial activity. Throughout the analysis for the presence or absence of disturbance responses, however, comparisons with the behavior of presumably undisturbed bowheads were made, as the only method to identify potentially disturbed behavior.

An example of the use of normal behavior data in the analysis of disturbance responses is the selection of undisturbed whales to serve as partial controls for the opportunistic observations of whales in the presence of seismic noise (Richardson et al. 1985c). Because we found considerable differences in surfacing, respiration and dive characteristics between calves and other bowheads, the few data from calves were excluded. Because we found suggestions of differences with depth of water, only whales in comparable water depths were compared. Because we found variations in behavior at different times during the summer, only whales observed during the same day or on adjacent days were compared, insofar as possible.

In some cases, data from several seasons of study were necessary in order to detect an important relationship. For example, in all five years of this study, the rate of socializing decreased progressively from early August to early September. If industrial activity were initiated in the middle of this period in a region frequented by bowheads, and if a lower rate of socializing were observed after the potential disturbance started, that change could be discounted as a reaction to the industrial activity as long as the decrease were comparable to the normal seasonal decrease in socializing identified during this study.

In addition to providing control observations against which to assess observations in the presence of specific kinds of potential disturbance, an understanding of the normal behavior of bowhead whales is necessary to make informed judgements on a more general level about the likelihood that industrial activity will have deleterious effects. For example, we observed that mothers and calves at times become separated while the mothers are presumably feeding, and that they apparently reunite by calling to each other. This indicates that prolonged masking of those calls by loud industrial noises might cause premature separation of calves from their mothers. Another example derives from our discovery that some bowheads feed at the bottom. This result shows that the availability of prey at or near the bottom should be taken into account in evaluating the importance of an area to bowheads.

Recommendations for Further Research

After five seasons of research, we have a solid base of information on the short term normal behavior of bowhead whales during summer. However, we know virtually nothing about affiliations between whales, lengths of times individual whales are engaged in specific behaviors before changing activity, and the relationship of feeding and other behaviors to distribution and availability of prey. Many avenues of research are possible, but we mention several major ones which would build directly on our foundation.

Bowhead whales are at times recognizable by natural markings peculiar to an individual. However, our usual aerial vantage point, which generally has us >1 km from whales as we circle around them, is not optimal for getting detailed information on the identifying features of individuals. In addition, whales can travel underwater for several km, and we often lose sight of them as they move unobserved out of our circle of observation.

A radio tag on the back of one or more whales would solve many of these observational difficulties: we would be able to observe an electronically identified whale throughout an observation session, locate it even when it travels away from the aircraft, monitor its affiliations with other whales not only during an observation session but also on subsequent days, obtain dive time and surface time information during multiple observation sessions, possibly including periods of bad weather and darkness, and monitor longer range movements than the ones we have been able to obtain. Because radio tagging would enhance our knowledge of the surfacing-dive pattern and allow us to stay with a whale for long times, this technique would also be extremely valuable for the monitoring of potential disturbance reactions during industrial activities. Several types of radio tags have been successful on gray, fin, humpback and bryde's whales (Ray et al. 1978; Watkins et al. 1981; Goodyear 1983; Mate and Harvey 1984). By whatever technique of attachment, the radio could be monitored directly from an airplane, a boat, or the shore, as opportunity permits. A more sophisticated radio tag could probably give heart rate information, which has proven useful in assessing harassment in free ranging bighorn sheep (MacArthur et al. 1979).

Davis et al. (1982, 1983) and Cubbage et al. (1984) recently showed that high-resolution photogrammetry can distinguish many individual bowheads by natural marks and pigmentation patterns. We recommend that such high resolution photography be continued and expanded, because it can give valuable information on site tenacity, large scale movement patterns of individuals, and whale-whale affiliations over time (including, perhaps, between years). The photogrammetric technique, which gives accurate data on sizes of whales, can also assess age segregation over the entire range of bowhead whales, and can therefore help us to determine the social structure of bowhead whales.

We have described several different feeding modes and feeding areas in our five-year study, and we have speculated that variations in feeding behavior and location are largely due to variations in prey distribution. We have no direct evidence for this assertion, however. To assess the importance of particular areas to bowhead whales, we need to confirm the link between distribution of prey and location and feeding mode of the whales. Trained behavioral observers should work in conjunction with any program to sample prey availability and factors controlling it. In this way, distribution of prey can be linked with distribution and feeding behavior of bowhead whales.

We know very little about the distribution and behavior of bowhead whales in winter or early spring. Although there are logistic difficulties, we recommend systematic observations, especially from the air, of bowhead whales during late winter and spring. Many calves may be born then, but we do not know what social affiliations occur in early spring, and how much feeding, if any, occurs at that time. A behavior study in early spring would not just fill a major gap in understanding of the normal behavior of bowhead whales, but would also allow us to assess the possibility of different reactions to potential disturbance during the time when bowhead whales are in the northern Bering Sea, with many engaged in mating and calving.

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DISTURBANCE RESPONSES OF BOWHEADS, 1980-84*

by

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TABLE OF CONTENTS

ABSTRACT

This report describes the behavior of bowhead whales near actual or simulated industrial activities in the Canadian Beaufort Sea. In the latter experiments we compared behavior of specific whales before, during and after exposure to simulated industrial activity:

- Aircraft at various altitudes.. 8
- Boat disturbance expt.......... 7
- Full-scale seismic expt........ 1
- Drillship noise playbacks...... 6
- Helicopter pass at 153 m alt.. 2*
- Airgun (40 in^3) expt.......... 5
- Dredge noise playbacks........ 3

* plus 3 opportunistic helicopter overflights

Most observations were from an Islander aircraft circling 457-610 m above the whales, high enough to avoid significant disturbance. A 12.5-m boat was used to conduct most tests. Underwater sounds (industrial and bowhead) were recorded in the aircraft by sonobuoys and on the boat by hydrophones.

Reactions to Aircraft.--Overt reactions to the observation aircraft were sometimes conspicuous when it was below 457 m a.s.l., uncommon at 457 m, and generally undetectable at 610 m. The usual reaction was a hasty dive when the aircraft first approached, with little or no detectable effect thereafter. On rare occasions, bowheads seemed to move away in response to the aircraft circling at ≤457 m. Reactions were most common in nearshore waters <15 m deep, where lateral propagation of aircraft noise was greatest. When we circled the same whales at high (457 and/or 610 m) and lower (305 m) altitudes, blow intervals tended to be shorter when the aircraft was low. We conclude that one pass by a small twin engined aircraft at altitudes <305 m

sometimes causes bowheads to dive; continued circling at ≤305 m affects respiration. Except in shallow nearshore areas, overflights at ≥457 m have little effect.

On 5 occasions we observed bowheads before, during and after a helicopter made a single pass overhead at 153 m altitude. No reactions were detectable in real time, but the bowheads were below the surface when the helicopters were directly overhead. The whales did not leave the area.

Reactions to Boats.--Bowheads reacted more strongly to close approach by various boats than to any other industrial activity. Bowheads began to swim rapidly away as boats approached within 1-4 km. The initial reaction was often an attempt to outrun the boat. When the boat was within a few hundred metres, whales either turned and swam away from the boat's track, or dove. Groups of whales scattered. Fleeing generally ceased a few minutes after the vessel passed, but scattering persisted longer.

Reactions to Seismic Impulses.--On 21 occasions we observed bowheads in the presence of noise from seismic vessels 6-99 km away; behavior was not dramatically affected. There was no evidence of avoidance at such ranges, but there were hints of subtle alterations in surfacing, respiration and diving behavior. We could not confirm that these weak and inconsistent trends were attributable to the seismic noise, but the trends were consistent with those for bowheads exposed to stronger noise pulses from closer seismic boats (Ljungblad et al. 1985, pers. comm.) or a single airgun nearby (this study). Hence, subtle effects may sometimes occur >6 km from seismic vessels and at received levels below the 160+ dB//1 µPa expected at that range.

Our test with a full-scale seismic boat showed that bowheads began to orient away when the airguns began to fire 7.5 km away. However, some whales continued apparent near-bottom feeding until the vessel was only 3 km away. Whales were displaced by about 2 km. Reactions were not much stronger than those to any conventional vessel. However, tests with one airgun fired from a quiet boat showed that bowheads move away from a source of strong seismic impulses even if no boat noise is present. Thus, some bowheads react to strong seismic impulses *per se*, and can detect their direction of arrival.

Reactions to Drillships and Dredges.--We saw bowheads <5 km from operating drillships and dredges, well within the zones ensonified by drillship or dredge noise. However, when bowheads were exposed to similar levels of drillship or dredge noise during playback experiments, they tended to orient away. In the drillship playbacks, call rate may also have decreased. During one dredge playback, near-bottom feeding ceased; in another, surfacing and respiration behavior changed. However, dispersal was not as rapid or consistent as when a boat approached.

Conclusions.—Bowhead behavior can be affected markedly but temporarily by the close approach of ships or aircraft. Reactions were less obvious in the cases of activities that continued for hours or days, such as distant seismic exploration, drilling and dredging; bowheads sometimes occurred close enough to these operations to be exposed to considerable noise. However, experiments showed that some bowheads oriented away from sources of drillship, dredge and seismic noise when the noise first became evident at levels equal to those several kilometres from actual drillships, dredges and seismic vessels.

INTRODUCTION

The Western Arctic stock of bowhead whales winters in the Bering Sea, summers in the eastern Beaufort Sea, and migrates around western and northern Alaska in spring and fall. Offshore oil and gas exploration is underway or planned in several parts of the summer and winter range and along the migration routes. Possible effects of oil and gas activities on bowheads are one of the main environmental concerns with respect to leases in Alaskan waters.

Noise from offshore industrial activities may affect whales (Acoust. Soc. Am. 1981). Sound, unlike light, can propagate long distances through water (Payne and Webb 1971; Urick 1975). Most baleen whales, including bowheads, produce low frequency calls (Thompson et al. 1979; Ljungblad et al. 1982b). Hearing sensitivity of baleen whales has not been measured, but the predominance of low frequency calls plus anatomical evidence (Fleischer 1976) suggest specialization for detecting low frequencies. Calls are important for communication between baleen whales (e.g. Watkins 1981b; Clark 1983; Tyack and Whitehead 1983), although detailed functions are rarely known. Detection of other environmental sounds, e.g. from ice, breaking waves, or perhaps prey, may also be important to bowheads.

Most underwater industrial sounds also have peak energy at low frequencies, predominantly below 1 kHz (Acoust. Soc. Am. 1981; Gales 1982; Greene 1982-85; Richardson et al. 1983b). Thus, baleen whales may be sensitive to industrial noise. The effects could, in theory, include short-term behavioral reactions, masking of communication or other sounds, physiological effects including stress, and short- or long-term displacement. Vision or other sensory modalities might also be involved in some of these hypothesized effects.

The limited evidence available up to about 1980 concerning reactions of whales to industrial activities was reviewed, from various viewpoints, by Geraci and St. Aubin (1980), Acoust. Soc. Am. (1981), Gales (1982), Malme et al. (1983), and Richardson et al. (1983b). Since 1980, several studies of this topic have been initiated, including Baker et al. (1982, 1983) for humpback whales (*Megaptera novaeangliae*), Malme et al. (1983, 1984) for gray whales (*Eschrichtius robustus*), and this study for bowheads.

The reactions of bowheads to industrial activities had not been described when this study began in 1980. In that year, the U.S. Bureau of Land Management (BLM) funded us to assess the short-term behavioral responses of bowheads summering in the eastern Beaufort Sea. The study continued each summer from 1980 to 1984, with the 1982-84 work being funded by the U.S. Minerals Management Service (MMS). Results from 1980-81, 1982 and 1983 were reported, respectively, by Fraker et al. (1982) and Richardson et al. (1983c, 1984). Richardson et al. (1985b) summarized the 1980-82 work. This report summarizes all results, including previously unreported studies in 1984.

Objectives

The general objective of the 'disturbance responses' portion of the study, as specified by BLM and MMS, was to determine 'how and to what extent acoustic and [other] stimuli from oil and gas exploration/development activities may be expected to affect the distribution, movements, activities and activity patterns, and, ultimately, the survival and productivity of bowhead whales.'

This general objective was further defined as involving analyses of

1. short-term behavioral reactions to five specific industrial activities, viz. aircraft and boat traffic, seismic exploration, drilling and offshore construction, and

2. long-term effects of offshore oil activities in general.

All five activities listed in (1) are major components of offshore oil and gas exploration on continental shelves. All are either underway or anticipated in the Alaskan Beaufort Sea. This section of the report describes studies of short-term behavioral reactions, and includes comments on their longer-term implications. A later section, Richardson et al. (1985a), examines distributional data to further assess possible long-term effects.

Approach

The study area was the eastern (i.e. Canadian) part of the Beaufort Sea (Fig. 1). Study conditions there are relatively favorable and offshore oil exploration is farther advanced than in Alaskan waters. The field season each year was from late July or 1 August to the end of August or early September. Oil industry activities in the eastern Beaufort Sea during late summer, 1980-84, involved 2-4 seismic boats, 4-5 drillships, 2-6 seagoing dredges, 5-10 twin-engined helicopters, 1-4 icebreakers, and many other boats -- supply, tug, crew, and sounding boats, barges, etc. (Richardson et al. 1985a). The overall level of offshore activity increased progressively from year to year.

We used a combination of (1) controlled experiments simulating industrial activities, and (2) opportunistic observations of distribution and behavior near ongoing full-scale industrial operations. The controlled tests were helpful in detecting changes attributable to the simulated industrial activity in the presence of natural variability. The opportunistic observations were more difficult to interpret. However, they provided evidence about the presence and behavior of whales near full-scale and prolonged activities that we could not simulate.

Over the 5 years, we obtained both opportunistic observations and controlled experimental data concerning reactions of bowheads to each of the five types of industrial activities identified in 'Objectives', above. Opportunistic data included observations of bowhead behavior in the presence of fixed-wing aircraft and helicopters, various boats, noise impulses from distant seismic vessels, drillships, and island construction. Experiments included fixed-wing aircraft overflights at different altitudes, helicopter overflights, boat disturbance trials, tests of reactions to an airgun and a full-scale seismic vessel, and underwater playbacks of recorded drilling and dredge noise.

Most behavioral observations in all years were from a fixed-wing aircraft circling high over bowheads. A 12.5-m boat was used to conduct most experiments. Sonobuoys dropped from the aircraft and hydrophones deployed from the boat were used to record industrial and bowhead sounds.

Characteristics of the industrial sounds are described in a companion section by Greene (1985).

In 1980 and 1981 we also attempted to study bowheads from shore stations at Herschel Island and King Point, Yukon (Fig. 1). In previous years, bowheads had sometimes been seen there close to shore (Fraker and Bockstoce 1980). In 1980-81, the shore stations provided few data because bowheads were too far offshore for detailed observation or experiments. Consequently, no shore-based observations were attempted in 1982-84. Bowheads were within 1-2 km of King Point on several days in mid and late August of 1983-84, and we conducted some of our boat- and aircraft-based experiments there (Fig. 1).

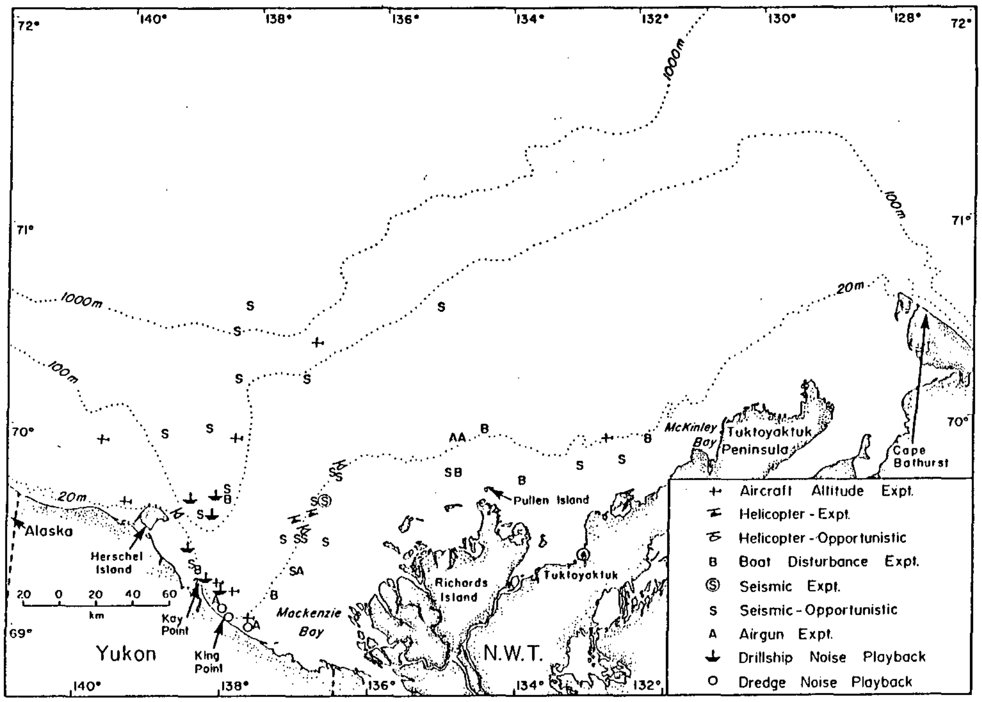

FIGURE 1. Map of the 1980-84 study area, the southeastern Beaufort Sea. Symbols show the locations where we tested the reactions of bowheads to simulated industrial activities, and locations where we observed the behavior of bowheads exposed to seismic impulses (S).

GENERAL METHODS

The general methods used in all years (1980-84) were very similar. Methods specific to each experiment or industrial activity are described later, in the section dealing with that industrial activity.

Aerial Observation Procedures

Almost all aerial observations were from a specially-outfitted Britten-Norman BN-2A-21 Islander (C-GYTC). This high-wing twin-engined piston aircraft had long-range fuel tanks, OnTrac VLF/Omega navigation system, inverters for AC power, side and bottom camera ports, and radar. The radar was valuable in measuring distances from whales to ships, islands, etc. For part of the 1983 season (1-13 Aug) the Islander was not available and we used a deHavilland DHC-6-300 Twin Otter aircraft (CG-BDR). This high-wing twin-engined turboprop aircraft had a VLF navigation system, long-range fuel tank, and bubble windows, but no inverters or radar. Our procedures in the two aircraft were the same, with the exception that seating arrangements required that we circle to the left in the Twin Otter and to the right in the Islander.

We rarely flew when wind speed exceeded 25 km/h, since high sea states make whales difficult to locate and observe. Flight routes were non-systematic. When we had arranged to rendezvous with the boat for an experiment, we often flew directly to that site, searching for but not pausing to circle whales en route. On other occasions, we searched within areas where we expected whales, with some emphasis on (1) places that would be convenient for future experiments, and (2) the offshore industrial sites. When whales were found near an industrial site, we circled for up to 4.2 h to observe behavior. In the absence of whales near our boat and near industrial sites, we tried to locate and observe whales elsewhere.

While circling whales, we flew at 457 or 610 m a.s.l. (1500 or 2000 ft) except during aircraft disturbance experiments or when clouds were below 457 m. In 1980-81 we found that bowheads often reacted to the aircraft when it was at 305 m (1000 ft) or below, but rarely did so when it was at 457 m or above. Thereafter we used a standard altitude of 457 m. In 1983, when we first observed many whales in shallow waters <5 km from shore, some whales seemed to react to the Islander aircraft even at 457 m. Hence, we adopted a standard altitude of 610 m for subsequent observations in shallow nearshore waters.

Dye markers (fluorescein solution in a plastic bag that burst upon impact with sea) were dropped to identify the approximate locations of whales during dives. We tried to select distinctively marked bowheads to observe. Natural markings (scars and pigmentation patterns) often allowed re-identification from one surfacing to the next, and thus determination of dive durations. However, many observations in 1983-84 were in Mackenzie Bay and involved small bowheads that lacked obvious distinctive markings--characteristics typical of immature bowheads (Davis et al. 1983). The turbid water in much of Mackenzie Bay also hindered individual recognition. Thus, in 1983 and 1984--unlike some previous years--we obtained few long series of observations of specific whales.

A sonobuoy (AN/SSQ-41B or AN/SSQ-57A) usually was dropped to monitor bowhead and industrial sounds while we circled overhead. Hydrophone depth was almost always 18 m or bottom, whichever was less (occasionally 9 m in 1981). The signals were recorded on calibrated equipment aboard the aircraft. The types and numbers of bowhead calls later were tabulated by C.W. Clark, who listened to the tapes at the same time as the signals were displayed on a real-time analyzer (see Würsig et al. 1985b for details). Intensities and spectral characteristics of industrial sounds recorded near bowheads were analyzed by calibrated digital processing techniques (Greene 1985).

The circling aircraft was usually at a radius of 0.5-2 km from the whales being studied. However, it occasionally passed directly over them when we dropped dye markers or sonobuoys, or when whales surfaced far from their previous location. Aircraft noise was clearly detectable in the water directly below the aircraft, but would be weak or undetectable at the center of our circles (Greene 1982, 1984a). Thus, whales being circled were exposed to strong aircraft noise only on the infrequent occasions when the aircraft passed almost directly overhead.

Overall, we flew for 593 h during 132 offshore flights in 1980-84. We circled over bowheads for 186.3 h during 85 of those flights. Of this time, 98.5 h and 87.8 h were under 'presumably undisturbed' and 'potentially disturbed' conditions, respectively. Potentially disturbed cases were defined as those when our aircraft was at <457 m a.s.l., a boat was underway within 4 km, or industrial noise was readily detectable in the water. The first half hour after any of those 'potential disturbances' was also counted as potentially disturbed. Locations of all behavioral observations are shown in Würsig et al. (1985b, Fig. 1).

Our procedures for behavioral observations are described by Würsig et al. (1985b). Up to three 'focal' whales were observed in detail simultaneously. Limited information about some other bowheads (e.g. orientation, speed, and relative location) was also obtained. Two observers, one watching the focal animals through binoculars and the other observing a broader area, dictated observations onto audiotape. A third observer operated a video camera whenever the focal whales were at the surface, and a fourth observer on the opposite side of the aircraft operated sonobuoy receivers and noted whales outside the area being circled.

After data were transcribed from audiotape, the videotape was examined for details not noted in real time. The combined data were coded with one record per surfacing or dive of each focal whale (up to 45 variables per record). Records were hand checked before entry into Apple II+ microcomputers for validation and analysis. In total, 4337 surfacing and 958 dive records were obtained in 1980-84, of which 2208 and 483, respectively, were in potentially disturbed conditions.

Because the surfacing, respiration and diving behavior of bowhead calves (<1 yr old) differs from that of 'non-calves' (Würsig et al. 1984, 1985a,b), most parts of this report exclude data from calves. We emphasize the quantitative variables that are amenable to statistical comparison and that are least susceptible to observer expectancy bias.

Observations from Boat

In 1981-84, we used MV 'Sequel', a 12.5-m vessel powered by a single 115 hp GM 471 diesel engine. Maximum speed was about 16 km/h and idling speed (engine idling; propeller engaged) was about 5.6 km/h. The crew included an acoustician and 1-2 biologists to observe behavior. For boat disturbance tests in 1980, we used the 'Imperial Adgo', a 16-m diesel-powered crew boat with top speed 41 km/h.

The behavioral observer(s) watched for whales when the boats were underway, while the aircraft circled nearby, and at some other times when drifting or anchored. The observers recorded the estimated distances of bowheads from the boat, heading relative to the boat, and the exact time of each blow. Group size and the durations of surfacings and dives were recorded when possible, but these variables were rarely recordable because of the low angle of observation from small boats. Locations and water depths were determined with a navigation satellite receiver and an echosounder.

Underwater sounds were recorded from the boat using hydrophones deployed at 9 m depth, and sometimes at other standardized depths. Greene (1985) describes the field and analysis procedures.

Experiments

Seven types of experiments were conducted (Table 1; Fig. 1). For one type of test, fixed-wing aircraft at various altitudes, only the observation aircraft was necessary. For all other experiments, either a boat or a helicopter as well as the observation aircraft had to be near whales. All experiments were conducted while we were using the Islander aircraft. We used the aircraft to locate bowheads, to direct the boat or helicopter toward them, and to obtain most of the behavioral observations. Experiments using a boat or helicopter usually were possible only when whales lingered in an accessible area under favorable weather and ice conditions. These requirements limited the number of experiments that could be done.

Table 1. Types and numbers of experimental tests of reactions of bowheads to simulated industrial activities, eastern Beaufort Sea, 1980-84.

Type of experiment	No. expts
Fixed-wing aircraft at various altitudes	8
Helicopter overflight at 153 m altitude	2*
Boat disturbance experiments	7
Airgun experiments	5
Experiment with full-scale seismic boat	1
Drilling noise playbacks	6
Dredge noise playbacks	3
Total, all experiments	32*

* Plus 3 opportunistic helicopter overflights.

When experiments were possible, the usual procedure was first to observe 'presumably undisturbed' behavior, and then to continue observations as the source of potential disturbance was introduced. When possible, observations continued after the end of the period of potential disturbance. With this approach, each whale or group of whales served as its own control, minimizing potential confounding by individual variation or extraneous factors. During some airgun tests and all drillship and dredge noise playback experiments, the boat was quiet (anchored or drifting) throughout the control, test and post-test periods. Observations during the first half hour after the boat's motor was turned off were not counted as 'control' data. The boat was underway during all boat and some airgun experiments. Detailed procedures for each type of experiment are described in later sections.

Distances and bearings of whales from the boat were estimated for many surfacings during experiments. Distances were often estimated relative to sonobuoys or dye markers whose locations relative to the boat were, in turn, estimated at frequent intervals. Whenever possible, we used the radar on the observation aircraft to calibrate our visual estimates of distance from the boat. The VLF navigation system on the aircraft was also helpful; the indicated absolute location was often incorrect by up to 2 km, but relative locations of two points overflown within a brief interval (e.g. boat and whales or sonobuoy) were much more precise.

In analyzing whale orientations observed from the aircraft during playback and airgun experiments, only the first observation of each 'non-calf' whale in each phase of the experiment was used. Headings of the whales were converted into deviations from the 'directly away from boat' direction, i.e. 0° = directly away, 180° = directly toward, 90° = tangential to right as viewed from boat, 270° = tangential to left, etc. The V-test (Batschelet 1981) was used to test the hypothesis that whales were oriented away from the boat against the alternative of uniformity. The Kuiper test, a modification of the Kolmogorov-Smirnov test applicable to directional data (Batschelet 1981), was used to compare orientations relative to the boat in different phases of the experiments.

Interpretation of repeated observations of the orientation of individual animals is difficult. Repeated observations of an animal that is continuing to move in a previously chosen direction provide only one meaningful value, in terms of contribution to sample size for statistical analysis. Subsequent observations are not independent of the first. One rarely can determine how quickly orientation becomes independent of orientation at a previous time (Batschelet 1972). Our use of only the first observation of each identifiable whale during a given phase of an experiment may be conservative in some cases. However, we were unable to recognize most whales for prolonged periods in 1983-84. Consequently, many whales undoubtedly are represented more than once in the orientation data for a particular phase of an experiment. Also, when 2 or 3 whales in a group headed in a particular direction, 2 or 3 orientations were recorded. It is arguable whether these should be treated as independent observations. Thus, the statistical tests on orientation data are approximate.

REACTIONS OF BOWHEADS TO AIRCRAFT

Aircraft are used extensively in all phases of offshore oil exploration and production. Fixed-wing aircraft are used principally for reconnaissance, while helicopters transport personnel and supplies. Aircraft may fly low enough to create underwater noise at frequencies and intensities that are presumably detectable to bowheads (Greene 1985). Thus, aircraft might disturb bowhead whales. It was also important to assess reactions of bowheads to our observation aircraft, since we assume that it does not disturb whales appreciably during our routine behavioral observation sessions. A third reason to assess reactions to aircraft was that aircraft are used to census bowheads and to evaluate population structure; reactions to the aircraft could bias the results.

Opportunistic observations suggest that responses of baleen whales to aircraft vary from dives and dispersal to no response (Bird 1983). Watkins and Schevill (1979) were able to observe northern right whales (Eubalaena glacialis) and other baleen whales feeding below a light aircraft at 50-300 m a.s.l. without any obvious response. Payne et al. (1983) found that southern right whales (E. australis) rarely reacted strongly to a small aircraft circling at 65-150 m a.s.l. Marquette et al. (1982) suggested that bowheads rarely 'reacted in a negative manner' to a fixed-wing survey aircraft flying as low as 75 m a.s.l. Ljungblad et al. (1982a, 1983, 1984a) noted variable sensitivity of bowheads to fixed-wing aircraft depending on date, whale activity, and year. Berzin and Doroshenko (1981) and Dahlheim (1981) observed that bowheads sometimes remain at the surface when helicopters pass or even circle overhead. However, none of these observations were from studies designed specifically to test reactions of whales to aircraft.

In the only other systematic study of baleen whale responses to aircraft, Malme et al. (1983, 1984) reported that gray whales (Eschrichtius robustus) tended to avoid a location where recorded helicopter noise (Bell 212) was played back into the water. However, the playback rate of one simulated pass every 10 s to 2 min greatly exceeded typical helicopter traffic rates along routes to offshore industrial sites.

During 1980-84 we compared bowhead behavior in the presence and absence of fixed-wing aircraft and helicopters, and we compared behavior of whales overflown or circled at different altitudes. Most data were recorded by aircraft-based observers using standardized techniques, but data from shore- and boat-based observers were used in some comparisons.

Methods

Reactions of bowheads to aircraft were observed primarily from our fixed-wing observation aircraft, almost always a Britten-Norman Islander, as it passed or circled over whales (see 'General Methods', above).

Observations of the same whales in the presence and absence of the aircraft were possible on 14 August 1984. Bowhead respiration data were collected from the vessel 'Sequel' while its engine was shut down at 69°43'N, 136°48'W, water depth 24 m, before, during and after the Islander aircraft circled nearby.

We conducted eight experiments to examine the effects of fixed-wing aircraft altitude on behavior patterns (Table 2). Typically, we circled and observed whales from high altitude (457 and/or 610 m a.s.l.) for 0.8-1.9 h, and then descended to 305 m and observed the same whales for 0.3-1.7 h. We once circled first at 260-305 m and then at 457 m, and we once circled at 457 m, then 305 m, and then 457 m again (Table 2). All eight experiments were done in the absence of other potential sources of disturbance.

To control for the possibility that any apparent responses were due to the length of time the aircraft was overhead regardless of altitude, we examined the 10 presumably undisturbed sessions when the aircraft circled at 457-610 m a.s.l. for ≥ 70 min. Results during the first and second half of each session were compared. To examine the possibility of initial 'startle' responses even when the aircraft was at ≥ 457 m altitude, we used 1984 data to compare mean blow intervals in the initial 10 min following arrival of the aircraft with those of the same presumably undisturbed whales in subsequent periods.

Opportunities to measure potential responses to helicopters occurred during two planned experiments and on three other occasions during 1981-84 (Table 3). The planned experiments involved overflights by Sikorsky S-76

Table 2. Summary of fixed-wing aircraft disturbance experiments during 1981-84.

Date	Location	Time (MDT)	Hr. of Obs.	Aircraft Alt. (m a.s.l.)	Water Depth (m)	# Whales Within Circle
6 Sep 81	69°57'N[a]	17:53-19:20	1.4	610	53[a]	6-10?
	139°55'W	19:22-19:40	0.3	457		
		19:41-20:02	0.4	305		
8 Sep 81	69°40'N[a]	21:12-22:00	0.8	610	25[a]	10-15
	139°30'W	22:00-22:16	0.3	305		
8 Aug 82	70°00'N	17:26-18:55	1.5	457	150-155	6
	137°58'W	18:57-20:05	1.1	305		
31 Aug 82	70°30'N	10:15-12:08	1.9	457	550	1
	136°50'W	12:08-13:47	1.7	305		
17 Aug 83[b]	69°16'N	11:29-12:29	1.0	260-305	30	15
	138°10'W	12:30-13:12	0.7	457		
22 Aug 83[b]	69°07'N	09:58-11:05	1.1	610	18	6
	137°40'W	11:07-11:38	0.5	305		3
22 Aug 83[b]	69°15'N	15:31-16:45	1.2	610	32	6
	137°54'W	16:47-18:03	1.3	305		
1 Sep 84	70°01'N	16:42-17:51	1.2	457	21	5
	132°42'W	17:51-19:02	1.2	305		
		19:02-20:12	1.2	457		

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[a] Locations approximate due to inoperable aircraft navigation system.

[b] Most whales in the area where this experiment was done were immatures (Würsig et al. 1985b).

Table 3. Summary of helicopter disturbance experiments and opportunistic helicopter overflights during 1981-84.

Date	Helicopter Type and Altitude	Location	Phase	Time (MDT)	Hours of Obs.	Water Depth (m)	# Whales Within Circle
Experiments							
31 Aug 84[d]	Sikorsky	69°39'N	Before	15:08-16:17	1.2	17	7
	S-76,	136°48'W	During	16:18-16:34	0.3		
	153 m		After	16:35-17:38	1.1		
2 Sep 84[d]	Sikorsky	69°35'N	Before	19:28-20:16	0.8	25	5
	S-76,	137°05'W	During	20:17-20:34	0.3		
	153 m		After	20:35-21:42	1.1		
Opportunistic							
28 Aug 84[d]	Bell	69°33'N	Before	12:31-12:54	0.4	21	8,
	214ST,	136°57'W	During	12:55-13:14	0.3		later
	153 m[a]		After	13:15-13:46	0.5		4
31 Aug 83[d]	Probably	69°51'N	Before	14:19-14:49	0.5	19	6
	Bell 412,	136°30'W	During	14:50-15:07	0.3		
	153 m[b]		After	15:08-16:08	1.0		
3 Sep 81	Unknown	69°37'N	Before	11:10-12:49	1.6	40?	6
	type,	138°45'W	During	12:50-13:06	0.3		
	153 m[c]	(Approx.)					

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[a] Strong seismic impulses from a vessel 18-23 km away were received throughout the 28 Aug 84 test (148 dB// μPa at time of overflight).

[b] Other potential sources of disturbance included seismic noise, industrial sites 13-19 km away, and overflights at 153 m a.s.l. by a Turbo-Commander fixed-wing aircraft.

[c] The Islander aircraft had been circling in the area at ≤457 m a.s.l. for 1.7 h before the helicopter arrived.

[d] Most whales in the area where this experiment was done were immatures (Würsig et al. 1985b; Davis et al., in prep.).

helicopters at 153 m a.s.l. following periods of control observations of the same whales from the Islander aircraft circling at 457 m a.s.l. Each experiment involved a single straight-line pass at normal cruising speed (250 km/h). The experiments included three phases: (1) 'before' the arrival of the helicopter, (2) 'during' the overflight and the 15 min period immediately following the pass, and (3) an 'after' period of variable length. Because of the brevity of the 'during' phase, only blow intervals were recorded sufficiently often to allow statistical analysis. The three opportunistic helicopter overflights were also single passes through our observation circle at or near altitude 153 m. However, comparisons of the latter three cases with the two experiments must be treated with caution as the opportunistic observations involved different or unidentified helicopters, and all involved other potential sources of disturbance (Table 3).

Results

Occasions With Apparent Reactions

In all years, instances when observers in the aircraft believed that whales were disturbed by the aircraft were recorded during searches for whales and during behavioral observation sessions. Only cases where the aircraft was the only potential source of disturbance are considered here. The criteria used in assessing the occurrence of disturbance in these cases were subjective, but were based on considerable experience concerning the normal behavior of bowheads. Indications of disturbance have included both instantaneous responses, such as unusual changes in orientation or unusually rapid surfacings or dives, and longer-term responses such as general movement out of the area under observation, changes in general activities, and changes in aerial behaviors, such as breaches, tailslaps, and pectoral flipper slaps (Table 4). These observations should not be analyzed quantitatively, given their subjectivity. However, reactions were most frequent when the aircraft circled at ≤305 m, less frequent when it was at 457 m, and very rare when it was at ≥610 m. This trend is even more evident if one allows for the fact that the aircraft was at ≤305 m for only a small fraction of the total observation hours. The whales were in water ≤25 m deep for 8 of 15 cases with reactions to the aircraft at 457 m, and for 2 of 2 cases at 610 m.

Table 4. Number of occasions when one or more bowheads apparently responded to the observation aircraft, as recorded in real time during 1980-84.

	Aircraft Altitude (m a.s.l.)		
Type of Response to Aircraft	≤305	457	≥610
Hasty dive or surfacing	16	4	1
Change in orientation	3	3	0
Dispersal or movement out of an area	1	7	1
Change in activity	1	1	0
Change in aerial behavior	2	0	0

Observations in the Presence and Absence of Aircraft

During 1980-84 there was only one opportunity to obtain an adequate sample of quantitative behavioral information on the same whales both in the presence and absence of our observation aircraft. Richardson et al. (1983c, 1985b) discussed two previous attempts at this comparison using shore and vessel observations, but different whales were observed under the 'aircraft present' and 'aircraft absent' conditions, making the comparisons of questionable value. On 14 August 1984, however, about 10 whales were observed from the vessel 'Sequel' before the Islander arrived, while it circled at 457 m, and after it departed, in the absence of other potential disturbances (Table 5). No significant differences were found between the two conditions.

Table 5. Respiration data collected by observers on 'Sequel' for bowheads in the presence and absence of the observation aircraft on 14 Aug 1984. Sample sizes for duration of surfacings and dives were too small for analysis.

	Blow Interval (s)			No. Blows/ Surfacing		
Condition	Mean	s.d.	n	Mean	s.d.	n
Plane Absent	8.81	2.234	242	9.35	2.390	20
Plane Present	8.49	1.906	33	8.25	4.113	4
t-test	t = 0.78, p > 0.2			t = 0.75, p > 0.2		

Observations from Different Altitudes

Eight experiments involving observations of whales from different altitudes in the absence of other potential disturbances were conducted during 1981-84. The results of all but the single 1984 experiment were detailed in Richardson et al. (1983c, 1984b, 1985b). During 7 of 8 experiments, intervals between blows were at least slightly reduced when the aircraft circled at lower altitudes; in 4 of 8 cases the reduction was significant ($p \leq 0.05$, Fig. 2). The pooled trend was highly significant ($p < 0.001$, unweighted z method of Rosenthal 1978). When all experiments were considered, duration of surfacings and number of blows per surfacing were not consistently or significantly different when the aircraft circled at lower altitudes. Too few dive duration data were available for analysis.

Four additional behavioral variables were examined during the four 1983-84 experiments. Frequency of pre-dive flexes was lower during the 305 m a.s.l. phase of two of the three experiments in which it was measured, and this relationship was significant when the data were pooled ($p < 0.01$, Table 6). Estimated speed, frequency of turns, and frequency of fluke-out dives were not significantly related to aircraft altitude.

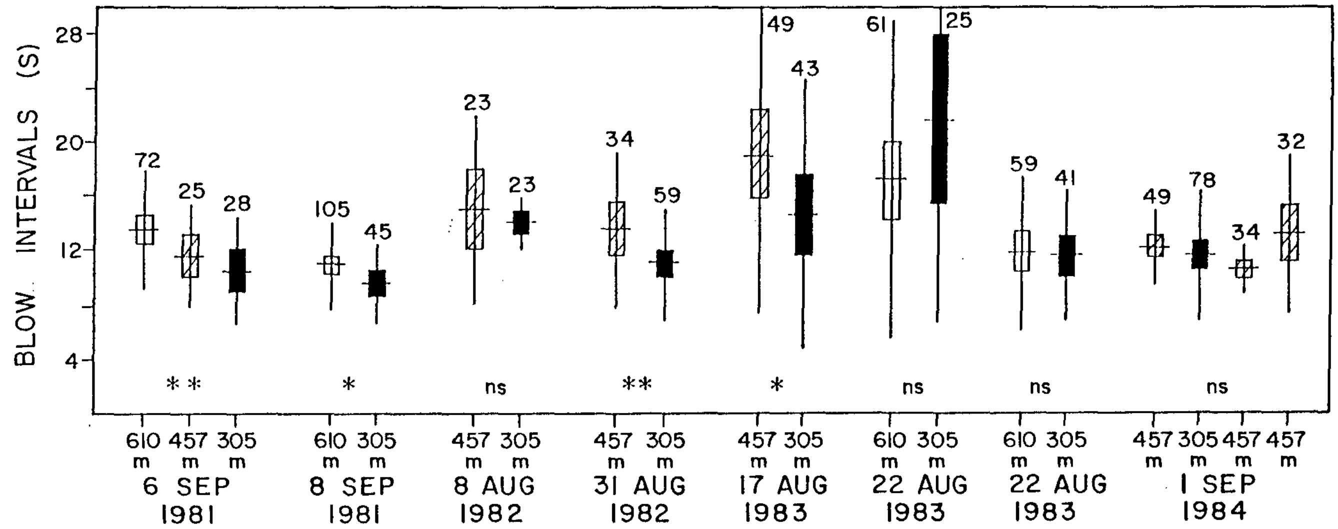

FIGURE 2. Blow intervals of bowheads observed from the Islander aircraft circling at different altitudes during eight altitude experiments. Calves are excluded. The mean ± 1 s.d., ± 95% confidence interval, and sample size are shown. Significance levels from t-tests or 1-way ANOVA are coded as follows: ns means p>0.1, * means 0.05 ≥ p > 0.01, and ** means 0.01 ≥ p > 0.001.

Table 6. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes-out' by non-calf bowheads observed during four aircraft altitude experiments, 1983-84. Each surfacing by a whale is a unit of observation.

Aircraft	Turn			Speed			Pre-Dive Flex			Pre-Dive 'Flukes-Out'		
Altitude (m asl)	No	Yes	Tot	Zero-Slow	Mod-Fast	Tot	No	Yes	Tot	No	Yes	Tot
≥457	47	18	65	58	23	81	54	17	71	71	58	129
305	43	14	57	50	12	62	66	5	71	76	41	117
Chi^2 (df=1)	0.15, ns			1.55, ns			7.75, p < 0.01			2.51, ns		

Bowhead calls were detected during both high and low altitude phases of all seven experiments during which underwater sounds were recorded. On three occasions, call rate was higher when the aircraft was at higher altitude; during two tests call rate was higher when the aircraft descended. (During the other two tests, the whales moved away from the sonobuoy, preventing us from obtaining comparable data on call rates.) Overall, the seven types of calls that we distinguished (Würsig et al. 1985b) occurred in similar proportions during the high and low altitude phases of the seven experiments:

Aircraft Altitude	% of Calls that Were							No. of Calls Recorded
	Up	Down	Con-stant	Infl-ected	High	Pulsed Tone	Pul-sive	
457-610 m	40	16	18	5	6	3	13	757
305 m	34	19	19	6	6	9	6	689

Hence, we found no evidence that the altitude of the circling aircraft affected bowhead calling in any consistent way.

Thus, the most consistent quantifiable response to an aircraft circling at low altitude was a reduction in the interval between blows, as measured in experiments during 1981-84. The 1983-84 experiments also showed a significant reduction in the frequency of pre-dive flexes when the aircraft circled at low altitude.

One alternative hypothesis that might explain the reduced blow intervals when the aircraft was low is the possibility that blow intervals decrease with prolonged exposure to a circling aircraft, even if it stays at one altitude. To test for this, we examined 10 observation sessions in which the same whales were observed for at least 70 min from a single high altitude ($\geq$457 m a.s.l.) in the absence of other disturbances. In no case were blow intervals in the first half of the session significantly different from those in the second ($p>0.1$ in each of 10 t-tests). The pooled results were also non-significant ($p>0.1$). Thus we conclude that blow intervals do not decrease upon prolonged exposure to an aircraft circling high overhead, and that the reduced blow intervals when the aircraft descended were directly attributable to the change in altitude.

A major methodological concern in this study is the possibility that presence of the observation aircraft at 457 m a.s.l. or more might cause subtle reactions. The aircraft altitude experiments showed that aircraft disturbance leads to reduced blow intervals. If whales are often disturbed by an aircraft circling 457 m or more overhead, one might hypothesize that blow intervals would be short when the aircraft first arrives (startle response), but then increase toward normal values. To test this, we compared blow intervals in the first 10 min following arrival of the aircraft with subsequent observations of the same whales (altitude $\geq$457 m, no other disturbances, 1984 data). In 6 of the 14 observation sessions considered, mean blow interval was lower in the first 10 min than subsequently (7 expected by chance). There was no significant difference between means in the first 10 min of observation vs. later (Wilcoxon matched-pairs test, $n = 14$, $T = 42$, $p>>0.1$). Hence, this test provided no evidence that blow intervals were affected by the observation aircraft at 457 m or above.

Helicopter Overflights

No overt responses of bowheads to helicopter overflights at approximately 153 m a.s.l. were noted during the two planned experiments and three opportunistic observations during 1981-84 (Table 3). In all 5 cases, the helicopter passed through our observation circle and within 300 m of at least some focal whales. However, whales were not at the surface at the exact times of passage. Because of the brevity of the helicopter passes, only blow interval data are available in sufficient quantities to warrant statistical comparisons (Table 7). No significant changes in blow intervals were found. Trends during the two most reliable cases--the Sikorsky S-76 experiments--were in opposite directions. However, in 4 of 5 cases, mean blow interval decreased (by a non-significant amount) from the 'before' phase to the 'during' phase. This trend is consistent with that in the aircraft altitude experiments. Thus, we have no conclusive evidence that a single helicopter pass at 153 m a.s.l. disturbs bowhead whales that are below the surface when the helicopter is overhead. However, the data provide hints that there may be a subtle reduction in blow intervals.

Table 7. Blow intervals of bowheads during planned and opportunistic helicopter overflights in 1981-84. The 'during' period includes the time of the overflight plus the next 15 min.

Date	Helicopter Type and Altitude	Time re Helicopter (Phase)	Blow Interval (s)			Before vs. During
			Mean	s.d.	n	
Experiments						
31 Aug 84	Sik.-76,	Before	12.40	5.124	118	t' = 0.24
	153 m	During	12.24	2.628	29	df = 90
		After	10.20	3.676	10	ns
2 Sep 84	Sik.-76,	Before	11.40	1.783	48	t' = 1.43
	153 m	During	12.52	4.236	33	df = 40
		After	12.59	3.308	64	ns
Opportunistic						
28 Aug 84	Bell 214ST,	Before	18.40	14.223	5	t' = 0.82
	153 m	During	12.80	5.675	5	df = 6
		After	35.00[a]	59.880	10	ns
31 Aug 83	Prob.	Before	16.25	6.496	16	t = 0.70
	Bell 412,	During	14.76	5.761	17	df = 31
	153 m	After	13.71	7.623	80	ns
3 Sep 81	Unknown,	Before	12.70	8.869	56	t = 0.28
	153 m	During	11.71	7.783	7	df = 61
						ns

[a] 16.11 ± 4.457, n = 9, if one highly atypical 205 s blow interval is excluded.

Discussion

Bowheads sometimes reacted when the observation fixed-wing aircraft flew over or circled at ≤305 m a.s.l. Reactions were infrequent when it was at 457 m, and virtually absent at ≥610 m. Except in shallow water, behavior can almost always be considered 'presumably undisturbed by aircraft' if the aircraft remains ≥457 m a.s.l.

Characteristics of Responses to Aircraft

Sudden or hasty dives are the most frequently reported responses by bowhead whales approached by aircraft, especially at low altitudes (Ljungblad et al. 1983; this study). Overall results from 1981-84 indicated that, when the aircraft was low, blow intervals were significantly reduced and pre-dive flexes were less common. These results are consistent with our subjective impression of a 'quickening' of the motions preceding a dive in apparent response to a low-flying aircraft. Reduced blow intervals occurred during prolonged periods of circling at low altitude over the same whales; hasty dives often occurred during single or initial passes. During actual offshore operations by the petroleum industry, whales will be exposed to single passes, but rarely to circling aircraft.

Changes in orientation, dispersal, and changes in activities may also occur in response to aircraft. However, we found no consistent relationship between aircraft altitude and frequency of turns or speed during our altitude experiments. Perhaps the initial response when an aircraft first passes over is more pronounced than was evident in our altitude experiments, in which most data were collected after the aircraft had been overhead for a prolonged period. Ljungblad et al. (1983) reported that swimming bowheads occasionally responded to a survey aircraft at 600 m a.s.l. by abruptly changing speed and/or direction. Payne et al. (1983) found that a few right whales (probably <2%) swam rapidly or dove as a light aircraft came overhead; however, most did not show such a clear startle reaction. Our finding that blow intervals of bowheads exposed to an aircraft circling at 457-610 m a.s.l. were no different in the first 10 min of observation than later suggests that an aircraft at ≥457 m usually causes little or no startle response.

Aerial behaviors have occasionally been reported as possible responses to aircraft (Table 4; Bird 1983). Ljungblad et al. (1983) reported that bowheads occasionally slapped their tails as an aircraft circled overhead, possibly as an overt display toward the aircraft. However, aerial activities also occur in the absence of potential disturbance, and our aircraft altitude experiments provided no evidence that aerial behavior was related to the presence of aircraft.

Variation in Sensitivity to Aircraft

Although bowheads often show a graded response relative to aircraft altitude, the response is not predictable. Under similar conditions, responses may range from no overt reaction (the usual situation) to a dramatic disruption of activities and dispersal (which are rare).

We observed disruption of activity and/or dispersal on several occasions (Table 4), but the most dramatic cases were on 17 August 1983. The whales were initially very close to shore in quite shallow water. They dispersed into deeper water when the observation aircraft began circling at 457 m a.s.l. Later in the flight, whales showed decreased socializing and again dispersed in apparent response to the aircraft. These unusually pronounced reactions may have been related to the multiple sources of disturbance (aircraft, boat, playback) and the shallow water.

Our observations during 1983-84 suggest that shallow water or proximity to shore may also increase sensitivity to potential disturbances. Some observations by Ljungblad et al. (1983) also suggest that factors restricting horizontal movement (ice in their case) may influence sensitivity to disturbances, but the data are inconclusive. Seasonal variations in response have also been suggested (Ljungblad et al. 1980).

The responsiveness of bowheads to aircraft may depend on behavioral state. Bowheads engaged in socializing appear less sensitive to aircraft than are bowheads engaged in other activities. Though a socializing group observed from 457 m altitude on 9 August 1983 seemed to be disrupted temporarily, the whales eventually resumed socializing, even in the continued presence of the aircraft and with seismic noise. Whales observed on 17 August 1983 continued socializing in spite of our aircraft circling at 305 m a.s.l. In August 1981, LGL personnel in a Twin Otter observed a group of apparently mating bowheads. Gradual descents from 457 m a.s.l. to 152 m did not cause any apparent changes in behavior. Similarly, socializing and mating groups of bowheads in the Bering Sea seemed less prone to disturbance than were migrating whales farther north in spring 1980 (Ljungblad 1981). Resting whales seemed most sensitive to aircraft, although reactions by quiescent whales may be more noticeable than those of whales engaged in higher levels of activity (Ljungblad et al. 1984a).

Reactions of right whales to aircraft may also be less pronounced when socializing. Payne et al. (1983) noticed that groups of interacting southern right whales showed little reaction to a Cessna 180 circling at 65-150 m a.s.l. In contrast, isolated individuals often reacted to the aircraft.

Bowheads may also be relatively insensitive to aircraft when feeding, especially in groups. For example, we once circled at 305 m a.s.l. over a group of skim-feeding bowheads for 30 min without causing apparent disturbance. On 26 August 1983, we observed skim-feeding bowheads in shallow water close to shore for several hours as the Islander circled at 610 m; no overt response to the aircraft was noticed.

Although responses of bowheads to aircraft appear related to behavioral states, the relationships between sensitivity to disturbance, behavioral states, and environmental factors remain unclear. Bowheads seem, in general, to be more sensitive to aircraft than are certain other species of baleen whales (see Richardson et al. 1983b for review).

Reactions in Relation to Aircraft Noise Characteristics

Our sonobuoys, and the measurements by Greene (1985), showed that aircraft noise was prominent in the water directly below the observation aircraft. The noise received at the sonobuoy hydrophone 18 m deep was strong for a few seconds, and often was audible (to humans) for 20-30 s. Directly below the obsrvation aircraft, received noise levels close to the surface (e.g. 3 m depth) were several decibels higher than those at 9-18 m depth, as expected from theory (Greene 1984a, 1985). The reduction in received level with increasing depth may be one reason why whales tended to dive hastily when the aircraft first passed overhead. However, the diving response may be a startle reaction to sound and/or sight of the aircraft, unrelated to the reduced noise level that can be achieved by diving.

Most of our behavioral observations were of whales 0.5-1.5 km to the side of the aircraft, at the center of our observation circle. Sound usually would be perceptible at 9-18 m depth no more than a few hundred metres ahead, behind, or to one side of an aircraft travelling at about 185 km/h (100 knots), given that our aircraft was usually audible for <30 s during a pass directly over a hydrophone 9 or 18 m deep (Greene 1982, 1985). Also, waterborne sound levels close to the surface (e.g. 3 m depth) at locations to the side of an aircraft are less than those at deeper depths, contrary to the trend directly below the aircraft (Urick 1972; Greene 1985). Consequently, when an observation aircraft circles to observe bowheads, little if any aircraft noise would be detectable in the water at the center of the circle.

Lateral propagation of aircraft noise is greatest when the water is shallow (Urick 1972; Greene 1985). This may have caused the seemingly high sensitivity of bowheads to our aircraft at some times in 1983 and 1984. Some of the most conspicuous responses in 1983-84 were in water <10 m deep, sometimes <1 km from shore. Besides the effect of the shallow water on lateral propagation, the background noise level was often low in these areas. Both factors would contribute to a high signal-to-noise ratio for aircraft noise relative to background noise.

The noise level in water below an aircraft does not diminish with increasing aircraft altitude in the same way that noise received from in-water sources diminishes with increasing horizontal range (Greene 1985). Nonetheless, bowheads reacted most strongly to the observation aircraft when it was low. Perhaps the response by bowheads is at least partly to the sight or shadow of the aircraft rather than to noise alone. While sight may be important, gray whales respond to helicopter noise per se, at least when the noise from a single pass is repeated at frequent intervals (Malme et al. 1983, 1984). Another possibility is that bowheads react more strongly to aircraft at low altitude because underwater noise levels increase more abruptly, and often to a slightly higher peak level, when the aircraft is low (Urick 1972; Greene 1982, 1984a, 1985).

Reactions to Helicopters

Helicopters are the most frequent sources of potential aircraft disturbance in offshore oil operations. Dahlheim (1981) stated that, during early spring, only 11% of the bowheads encountered 'displayed an escape reaction' to two Sikorsky H-52A (= S-62A) turbine-powered helicopters flying surveys at 152-228 m a.s.l. Berzin and Doroshenko (1981) indicated that some bowheads in the Sea of Okhotsk during August paid 'no attention' to a Mil-8 turbine-powered helicopter circling at low altitude and speed, while others dove when it first approached. However, none of these observations were detailed or well controlled. Our limited results showed no major effect of single helicopter passes, although there were hints of a slight reduction in blow intervals, similar to that below fixed-wing aircraft at low altitudes.

Malme et al. (1983, 1984) tested responses of migrating gray whales to playbacks of Bell 212 sounds that we had recorded in the Beaufort Sea (Greene 1982). The noise was projected at random intervals of 10 s to 2 min (average of 3 simulated passes per min). There were significant course changes in apparent avoidance of the sounds, and in some cases the whales also slowed down. The tests were not designed to determine whether gray whales would respond to noise from a single helicopter overflight, a more realistic case. Also, during playbacks it was impossible to reproduce the strong low frequency components of the helicopter noise. The results of Malme et al. are important in showing that gray whales respond to helicopter noise *per se*; vision was not involved.

Reactions to Helicopters vs. Fixed-Wing Aircraft

It is difficult to comment on this topic because of the paucity of comparative data. All of our observations of reactions to helicopter overflights involved single passes, whereas all quantitative observations of the effects of fixed-wing aircraft involved prolonged circling above whales. We noticed no overt responses to helicopters, whereas apparent responses to the fixed-wing aircraft have occasionally been noticed in real time during both single passes and while circling. However, there were far more opportunities for such observations during our 593 h of fixed-wing flight time as opposed to the five brief helicopter passes that were observed. With caution, we have noted that single helicopter passes at low altitude *may* reduce blow intervals temporarily, as does a fixed-wing aircraft circling at low altitude.

A twin-engine Bell 212 helicopter, a type frequently used offshore, produced underwater noise more intense than that from either an Islander or Twin Otter fixed-wing aircraft (Greene 1982, 1985). If reactions to aircraft are actually in response to aircraft noise, then responses to a Bell 212 might be stronger than the documented reactions to the Islander. Nonetheless, straight-line passes by the Bell 212 produced underwater noise for only a brief period--little different than that from the Islander or Twin Otter (Greene 1985). During straight-line passes at 152-610 m a.s.l. and 185 km/h, the Bell 212 sound was detectable at 9 m depth for only 16-27 s, and was strong for only a few seconds (Greene 1985). This, along with our behavioral observations during helicopter passes, suggests that occasional single passes by helicopters are unlikely to produce prolonged or significant reactions by bowhead whales.

REACTIONS OF BOWHEADS TO BOATS

Vessel traffic is a major source of potential disturbance to bowhead whales near areas being explored or developed by the petroleum industry. In the Canadian Beaufort Sea, marine traffic includes supply vessels, crew-change boats, tug/barge trains and icebreakers, plus dredges, seismic vessels and drillships moving between sites. Most vessel traffic is within the area where oil exploration is now occurring. Bowhead whales summering in this area are exposed to potential vessel disturbance, and there is also the possibility of collisions.

This is the first systematic study of the short-term reactions of bowheads to boats. Other baleen whales show considerable tolerance of boats, but often avoid rapidly or erratically moving vessels (Swartz and Cummings 1978; Ray et al. 1978; Bogoslovskaya et al. 1981; Watkins 1981a; for reviews see Bird 1983; Mansfield 1983; Richardson et al. 1983b). Baker et al. (1982) found changes in the respiration and diving behavior of humpback whales (*Megaptera novaeangliae*) when boats were within about 900 m; vessels that approached closely and moved erratically had the greatest effects. Sorensen et al. (1984) found evidence that 'squid eating' toothed and beaked whales were less common near boats than elsewhere; no such effect was found for 'fish eating' cetaceans, including some baleen whales.

Long-term effects of boats on whales are especially difficult to assess. Increased vessel traffic may have caused gray whales to abandon one wintering lagoon, which was subsequently reoccupied when shipping decreased (Gard 1974; Reeves 1977; Bryant et al. 1984). Possible long-term displacement of minke (Balaenoptera acutorostrata) and humpback whales as a result of increased vessel traffic (Nishiwaki and Sasao 1977; Norris and Reeves 1978; U.S. Marine Mammal Commission 1979/80) is not adequately documented. In some situations, whales do occur each year in areas where there is much boat traffic (Brodie 1981; Mayo 1982; Mitchell and Ghanime 1982).

Boat disturbance studies were given high priority during 1980-81, but not thereafter. During 1980-81, two planned and two opportunistic experiments were conducted. One experiment was conducted each year during 1982-84. Opportunistic observations of whales from vessels were obtained during all years.

Methods

Boat-based Observations

Orientations of whales relative to boats were recorded from two vessels during 1980-84. In 1980, we used a single observer aboard 'Imperial Adgo', a 16-m diesel-powered crew boat with top speed 41 km/h (Richardson et al. 1985b). During 1981-84, we used 1-2 observers aboard 'Sequel', a 12.5-m diesel-powered (115 hp) fishing boat with top speed 16 km/h. Boat-based observers estimated boat-to-whale distances and whale orientations for each surfacing. It generally was not possible to re-identify a whale following a dive; thus whales were rarely followed through more than one surfacing. Whale orientations were recorded once per surfacing in clock-face coordinates. Whales that oriented from 10 through 2 o'clock were considered to be oriented 'away'; those oriented from 4 through 8 o'clock were facing 'toward' the boat. The 'neutral' orientations of 3 and 9 o'clock were not included in our analyses. Data recorded from 'Sequel' during opportunistic observations and boat disturbance experiments in 1981-84 were categorized as (1) engine off for >30 min, (2) engine off for ≤30 min, and (3) engine engaged and boat underway at 5-16 km/h. Data from 'Adgo' in 1980 were collected and analyzed in a similar manner.

Aircraft-based Observations

On 7 days during 1980-84, personnel in the Britten-Norman Islander aircraft circling at 457-762 m a.s.l. observed bowhead behavior during close approach by a boat (Fig. 1; Table 8). In five of these cases, small boats ('Sequel' and 'Adgo') were directed by radio from the aircraft. In the other two cases, bowheads were watched while larger vessels not under our control passed near whales. 'Canmar Supplier IV' was a 65-m diesel-powered (7200 hp) supply boat typical of the larger vessels used in support of offshore drilling. 'Arctic Surveyor' was a diesel-powered (1700 hp) seismic boat that was underway but not producing seismic signals. In all except the 'Arctic

Table 8. Summary of boat disturbance experiments and observations during 1980-84. The observation aircraft was at $\geq$610 m altitude in all cases except 16 Aug 1982, when it was at 457 m.

Date	Vessel	Location	Time (MDT)	Hours of Obs.	Water Depth (m)	No. of Whales Obs.	Closest Point of Approach
19 Aug 80	'Canmar Supplier IV'	E of Pullen Isl.	19:19-20:32	1.2	7-8	15+	50 m
27 Aug 80	'Imperial Adgo'	W of McKinley Bay	14:12-16:33	2.4	17-19	4	<100
23 Aug 81[a]	'Arctic Surveyor'	N of Pullen Isl.	20:28-20:41	0.2	23	7+	100
25 Aug 81	'Sequel'	NW of Pullen Isl.	11:10-14:25	3.3	11	4	100
16 Aug 82	'Sequel'	NE of Herschel Isl.	14:04-17:18	3.2	160	6-11	400
18 Aug 83	'Sequel'	Kay Pt.	19:55-21:41	1.8	10	15-20	150
18 Aug 84[b]	'Sequel'	Mackenzie Bay	13:48-15:29	1.7	12-6	5	400

[a] No observations in the absence of the boat on 23 Aug 1981.

[b] Most whales in the area where this experiment was done were immatures (Davis et al., in prep.).

Surveyor' case, the whales were also observed before and/or after the boat passed.

Behavioral data were recorded on all seven days; however, distance and orientation data were obtained in sufficient quantities for analysis only during the 1981-84 'Sequel' experiments. The analyses considered 4 conditions: (1) 'Quiet Boat' when the boat's engine had been off for more than 30 min, (2) 'Far Boat', when the boat was underway 4-12 km from whales, (3) 'Near Boat', underway 2-4 km from whales, and (4) 'Close Boat', underway within 2 km.

Results

Boat-based Observations

Bowheads at all distances within view of observers tended to orient away from 'Adgo' when its engines were either engaged or idling disengaged (Fig. 3A, Richardson et al. 1985b). When the engines were off, the proportions of whales orienting away from the boat were not significantly higher than

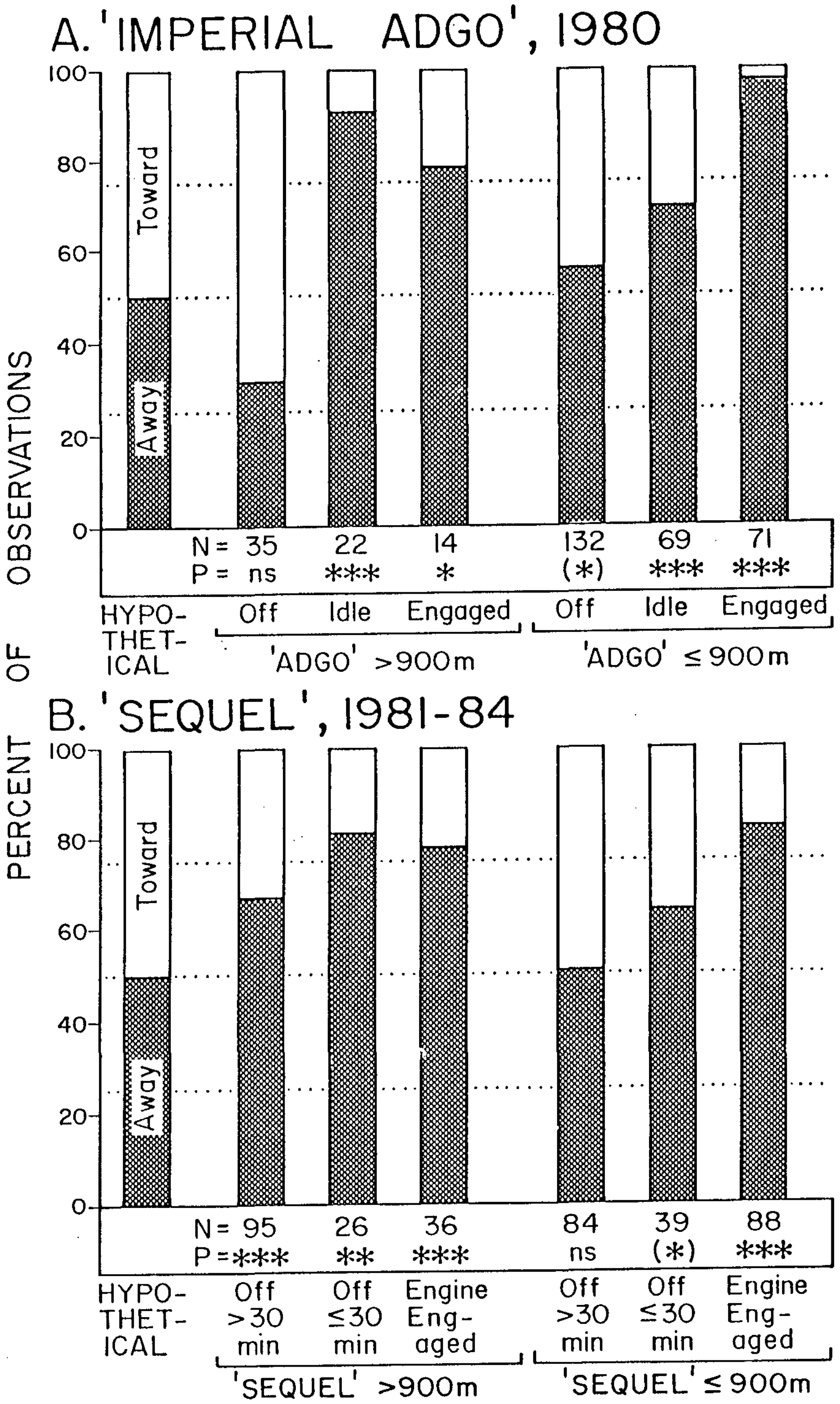

FIGURE 3. Orientations of bowheads observed from (A) the crew boat 'Imperial Adgo' and (B) the fishing boat 'Sequel'. Includes data from boat disturbance experiments as well as opportunistic observations. Hypothetical orientations are those expected if whales were oriented randomly with respect to the boat; whales moving tangentially are excluded (see text). Significance determined by one-sided binomial tests; ns means $p > 0.1$, (*) means $0.1 \geq p > 0.05$, * means $0.05 \geq p > 0.01$, ** means $0.01 \geq p > 0.001$, and *** means $p \leq 0.001$.

expected by chance ($p>0.05$). Once when 'Adgo' was travelling at 41 km/h, she nearly collided with a bowhead calf that was not noticed until the last moment. Bowheads, or at least calves, may have difficulty avoiding high-speed boats.

A similar pattern of response was observed from 'Sequel' during 1981-84. Whales within 900 m showed a strong tendency to orient away when the boat was underway, also tended to orient away in the 30 min following shutdown, and were randomly oriented if the boat had been quiet for >30 min (Fig. 3B). Unexpectedly, whales >900 m from 'Sequel' tended to orient away from the boat during all three phases. Reactions to 'Adgo' in 1980 were stronger than those to 'Sequel' in 1981-84 (Fig. 3), probably because 'Adgo' is a more powerful, faster, and noisier boat.

Aircraft-based Observations

The responses of bowheads to boats were the strongest and the most consistent of any of the apparent responses to potential disturbances that we studied. Changes in orientations, swimming speeds, surfacing and respiration characteristics, and general activities were recorded in response to boats. These responses were graded relative to distance from boats.

In all seven cases involving 'Sequel' or other boats, bowheads observed from the circling aircraft responded strongly to the approaching boat by swimming rapidly away from the vessel. Direct observations of individual whales moving away from the boat at high speed showed that some bowheads reacted strongly at distances as great as 4 km. (Bowheads rarely travelled at high speed in the absence of disturbance.) On the other hand, some whales showed no avoidance response until the approaching boat was <1 km away. The initial reaction of whales directly on the boat's path was often to attempt to 'outrun' the boat. When the boat was within a few hundred metres, whales either dove or turned and swam more or less perpendicularly away from the boat's track.

Pooled results from the four experiments with 'Sequel' showed that whales oriented randomly with respect to the boat when it was underway >4 km away. However, whales tended to orient away from the boat when it was underway 2-4 km or <2 km away ($p<0.05$ and $p<0.005$, respectively; Fig. 4). Also, orientation of whales with respect to the boat differed significantly between the 2-4 km and the >4 km categories (Kuiper test, $K = 1231$, $n = 40, 74$, $p<0.005$), but not between the 2-4 km and <2 km categories ($K = 283$, $n = 29,40$, $p>0.1$). Thus, bowheads showed clear reactions to vessels as much as 4 km away.

Reactions of whales to boats were also evident in comparisons of behavioral variables other than orientations. Rapid movement was noted in response to approach by 'Sequel' in all four experiments. Significantly more whales moved at moderate to fast speed when the boat was within 4 km ($p<0.001$, Table 9). The increase in speed was evident when the boat was 2-4 km away, and was even more pronounced when the boat was <2 km away (Table 9). During the 'Adgo' and 'Canmar Supplier IV' experiments, apparently feeding whales scattered as the boats approached; some whales moved as much as 2 or 3 km. In one case, mean inter-animal distance increased from 7.5 to 37 whale lengths, and the increase persisted for at least 1 h. During the 1981 'Sequel' experiment, whales engaged in socializing and playing with a

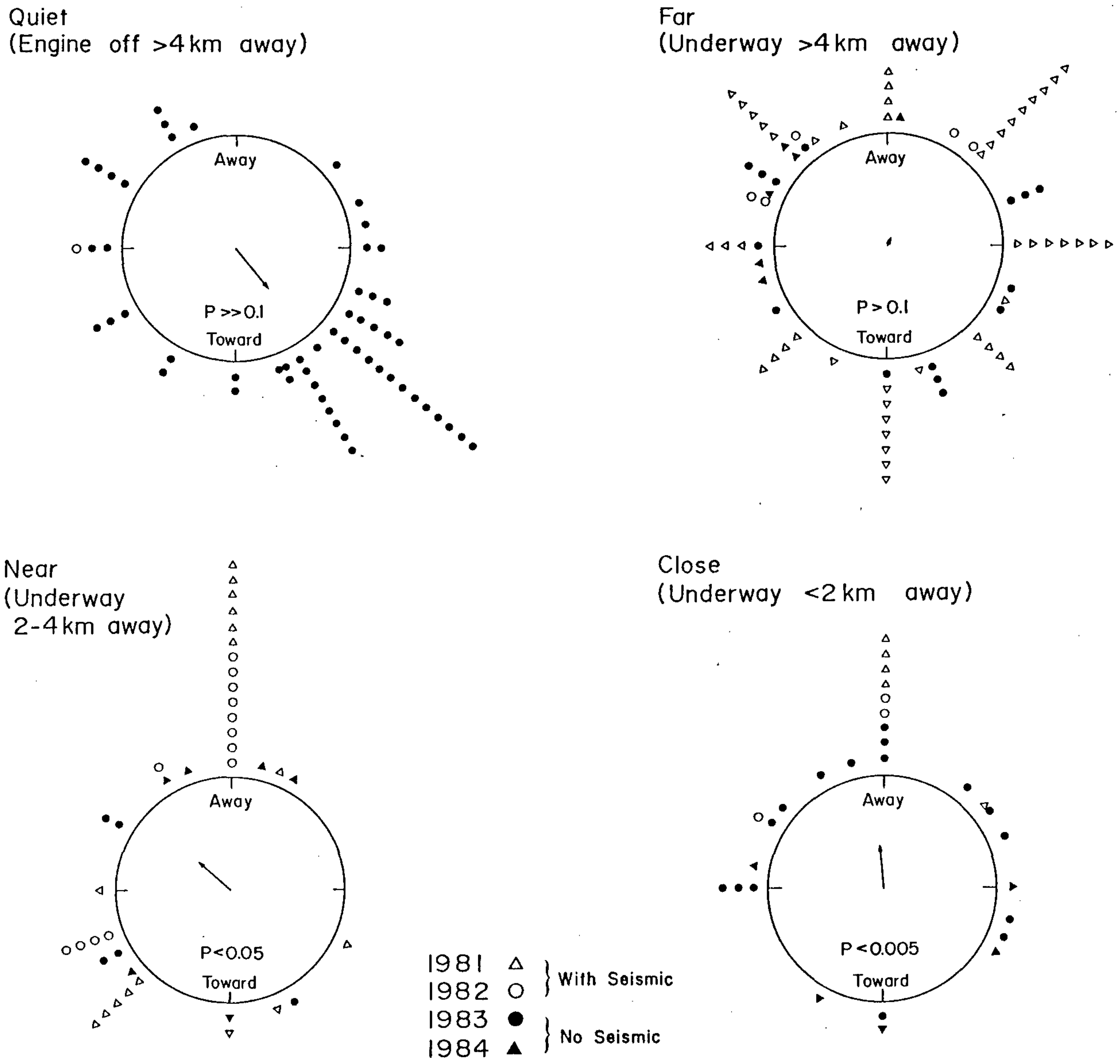

FIGURE 4. Orientations of bowheads during four phases of four boat disturbance experiments, 1981-84. Each symbol represents the heading of one whale relative to 'Sequel' as observed from the observation aircraft. The direction and length of the mean vector are shown. The p values summarize V-tests (Batschelet 1981) of the hypothesis that there was significant orientation away from 'Sequel'. In the 1981 and 1982 tests, there was seismic noise throughout the experiments.

Table 9. Estimated speed and occurrence of turns, pre-dive flexes and 'flukes-out' by non-calf bowheads observed during four boat disturbance experiments involving 'Sequel', 1981-84. Each surfacing of a whale is a unit of observation.

	Estimated Speed			Chi^2 (df = 1) for comparison with >4 km away
	Zero-Slow	Moderate-Fast	Total	
Boat >4 km away or quiet	50	30 (38%)	80	
Boat ≤4 km away and underway	12	39 (76%)	51	18.97 ***
Boat 2-4 km and underway	9	15 (63%)	24	4.70 *
Boat <2 km and underway	3	24 (89%)	27	21.33 ***

	Turn			**Pre-Dive Flex**			**Pre-Dive 'Flukes-Out'**		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Boat >4 km away or quiet	62	14	76	64	8	72	25	12	37
Boat ≤4 km away and underway	48	7	55	48	4	52	19	8	27
Chi^2 (df = 1)	0.77, $p > 0.25$			0.40, $p > 0.5$			0.06, $p > 0.5$		

* $P < 0.05$; *** $p < 0.001$.

log ceased these behaviors and moved rapidly away from the approaching boat. Thus, boat disturbance caused temporary disruption of activities, and sometimes disrupted social groups.

Boat disturbance also tended to cause brief surfacings with unusually few respirations per surfacing. Significantly shorter surfacings ($p<0.01$) and fewer respirations per surfacing ($p<0.02$) were recorded when the boat was underway within 4 km than when it was farther away, considering the six occasions when whales were observed in both situations (Table 10). Brief surfacings were also noted during the seventh situation, when whales were near 'Arctic Surveyor'.

Discussion

Bowheads respond strongly to close approach by vessels of a variety of sizes. In general, whales began to orient away from the approaching vessel when it was as much as 4 km away. Some whales increased swimming speed when the boat was 2-4 km away, and most whales were travelling away at increased speed when the vessel was within 2 km. Changes in surfacing and respiration patterns also became evident. Overall, our experiments revealed a significant reduction in mean duration of surfacing, similar to that reported for a fin whale (Balaenoptera physalus) by Ray et al. (1978).

Table 10. Pooled surfacing and respiration characteristics of non-calf bowheads observed during six boat disturbance experiments, 1980-1984. All observations were by aircraft-based observers. Too few dive data were collected for analysis of dive durations.

Phase	Mean	s.d.	n	Test[a]	Mean	s.d.	n	Test[a]
	Blow Interval (s)				**No. Blows/Surfacing**			
Boat >4 km away or quiet	12.56	8.44	373	ns	3.86	3.10	76	*
Boat underway <4 km away	13.12	7.14	227		2.97	2.74	66	
	Duration of Surfacing (min)							
Boat >4 km away or quiet	0.99	0.63	108	**				
Boat underway <4 km away	0.70	0.73	75					

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$.

[a] t-tests for individual experiments were pooled via the unweighted z method of Rosenthal (1978).

The response of bowheads to boats was most dramatic within several hundred metres of the boat and, as expected, diminished with increasing range. However, sensitivity to boats seemed quite variable. Some bowheads responded at ranges of at least 3 or 4 km, and perhaps 5-7 km. Others did not begin to move away until the boat was within 1 km (e.g. 'Adgo' and 'Canmar Supplier IV' cases). The latter two cases were in water 7-19 m deep, contradicting the idea that bowheads in shallow water might be more sensitive because avoidance by deep diving is impossible. In three cases when whales began to move away when boats were 2-4 km away, noise from seismic vessels or drillships was detectable throughout the boat experiment. This suggests that cumulative effects of multiple noise sources may increase sensitivity. However, other whale species sometimes react to boats at similar ranges. Humpback whales 2-4 km from boats engaged in 'horizontal avoidance', in which speed and blow intervals increased while dive durations decreased (Baker et al. 1983). Within 2 km of vessels, humpbacks began 'vertical avoidance', in which blow intervals and speed decreased, but the whales made longer (though not necessarily deeper) dives.

The escape response did not persist for long after the boat moved away. However, bowheads did tend to orient away from boats for some time after they had passed, and sometimes even after the engine had stopped. Similarly, some humpbacks were most likely to move away from the paths of vessels after the vessels had reached their point of closest approach (Baker et al. 1983). Groups of bowheads sometimes scattered when a boat approached. The increased spacing sometimes continued longer than the escape reaction. This indicates some degree of social disruption.

The long-term biological effects of one-time or cumulative disturbance of bowheads by boats remain unknown. As noted in the introduction to this section, other species of baleen whales do occur each year in some areas where there has been much boat traffic for many years. However, in at least one case intense boat traffic probably displaced gray whales from a calving lagoon (Reeves 1977). Bowheads seem more sensitive than summering gray whales to short-term behavioral disturbance (Richardson et al. 1983b, 1985b; cf. Bogoslovskaya et al. 1981), so one could hypothesize that bowheads would be at least as likely to be displaced by repeated boat disturbance.

Bowheads responded to boats more dramatically and consistently than to any of the other industrial activities that we studied. This suggests that boat disturbance experiments under a variety of water depths, ice conditions, distances from shore, etc., would be a good way to measure the effects of those factors on sensitivity of bowheads to disturbance.

REACTIONS OF BOWHEADS TO SEISMIC EXPLORATION

Seismic surveys are the main method of determining the likelihood that oil and gas occur beneath the sea. Intense underwater noise pulses are created, and echoes from rock strata are recorded for later analysis. Seismic surveys in ice-free areas are conducted by ships. The ship travels in a grid pattern and creates a noise pulse every several seconds. Broad-scale surveys occur during the early stages of exploration in an area; grid lines are often 50-100 km long and a few km apart. Later, fine-scale surveys are conducted to choose exact drilling locations; grid lines may then be only a few kilometres long and a few hundred metres apart. In either case, the survey ship usually operates in an area for at least several days, and sometimes several weeks. In recent years, several seismic vessels have operated in the Alaskan and Canadian Beaufort Sea each summer.

Marine seismic exploration produces underwater noise with source levels far above those of other routine activities associated with offshore oil exploration. Nowadays, this noise is usually created by arrays of airguns (Barger and Hamblen 1980) towed behind the survey ship and fired simultaneously several times per minute. High explosives, which can produce even more intense and instantaneous sounds, are now rarely used in North American waters (Brooks 1981).

Airgun arrays used to study deep geological formations typically contain 20 or more guns with total gun volume 20-65 L (1200-4000 in^3) of compressed air. Source levels are about 245-252 dB//1 µPa-m (R.C. Johnston and B. Cain, in Richardson et al. 1983b). Received levels exceed 150 dB//1 µPa to a radius of several kilometres, and weaker noise is often detectable 25-90 km away (Ljungblad et al. 1980, 1982a, 1984b; Greene 1982-85; Malme et al. 1983; Reeves et al. 1983). Characteristics of received pulses depend on propagation conditions, range and depth. However, received pulses typically are about 0.5 s in duration, with most energy below 500 Hz. When the source is an array of airguns, more energy propagates perpendicular than parallel to the axis of the array (e.g. Malme et al. 1983). Also, the received level is a few decibels less just below the surface (e.g. 3 m deep) than at greater depths (Greene 1985).

Before 1980, reactions of whales to seismic exploration had not been studied systematically. There had been a few observations of baleen whales in the presence of noise pulses (Fitch and Young 1948; Payne and McVay 1971; Ljungblad et al. 1980). However, there was insufficient evidence on which to judge whether any whale species was affected by seismic noise.

Since 1980, one of the primary objectives of the present study has been an assessment of the effects of seismic noise on bowheads. We used five approaches:

1. Opportunistic observations of bowhead behavior in the presence of noise from actual seismic exploration;
2. Controlled tests of reactions to a single airgun at close range, simulating a full-scale seismic vessel farther away;
3. Controlled tests of reactions to an actual seismic vessel under our direction;
4. Comparison of year-to-year trends in distribution of whales and seismic exploration;
5. Measurement of levels and characteristics of seismic impulses at various distances from seismic vessels.

In this section, we report the results of approaches (1)-(3) from all five years. Results of approaches (4) and (5) are treated in separate sections (Greene 1985; Richardson et al. 1985a). Some of the same approaches have been used in two simultaneous studies. Approaches (1), (3) and (5) have been applied to bowheads feeding in or migrating through the Alaskan Beaufort Sea in autumn (Ljungblad et al. 1982a, 1984b, 1985; Reeves et al. 1983, 1984; Greene 1984b). Approaches (2)-(5) have been applied to gray whales migrating along the California coast (Malme et al. 1983, 1984). The Discussion section below compares the results of these two studies with our results.

Methods

Opportunistic Observations with Seismic Noise

On 21 occasions, observers in a circling aircraft watched bowheads in waters ensonified by noise pulses from distant seismic vessels (Table 11; Fig. 1). All observations described here were obtained when the aircraft was at altitude 457 m or greater, and no other source of potential disturbance was within 4 km.

On 17 of 21 occasions, sounds near the whales were monitored by sonobuoys dropped from the aircraft and/or by hydrophones deployed from a quiet boat ('Sequel'). On the other four occasions (identified in Table 11), sounds could not be monitored, but the whales were close to an operating seismic vessel and the water was deep enough to ensure propagation of seismic noise to the whales. On all 17 occasions when sounds were monitored, the seismic pulses were prominent to the human ear; no 'barely detectable' cases are considered here. Signal to noise ratios were usually at least 15 dB, and often much more (peak pulse level vs. 20-1000 Hz band level between pulses; see Greene 1982, 1983, 1984a, 1985 and Table 11).

Four different seismic vessels and six different sources of seismic pulses were involved. However, noise pulses from all sources were similar in spectral and temporal characteristics (Greene 1982, 1983, 1984a, 1985).

Table 11. Circumstances when bowhead whales were observed in the presence of noise from actual or simulated seismic exploration, Canadian Beaufort Sea, 1980-84.

	Whale Position (Deg.Min)		Water Depth (m) at				Observation Aircraft		Minutes of Observation		Whale Position Re Boat				Sound Levels Near Whales (dB//1 µPa)[f]		Approx. No. of Whales	
Date	North Lat.	West Long.	Whale Loc'n	Seis. Boat	Sea State	Ice Cover (%)	Type	Alti- tude (m)	With Seis.	No Seis.	Vessel Name	Range (km)	Bearing to Boat	Aspect (0 = Ahead)[e]	Seismic Pulses	Between Pulses	Obs- erved	Activity of Whales
OPPORTUNISTIC																		
20 Aug 1980	69.53	133.03	12	20	2	0	Isl	610	108	0	Sur	c. 8	WNW	330	c. 150[g]	?	5	Some mud churned up
21 Aug 1980	69.55	132.29	12-13	12	c. 1	0	Isl	610	64	0	Sur	13	WSW	?	c. 141	?	7	Socializing
5 Aug 1981	70.41	135.06	68	60	3-4	0	Isl	457-610	70	0	Vet	45-54	SW	220	117	88-96	5	Socializing, defecating
25 Aug 1981	69.52	134.50	11	10	2-3	0	Isl	610	84	0	Sur	6-8	E	115	c. 150	96-104	4	Mud from mouths, socializing, log play
1 Aug 1982	70.19	138.00	300	400-500	4	0	Isl	457	95	0	Mar	39-24	SW	20	?[g]	?	1	Log play
7 Aug 1982	70.19	137.01	65	75-50	2	0	Isl	457	63	0	Mar	49-40	SSW	340	107-113	89-95	6-7	Swimming westward
16 Aug 1982	69.45	138.05	150	c. 200	1	0	Isl	457	65	0	Mar	54-58	N-NE	90-120	127-132	98-101	6-11	Slow travel, social, possible nursing
18 Aug 1982	69.36	138.22	125	45-95	1-2	0	Isl	457	159	0	Mar	73-62	NE-NNE	300	<125-133	92-99	10-14	Slow-rapid travel; some social & aerial
7 Aug 1983 A	70.32	138.10	950	190	2	40	TOt	457	44	0	Mar	79	S	95	127-131	105-107		Unknown
7 Aug 1983 B	70.40	137.53	1370	190-150	2	0	TOt	457	70	20[a]	Mar	95-99	SSW	105	?[g]	?	7	Calves interacting; some rapid travel
9 Aug 1983	70.00	139.00	190	20-?	1	0	TOt	457	204	28[b]	Mar	57-?	SW-?	?	110-123	92-97	12	Much socializing
31 Aug 1983	69.51	136.31	19	18	1-3	0	Isl	610	182	0	Sur	53-52	E	310	125-107	101-111	15	Bottom feeding; some socializing[k]
1 Sep 1983	69.50	136.30	19	40-33	1-3	0	Isl	137-457	204	0	Aleu	31-26	NNW-NE	55-120	135-120	96-104	5	Bottom feeding; some socializing[k]
1 Aug 1984 A	69.30	137.14	33	60	1	10	Isl	457	49	0	Mar	36-40	W	125	130-125	105-107	3	Lone whales; medium speed
1 Aug 1984 B	69.23	138.30	10	70	1	0	Isl	457	63	0	Mar	17-23	N	220	119-117	82-89	3	Zig-zag travel; short surfacings
7 Aug 1984	70.04	138.21	250	150	1	0	Isl	457	23	55[a]	Mar	33	W	90	137	?	3	Slow travel
14 Aug 1984	69.43	136.48	24	55-30	1-3	0	Isl	457	110	23[c]	Mar	20-10	W-NW	225;0-100	<143-158	108-122	10	Bottom feeding; socializing[k]
24 Aug 1984	69.30	136.40	9	45	1-2	10	Isl	457	69	37[b]	Mar	36-29	NW	315	?[g]	?	3	Bottom feeding; then med. speed travel[k]
27 Aug 1984 A	69.33	137.00	23	40-60	2	0	Isl	457	77	0	Mar	11-20	WNW	215-195	130-125	111-116	7	Bottom feeding; med. speed; synchrony[k]
27 Aug 1984 B	69.21	137.05	12	65-80	2	0	Isl	457	64	3[a]	Mar	32-37	NW	235	122-131	98-108	6	Lone whales; low-medium speed travel[k]
28 Aug 1984	69.33	136.57	21	40-30	2-3	0	Isl	457	80	79[c]	Mar	18-23	NW-N	Various	137-148	100	8	Lone whales; med. speed; tail slapping[k]
SINGLE AIRGUN EXPT.																		
18 Aug 1981	70.03	134.46	25	20	2	0	Isl	457	20	152[d]	Seq	5	Circ.	090	≥123	90-98	19	Skim feeding, mainly in echelons
19 Aug 1981	70.03	134.48	25	28	2	0	Isl	610	19	135[d]	Seq	3	Circ.	090	≥118	97-100	10	Slow travel to SW; surfacing & diving
28 Aug 1983	69.06	137.33	15	13	1-3	0	Isl	610	25	198[d]	Seq	3.5	Circ.	270	133-125	88-98	4-6	Surfacing & diving; medium speed travel[k]
17 Aug 1984	69.12	138.06	18	20	1	<1	Isl	610	30	188[d]	Seq[h]	2-4.5	Various		124-131	92-102	6	Most travelled away while airgun firing[k]
27 Aug 1984[i]	69.21	137.05	12	12	2	0	Isl	457	.3+2	39[a]	Seq[h]	0.2-1.2	Various		>124-134	98-108	6	Medium-fast speed travel away[k]
GSI MARINER EXPT.																		
16 Aug 1984	69.43	136.43	18	25-14	1	0	Isl	457	86	141[d]	Mar	7.5-1.5	Various		>>134-138	<100[j]	6	Bottom feeding; then moved slowly away[k]

[a-d] [a] = after seismic ended. [b] = before seismic began. [c] = seismic before and after period(s) with no seismic. [d] = periods with no seismic both before and after seismic period.

[e] Aspect given as 0° if whales ahead of ship, 90° if whales abeam to starboard, 180° if whales astern, 270° if whales abeam to port.

[f] Noise levels are for the 20-1000 Hz band; Richardson et al. (1985b) give 10-500 Hz data for 1980-82. Values denoted 'c.' are estimates based on Greene's (1982, p. 317) equation for received level vs. range for this ship. Other values are from sonobuoys or hydrophones deployed near the whales.

[g] No direct measurement of sounds near the whales on this occasion.

[h] Sequel was anchored and quiet during the airgun experiments in 1984.

[i] Airgun experiment on 27 August 1984 was incomplete.

[j] Background noise level before and after seismic phase of experiment. Levels between pulses during seismic phase were 118-121 dB.

[k] Most whales in the area where these data were acquired were immatures <13 m long (Würsig et al. 1985b; Davis et al. in prep.).

1. 'Arctic Surveyor', sleeve exploders. On three occasions in 1980-81 (Table 11), we observed whales in shallow water 6-13 km from this ship while it fired 12 large (0.3 x 1.2 m) sleeve exploders. These produced six noise pulses at intervals of 6-10 s and then were silent for 0.5-2 min before beginning the next series of six pulses. Received noise levels were about 154 dB//1 μPa at 6 km and 141 dB at 13 km (Greene 1985).

2. 'Arctic Surveyor', open bottom gas guns. In 1982-84, this ship used 12 open bottom gas guns as the source of seismic pulses. The source level was about 17-18 bar-m, or 239 dB//1 μPa-m; this was slightly greater than the level produced by the sleeve exploders (T. Buckley, Esso, pers. comm.). Whales were observed 52 km from this vessel on 31 Aug 1983.

3. 'GSI Mariner', 23 L airgun array. On 7 occasions in 1982-83 (Table 11), we observed bowheads 24-99 km from this 36-m vessel. It used an array of 27 airguns of various sizes from 10 to 100 in^3 (0.16-1.6 L). The source level was 38 bar-m, peak to peak, or 246 dB//1 μPa-m (G. Bartlett, GSI, pers. comm.).

4. 'GSI Mariner', 47 L airgun array. This vessel was fitted with more powerful compressors and a larger array of airguns in 1984. There were about 30 guns, each of volume 80-125 in^3 (1.3-2.0 L). On 8 occasions in 1984, we obtained opportunistic observations of bowheads at distances of 10-40 km.

5. 'Edward O. Vetter', 33 L airgun array. On 5 Aug 1981 we observed bowheads 45-54 km from this 56 m vessel.

6. 'Western Aleutian', airgun array. On 1 Sept 1983, we observed bowheads 26-31 km from this vessel, which uses an array of airguns with source level 250 dB//1 μPa-m (Reeves et al. 1983).

Statistical comparisons of bowhead behavior in the presence and absence of seismic noise were complicated by day-to-day and place-to-place variations in behavior. Ideally, each set of observations in the presence of seismic noise should be matched with corresponding control observations differing only by the absence of seismic noise. During our opportunistic observations this ideal often was not met, since we had no control over the seismic vessels. Three types of situations were actually encountered.

1. On some occasions in 1983-84, seismic noise either started or stopped while we were watching a group of whales. This provided 'seismic' and 'control' information from the same whales at the same place on the same day--the ideal situation.

2. More commonly, seismic noise was present throughout the observations. We used data from 'presumably undisturbed' whales observed nearby on the same or an adjacent day as the control data. When 2 or 3 small samples of 'seismic' or 'control' observations were obtained in an area within 2 or 3 days, we pooled the data in an attempt to obtain one sample of usable size.

3. On a few occasions, no 'presumably undisturbed' whales were observed in the general area within a few days of the 'seismic' occasion. In these cases we used as control data the average results for presumably undisturbed whales at the corresponding water depth in that year.

After the data from each 'seismic' occasion were compared with the corresponding control data, the results were pooled with the unweighted z method (Rosenthal 1978). For example, there were 16 pairs of 'seismic' and 'control' data for which blow intervals could be compared. The results of these 16 separate statistical tests were pooled for an overall test of the null hypothesis that blow interval is unaffected by seismic noise.

Airgun Experiments

We completed four controlled tests with a single Bolt 40 in^3 (0.66 L) airgun deployed from 'Sequel'. The airgun was 2-5 km from the whales during these four tests. It was fired at 6 m depth every 10 s for 19-20 min on two occasions in 1981, and every 15 s for 25-30 min on two occasions in 1983-84 (Table 11). The whales were observed from the Islander aircraft circling overhead at 457 or 610 m a.s.l. before, during and after the period of airgun firing.

Two different protocols were used. (1) During the 3 tests in 1981 and 1983, 'Sequel' travelled slowly (about 6 km/h) around the whales at a preselected radius throughout the entire observation period, towing the airgun. The rationale was that boat disturbance, if any, would be constant throughout all phases of the experiment. In fact, sonobuoys deployed near the whales showed that engine noise from 'Sequel' was not detectable at the whales' location during the 18 Aug 1981 experiment (5 km range), and was barely detectable in the 19 Aug 1981 and 28 Aug 1983 experiments (about 3 km range). (2) During the 1984 experiment, 'Sequel' was anchored with engine off. Thus, engine noise was not a factor in 1984.

The airgun operated from compressed air tanks filled to at least 1900 psi (131 bars) before pre-airgun control observations began. Thus there was no compressor noise during the experiment. By the time firing ceased, air pressure had dropped to about 400-500 psi and noise pulses received by the whales had decreased by several decibels. In each experiment, airgun sounds were monitored by one or two sonobuoys near the whales. Airgun pulses were always clearly audible, and sounded similar to pulses from distant seismic vessels (Table 11; Greene 1982, 1984a, 1985).

In addition to the four completed airgun tests, a fifth incomplete test with whales closer to the airgun was conducted (27 Aug 1984; Table 11). Our permits did not allow us to fire the airgun when bowheads were within 500 m. On 27 Aug 1984 we twice began to fire the airgun when we believed that the closest whales were >500 m away. In each case, a whale soon came to the surface about 200 m from the airgun. We ceased firing after two shots in the first attempt, and nine shots in the second. Quantitative analysis of data from this aborted experiment was not warranted: (1) There were few observations during the brief airgun firing periods. (2) The results were confounded by noise pulses (122-131 dB//1 μPa) from a distant seismic vessel for most of the pre-airgun period. (That vessel stopped shooting 3 min before the airgun firing period.)

Experiment with Full-Scale Seismic Vessel

To resolve uncertainties associated with uncontrolled opportunistic observations and single airgun experiments, we wanted to conduct controlled tests with a full-scale seismic vessel. The aim was to direct such a vessel to pass about 1-1.5 km to the side of a group of whales and to observe their reactions. No opportunities for such tests were encountered before 1984. However, with the cooperation of Geophysical Service Inc., one test was possible during August 1984.

From 12:21-12:39 MDT on 16 Aug 1984, we observed several bowheads near the eastern edge of pan ice in Mackenzie Bay. 'GSI Mariner' was conducting seismic surveys about 27 km to the southwest. 'Mariner' was heading generally toward the whales, and was expected to pass several kilometres to the west of them in mid afternoon. We therefore refueled the aircraft and returned to the whales at 15:01. At that time 'Mariner' was shooting toward the northeast at a location 10 km west of the whales. At 15:06 'Mariner' stopped shooting because ice prevented normal operations. We were in radio communication from our observation aircraft to the 'GSI Mariner' and to GSI's field manager aboard another aircraft in the area. GSI then placed the vessel at our disposal for 2 h.

We requested that the vessel proceed eastward on a course that would take her to a closest point of approach (CPA) 1-1.5 km north of the whales. For 33 min (15:06-15:39) we observed six bowheads in the absence of seismic pulses as 'Mariner' maneuvered around ice, heading generally east from 9 km to 7.5 km away (Fig. 5). At 15:39, when 'Mariner' was 7.5 km to the west and travelling east at normal shooting speed (7.4 km/h), she began--at our request--to fire her airgun array at a typical rate of one pulse every 10-15 s. By 16:22, 'Mariner' was about 1.5 km north of the closest whale. At 17:00, when 'Mariner' was about 6 km to the east, she ceased shooting and turned northeast. She continued travelling northeast and then northwest for several more minutes before stopping to haul her airguns and cable aboard. During this 'post-seismic' period, 'Mariner' was 6-11 km from the whales. We continued observing the bowheads until 18:48.

Thus, we observed for an initial 5 min period while 'Mariner' fired her airgun array 9-10 km away, for 33 min while she was not shooting (approaching from 9 to 7.5 km), for 81 min while she fired her array along a line from 7.5 km west to 6 km east of the whales (CPA=1.5 km), and for 108 min after she ceased shooting (Fig. 5). The water depth was 18 m, the sea state was 1, and the closest significant ice (15% cover) was about 4 km to the west. The observation aircraft circled the whales at altitude 457 m.

We dropped a sonobuoy amidst the whales near the start of the experiment. After the vessel had passed the whales, we dropped a second sonobuoy about 2 km farther south, where whales were then located. While the ship maneuvered from 9 to 7.5 km away, engine sounds were detectable but not strong enough to mask water noise (received levels 98-105 dB//1 µPa in 20-1000 Hz band).

When 'Mariner' began to fire her airgun array 7.5 km away, the seismic pulses were extremely strong--too intense to measure accurately with the sonobuoy system. The pulses seemed even more intense as 'GSI Mariner' approached the whales. The sonobuoy showed that received levels were at least

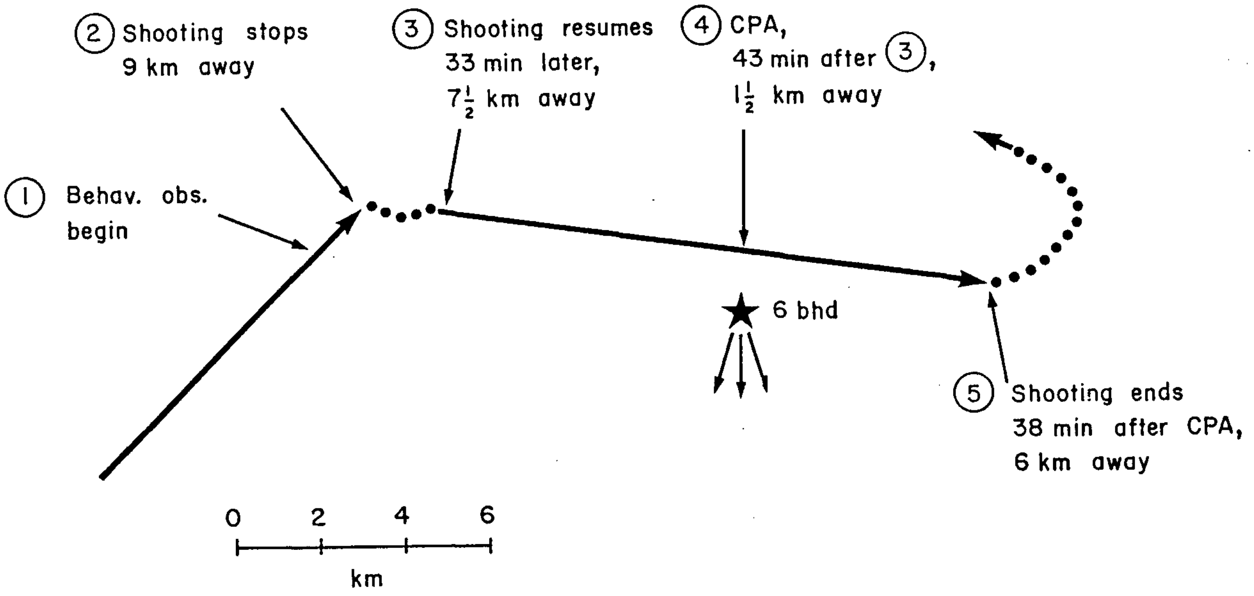

FIGURE 5. Movements of 'GSI Mariner' during test of reactions of bowheads to full-scale seismic vessel, 16 Aug 1984.

134-138 dB, even when the ship was 7 km away. Actual levels when the ship was 1.5 km away were probably well over 160 dB, the level measured by hydrophone about 12 km abeam from 'GSI Mariner' on 14 Aug 1984 (water depth 24 m; Greene 1985). Throughout the period while 'Mariner' was shooting, reverberations from the pulses were audible for most or all of the 15 s interval between pulses. Minimum received levels 'between' pulses were 118-121 dB in the 20-1000 Hz band. The second sonobuoy revealed that engine sounds and various intermittent banging and whining sounds were reaching the whales during the 108 min 'post-seismic' period, when 'Mariner' was hauling her airguns and cable aboard. However, these sounds were not strong enough to mask the water noise (99-103 dB in 20-1000 Hz band).

Results

Opportunistic Observations with Seismic Noise

General Activities.--Activities of whales in the presence and absence of seismic noise were usually indistinguishable. In both situations, bowheads surfaced, dove and called, and sometimes travelled, socialized or fed near the bottom.

During 1 of 21 occasions, unusual behavior was noticed. On 1 Aug 1984, three bowheads in water 10 m deep were observed as 'GSI Mariner' travelled northwestward 17-23 km to the north. One whale travelled back and forth on an irregular course at moderate or fast speed, diving and surfacing repeatedly. The dives and surfacings were very short (average durations 0.77 and 0.13 min, respectively), with only one blow during most surfacings. We believe that the whale was disturbed by seismic sounds, the observation aircraft, or both. Seismic sounds were of moderate intensity (at least 117-119 dB//1 µPa), but were concentrated at unusually high frequencies (500-1300 Hz, Greene

1985). Lower frequencies had probably been attenuated more rapidly by the shallow water. However, given the shallow water, where lateral propagation of aircraft noise is most pronounced (Urick 1972; Greene 1984a), aircraft disturbance is a possibility even though we circled at 457 m a.s.l.

On 5 of 6 occasions when seismic noise started or stopped as we watched whales, behavior did not change noticeably. The possible exception was on 24 Aug 1984. An identifiable whale had been surfacing and diving repeatedly in one area before seismic began. This continued for 3/4 h after 'GSI Mariner' began shooting 36 km to the northwest, but the whale then began swimming rapidly. It is doubtful that this change was attributable to the seismic noise, since (1) the change did not begin until well after the seismic vessel began to shoot, and (2) the whale headed north, partially toward the ship.

There was usually no evidence that bowheads were moving away from the seismic vessel. The only possible case was on 7 Aug 1982, when whales 49-40 km ahead of the approaching 'GSI Mariner' were swimming consistently west at moderate or fast speed. The ship was travelling northeast at a location SSW of the whales. To travel directly away from the ship, the bowheads would have had to move north, not west. However, their westward course took them away from the projected track of the ship--i.e., away from the anticipated closest point of approach of the ship. The westward movement probably was unrelated to the seismic vessel. Whales seen in that general area under presumably undisturbed conditions on 6 August were also moving west. The overall distribution of bowheads seemed to be shifting westward during early August 1982 (Ljungblad et al. 1983; Richardson et al. 1985a).

On two occasions with seismic noise, we observed bowheads playing with logs at the surface (25 Aug 1981, 1 Aug 1982). On 1 Aug 1982, the whale did not dive during 1.6 h of observation. By remaining at the surface for prolonged periods, bowheads would reduce the received level of seismic sounds by several decibels (Greene 1985). However, there is no proof that log play, or failure to dive for a prolonged period, was related to seismic sounds. We have observed log play in the absence of seismic sounds (18 Aug 1984; Würsig et al. 1985b).

In summary, general activities of bowheads were similar in the presence and absence of noise pulses from seismic vessels 6-99 km away. In the few cases when we suspected an overt reaction to the seismic vessel, the seemingly unusual behavior may have been a reaction to something other than the seismic vessel, or an uncommon component of normal undisturbed behavior.

Surfacing, Respiration and Dive Characteristics.--When all observations in the presence and absence of seismic noise were combined, number of blows per surfacing, surface time, and dive time all tended to be lower in the presence of seismic noise (Fig. 6). Blow intervals were similar with and without seismic noise. Although suggestive, these results were confounded by the many factors, aside from presence or absence of seismic noise, that varied from day to day. Consequently, we compared the data from each 'seismic' occasion with matched data from presumably undisturbed whales observed under similar circumstances (see Methods).

Our matched results from 1980-84 provided some evidence of subtle differences in surfacing, respiration and dive cycles in the presence and absence of seismic noise. In 4 of 7 situations examined in 1980-82

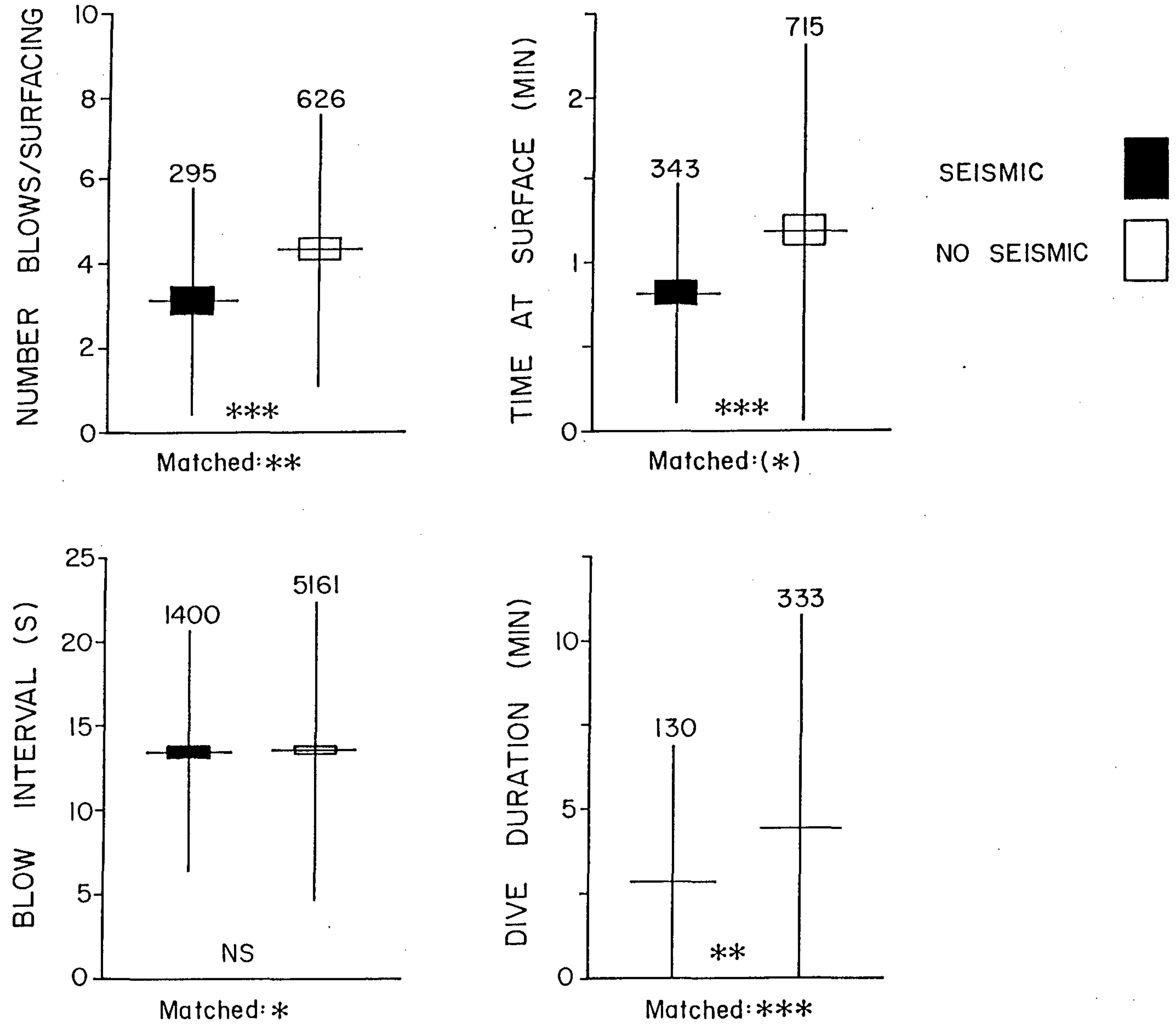

FIGURE 6. Surfacing, respiration and dive characteristics of bowheads in the presence and absence of seismic noise, 1980-84. 'Seismic' data are from 18 dates with opportunistic data (Table 12A). 'No Seismic' data, from Würsig et al. (1985b), include all 'presumably undisturbed' observations in 1980-84. Calves are excluded. The mean, ± 1 standard deviation (vertical line), and ± 95% confidence limits (wide bar) are shown. Sample sizes are given at the top, and the significance of the seismic vs. no seismic difference is coded as in Table 12. See text for discussion of simple vs. matched comparisons.

(Richardson et al. 1983c, 1985b) and in 6 of 9 situations examined in 1983-84 (Fig. 7), at least one of four variables differed significantly ($p \leq 0.05$) from values for 'presumably undisturbed' bowheads observed under similar conditions (summarized in Table 12A).

When matched results from all 5 years were pooled (Table 12D), bowheads in the presence of seismic noise tended to have fewer blows per surfacing ($p<0.01$), marginally shorter surfacings ($p = 0.052$), longer blow intervals ($p<0.05$), and shorter dives ($p<0.001$). The fact that trends for two variables (number of blows per surfacing and dive duration) were similar in 1980-82 and 1983-84 (Table 12D) makes it more likely that the effect is real.

These results must be interpreted cautiously: (1) The whales observed in the presence and absence of seismic noise usually were different animals. (2) No one variable was consistently different in all situations. (3) In 3 of 4 cases when the seismic ship was within 13 km, no significant differences were found. (4) Most sample sizes were small and came from repeated observations of still smaller numbers of different whales. Without experimental control, it is impossible to be sure whether the apparent effects were attributable to seismic noise or to some other variable. A further reason for caution is that the pooled results depend strongly on the data from 1 Aug 1984 (site B). On that occasion, the behavior of one whale was quite unusual, possibly because of aircraft rather than seismic disturbance (see above). If that occasion is excluded, the trends in number of blows per surfacing and duration of surfacing become non-significant ($p>0.1$). However, mean blow interval remains significantly longer ($p<0.05$) and mean dive duration significantly shorter ($p<0.001$) in the presence of seismic noise (Table 12D).

In summary, opportunistic observations indicated that blow intervals tended to be longer and dive durations shorter in the presence of seismic noise than in matched 'no seismic' cases. There were also indications that mean duration of surfacing and mean number of blows per surfacing tended to be reduced in the presence of seismic noise. However, there was much variability and overlap; these trends were not always evident, and contrary trends were found on some occasions. In the absence of experimental control, it is impossible to be sure that the trends were attributable to seismic noise as opposed to other factors (see 'Multivariate Analyses', below).

Other Behavioral Variables.--Estimated speeds of bowheads usually were similar in the presence and absence of seismic noise. One exception was the aforementioned '1 Aug 1984 (site B)' case, when a whale travelled at moderate or fast speed during most surfacings. It is uncertain whether seismic noise, aircraft disturbance, or some other factor was responsible. Aside from that one case, there was no evidence that speed was affected by seismic noise (Table 14).

Turns and pre-dive flexes occurred more often without than with seismic noise, considering all available occasions together (Table 14). The presence of seismic noise did not affect whether bowheads raised their flukes above the water while diving (Table 14).

Bowhead Calls.--Calls were heard during 11 of the 14 occasions when underwater sounds were recorded near bowheads exposed to seismic noise. The overall calling rates for the 14 cases were 11.07 calls/whale-h and 1.72 loud calls/whale-h (Table 15). These rates were only slightly less than rates

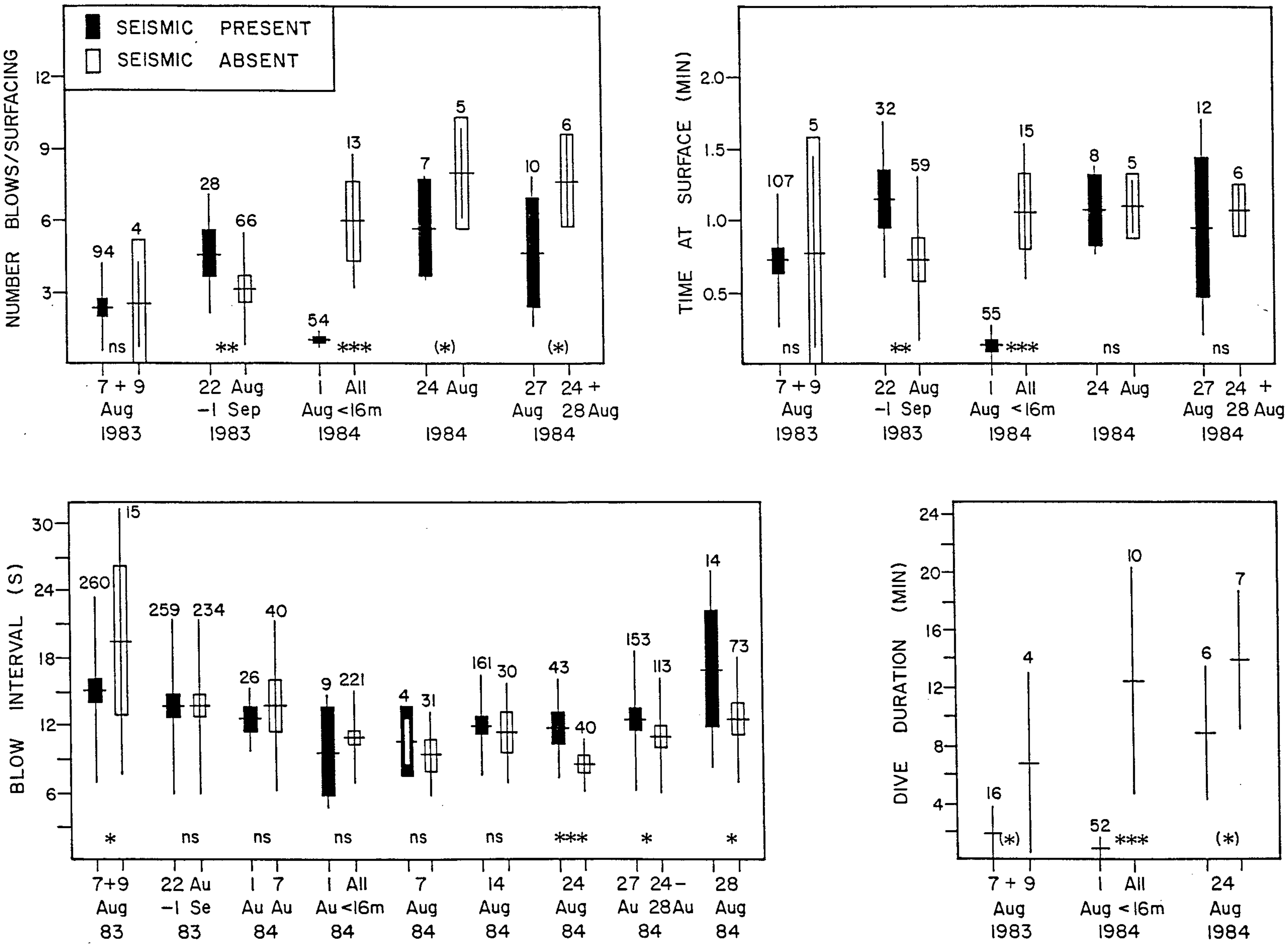

FIGURE 7. Surfacing, respiration and dive characteristics of bowheads in the presence and absence of seismic noise on specific occasions in 1983-84. The 'Seismic Absent' results are from 'presumably undisturbed' whales observed in situations similar to those when the corresponding 'Seismic Present' data were collected. Calves are excluded. Presentation as in Fig. 6. For 1980-82 data, see Richardson et al. (1983c) or (1985b).

Table 12. Summary of statistical comparisons of surfacing, respiration and dive characteristics of non-calf bowheads observed in the presence and absence of seismic noise. See Richardson et al. (1983c, 1985b) for 1980-82 data; Richardson et al. (1984b) for 1983 data; and Tables 13, 16 for 1984 data[a].

Circumstances Compared		Seismic Sound			Variable[a]			
Seismic	Control[b]	Seismic Vessel	km from Vessel	Received Level (dB//1 μPa)	Blows/ Surfacing	Surface Time	Blow Interval	Dive Time
A. OPPORTUNISTIC								
20 Aug 80	20 + 22 Aug 80	Ar Surv	c. 8	c. 150	ns	++	+	(+)
21 Aug 80	20 + 22 Aug 80	Ar Surv	13	c. 141	ns	ns	ns	
5 Aug 81	6-13 Aug 81	Vetter	45-54	117	ns	ns	ns	ns
25 Aug 81	All in <16 m	Ar Surv	6-8	c. 150	ns	ns	(-)	ns
7 Aug 82	All 1982	Mariner	49-40	107-113	ns	-	--	-
16 Aug 82	14-19 Aug 82	Mariner	54-58	127-132	--	-	+	(-)
18 Aug 82	14-19 Aug 82	Mariner	73-62	<125-133	-	-	++	-
7 + 9 Aug 83	7 + 9 Aug 83[c]	Mariner	?-99	110-131	ns	ns	-	(-)
31 Aug + 1 Sept 83	22-28 Aug 83	Ar Surv/ W Aleut	26-53	107-135	++	++	ns	
1 Aug 84 A	7 Aug 84	Mariner	36-40	130-125			ns	
1 Aug 84 B	All in <16 m	Mariner	17-23	119-117	---	---	ns	---
7 Aug 84	7 Aug 84[c]	Mariner	33	137			ns	
14 Aug 84	14 Aug 84[c]	Mariner	20-10	<143-158			ns	
24 Aug 84	24 Aug 84[c]	Mariner	36-29	?	(-)	ns	+++	(-)
27 Aug 84	24 + 28 Aug 84	Mariner	11-37	122-131	(-)	ns	+	
28 Aug 84	28 Aug 84[c]	Mariner	18-23	137-148			+	
B. SINGLE AIRGUN EXPT								
18 Aug 81	Pre & Post Gun[c]	1 gun	5	≥123	(-)	ns	ns	ns
19 Aug 81	Pre & Post Gun[c]	1 gun	3	≥118	ns	ns	+	
28 Aug 83	Pre Airgun[c]	1 gun	3.5	133-125	ns	ns	ns	
17 Aug 84	Pre & Post Gun[c]	1 gun	2-4.5	124-131			ns	
C. GSI MARINER EXPT								
16 Aug 84	Pre & Post Firing[c]	Mariner	7.5-1.5	>>134	ns	ns	---	
D. POOLED[d]								
All 1980-82 Opportunistic					(-)	(-)	ns	(-)
All 1983-84 Opportunistic					-	ns	+	---
All Opportunistic					--	(-)	+	---
All Opportunistic except '1 Aug 84 B'					ns	ns	+	---
All Single Airgun Expt					(-)	(-)	(+)	ns
All Single Airgun Expt + 'Mariner' Expt					ns	ns	ns	ns

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[a] Test results are coded as

ns if $p > 0.1$,
(+) if mean value higher with than without seismic noise, and $0.1 \geq p > 0.05$,
(-) if mean value lower with than without seismic noise, and $0.1 \geq p > 0.05$,
\+ or - if $0.05 \geq p > 0.01$,
++ or -- if $0.01 \geq p > 0.001$,
+++ or --- if $p \leq 0.001$.

Missing values indicate $n \leq 4$ for at least one of the situations being compared. See the references and tables cited above this table for details concerning the types of statistical tests applied.

[b] All 'control' data came from 'presumably undisturbed' whales.

[c] The same whales were observed in both the presence and absence of seismic noise on this occasion.

[d] Pooling done by the 'unweighted z' method (Rosenthal 1978).

Table 13. Surfacing, respiration and dive characteristics of non-calf bowheads observed in the presence and absence[a] of seismic noise, 1984. See Richardson et al. (1983c, 1984b) for corresponding results from 1980-82 and 1983, respectively.

Date(s)	Distance from 'Mariner' (km)	Mean	s.d.	n	Test[b]	Mean	s.d.	n	Test[b]
		Blows/Surfacing				**Duration of Surfacing (min)**			
1 Aug 1984 A	36-40	1.00	-	1		0.12	-	1	
7 Aug 1984	Absent	5.00	2.449	6		1.00	0.510	6	
1 Aug 1984 B	17-23	1.07	0.328	54	t'	0.14	0.138	55	t'
All depth <16 m	Absent	6.00	2.769	13	***	1.07	0.469	15	***
7 Aug 1984	33	3.00	1.414	2		0.36	0.167	3	
7 Aug 1984	Absent	4.86	1.574	7		0.76	0.249	7	
14 Aug 1984	20-10	7.40	3.286	5		1.63	0.601	8	
14 Aug 1984	Absent	6.00	-	1		1.25	-	1	
24 Aug 1984	36-29	5.71	2.138	7	t	1.08	0.292	8	t
24 Aug 1984	Absent	8.00	1.871	5	(*)	1.11	0.177	5	ns
27 Aug 1984	11-37	4.70	3.093	10	t	0.96	0.742	12	t'
24 + 28 Aug '84	Absent	7.67	1.862	6	(*)	1.08	0.174	6	ns
28 Aug 1984	18-23	-	-	0		-	-	0	
28 Aug 1984	Absent	6.00	-	1		0.93	-	1	
		Blow Interval (s)				**Dive Duration (min)**			
1 Aug 1984 A	36-40	12.58	2.701	26	t'	0.15	-	1	
7 Aug 1984	Absent	13.80	7.356	40	ns	1.69	1.418	7	
1 Aug 1984 B	17-23	9.67	5.099	9	t	0.76	0.767	52	U
All depth <16 m	Absent	10.99	4.110	221	ns	12.44	7.809	10	***
7 Aug 1984	33	10.50	1.915	4	t	6.11	1.752	3	
7 Aug 1984	Absent	9.36	3.800	31	ns	8.07	1.368	6	
14 Aug 1984	20-10	11.95	4.442	161	t	-	-	0	
14 Aug 1984	Absent	11.33	4.381	30	ns	-	-	0	
24 Aug 1984	36-29	11.77	4.418	43	t	8.87	4.647	6	U
24 Aug 1984	Absent	8.40	2.340	40	***	13.93	4.788	7	(*)
27 Aug 1984	11-37	12.41	6.136	153	t	0.65	0.509	3	
24 + 28 Aug '84	Absent	11.01	5.038	113	*	13.93	4.788	7	
28 Aug 1984	18-23	16.93	8.704	14	t	-	-	0	
28 Aug 1984	Absent	12.44	5.538	73	*	-	-	0	

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[a] The 'Mariner Absent' lines include only 'presumably undisturbed' non-calf bowheads.

[b] Values in the presence and absence of seismic noise were compared using the Student's t-test (t), the t-test not assuming equal variances (t'), or the Mann-Whitney U test (U). *** indicates $p \leq 0.001$, ** means $0.001 < p \leq 0.01$, * means $0.05 < p \leq 0.01$, (*) means $0.05 < p \leq 0.1$, and ns means $p > 0.1$. Test not done when $n < 4$ for either group.

Table 14. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed in the presence and absence of seismic noise, 1980-84. Each surfacing by a whale is a unit of observation.

	Speed				
	Zero	Slow	Moderate	Fast	Total
Seismic[a]	35	76	113	12	236
No Seismic[b]	39	53	67	6	165
Chi^2 (df = 3)			5.68, $p > 0.1$		

	Turn			**Pre-Dive Flex**			**Pre-Dive 'Flukes Out'**		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Seismic	238	44	282	323	35	358	253	159	412
No Seismic[b]	127	44	171	170	46	216	173	117	290
Chi^2 (df=1)	6.98, $p < 0.01$			14.75, $p < 0.001$			0.22, $p > 0.1$		

[a] Speed analysis excludes data from 1 Aug 1984 (site B).

[b] 'No seismic' lines include only the 'control' occasions that were matched with 'seismic present' occasions.

recorded near 'presumably undisturbed' whales in 1980-84, 14.26 total and 3.75 loud calls/whale-h. The slight reduction with seismic noise may not be meaningful because numbers of whales responsible for the calls were only roughly known. The proportional frequencies of the seven call types that we distinguished were almost identical in the presence and absence of seismic noise (Table 15). Thus, noise from distant seismic boats did not have a strong effect on calling by bowheads.

Summary.--Opportunistic observations indicated that general activities of bowheads are rarely if ever altered in any noticeable way by noise from seismic vessels 6 km or more away. There were, however, indications of subtle alterations in surfacing-respiration-dive cycles, and in frequency of turns and pre-dive flexes. Whether these subtle trends were attributable to seismic noise or to other factors cannot be determined with certainty from opportunistic observations. Bowheads produced calls of the usual types when exposed to seismic pulses; the rate of calling was only slightly (if at all) reduced.

Airgun Experiments

Strong pulses of airgun noise reached the whales during all five airgun experiments. During the four completed experiments, the whales were 2-5 km from the airgun. Received levels of the airgun pulses were at least 118-133 dB//1 μPa. In contrast, ambient noise levels between airgun pulses were

Table 15. Numbers and types of bowhead calls recorded in the presence and absence of seismic noise, Canadian Beaufort Sea, 1980-84. Data compiled by C.W. Clark.

Date	Observation Time (MDT)[a]		Source of Seis. Noise[b]	Whale Activities[c]	Approx No. of Whales	Whale-Hours of Obs	Total No. Calls of Each Type								Calls Per Whale-Hour	
	Start	End					Up	Down	Constant	Inflected	High	Pulsed Tone	Pulsive	Total	Total	Loud
21 Aug 1980	22.25	23.25	Sl-Exp	So	7	7.00	17	6	1	3	9	3	31	70	10.00	
5 Aug 1981	10.11	10.41	Array		5	2.50	18	4	6	2	8	1	13	52	20.80	
25 Aug 1981	11.25	12.34	Sl-Exp	So,Bo	4-15	15.42	11	0	0	0	0	0	0	11	0.71	
7 Aug 1982	10.15	11.06	Array	So	5	4.25	66	70	25	11	4	0	8	184	43.29	8.00
16 Aug 1982	15.25	16.30	Array	So,Ca	7	7.58	101	32	24	19	2	2	19	199	26.25	2.90
18 Aug 1982	16.38	18.00	Array	Ca	8	10.93	63	80	90	17	13	56	8	327	29.92	2.56
7 Aug 1983	17.15	18.50	Array	?	2	3.17	0	0	0	0	0	0	0	0	0.00	0.00
9 Aug 1983	13.48	17.20	Array	So	12	39.40	61	54	29	25	36	1	59	265	6.73	1.04
31 Aug 1983	14.54	17.18	Gas-G	So,Bo	6	14.20	125	29	25	58	6	1	2	246	17.32	3.03
1 Sep 1983	16.57	18.26	Array	So,Bo	5	7.41	4	1	1	0	0	0	0	6	0.81	0.00
1 Aug 1984 A	16.38	17.23	Array		3	2.25	1	0	0	0	0	1	0	2	0.89	0.44
1 Aug 1984 B	18.37	19.24	Array		2	1.57	0	0	0	0	0	0	0	0	0.00	0.00
27 Aug 1984 A	17.52	18.45	Array	Bo	6-7	4.35	0	0	0	0	0	0	0	0	0.00	0.00
27 Aug 1984 B	19.43	20.54	Array		6	3.20	0	0	2	0	0	0	0	2	0.63	0.00
All 1980-81 Seismic						24.92	46	10	7	5	17	4	44	133	5.34	
All 1982 Seismic						22.76	230	182	139	47	19	58	35	710	31.20	3.69
All 1983 Seismic						64.18	190	84	55	83	42	2	61	517	8.06	1.31
All 1984 Seismic						11.37	1	0	2	0	0	1	0	4	0.35	0.09
All Seismic	Totals					123.23	467	276	203	135	78	65	140	1364	11.07	1.72
	Percent						34	20	15	10	6	5	10			
All 1980-81 Undisturbed[d]						114.14	69	20	8	15	29	29	83	253	2.22	
ALL 1982 Undisturbed						108.82	1655	1159	976	398	194	278	273	4933	45.33	8.25
All 1983 Undisturbed						91.64	103	34	17	31	16	43	9	253	2.76	0.91
All 1984 Undisturbed						82.00	111	32	21	22	3	22	5	216	2.63	0.94
All Undisturbed	Totals					396.60	1938	1245	1022	466	242	372	370	5655	14.26	3.75
	Percent						34	22	18	8	4	7	7			

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[a] Recordings were not always continuous from start to end time.

[b] Sl-Exp = 12 sleeve exploders. Gas-G = 12 open bottom gas guns. Array = array of airguns.

[c] So = socializing. Bo = bottom feeding. Ca = calf present.

[d] See Würsig et al. (1985b) for details concerning calls by presumably undisturbed bowheads.

88-102 dB in the 20-1000 Hz band. Signal to noise ratios were at least 18-45 dB (Table 11; data from Greene 1982, 1984a, 1985). During the aborted experiment on 27 Aug 1984, the whales were only 0.2-1.2 km away. Received levels at range 1.5 km were probably above the measured 124-134 dB values, and levels near the closest whales were undoubtedly greater.

General Activities.--General activities of bowheads observed during the three airgun experiments in 1981 and 1983 were unremarkable--skim feeding in echelon formations on 18 Aug 1981, and slow to moderate travel with surfacing and diving on the next two occasions. General activities did not change during the period of airgun firing (Table 11). However, during the first experiment, echelons averaged smaller in size during the airgun firing period than before or after (4.7 ± s.d. 2.20 before, 2.8 ± 1.33 during, 3.7 ± 1.56 after; n = 21, 6, 12, respectively; lack of independence precludes statistical comparison). We do not know whether the apparent reduction in echelon size during the airgun firing period was a result of the airgun noise. Replication would be necessary to establish this. Unfortunately, we had no opportunity for another airgun experiment while bowheads were echelon feeding. In any case, general activities remained the same during the airgun firing periods of all three experiments in 1981 and 1983.

During the two experiments in 1984, one completed on 17 August and one aborted on 27 August, behavior was unremarkable before the airgun began to fire. However, during and shortly after the airgun firing period, most bowheads seen were travelling away from the airgun site (see Orientation section, below). One difference in protocol was that the airgun was deployed from a travelling vessel in 1981-83, but from a stationary and quiet vessel in 1984. Received levels of airgun noise on 17 Aug 1984 may have been higher than those during the 1981-83 experiments. Received levels on 27 Aug 1984 were the highest because the airgun was closest to the whales on that date (Table 11).

Surfacing and Respiration Characteristics.--In general, there was much overlap in values of surfacing and respiration variables before, during and after the airgun firing periods (Fig. 8; Table 16). In most experiments, values did not differ significantly in the presence and absence of airgun noise (Table 12B; Fig. 8). However, the sample sizes during the period of airgun firing were small. Durations of dives were recorded too infrequently for analysis (Fig. 8).

The slight differences that did occur showed some consistency across experiments. During all three experiments with data, mean surface time and mean number of blows per surfacing were slightly reduced during the airgun firing period relative to pre-airgun values (Fig. 8). Pooled results from the three experiments showed a marginally significant effect ($p \leq 0.1$ for both variables, Table 12D). Conversely, mean blow intervals increased from the pre-airgun to the airgun period in 3 of 4 experiments (Fig. 8). The trend was significant on 19 Aug 1981 ($p<0.05$), but the pooled trend was not significant ($p = 0.1$).

The trends in these three variables were all weak. The airgun experiments do not prove that surfacing and respiration behavior is altered in the presence of noise pulses. However, it is noteworthy that trends in all three variables were in the same direction as was found during analyses of opportunistic observations (Table 12D).

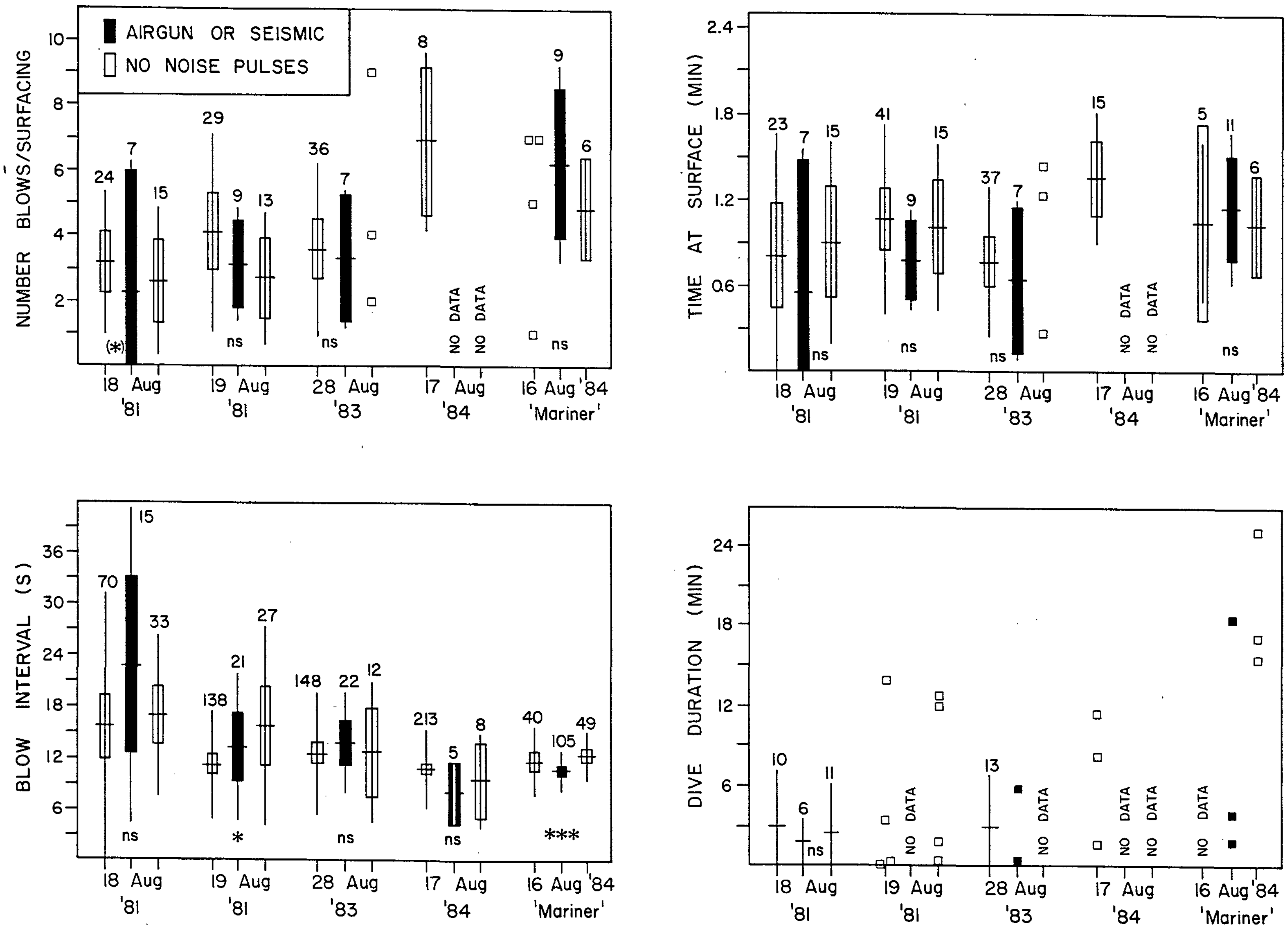

FIGURE 8. Surfacing, respiration and dive characteristics of bowheads before, during and after an airgun or airgun array fired. Calves are excluded. Presentation as in Fig. 6. For numerical data, see Table 16.

Table 16. Surfacing, respiration and dive characteristics of non-calf bowheads observed during airgun and full-scale seismic experiments, Canadian Beaufort Sea, 1981-84[a].

Date	Phase	Mean	s.d.	n	Test	Mean	s.d.	n	Test
		Blows/Surfacing				**Duration of Surfacing (min)**			
SINGLE AIRGUN EXPT									
18 Aug 1981	Before	3.17	2.180	24	KrWal	0.82	0.829	23	KrWal
(5 km range)	During	2.29	3.904	7	(*)	0.56	0.983	7	ns
	After	2.60	2.230	15		0.91	0.694	15	
19 Aug 1981	Before	4.10	3.004	29	KrWal	1.06	0.653	41	KrWal
(3 km range)	During	3.11	1.691	9	ns	0.78	0.343	9	ns
	After	2.69	1.974	13		1.01	0.571	15	
28 Aug 1983	Before	3.58	2.612	36	t	0.77	0.515	37	t
(3 km range)	During	3.29	2.059	7	ns	0.64	0.543	7	ns
	After	5.00	3.606	3		0.98	0.624	3	
17 Aug 1984	Before	6.88	2.696	8		1.35	0.452	15	
(2-4 km range)	During	–	–	0		–	–	0	
	After	–	–	0		–	–	0	
GSI MARINER EXPT									
16 Aug 1984	Before	5.00	2.828	4	ANOVA	1.04	0.544	5	ANOVA
	Seismic	6.22	2.949	9	ns	1.14	0.526	11	ns
	After	4.83	1.472	6		1.02	0.328	6	
		Blow Interval (s)				**Dive Duration (min)**			
SINGLE AIRGUN EXPT									
18 Aug 1981	Before	15.80	15.362	70	ANOVA	3.04	4.124	10	KrWal
(5 km range)	During	22.93	18.215	15	ns	1.81	1.596	6	ns
	After	17.15	9.176	33		2.47	3.673	11	
19 Aug 1981	Before	11.45	6.262	138	ANOVA	4.40	6.542	4	
(3 km range)	During	13.43	8.441	21	*	–	–	0	
	After	15.89	11.580	27		6.72	6.591	4	
28 Aug 1983	Before	12.67	7.044	148	t	3.02	3.839	13	
(3 km range)	During	13.91	5.773	22	ns	3.13	3.948	2	
	After	12.83	8.133	12		–	–	0	
17 Aug 1984	Before	10.88	4.390	213	t	7.21	4.999	3	
(2-4 km range)	During	8.00	3.000	5	ns	–	–	0	
	After	9.50	5.292	8		–	–	0	
GSI MARINER EXPT									
16 Aug 1984	Before	11.73	3.769	40	ANOVA	–	–	0	
	Seismic	10.64	2.206	105	***	8.14	9.152	3	
	After	12.39	2.745	49		19.26	5.119	3	

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[a] Presentation as in Table 13.

Orientation of Whales.--During the three airgun experiments in 1981-83, we found no evidence that bowheads were moving away from the airgun and boat (Fraker et al. 1982; Richardson et al. 1983c, 1984b). On 18 Aug 1981, bowheads continued to skim feed in echelon formation during and after the airgun firing period. They continued to swim back and forth through the same area of high copepod abundance (Griffiths and Buchanan 1982) where they had been feeding before the airgun began firing. On 19 Aug 1981, bowheads were travelling southwest during all phases of the experiment. On 28 Aug 1983, only four directional observations were obtained during the airgun firing period; the whales were oriented tangentially, not away.

On 17 Aug 1984, bowheads tended to orient away from the airgun when it fired 2-4.5 km away (Fig. 9; $p<0.005$ by V-test). In contrast, bowheads were oriented more or less randomly with respect to the airgun before and after the airgun firing period ($p>0.1$ in each case). The difference in orientation between the pre-airgun and airgun firing periods was significant (Kuiper test; $K = 398$; $p = 0.005$). These tests include one data point for each surfacing, excluding the very few occasions when an identifiable individual was resighted within the same phase of the experiment.

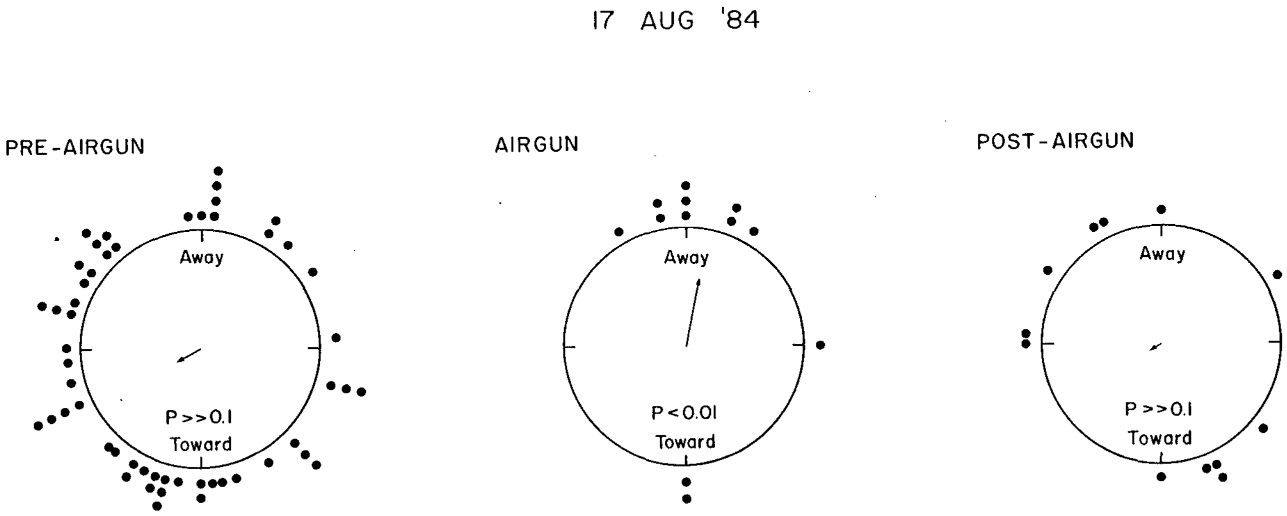

FIGURE 9. Relative orientations of bowheads before, during and after an airgun fired 2-4½ km away, 17 Aug 1984. Each symbol represents the heading (relative to airgun) of one whale during one surfacing, as observed from the observation aircraft. The directions and lengths of the mean vectors are shown. The p values are from V-tests of the hypothesis that there was significant orientation away.

Similarly, on 27 Aug 1984, bowheads swam away from the airgun on both occasions when it was fired. Whales seen during the two brief airgun firing periods and within 5 min after they ended were oriented within 40° of directly away ($n = 5$), and were travelling at moderate or fast speed ($n = 5$). These whales were estimated to be 0.2-1.2 km from the airgun and boat. 'Sequel' had been anchored near whales for 3 h before the airgun began firing, so their departure was presumably attributable to the airgun and not to 'Sequel'. Also, orientations and speeds were more variable before the airgun began firing, with some whales heading toward 'Sequel' and speeds ranging from zero to moderate. The effect was obvious in real time to the aerial observers, but quantitative analysis is not practical, as noted above in 'Methods'.

Other Behavioral Variables.--Most whales moved at slow or medium speed during all three phases of the four completed experiments (Table 17). Only during the aborted 27 Aug 1984 experiment at ranges 0.2-1.2 km was there evidence that bowheads tended to travel faster than normal during the airgun firing period. Speeds may have been affected only on that occasion because bowheads were closest to the airgun on that date, and received noise levels were highest (Table 11).

Table 17. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed during four airgun experiments, 1981-84. Each surfacing by a whale is a unit of observation.

	Speed				
	Zero	Slow	Moderate	Fast	Total
Pre-Airgun	30	34	54	6	124
Airgun	1	3	4	0	8
Post-Airgun	7	6	7	4	24

	Turn			**Pre-Dive Flex**			**Pre-Dive 'Flukes Out'**		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Pre-Airgun	81	30	111	98	33	131	54	84	138
Airgun	12	5	17	13	4	17	5	8	13
Post-Airgun	20	10	30	19	7	26	3	6	9
Chi^2 (df=2)	0.47, p > 0.1			0.07, p > 0.1			0.12, p > 0.1		

Analysis of other variables provided no further indication that bowhead behavior was affected by airgun noise. The frequencies of turns, pre-dive flexes, and fluke-out dives were all similar before, during and after the airgun was fired (p>>0.1 in each case; Table 17).

Bowhead Calls.--Calls were heard within the airgun firing period during 3 of the 4 completed airgun tests. During the 18 August 1981 test, whales apparently stopped calling during the airgun firing period and resumed thereafter (Table 18). However, the pre-airgun rate was sufficiently low that only 2.5 calls would be expected during the airgun firing period if there were no change in rate. Thus, the absence of calls while the airgun fired could have been a sampling artefact. Overall, there was no consistent trend toward reduced call rates while the airgun fired, but sample sizes were small

Table 18. Call rates (total calls/whale-h) of bowheads during four completed airgun experiments, 1981-84. Data compiled by C.W. Clark.

	Before Airgun Fired	During Airgun Firing	After Airgun Fired	Total Number of Calls[a]
18 Aug 81	0.3	0.0	1.1	11,0,36
19 Aug 81	0.5	0.6	0.3	4,1,1
28 Aug 83	2.7	3.2	-	40,8,-
17 Aug 84	1.3	0.6	0.8	15,2,3

[a] Values given are numbers of calls before, during and after the airgun fired, respectively.

(Table 18). 'Up' calls were the most common call type in both the pre-airgun periods (28 of 70 calls) and the airgun firing periods (7 of 11).

Summary.—Bowheads sometimes continued normal activities (e.g. skim feeding in echelons; surfacing and diving; travel) when an airgun began firing 3-5 km away (received noise levels at least 118-133 dB//1 µPa). However, bowheads oriented away during one experiment at range 2-4.5 km and another at range 0.2-1.2 km (received levels at least 124-131 and >124-134 dB, respectively). All of these received levels are minimum estimates, constrained by sonobuoy limitations. In the 0.2-1.2 km case, there was also evidence of increased speeds when the airgun fired. Surfacing and respiration variables did not change dramatically when an airgun began firing 2-5 km away, but trends were consistent with those in the opportunistic data. Frequencies of turns, pre-dive flexes, and fluke-out dives were similar with and without airgun noise. Call rates and types did not change dramatically during experiments.

Multivariate Analyses

Surfacing and Respiration Variables With and Without Seismic Noise.--In the 'Normal Behavior' section, we used multiple regression analysis (MRA) to examine the relationships of three surfacing and respiration variables to 17 environmental and 'whale activity' variables (Würsig et al. 1985b). Here we use MRA to assess whether seismic noise affected surfacing and respiration variables, after allowing for their partial correlations to the 17 environmental and activity variables. The approach was as described in the 'Normal Behavior' section, with two changes:

1. We used 1981-84 observations in the presence of noise pulses from (a) distant seismic vessels and (b) single airguns simulating them, along with (c) observations of presumably undisturbed bowheads. We excluded data from calves, from '1 Aug 1984, site B' where a whale may have been affected by the aircraft, and from the 16 Aug 1984 experiment with 'GSI Mariner' (see next subsection).

2. SEISMIC, an 18th predictor variable representing the presence (1) or absence (0) of seismic pulses, was considered as a predictor.

As in the earlier analyses, the dependent variables were logarithmic transformations of number of blows per surfacing (LOGNBL, n = 690), duration of surfacing (LOGSFC, n = 787), and mean blow interval (LOGMBI, n = 1366).

Univariate analyses excluding the '1 Aug 1984B' data failed to find any relationship between seismic noise and either number of blows per surfacing or duration of surfacing ($p>0.1$; Table 12D). Similarly, after excluding the '1 Aug 1984B' data, SEISMIC showed little simple correlation with LOGNBL ($0.1>p>0.05$) and none with LOGSFC ($p>>0.1$). There was also no significant partial correlation between SEISMIC and these two variables after relationships to other variables (year, date, water depth, sea state, occurrence of skim-feeding or active socializing) were taken into account.

Univariate analyses showed that blow intervals tended to be slightly greater in the presence of seismic noise. This was true whether or not the '1 Aug 1984B' data were included ($p<0.05$ in either case, Table 12D). However, after taking into account year-to-year differences in LOGMBI and positive partial correlations of LOGMBI with date, water depth, occurrence of skim-feeding and group size, there was no evidence that LOGMBI was related to presence or absence of seismic noise ($p>0.1$).

In summary, multiple regression analyses did not find any clear evidence that noise pulses from distant seismic vessels (actual or simulated by one airgun) affected various surfacing and respiration characteristics of bowheads. These multivariate analyses did not confirm the apparent univariate trends for reduced surface times, fewer blows per surfacing, and longer blow intervals in the presence of seismic noise. The univariate trends may have been spurious, arising from the effects of covarying factors such as water depth, sea state, occurrence of skim-feeding or socializing, and group size, on surfacing and respiration behavior.

The multiple regression analyses show that there was no strong effect of noise from distant seismic vessels on our standard surfacing and respiration variables. These analyses do not rule out the possibility of weak effects. Too many intercorrelated disturbance, environmental and 'whale activity' variables were changing simultaneously for the analyses to detect weak effects that may have existed.

Overall Behavior With and Without Seismic Noise.--Stepwise multiple discriminant analysis (Dixon and Brown 1977) was also used to compare whale activities and behavior, as defined by 12 variables, in the presence and absence of noise from distant seismic vessels (actual or simulated by one airgun). Each surfacing by a whale constituted a case. The 12 variables considered were

- LOGNBL, LOGSFC and LOGMBI, as in the previous analyses;
- presence (1) or absence (0) of SKIM-feeding, DEFECation, and MUD (MUD being indicative of near-bottom feeding);
- presence or absence of active socializing (ACTSOC) and of group size greater than one (GTONE); actual group size (GRPSIZ);
- presence or absence of TURN, pre-dive FLEX, or pre-dive FLUKES-out.

In a preliminary analysis we also considered estimated speed, but speed was estimated too infrequently to allow inclusion in the final analysis. We again excluded calves, the 1 Aug 1984B data, and data from the 16 Aug 1984

'Mariner' experiment. This analysis did not control for differences in environmental factors such as year, water depth, and so on.

Surfacings in the presence and absence of distant seismic noise differed significantly (F = 14.68, df = 3,437, p<0.001; n = 297 undisturbed and 144 seismic cases). Behavioral variables that differed significantly between surfacings with and without seismic noise were

- bottom feeding (p<0.025, more common with seismic noise),
- active socializing (p<0.001, more common with seismic noise), and
- turns (p<0.001, more common without seismic noise).

Once these three variables were taken into account, none of the other nine variables differed significantly in the presence and absence of noise from distant seismic vessels (p>0.05 for GTONE; p>0.1 for all others).

This discriminant analysis provided further evidence that surfacing and respiration behavior was not strongly affected by noise from distant seismic vessels. The reduced frequency of turns in the presence of seismic noise was also evident from univariate analysis (Table 14). The greater frequency of apparent bottom feeding and active socializing with seismic noise had not been identified earlier. The combination of more socializing but less turns with seismic noise was unexpected, since undisturbed bowheads tended to turn more frequently when socializing (Würsig et al. 1985b). Whether occurrence of turns, bottom feeding and socializing were actually affected by seismic noise remains unknown. The apparent relationships may have been coincidental. The active socializing seen with and without seismic noise was similar; we did not observe behavior similar to the 'huddling' described by Reeves et al. (1984).

Experiment with Full-Scale Seismic Vessel

General Activities.--Prior to the start of the 'experimental seismic' period, bowheads surfaced and dove, and moved at slow to medium speed while at the surface. During 7 of 16 surfacings (44%) bowheads brought mud to the surface, indicative of feeding near the bottom. During this period, 'GSI Mariner' concluded shooting 9 km away and then approached (not shooting) to range 7.5 km (Fig. 5).

There was no conspicuous change in behavior when 'Mariner' resumed shooting 7.5 km away. Bowheads continued to surface and dive, move at slow to medium speed, and bring mud to the surface. The last surfacing with mud occurred when 'Mariner' was 3 km away. When the ship was near its closest point of approach (CPA), about 1.5 km north of the whales' original location, some whales were still in the area. However, it became evident that some whales had moved southward; there were fewer sightings in the original location and more sightings about 1-2 km to the south. This was confirmed when two recognizable whales first seen at the original location were later seen about 2 km farther south. However, the movements of whales--at least while they were at the surface--were at the usual slow to moderate speeds.

No conspicuous change in behavior occurred when 'Mariner' ceased shooting 6 km beyond the whales. The bowheads were still surfacing and diving, and moving at slow to medium speed. During the 108 min of post-seismic observations, whales brought mud to the surface during only 1 surfacing, 40 min after the end of seismic noise.

Surfacing, Respiration and Dive Characteristics.--We compared behavior during the three main phases of the experiment: (a) pre-seismic, with 'Mariner' approaching at range 9-7.5 km; (b) seismic, range 7.5 to 1.5 to 6 km; and (c) post-seismic, range 6-11 km. The duration of surfacing and number of blows per surfacing were both similar during the three main phases of the experiment ($p>0.1$ in each case; Fig. 8 and Table 16). However, mean blow interval was significantly shorter during the seismic phase than during the pre- or post-seismic phases ($p<0.001$; Fig. 8 and Table 16). Few data concerning dive duration were recorded, but there was a hint that dives were shorter in the seismic than in the post-seismic phase (Fig. 8).

Mean blow interval was significantly lower when the airgun array was firing, but the difference was small--11.7 s in the pre-seismic phase vs. 10.6 s in the seismic phase (Fig. 8, Table 16). Interestingly, the reduction seemed to begin when the approaching ship was about 8 km away, before the airgun array began firing (Fig. 10). Engine noise from the ship was already being detected by the sonobuoy near the whales at that time.

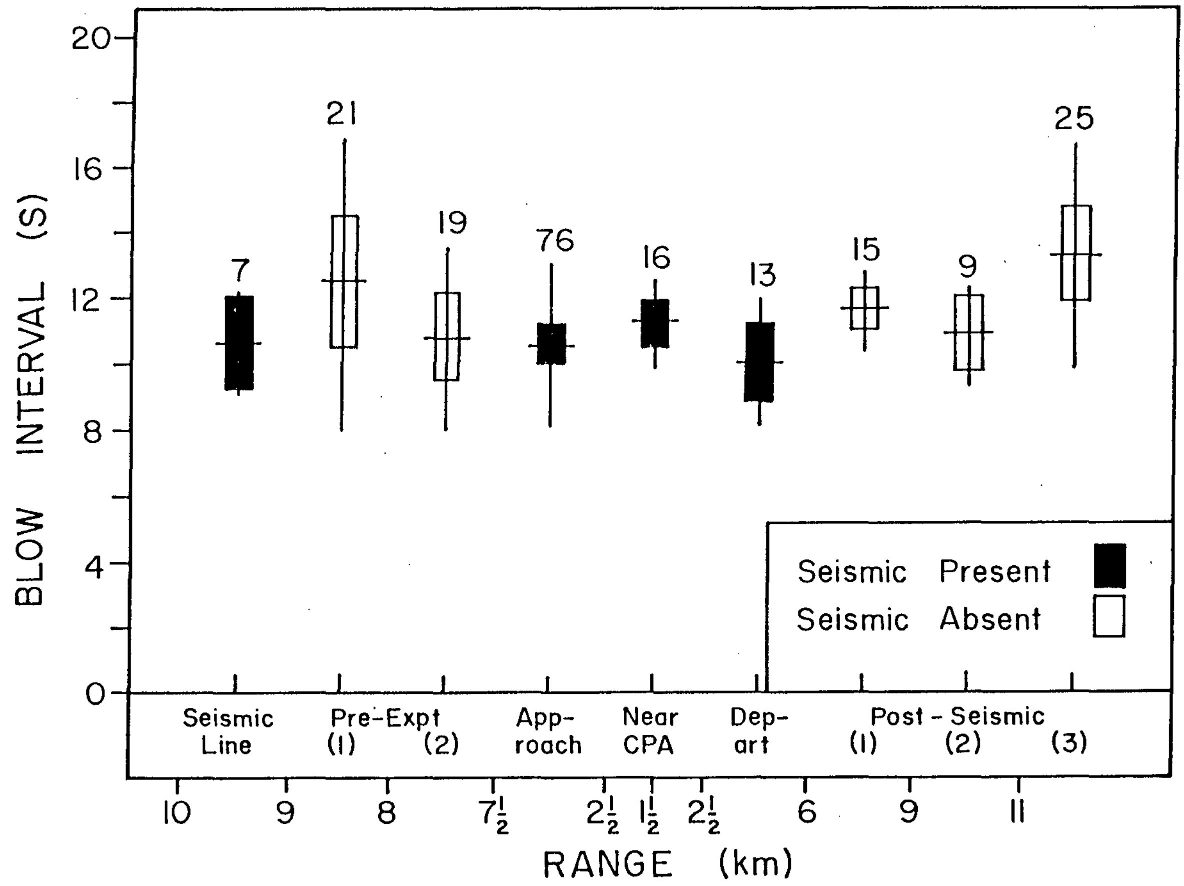

FIGURE 10. Blow intervals of bowheads at various times during the experiment with, 'GSI Mariner', 16 Aug 1984. Times (and ship-whale distances) are divided into more categories here than in Fig. 8; see Table 20 for definitions of these categories. No calves present. Presentation as in Fig. 6.

Orientation of Whales.--Predominant orientations of the whales changed in ways that can be related to the movements of 'GSI Mariner' (Fig. 11). These data concern orientations while whales were at the surface. Repeated sightings of the two recognizable animals provided our only data on orientation of underwater movements (see above).

Initially the whales were oriented mainly to the northwest and north (Fig. 11A). As the ship approached from 7.5 km west to 2.5 km northwest of the whales, firing her airgun array, the bowheads oriented mainly northeast and east, away from the ship (Fig. 11B). When the ship was near CPA, ≤2.5 km to the NW, N or NE, the whales oriented mainly SW. This was not directly away from the ship, but rather in the opposite direction to the ship's track (Fig. 11C). The few orientations recorded while the ship was 2.5 to 6 km to the east were directed generally south (Fig. 11D).

In the post-seismic period, there was a tendency for northward orientation (Fig. 11E). The aforementioned observations of general activities and recognizable individuals showed that some whales moved south as the ship passed. Northward movement would tend to return them toward their original locations.

Other Behavioral Variables.--Speeds of bowheads were slow to moderate during most surfacings in all phases of the experiment (Table 19). Sample sizes for turns and pre-dive flexes were small, but there was no evidence of any change. Bowheads raised their flukes above the surface during 82% of 11 dives in the pre-seismic phase, but in only 47% of 30 dives in the seismic phase (chi^2 = 4.04, $p<0.05$). This apparent effect, unlike the reduction in blow intervals, did not become evident until the ship was near CPA (Table 20).

Bowheads brought mud to the surface during 7 of 16 surfacings in the pre-seismic period and 5 of 21 surfacings as 'Mariner' fired her airguns while approaching from 7.5 to 2.5 km away (chi^2 = 1.65, df = 1, $p>0.1$). The last case was at range 3 km. Mud was not seen during any of the subsequent 13 surfacings while 'Mariner' was firing at ranges 2.5 to 1.5 to 6 km (chi^2 = 7.50, df = 1, $p<0.01$ for comparison with pre-seismic period). Thus, this effect also became evident only when the ship was near CPA. Mud was seen during only 1 of 19 surfacings (5%) in the post-seismic period.

Only two calls were detected when 'GSI Mariner' was 9 to 7.5 km away and not shooting, and no calls were detected during the shooting or post-seismic periods.

Summary.--Bowhead whales reacted to close approach by an operating seismic vessel, but not in an abrupt or conspicuous manner. There was no obvious change in activities when the ship began to fire its airgun array 7.5 km away. Near-bottom feeding ceased when the ship was 3 km away, and was not seen again until 40 min after seismic noise ceased. Whales tended to orient away from the ship or, near CPA, in the opposite direction to the ship's track. Orientation away from the ship began when the airguns started to fire, 7.5 km away.

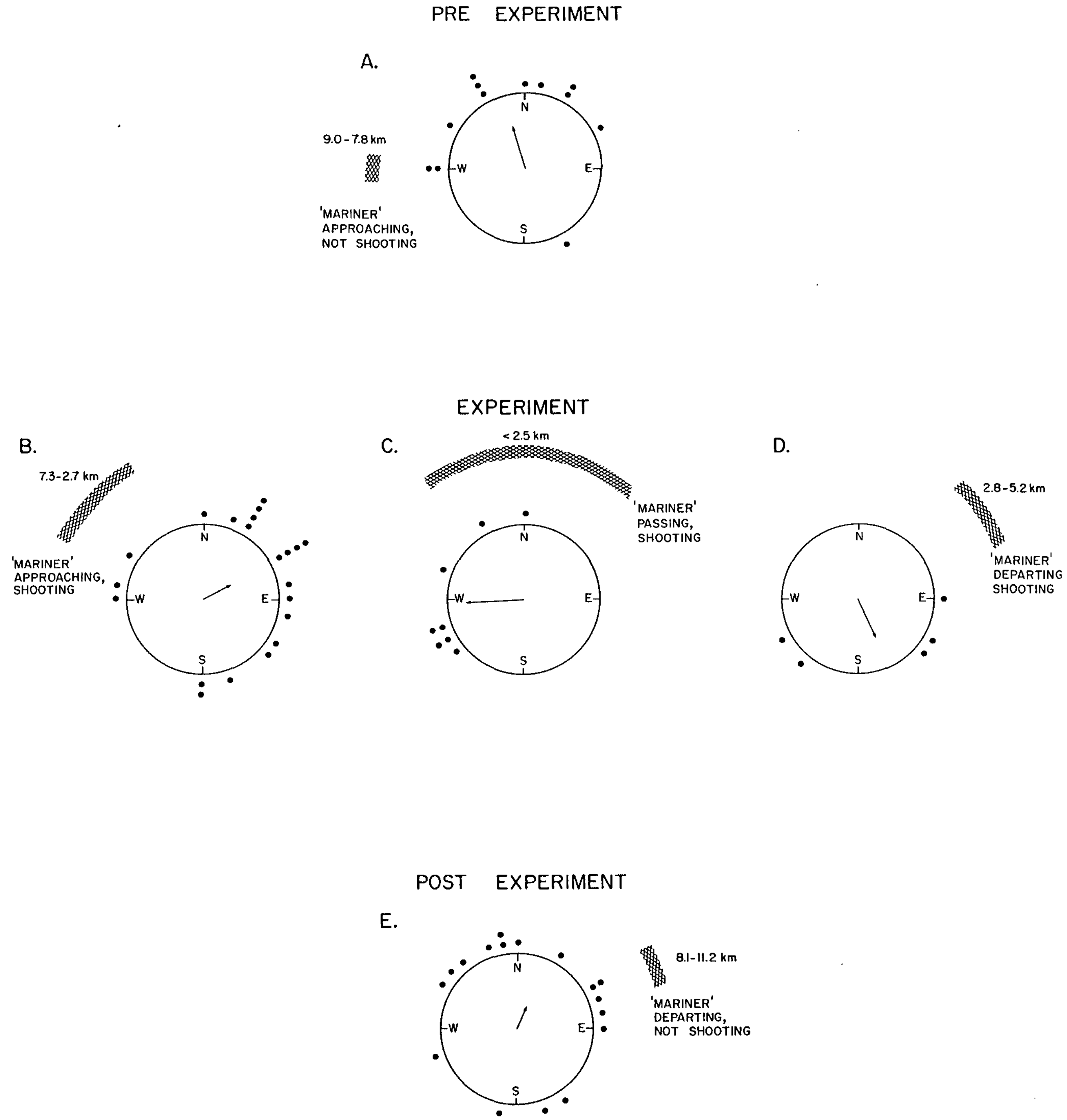

FIGURE 11. Compass orientations of bowheads during various phases of the experiment with 'GSI Mariner', 16 Aug 1984. Each symbol represents the compass heading of one whale during one surfacing, as observed from the observation aircraft. The hatched band represents the bearing of the ship from the whales.

Table 19. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed during full-scale seismic experiment, 16 August 1984. Each surfacing by a whale is a unit of observation.

	Speed				
	Zero	Slow	Moderate	Fast	Total
Pre-Seismic[a]	1	3	5	0	9
Seismic[b]	2	13	12	1	28
Post-Seismic[c]	1	6	3	0	10

	Turn			**Pre-Dive Flex**			**Pre-Dive 'Flukes-Out'**		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Pre-Seismic[a]	5	0	5	6	3	9	2	9	11
Seismic[b]	9	2	11	14	5	19	16	14	30
Post-Seismic[c]	3	1	4	10	2	12	6	9	15

[a] 'GSI Mariner' approaching, 9 to 7.5 km away, not shooting.
[b] 'GSI Mariner' shooting, 7.5 to 1.5 to 6 km away.
[c] 'GSI Mariner' underway or hauling gear aboard, 6-11 km away.

Table 20. Occurrence of fluke-out dives at various times during the full-scale seismic experiment, 16 Aug 1984. Each surfacing by a whale is a unit of observation.

Phase	Range (km)	No Flukes	Flukes	Total	Percent Flukes
Finish seismic line	10-9	1	3	4	75
Pre-expt, first 15 min	9-8	2	4	6	67
Pre-expt, remainder	8-7.5	0	5	5	100
Seismic expt, approaching	7.5-2.5	7	12	19	63
Seismic expt, near CPA	<2.5	4	2	6	33
Seismic expt, departing	2.5-6	5	0	5	0
Post-seismic, first 15 min	6-9	1	3	4	75
Post-seismic, next 15 min	9-11	3	2	5	40
Post-seismic, remainder	7-11	2	4	6	67

Two recognizable whales moved about 2 km away from the ship's path. Speeds were slow to moderate in all phases of the experiment. Aside from orientation and near-bottom feeding, the only behavioral variables in which changes were found were blow intervals and frequency of fluke-out dives; both were significantly reduced during the seismic period. Slightly reduced blow intervals first became evident when the approaching ship was 8 km away, before the airguns began firing but while engine noise was clearly detectable near the whales. The frequency of fluke-out dives did not decrease markedly until the ship was within about 2.5 km, well after the airguns began firing.

Discussion

Results of This Study

Short-term behavioral reactions of bowheads to seismic exploration were surprisingly mild, considering the high intensity of the noise pulses at distances up to many kilometres from a seismic vessel. Our opportunistic observations 6-99 km from active seismic vessels showed that bowheads engaged in normal activities as close as 6 km away (received noise levels up to 158 dB//1 μPa). These activities included surfacing and diving, calling, and sometimes travelling, socializing or feeding.

Surfacing-respiration-cycles may have been altered subtly in the presence of noise from distant seismic vessels. Our inconsistent evidence was as follows:

1. Durations of surfacings and dives and number of blows per surfacing all tended to be reduced with seismic noise. Intervals between successive blows tended to be greater with seismic noise. In the case of the uncontrolled opportunistic observations, it was impossible to be sure that these weak trends were really attributable to the seismic noise and not to other factors varying simultaneously.
2. Similar weak trends were evident during airgun experiments (Table 12D), when the same whales were observed before, during and after the airgun fired, and when most other factors were constant. This strengthens the evidence that the trends were attributable to seismic noise.
3. Multivariate analyses did not either confirm or rule out the existence of these trends after allowing for effects of other intercorrelated variables.
4. Such trends were not evident during our controlled test with a full-scale seismic vessel, when blow intervals were shorter, not longer, with seismic noise.

Based on our data alone, there was no proof that distant seismic noise affected surfacing-respiration-dive cycles. However, the trends were consistent with results obtained within a few kilometres of seismic vessels in four experiments conducted by Ljungblad et al. (1985, pers. comm.). Thus, our results concerning surfacing-respiration-dive cycles probably were indicative of weak and barely detectable effects of noise from distant seismic vessels.

Our opportunistic observations 6-99 km from seismic boats provided no unequivocal evidence that bowheads oriented away. The same was true during three single-airgun experiments at ranges 3-5 km, when noise levels reaching the whales were at least 118-133 dB//1 μPa. However, bowheads did tend to orient away during two additional single-airgun experiments at ranges 0.2-4.5 km (received levels at least 124-134 dB; sometimes considerably greater). In the brief test at range 0.2-1.2 km, the limited data suggested that bowheads reacted strongly when firing began; they moved away at increased speed. During the test with a full-scale seismic vessel, bowheads also moved away, although at only slow to moderate speed. The whales started to orient away when the airgun array began to fire 7.5 km away.

These results provide the first evidence that some bowheads move away from sources of intense seismic impulses. In the full-scale test, it is not known whether whales reacted to the seismic impulses or to the vessel's engine noise. However, in the two airgun experiments that demonstrated avoidance, the airgun was deployed from a quiet, anchored vessel. Thus, bowheads apparently can determine the direction from which intense noise impulses are arriving, and move in the opposite direction. However, strong avoidance reactions do not appear to occur unless the seismic impulses are very intense.

Certain other behavioral variables sometimes differed significantly in the presence and absence of seismic noise. Opportunistic data suggested that there were lower frequencies of turns and pre-dive flexes with seismic noise. The scarcity of pre-dive flexes and the tendency for shorter dives with seismic noise may have been related; in undisturbed bowheads, pre-dive flexes tend to be followed by long dives (Würsig et al. 1985b). The full-scale seismic experiment suggested that fluke-out dives became less frequent when the vessel was within 2.5 km. In the absence of consistent trends, it is uncertain whether these differences were directly attributable to seismic noise. However, bowheads clearly ceased bringing mud to the surface during the full-scale experiment when 'GSI Mariner' approached within 3 km.

Comparisons with Other Studies

Bowheads in the Alaskan Beaufort Sea.--Personnel from the U.S. Naval Ocean Systems Center (NOSC), working in the Alaskan Beaufort Sea and the western part of the Canadian Beaufort, have reported opportunistic observations of bowheads as close as 3 km from operating seismic vessels (Ljungblad et al. 1980, 1982a, 1984b; Reeves et al. 1983, 1984). Most NOSC observations were obtained slightly later in the season (Sept-early Oct) and slightly farther west than our observations. They, like we, have heard bowhead calls in the presence of seismic noise, and during opportunistic observations have found no clear indications of whales moving away from approaching seismic boats.

Reeves et al. (1983, 1984) described bowheads 'huddling' in a compact group in the presence of noise from 'GSI Mariner' 33 and 21 km away. However, it was not certain that this behavior was in response to seismic noise. Reeves et al. did not see such behavior when they observed bowheads closer to seismic vessels. We have not observed this behavior in either the presence or the absence of seismic noise.

Average surface times in Alaskan waters during 1982 were marginally higher in the presence of seismic noise, contrary to most of our results from the Canadian Beaufort Sea (Reeves et al. 1983, 1984). However, they found increased surface times on only 1 of 3 days when whales were watched both with and without seismic noise, and could not determine whether the apparent difference was attributable to the seismic noise. The few data obtained with seismic noise in 1983 suggested that mean number of blows per surfacing was lower and mean blow interval higher with seismic noise (Ljungblad et al. 1984b). Both 1983 trends were consistent with the weak trends that we observed.

Important information about seismic effects was obtained in Alaskan waters in 1984, including both opportunistic observations and four seismic experiments. Detailed results are not yet available, but there was evidence of avoidance reactions when seismic ships were 3.5-6.7 km from bowheads (Ljungblad et al. 1985). The vessel to which a reaction was first noted at range 3.5 km used a relatively low-intensity noise source; reactions to the three vessels with large arrays of airguns were noted at 4.4-6.7 km. There was also a consistent tendency for reduced surface and dive times and for fewer blows per surfacing when seismic vessels were nearby (D. Ljungblad, pers. comm.). These tendencies were consistent with our pooled opportunistic observations (e.g. Fig. 6) and with the weak trends found in our airgun experiments. However, we did not find these tendencies during our one experiment with 'GSI Mariner'.

Gray Whales Migrating Past California react to seismic impulses, but only when received levels are high (Malme et al. 1983, 1984). This study, conducted by Bolt Beranek & Newman (BBN), tested reactions to a full-scale seismic vessel at 1-90 km range, and to a towed and stationary 100 in^3 airgun at ranges from <1 km to 15 km.

The 1983 BBN study showed that average pulse pressure levels of $\geq$160 dB//1 µPa produced clear behavioral reactions: the whales generally slowed, turned away from the noise source, and increased their respiration rates. They sometimes moved closer to shore, or into a 'sound shadow' created by topography. Reactions to the full-scale array seemed most pronounced when it was oriented broadside to the whales, the horizontal direction in which most energy was radiated. The $\geq$160 dB average pulse pressure level corresponded to peak levels $\geq$170 dB, and to ranges <5 km from the full-scale vessel and <1 km from the single airgun (Malme et al. 1983, p. 9-2).

The 1984 BBN study showed that some gray whales began to deflect their tracks when as much as 2 or 3 km from the 100 in^3 airgun. However, by another measure the radii of 10%, 50% and 90% avoidance were 750 m, 400 m and 100 m (effective received levels 164 dB, 170 dB and 180 dB, respectively). In the situation studied by Malme et al., these levels were equivalent to those found 2.8, 2.1 and 1.2 km from a full-scale seismic vessel, assuming source and receiver depths of 50 m. Assuming a typical 6 m depth for a seismic array and our standard receiver depth of 18 m, the 164, 170 and 180 dB levels would be found 550, 365 and 145 m from the 100 in^3 airgun and 1.35, 1.13 and 0.80 km from the full-scale seismic vessel, according to the equation of Malme et al. (1983, p. 8-21).

Ranges and Noise Levels Where Effects Are Evident

The three studies (LGL, NOSC, BBN) of two whale species all show that whales tend to move away from a full-scale seismic ship when seismic impulses are very strong (ship within about 4.4-7.5 km; received levels >160-170 dB//1 µPa). No unequivocal reactions to seismic ships have been demonstrated at ranges exceeding about 7.5 km, even though strong noise impulses propagate much farther. However, in both studies of bowheads there sometimes were hints of subtle effects on surfacing-respiration-dive cycles at ranges far beyond 5 km. (In the gray whale study, these variables were not studied in detail.) The 'huddling' seen at ranges up to 33 km in the NOSC study may also have been a reaction to seismic noise, but was not seen in our 5-yr study.

Results of single-airgun experiments have been consistent with observations near full-scale seismic ships. In both bowheads and gray whales, avoidance was found at close ranges (primarily <2 km) where noise levels were high. At greater ranges, no conspicuous effects were found. However, in bowheads there may have been subtle alterations in surfacing and respiration behavior at ranges 2-5 km, where received levels were at least 118-133 dB.

Levels of Seismic Noise Tolerated by Whales

Our results and those from Alaska show that bowheads do not exhibit strong, consistent reactions to seismic noise pulses at levels as high as 150 dB//1 µPa, which is about 50 dB above the ambient level in the 20-1000 Hz band. Similarly, gray whales reacted clearly to seismic noise only when received levels were at least 160-170 dB, about 60-70 dB above ambient levels in the 50-315 Hz or similar band (Malme et al. 1983, 1984). These figures and signal-to-noise (S/N) ratios are not exactly comparable because of differences in measurement procedures. In general, however, it is clear that bowhead and gray whales sometimes tolerate remarkably strong noise pulses.

In contrast, bowheads react to approaching boats when their received noise levels are much lower. For example, when bowheads reacted to the crew boat 'Imperial Adgo' idling 3-4 km away with propellers disengaged (Richardson et al. 1985b), the received boat plus ambient noise was 107 dB//1 µPa in the 20-1000 Hz band, only 3 dB above ambient (C.R. Greene, unpubl. data). Similarly, we found weak reactions to drillship noise at levels of about 100-113 dB (this study). Malme et al. (1983, 1984) found that some gray whales react to industrial noises at S/N ratios as low as 0 dB in the 1/3 octave band of maximum signal level.

Why are whales more tolerant of strong seismic pulses than of certain continuous industrial noises? One probable factor is that seismic pulses are brief. Perhaps baleen whales, like humans, perceive the noisiness of an impulsive sound to be much lower than that of a continuous sound of equivalent received level (Fidell et al. 1970).

A related factor is that typical seismic impulses mask other sounds for only a fraction of a second every 10-15 s. In contrast, continuous industrial noise, even at a considerably lower level, may mask other sounds completely. Masking has the potential to interfere with detection of environmental sounds and with acoustic communication, particularly communication over long ranges

(Payne and Webb 1971; Richardson et al. 1983b). However, it is not known how often weak (and therefore maskable) sounds from distant sources are important to whales.

The minimum level of noise impulses necessary to cause physical damage to a bowhead's auditory system is not known. However, intermittent low-frequency noise at levels of 160-170 dB probably is not harmful, since whales presumably tolerate calls by conspecifics nearby. Source levels of baleen whale calls are often 180 dB//1 µPa-m (Thompson et al. 1979), and possibly as much as 196-200 dB in bowheads, based on a received level of 156 dB at 100-150 m (Clark and Johnson 1984). If bowheads emit intense calls when other bowheads are nearby, received levels would exceed 160 dB at distances up to 10 and possibly 100 m.

Most measurements of seismic sounds have been taken at 9-18 m depth (Greene 1984a, 1985). Whales are exposed to those levels of noise when they dive. However, most behavioral data come from whales visible at or very near the surface (exceptions: data on call rates and dive durations). Within a few metres of the surface, received levels of seismic pulses are reduced by several decibels because of pressure release effects (Greene 1984b, 1985). Received levels of seismic pulses were 4-10 dB less at 3 m than at 9 m (Greene 1985).

Thus, whales at the surface are exposed to lower levels of seismic noise than are present a few metres below. The difference could be important when whales remain at the surface for prolonged periods. For example, whales that were skim feeding during our airgun experiment on 18 Aug 1981 presumably were rarely exposed to the level of airgun noise received by our sonobuoy. Similarly, the whale engaged in 'log play' 24-39 km from a seismic vessel on 1 Aug 1982 did not dive during 1.6 h of observations (Würsig et al. 1983). It probably was not exposed to noise levels quite as high as those present deeper in the water at that range.

The difference of several dB between received levels at 3 and 9 m depth is significant, but small relative to measured S/N ratios (up to 50 dB) at 9 or 18 m depth during most of our observations of bowheads in the presence of seismic or airgun noise. Thus, seismic pulses were presumably detectable to whales at 3 m depth during most observations. The effective receiver depth for a bowhead at the surface is unknown. However, the ventral surface of the whale would be >3 m below the water's surface. Furthermore, most whales observed in the presence of seismic noise dove at least occasionally, and were exposed to the measured noise levels during dives.

Because received levels of seismic noise are reduced near the surface, whales exposed to seismic noise might spend more time at the surface or might dive for shorter periods. Some of our observations are consistent with this hypothesis (e.g. prolonged log play at the surface and reduced average dive duration with seismic noise; cessation of near-bottom feeding during 'GSI Mariner' experiment). Ljungblad et al. (pers. comm.) have also observed reduced dive durations by bowheads when seismic vessels were nearby. However, whales often dove even with strong seismic noise, even when 'GSI Mariner' was near its closest point of approach 1.5-2.5 km away. Thus, the reduced tendency to dive into the zone of greater received noise levels is slight, at least for seismic vessels more than a few kilometres away.

REACTIONS OF BOWHEADS TO DRILLING

Offshore drilling can be from artificial or natural islands, platforms of various types, and drillships. In the Canadian Beaufort Sea, **artificial islands** constructed of uncontained sand and gravel have been used to drill in waters as deep as 18 m. Since 1981, **caisson-retained islands** and self-contained drilling caissons have been used to drill in waters 12-33 m deep. The former are steep-sided rings filled by sand; the latter are steel or concrete structures ballasted down onto underwater berms. Drilling from artificial islands and caissons can occur at any time of year. **Drillships,** in contrast, operate only during summer or autumn when ice is absent or thin. Each year since 1976, 3 or 4 ice-strengthened conventional drillships have drilled in the Canadian Beaufort Sea, usually in water 25-75 m deep. In 1983 and 1984, a new circular drilling vessel, 'Kulluk', was also operating.

To date, there has been much less drilling in the Alaskan than in the Canadian Beaufort Sea. In Alaska, most offshore wells have been on uncontained artificial islands or natural barrier islands. However, drilling from a concrete caisson (CIDS) began in the Alaskan Beaufort Sea in 1984, and industry hopes to begin using drillships there in 1985.

All offshore drilling produces underwater noise, mainly below 1000 Hz, although noise intensity and characteristics depend on type of platform (Richardson et al. 1983b; Greene 1985). Besides the noise emanating from the island, caisson or drillship, support traffic also creates noise. Drillsites in the Canadian Beaufort Sea are supported by helicopter traffic from shore. During the open water season, support vessels are often present near islands and caissons. At least one stand-by vessel is stationed near each drillship. Underwater noise from drilling per se usually cannot be distinguished from that produced by other machinery and nearby vessels (Greene 1985).

Baleen whales have been seen near drillships and drilling platforms (Kapel 1979; Gales 1982; Sorensen et al. 1984). However, these authors did not provide systematic information about distances of closest approach or behavioral reactions to offshore drilling.

Malme et al. (1983, 1984) tested reactions of migrating gray whales to underwater playbacks of noise from a drilling platform, semi-submersible drillship, and conventional drillship. For each noise type, gray whales slowed as they approached the playback site. Whales first reacted at ranges where drilling sounds were barely detectable, i.e. S/N ratios of 4 dB or less (Malme et al. 1983, p. 8-3). At closer ranges, whales altered course slightly to avoid the playback site. Malme et al. (1984, p. 9-6) estimated that 50% of migrating gray whales would alter course if 1.1 km from the actual drillship (broadband received noise level 117 dB//1 µPa). Estimated 50% avoidance ranges for the drilling platform and semi-submersible were <50 m, reflecting their lower noise levels. These estimated avoidance ranges were based on playback tests; Malme et al. did not study gray whales near actual drillsites.

We obtained two types of data concerning reactions of bowheads to drilling: (1) opportunistic observations of bowheads near drillsites, and (2) controlled tests of reactions to underwater playbacks of recorded drillship noise. We also recorded and analyzed underwater noise near drilling caissons and drillships (Greene 1982, 1983, 1984a, 1985). For the playbacks, we used

Greene's (1982) recording of noise from the conventional drillship 'Canmar Explorer II' drilling in the Canadian Beaufort Sea. Malme et al. (1983, 1984) used the same recording for their playbacks near gray whales.

Methods

Observations near Drillsites

Routes of our observation aircraft were chosen to pass, when practical, near drillships and caissons drilling in the eastern Beaufort Sea. Four or five drillships were operating during each of our five field seasons. Drilling from caisson-retained islands occurred for only a few days during two field seasons, and there was no drilling from uncontained artificial islands during our field seasons. (Most drilling from artificial islands and caissons is in autumn, winter and spring.) When bowheads were seen near drillsites, a sonobuoy was dropped to record industrial and bowhead sounds. Behavioral observations were obtained by our usual methods for aerial observations. In addition, industry personnel were requested to report promptly any bowhead sightings near drillsites.

Drillship Noise Playback Experiments

On six occasions in 1982-83, we broadcast recorded drillship noise into the water near bowheads (Table 21). Playbacks were from MV 'Sequel', whose engine was off during experiments. The 1982 tests were in water 125-150 m deep northeast or east of Herschel Island; the 1983 tests were in water 12-36 m deep near the Yukon coast southeast of Herschel Island (Fig. 1). Whale behavior before, during and after playbacks was observed from the Islander aircraft circling at 457 m or 610 m a.s.l.

The recording of drillship noise used in all playbacks was made on 6 Aug 1981 at a point 185 m from 'Canmar Explorer II', which was drilling at depth 2031 m below water 27 m deep; hydrophone depth was 9 m (Greene 1982). At the recording location, the received level was 134 dB//1 µPa in the 20-1000 Hz band, with a strong (128 dB) tone at 275-278 Hz.

The sequence of activities preceding an experiment was as follows. 'Sequel' maneuvered slowly (5.5 km/h) to a point about 1 km from a group of bowheads and the motor was stopped. The observation aircraft arrived overhead either before or after 'Sequel' was in position (Table 21). Control 'pre-playback' observations began 30 min or more after 'Sequel' stopped. We intended the control phase to last 45-60 min, but it was usually longer because of logistical problems.

Drillship noise was broadcast by a U.S. Navy J-11 projector at 9 m depth, powered by a 250 W Bogen MT250 amplifier operating from four 12 V batteries. The sound level gradually increased for 10-13 min, then was constant for 10 min (1982) or 20 min (1983), and then gradually decreased for 10 min. This approach was used to avoid a sudden onset of sound at peak intensity and the startle response that this might evoke. We hoped that the gradual change in level would roughly simulate what a bowhead would encounter as it approached a drillship.

Table 21. Circumstances of drillship noise playback experiments off the Yukon coast, 1982-83.

	16 Aug '82	18 Aug '82	19 Aug '82	17 Aug '83[i]	18 Aug'83[i]	22 Aug '83[i]
Location - N. Lat.	69°43'	69°36'	69°41'	69°18'	69°26'	69°15'
- W. Long.	138°13'	138°22'	138°32'	138°17'	138°32'	137°54'
Water Depth (m)						
Boat	150	125	150	18	15	36
Whales	150	125	150	16	12	32
Sea State	1-2	1-2	1	1	1	3
Aircraft Altitude (m)	457	457	457	457	610	610
Durations (min) of						
Post-Boat	30	-	20	28	-	-
Quiet Boat	52	159[a]	94[a]	-	69[b] + 26	45
Playback, incr. level	13	10	9[c]	10	10	10
Playback, peak level	10	10	-	20	20	20
Playback, decr. level	10	10	-	10	10	10
Post-playback	7	11	34	39 + 63[b]	57	104
Time (MDT) of Observ.	21:25-23:27	15:21-18:41	10:22-12:59	19:11-22:01	11:27-14:39	13:36-16:45
'Sequel' Quiet After	21:25	09:10	c. 10:12	19:11	17 Aug, 23:42	11:35
Source Level of Sound during Peak Period (dB//1 μPa-m)	155	164	157	162	164	164
Approx. Distances (km),						
Projector to Sonobuoy	2	2	1.5	?[d]	1.2	1.2
Projector to Whales	2-4.5	3-6.5	2-4.5	0.7-3.0	0.4-1.7	0.8-1.8
Noise level at Sonobuoy (dB//1 μPa)						
Ambient, 20-1000 Hz[e]	84	99[f]	92	91[g]	78	93
Playback, 20-1000 Hz[h]	100	110	99	-	108-112	112-113
Playback, 275 Hz tone[h]	94	105	92	-	104-109	107-110
Approx. No. of Whales	5-7	8+	9+	10+	13	10
Activity of Whales	Slow travel; some faster travel during playback	Slow to rapid travel; some aerial activity and socializing	Slow travel, nursing; calf moves along windrow of debris	Mostly lone whales with unknown behavior; dispersing before & during playback	Some socializing; some alone. Mostly medium or slow forward movement	Mostly lone whales with little forward movement; some brief socializing

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[a] Playback delayed because calf present.

[b] Minutes of observation of whales near 'Sequel' (<3 km away) but not the whales observed during the playback.

[c] Playback terminated early because calf present.

[d] Sonobuoy from previous flight still transmitting; precise location unknown.

[e] 20-1000 Hz band, immediately before and/or after playback.

[f] Seismic pulses with intensities up to 133 dB//1 μPa were present at several-second intervals throughout the 18 Aug '82 experiment; 99 dB was the ambient level between seismic pulses.

[g] Measured with a hydrophone at depth 9 m below 'Sequel'.

[h] The levels for the 20-1000 Hz band and for the 275 Hz tone are given for the period of peak playback level.

[i] Most whales in the area where this experiment was done were immatures (Würsig et al. 1985b).

The source and received levels of projected drillship sound were measured. Source level was monitored by a hydrophone 1.9 m (1982) or 1.0 m (1983) in front of the projector. This monitor hydrophone also allowed us to limit power output to avoid distortion. Peak source levels were 155-164 dB//1 µPa-m (Table 21). During 5 of 6 experiments, ambient and drillship noise reaching the bowheads was recorded via sonobuoys dropped near the whales, 1.2-2.0 km from 'Sequel'. The closest bowheads were, during the playback phases of the six tests, 0.4-3 km from 'Sequel' (Table 21).

For purposes of data analysis, a 'mid-playback' period was defined. It began 5 min into the increasing level phase and ended 5 min before the end of the decreasing level phase. Thus, observations when the projected noise level was weak and possibly inaudible to the whales were excluded. At the sonobuoy locations, drillship noise was detectable to the human ear throughout the mid-playback phase of each experiment.

In 1983 we monitored behavior for longer periods after the playbacks ended than was possible in 1982 (39-104 min in 1983; 7-34 min in 1982). In 1982, post-playback observations were curtailed by limited aircraft endurance or approach of fog. In each case 'Sequel' remained quiet throughout the period of post-playback monitoring. In our analyses, data from the first 30 min after playbacks ended ('post-playback' phase) were distinguished from subsequent observations ('post-control').

Of the six playbacks attempted, only four were successful. On 19 Aug 1982, the playback was aborted 9 min into the increasing level phase when a bowhead calf appeared about 2 km from 'Sequel'; permit restrictions prevented tests on calves. On 17 Aug 1983, the experiment was in shallow water <1 km off the Yukon coast. The whales were already dispersing before the playback began, probably in response to noise from our observation aircraft circling at 457 m a.s.l. As discussed earlier, bowheads in shallow water seem especially sensitive to aircraft noise. During subsequent playback experiments in shallow water, the aircraft circled at 610 m a.s.l. to avoid this problem. Except where specifically noted, data from the two unsuccessful tests are not presented below.

Results

Observations near Drillsites

We saw bowheads within 4-20 km of drillships on several days in August of 1981-84. Some bowheads 8-20 km from a drillship were also exposed to sounds from various combinations of seismic exploration, helicopter and boat traffic, and island construction. Despite this, whales were present in the area for at least a few days (Fraker et al. 1982; Richardson et al. 1984, 1985b).

On five occasions when bowheads were seen 4-20 km from drillships (Table 22), the drillships and their standby vessels were the only sources of possible disturbance. General activities of these bowheads seemed characteristic of undisturbed bowheads (Table 22). The whales were not heading away from the drillship on any of these five occasions. Bowheads seen 4 km from 'Explorer II' were socializing even though exposed to strong drillship noise. The apparent lack of calling by whales 4 km from the ship is noteworthy, since socializing bowheads usually call frequently (Würsig et al.

Table 22. Circumstances of observations of bowheads near drillships, 1981–82. These were the only observations when the drillship was the only source of potential disturbance.

	23 Aug '81	23 Aug '81	11 Aug '82	31 Aug '82	31 Aug '82
Location – N. Lat.	70°04'	70°05'	70°50'	70°28'	70°27'
W. Long.	134°54'	134°28'	134°18'	136°51'	136°30'
Water Depth (m)	31	23	90	550	150–390
Sea State	1	1	3–4	1–2^a	2
Aircraft Altitude (m)	457–610	610	457	457^b	457
Duration of Obs. (min)	62	63^c	26	113^b	194
Drillship					
Identity	Expl. II	Expl. II	Expl. IV	Expl. III	Expl. III
Range (km)	15–20	4	17	18–19	10–12
Activity	Drilling	Drilling	Not drilling	Drilling	Drilling
Detectable^d	Yes	Yes–strong	Yes–weak	No	No
Approx. No. of Whales	8+	3	1+	1	2
Activity of Whales	Some echelon feeding & socializing; calling	Mainly socializing; no calls detected	Unknown; some calling	Slow to medium speed travel; calling	Long dives; slow to medium travel; some calling

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[a] No whitecaps but heavy swell.
[b] Subsequent observations from 305 m a.s.l. are not considered here.
[c] Excludes subsequent observations when boats nearby.
[d] Industrial noise detected by sonobuoy dropped near whales.

1985b). However, faint calls might have been present but not detected because of the high noise level.

Surfacing, respiration and dive characteristics of bowheads near drillships were usually within the ranges for undisturbed whales (see Richardson et al. 1983c, p. 195–8 for details). The one exception involved two whales 10–12 km from 'Explorer III' on 31 Aug 1982. Their dive times were consistently long (23.4–31.0 min). However, there was no evidence that the long dives were related to the proximity of the drillship. Indeed, a sonobuoy near these whales did not detect drillship sound.

Industry personnel reported sightings of bowheads near 'Explorer IV' and 'Explorer III' on several occasions from mid-July to early August 1980. The distance of the whale(s) from the drillship was estimated for 7 sightings as 0.2–5 km. In 1982 and 1983, industry personnel reported 3 sightings of single bowheads near drillships, in each case at an estimated distance of 3.7 km (2 n.mi.). We probably did not learn of all sightings by industry personnel.

There was no drilling from uncontained artificial islands and little from caissons during our field seasons. We saw no bowheads within 20 km of caissons on which drilling was underway. However, personnel at Tarsiut caisson-retained island reported two sightings during a drilling period, one only 0.2 km away. Two more bowheads were reported about 0.3 km away after drilling ended. Tarsiut was located at 69°54'N, 136°20'W, in 23 m of water. Sound levels near Tarsiut and its attending support vessels during drilling are unknown. However, noise levels were quite high during periods without drilling: e.g. 121-130 dB//1 μPa in the 20-1000 Hz band at range 1.1 km on one day; 119-125 dB at 0.46 km another day (Greene 1985).

In summary, on several occasions we saw bowheads well within the zones ensonified by drillships. These whales were engaged in normal activities and were not moving away. Industry personnel also reported seeing bowheads close to drillships and to a caisson-retained island.

Drillship Noise Playback Experiments

Sound Levels to Which Bowheads Were Exposed.--On 16 and 18 Aug 1982, the closest whales were 2-3 km from the projector when the playback began; the sonobuoy was 2 km away (Table 21). Thus, noise levels received by the closest whales were similar to those at the sonobuoys. At 2 km range, the broadband (20-1000 Hz) noise level during playbacks exceeded that before and after playbacks by 16 and 11 dB on 16 and 18 Aug 1982, respectively (Table 21). Signal to noise (S/N) ratios and levels received by the most distant whales, 4.5 and 6.5 km from the projector, were unmeasured but would have been several decibels lower. On 18 Aug 1982, noise pulses from a seismic vessel 60-73 km away were detectable throughout both the control and playback periods at received levels up to 133 dB//1 μPa. However, ambient, playback and bowhead sounds were readily detectable in the periods between seismic pulses.

On 18 and 22 Aug 1983, the bowheads were 0.4-1.7 km and 0.8-1.8 km from the projector, and the sonobuoys were amidst the whales 1.2 km from the projector (Table 21). At 1.2 km range, the broadband S/N noise level during playbacks averaged 32 and 19.5 dB, respectively. Drillship noise levels and S/N ratios at half and twice the 1.2 km range were probably about 3-6 dB higher and lower, respectively.

Noise received at the sonobuoys during drillship playbacks sounded, to the human ear, similar to the original recording of drillship noise. The strong 275 Hz tone and some other less prominent tones in the projected sound were also evident in the received signals (Fig. 12; Greene 1982, 1983, 1984a). However, during some experiments, especially the 1983 tests in shallow water, the spectrum of the received sound had been modified considerably by differential attenuation of certain frequencies. This is a natural phenomenon; sound emanating from an actual drillship would also be affected by differential attenuation.

How far from the actual drillship would a whale have to be in order to receive underwater noise at the same level as that received during our playbacks? To determine this, we used the sonobuoys to measure the received level of the strong 275 Hz tone present in the drillship noise. We compared these levels with Greene's (1982) equation for the received level of this tone in shallow water (27 m) at various distances from the actual drillship:

$$RL\ (\mathrm{dB}//1\ \mu\mathrm{Pa}) = 122.9 - 1.52R - 10*\mathrm{Log}(R)$$

where R is range in kilometres. On 16 and 18 Aug 1982, received levels 2 km from the projector (94 and 105 dB) equalled levels 12 and 6.5 km from the actual drillship. On 18 and 22 Aug 1983, received levels 1.2 km from the

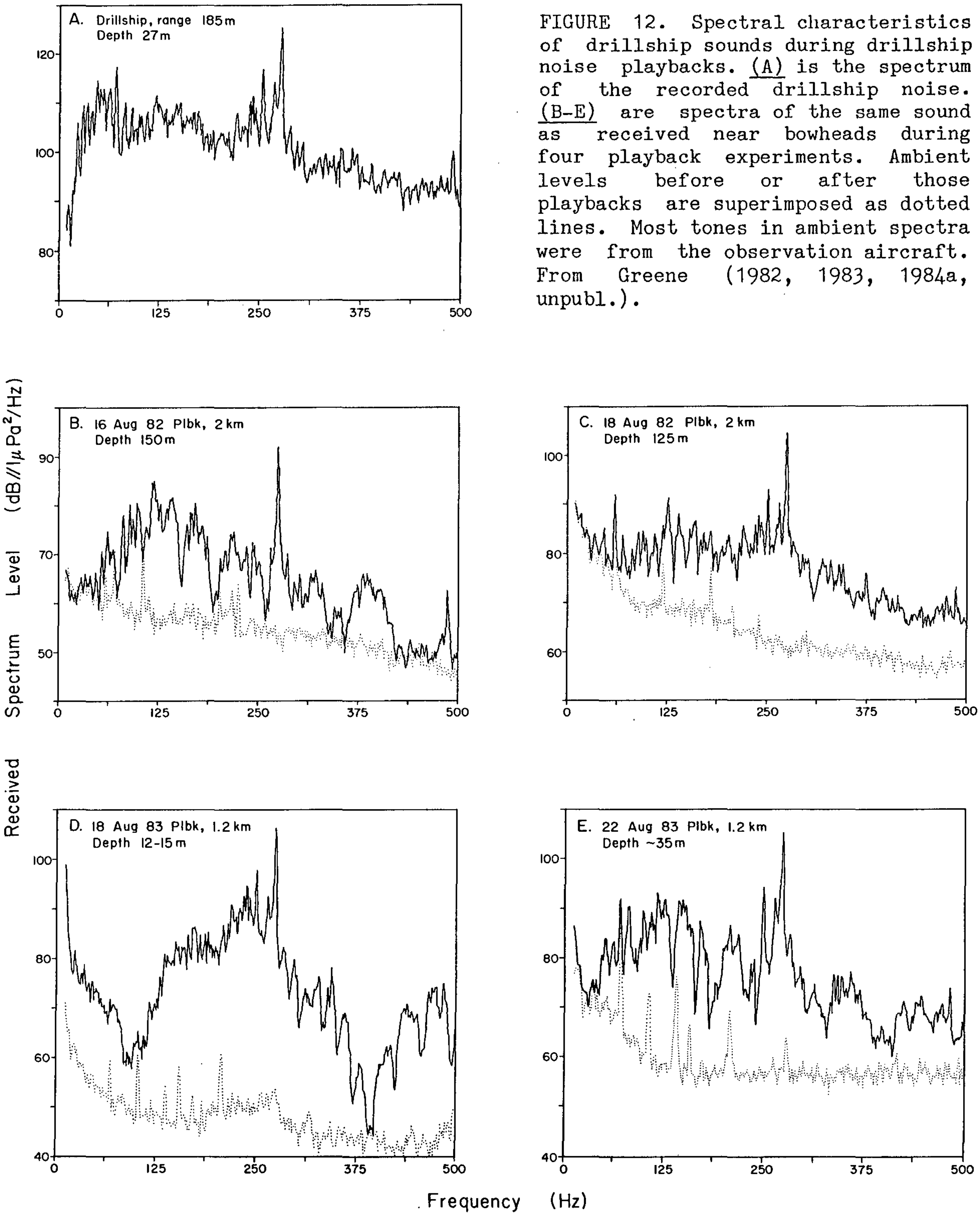

FIGURE 12. Spectral characteristics of drillship sounds during drillship noise playbacks. (A) is the spectrum of the recorded drillship noise. (B-E) are spectra of the same sound as received near bowheads during four playback experiments. Ambient levels before or after those playbacks are superimposed as dotted lines. Most tones in ambient spectra were from the observation aircraft. From Greene (1982, 1983, 1984a, unpubl.).

projector (106.5 and 108.5 dB) equalled levels 6 and 5 km from the actual drillship.

General Activities.--General activities of the whales before the playbacks began included many of the usual activities of undisturbed summering bowheads (Table 21). In each case the whales were surfacing and diving in the usual manner. On 16 and 18 Aug 1982, the average distance of the whales from 'Sequel' increased gradually during the pre-playback control period, although the whales showed no consistent tendency to orient away from 'Sequel' while they were at the surface. In contrast, on 18 Aug 1983 the majority were travelling toward 'Sequel'. On 22 Aug 1983 there was little net motion.

During playbacks, general activities changed only slightly. In the two successful tests in 1982, the observers believed that the whales travelled more consistently and rapidly away from 'Sequel' than had been true in the pre-playback control periods. During the 18 Aug 1983 playback, most whales seemed to interrupt their gradual travel toward 'Sequel'. However, in all three of these tests, the reaction was less conspicuous than the reaction of bowheads to an approaching boat. On 22 Aug 1983, no change in behavior was noted in real time.

Surfacing, Respiration and Dive Characteristics.--Neither duration of surfacing nor number of blows per surfacing differed significantly among phases of the experiment on 18 Aug 1983, the only experiment when sample sizes were adequate for analysis (Table 23).

Blow intervals differed significantly among the four phases of the 18 and 22 Aug 1983 experiments, but the trends were in opposite directions on the two dates (Table 23). Blow intervals were rather long in the playback and post-control phases on 18 August, but rather short in those phases on 22 August. When these two disparate sets of results were pooled, the differences were non-significant ($p>0.1$). Blow intervals also did not differ significantly among phases during the 1982 experiments (Table 23).

Dive duration was rarely measurable, mainly because the whales were difficult to reidentify after a dive. On 18 and 22 Aug 1983, dives during the playback periods tended to be shorter than those after playbacks ended (means 1.30 vs. 3.37 min). The sample sizes were small, but the difference was significant ($0.05>p>0.02$; Table 23).

In general, there was little change in surfacing and respiration behavior during drillship noise playbacks, but there was a hint of reduced dive durations during playbacks.

Orientation of Whales.--In both 1982 and 1983, the experiments provided weak evidence that bowheads tended to orient away from 'Sequel' during playbacks (Fig. 13). We describe the tendency as weak because some whales headed toward 'Sequel' even during playbacks, and because the results of the statistical tests were often only marginally significant.

Before playbacks began, there was no evidence that the whales were orienting away from 'Sequel' in either year or in both years pooled ($p>>0.1$ in each case; see V-test results in Fig. 13). During the playbacks, there was evidence of weak orientation away in both years ($p<0.05$ in each year; $p<0.01$

Table 23. Surfacing, respiration and dive characteristics of non-calf bowheads observed before, during and after four playbacks of drillship noise, 1982-83.

Date and Phase of Experiment	Mean	s.d.	n	Test	Mean	s.d.	n	Test
	No. Blows/Surfacing				**Duration of Surfacing (min)**			
A. 18 Aug '83								
Pre-Control	2.50	2.070	8	ANOVA	0.66	0.476	8	ANOVA
Mid-Playback[a]	2.73	1.831	15	F = 2.11	0.63	0.556	15	F = 1.55
Post-Playback[b]	5.00	3.162	6	df = 3,29	1.16	0.750	6	df = 3,29
Post-Control[b]	4.25	2.217	4	$p > 0.1$	0.98	0.477	4	$p > 0.1$
B. 22 Aug '83								
Pre-Control	-	-	0	-	-	-	0	-
Mid-Playback	5.00	3.367	4		0.97	0.672	4	
Post-Playback	4	-	1		1.12	-	1	
Post-Control	2.15	1.089	20		0.66	0.362	20	
C. 18 + 22 Aug '83								
Pre-Control	2.50	2.070	8	ANOVA	0.66	0.476	8	ANOVA
Mid-Playback	3.21	2.323	19	F = 2.58	0.70	0.580	19	F = 1.67
Post-Playback	4.86	2.911	7	df = 3,54	1.16	0.685	7	df = 3,54
Post-Control	2.50	1.504	24	(*)	0.72	0.391	24	$p > 0.1$
D. 16 + 18 Aug '82								
Pre-Control	7.28	4.873	18	-	1.84	0.822	22	-
Mid-Playback	2	-	1		1.77	1.131	2	
Post-Playback	-	-	0		-	-	0	
	Blow Interval (s)				**Dive Duration (min)**			
A. 18 Aug '83								
Pre-Control	11.32	4.667	28	ANOVA	-	-	0	-
Mid-Playback	14.95	6.155	63	F = 3.63	1.42	2.971	9	
Post-Playback	13.21	2.957	29	df = 3,144	3.92	3.778	3	
Post-Control	17.04	11.689	28	*	4.14	0.884	2	
B. 22 Aug '83								
Pre-Control	15.40	10.407	5	ANOVA	-	-	0	-
Mid-Playback	13.10	5.747	48	F = 5.16	0.23	-	1	
Post-Playback	19.71	11.505	14	df = 3,122	-	-	0	
Post-Control	11.93	5.696	59	**	1.77	1.815	2	
C. 18 + 22 Aug '83								
Pre-Control	11.94	5.841	33	ANOVA	-	-	0	Mann-
Mid-Playback	14.15	6.026	111	F = 1.54	1.30	2.826	10	Whitney
Post-Playback	15.33	7.505	43	df = 3,270	3.92	3.778	3	U = 13
Post-Control	13.57	8.398	87	$p > 0.1$	2.95	1.800	4	*
D. 16 + 18 Aug '82				ANOVA				
Pre-Control	14.19	6.623	173	F = 0.98	7.39	7.304	10	-
Mid-Playback	12.88	5.004	57	df = 2,232	-	-	0	
Post-Playback	14.60	2.191	5	$p > 0.1$	-	-	0	

(*) means $0.1 \geq p > 0.05$, * means $0.05 \geq p > 0.01$, and ** means $0.01 \geq p > 0.001$

[a] The 'Mid-Playback' phase excludes the first 5 min of the increasing level phase and the last 5 min of the decreasing level phase.

[b] The 'Post-Playback' phase is 0-30 min after the end of the playback. The 'Post-Control' phase begins 30 min after the playback.

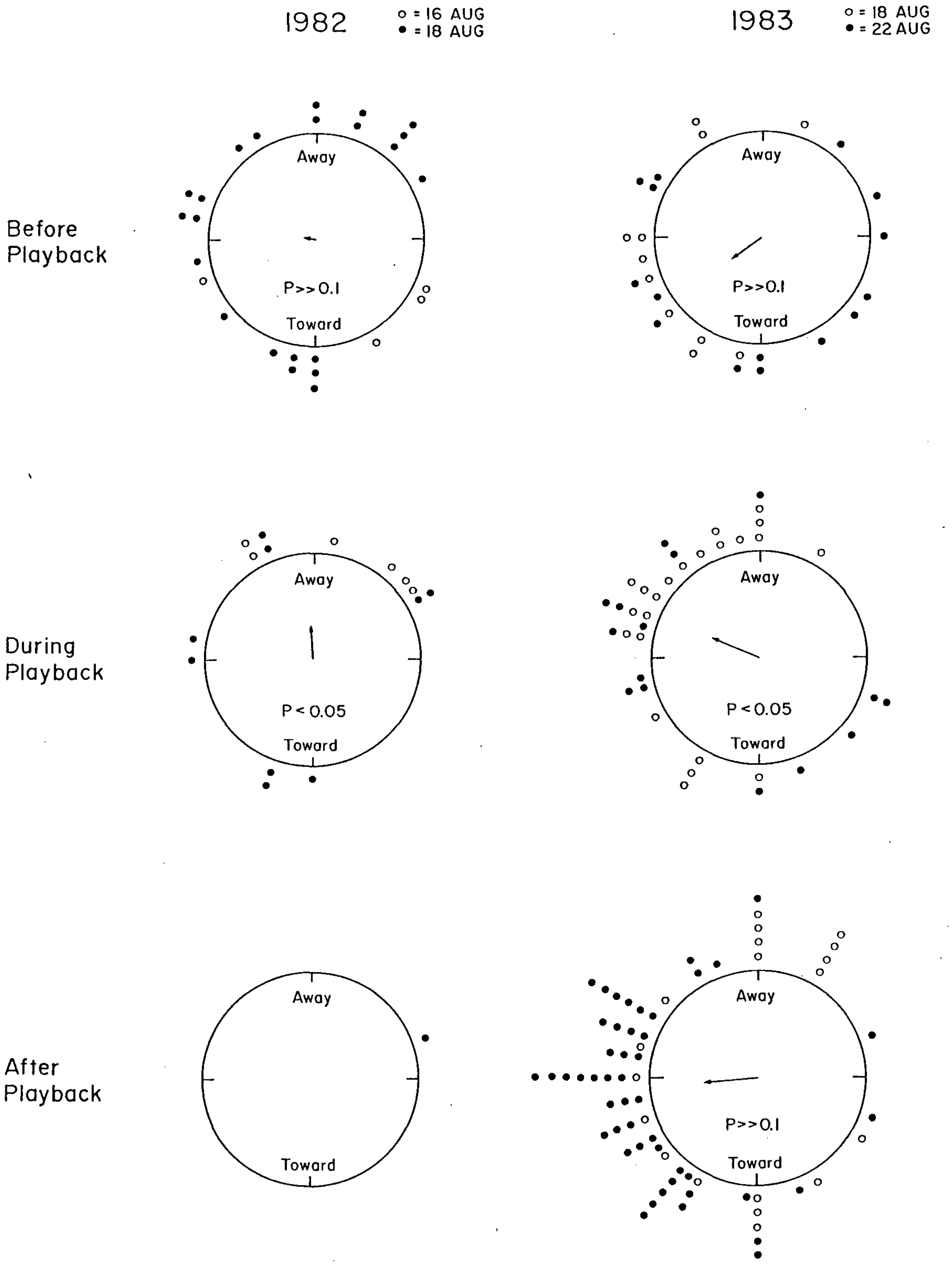

FIGURE 13. Relative orientations of bowheads during four drillship noise playback experiments, 1982-83. Distances from projector to whales were 2-6½ km in 1982 and 0.4-1.8 km in 1983. Presentation as in Fig. 9.

for pooled 1982 + 1983 data). In 1982 there were almost no post-playback data, but in 1983 the data showed no evidence of orientation away after playbacks ended ($p >> 0.1$, V-test; Fig. 13).

The V-tests and inspection of the data in Figure 13 show a greater tendency for orientation away from 'Sequel' while drilling noise was being broadcast than during the pre- or post-playback periods. However, the difference between the orientations (relative to 'Sequel') before and during playbacks was not significant in 1982 ($p > 0.5$; Kuiper test), marginal in 1983 ($p = 0.05$), and very marginal overall ($p = 0.1$).

Because of small sample sizes during individual experiments, we pooled data from 2 or 4 experiments in these comparisons. However, the tendency for orientation away was evident in only one of two experiments in each year (Fig. 13). A possible reason for the stronger reaction on 18 than on 22 Aug 1983 is that the ambient noise level was lower on 18 August (Table 21). Consequently, the signal-to-noise ratio during the playback period was higher on 18 than 22 August (32 vs. 19.5 dB). To the human ear, drillship sound reaching the sonobuoy and whales on 18 Aug 1983 completely dominated the underwater sound field. In contrast, water noise was still detectable along with drillship noise on 22 Aug 1983.

The variable tendency of bowheads to orient away from the source of drilling noise might also be related to received noise level, which is a function of distance. The above analyses include whales 2-6.5 km from 'Sequel' in 1982, and 0.4-1.8 km away in 1983. To test whether the tendency to orient away during playbacks was a function of distance, we converted the orientation relative to 'Sequel' data into a 0°-180° scale, where 0° was directly away, 90° was tangential to either the right or left, and 180° was directly toward. One would expect a positive correlation between this orientation score and distance if whales close to 'Sequel' were most likely to orient away. In actuality, there was no significant correlation in either 1983 (Spearman $r_s = 0.09$, $n = 36$, 1-tailed $p > 0.1$) or in 1982 plus 1983 pooled ($r_s = -0.01$, $n = 51$, $p >> 0.1$). Hence the tendency to orient away from the source of drilling noise during playbacks did not seem to depend on range from the projector, within the range of distances studied.

Thus, playback experiments showed a weak tendency for bowheads to orient away from the source of drillship noise. All orientation data discussed above were obtained by aerial observers. Boat-based observers recorded too few observations of bowhead orientations during drillship playbacks to warrant analysis.

A gray whale appeared 5.5 km from 'Sequel' and headed toward her 3 min into the increasing level phase of the 18 Aug 1982 experiment. By 1 min into the peak level phase, the gray whale was 4.5 km away and had turned to move tangentially. The last sighting was 7 min into the decreasing level phase, when the whale was moving slowly away. Whether the reorientation was attributable to the drillship noise is unknown.

Other Behavioral Variables.--Pooled results from the 4 experiments provided no evidence of greater speeds during the mid-playback period than before playbacks. There was an indication of such an effect in the 1982 experiments (Richardson et al. 1983c, 1985b), but this trend was not evident in 1983 or in the pooled results. Frequencies of turns, pre-dive flexes, and fluke-out dives were apparently unaffected by the playbacks (Table 24).

Four minutes into the increasing level phase of the aborted experiment on 19 Aug 1982, a bowhead calf was observed moving along a windrow of debris 2 km from 'Sequel'. The playback was stopped 4.5 min later, by which time the received level of drillship sound 1.5 km from 'Sequel' was 7 dB above ambient (Table 21). The calf followed the debris during the brief playback and for 8 min thereafter. The calf stayed at or just below the surface, orienting directly along the windrow and changing course as the windrow meandered right or left. The calf's movements disrupted the line of debris. We believe that the calf was playing with the debris rather than feeding (Würsig et al. 1983, p. 80). In any event, the activity continued as the drillship noise level increased, and then for 8 subsequent minutes after the abrupt end of the playback.

Table 24. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed before, during and after four drillship noise playback experiments, 1982-83[a]. Each surfacing by a whale is a unit of observation.

	Speed				
	Zero	Slow	Moderate	Fast	Total
Pre-Control	5	9	17	2	33
Mid-Playback[b]	8	5	25	5	43
Post-Playback	6	6	4	0	16
Post-Control	7	17	5	0	29
Chi^2 (df = 1)[c]			1.21, $p > 0.25$		

	Turn			**Pre-Dive Flex**			**Pre-Dive 'Flukes-Out'**		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Pre-Control	29	7	36	36	3	39	31	17	48
Mid-Playback[b]	23	8	31	34	0	34	41	16	57
Post-Playback	6	2	8	10	0	10	15	5	20
Post-Control	19	6	25	10	1	11	39	11	50
Chi^2 (df = 1)[c]	0.39, $p > 0.5$			2.73, $p > 0.05$			0.65, $p > 0.25$		

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[a] Includes experiments on 16 and 18 August 1982, and on 18 and 22 August 1983.

[b] The 'Mid-Playback' phase excludes the first 5 min of the increasing level phase and the last 5 min of the decreasing level phase.

[c] Chi^2 tests compare frequencies in the pre-control vs. mid-playback phases. In the analysis of speeds, zero plus slow were compared with moderate plus fast.

Bowhead Calls.--Results from 1982 indicated that bowheads called less during drillship noise playbacks than before those playbacks (Table 25). Results from 1983 were not as clear because of the lower overall calling rate in 1983 (Würsig et al. 1985b). However, both total calls and loud calls were again less common during playback periods. The lower total number of calls during playbacks was probably partly an artefact of masking by drillship noise. However, drillship noise did not mask the louder calls, so the reduced rate of loud calls during playbacks was probably real. The proportional frequencies of occurrence of the various call types were similar before, during and after playbacks (Fig. 14).

In summary, call rates seemed lower during drillship noise playbacks, and bowheads tended to turn away from locations where drillship noise was originating. However, the effect was weak, and not all whales reacted. In 1983, dives were briefer when the water was ensonified by drillship noise

Table 25. Call rates of bowheads during four drillship noise playback experiments, 1982-83. Data compiled by C.W. Clark. See Richardson et al. (1984, p. 193) for a more detailed breakdown of these data.

	Before Playback	During Playback	After Playback
Loud Calls/Whale-h			
16 + 18 Aug 82[a]	4.4	1.8	1.6
18 + 22 Aug 83	0.9	0.1	0.7
Total Calls/Whale-h[b]			
16 + 18 Aug 82[a]	36.1	17.5	35.0
18 + 22 Aug 83	1.7	1.0	2.7
Total Calls/h[b]			
16 + 18 Aug 82[a]	261	122	254
18 + 22 Aug 83	17	11	30
Whale-h			
16 + 18 Aug 82[a]	16.13	7.43	5.80
18 + 22 Aug 83	2.33	14.47	29.25
Hours of Recording			
16 + 18 Aug 82[a]	2.23	1.07	0.80
18 + 22 Aug 83	0.23	1.27	2.65

[a] Seismic impulses were present throughout the experiment on 18 Aug 1982.

[b] 'Total Calls/Whale-h' figures are especially imprecise because (1) the number of whales within acoustic range probably exceeded the number under observation, and (2) some otherwise detectable faint calls probably were masked during noise playbacks. Limitation (2) also applies to 'Total Calls/h'.

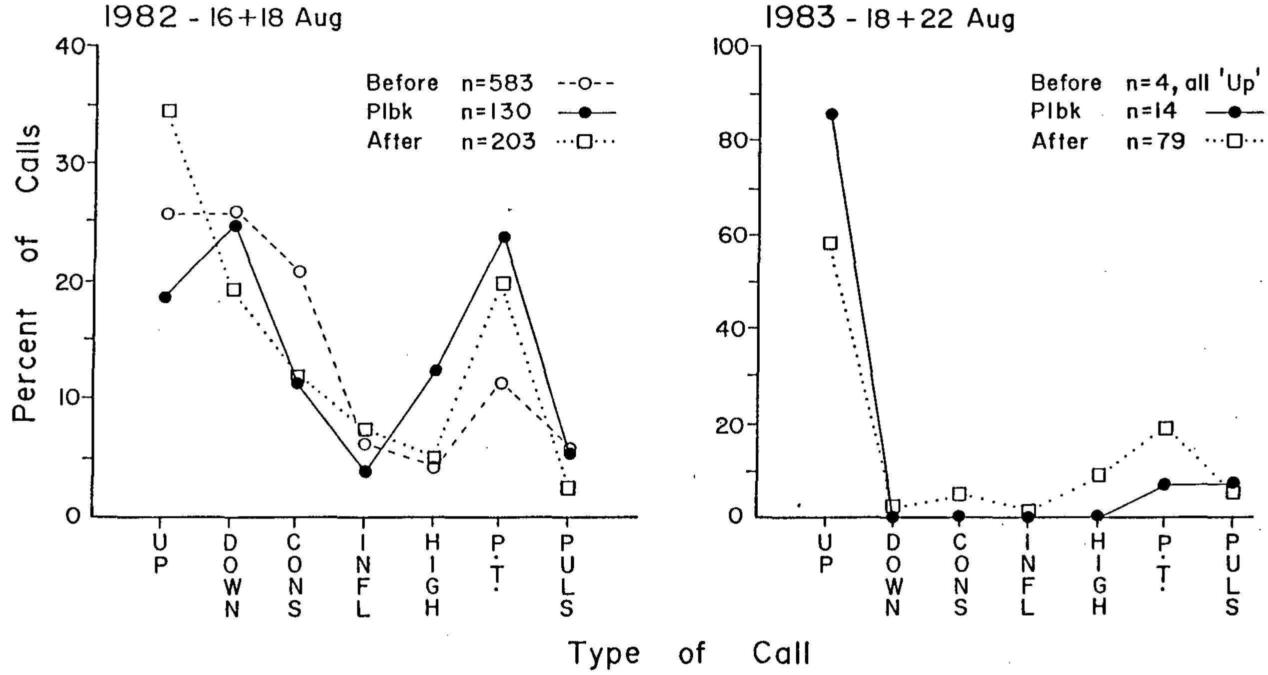

FIGURE 14. Relative frequencies of seven call types during four drillship noise playbacks, 1982–83. Numbers of calls detected were much higher in 1982, when the whales were in deeper water. P.T. = Pulsed Tone. Data compiled by C.W. Clark.

than after such playbacks, but the sample sizes were very small. None of the other behavioral variables analyzed differed significantly between pre-playback and playback periods.

Discussion

Bowheads sometimes were found within a few kilometres of operating drillships, well within the zone where drillship noise is clearly detectable. General activities there seemed normal, and there was no conclusive evidence that the noise affected surfacing, respiration or dive cycles.

The sightings near drillships show some tolerance of drilling, but do not prove that bowheads are unaffected by drillships. We do not know how many more whales might have been present if drillships had been absent, or whether bowheads departed sooner because of the drillships, or whether the likelihood of return in subsequent years was affected by exposure to drillship noise. Similar questions arise with respect to occurrence of bowheads near dredges, and we discuss these possibilities in the 'Reactions of Bowheads to Dredging' section, below.

Playback experiments showed that some bowheads reacted, although not strongly, to drillship noise at intensities similar to those several kilometres from a real drillship. During playbacks, there was a weak tendency to orient away from the playback site, and perhaps for reduced dive durations and calling rates.

Our results from summering bowheads were generally consistent with reactions of migrating gray whales to the same drillship noise (cf. Malme et al. 1983, 1984). Approaching gray whales tended to change speed and course slightly. Most avoided the area within a few hundred metres of the playback site. About 10%, 50% and 90% of the gray whales avoided the zones where drillship noise levels (50-315 Hz band) were 110, 117 and 122 dB//1 μPa, respectively. Initial reactions by gray whales occurred at longer ranges, where noise levels were lower--within 4 dB of ambient levels. Similarly, in our 1982 experiments, the closest bowheads received drillship noise at levels of only 100-110 dB (Table 21); most bowheads were more distant and thus received slightly lower levels. Even in the 1983 tests, when bowheads were closer to the playback sites, average received levels (range 1.2 km) were only about 110 dB and 112.5 dB*. Thus, reaction thresholds of bowheads and gray whales to playbacks of drillship noise were similar.

Why did bowheads seem more strongly affected by playbacks than by drillships themselves? Bowheads remained near drillships for hours and perhaps days, whereas some bowheads oriented away from playback sites within minutes. During playbacks, bowheads received drillship noise with levels and spectral characteristics similar to those several kilometres from actual drillships. One difference between the two situations is that playbacks lasted only 30-40 min, whereas a drillship produces sounds continuously. We increased the playback intensity gradually over 10-13 min in an attempt to avoid startle responses. However, a 10-min period of increasing noise may be perceived differently than the slower increase that a whale would experience as it swam toward a drillship.

Another possibility is that some bowheads avoid drillships whereas others do not. During playbacks, only some of the whales moved away. We do not know whether bowheads were as numerous near drillships as they would have been in the same areas and times in the absence of drillships.

In any case, sightings near drillships and the limited reactions to playbacks show that some bowheads tolerate considerable drillship noise. Reactions of bowheads to drilling on artificial islands and caissons are not known. However, underwater noise levels at various distances from a drill rig operating on a caisson-retained island (with support vessels nearby) were similar to levels at corresponding distances from the 'Explorer II' drillship (Greene 1985). In the case of gray whales, the received noise level that caused 50% avoidance was similar for a drillship, semisubmersible and drilling platform (117-120 dB) despite differences in source levels and spectral characteristics (Malme et al. 1984). Sound levels near artificial islands and caissons not attended by support vessels are probably lower than those near attended structures or drillships. It is reasonable to predict that reactions of bowheads to such unattended drillsites would be less than those to drillships.

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* In 1983, the closest whales (0.4 km on 18 Aug) probably were exposed to no more than 125 dB, the received level at range 0.4 km during a dredge noise playback with similar source level and water depth (Table 26).

REACTIONS OF BOWHEADS TO DREDGING

Several seagoing dredges are used in the eastern Beaufort Sea throughout each open water season (Richardson et al. 1985a). They construct artificial islands and undersea berms from sea bottom materials. They also excavate glory holes for wells to be drilled by drillships. Two types of dredges are used. Suction dredges remain nearly stationary and continuously deposit the material nearby via floating pipeline. Hopper dredges carry material to the construction site, sometimes from over 100 km away, and dump it either through gates in the bottom of the ship or via pump-out methods. Both types of dredges create continuous underwater noise detectable many kilometres away (Greene 1982, 1983, 1984a, 1985).

Previous to 1980 there had been no studies of reactions of any baleen whale species to dredging. Limited data were available from a toothed whale, the white whale Delphinapterus leucas, in nearshore waters of the eastern Beaufort Sea. This species seemed to react less strongly to stationary dredges than to moving tugboats with barges (Fraker 1977a,b), despite similarities in acoustic source levels and frequencies (Ford 1977). Fraker concluded that passage of white whales along a shoreline was temporarily blocked by a nearshore dredging operation involving frequent barge traffic, but not by dredging with little barge traffic. Shallenberger (1978) suggested that spinner dolphins Stenella longirostris ceased using a Hawaiian bay because a noisy construction project began there.

We obtained two types of data concerning reactions of bowheads to dredging and associated island-construction activities: (1) Opportunistic observations of bowheads near such activities, including measurements of underwater noise levels. (2) Controlled tests of reactions to underwater playbacks of dredge noise.

Methods

Observations near Island Construction Operations

Issungnak, 1980.--In August 1980, many bowheads occurred around a dredge at Issungnak artificial island in 19 m of water north of the Mackenzie Delta (70°01'N, 134°19'W). This island was being improved by the suction dredge 'Beaver Mackenzie', an 87 m vessel which uses 3 pumps of 1500-1700 hp to move dredged materials (up to 70,000 m^3/d) along its suction and discharge pipes. The operation also included a barge, tug boats, and helicopter and crew boat traffic from shore. Underwater sounds from 'Beaver Mackenzie' and associated vessels were recorded at Issungnak on 7 Aug 1980, and sounds from the same dredge have also been recorded at other times (Greene 1982, 1984a, 1985).

To document bowhead distribution, aerial surveys of a grid centered at Issungnak were flown six times in the 5-22 August 1980 period. There were 10-16 transect lines, depending on date and fog, spaced 3.2 km apart (for details, see Norton Fraker and Fraker [1981], Fraker et al. [1982]). Whale sightings by industry personnel working at Issungnak were also tabulated.

Amerk, 1983.--Throughout our 1983 field season, the suction dredge 'Beaver Mackenzie' was constructing an underwater berm at Amerk (69°59'N, 133°31'W; depth 26 m). Two or more support boats were usually present, and there was daily helicopter traffic. The Amerk berm was the base for a drilling caisson, which was floated onto the berm in 1984. Industry personnel reported bowheads near Amerk on 12 August 1983. Low ceilings prevented aerial observations, but our chartered boat, 'Sequel', travelled to Amerk on 13 August to observe bowheads and record underwater sounds.

Minuk, 1984.--On 30 and 31 August 1984, we observed bowheads in 17-20 m of water 13 km southwest of an artificial island under construction at Minuk (69°43'N, 136°28'W; depth 12 m). One or both of the hopper dredges 'Cornelis Zanen' and 'W.D. Gateway' were unloading at Minuk via the pump-out method during our observations. 'Zanen' is a 15,000 hp ship that can carry 8000 m^3 of dredged material. 'Gateway' is a 14,000 hp ship with capacity 6000 m^3. Sonobuoys showed that strong industrial sounds were reaching the whales as the ships unloaded 13 km away (Greene 1985). On 30 August, we observed bowheads for 2.0 h with no dredge in the area, for 0.33 h as 'Cornelis Zanen' approached from 22 to 13 km away, and for 1.67 h as she unloaded at Minuk 13 km away. On 31 August, we observed whales at the same location for 1.15 h as one and then both ships unloaded at Minuk. (Subsequent observations during a helicopter overflight experiment were described earlier.)

Dredge Noise Playback Experiments

Three dredge noise playback experiments were conducted near the Yukon coast in 1983-84 (Fig. 1; Table 26). Recorded noise from the 'Beaver Mackenzie' suction dredge was broadcast via a J11 projector deployed at 9 m depth from 'Sequel' in the same manner as during playbacks of drillship noise (see Reactions to Drilling section, above). In each experiment, 'Sequel' had been quiet (drifting or anchored) for at least 0.6 h before the Islander observation aircraft arrived.

The recording of dredge noise used in all experiments had been made 1.2 km from 'Beaver Mackenzie' in water 18 m deep (hydrophone depth 13 m) on 7 Aug 1980 (Greene 1982). At the recording location, the received level was 120 dB//1 µPa in the 20-1000 Hz band and 121 dB in the 20-2000 Hz band. There were strong tones at 329 Hz (103 dB), 384 Hz (103-107 dB), and 1775 Hz (94-101 dB) (see Fig. 16A, later).

Pre-playback control observations were obtained for 46-77 min (Table 26). Each playback consisted of a 10 min increasing level phase, a 20 min peak level phase, and a 10 min decreasing level phase. The source level of the noise during the peak period was 161 dB//1 µPa-m. For purposes of data analysis, a 'mid-playback' period was defined. It included the last 5 min of the increasing level phase, the entire peak level phase, and the first 5 min of the decreasing level phase. Post-playback observations were collected for 21-34 min; they were curtailed by darkness twice and by fog once.

During the first two tests, distances of whales from 'Sequel' were 0.5-2 km and 0.15-2.25 km. In the third experiment, five whales under detailed observation were only 0.1-0.8 km from 'Sequel' at the start of the playback period. During 2 of 3 experiments it was possible to drop a sonobuoy amongst the whales. Sonobuoy locations, received noise levels, and general activities of the whales before playbacks began are summarized in Table 26.

Table 26. Circumstances of the three dredge noise playback experiments in Mackenzie Bay, 1983-84.

	26 Aug '83	16 Aug '84	24 Aug '84
Location of 'Sequel'	69°07'N 137°55'W	69°11' 138°08'	69°05' 137°35'
Water Depth (m) at			
Boat	18	22	12
Whales	c.10	22	12
Sea State	1	1	2-3
Aircraft Altitude (m)	610	610	457
Durations (min) of Obs.			
Quiet Boat	72	77	46
Playback, incr. level	10	10	10
Playback, peak level	20	20	20
Playback, decr. level	10	10	10
Post-playback	32	21	34
Time (MDT) of Observ.	20:58-23:22	21:15-23:33	15:49-17:49
'Sequel' Quiet After	18:35	20:40	09:42
Source Level of Sound during Peak Period (dB//1 µPa-m)	161	161	161
Approx. Distances (km)			
Projector to Sonobuoy	–[a]	1	0.4
Projector to Whales	0.5-2	0.15-2.25	0.1-0.8[b]
Noise level at Sonobuoy (dB//1 µPa)			
Ambient, 20-1000 Hz	–[a]	100-106	101-102
Playback, 20-1000 Hz	–	111-118	121-125
Initial No. of Whales			
Within 5 km	c. 15	9	c. 25
Within 2 km	c. 8	3	c. 8
Activity of Whales Before Playback	Mostly lone whales, zero-med. speed between dives. Occasional socializing.	Mostly lone whales moving at medium speed.	Lone whales moving at zero-medium speed. Apparent near-bottom feeding.

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[a] No sonobuoy on 26 Aug 83.

[b] Most whales 2+ km away by end of playback period on 24 Aug 84.

Results

Observations near Island Construction Operations

Issungnak, 1980.—Underwater industrial noise was readily detectable 1.2 and 4.6 km from the dredging operation at Issungnak (119-120 and 117 dB//1 µPa in 20-1000 Hz band, respectively; Greene 1982, 1985). There were tonal components at various frequencies up to 1775 Hz. No attempt was made to detect dredge noise >4.6 km from Issungnak. However, the same dredge operating in shallower water in 1981 was detectable at range 7.4 km. Hence, the dredge was presumably detectable >7.4 km from Issungnak.

During six surveys around Issungnak on 5-22 Aug 1980, bowheads were seen as close as 0.8 km from the construction operation. As many as 12 bowheads were seen within 5 km during a single survey, although bowheads were not always that close (Fig. 15). Totals of 20 and 49 bowheads were seen within 5 and 10 km, respectively, during all surveys combined. Although these totals probably include some repeated sightings of the same animals, other unseen bowheads were no doubt present below the surface.

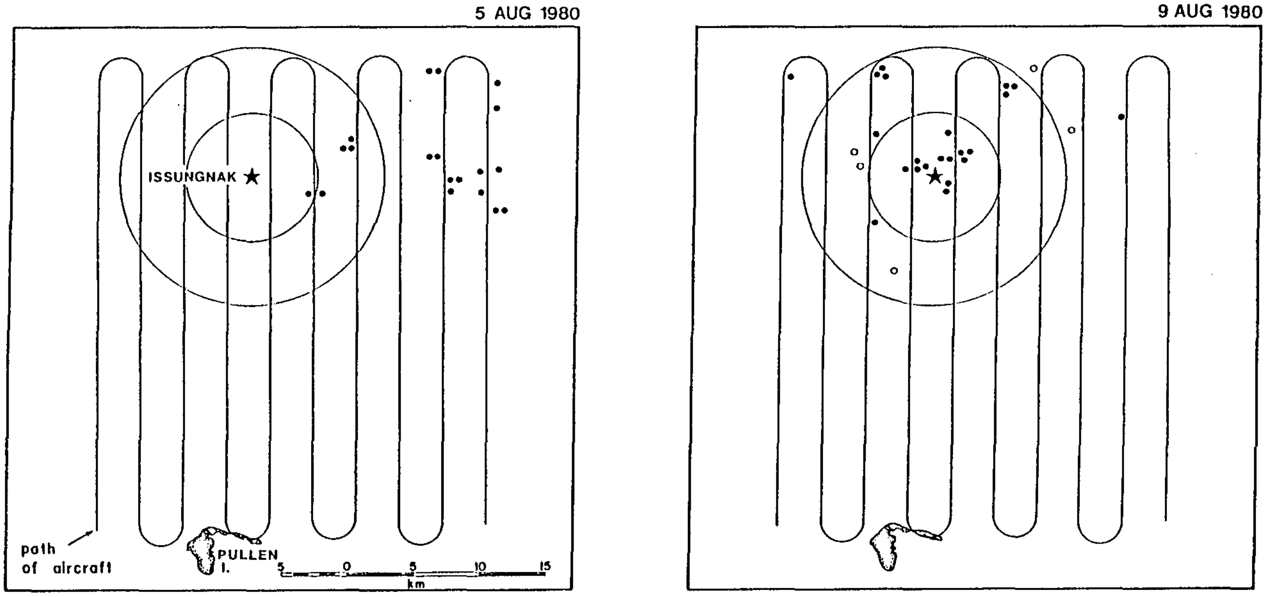

FIGURE 15. Observations of bowheads during two systematic surveys around an island-construction operation at Issungnak, 5 and 9 Aug 1980. Closed and open dots represent whales ≤ 0.8 km and > 0.8 km, respectively, from the survey lines. Circles denote radii of 5 and 10 km. From Norton Fraker and Fraker (1981).

Industry personnel working at Issungnak reported 17 sightings of a total of at least 135 whales on 2-18 Aug 1980 (see Fraker et al. 1982, p. 210, for list). Several whales were estimated to be <500 m from the dredge. Sightings by industry personnel and ourselves were consistent in indicating that bowheads were common within 5-10 km of Issungnak for about 17 days. Whether specific individual bowheads remained nearby for 17 d is unknown.

In contrast, neither biologists nor industry personnel saw many bowheads near Issungnak while it was being constructed in 1978 and 1979 (Fraker 1978; Fraker and Fraker 1979). Bowheads also were infrequent or absent there in 1981 in the absence of construction, and in 1982-84 after Issungnak was abandoned (Richardson et al. 1985a). Thus, bowheads are not abundant in the Issungnak area during most summers. The abundance of bowheads there in 1980 despite construction activity suggests that they exhibit some tolerance of dredging and associated construction activities.

Amerk, 1983.--Industry personnel reported one or more bowheads near the Amerk dredging site on 12 Aug 1983. 'Sequel' travelled to Amerk on 13 August and, for about 2 h, observed two bowheads 2-4 km from the dredge and support vessels. Deteriorating weather prevented further observations from 'Sequel', but industry personnel reported three bowheads there at 00:20 on 15 August. Thus, one or more bowheads were apparently within a few kilometres of Amerk at least intermittently for >2 days. Underwater sounds 1.85 km from Amerk were recorded on 13 August. Industrial noise was very noticeable, with received levels 111-114 dB//1 µPa in the 20-1000 Hz band at 9 and 18 m depth (Greene 1984a, unpubl.).

Minuk, 1984. -- Bowheads observed 13 km from hopper dredges unloading at Minuk on 30 and 31 Aug 1984 were mostly lone whales moving at slow to moderate speed, with no tendency to orient away from the dredges. Numbers present were about 12 and 7 whales on 30 and 31 August, respectively. The observation site was the same on the two days, but we cannot be sure that individuals present on 30 August were still present the next day. While the whales were at the surface, mud was often seen streaming from the body and, especially on 30 August, the mouth. This indicates that near-bottom feeding was occurring during dives. Sonobuoys showed that strong industrial sounds were reaching the whales on both 30 and 31 Aug 1984. On 31 August when 1-2 dredges were unloading, the received level was 115-117 dB//1 µPa in the 20-1000 Hz band, with no particularly strong tones (Greene, unpubl.).

On 30 August, when observations began 2.33 h before the dredge arrived at Minuk, general activities did not change when the dredge approached or began unloading. Most standard behavioral variables (duration of surfacing; number of blows per surfacing; blow interval; estimated speed) were also similar before and after the dredge arrived at Minuk. Similarly, values of most behavioral variables recorded in the presence of dredges on 31 August did not differ significantly from values recorded on control occasions--i.e., in the same area in the absence of potential disturbance sources on 28 Aug, 30 Aug and 2 Sept 1984.

Frequency of flukes out upon diving did differ in the presence and absence of dredges. However, the trends were in different directions on the two days:

	No Flukes	Flukes		No Flukes	Flukes
30 Aug, pre-dredge	16	16	31 Aug, dredge(s)	6	23
" , with dredge	15	4	Three 'control' days	66	44
Chi^2 (df=1)	4.19 ($p<0.05$)			14.20 ($p<0.001$)	

The lack of consistency in these trends suggests that some factor other than the dredges was responsible.

Summary.--Even in the shallow waters where seagoing dredges operate, dredge noise is detectable underwater for at least several kilometres. Bowheads engaged in seemingly normal activities have been seen well within the zone ensonified by suction and hopper dredges. Bowheads have been seen in areas with dredge noise for as much as 17 d, but it is uncertain whether specific individuals ever remain in an ensonified area for that long.

Dredge Noise Playback Experiments

Sound Levels to Which Bowheads Were Exposed.--On 26 Aug 1983, bowheads were 0.5-2 km (mean 1.4 km) from the sound projector. Sound levels reaching the whales were not measured. The three experiments were done in similar areas and water depths (Fig. 1, Table 26). Hence, dredge noise levels on 26 Aug 1983 were probably comparable to those at corresponding distances during later tests.

On 16 Aug 1984, the whales were 0.15-2.25 km away (mean 1.0 km). The received noise level 1 km away was 111-118 dB//1 µPa in the 20-1000 Hz band, or 5-18 dB above ambient (Table 26). Based on the average level of 114.5 dB at range 1 km, received levels 0.15 and 2.25 km away were probably about 127 and 109 dB, given that attenuation from 1 m to 1 km was about 46.5 dB (Table 26), or 15.5 log (range). The received level 1.2 km from the actual dredge was 120 dB, or about 7 dB above the expected level at a corresponding distance from the playback site. Hence, received levels at any given range from the projector were several decibels less than those at comparable range from the actual dredge. The 114.5 dB level received 1 km from the playback site would be found about 2.7 km from the actual dredge, given the 15.5 log R relationship and the measured 120 dB level 1.2 km from the dredge.

On 24 Aug 1984, bowheads were initially 0.1-0.8 km away from the sound projector (mean 0.5 km). The received noise level 0.4 km away was 121-125 dB//1 µPa, or 19-24 dB above ambient (Table 26). Received levels 0.1 and 0.8 km away were probably about 132 and 119 dB, given that attenuation from 1 m to 400 m was about 38 dB or 14.6 log (range). The estimated level at 0.8 km was similar to the measured level 1.2 km from the actual dredge. The average received level 0.4 km from the projector (123 dB) would be expected 0.75 km from the actual dredge.

Noise received at the sonobuoys during dredge playbacks sounded similar to the original recording of dredge noise. Several of the strong tones in the original recorded sound were also prominent in the dredge noise recorded at the sonobuoy locations amongst the whales that were under observation (Fig. 16).

General Activities.--On 26 Aug 1983 (ranges 0.5-2 km), activities were the same before, during and after the noise playback--mostly lone whales surfacing and diving in shallow water; speeds zero to moderate while at the surface; infrequent socializing. The aerial observers did not notice, in real time, any obvious response of the whales to the playback, and the whales remained in the area during and after the playback.

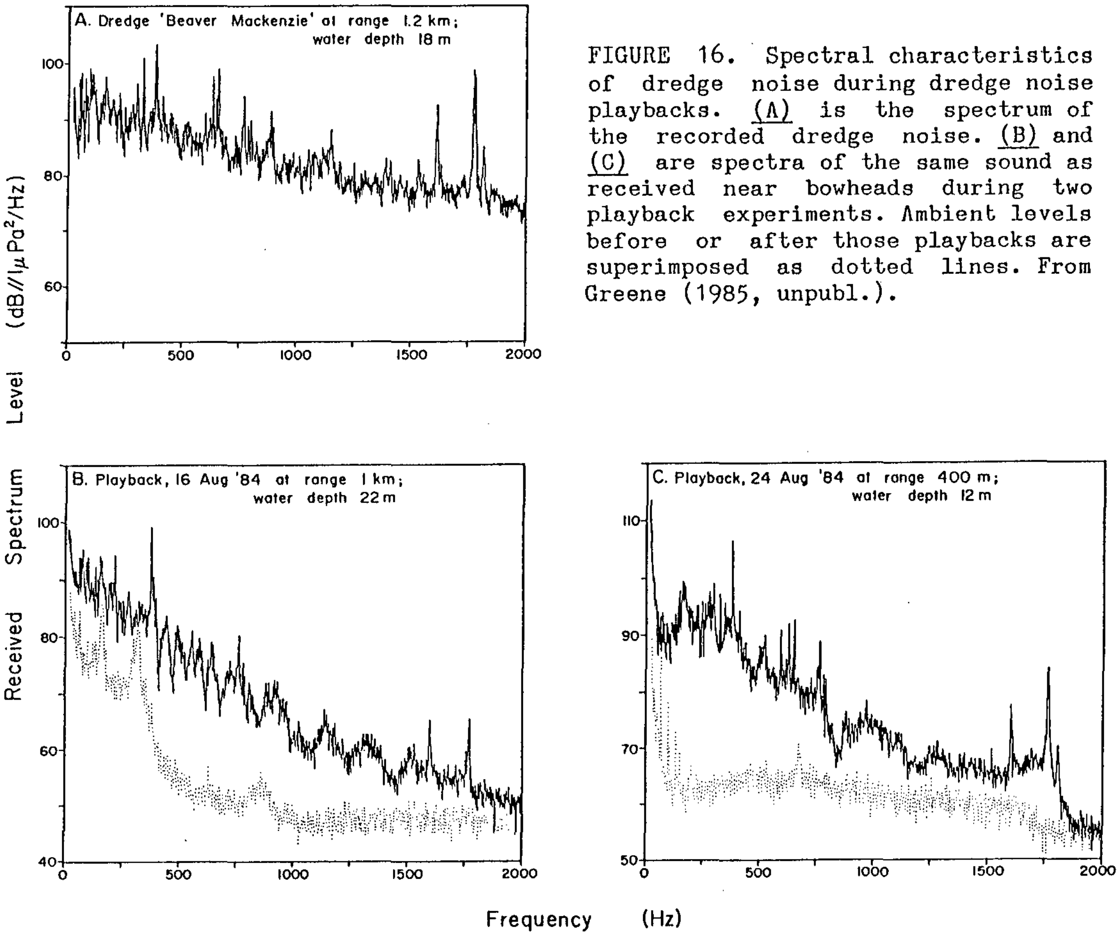

FIGURE 16. Spectral characteristics of dredge noise during dredge noise playbacks. (A) is the spectrum of the recorded dredge noise. (B) and (C) are spectra of the same sound as received near bowheads during two playback experiments. Ambient levels before or after those playbacks are superimposed as dotted lines. From Greene (1985, unpubl.).

On 16 Aug 1984 (ranges 0.15-2.25 km), general activities were again similar before, during and after the playback: mostly lone animals moving at medium speed while at the surface. However, during the playback we noticed that an increased proportion of surfacings were quite short with only 1 or 2 blows. Only a fraction of these short surfacings are reflected in the quantitative data (see below); surfacings known to be short but whose exact durations were unknown could not be used in the analysis of surfacing-respiration-dive data.

On 24 Aug 1984 (ranges 0.1-0.8 km), bowheads near 'Sequel' were lone individuals moving at zero-medium speed. Mud was brought to the surface, indicative of near-bottom feeding. About 8 bowheads were within 2 km of 'Sequel'; of these, about 5 were within 700 m. During most surfacings within the playback period, the whales were swimming away from 'Sequel' at moderate speed. This change in behavior was obvious in real time to observers in the aircraft and on 'Sequel'. Near-bottom feeding apparently ceased (no mud seen). By the end of the peak level phase (30 min after start of playback), we could find no bowheads within 2 km of 'Sequel'.

Surfacing and Respiration Characteristics.--During the first experiment (26 Aug 1983), the dredge playback had no apparent effect on (a) mean number of blows per surfacing, (b) duration of surfacing, or (c) blow interval (Table 27). During the second experiment (16 Aug 1984), (a) and (b) were both significantly reduced during the playback period, as had been noted in real time; (c) was not affected. During the third experiment (24 Aug 1984), sample sizes for (a) and (b) were negligible, and there was no apparent effect on

Table 27. Surfacing, respiration and dive characteristics of non-calf bowheads observed before, during and after playbacks of dredge noise, 1983-84. The 'Mid-Playback' phase excludes the first 5 min of the increasing level phase and the last 5 min of the decreasing level phase.

Date and Phase of Experiment	Mean	s.d.	n	Test	Mean	s.d.	n	Test
	No. Blows/Surfacing				**Duration of Surfacing (min)**			
26 Aug '83								
Pre-Control	4.00	3.140	15	t=0.27	0.78	0.604	16	t=0.86
Mid-Playback	3.60	1.949	5	df=18	1.03	0.421	5	df=19
Post-Playback	–	–	0	p>0.5	0.85	–	1	p>0.2
16 Aug '84								
Pre-Control	5.80	3.271	5	t'=2.46	1.16	0.399	9	t=2.48
Mid-Playback	1.75	1.500	4	df=7	0.50	0.537	4	df=11
Post-Playback	–	–	0	p<0.05	–	–	0	p<0.05
24 Aug '84								
Pre-Control	4.00	1.414	2	–	1.04	0.790	2	–
Mid-Playback	4	–	1		0.58	–	1	
Post-Playback	1	–	1		0.13	–	1	
	Blow Interval (s)				**Dive Duration (min)**			
26 Aug '83								
Pre-Control	12.31	4.603	85	F=1.08	4.44	4.054	9	–
Mid-Playback	14.58	10.684	19	df=2,113	–	–	0	
Post-Playback	12.83	5.906	12	p>0.1	–	–	0	
16 Aug '84								
Pre-Control	10.51	4.022	104	t=0.46	–	–	0	–
Mid-Playback	10.12	2.891	25	df=127	0.22	–	1	
Post-Playback	7.50	2.121	2	p>0.1	–	–	0	
24 Aug '84								
Pre-Control	11.26	5.006	31	F=1.30	–	–	0	–
Mid-Playback	12.71	5.213	28	df=2,61	–	–	0	
Post-Playback	14.80	5.630	5	p>0.1	0.63	–	1	

blow intervals (Table 27). There were too few data on dive duration to allow analysis.

Orientation of Whales.--If bowheads respond to dredge noise, we hypothesized that they would orient more consistently away from 'Sequel' during the playback period than before or after the playback. Orientation data collected from both the observation aircraft and 'Sequel' confirmed that bowheads responded to the noise. The effect was weak on 26 Aug 1983 (ranges 0.5-2 km) but strong in the subsequent experiments (ranges 0.15-2.25 and 0.1-0.8 km):

1. On 26 Aug 1983, aerial observations showed that orientations during the pre-playback and playback periods were only marginally different (Kuiper test, K=344, n=26,31, p<0.1). There was a slightly greater tendency for orientation away during the playback (Fig. 17).

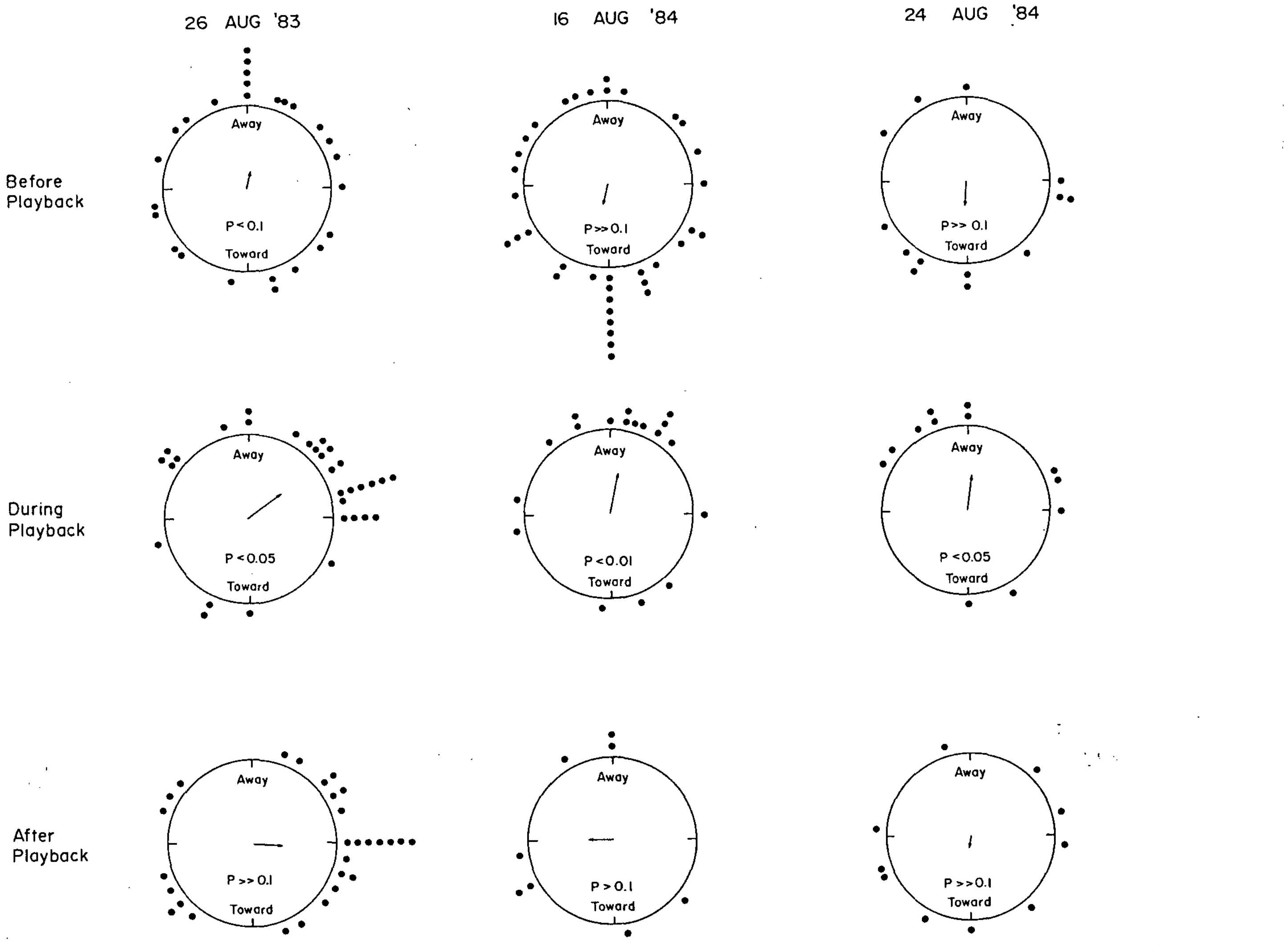

FIGURE 17. Relative orientations of bowheads during three dredge noise playback experiments, 1983-84. Presentation as in Fig. 9.

Observations from 'Sequel' provided more convincing evidence:

	Away	Toward	% Away
Pre-playback	18	28	39
Mid-playback	15	4	79
Post-playback	5	4	56

For 'Sequel' data, 'away' represents whales heading within 60° of directly away; 'toward' means within 60° of directly toward; whales heading tangentially are excluded. The pre- and mid-playback values differ significantly ($chi^2=8.53$, df=1, $p<0.005$).

2. On 16 Aug 1984, aerial observations showed a clear tendency for orientation away during the playback period but not before or after the playback (Fig. 17). Orientations during the pre- and mid-playback periods were significantly different (Kuiper K = 324, n = 36,18, $p<0.05$). Observations from 'Sequel' showed the same trend, although sample size was small during the mid-playback period (pre-playback, 61% away; mid-playback, 100% away; n = 28 and 4).

3. Results on 24 Aug 1984 were similar; orientations were non-random and predominantly 'away' during the mid-playback period, but random before and after the playback (Fig. 17). (Observers on 'Sequel' could not record orientations during the playback period.)

When results from the three experiments were pooled, orientations in the pre- and post-playback periods were both random ($p>>0.1$, V tests). Orientations during playbacks were significantly non-random in the 'away' direction ($p<0.0001$). Orientations in the pre- and post-playback periods did not differ significantly, but both differed from orientations in the mid-playback period:

	K	n	p
Pre vs. Post	K = 878	n = 75,47	$p>0.2$
Pre vs. Mid	1830	75,61	$p<0.001$
Mid vs. Post	1121	61,47	$p<0.01$

One would expect a stronger reaction from the whales closest to the boat. To a first approximation, this was evident through the lesser effects on orientation and surfacing/respiration variables in the first experiment (mean range 1.4 km) than in the second (1.0 km) and third (0.5 km). A more direct test was done using the same procedure as applied in the analysis of drillship noise playbacks. Unexpectedly, the Spearman rank correlation between 'deviation of heading from directly away' and 'distance from projector' was only 0.105 (n = 58, $p>0.1$). Thus, within the range of distances considered (0.1-2.25 km), there was no evidence that orientation was more consistently 'away' among the closer bowheads.

Other Behavioral Variables.--Overall, estimated speeds were similar in the pre- and mid-playback periods, although there were fewer motionless whales during playbacks (Table 28). The frequencies of turns, pre-dive flexes, and fluke-out dives were unaffected by the playbacks (Table 28).

During the pre-playback period on 24 Aug 1984, bowheads brought mud to the surface, indicative of feeding near the bottom. This behavior ceased during the playback, and did not resume during our limited post-playback

Table 28. Estimated speed and occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed before, during and after three dredge noise playback experiments, 1983-84. Each surfacing by a whale is a unit of observation.

	Speed				
	Zero	Slow	Moderate	Fast	Total
Pre-Control	10	10	25	4	49
Mid-Playback[a]	1	8	14	3	26
Post-Playback	3	4	10	1	18
Chi^2 (df = 1)[b]			0.28, $p > 0.5$		

	Turn			Pre-Dive Flex			Pre-Dive 'Flukes-Out'		
	No	Yes	Total	No	Yes	Total	No	Yes	Total
Pre-Control	19	7	26	29	9	38	32	40	72
Mid-Playback[a]	5	2	7	10	7	17	13	14	27
Post-Playback	2	1	3	5	4	9	14	12	26
Chi^2 (df=1)[b]	0.01, $p > 0.5$			1.74, $p > 0.1$			0.11, $p > 0.5$		

[a] The mid-playback phase excludes the first 5 min of the increasing level phase and the last 5 min of the decreasing level phase.

[b] Chi^2 tests compare frequencies in the pre-control vs. mid-playback phases. In the analysis of speeds, zero plus slow were compared with moderate plus fast.

observations. Mud was brought to the surface during 5 of 18 surfacings in the pre-playback period and 0 of 19 during the playback ($chi^2 = 6.10$, df = 1, $p<0.05$). No mud was seen during 11 surfacings in the post-playback period.

Bowhead Calls.--Few bowhead calls were heard during and after the playbacks on 16 and 24 Aug 1984 (0.34 calls/whale-h during and 0.28 after). No recordings were possible in the pre-playback periods on these dates, or at any time during the 26 Aug 1983 test. Thus, we do not know whether call rate changed when dredge noise began.

Summary.--The three dredge noise playback experiments showed that bowheads often respond to the onset of strong dredge noise, even when the noise level is increased gradually over 10 min as in our experiments. Whales tended to orient away from the playback site. In 2 of 3 tests the tendency to move away was strong. On 24 Aug 1984, whales ceased feeding near the bottom and vacated the area within 2 km of the playback site within 30 min. On 16 Aug 1984, there was evidence of reduced surface times and number of blows per surfacing during the playback.

Discussion

Observations of bowheads near island and berm construction sites during 1980, 1983 and 1984 showed that some bowheads occasionally tolerate these industrial activities and their associated underwater noise. Only a few bowheads approached industrial sites in 1983, but some whales apparently remained near the Amerk dredging operation for at least a day or two. In 1980, larger numbers of bowheads were found near the Issungnak dredge site, sometimes feeding, for about 17 days. Sometimes several whales were within 5 km of the dredge; on other days there were no sightings that close. The 1980 and 1983 cases involved a suction dredge that operated continuously at one site. In 1984, bowheads were seen on successive days well within the zone ensonified by hopper dredges unloading at Minuk.

The sightings near dredges show some tolerance of those operations, but do not demonstrate that bowheads are unaffected by construction operations.

1. We do not know whether numbers at any given distance were as high as they would have been if there had been no industrial activity. Densities of bowheads were too low and too variable to allow a meaningful statistical comparison of numbers at different distances from dredge sites.

2. It is uncertain how long particular individuals remained within the area ensonified by the dredge noise in 1980. Although bowheads were in the area for about 17 days, the distances from the dredge varied from day to day (e.g. Fig. 15). We do not know whether the same individuals moved back toward the dredge after having once moved away from it, or whether whales remained as long as they would have if there had been no dredging.

3. It is not known whether exposure to dredge noise reduced the probability that specific bowheads would return to the same areas in subsequent years. (Indeed, there is no information about the propensity of specific bowheads to return to any location in subsequent summers.)

To resolve points (2) and (3), we would need data concerning movements of individuals identifiable by natural markings or radio tags. This type of information could not be obtained within the scope of the present study of short-term behavioral reactions of bowheads. Photo identification studies have been conducted in our study area since 1981 (Davis et al. 1982, 1983, in prep.; Cubbage et al. 1984). However, 1984 was the first year when the identification work was specifically designed to address points (2) and (3), and no definitive results bearing on these points are available yet.

We emphasize the above limitations of the opportunistic observations near dredges because our playback experiments showed conclusively that, in some situations, bowheads do react to dredge noise. During the 1983 test, the response was barely detectable. However, during the two tests in 1984 bowheads definitely moved away from the playback site. In one of the 1984 cases, near-bottom feeding was interrupted and some whales moved as much as 2 km. During the one 1984 test when surfacing and respiration behavior could be documented quantitatively, mean duration of surfacing and mean number of blows per surfacing were reduced as the whales swam away during the noise playback.

Received levels of dredge noise at various distances from the 'Beaver Mackenzie' suction dredge were several decibels greater than those at corresponding distances during our playbacks of her noise. Despite this, bowheads were seen within 1-5 km from 'Beaver Mackenzie' on several days whereas bowheads at distances up to 2 km from the playback site reacted to dredge noise. Furthermore, whales 13 km from two hopper dredges unloading at Minuk on 31 Aug 1984 were receiving dredge noise as intense as that 1 km from the playback site on 16 Aug 1984 (115-117 dB vs. 111-118 dB). Bowhead behavior seemed normal 13 km from the dredges at Minuk, but bowheads headed away during the 16 Aug 1984 playback.

The obvious response to some playbacks despite the tolerance of similar levels of noise from actual dredging operations was presumably related to the fact that the level of industrial noise increased rapidly during the playbacks. However, the reaction to the playbacks was not a startle reaction in the usual sense of a response to a sudden intense stimulus. During our playback experiments, noise intensity increased gradually from zero to maximum over 10 min. For example, during the 24 Aug 1984 test, when the ambient noise level was 101-102 dB//1 μPa in the 20-1000 Hz band, the noise level 0.4 km from the playback site was 107 dB 5 min into the playback period, and 122-124 dB 5 min later at the start of the period of peak level.

Besides the rapid onset of noise during playback experiments, there may be additional reasons for the seemingly greater reaction to some playbacks than to actual dredges. Levels and spectral characteristics of dredge noise close to the playback site were similar to those somewhat farther away from the actual dredge (Greene 1985). However, two other attributes of the sounds may have differed:

1. Received levels decrease with increasing range faster at short range than at longer range. A whale 200 m from the playback source would be exposed to a noticeably reduced level (a few dB lower) if it swam a few body lengths. In contrast, a whale exposed to the same noise level 1 km or more from an actual dredge would experience much less change in received level if it swam the same distance. This difference may affect the motivation of the whale to swim away from the noise source.

2. Especially in the shallow water where dredges operate, multi-path distortion of underwater sounds increases with increasing range. This might reduce the ability of a bowhead to sense the direction of a distant noise source. The acoustic localization ability of baleen whales is poorly known. Humpback and fin whales are known to orient toward conspecifics calling several kilometres away (Tyack 1981; Watkins 1981b), but these observations were in deeper water where multi-path effects might be reduced.

Thus, the proximity of some whales to the playback site may have enhanced their motivation or ability to move away. However, the fact that many did move away when playbacks began indicates that bowheads preferred to avoid dredge noise at levels equal to those a few kilometres from an actual dredge. Bowheads a few kilometres from an actual dredge beginning operations presumably would have the same preference to avoid the sound, even if they had less ability to do so because of (1) and (2).

The above discussion suggests some reasons why bowheads might react more strongly during our dredge noise playbacks than to actual dredges. However, it is also possible that some bowheads *did* react to actual dredges in the same way as others reacted to playbacks. As already noted, we do not know whether bowhead numbers near dredges were reduced relative to numbers that would have been there in the absence of dredging. During playbacks, some bowheads failed to move away from the playback site even when others at comparable ranges did move away. Thus, there are variations in reactions to dredge noise. The whales seen near actual dredges may have been some of the less sensitive animals; those that were more sensitive may have moved away earlier, or may have avoided the area when they first encountered the noise field.

GENERAL DISCUSSION

Progress During This Study

This study was designed to determine, by experimental and observational means, the immediate behavioral reactions of bowhead whales to potential sources of disturbance. We found strong reactions to approaching boats and, less consistently, to aircraft at low altitudes. We did not find such strong reactions to seismic, drilling and dredging operations, although the onset of intense stimuli of these types did cause local displacement. Table 29 summarizes the types of reactions detected during our experiments, and the approximate noise levels and radii at which effects became detectable. It should be noted that some bowheads tolerated industrial noise at levels exceeding those listed in Table 29; others may have reacted subtly to noise levels less than those listed in the table.

Reactions of bowheads to our fixed-wing observation *aircraft* were frequent when it was ≤305 m (1000 ft) a.s.l., infrequent when it was at 457 m (1500 ft), and rare when it was at ≥610 m (2000 ft). Reactions to aircraft at ≥457 m were more frequent and pronounced when the whales were in shallow water. Measurements of aircraft noise confirmed that lateral propagation of aircraft noise in the Beaufort Sea is greater in shallow than in deep water (Greene 1985).

When helicopters at about 153 m a.s.l. flew single passes over bowheads (submerged at times of passes), we detected no pronounced reactions; the whales remained in the area. The most reaction that we would expect is a hasty dive.

Boat disturbance experiments and opportunistic observations showed that bowheads react strongly and rather consistently to approaching boats. Bowheads began to swim rapidly away when boats approached within 1-4 km, and continued to do so for several minutes after the boat passed. Scattering and alteration of activities sometimes continued longer. Approaching boats also resulted in shorter surfacings with fewer respirations per surfacing.

The behavior of bowheads in the presence of noise from *seismic vessels* 6 km or more away was not dramatically different from behavior in the absence of industrial activities. We found no evidence of avoidance at such ranges.

Table 29. Summary of reactions of bowhead whales to five types of industrial activities. Threshold radii and noise levels listed here are approximate. Subtle effects may occur at longer distances and lower noise levels.

	Fixed-Wing Aircraft	Boat	Full-Scale Seismic[a]	Drillship Noise Playback[a]	Dredge Noise Playback[a]
Approx. radius of strong or frequent reaction	310 m altitude	1-2 km	3 km	6 km[b]	1.2 km[b]
Approx. max. radius of influence (mild or occasional reaction)	457 m altitude	4 km	~ 7.5 km	12 km[b]	2.7 km[b]
Approx. min. noise level causing reaction (dB//1 μPa)[c]	105 dB	107 dB	>130 dB[d]	100 dB	114 dB
Approx. min. S:N ratio causing reaction (dB)[c]	–[e]	3 dB	>30 dB[d]	16 dB	13 dB
Reactions					
Hasty Dive	Yes	Yes	No	No	No
Change in Activity	Rare	Yes	Yes	Slight	Yes
Orient Away	Rare	Yes	Yes	Yes	Yes
Displacement	Rare	Yes	Yes	Prob.[f]	Yes
Scattering	–	Yes	–	–	–
Change in Surface Time	No	Yes	Prob.[f]	No	Yes
Change in Blows/Sfcing	No	Yes	Prob.	No	Yes
Change in Blow Interval	Yes	No	Prob.	No	No
Change in Dive Duration	–	–	Prob.	Poss.[f]	–
Change in Speed	No	Yes	Yes[d]	No	No
Change in Turn Freq.	No	No	Poss.[f]	No	No
Change in Pre-Dive Flex	Yes	No	Poss.	No	No
Change in Flukes-Out	No	No	Prob.	No	No
Change in Call Rate	No	–	No	Prob.	–
Change in Call Types	No	–	No	No	–

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[a] Some bowheads exposed to ongoing noise from actual seismic, drillship or dredge operations tolerated noise levels exceeding those to which bowheads reacted during controlled experiments.

[b] Equivalent distance from actual drillship or dredge.

[c] Noise levels for 20-1000 Hz band at 9-18 m depth (from Greene 1985).

[d] Results from experiments with single airguns are taken into account here.

[e] "–" denotes "no data".

[f] "Prob." and "Poss." denote "probable" and "possible"; evidence is equivocal.

There were hints of subtle alterations in surfacing, respiration and diving behavior in the presence of noise pulses from seismic vessels 6-99 km away, but we were unable to confirm that these weak and inconsistent trends were attributable to the seismic noise. The overall trends were consistent with those found when bowheads were exposed to stronger noise pulses from closer seismic boats (Ljungblad et al. 1985, pers. comm.) or a single airgun nearby (this study). Hence it is possible that subtle effects sometimes do occur at distances >6 km from seismic vessels and at received noise levels below the 160+ dB//1 μPa expected at that range.

A test with a full-scale seismic boat showed that bowheads began to orient away from the vessel when it began firing its airguns 7.5 km away. However, the reaction was not strong, and some whales continued apparent near-bottom feeding until the vessel was only 3 km away. Whales were displaced by about 2 km. Reactions were not much stronger than those to any conventional vessel. However, tests with a single airgun fired from a quiet boat showed that bowheads will move away from a source of strong seismic impulses even if no boat noise is present. This confirms not only that they react to seismic impulses, but that they can detect the direction from which the impulses are arriving.

We saw bowheads <5 km from operating drillships and dredges, well within the zones ensonified by drillship and dredge noise. However, playback experiments showed that some bowheads oriented away when they received drillship and dredge noise comparable in level and characteristics to that several kilometres from the actual drillship or dredge. Clear reactions were detected during the 16 Aug 1984 dredge noise playback, and the 18 Aug 1983 drillship noise playback, when noise received by the whales was similar to that about 2.7 km and 6 km from the dredge and drillship, respectively. There were hints of reactions during the 16 Aug 1982 drillship noise playback, when the received noise was similar to that ≥12 km from the actual drillship. In the drillship playbacks, call rate may have decreased. During one dredge playback, near-bottom feeding ceased; in another surfacing and respiration behavior changed. The reactions to drillship and dredge noise were not nearly as consistent or dramatic as those to an approaching boat.

Table 29 shows that more types of reactions were evident in the case of dredge playbacks than for drillship playbacks. This was probably a result of the fact that some whales were closer to the playback site during dredge playbacks. We found no evidence that bowheads were more sensitive to dredge noise than to drillship noise.

Overall, the study showed that bowhead behavior can be affected markedly but temporarily by the close approach of ships or aircraft. Reactions were less obvious in the cases of industrial activities that continued for hours or days, such as distant seismic exploration, drilling and dredging. Summering bowheads sometimes occurred close enough to drillships, dredges and especially seismic vessels to be exposed to considerable industrial noise. When seen near these ongoing operations, activities seemed normal and the whales were not swimming consistently away. However, tolerance of these types of activities was not complete. Our experiments showed that bowheads tended to orient away from sources of drillship, dredge and seismic noise when this noise first became evident at levels equal to those several kilometres from actual drillships, dredges and seismic vessels.

Recommended Research

Reactions of bowheads to helicopters have not been documented in detail. Some data were obtained in this study, but the whales were below the surface at the moments the helicopters were overhead (also see comments by Berzin and Doroshenko 1981; Dahlheim 1981). Reactions to fixed-wing aircraft are better known, and we expect that reactions to helicopters and fixed-wing aircraft are similar. However, some helicopters produce rather intense noise with strong low frequency components and many tones (Greene 1985), so reactions of bowheads to helicopters may be more pronounced than those to fixed-wing aircraft. Playback experiments indicate that gray whales react to repeated underwater playbacks of helicopter noise (Malme et al. 1983, 1984). However, reactions of gray whales to the more realistic case of single or widely-spaced overflights by an actual helicopter are unknown.

Short-term reactions of bowheads to boats are comparatively well documented. However, sensitivity seems to vary, and the factors affecting this variation are not well documented. Reactions to repeated boat traffic are unknown, although groups of bowheads have been seen repeatedly at specific locations near major traffic lanes over periods of days (Richardson et al. 1985a). To test the effects of repeated vessel traffic, it would be necessary to study bowheads that were individually recognizable either from natural markings or radio tags. Reactions to icebreakers breaking ice and to hovercraft are unknown.

Much has been learned about reactions of bowheads to seismic impulses. Bowheads often tolerate noise impulses from distant seismic vessels (≥6 km away) without exhibiting avoidance or conspicuous changes in behavior. In the presence of strong seismic noise (i.e. seismic vessel within a few kilometres), normal activities of many bowheads are affected, avoidance occurs, and surfacing, respiration and dive behavior changes (this study; Ljungblad et al. 1985, pers. comm.). However, a number of questions about the effects of this noise remain unanswered.

1. Are there subtle reactions to noise from distant seismic boats (>6-10 km away)? This could be addressed by controlled, replicated experiments in which bowhead behavior is observed before, during and after exposure to noise from distant seismic vessels. However, much effort may be necessary to detect subtle effects in the presence of the great natural variability in bowhead behavior.

2. When bowheads alter their activities and avoid a nearby seismic vessel, is there any negative effect on the individuals? Telemetry of physiological data could be helpful here. A further requirement would be an analysis of food availability and patchiness relative to the needs of bowheads.

3. If the area from which they moved was important to them, e.g. because of high food abundance, do they return to that area after the seismic vessel has left? To address this question, it would be necessary to recognize individuals, e.g. from natural markings or radio tags.

4. Does exposure to intense seismic noise have any negative effect on the hearing system of bowheads? Question (4) would be difficult to answer, but data about the sensitivity of any baleen whale to sounds of different frequencies would be helpful (see Ridgway and Carder [1981] for possible approach). Any such effect is likely to be confined to short ranges.

5. Does exposure to seismic noise affect the probability that bowheads will return to that area in future years? (see Richardson et al. 1985a for discussion of available evidence.) To obtain definitive data on this point, individually identifiable whales would have to be detected over two or more years.

Much also remains to be learned about the long-distance propagation of seismic noise through water. Received levels decrease with increasing range, but there is variation in the rate of attenuation of seismic pulses (Greene 1983-85). Besides distance, factors known or suspected to affect the intensity and characteristics of the received noise pulse include characteristics and depth of the noise source, aspect, water depth, ice and bottom conditions, and receiver depth (Greene 1982-85; Malme et al. 1983). Although Greene (1982-85) and others have obtained some data on all of these points, no detailed study of their interactions has been done.

Reactions of bowheads to drillships and to playbacks of drillship noise have been examined in this study. Reactions of bowheads to other types of drilling operations, e.g. on artificial islands and caissons, have not been studied. Natural and artificial islands and caissons are the main types of drilling platforms being used for drilling in the Alaskan Beaufort Sea, although drillships may come into use there in 1985. Malme et al. (1984) found that, for gray whales, reaction thresholds occurred at varying distances from the drillsite, depending on differences in the source levels of different drilling operations. Greene (1985) found that a drilling caisson and attending support vessels produced noise levels comparable to those around a drillship. Thus, we predict that zones of influence around drillships and caissons would be similar.

No measurements of underwater noise from drilling on an uncontained island in the open water season have been reported; no such operation occurred in the eastern Beaufort Sea during our five field seasons. This data gap makes it difficult to predict the relative zones of influence around uncontained artificial islands vs. drillships and caissons.

Bowheads sometimes tolerated considerable noise from drillships and dredges, but playback experiments showed that some bowheads oriented away from drillship and dredge noise. The importance of short-distance displacement to the well-being of the whales is unknown. It is also unknown whether the whales that remained within the ensonified area were stressed or otherwise affected in any way. Techniques similar to those suggested in points (1)-(3) under seismic noise would be helpful in addressing these questions.

It would be desirable to perform playback experiments to determine whether bowheads react as strongly to non-industrial noise as they do to drillship or dredge noise. If so, then the importance of their rather weak reactions to drillship and dredge sounds would be questionable. Control playbacks of this type were recognized as being a desirable part of this study, but there were too few opportunities for playback tests to permit this work.

In general, we now have considerable information about the short-term responses of bowheads to offshore industrial activities--the topic of this study. We know much less about the significance of those reactions to the well-being of the whales, and about long-term effects on individuals and on the population. To address these more refined questions, techniques that allow physiological monitoring, repeated observations of identifiable individuals, or both, are increasingly necessary. Radio telemetry or intensive photographic work (Davis et al. 1983) are two promising approaches.

Another possible approach to the question of long-term effects is to determine whether there has been displacement of bowheads from areas with much industrial activity. The number of bowheads within the main industrial area in the Canadian Beaufort Sea has varied dramatically during 1980-84 (Richardson et al. 1985a). However, it is not known whether any of this variability is attributable to industrial activity rather than to variations in natural factors such as food supply, ice conditions, etc. A better understanding of production processes and of the feeding ecology of bowheads will be necessary to determine the importance of oceanographic variation in affecting the variable summer distribution of bowheads in and near the industrial area (Borstad 1984; LGL, ESL and ESSA 1984; Richardson et al. 1985a). One important point that did emerge from analysis of bowhead distribution in the summers of 1980-84 is that bowheads have not been excluded from the wide area where seismic exploration has occurred each summer in recent years (Richardson et al. 1985a).

Implications of Short-term Behavioral Reactions

Interruption of Feeding

Strong responses to boats and aircraft have been found in some situations, and weaker responses to other industrial activities have been detected or suspected, especially when those activities or noise sources first start up or approach. However, even the strong responses do not seem to persist for long. Bowheads do not seem to travel more than a few kilometres in response to a single disturbance incident, and their activities do not seem to be interrupted for long.

Occasional brief interruption of feeding by a passing boat or aircraft is probably not of major significance. Similarly, the energetic cost of travelling a few kilometres is very small in comparison with the cost of migration between the central Bering and eastern Beaufort Seas. These factors might become significant if industrial activity were sufficiently intense to cause repeated displacement of specific individuals. A better understanding of the energy balance, feeding dependencies and site tenacity of bowheads would be necessary to address this question.

Social Disruption

Disruption of social groupings, especially mother-calf pairs, could be more important. Upon the approach of a boat, socializing whales ceased socializing and swam rapidly away. We noticed increased spacing between whales after some boat disturbance incidents, and there was an indication of reduced echelon size among skim-feeding whales during one airgun experiment. Our data on the durations of periods of increased spacing after boat disturbance are not extensive, but scattering persisted longer than the flight response, in one case for at least 1 h. Since the functions of most forms of socializing are unknown, we cannot predict whether disruption of socializing groups would affect individuals significantly.

Disruption of mating groups or mother-calf pairs could be particularly serious. In the absence of industrial noise, mothers and calves that were separated by a few hundred metres commonly rejoined, apparently through acoustic communication (Würsig et al. 1985a,b). Female bowheads sometimes became separated from their calves by distances up to 1 km. If a boat approached during one of these temporary separations and caused the whales to flee, the mother and calf might become separated permanently. This would be especially likely in an industrialized area where elevated noise levels would reduce the effective range of acoustic communication (see below).

Stress

The subtle alterations in behavior that we sometimes detected might be significant as indicators of otherwise-unobservable stress. Stress effects are difficult to detect in any animal, and would be especially so in large free-ranging whales. Nonetheless, stress might occur as a result of noise or other stimuli from industrial activity, and seemingly minor changes in overt behavior might be the one observable manifestation. Radio telemetry of physiological data may provide a means to study such phenomena in whales exposed to human activity, as has been done in a few terrestrial mammals (e.g. MacArthur et al. 1979).

Masking of Important Sounds

Continuous noise reduces the maximum range to which a bowhead call or other sound is detectable if the noise and the sound of interest are at similar frequencies. The 50-400 Hz band contains the peak energy of most industrial sounds (Fig. 18A; Greene 1985), and also contains most bowhead calls (Fig. 18B; Ljungblad et al. 1982b; Clark and Johnson 1984; Würsig et al. 1985b). Calls are presumably important to bowheads for communication (Clark 1983). Detection of ice and water noise also may be important for a species that depends on its ability to find open water in pack ice. With spherical spreading, a 20 dB increase in noise level will, theoretically, reduce the range of detectability of a given sound of similar frequency by a factor of 10, e.g. from 10 km to 1 km (e.g. Møhl 1981; Richardson et al. 1983b). With cylindrical spreading, the effect is even greater--a 20 dB increase in noise reduces the range of detectability 100-fold.

Whether the masking effect would actually be this severe, or important to the whales, depends on many factors, most of which are poorly known or unknown:

1. Is long-distance communication important to bowheads? Fin whales sometimes respond to calls from other fin whales 25 km away, but most acoustic communication is apparently over much shorter distances, possibly <1 km (Watkins 1981b). Humpback whales react to calls from other humpbacks up to 9 km distant (Tyack and Whitehead 1983). However, these are the extreme cases known to us, even though

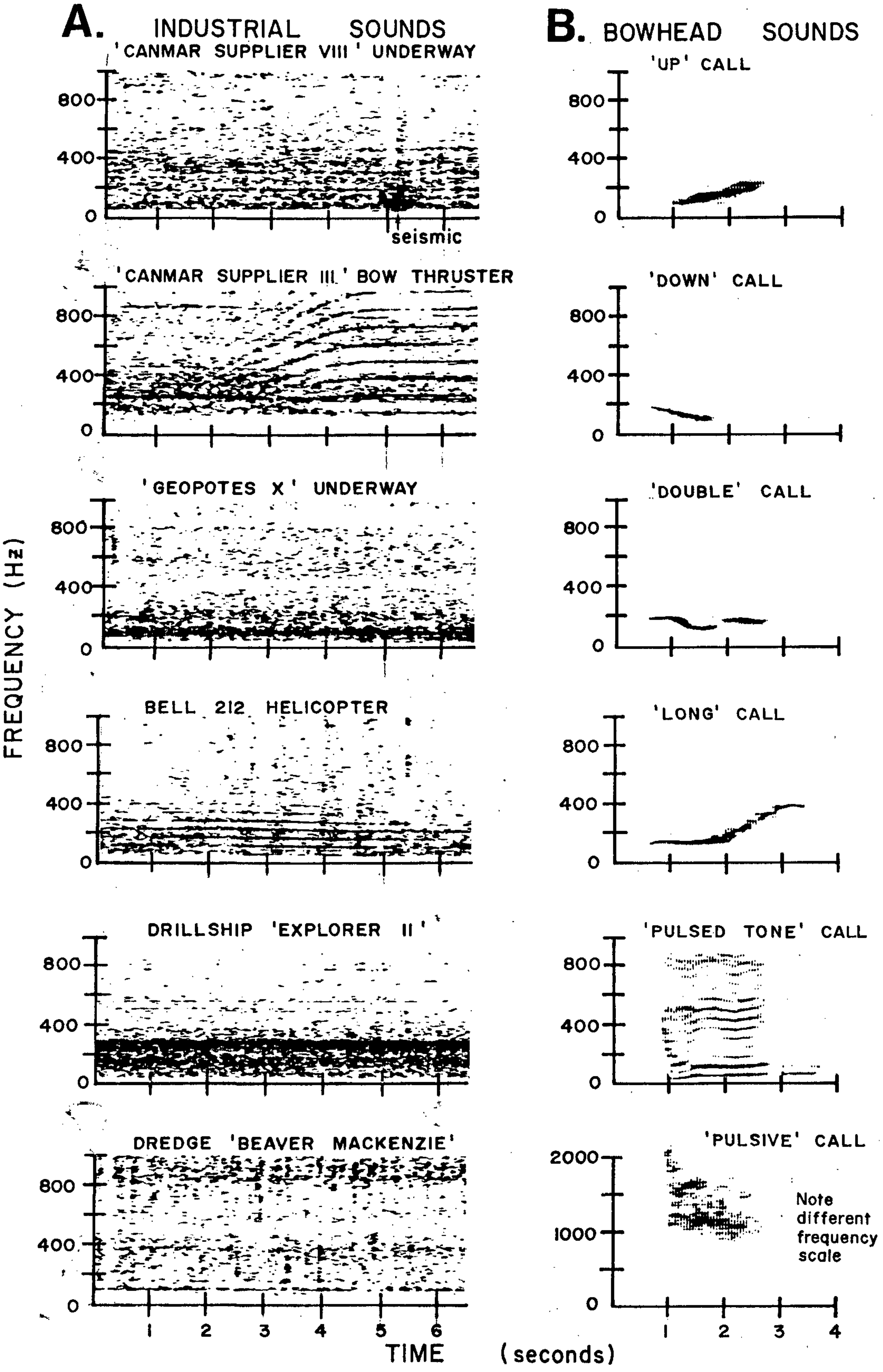

FIGURE 18. Spectrograms of certain industrial sounds (left) and bowhead sounds (right) recorded in the eastern Beaufort Sea. Spectrograms are by C.W. Clark. See Greene (1985) and Würsig et al. (1985b) for more details.

baleen whales are theoretically capable of communicating over much greater distances in certain deep water situations (Payne and Webb 1971).

Since bowheads can produce calls with source levels of 185 dB//1 µPa-m or more (Clark and Johnson 1984), calls would be detectable at ranges of 10 km or more given typical ambient noise levels (Greene 1985) and the conservative assumption of spherical spreading. If acoustic communication is normally over shorter ranges, say 1 km or less, then bowheads could still communicate over at least this range if background noise levels increased.

2. Background noise levels are naturally high during storms and near moving ice. The high source level of some bowhead sounds may be an adaptation to allow continued short-medium range communication in these situations, rather than long distance communication in quiet conditions.

3. If bowheads sometimes do need to communicate acoustically over long distances, or to detect other faint environmental noises, how often is this important? Presumably bowheads can tolerate occasional storm-induced interruption of their ability to detect faint sounds. Can they tolerate additional restrictions imposed by industrial noise? Levels of industrial sounds from some stationary sites, e.g. island construction sites, vary from time to time (Greene 1985). Other sound sources move, such that high levels are present in one area only temporarily.

4. Can bowheads increase the intensities of their calls to increase communication range in the presence of elevated noise levels? Some toothed whales adjust their echolocation calls as a function of ambient noise and target range (Au 1980; Au et al. 1985). The intensity of fin whale calls varies considerably (Watkins 1981b). Ongoing work on acoustic localization of bowheads (Clark et al. 1985) should provide information about the typical levels of bowhead calls. Received levels of FM upsweep calls average 6-10 dB greater than the levels of all other call types, and are the least variable (C.W. Clark, pers. comm.). This is consistent with the suggestion that FM upsweeps serve a long range communicative function. This would also imply that calls other than upsweeps are more easily masked by continuous industrial noise, although the whales could possibly increase the source levels of these other calls and thereby reduce masking effects.

5. Can bowheads change the frequencies of their calls to avoid frequency bands with much industrial noise? Again, some toothed whales seem to do this in chronically noisy situations (Au 1980; Au et al. 1985). Bowhead calls occur over a considerable range of frequencies. For particular types of tonal calls the range is narrower but there is still some variation, e.g. 146 ± s.d. 62 Hz for the initial frequency of 'Up' calls; 720 ± 295 Hz for 'high' calls (Würsig et al. 1985b). For mammal species in which masking has been studied experimentally, significant masking effects only occur when the frequencies of the masking noise and the call are within

about 1/3 octave of one another. Thus, it is possible that bowheads can reduce masking effects by altering call frequencies.

6. Are bowhead calls emitted uniformly in all directions, or are they to some extent 'beamed'? Acoustic localization work during spring migration past Barrow, Alaska, provides hints of directional effects (C.W. Clark, pers. comm.). Similarly, can bowheads localize the directions from which sounds are arriving? The fact that bowheads tended to orient away during some playback and airgun tests (this study) shows that bowheads have some localization capability. Directionality in either the emission of calls or in auditory sensitivity could reduce the masking effect (Zaytseva et al. 1975).

Given these uncertainties, quantitative assessment of the masking potential of noise from oil industry activities is difficult. In general, background levels of continuous underwater noise are elevated by $\geq$20 dB only within a few hundred metres of most industrial sites, and within a few kilometres of the strongest sources (Greene 1985). Assuming that bowheads can produce calls as intense as 185 dB//1 µPa when necessary, short-distance communication would only be impaired for whales very close to industrial sites, at distances where disturbance effects are already likely to have displaced the animals.

Long-distance communication and detection of faint environmental sounds are much more likely to be affected, assuming that these abilities are important to bowheads. However, even within the main area of offshore oil exploration in the eastern Beaufort Sea, there are wide zones between industrial sites where continuous industrial noise is barely or not detectable most of the time. (Passing ships and helicopters in these zones cause only temporary increases in noise.) Hence, even in considerable portions of the main industrial area, bowheads would not have to travel far or wait long in order to avoid strong masking effects. It is not known whether such limitations on detection of faint sounds are a significant problem for bowheads, given that natural factors (storm and ice noise) sometimes limit detection of faint sounds.

Seismic impulses, even at high received levels, probably do not cause significant masking. During most seismic operations, especially when high-energy sources are used, the pulses are <1 s long and are spaced several seconds apart. Ambient sounds and bowhead calls were readily detectable by our hydrophones, and presumably by bowheads, in the intervals between pulses. Bowheads do not stop calling in the presence of seismic impulses (this study; Ljungblad et al. 1980).

Applicability to Alaska

Behavior of bowheads in the Alaskan Beaufort Sea in late summer and early autumn is quite similar to that in the Canadian Beaufort Sea in late summer. In both areas, bowheads feed, socialize and travel in areas of open water and in pack ice (Ljungblad et al. 1984b; Würsig et al. 1985a,b). Also, some of our results were obtained off the Yukon coast, not far from Alaskan waters (Fig. 1). Hence, we believe that reactions of bowheads in the Alaskan Beaufort Sea up to late September would be similar to those that we observed. Reactions to seismic noise, the only disturbance effects studied systematically in both the Alaskan and Canadian Beaufort Sea, were generally consistent in the two areas (no strong reaction by bowheads more than a few kilometres away from seismic vessel; displacement of bowheads within a few kilometres).

Later in autumn, bowheads begin to travel more consistently westward through the Alaskan Beaufort Sea as freeze-up occurs. Our results from late summer may be less applicable to these actively travelling whales. The activities and habitat of bowheads in winter and spring also differ considerably from those in summer, so our findings may be less applicable to those situations than to late summer and autumn. If detection of sounds from ice, leads or other bowheads far away is important during migration or winter (e.g. to find openings in ice), continuous industrial noise along migration routes and in wintering areas might have effects that summer and autumn studies could not detect.

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CHARACTERISTICS OF
WATERBORNE INDUSTRIAL NOISE, 1980-84*

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TABLE OF CONTENTS

ABSTRACT

This section documents underwater sounds to which bowhead whales were exposed during disturbance experiments and other behavioral observations in the Canadian Beaufort Sea, 1980-84. Data were collected with calibrated low noise hydrophones suspended 3-18 m beneath a sparbuoy, and with sonobuoys dropped and monitored from the aircraft used to study bowhead behavior. Results are for hydrophone depth 9-18 m unless otherwise stated. Laboratory analysis included power spectrum analyses of continuous sounds, and waveform and peak signal analyses for seismic survey pulses. Overall levels are given for the 20-1000 Hz band, which includes most components of the industrial and bowhead sounds.

Ambient noise ranged from below the typical values for sea state zero to high levels characteristic of storms at sea. The median level for the 20-1000 Hz band in August 1980-84 was 99 dB, equivalent to sea state three.

Fixed-wing aircraft sounds beneath the aircraft averaged a few decibels greater at 3 m depth than at 9 m. Noise levels were highest when the passing aircraft was low, but peak levels persisted for only a few seconds, especially at low aircraft altitudes. During straight line passes, aircraft were audible for longer in shallow than in deeper water. Sounds from an Islander and Twin Otter included numerous tones at frequencies related to propeller and engine rotation rates.

Helicopter sounds included tones associated with the main and tail rotor rotation rates. The overall levels below a Bell 212 were 3 dB higher for passes at 305 m altitude than for 610 m. For oblique passes, the shallow (3 m) hydrophone detected the lowest levels.

Boat and ship sounds for the 20-1000 Hz band included the following:

-Crew boats underway	118 dB at 0.2 km	105 dB at 4.6 km
-Supply & survey boats underway	129 dB at 0.2 km	103 dB at 4.6 km
-'Geopotes X' dredge underway	150 dB at 0.5 km	131 dB at 7.4 km
-Anchored supertanker	120 dB at 0.2 km	95 dB at 9.3 km

'Geopotes X' was the strongest source of continuous noise studied during this project. Received levels of boat noise were usually several dB less at depth 3 m than at 9-18 m, as expected for an in-water source.

Seismic signals from sleeve exploders, open-bottom gas guns, airgun arrays, and a single airgun were similar. Propagation in shallow water elongated the initially-sharp pulse into a longer pulse with quasi-sinusoidal waveform gradually decreasing in frequency. At ranges of a few kilometres, waterborne pulses are typically 0.25-0.5 s long. The predominant frequency at the leading edge of the pulse is often 200-400 Hz, diminishing to 100-200 Hz at the end of the pulse a fraction of a second later. Energy at frequencies <100 Hz is rapidly attenuated in shallow water, but can travel long distances in some sediments and may reenter the water far from the source. The strongest seismic signal recorded was 177 dB//1 μPa from an array of open bottom gas guns at range 0.9 km. Signals from airgun arrays ranged from 160 dB at 12 km to ≤110 dB at 75 km. Received levels were several dB less at depth 3 m than at 9 or 18 m.

Drillship sounds, including adjacent support vessels, were as follows:

-'Explorer I', logging	122 dB at 0.17 km	100 dB at 10.3 km
-'Explorer II', drilling	134 dB at 0.2 km	111 dB at 7.4 km
-'Kulluk' CDU, drilling	143 dB at 0.9 km	117 dB at 14.8 km

Dredging sounds recorded near suction and hopper dredges were as strong as 145 dB 0.6 km from a hopper dredge that was loading, and 118 dB from a dredge at range 14.8 km. Hopper dredge sounds tended to vary over time. Caisson-retained islands where there was construction, well testing, or drilling produced sound levels of 130 dB at ranges 0.22 to 1.1 km, and 111-118 dB near 3.8 km. Some of this noise came from attending support vessels.

In general, many industrial sources increased the level of continuous noise (20-1000 Hz band) by about 25 dB at 1 km radius and 10 dB at 10 km radius, relative to the median ambient level. The noisiest ships produced higher levels. Noise pulses from seismic surveys were far stronger and often detectable ≥50 km away.

INTRODUCTION

Marine mammals (including bowheads) use sound to communicate and to receive information about their environment. Sound travels very efficiently in water, day or night, winter or summer, and regardless of the water's clarity. At least in deep water, the intense, low-frequency sounds produced by baleen whales, including bowheads, are believed to be transmitted especially well and with little attenuation (Payne and Webb 1971). The very advantages of underwater sound so useful to marine mammals give rise to potential problems related to underwater industrial sounds (Acoustical Society of America 1981). Many industrial sounds are also intense and of low frequency, and consequently are transmitted efficiently over relatively long distances. Thus, the acoustic effects of industrial operations may be manifested far from their source, and this greatly expands the area potentially affected. Possible ways in which underwater industrial sounds could affect whales include direct disturbance and the masking of important communication, echolocation and/or environmental sounds (Møhl 1981; Richardson et al. 1985).

From 1980 to 84, the Bureau of Land Management and Minerals Management Service, U.S. Department of the Interior, have supported a study of the behavior of bowhead whales and how they may be influenced by oil industry activities offshore in the Beaufort Sea. Motivation for the research came from the potential for oil exploration and development north of Alaska, and questions about its effects on bowheads. However, the field work was conducted during August of 1980-84 in the Canadian part of the Beaufort Sea, east of Alaska (Fig. 1.). Bowheads feed there at that time, and offshore oil exploration is considerably more advanced in the Canadian than in the Alaskan part of the Beaufort Sea. Thus, the Canadian Beaufort Sea provided a study area with both animals and potential sources of disturbance.

Approach

Our general approach to the research centered on boat- and airplane-based observations of whale behavior and measurements of underwater sounds. It was important to know what sounds the whales were exposed to while being studied from the air, and the air crew deployed sonobuoys and recorded the signals on the airplane. The boat crew, which included the acoustician, recorded signals from hydrophones deployed from a sparbuoy drifting near the boat. The boat motored to various industrial sites to record the sounds of dredges, drillships, boats, and artificial islands; it anchored in open areas to record the sounds of passing ships and aircraft. In 1980-81 we attempted shore-based studies of sounds and whale behavior from camps at Herschel Island and King Point, Yukon Territory (Fig. 1), but bowheads were not close enough. In 1983-84 the whales were in those areas and we studied them from the airplane and boat.

An underwater projector was used from the boat to perform controlled 'playback' experiments. Previously recorded underwater industrial sounds were played back near whales being observed from the airplane. We also used a single 40 in^3 (0.66 L) airgun deployed from the boat to conduct controlled tests of bowhead reactions to seismic survey impulses. It was necessary to measure the sound levels to which bowheads were exposed during playback and airgun tests.

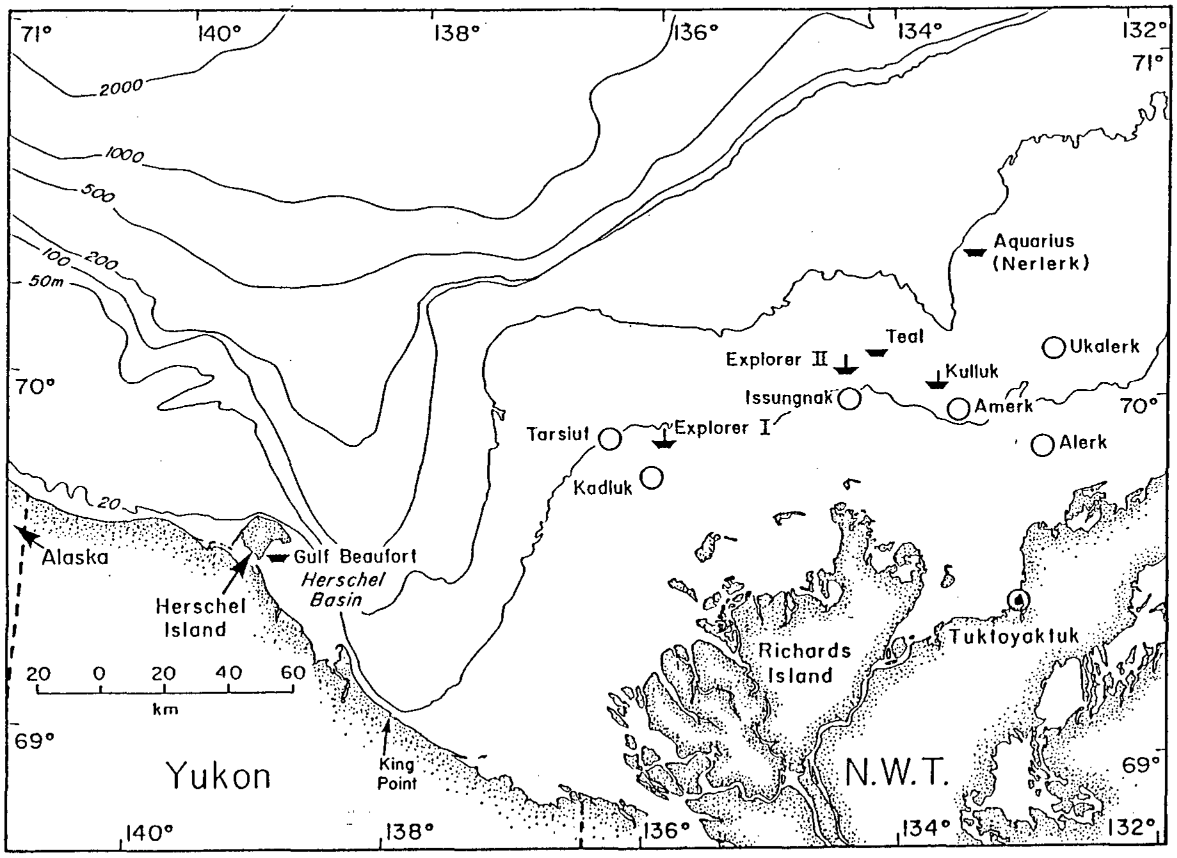


FIGURE 1. Map of the study area, east-central Beaufort Sea, showing major industrial sites mentioned in the text.

The report describes our experimental methods and equipment, the measurement results, and their significance. The results section is organized by type of sound source (e.g., aircraft, boats and ships, seismic survey signals, drillships, dredges), paralleling the preceding 'Disturbance Responses of Bowheads' section. For each type of industrial sound source, the report contains a review of what was known before, our own results, and a discussion.

Acoustic Terminology

This section is provided to acquaint readers who are not acousticians with the acoustical terminology used in this report. A good discussion of these terms appears in Ross (1976, p. 4-8). In the following discussion I have used the term 'signal' to mean the waveform of the sound pressure at the hydrophone. I am not distinguishing among the sources of that waveform as being signals or noises but include them all.

A simple form of a 'sonar equation' is

$$\text{Received level (dB//1 }\mu\text{Pa)} = \text{Source level (dB//1 }\mu\text{Pa at 1 m)} - \text{transmission loss (dB)}.$$

The terminology used in this equation is defined below. In general, the equation defines the transmission loss in terms of the difference in dB between the source level and the received level. Note that all terms in the equation may vary with frequency and with direction from the source. The equation could relate spectrum levels at source and receiver by changing the reference unit from 1 μPa to 1 $\mu Pa^2/Hz$.

dB, decibel: A unit on a logarithmic scale for sound levels. Sound pressure level in dB is defined by 20 log (P2/P1) where P2 is a pressure of interest, P1 is a reference pressure such as 1 microPascal, and the logarithm is to the base 10.

Source level: An idealized description of the intensity or power of a sound source in terms of a root mean square pressure at some short reference distance (e.g. 1 m) from the source. Idealization is essential because most sources of interest (e.g. drillship or dredge) are not point sources and an actual measurement at 1 m would not yield the effective source level. There is a strong possibility of inaccurately computing source level (at 1 m) from measurements at practical distances (say 200 m) when transmission loss from 1 m to the practical distance is assumed rather than measured. The uncertainty is especially high in shallow water.

Received Level: The sound level from a particular source of interest, as received at some location of interest. Conceptually, received level is the source level reduced by the transmission loss for the distance between source and receiver.

Tone: A signal component whose energy is at one specific frequency--i.e., whose bandwidth is infinitesimal or at least small compared to the resolution bandwidth of a spectrum analyzer. It is difficult to present tones and broadband components on the same graph correctly because the ordinates differ: dB//1 μPa for tones and dB//1 $\mu Pa^2/Hz$ for broadband components.

Spectrum Level: This is a measure of sound intensity per unit frequency. It is usually expressed in dB referred to 1 microPascal squared per Hz (1 $\mu Pa^2/$ Hz), or to 1 μPa per square root Hz. 'Spectrum density' and 'power spectrum density' or 'power spectrum' are other terms used to describe the levels of broadband signals and noises. Generally, a sound is analyzed with some non-zero bandwidth filter and the result is 'reduced to a 1 Hz band' assuming implicitly that the spectrum is constant across the analysis band.

Broadband Level: The total mean square pressure level of a signal in a wide frequency band. 'Wide' generally means large compared to 1 Hz. The broadband level is obtained by integrating spectrum levels over the band. Narrowband components (tones) falling within the band should be included.

Spherical Spreading: The attenuation of intensity or power proportional to the square of the distance travelled. It is described in dB by 20 log (R2/R1) where R1 is the reference range. Often, R1 is 1 m and the relationship reduces to "spreading loss = 20 log (range in metres)". Ideally, spherical spreading is ascribed to sound propagation where the surface and bottom are far removed from the source and receiver, and the ray paths are not refracted significantly. With spherical spreading the attenuation rate is 6 dB per distance doubled.

Cylindrical Spreading: The attenuation of intensity or power proportional to the distance travelled. It is described in dB by 10 log (R2/R1) where R1 is the reference range. Ideally, cylindrical spreading is ascribed to sound propagation where the source and receiver are far apart compared to the water depth. The surface and bottom reflections or special channeling processes serve to retain the energy within the water. With cylindrical spreading the attenuation rate is 3 dB per distance doubled.

Units of Pressure: 1 Pascal = 1 newton/m^2
1 μbar = 1 dyne/cm^2
1 Pascal = 10 μbars
100,000 μPa = 1 μbar

Thus, sound level (dB//1 μPa) = sound level (dB//1 μbar) + 100.

METHODS

Two main data collection systems were used: the system used on the airplane to record sonobuoy signals, and the system used on the sound boat. This section also describes the analysis techniques.

Airplane System

The airplane sound recording system was based on sonobuoys. During flights to observe whales, at least three sonobuoys were carried. On most occasions when whales were found and observations of their behavior were to be made, at least one sonobuoy was deployed. Occasionally a second sonobuoy was deployed nearby, sometimes with a second group of whales, sometimes with the first group after it had moved away from the first sonobuoy, and sometimes at a different distance from a nearby source of actual or simulated industrial noise. Sonobuoy hydrophones were set to deploy to 18 m depth, with the exception of a few sonobuoys modified for 9 m deployment in 1981. Two calibrated receivers for sonobuoy FM radio signals were carried. The signals were recorded on the two channels of a calibrated Sony Model TC-D5M cassette tape recorder with servo-controlled capstan for precise speed control. The operator maintained a log of activities, sounds recorded, and tape recorder settings, and he made voice announcements at the beginning of each tape and otherwise as necessary. Positions were determined from the aircraft's VLF/Omega navigation system, and an airborne radar provided measurements of distances from industrial sites.

We used two types of sonobuoys: AN/SSQ-57A and AN/SSQ-41B. The 57A's are delivered with calibration data and the 41B's are not, but otherwise both models perform to the same specification. In 1980-81 we used the middle of the allowable response envelope as the calibration response for the 41B's. In 1982-84 we used the average of the 57A calibrations as the calibration for the 41B's. The two 41B calibrations were essentially the same. Comparison of results from the sonobuoy system and from simultaneous recordings with the calibrated hydrophones on the boat (see below) confirmed that the sonobuoy system provided accurate data on sound levels and characteristics.

To permit wider signal dynamic range without distortion, the sonobuoy acoustic response attenuates low frequencies relative to high frequencies. Sounds at 10 Hz are deemphasized by about 35 dB relative to those at 10 kHz (see Greene 1982, Fig. 2, p. 269, or Military Specification, sonobuoy AN/SSQ-41B, MIL-S-22793E (AS). U.S. Navy, 24 p., 1979). The rising slope of the sonobuoy response with increasing frequencies is roughly opposite to the falling slope of average sea noise (low frequency ambient sounds tend to have higher spectrum levels than do high frequencies). This procedure provides, on average, an overall flat ambient sound spectrum through the sonobuoy/ receiver system. We corrected all received signal spectra to remove the effect of the sloped sonobuoy system response and to provide sound spectra based on a unit acoustic pressure of 1 µPa (microPascal), root mean square.

Boat System

The boat-based sound recording system used hydrophones suspended beneath a 4-6 m long sparbuoy made from 76 mm (3 in) i.d. PVC pipe. The sparbuoy drifted vertically near the sound boat and served to decouple the hydrophones from wave and boat motion. The boat was the 14-m wooden-hulled ketch 'Ungaluk' in 1980 and the 12.5-m fishing boat 'Sequel' in 1981-84. The hydrophones were of two types: (1) U.S. Navy model H56 wide band, low noise hydrophones, and (2) low frequency, low noise bender hydrophones made by Polar Research Laboratory. Both types had preamplifiers with the sensing element. The nominal sensitivity of the H56's was -172 dB//1v/µPa (dB referred to 1 volt per microPascal); the nominal sensitivity of the benders was -152 dB//1v/µPa.

In 1980 we attempted to make the recordings with hydrophone depth 18 m, for compatibility with the sonobuoys, but shallower water forced compromises. In 1981-82 we adopted 9 m as the standard hydrophone depth. In 1983-84 we used a vertical string of hydrophones at depths 3, 6, 9, and 18 m. (Not all these depths could be recorded all the time.)

We always used a Sony Model TC-D5M cassette tape recorder (low noise, servo-controlled capstan drive for constant tape speed) on the boat, as on the airplane. On the boat in 1983-84 we also had a Fostex model 250 4-channel cassette recorder, permitting simultaneous recording of hydrophones at multiple depths. All equipment was battery-powered.

To test the reactions of bowhead whales to playbacks of recorded industrial sounds, we used a U.S. Navy model J11 underwater sound projector driven by a 250 watt Bogen power amplifier. We operated the projector at depth 9 m. A monitor hydrophone was mounted (1982) or suspended (1983-84) a measured distance (1.9 m in 1982; nominally 1 m in 1983-84) in front of the projector face to measure the projected sound level. The sample of industrial sound being played back was recorded on a two-minute tape loop.

Other essential equipment on the boat included radar for distance measurements to industrial sources, coastlines, etc., a satellite navigation set to determine geographical positions accurately, and marine VHF and HF radios for communications. There was also a portable aviation VHF radio for communication with the project airplane. All recording and playback equipment was battery-powered; no generator or other engines were running on the boat during acoustical work, although a small refrigerator compressor motor sometimes ran.

Data Analysis

The recorded signals were analyzed using an analog-to-digital converter and a general purpose digital computer to process the digitized samples. For data collected in 1980-82, the analysis was done with Polar Research Lab's Data General Nova 3. In 1983 the work was done partly at Polar Research and partly at Greeneridge on a Hewlett-Packard 9816 technical desktop computer. Some analyses were done on both systems to assure identical results. In 1984 all the work was done on the Greeneridge system.

Spectral Analyses

Sounds that continued more or less without change (continuous signals) were analyzed for their frequency content using Fourier analysis to compute average power spectra. The results were displayed in a graph of spectrum level (dB//1 $\mu Pa^2/Hz$) vs. frequency (Hz or kHz). The process began with lowpass filtering ('anti-aliasing') at a frequency just below half the sample frequency, then sampling and conversion to 12-bit numbers, and storage of the digitized data on disk. The sample size was typically 17,408 values. At a sample rate of 2048 samples/s, one of the standard rates, 8.5 s of data were stored.

Power spectrum analysis was done on weighted, overlapped blocks of data (Carter and Nuttall 1980). A block of samples, typically 2048 or 1024 samples in length, was multiplied by a 'window' function (Blackman-Harris minimum 3-term window, Harris 1978) to minimize 'leakage' of the power in one frequency cell from appearing in adjacent cells. The result was then analyzed with a fast Fourier transform routine to compute the power spectrum for that block. Then another block of samples was selected, half of which had been in the previous block; it was analyzed the same way as the previous block and the results were added to those from the previous block. This process was continued until the entire set of samples was analyzed and the averaged power spectrum determined. The parameters of power spectrum analysis and the relationship of sample frequency and analysis block size to spectrum cell spacing and resolution are presented in Table 1.

Table 1. Parameters of spectrum analysis. The number of cells in the resulting spectrum was always 1 more than half the number of samples in the block.

Sample Rate (samp./s)	Block Size (samples)	Data Averaged (s)	Cell Spacing (Hz)	Cell Resol. (Hz)	Analysis Range (Hz)
1024	1024	16.5	1	1.7	0-512
2048	1024	8.25	2	3.4	0-1024
2048	2048	8.5	1	1.7	0-1024
4096	2048	4.25	2	3.4	0-2048
4096	1024	4.125	4	6.8	0-2048
8192	1024	2.06	8	13.7	0-4096
16384	1024	1.03	16	27.4	0-8192

Our calibrations did not generally extend below 10 Hz and we did not compute results below that frequency. High and extremely variable levels of water and wave noise often dominated the very low frequencies, and 20 Hz was often the lower practical limit for consistent results. For an upper limit we selected 500, 1000, 2000, 4000, or 8000 Hz as appropriate for the sampling rate.

From the spectrum analysis results we derived two other types of results. One was the level of each tonal component in the sound. These sinusoidal components, which may themselves be harmonics of complicated periodic components, theoretically have an infinite power density because there is actually non-zero power at the exact frequency of the tone. We computed the level of each tonal component by removing the correction for the analysis cell bandwidth. The result was a sound level expressed in dB//1 µPa.

The other result derived from spectrum analysis was the sound level within a band of frequencies--the band level, expressed in dB//1 µPa. For specified band limits, we integrated the spectrum to compute the band level within those limits. We generally used the band from 20-1000 Hz, because most industrial (and bowhead) sounds contained very little power at higher frequencies. Because most industrial sounds were mainly at <500 Hz, band levels for 20-1000 Hz, 20-8000 Hz, etc., were usually <1 dB greater than those for 20-500 Hz.

Waveform Analyses

For transient signals, those with definite starts and finishes like seismic survey signals and bowhead tail slaps, we plotted the signal waveform and measured the peak amplitude. Transient signals generally took on an oscillatory form after travelling a few kilometres in the shallow water of the Beaufort Sea, and we converted the peak amplitude into an 'effective level' by (1) assuming a sinusoid of the measured peak amplitude, (2) determining the corresponding rms level, and (3) converting the result to a level in decibels referred to 1 µPa.

Waterfall Diagrams

It is often valuable to see how the frequency content of an acoustic signal varies with time. For example, during the fraction of a second while a waterborne seismic signal is received, its peak frequency decreases with increasing time when the receiver is more than 3 or 4 km from the source in shallow water. Whale calls often change in frequency across the duration of the call. Sounds from an aircraft wax and wane as it passes overhead. To display spectral amplitudes vs. frequency and time, we used a 'waterfall' spectrogram. The same discrete Fourier transform process used to compute average power spectral densities was used to compute the waterfalls except that (1) the overlap was 75-90% rather than 50%, and (2) the results of analyzing each block were not averaged but were presented in a tight progression of spectra plotted against time. The spectral magnitudes were plotted, not powers or log spectra, and all magnitudes were scaled relative to the largest magnitude in each waterfall display.

RESULTS AND DISCUSSION

Sound Propagation Conditions

Figure 2 presents some examples of sound ray paths computed from measured temperature-salinity-depth profiles in our study area. Urick (1983, p. 111-128) presents a useful discussion of sound velocity and ray paths. The upper 10 m of the depth dimension in Figures 2B and C demonstrate how an increasing sound speed with increasing depth causes sound rays to bend upward, reflecting from the surface but also being scattered by waves or ice. Figure 2A demonstrates how a decreasing sound speed with increasing depth causes sound rays to bend downward, reflecting from the bottom but also being absorbed and scattered. In fact, for the generally shallow waters studied, sound waves would be continually reflected from the surface and the bottom, continually losing energy to scattering and absorption.

Ambient Noise

Background

In discussions of underwater sound, the standard ambient noise fiducials have been the average noise spectra of Knudsen et al. (1948) for various sea states. His data were generally for deep water and did not extend below 500 Hz; his noise spectra were for 1 kHz and above. His curves show the ambient noise spectrum level to vary with sea state or wind force and to decrease at 5 dB per octave with increasing frequency. Knudsen's curves are often extended to lower frequencies by extrapolation at slope -5 dB/octave, although Wenz (1962) showed that noise at lower frequencies (10-200 Hz) depends strongly on shipping traffic density rather than wind force. Urick (1983, p. 202-236) presents a comprehensive discussion of ambient noise in the sea. Other reviews of ambient noise in cold water regions appear in Greene (1981) and Richardson et al. (1983). Shallow water noises can extend over a wide range of levels and should be measured on a site-specific basis.

In this report we use the sound level in the 20-1000 Hz frequency band as an overall summary value for industrial sounds. For comparison, the integrated 20-1000 Hz level for Knudsen's Sea State Zero spectrum extended to low frequencies is 87 dB//1 µPa. For Beaufort Wind Force Five (approx. 31-39 km/h; Sea State Four), the corresponding level is 107 dB.

Measurements

We did not make comprehensive measurements of underwater ambient noise, but numerous recordings were analyzed to determine background levels during bowhead observations and to compare with the strength of industrial sounds. The data summarized here were from recordings made specifically to document background noise. Weak industrial or aircraft sounds were sometimes present, but man-made sounds were not dominant. Such background sounds are a part of the ambient noise near the industrial part of the Beaufort Sea. When several ambient noise measurements were made at nearly the same time and place, we averaged them to obtain a single independent measurement. However, data from different hydrophone depths were not averaged. There were 81 independent measurements over the five years of study, although only 15 came from 1980-82. The data are the 20-1000 Hz band levels, in dB referred to 1 microPascal:

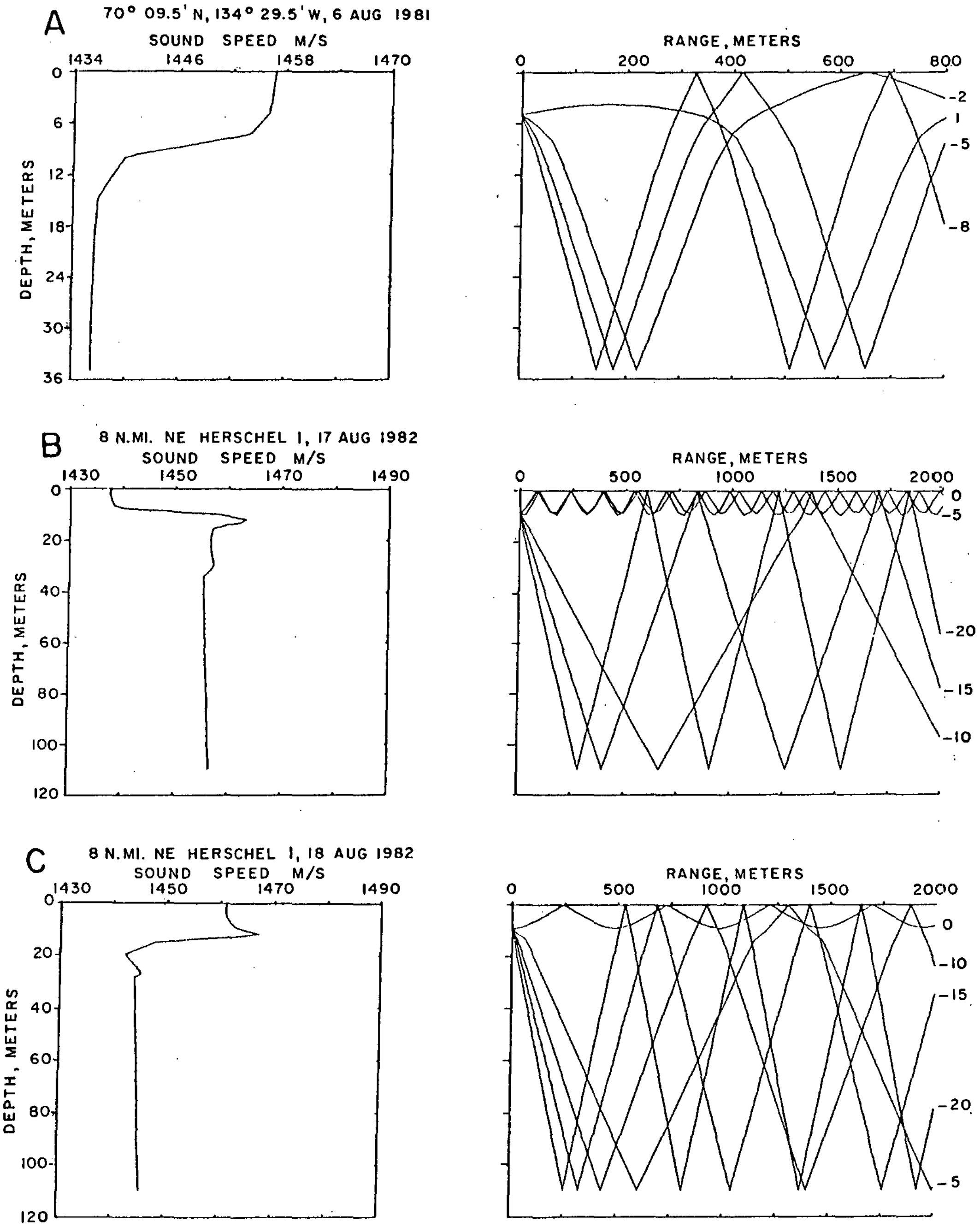


FIGURE 2. Sound speed profiles and examples of associated sound ray paths. **(A)** is from the industrially active area north of Tuktoyaktuk, 6 August 1981. The source depth for the ray paths was 5 m and the initial ray angles are specified at the right end of each ray. **(B)** is for the deeper (110 m) area northeast of Herschel Island from within an area dominated by ice. The cold surface water and the warmer layer beneath account for a shallow surface duct. **(C)** is the same area as **(B)** but one day later and without ice.

Measurement Source	Depth (m)	No. of Obs.	Percentiles		
			10%	50%	90%
Sonobuoys	18	29	86 dB	99 dB	111 dB
Boat	18	22	81	99	117
Boat	9	15	77	94	112
Boat	3	15	71	99	121

For comparison, the expected levels for sea states 0, 1, 2, 4 and 6 are 87, 95, 100, 107 and 112 dB, based on Knudsen's curves extended to low frequencies.

Median levels for the sonobuoy and boat measurements at hydrophone depth 18 m were the same, 99 dB. This is 1 dB less than the fiducial level (extended to low frequencies) of 100 dB for Sea State Two (wind 13-18 km/h). It is important to recognize that most measurements from both the boat and aircraft were made in low wind conditions (Sea State 0-3). Thus, our analysis excludes data from times expected to have high noise.

Analysis of the 1984 data alone revealed that the median level for hydrophone depth 3 m was 8 dB lower than the median level for depth 18 m. Adding the 1983 measurements resulted in a median level for depth 3 m equal to the median level at depth 18 m. In both 1983 and 1984, the range of the measured noise levels was greater at depth 3 m than at depths 9 and 18 m. Levels at 3 m were sometimes much higher than at 9 and 18 m depths, probably because of surface wave action that affected low frequencies (<40 Hz). This surface effect was not observed at depth 9 m.

Figure 3 presents five representative spectra for ambient noise observed during the project. In 1982 we worked with bowheads near an area of ice floes northeast of Herschel Island. Figure 3A is the background noise spectrum, frequency resolution 1.7 Hz over the 10-500 Hz band, detected with a sonobuoy near ice. The water depth was 80 m, the sea state was zero, and the ice coverage was 10%. Three strong tones appear from the Britten-Norman Islander airplane. The 10-500 Hz and 20-1000 Hz band levels for this sample were 97 and 98 dB, respectively. Excluding the three strong airplane tones, the band level was 96 dB. Figure 3B is the 160-8000 Hz spectrum, frequency resolution 27.4 Hz, for the same time. The 160-8000 Hz band level was 98 dB, exemplifying the observation that the energy in the noise was concentrated at lower frequencies. The high levels, relative to the expected values for sea state zero, were probably attributable to the ice. The dip in the spectrum near 3000 Hz is unexplained.

Figures 3C and 3D are presented to provide a comparison of the ambient noise spectra at hydrophone depths 3 and 18 m, respectively. At the time of the recording, 'Sequel' was in Mackenzie Bay, water depth 26 m, low sea state. The 20-1000 Hz band levels were 73 dB//1 µPa for depth 3 m and 85 dB for depth 18 m, exemplifying the common tendency for lower levels at shallow receiver depths. The relatively low level spikes at frequencies <60 Hz

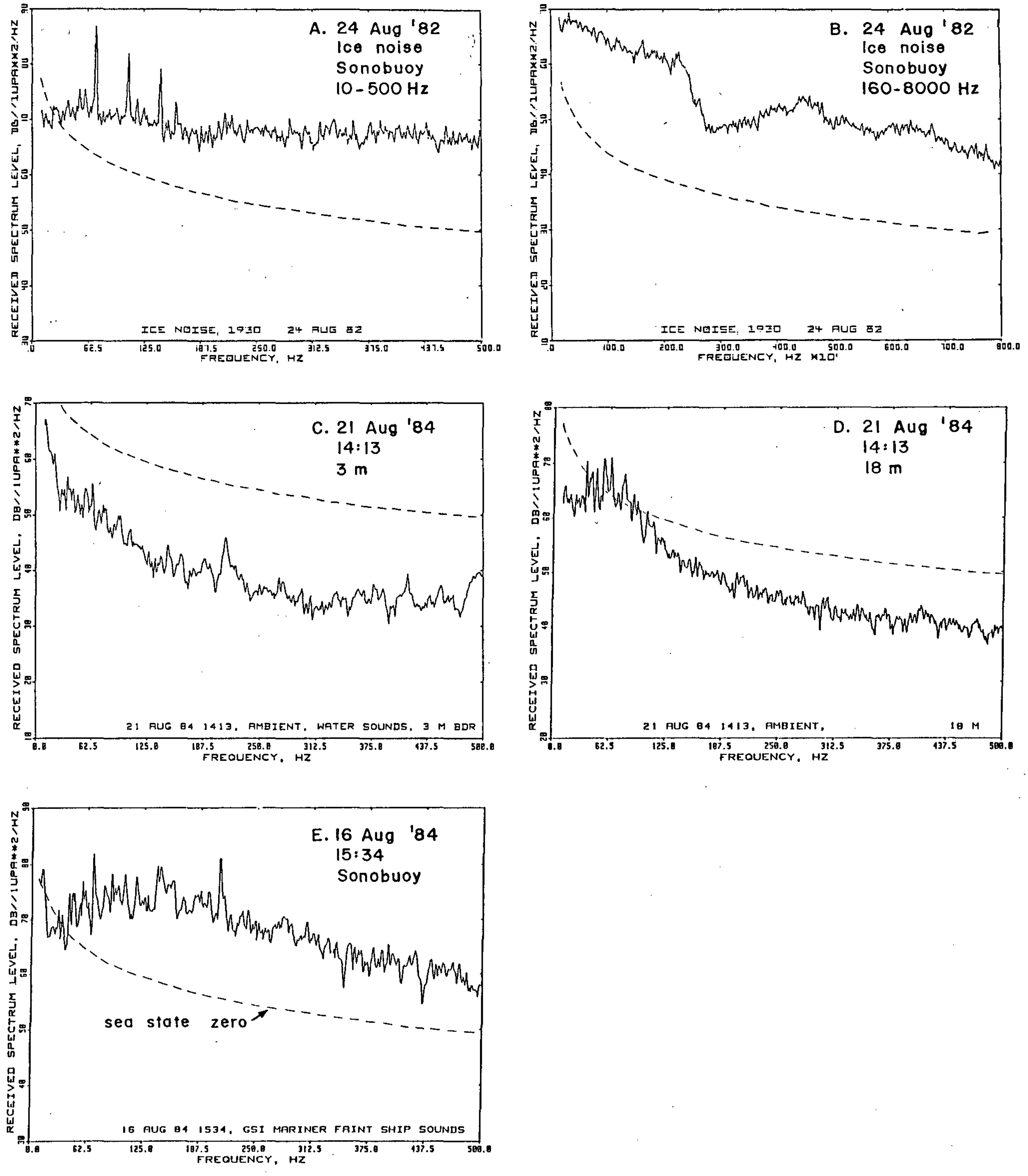


FIGURE 3. Examples of ambient noise sound pressure spectra. The extended sea state zero spectrum has been added for reference. Note the variable vertical scales.

suggest the presence of weak machinery sounds, probably from a distant source. This was a time of very low background noise.

Figure 3E shows the background noise spectrum in Mackenzie Bay just before the start of a disturbance experiment with a full-scale airgun array, 16 August 1984. The water depth was 18 m, as was the sonobuoy hydrophone depth, and the sea state was one. The 20-1000 Hz band level was 98 dB. Faint ship sounds could be heard, and the spectrum shows the presence of tones; these probably came from the vessel 'GSI Mariner', which was about 7.5 km from the sonobuoy.

Discussion

Our data show instances of sound spectrum levels well below Knudsen's fiducial curve for Sea State Zero extended, which is not surprising considering the shallow water, relatively calm weather, and the absence of shipping noises in some of the areas where we worked. At other times, we recorded high levels of ambient noise, similar to levels expected in stormy seas. We sometimes found that sound levels at depth 3 m were lower than at depth 18 m, as theory predicts for sound pressure near the air/water boundary (Urick 1983, p. 131-4). However, levels at 3 m depth in open water appeared to be strongly affected by wave action, and sometimes exceeded those at deeper depths. Greene and Buck (1964) reported measurements of ambient noise below ice in deep water (Beaufort Sea) and noted that the level was nearly constant below a depth corresponding roughly to one-half the wavelength. Above that depth the level decreased. In shallow water the effect would be modified by the influence of the bottom, depending on frequency, depth, and bottom material characteristics.

Aircraft Sounds

Background

The theory of sound propagation from a source in air to a receiver underwater has been well documented, but there are relatively few published measurements of aircraft noise in water (Medwin and Hagy 1972; Urick 1972; Waters 1972; Young 1973). Although sound power or energy is poorly transmitted from air into water, it is also true that sound pressure is rather well transmitted from air into water under the right circumstances. Snell's law predicts a critical angle of 13° from the vertical for the transmission of sound pressure from air into water. For greater angles the sound is totally reflected.

For vertical incidence, the sound pressure at the water surface is twice what the sound pressure would be at that distance from the source if the water were not present. Within the water, the levels decrease as the receiver depth increases. For receivers not directly beneath the source, the pressure pattern is complex. For intermediate lateral distances, on the order of the aircraft height and somewhat greater, the sound pressure is less near the surface than at greater depths, contrary to the situation directly below the aircraft (Urick 1972). In rough water we expect the sound to enter the water over a larger area than in smooth water because the slope of the waves extends the range at which sound rays impact the surface within 13° of normal to the wave face. In shallow water we expect bottom and surface reflections to carry the sound farther horizontally than would be the case in deep water.

Measurements

Sounds from five types of aircraft were measured during the project, two types of fixed-wing airplanes (deHavilland DHC-6 Twin Otters and a Britten-Norman BN-2A-21 Islander) and three helicopters (Bell 212, Bell 214ST, and Sikorsky 61). Table 2 presents the 20-1000 Hz band levels for these measurements. The power settings were not all comparable for these aircraft, as the Islander was at circling power for some of its passes. The level in the 20-40 Hz band was highly variable in the data for the Islander overflights, especially at depth 3 m. Hence, we also present Islander measurements for the 40-1000 Hz band, along with the levels of the dominant blade rate tone in the Islander's noise spectrum (Table 3). This tone was at 68-74 Hz, depending upon operating power levels.

Table 2. Measured 20-1000 Hz band levels, in dB//1 µPa, for five types of aircraft vs. aircraft altitude (152-610 m) and hydrophone depth (3-18 m). All measurements are for the 4 s during which peak sound level was received (i.e. while the aircraft was directly overhead or almost so).

Type	Water Depth (m)	Alt. 610 m		Alt. 457 m		Alt. 305 m		Altitude 152 m		
		3 m	9 m	3 m	9 m	3 m	9 m	3 m	9 m	18 m
Twin Otter	22		106		101		113			
	22		104		106					
B-N Islander	15	108	107	116	105	121	110	117	114	
	15	106[a]	103[a]		105[a]	122	112	123	113	
	15	104[a]	105[a]	119[a]	106[a]					
	15	109	108							
Bell 212	25		108				111			
Bell 214ST[b]	22							104		amb.
Sikorsky 61[c]	37							102	111	105

[a] Islander was circling at reduced power.

[b] The Bell 214ST did not pass directly overhead and was barely audible at depth 18 m; the ambient level was 110 dB in the 20-1000 Hz band. The Bell 214ST passed about 150 m astern of the sound boat. The peak sound levels were received when the helicopter was approaching at range about 200 m.

[c] The Sikorsky 61 was not audible underwater during a pass at altitude 1070 m. Its pass at altitude 152 m was not overhead, but about 50 m to the side (i.e. at an estimated elevation angle of 70°).

Table 3. Level of the 68-74 Hz blade rate tone and the 40-1000 Hz band level, in dB//1 μPa, for the Britten-Norman Islander overflights at 152-610 m altitude on 18 August 1983. Levels were measured over the 4 s period of maximum amplitude. The background level in the 40-1000 Hz band was 83 dB at hydrophone depth 3 m and 85 dB at 9 m. Water depth 15 m.

610 m		457 m		305 m		152 m	
3 m	9 m	3 m	9 m	3 m	9 m	3 m	9 m
Level of blade rate tone at 68-74 Hz							
102*	94*	105	101	105	103	113	107
93*		97	103	109	106	114	108
90*	89*	98*	102*				
105	103	102*	102*				
101	**97**						
40-1000 Hz band level							
106*	103*	109	107	112	110	117	114
106*		102	105	113	112	117	113
103*	105*	106*	105*				
109	108	108*	106*				
108	107						

* These values came from 'circling' passes at 140 km/h. Other values came from straight-line passes at 200 km/h.

Tables 2 and 3 indicate that, for flights overhead, the sound levels decreased with increasing aircraft altitude. This is especially clear from Table 3, where wave and water noise have been reduced by restricting the frequency band to 40-1000 Hz. Also, the shallowest hydrophone usually received the highest sound level. Noise levels from the Twin Otter and Islander, at least in the 20-1000 Hz band, were similar to one another.

The limited sound level data for the Bell 212 helicopter were similar to those for the fixed-wing aircraft in the 20-1000 Hz band (Table 2). However, levels at <20 Hz were higher for the Bell 212 because of its strong blade rate tone near 11 Hz (see below). A comparison of the sound levels from the three helicopters would be misleading, as there are no data for the Bell 212 at altitude 152 m, and neither the Sikorsky 61 nor the Bell 214ST flew directly overhead. In general, for helicopters it may be important to include lower frequencies, at least down to 10 Hz, to assure that the fundamental frequency resulting from the main rotor blade rate is included. Whether bowhead whales can hear sounds at these low frequencies is unknown.

The Islander airplane was audible for longer periods at depth 3 m than at 9 m (Table 4). The shallower water and the significantly lower background levels account for the longer durations of audibility of the Islander than of other aircraft. Sound physics predicts this shallow water effect because, theoretically, airborne sound is reflected from the water surface except within a cone delimited by 13° from vertical. The shallow water permits the

Table 4. Duration of audibility of various aircraft.

Aircraft Type	Aircraft Altitude	Water Depth	Sea State	20-1000 Hz Ambient Noise at 9 m	Duration (s) at Depth	
					3 m	9 m
B-N Islander (circling)	457 m	15 m	1	86 dB	continuous	58-75
"	610	15	1	86	84-110	66-78
B-N Islander (Cruise Power)	152	15	1	86	72-87	52-60
"	305	15	1	86	53-76	49-75
"	457	15	1	86	44-58	34-42
"	610	15	1	86	59-84	39-52
Bell 212	152	25	1	100		16-21
"	305	25	1	100		18-27
"	457	25	1	100		
"	610	25	1	100		26
Twin Otter	152	22.5	0	95		33-36
"	305	22.5	0	95		29
"	457	22.5	0	95		37
"						
Bell 214ST (oblique pass)	152	22	3	100[a]	38	11[a]

[a] Hydrophone depth was 18 m, not 9 m, in this case.

sound entering the water within the cone to be reflected from the bottom to the surface and back, spreading out to more distant ranges than would be possible in deeper water. In theory, an aircraft flying over calm deep water at an altitude of 610 m and a speed of 200 km/h would be heard for only about 5 s with a shallow hydrophone.

In general, the sounds from approaching aircraft were detectable much earlier in the air than in the water. For example, prior to the arrival of the Bell 214ST, it was audible for over 4 min in the air but for only about 20 s in the water (depth 3 m).

Tones were present in the sound spectra from all these aircraft (Fig. 4). In the five power spectra displayed (Fig. 4A-E), the frequency range is 20-1000 Hz, the analysis cell spacing is 2 Hz, the effective cell bandwidth is 3.4 Hz, and the averaging time is 4 s. For comparison, the dashed spectra show the background noise at the times of the measurements.

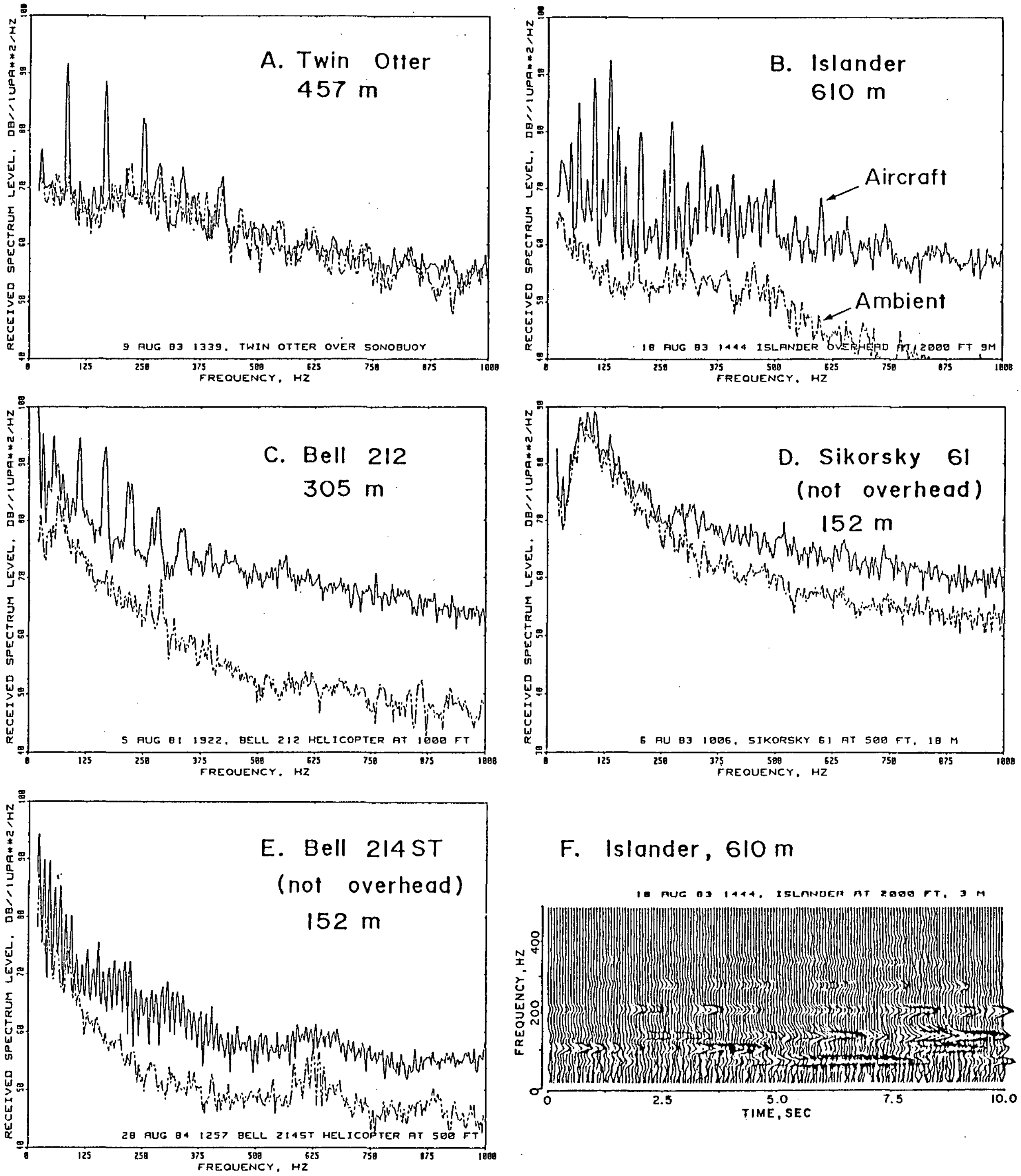


FIGURE 4. Aircraft spectra compared with ambient noise: **(A)** deHavilland Twin Otter overhead at altitude 457 m; **(B)** Britten-Norman Islander overhead at altitude 610 m; **(C)** Bell 212 helicopter overhead at altitude 305 m; **(D)** Sikorsky 61 helicopter about 20° from overhead, altitude 152 m; **(E)** Bell 214ST helicopter about 55° from overhead, altitude 152 m; **(F)** waterfall spectrogram of the Islander overhead at 610 m. Spectra in (A)-(E) were averaged over 4 s.

For a DHC-6-300 Twin Otter circling at altitude 457 m over a sonobuoy (hydrophone depth 18 m) in water 210 m deep (Fig. 4A), the fundamental frequency of the harmonic family is 83 Hz, corresponding to the propeller blade rate on a shaft turning 1670 rpm (3-bladed propellers). The 20-1000 Hz band level was 102 dB//1 µPa. Only the tonal components in the Twin Otter spectrum extended above the ambient noise spectrum, whose 20-1000 Hz band level was 95 dB.

For the Islander circling over 'Sequel' at altitude 610 m, hydrophone depth 9 m, water depth 15 m (Fig. 4B), the propeller blade rate tone is at 68 Hz, the fundamental frequency of a harmonic family corresponding to an engine shaft speed of 2040 rpm (2-bladed propellers). The cylinder firing rate is 102 Hz, the fundamental frequency of another harmonic family whose second and higher harmonics coincide with harmonics from the blade rate. The 20-1000 Hz band level was 103 dB; for the background noise it was 83 dB.

For a Bell 212 helicopter flying straight over 'Sequel' at 185 km/h, altitude 305 m, hydrophone depth 9 m, water depth 25 m (Fig. 4C), strong tones occur for harmonic families with fundamentals at 10.67 and 55 Hz. The 10.67 Hz tone corresponds to a (2-bladed) main rotor rate of 320 rpm, compared to 324 rpm reported by a factory representative as normal. The fundamental frequency is not displayed in Figure 4C, as data are displayed only for the frequency range 20-1000 Hz. The 55 Hz fundamental frequency is for the tail rotor blade rate and corresponds to a rotation rate of 1650 rpm (2-bladed tail rotor). This agrees with the normal speed reported to us by the Bell factory representative. The 20-1000 Hz band level for this overflight by the Bell 212 was 111 dB//1 µPa. The corresponding level for the background noise was 99 dB.

For a Sikorsky 61 helicopter at altitude 152 m flying past 'Sequel' at an elevation angle of approximately 70°, hydrophone depth 18 m, water depth 37 m (Fig. 4D), the 20-1000 Hz band level was 105 dB. The two strongest tones occurred at 68 and 102 Hz, but their levels were not much greater than the background spectrum levels. The 20-1000 Hz level for the background noise was 104 dB.

For a Bell 214ST helicopter flying past 'Sequel' at an altitude of 152 m, about 150 m aft of the boat, the strongest sounds underwater occurred before the closest point of approach, when the range was about 210 m and the elevation angle was about 35° (Fig. 4E). The water depth was 22 m, the hydrophone depth was 3 m, and the 20-1000 Hz band level was 104 dB//1 µPa (vs. 97 dB for background noise). This level cannot be compared with those for other aircraft that flew directly overhead. The spectrum for depth 3 m displays a harmonic family whose fundamental frequency is close to 11.8 Hz, corresponding to a main rotor rate of 354 rpm (2-bladed rotor). For tones at 36 and 154 Hz, levels at depth 18 m were 2 and 13 dB greater, respectively, than levels at 3 m depths. The theory of sound travelling from air to water predicts higher levels at greater depths for horizontal ranges greater than the altitude (Urick 1972), which was the case here.

Figure 4F is a waterfall spectrogram of the same Islander overflight whose average spectrum for depth 9 m is presented in Figure 4B. However, the waterfall is for depth 3 m. Perhaps because of aspect changes as the airplane flew over, or perhaps because of changes in reflection interference (water depth only 15 m) as the airplane flew over, the waterfall shows the different tonal frequency components fading in and out over the 10 s period.

Discussion

Our measurements demonstrated that aircraft sounds are received at significant levels underwater. It is not clear from the band level data that any particular aircraft is louder than the others. However, the Bell 214ST and the Sikorsky 61 did not pass over the hydrophone and are presumably louder than the measurements indicate. In air, the Bell 214ST seems particularly noisy to the human ear. The Islander overflights were over shallower water than those of the Bell 212 or Twin Otter (15 m vs. 22-25 m), which probably accounts for the longer periods of audibility for the Islander.

Moore et al. ([1984] p. 40-42) report a sound power spectrum for a Twin Otter at altitude 450 ft (137 m), presumed to be nearly directly over a sonobuoy. They found a strong family of tones with fundamental frequency 83.75 Hz; the shape of their spectrum was similar to ours (Fig. 4A).

Summarizing the main conclusions regarding underwater noise from aircraft: (1) the levels are high for only a few seconds; (2) the duration of audibility depends on the hydrophone and water depths; (3) immediately below the aircraft, the levels are highest just below the surface; (4) to the side, in shallow water, the levels appear to be higher at greater depths; and (5) there are many tones in aircraft signatures, and most of the energy occurs at frequencies below 500 Hz.

Boat and Ship Sounds

Background

Ship-radiated noise has always been of interest to navies because such noise, depending on its source, either permits or interferes with detection and tracking of submarines. Much information on ship-radiated noise is not available to the public. However, Ross (1976) provided an overview of noise generation, and Buck and Chalfant (1972) and Cybulski (1977) provided specific measurements of the sounds from large vessels. Recent summaries include Ross (1981) and Richardson et al. (1983, p. 41-46).

On a ship or boat, the propulsion machinery accounts for a major portion of the radiated sound. This includes the main engines, motors (if diesel-electric drive), gear reduction transmissions, and propellers. Other sources of sound include pumps, ship's service electric generators, ventilators, compressors and the like. Flow noise from the water dragging along the hull is also a source of noise, as are the bubbles breaking in the wake.

The sounds may be of two types: (1) broad band 'hissing' sounds not concentrated at any particular frequencies but spread continuously over a band of frequencies, and (2) narrowband tonal sounds concentrated at particular frequencies associated with rates of events in machinery operation. Examples of tonal sources are engine cylinder firing rates, shaft rotation rates, and blade rotation rates in propeller and turbine operation. Typically, tonal components from propulsion machinery are at low frequencies, rarely exceeding 100 Hz. Auxiliary machinery tones may occur at frequencies up to a few kiloHertz. These types of machinery often give rise to harmonic families of tonal components. Examples of broadband noises include the rushing sounds of fluids in pipes, and the sounds of propeller cavitation. Cavitation is a major source of sound, and it may be modulated by low frequencies associated with the shaft and blade rates.

Although sound levels emitted by a ship can be strongly affected by its design and speed, there is a rough correlation between sound levels and the size of the vessel. Large size implies high power. Even if only a small fraction of this power is radiated as acoustic power, it may create a strong sound. Large vessels also tend to have large drafts, creating large hull areas for efficient coupling to the water. Small vessels typically radiate higher proportions of their sound at higher frequencies. Their propellers are relatively small and turn relatively fast, operating under ideal conditions for noisy cavitation.

Depending on the background noise, low frequency sound from ships (below 100 Hz) sometimes can be detected at great distances, on the order of hundreds of kilometres, in deep oceans. Higher frequency sounds do not travel as far because of their generally lower source levels and higher rates of absorption.

Measurements

During the project we measured the sounds from three small diesel-powered boats (personnel transports, our sound boat), four supply and survey vessels, three dredges underway, and a large tanker at anchor. The results of band level analyses are summarized in Table 5, which presents the received sound levels for different measurement distances and different hydrophone depths. Data for the 18 m hydrophone depth, and the 9 m depth when 18 m was not available, are also summarized in Figure 5 to show how the various boat and ship sounds compare with one another.

The highest levels were from hopper dredge 'Geopotes X' underway at 24 km/h, reportedly with a damaged propeller. Somewhat lower levels were received from the bow thrusters on 'Canmar Supplier III', 'Canmar Supplier VIII' underway, and hopper dredges 'Gateway' and 'Cornelis Zanen' underway. Then, at somewhat lower values, are the levels from the anchored supertanker 'Gulf Beaufort', the crew boats 'Imperial Adgo' and 'Imperial Sarpik', the fishing boat 'Sequel', and survey vessel 'Canmar Teal'. The lowest levels, predictably, came from the anchored, small survey vessel 'Arctic Sounder' running only a generator for ship's service.

Figure 5 also provides an indication of the rate of attenuation of a signal with increasing range. A reasonable model for received level vs. range includes a log term for spreading loss and a linear term for the combination of absorption, scattering, and reflection losses. The log term plots as a straight line on a graph scaled like Figure 5, and the linear term causes the line to droop with increasing range. This effect can be seen in the plotted points for hopper dredge 'Cornelis Zanen' and for the three longer ranges for hopper dredge 'Geopotes X'. The amount of droop, i.e., the magnitude of the linear coefficient of range, will be greater for higher frequency and/or shallower water (Greene 1982).

Table 5. Boat and ship sound levels, in dB//1 μPa, in the 20-1000 Hz band. Vessels were underway unless noted as "anchored" or "bowthrusters".

	Water Depth (m)	Range (km)	Level at Depth		
			3 m	9 m	18 m
Small Diesel Boats	18.5	0.2			118
Imperial Adgo	18.5	0.4			117
(16 m crew boat)	18.5	3.7			107
Imperial Sarpik	11	2.8	107	110	
(21 m crew boat)	11	4.6		105	
Sequel (12.5 m fishing boat)	18	2.6			104
Survey & Supply Boats					
Arctic Sounder, anchored	11	0.5		103	
	11	0.9		97	
Canmar Supplier III, bowthrusters	27	0.19		137	
Canmar Supplier VIII	46	0.2			129
Canmar Teal	34	4.6	98	103	105
Dredges Underway					
Geopotes X	25	0.46		150	
(17,981 tons)	25	7.4		131	
Gateway	12	1.1		123	
(14,000 hp; cap. 6000 m^3)	12	1.1		130	
	12	1.3		131	
	12	1.5		128	
	12	1.5		131	
Cornelis Zanen	20	2.4		128	
(15,000 hp; cap. 8000 m^3)	20	3.2		124	
	20	5.0		116	
	29	7.4		108	
Tanker Anchored					
Gulf Beaufort	20	0.19	114	120	120
(153,000 dwt)	20	0.37	113	118	118
	20	0.93	115	120	120
	20	0.93	116	121	122
	20	1.85	103	110	111
	20	3.7	88	101	103
	20	9.3	89	95	95

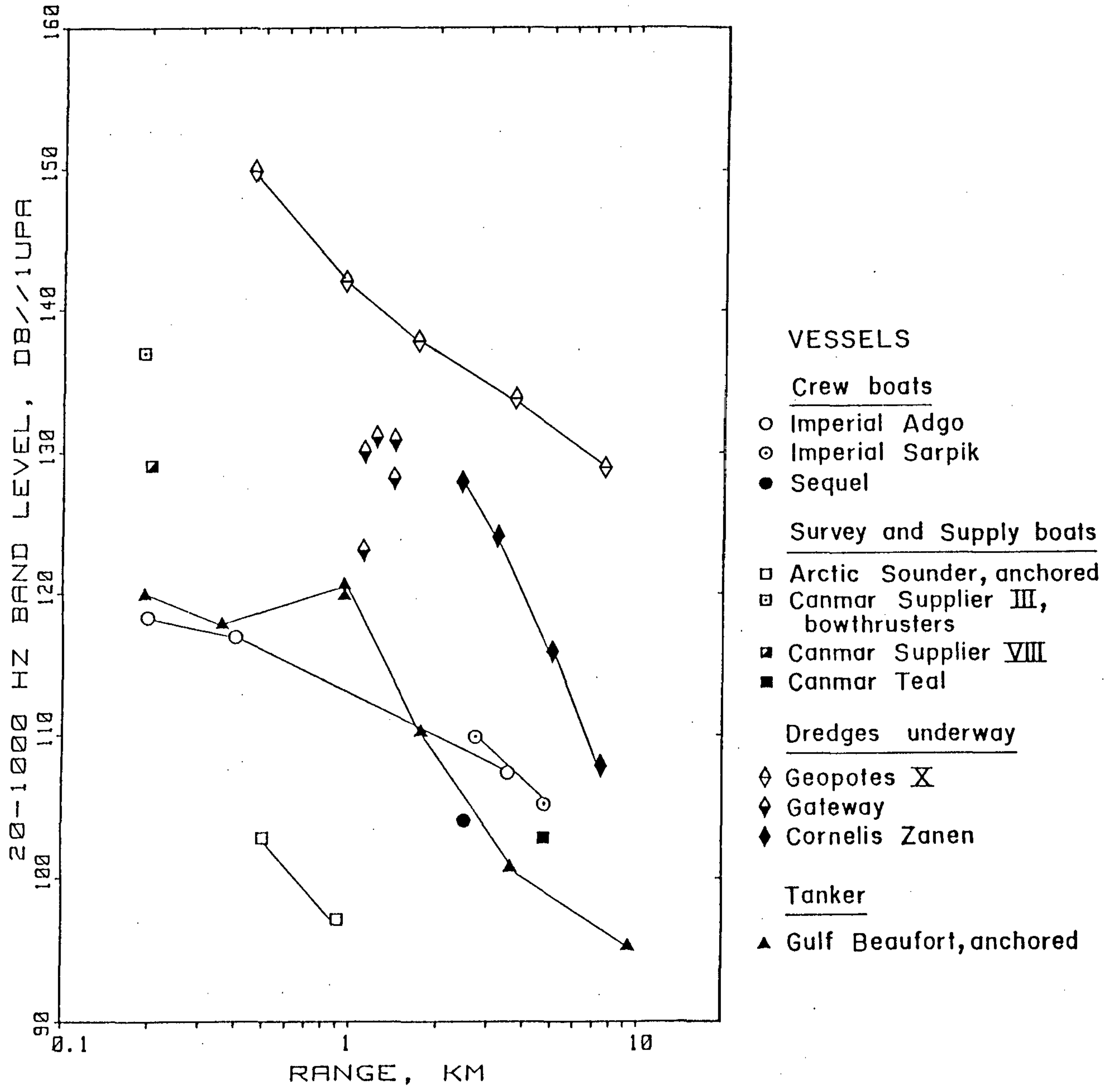


FIGURE 5. Boat and ship sound levels in the 20-1000 Hz band, in dB//1 μPa, vs. range. All values are from hydrophones at depths 18 or 9 m. These data are also presented in Table 5. Vessels were underway unless noted as "anchored" or "bowthrusters".

The peak in the data for 'Gulf Beaufort' at 0.93 km (Fig. 5) shows clearly that the source level of the sounds increased between the recordings at 0.37 and 0.93 km. The final point, at range 9.3 km, may have included a substantial level of background noise; unfortunately, we could not measure the background without the tanker sounds.

Representative boat and ship spectra are presented in Figure 6, along with corresponding background noise spectra. All spectra span the frequency range from 10-500 Hz with analysis cell spacing of 1 Hz, effective bandwidth of 1.7 Hz, and 8.5 s averaging. Figure 6A shows the tones in the signature of crew boat 'Imperial Sarpik' underway at high speed at range 2.8 km, water depth 11 m. The strongest tone was at 195 Hz, and other tones were separated by 15-17 Hz. However, there was no clearly defined harmonic family. The tones can be accounted for by a modulation model in which the 195 Hz tone is modulated by a signal rich in the harmonics of frequency 16 Hz, which may be the blade rate. The 20-1000 Hz band level was 110 dB. The background spectrum included tones presumed to be from 'Arctic Sounder' anchored 0.93 km away and operating only housekeeping generators. The 20-1000 Hz background noise level was 99 dB. 'Arctic Sounder' was 2.2 km away when 'Sarpik' sounds were recorded.

Figure 6B shows a harmonic family from operation of the bow thrusters on 'Canmar Supplier III' as it pulled away from drillship 'Explorer II', range 0.2 km. The fundamental frequency was at 118 Hz, corresponding to a rate of 7080 events/s, probably the blade rate of a multibladed wheel. Although not all are shown in this graph, the first nine harmonics were prominent, to 1064 Hz. The 20-1000 Hz band level of this signal was 138 dB. The corresponding background noise level was 130 dB, the result of drillship 'Explorer II' being only 0.2 km away.

For 'Canmar Supplier VIII' underway at range 0.2 km (Fig. 6C), the 20-1000 Hz band level was 129 dB. The strongest tone was at 57 Hz, 119 dB//1 µPa. The background noise, recorded 1 min later, included sounds from vessels 3.7 km away; the 20-1000 Hz level was 126 dB.

Figure 6D is the spectrum for hopper dredge 'Geopotes X' underway at 24 km/h at range almost 500 m, water depth 25 m, hydrophone depth 9 m. We were informed that the ship had a damaged propeller that season, which probably is at least partly responsible for the broad spectral hump whose maximum is at 80 Hz. A family of tones can be seen along the left, rising slope of the hump. These peaks were 4-7 Hz apart. The 20-1000 Hz band level was 150 dB at range 0.5 km. 'Geopotes X' produced the strongest continuous noise recorded during this project. The 20-1000 Hz background noise level was 99 dB, but only a few components appear on Figure 6D because of the scale needed to show the strong ship sounds.

The relatively low received levels at frequencies below 50 Hz are probably a result of the high rate of attenuation of these long-wavelength sounds in shallow water. Although we have no data at ranges less than 0.5 km, it is very probable that much energy was produced at frequencies below 50 Hz as well as near 80 Hz. This same effect is evident in Figures 6E and 6F, and in some similar diagrams later in the report.

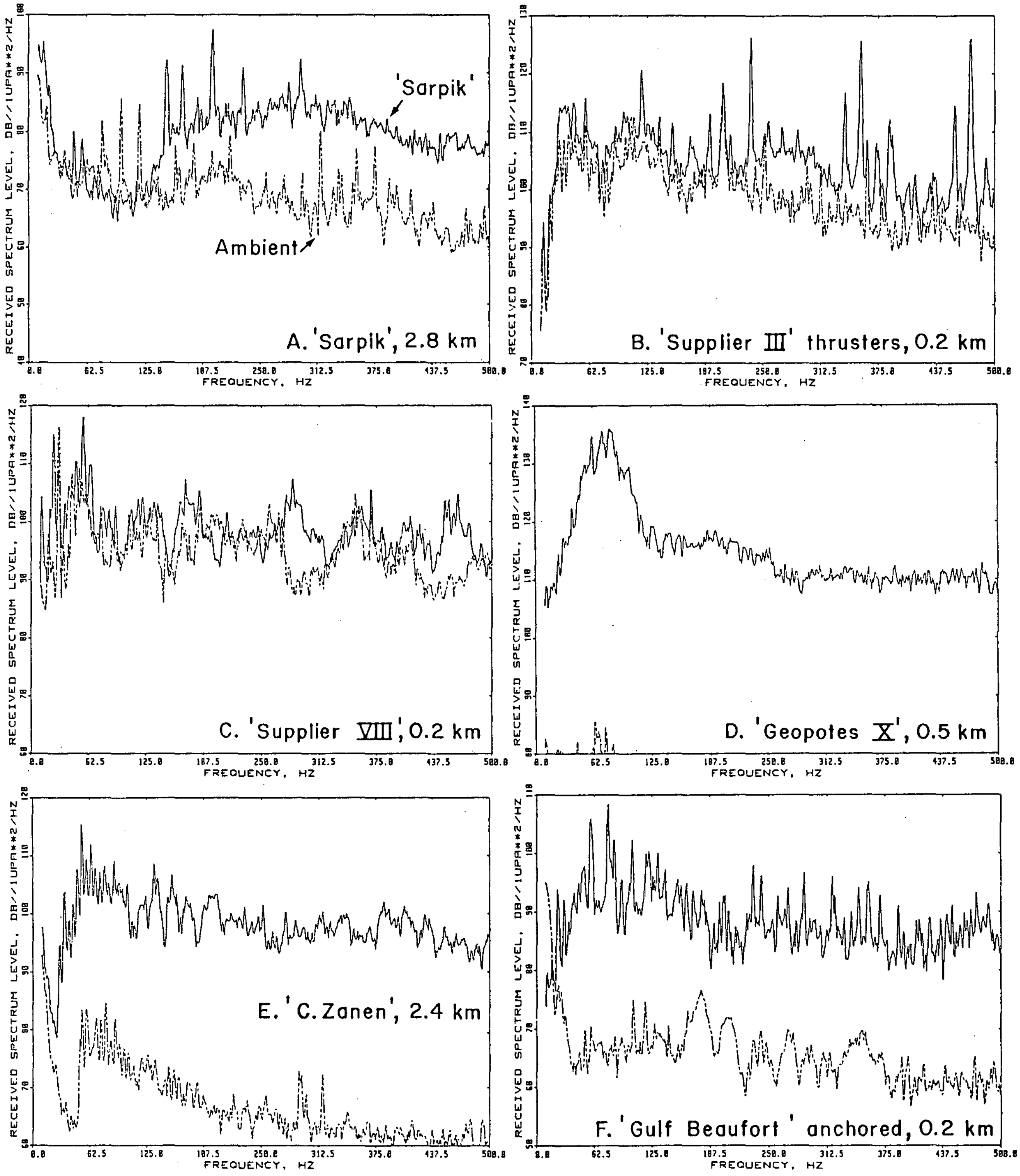


FIGURE 6. Representative boat and ship sound spectra (continuous lines), superimposed onto ambient noise spectra (dashed lines). **(A)** crewboat 'Imperial Sarpik' at range 2.8 km. **(B)** bow thrusters on 'Canmar Supplier III' at range 0.2 km. **(C)** 'Canmar Supplier VIII' at range 0.2 km. **(D)** hopper dredge 'Geopotes X' underway at range 0.5 km. **(E)** hopper dredge 'Cornelis Zanen' underway at range 2.4 km. **(F)** anchored tanker 'Gulf Beaufort' at range 0.2 km. Hydrophone depth was 9 or 18 m in each case.

For another hopper dredge underway, 'Cornelis Zanen' at range 2.4 km (Fig. 6E), the 20-1000 Hz band level was 128 dB. The spacing between tones was 5 Hz, but again these appear to be modulation components, perhaps around the peak tone at 54 Hz. The 20-1000 Hz background noise level was 98 dB, including some weak ship sounds.

An anchored supertanker in Herschel Basin, 'Gulf Beaufort', was running only generators and housekeeping auxiliaries, perhaps including pumps. The spectrum at range 0.2 km includes many spikes from tones (Fig. 6F). The 20-1000 Hz band level was 120 dB at both the 9 and 18 m hydrophone depths. The 'background' noise, for comparison, was measured 9.3 km from 'Gulf Beaufort'; the 20-1000 Hz level was 95 dB.

Figure 7 presents spectra of the two diesel-powered boats used in boat disturbance tests during the project, the crewboat 'Imperial Adgo' and the sound boat 'Sequel'. The 20-1000 Hz band levels were 119 dB for 'Adgo', range approximately 0.2 km, underway at 41 km/h, and 102 dB for 'Sequel', range 2.6 km, underway at 13 km/h. The spectrum for 'Adgo' shows several tones below 400 Hz. Both boats produced considerable broadband noise at frequencies of several hundred Hertz. The 20-1000 Hz background noise levels for the 'Adgo' and 'Sequel' measurements were 102 dB and 94 dB, respectively.

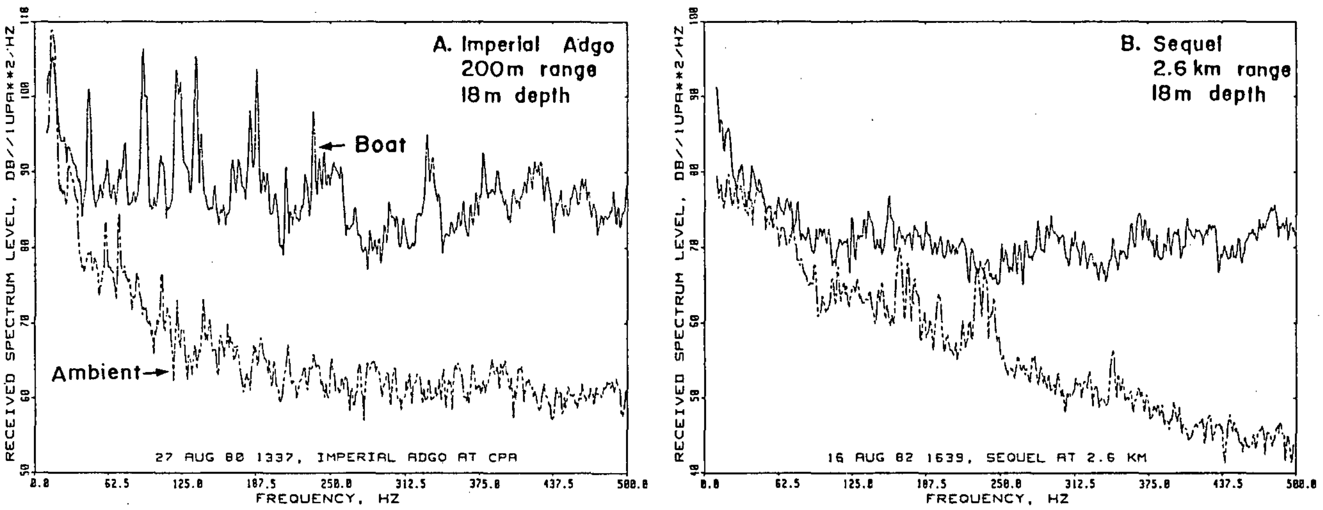


FIGURE 7. Sound pressure spectra for two diesel-powered small boats used in bowhead disturbance tests, the crewboat 'Imperial Adgo' and the sound boat 'Sequel'.

'Adgo and 'Sequel' produced waterborne noise with levels generally comparable to levels from crewboat 'Imperial Sarpik', survey vessel 'Canmar Teal', and the anchored tanker 'Gulf Beaufort' (Fig. 5). Only the anchored survey boat 'Arctic Sounder' was significantly quieter. The large dredges and supply boats produced levels 25-30 dB higher than those of 'Sequel' and 'Imperial Adgo' at corresponding ranges (Fig. 5).

Discussion

Few detailed reports of noise from small vessels and ships exist in the open literature (for review, see Richardson et al. 1983). However, the levels and the spectral characteristics measured during this project are consistent with those reported by others (Buck and Chalfant 1972; Ross 1976; Cybulski 1977); viz, high levels at low frequencies, broadband humps in the spectra (from propeller cavitation), and tones.

Seismic Signals

Background

Marine geophysical surveys are conducted to search beneath the sea for strata and locations that may contain producible quantities of hydrocarbons. Seismic survey signals were formerly produced by underwater detonations of explosives, but that technique now is rarely used in open waters, mainly because explosives can damage marine life. During the open water season in the Beaufort Sea, most seismic exploration is with arrays of airguns, but arrays of sleeve exploders or open-bottom gas guns are also used. Although these techniques are not based on chemical high explosives, a sharp, impulsive shock wave is generated at each source in the array, and the accumulation of the individual impulses provides a strong impulse beneath the sea floor. Useful summaries of the technology may be found in Kramer et al. (1968), Barger and Hamblen (1980), Fricke et al. (1981) and Johnston and Cain (1981).

Bowhead whales may be disturbed by seismic survey signal sources. To determine the sound levels that might cause a disturbance, it was important to measure the noise levels near whales that were being studied by Richardson et al. (1985). Also, measurements of received level vs. range were desirable to permit prediction of levels at different ranges. With such data, a 'range of disturbance' for bowheads around survey vessels might then be determined for areas with similar transmission loss.

Until recently, little was published about the waterborne sounds created by airgun arrays and other seismic sources. In 1979, Ljungblad et al. (1980) found that bowhead whales were sometimes exposed to noise pulses from seismic vessels operating many kilometres away. Richardson et al. (1983) summarized the early results from the present project and other data available up to 1981. Additional data on characteristics of waterborne impulses from seismic ships appear in Malme et al. (1983) and Moore et al. (n.d.).

Measurements

We recorded seismic signals from six survey vessels plus a single 40 in^3 airgun that we operated from the sound boat 'Sequel'. Many of the measurements were of sets of signals from the same source vessel at different ranges. We used multiple linear regression to determine coefficients of equations to model the received signal level vs. range.

Sleeve Exploder Signals.--Signals from the seismic survey vessel 'Arctic Surveyor' were received at 'Sequel' numerous times during 1981 while we were recording background and industrial noises. The signal source consisted of four sets of sleeve exploders, three sleeves per set, suspended over the side of 'Surveyor'. The geometry was a rectangle approximately 12 m long and 25 m wide (athwartship). The cylindrical sleeves were each about 1.2 x 0.3 m, and were deployed 6 m below the surface, water depth permitting. A mixture of propane and oxygen was exploded simultaneously in all the sleeves to produce a strong signal focused vertically. The signal echoes from bottom inhomogeneities were received at hydrophones in a long linear array deployed behind the ship. At each station, echoes from six 'pops' (= explosions) were recorded before the ship moved 40 m to the next station along the survey track. Six to ten seconds elapsed between pops while the exhaust gas was purged and the sleeves were recharged; 1/2-2 min elapsed between series of 6 shots as the ship moved to the next station.

For our measurements, the source (sleeve exploder array) depth was 6 m, the hydrophone depth was 9 m, and the water depths at the recording sites were about 15-30 m. Several signals were analyzed from each of three ranges: 8 km, 13 km, and 25.3-28.7 km. The received level of the pulses was 148-153 dB//1 µPa at 8 km and 115-117 dB at 28-29 km. After starting as an impulse at the source, the signal length was about 250 ms when received at 8 km and over 400 ms at 28.7 km; the reverberation extended much longer. At our working ranges, the impulse was received as a 'chirp' signal in which high frequencies were received first, followed by a downward transition to lower frequencies (Fig. 8B,D,F). This frequency change is represented in Figure 8A,C,E by the closer spacing of the oscillations at the left than at the right side of each pulse. These properties of impulsive signal propagation are characteristic of geometrical dispersion, which occurs when signals undergo multiple reflections between the surface and bottom.

Open Bottom Gas Guns.--In 1982 we again recorded seismic survey signals from 'Arctic Surveyor', but the sleeve exploders had been replaced by open bottom gas guns. Our recordings were made in water 9-11 m deep, hydrophone depth 8 m, ranges 0.9 to 14.8 km. Received levels ranged from 177 dB//1 µPa at 0.9 km to 123 dB at 14.8 km.

At the shortest range studied (0.9 km), frequencies below 100 Hz predominated (Fig. 9). At an intermediate range (3.7 km), low frequencies below 100 Hz arrived first, presumably via a bottom path, followed by frequencies above 200 Hz, presumably via a water path. At range 14.8 km, only frequencies above 200 Hz were received. Information on bottom stratigraphy might help explain the propagation of the low frequency components. At 14.8 km, it is noteworthy that high frequencies tended to arrive slightly before lower frequencies (Fig. 9F), consistent with the sleeve exploder results.

In 1983 seismic signals were received from the gas guns on 'Arctic Surveyor' at ranges of 52-53 km. The received signal levels ranged from 122-128 dB//1 µPa over 65 min. Then, 24 min later, the level was 119 dB, and another 24 min later the level was below the ambient level of 107 dB. We concluded that there had been enough movement of the ship that some propagation anomaly within the 52 km range intruded to blank out the signal. Water depth at the receiving location was 19 m.

Airgun Arrays.--Seismic signals were received from 'GSI Mariner' on numerous occasions. Airguns were discharged every 12-16 s as the ship steamed continuously at about 7 km/h along preselected lines. In 1982-83 the airgun array volume was 23 L and its source level was reported to be about

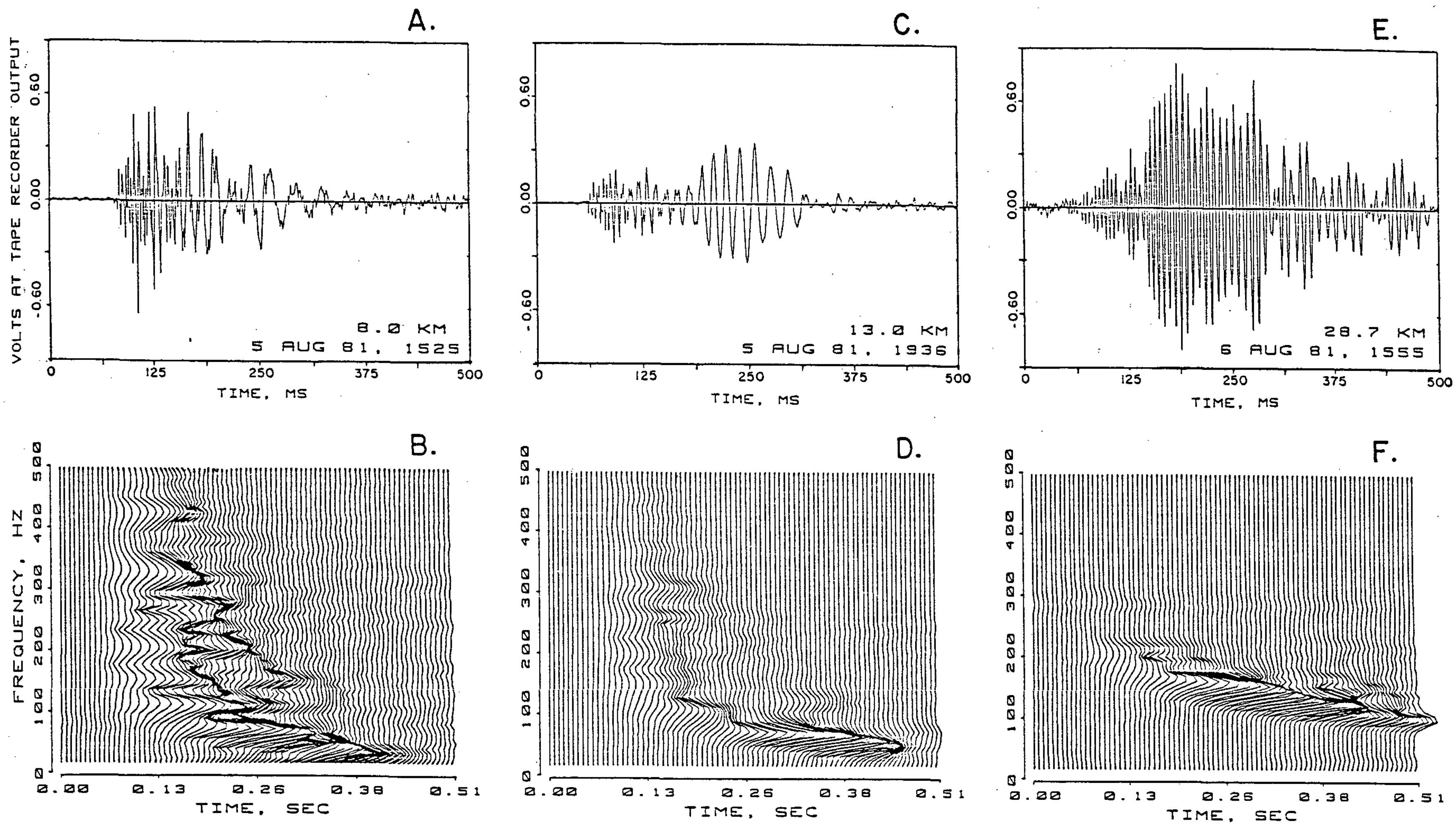


FIGURE 8. Waveforms and waterfall spectrograms for sleeve exploder signals received from 'Arctic Surveyor' in August 1981 at (A,B), 8 km range, (C,D) 13 km, and (E,F) 28.7 km. The signal in (E) was amplified by 40 times, compared to (A) and (C).

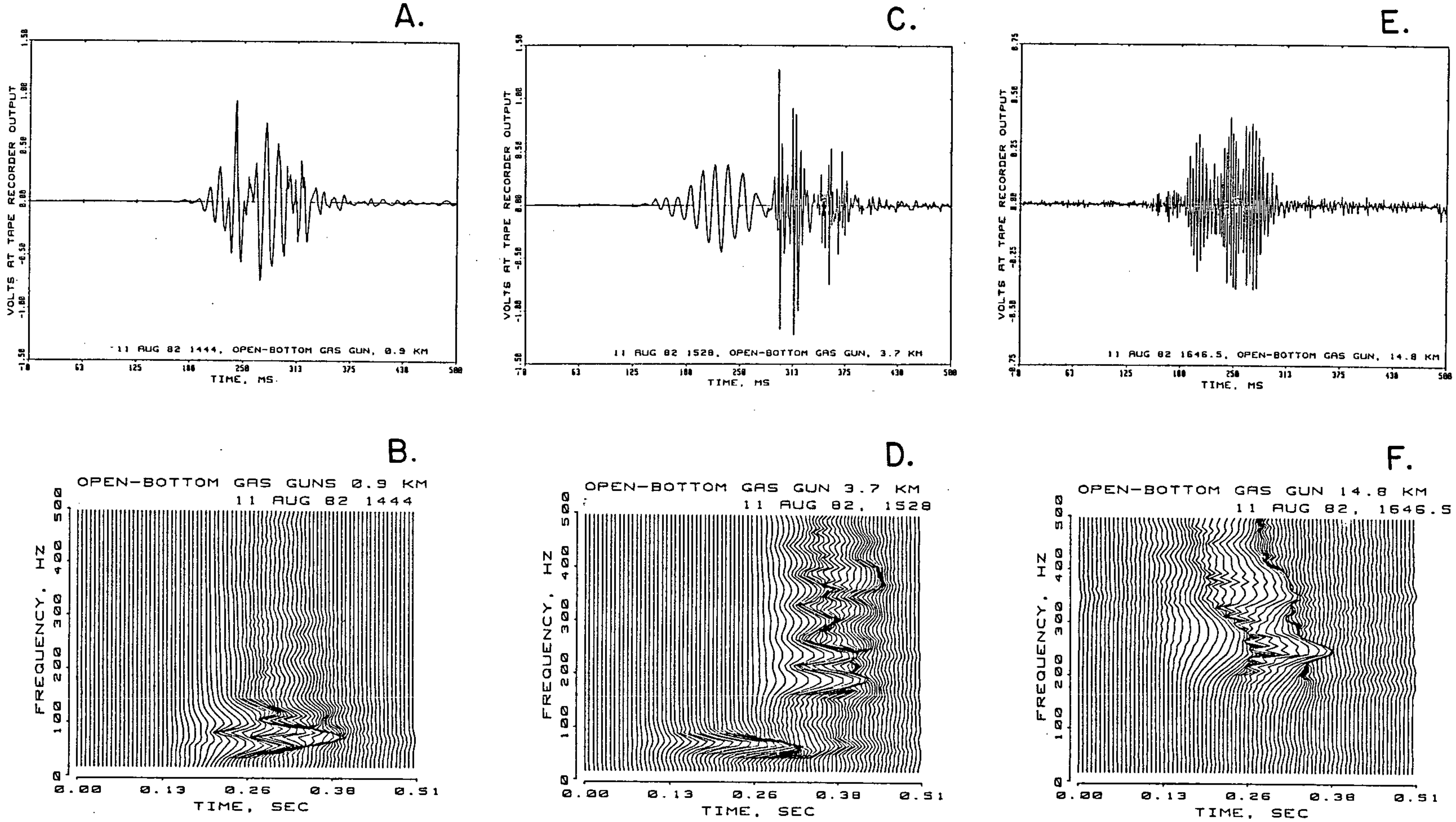


FIGURE 9. Waveforms and waterfall spectrograms of signals from open-bottom gas guns at ranges 0.9, 3.7, and 14.8 km. Water depth was 9-11 m; hydrophone depth was 8 m.

246 dB//1 µPa-m. In 1982, received levels included 119 dB//1 µPa at range 52 km, 128 dB at range 54 km (different time and transmission path), 126 dB at range 66 km, and 110 dB at range 75 km. In 1983, with the same airgun array, received levels were 127-131 dB for ranges 79-81 km on 7 August and 123 dB for range 57 km on 9 August. These signals were received at sonobuoys, which distort high amplitude signals; consequently, the foregoing levels should be taken as minimum estimates. The water depth for these signals was greater than the depth for the 'Arctic Surveyor' signals, assuring longer range transmission.

In August 1984 seismic signals were recorded from 'GSI Mariner' on several dates. The array volume had been increased to 47 L. Measurements from the sound boat on 14 August revealed levels between 143 and 160 dB for ranges 12-17 km (water depth 20-24 m, hydrophone depth 18 m). Several hours earlier, on a different track, 'Mariner' signals had been 154-158 dB for ranges 16-16.7 km, water depth 20 m. In general, there was considerable variability in received levels at specific ranges. Water depth, bottom characteristics, and horizontal aspect of the array were probably responsible. (Aspect is the orientation of the airgun array relative to the bearing to the receiver; see Malme et al. 1983.) At the 12 km range, the array was oriented broadside; thus, maximum received levels were expected on that occasion.

On 16 August 1984, 'GSI Mariner' participated in a bowhead disturbance experiment (see Richardson et al. 1985, in this volume). Although the ranges were no greater than 7.5 km, the airgun signal reverberation was longer than the 15 s period between firings. Such long reverberation times had not been seen previously, regardless of range. Because of the reverberations the received level between pulses did not decrease below 118 dB//1 µPa, which was 19 dB above the ambient level before the airguns began firing and after they stopped. Figures 10A-B contain the recorded waveform and waterfall spectrogram of a signal from range 7.5 km, water depth 25 m at ship and 18 m at sonobuoy. The received signal sounded distorted because of its high amplitude relative to the limited dynamic range of the sonobuoy. This signal was from the start of the full scale airgun array disturbance test on 16 August 1984. The long reverberation was characteristic of all the signals received at the sonobuoy during the test. It is possible that this long 'reverberation' was an overload response of the sonobuoy or the receiver, although this was not seen with other less severe overload signals.

Figures 10C-F were recorded with a hydrophone in an area somewhat west of the disturbance test area, water depth 44 m, 'Sequel' at anchor. Figures 10C-D were for range 8.7 km from 'GSI Mariner', just slightly longer than the range of Figures 10A-B, but with "Sequel's" hydrophones and without the severe reverberation. Figures 10E-F were for range 20.3 km. The waveforms in Figures 10C and 10E exemplify airgun signal propagation in shallow water over increasingly higher velocity strata beneath the water. The signals first received have travelled down through the bottom, bending upward back to the hydrophone. The solid black areas of the signal correspond to the sound carried solely by the water path. This is a short burst of high frequency sound, evident in Figures 10D,F at about 200 and 400 Hz, respectively. The waterborne signal is followed by additional bottom-travelling energy. Multiple propagation modes are evident, but the basic property to be observed is that the waveform in Figure 10E, range 20.3 km, is much longer than the

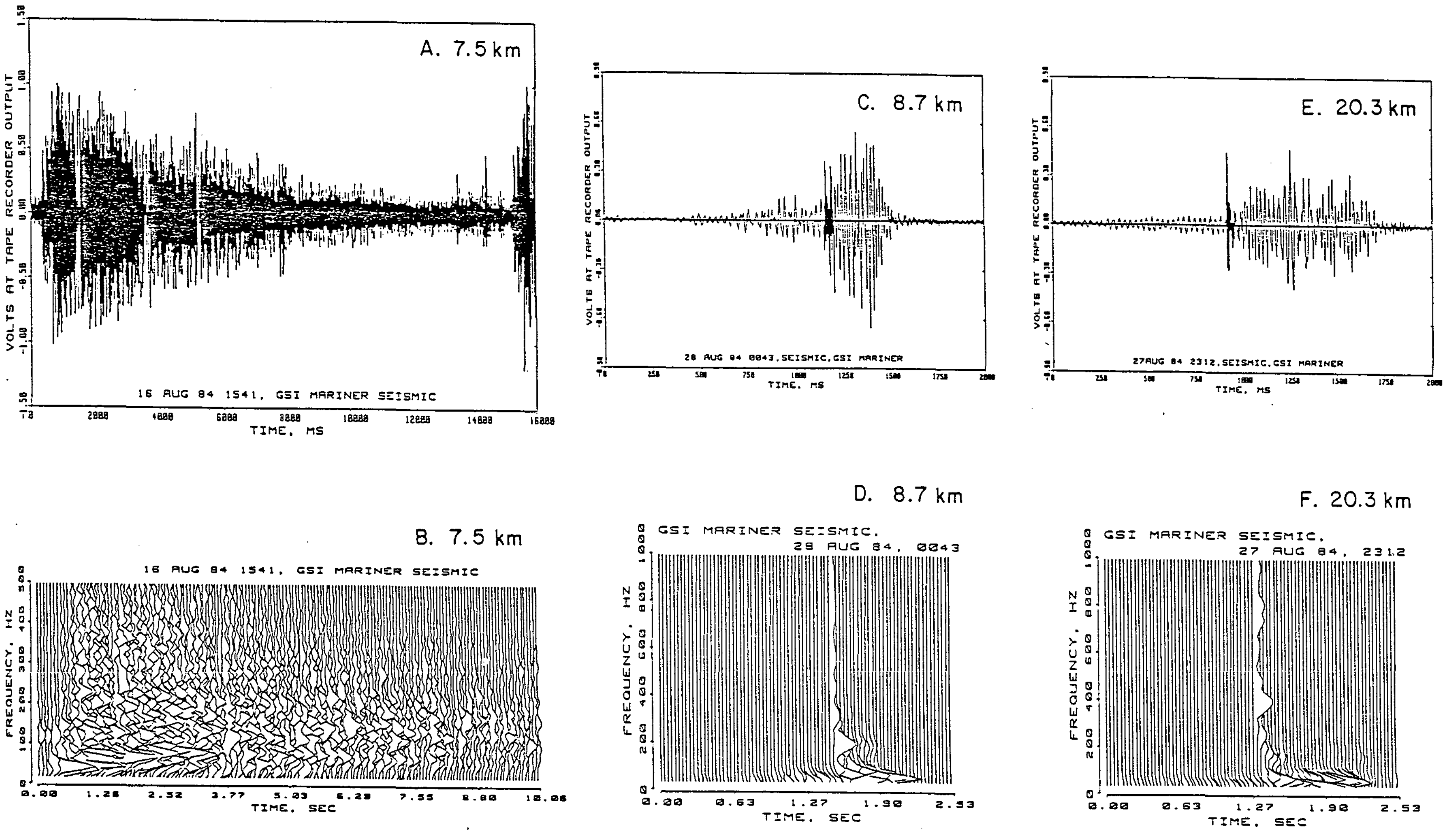


FIGURE 10. 'GSI Mariner' airgun array waveforms and corresponding waterfall spectrograms. (A) and (B) are from a sonobuoy and are undoubtedly distorted; (C-F) are from a hydrophone at 18 m depth.

waveform in Figure 10C, range 8.7 km. This demonstrates that the received signal lengthens as range increases.

The amplitudes of the signals in Figure 10C and 10E were as follows:

Figure	Range	Effective Pressure dB//1 µPa	Receiving System
10 C-D	8.7	157	Hydrophone
10 E-F	20.3	147	Hydrophone

Because of the limitations of sonobuoys, the received levels of seismic pulses could not be measured reliably during the experiment on 16 August 1984. Given the received levels of about 160 dB at ranges 9-12 km nearby on 14 and 28 August 1984, received levels were presumably far above 160 dB when 'GSI Mariner' reached its closest point of approach 1.5 km from the bowheads on 16 August. In both the 12 km and the 1.5 km cases, the long axis of the airgun array was oriented broadside to the receiver--the condition in which peak received levels are expected (Barger and Hamblen 1980; Malme et al. 1983).

On six occasions, pulses from 'GSI Mariner' operating 9-17 km away were received simultaneously at hydrophone depths of 9 and 18 m. The received level at 9 m was always 1-4 dB less than that at 18 m.

Received seismic survey signals rarely included much energy at frequencies above 500 Hz. However, on 1 August 1984 we received pulses of 500-1300 Hz energy from 'GSI Mariner'. The signals were received by a sonobuoy hydrophone on the bottom in 10 m of water, range 17-23 km, depth at boat 70 m, received level at least 119-117 dB. Within these pulses, there was the usual downsweep of frequencies. Although the pulses were consistently at 500-1300 Hz on this occasion, this was a unique and apparently anomalous situation.

Seismic signals from two other large arrays of airguns were recorded via sonobuoys. Airgun signals 50 km from 'Edward O. Vetter' were received at hydrophone depth 9 m with level 117 dB. Airgun array signals 26-31 km from 'Western Aleutian' were received at hydrophone depth 18 m, water depth 19 m, levels 120-135 dB. These levels may be underestimates because of sonobuoy limitations.

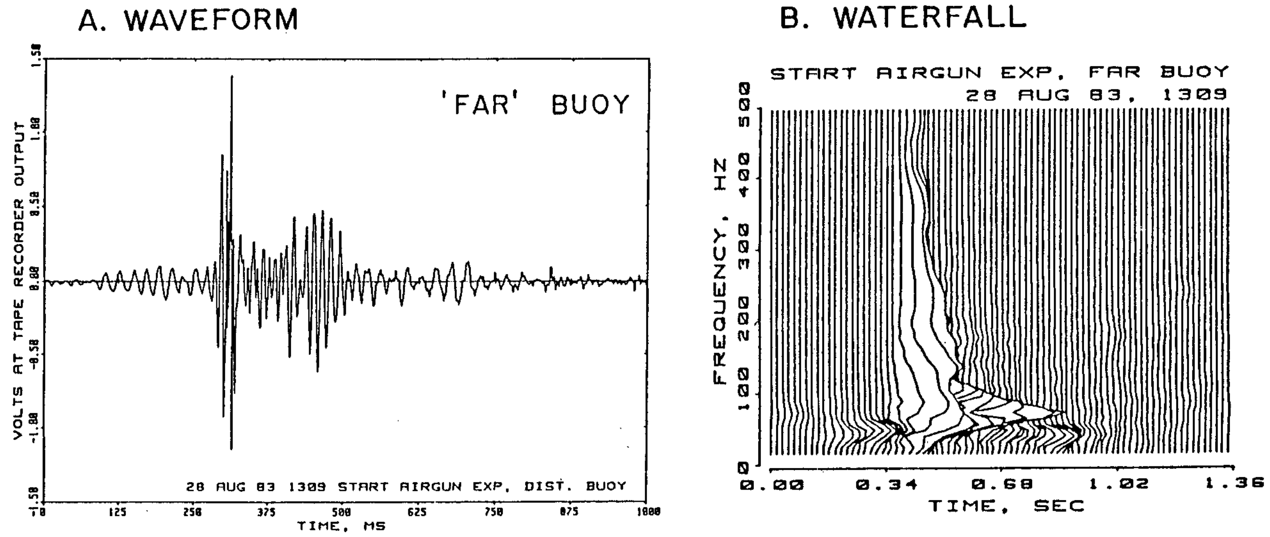
In 1983, signals from a small 3-gun 5.4 L array on 'Canmar Teal' were received simultaneously at 3, 9 and 18 m depth (water depth 34 m) for each of several ranges (Table 6). These data came from the hydrophones on the sound boat, and do not suffer from the limitations of sonobuoys. On average, levels at 3 m depth were 7 dB less than those at 9 m. Nominal signal frequencies were above 100 Hz, and approached 200 Hz at the shorter ranges. Within pulses, there was the usual decrease in peak frequency with increasing time.

Single Airgun.--The crew on 'Sequel' deployed a 40 in^3 (0.66 L) single airgun for controlled seismic disturbance tests when the aircrew could observe bowheads before, during, and after a period of firing. We began most tests with an air tank at pressure 1900-2200 psi and ran it down to about 500 psi. Except for being a single unit and therefore weaker in output pulse level, the waveform and frequency properties of our airgun were similar to

Table 6. Effective levels (dB//1 μPa) vs. range and hydrophone depth for airgun signals from 'Canmar Teal', 11 August 1983.

Range (km):	3.0	5.9	8.2	9.3	10.4	ukn.
Time (MDT):	08:23	07:31	15:02	16:35	16:38	14:33
3 m level:	161	141	135	137	141	143
9 m level:	167	151	145	143	145	150
18 m level:	158	152	147	146	149	151

those of a full-sized array of airguns. The firing period was 19-20 min with 10 s between firings (1981) or 25-30 min with 15 s between firings (1983-84). We operated the airgun at depth 6 m, attempting to simulate the operating conditions of a full-sized airgun array. Figure 11 contains the waveform and waterfall spectrogram of an airgun signal from 'Sequel' recorded during a disturbance test on 28 August 1983 at range 5 km. The water depth was 15 m. The received sound level of this and the other signals during the test ranged from 125 to at least 133 dB. The circumstances and sound levels of all airgun tests are summarized in Richardson et al. (1985: in this volume).


A. WAVEFORM

B. WATERFALL

FIGURE 11. Waveform and waterfall of a signal from the single 40 in^3 airgun fired from 'Sequel' during a controlled seismic disturbance test on 28 August 1983. The range was about 5 km, water depth 15 m.

Sound Transmission Loss

Transmission loss information can be extracted from the measurements of received levels at various ranges. Figure 12 shows the data and the associated fitted curves for four seismic sources. The hydrophone was always an H56 deployed at depth 18 m except when the water depth was less. Sonobuoy data were not used.

The sleeve exploder measurements spanned the range 8-29 km; water depths were 15-30 m. When we fitted a simple logarithmic spreading loss model, we obtained the term -61.6*log(range). This was far from the expected -10*log (range) term for cylindrical spreading or even -20*log(range) for spherical spreading. When we added a term linear in range, appropriate for absorption and scattering losses, the fitted spreading loss term became -10.12*log (range)--very close to the expected -10*log(range) for cylindrical spreading. When we forced the spreading loss term to be cylindrical, the resulting regression equation was

$$\text{Received level (dB//1 } \mu\text{Pa)} = 170.1 - 1.39*R - 10*\log(R),$$

where R is range in km. The standard error (se) was 2.2 dB, the coefficient of determination (r^2) was 0.972, and the number of measurements (n) was 12. The equation is plotted in Figure 12. The result was reasonable because cylindrical spreading is expected in shallow water and because the losses from scattered reflections and absorption by the bottom are accounted for at the rate of about 1.4 dB/km. Strictly speaking, this equation is valid only for the ranges studied (8-29 km), for water depths of 15-30 m, and for the specific area where the data were collected. In particular, the equation is probably not valid at ranges less than 5 km because of the nature of impulsive sound propagation in shallow water.

The general regression equation for the open-bottom gas guns in water 9-11 m deep was RL = 177 - 1.55*R - 26.6*log(R), se = 1.5 dB, r^2 = 0.997, n = 6. The higher spreading loss coefficient of 26.6 dB per range decade is a result of including the much shorter ranges, and probably also the shallow water depth. When only the data from the three longest ranges (3.7, 7.4, 14.8 km) were used, and cylindrical spreading was forced, the best-fit equation for received level was

$$RL = 169.2 - 2.33*R - 10*\log(R),$$

se = 0.26, r^2 = 1.000, n = 3. This result was for ranges comparable to the ranges studied in 1981 with the sleeve exploder. The higher linear loss (2.33 vs. 1.39 dB/km) was probably attributable to the shallower water.

The 'GSI Mariner' airgun array data plotted in Figure 12 were not measured at the same time or place, and the source level of the array was slightly greater for the 1984 data than for 1982. The four points spanning ranges 9-20 km were measured from 'Sequel' while anchored on 27 and 28 August 1984, water depth 44 m. Six other measurements were also made of 'Mariner' seismic signals at that time and within that range span. The two points plotted for ranges 52 and 75 km were measured from 'Sequel' on 16 and 18 August 1982, water depth 110-130 m. Because of the heterogeneous data, the fitted equations may be only rough approximations of the results that would be obtained in any one situation. All 12 measurements were used to fit the

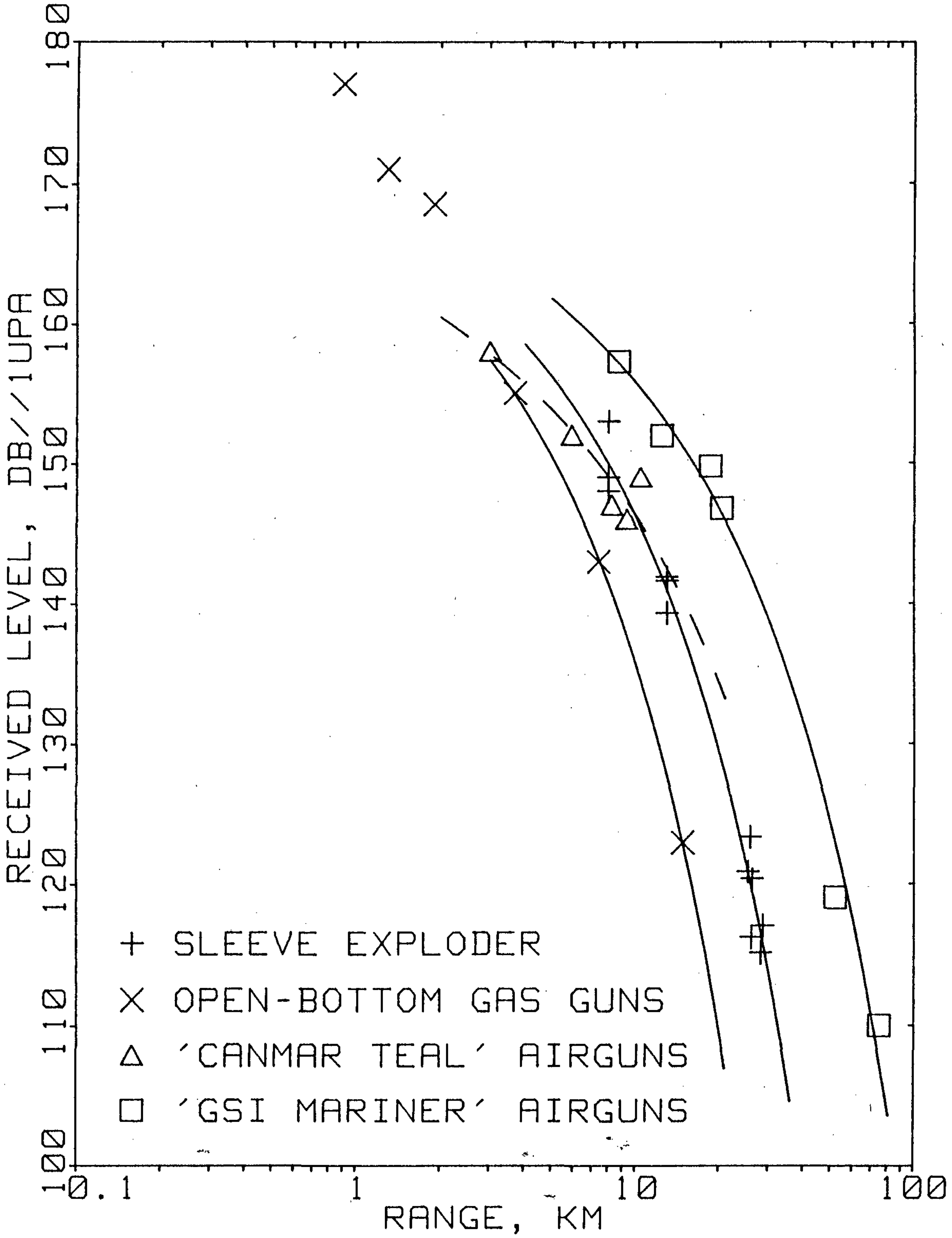


FIGURE 12. Received levels of seismic signals vs. range. Data and equations derived by regression are shown for four seismic signal sources: the sleeve exploder array on 'Arctic Surveyor' in August 1981; the open-bottom gas gun array on 'Arctic Surveyor' in August 1982; the 3-airgun array on 'Canmar Teal' in August 1983; and the large arrays of airguns on 'GSI Mariner' in 1982 and 1984. All data included in this figure were recorded on the boat; no sonobuoys were involved.

general equation RL = 177.2 - 0.53*R - 15.67*log(R), se = 2.1, $r^2 = 0.984$, n = 12. When cylindrical spreading was forced in the model, the result was

$$RL = 171.8 - 0.61*R - 10*\log(R),$$

se = 2.0 dB, $r^2 = 0.975$, n = 12. The absorption/scattering loss coefficient of 0.61 dB/km is smaller than the 1.39 and 2.33 dB/km terms derived for the shallower water measurements of the sleeve exploders and open-bottom gas guns. This was expected; we expect lower rates of scattering loss and bottom absorption loss in the deeper water where these data were collected.

Five measurements from the 3-airgun array on 'Canmar Teal' are plotted on Figure 12. The water depth for these measurements was 34 m. An 'outlier' received level of 149 dB at range 10.4 km caused a poor regression result. When we averaged the measurements at the three longest ranges, 8.2-10.4 km, to obtain one 'long-range' datum, we obtained the following fitted equation with the -10*log(R) term forced:

$$RL = 165.3 - 0.90*R - 10*\log(R),$$

se = 0.36 dB, $r^2 = 0.992$, n = 3. The equation is plotted as the dashed line on Figure 12.

The four equations for received level provide an indication of the behavior of seismic signals in the shallow Beaufort Sea. The reliability and utility of the equations could be enhanced with data from a wider span of ranges (especially longer ranges). However, more attention should be paid to the dependence of transmission loss on frequency, water depth, sea state, and bottom characteristics, and to the effects of aspect of the source array.

Discussion

When received at distances of at least a few kilometres, pulses from sleeve exploders, open-bottom gas guns and airgun arrays were very similar. Their characteristics can be summarized as follows:

Seismic survey signals were by far the strongest sounds encountered, but they were almost always of short duration, with 8-15 s between pulses. The amplitudes at ranges 9-20 km were 12-30 dB greater than the 20-1000 Hz band level of 'Geopotes X' at range 7.4 km. 'Geopotes X' produced the strongest non-seismic sounds detected in this study. The levels of seismic pulses attenuated with increasing range in the same way that other sounds attenuated. However, because of the very high source levels of seismic impulses, they were received above the typical background level to distances approaching 100 km, even in relatively shallow water.

For concentrated measurements of seismic signals from one vessel operating in one area at modest ranges (to about 15 km), we observed consistent relationships between range and amplitude. As the range decreased, the received levels increased. However, when we compared results from different survey tracks, the level vs. range relationships were not always consistent. Contrary to expectation, the signal level was sometimes stronger at longer ranges. Consistent with theory, the water depth and bottom materials appear to have an important influence on the levels of the received seismic signals.

As with other sounds originating underwater, the received levels of seismic signals were less at shallower depths, increasing at least until the hydrophone depth was 18 m. This is consistent with theory, which predicts zero pressure at a pressure release boundary like the sea surface (Urick 1983, p. 131-4).

Pulse lengths tend to increase with increasing distances because of the effects of different sound speeds for different modes of propagation. Within each mode, different frequencies are received at different times. For shallow water propagation, high frequencies are received first, followed by low frequencies. This leads to the 'chirp' signal characteristic of many seismic impulses as received at long ranges. The opposite occurs for propagation via bottom sedimentary layers. At ranges beyond a few kilometres, the waterborne sound is mainly at frequencies of 200-400 Hz, even though most energy at the source is <100 Hz (Barger and Hamblen 1980). Lower frequencies (<100 Hz) are sometimes received via bottom pathways, but the low frequency energy apparently is attenuated more quickly than the slightly higher frequencies in the shallow waters where most of our data were obtained.

Drillships

Background

Drillship sounds had not been reported before this project began, although there were reports of sound measurements near offshore drilling platforms and semi-submersibles (Buerkle 1975; Gales 1982). Results from those studies are difficult to interpret because of low frequency resolution (Buerkle 1975) or restrictions to near-field measurements (Gales 1982). Sounds from the 'SEDCO 708' semi-submersible were measured recently during drilling operations in the Aleutians (Greene, in press). Several tones from 'SEDCO 708' operating in water 114 m deep could be detected at range 18.5 km, although they were weak. Broadband components were generally down to background levels for ranges >1.9 km. The background levels were 102-112 dB//1 μPa for the 10-4000 Hz frequency band.

One might predict that drillships would be noisier underwater than semi-submersibles or drilling platforms, given the broad hull area in contact with the water. The hull would be expected to serve as a relatively efficient radiator of low frequency sounds into the water.

Measurements

Sound levels and spectra were measured at various ranges from three drilling vessels: drillship 'Explorer I' while logging, drillship 'Explorer II' while drilling, and the Conical Drilling Unit (CDU) 'Kulluk' while drilling (Fig. 13). 'Kulluk' is a circular platform 81 m across and sloping inward below the water line to deflect ice. It must be moved by support vessels and tugs, but it can operate longer in the fall because of its ice deflection design. 'Explorer I' and 'Explorer II' are conventional drillships; four of these vessels operated in the Canadian Beaufort Sea during each year of our study. Logging operations were not as noisy as drilling,

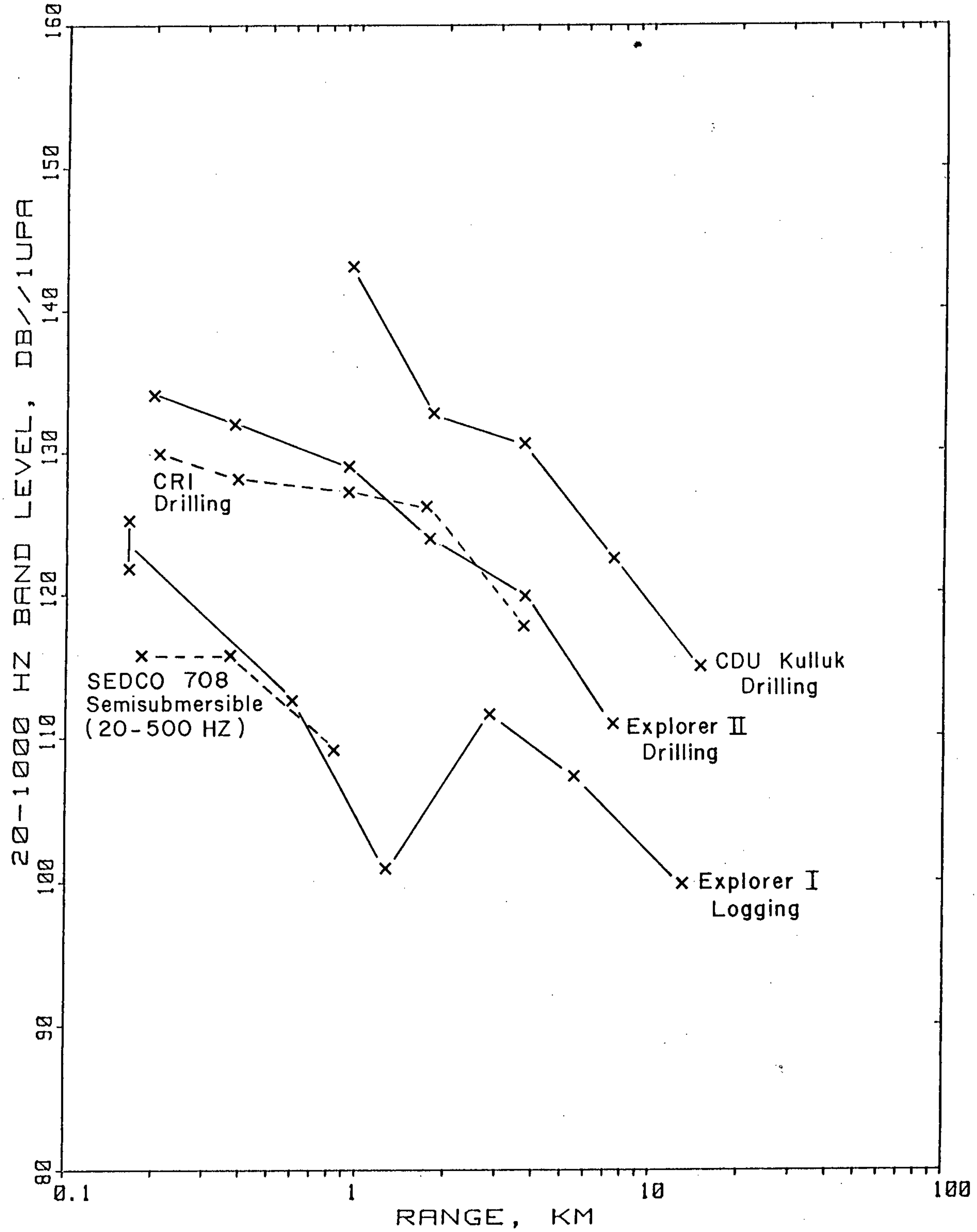


FIGURE 13. Drillship sound levels in the 20-1000 Hz frequency band vs. range for three drilling vessels. Levels near drilling operations on a caisson-retained island (CRI) in the Canadian Beaufort Sea and a semisubmersible near the Aleutians (Greene, in press) are also shown for comparison. The hydrophone depth was 9-18 m in each case.

and the CDU drilling was clearly the noisiest of the three operations (Fig. 13). Stand-by vessels were near each of the three drillships during our recording sessions, and their variable activities were probably responsible for some of the apparent differences in sound levels near the three operations.

'Explorer I' was northwest of the Mackenzie Delta (Fig. 1) in 1982 when we recorded its sounds while it was conducting logging operations. The water depth was 17 m; hydrophone depth was 9 m. The variability in the received levels vs. range shown in Figure 13 probably was partly due to the changing nature of machinery operations during the time of our measurements. The relatively low level at range 1.3 km is conspicuous in this regard. The support vessels in the vicinity did not appear to be active.

'Explorer II' was drilling north of the Mackenzie Delta (Fig. 1) at depth 2030 m, water depth 27 m, when we measured its noise in 1981. The hydrophone depth was 9 m. 'Supplier III' was drifting nearby.

Gulf Canada's CDU 'Kulluk' was drilling at East Amauligak in 1984 when we recorded the sounds. Our sound boat was not permitted within the mooring lines, restricting our closest range to about 1 km. A tug was grappling for lost mooring anchors nearby, and there were other work boats around. It is certain that our measurements of 'Kulluk' sounds also contain sounds from these other active vessels. The vessel sounds overlap 'Kulluk' sounds in both time and frequency, and the sounds of 'Kulluk' and other vessels cannot be separated.

Figure 14A,B shows examples of spectra computed for 'Explorer II' drilling at ranges 0.2 and 7.4 km. The strong tone at 278 Hz was characteristic and easy to identify when heard on sonobuoys or the 'Sequel' hydrophones. This tone varied in frequency during the drilling operations but was always accompanied by a weaker tone at a slightly lower frequency. The 20-1000 Hz band level for range 0.2 km was 134 dB//1 μPa; for range 7.4 km it was 111 dB.

Figure 14C-F shows spectra for 'Kulluk' drilling at ranges 1.0 and 14.8 km, including spectra for hydrophone depths 3 m and 12 or 18 m (at 14.8 km range, water depth was only 15 m, denying us the use of a hydrophone at depth 18 m). The 'Kulluk' spectra are not especially distinctive, although tones at 51 and 89 Hz were persistent. The strong tone at 333 Hz in Figure 14F was not detected at ranges less than 7.4 km, presumably because of some change in the industrial activities between the recording times. Broadband levels were unusually flat up to 750 Hz; the typical decrease in level with increasing frequency was not evident in this frequency range (Fig. 14C-F). Received levels at 18 m depth were 20 dB higher than those at 3 m for frequencies 30-100 Hz, and about 9 dB higher for frequencies 250-500 Hz (Fig. 14E vs. C; Fig. 14F vs. D). This difference was consistent in direction with results for other in-water sources, but greater in magnitude than some others.

In some of the spectra shown in Figure 14, received levels for frequencies below about 50 Hz were lower than those for some higher frequencies. This was probably attributable to the high rate of attenuation of low frequency sounds in shallow water.

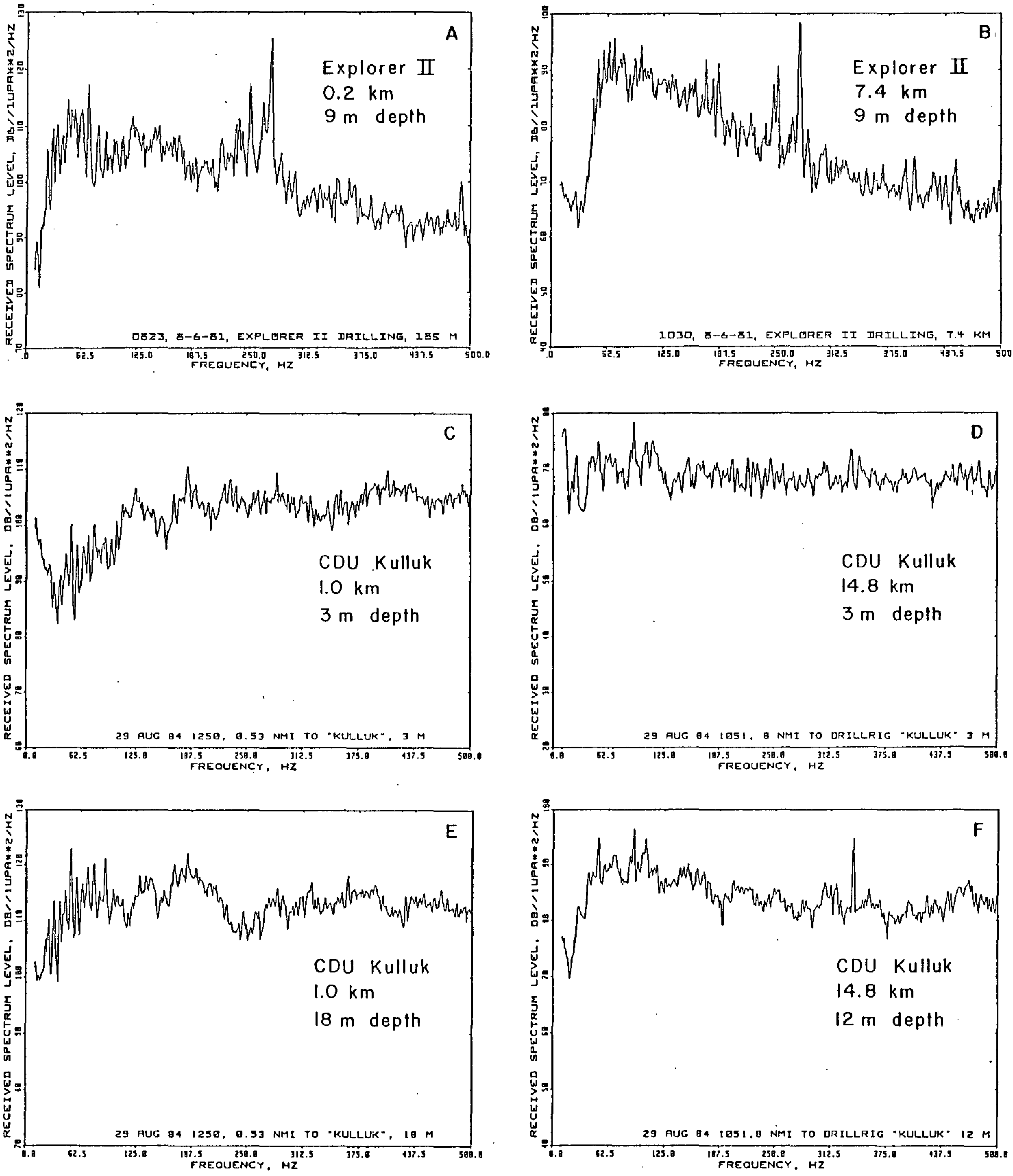


FIGURE 14. Sound pressure spectra for drillships 'Explorer II' and Conical Drilling Unit 'Kulluk' from recordings made while drilling. Note the varying vertical scales.

Discussion

The sound level for the 'SEDCO 708' drilling at range 0.19 km, hydrophone depth 10 m, 20-500 Hz band, was 116 dB//1 μPa (Fig. 13; Greene, in press). The sound level in the 400-1600 Hz band was 110.8 dB, making the level in the 20-1600 Hz band 117 dB at 0.19 km range. In contrast, the quietest drillship we measured during this project was the 'Explorer I' conducting logging operations; its sound level in the 20-1000 Hz band was 122-125 dB at range 0.17 km. Clearly, noise from the quietest drillship operation was stronger than the semi-submersible during drilling. Drillship levels were similar to levels near an actively drilling caisson-retained island (CRI) (Fig. 13).

The Conical Drilling Unit 'Kulluk' was the noisiest of the drilling vessels studied during this project. Its large size and large hull area in contact with the water probably contributed to the high noise levels. The nearby tug grappling for anchors probably accounted for some of the noise measured near 'Kulluk'.

Dredging

Background

Ford (1977) measured the sounds from cutter suction dredge 'Beaver Mackenzie' during construction of the Arnak artificial island in the southeastern Beaufort Sea, July 1976. He found that most energy in the sounds was at frequencies between 250 and 2000 Hz. We are unaware of other reports concerning dredge sounds.

There are two main types of dredge operation in the Beaufort Sea. In one, a dredge like 'Beaver Mackenzie' is moored in place and extends suction pipes to the bottom and discharge pipes to a barge or construction site. In the other, a hopper dredge moves over the dredging site picking up material to fill its hoppers, and then steams to the construction site to dump the load either through gates in the bottom of the ship or by pump-out methods.

Measurements

We measured sounds both from dredges moored in place and from moving hopper dredges during this project. We discussed the sounds of hopper dredges underway in 'Boat and Ship Sounds' earlier in this report; here we confine our presentation to the sounds of dredging.

Figure 15 displays measured 20-1000 Hz band levels vs. range for several operating dredges. The strongest sounds came from hopper dredge 'Cornelis Zanen' picking up a load at Ukalerk on 7 August 1983. 'Zanen' is powered by 11.1 MW, can make 28.7 km/h, and carries a load of 8000 m^3. The water depth was 20 m, the hydrophone depth was 9 m, and the ranges varied from 0.63 to 2.45 km. The levels were on the same order as levels measured for 'Geopotes X' picking up a load at comparable ranges at the same site on 29 August 1982, for 'Gateway' dumping a load at Kadluk on 11 August 1982, and for 'Cornelis Zanen' pumping out material on 31 August 1984. All three are hopper dredges. These dredging data for 'Cornelis Zanen' were taken at shorter ranges than the underway data for the same ship (see Fig. 5) but the two sets

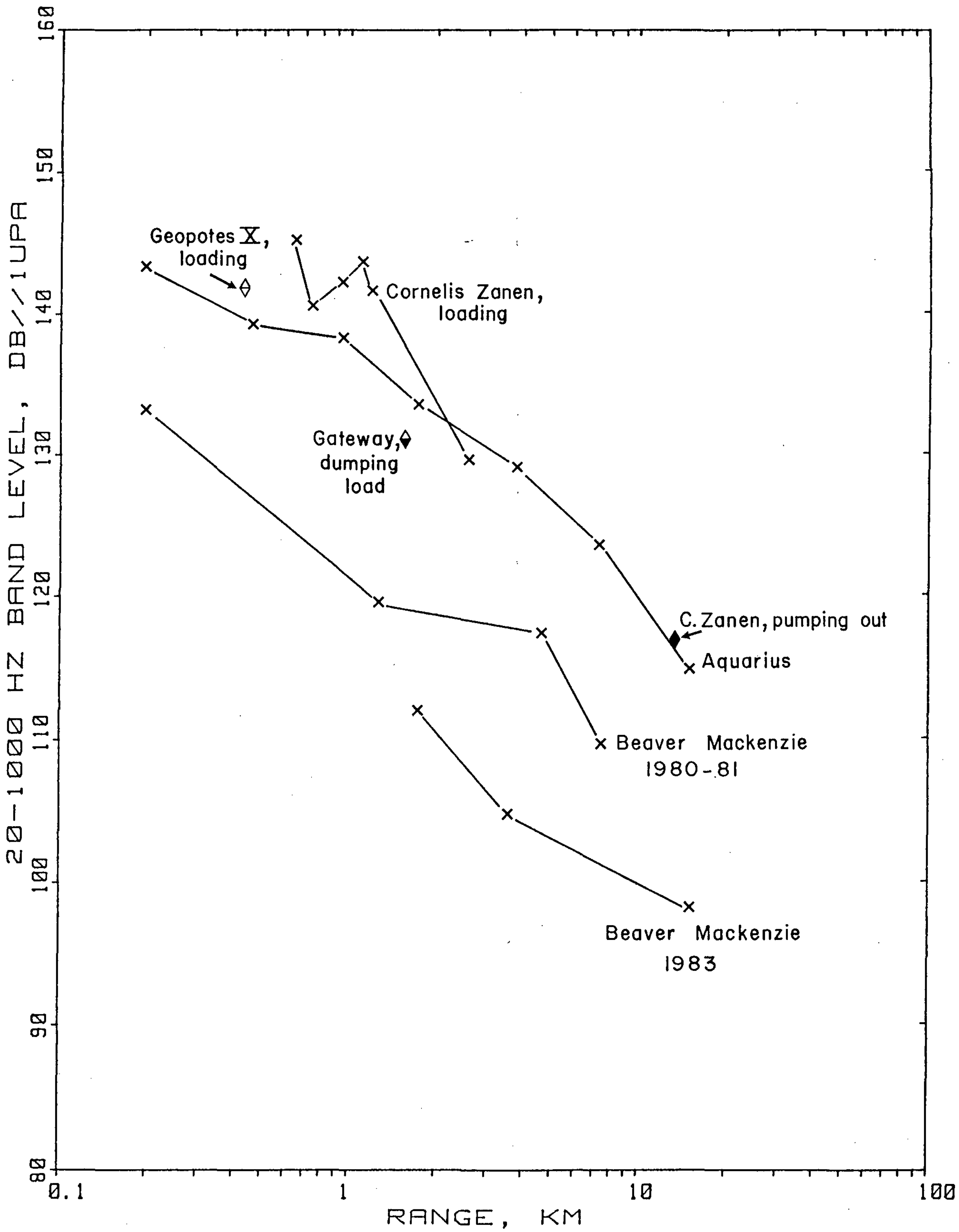


FIGURE 15. Dredge sound levels in the 20-1000 Hz frequency band vs. range for dredges that were actively dredging; hydrophone depths 9-18 m.

of levels line up, suggesting that the sound levels while dredging may not be much different than the levels while underway.

'Aquarius' is a suction dredge about 90 m long and 12 m wide; it was moored at Nerlerk on 12 August 1983 transferring material from the bottom to a berm construction site. It can transfer up to 100,000 m^3/day. The sounds were notably stronger (by 10-15 dB) than those recorded for dredge 'Beaver Mackenzie', which also operated as a transfer dredge capable of moving 70,000 m^3/day. We recorded 'Beaver Mackenzie' sounds on 7 August 1980 at the Issungnak artificial island construction site, and on 6 August 1981 at the Alerk artificial island site. Interestingly, noise levels from 'Beaver Mackenzie' at Amerk on 13 August 1983 were 7-12 dB quieter than they had been in 1980-81. The dredge sounded different to the human ear, and the spectrum revealed more tones in 1983 than in 1980-81. Water depths were 46 m at Nerlerk, 18 m at Issungnak, 13 m at Alerk, and 29 m at Amerk (see Fig. 1 for locations).

Figure 16 presents sound level spectra for three dredges. Figures 16A and B are from two analyses of the same sound from 'Beaver Mackenzie' at Issungnak. This recorded sound was used in the dredge playback experiments on 16 and 24 August 1984 (Richardson et al. 1985); the tone at 1775 Hz was unusually strong for a tone at a frequency above 500 Hz. Figure 16C is for the same dredge at Amerk in 1983, when there was no strong tone between 1 and 2 kHz. Figure 16D is for 'Cornelis Zanen' picking up a load at Ukalerk, and Figures 16E and F are for the dredge 'Aquarius' at Nerlerk, 0.2 and 14.8 km ranges. All these spectra are for dredges whose band levels are plotted against range in Figure 15. In some spectra, received levels were rather low for the lowest frequencies. As discussed earlier for boat and drillship sounds, low frequency sounds often attenuate at a high rate in shallow water.

Discussion

Based on our measurements, suction hopper dredges and some transfer dredges are the strongest sources of continuous industrial noise of any activities associated with offshore oil exploration in the Beaufort Sea. The higher levels from hopper dredges than from 'Beaver Mackenzie' are probably explained by the absence of sounds from propulsion machinery in the cases of moored dredges. Although the measurements did not overlap in range, data for 'Cornelis Zanen' indicated that sound levels from hopper dredges may be similar while dredging and underway. Sound levels for hopper dredges dumping a load and pumping out a load were also similar to the levels for picking up a load.

Spectrum analysis did not reveal any unusual frequency characteristics in dredging sounds other than the tone at 1775 Hz from 'Beaver Mackenzie' in 1980-81. There was no similar tone in 1983.

Operations at Islands

Background

Once an artificial island or berm has been constructed, equipment and facilities for exploration drilling are moved onto it. Malme and Mlawski (1979) reported on the sounds of drilling from islands during winter. They reported, 'the broadband component decayed rapidly within 0.5 to 1.0 miles

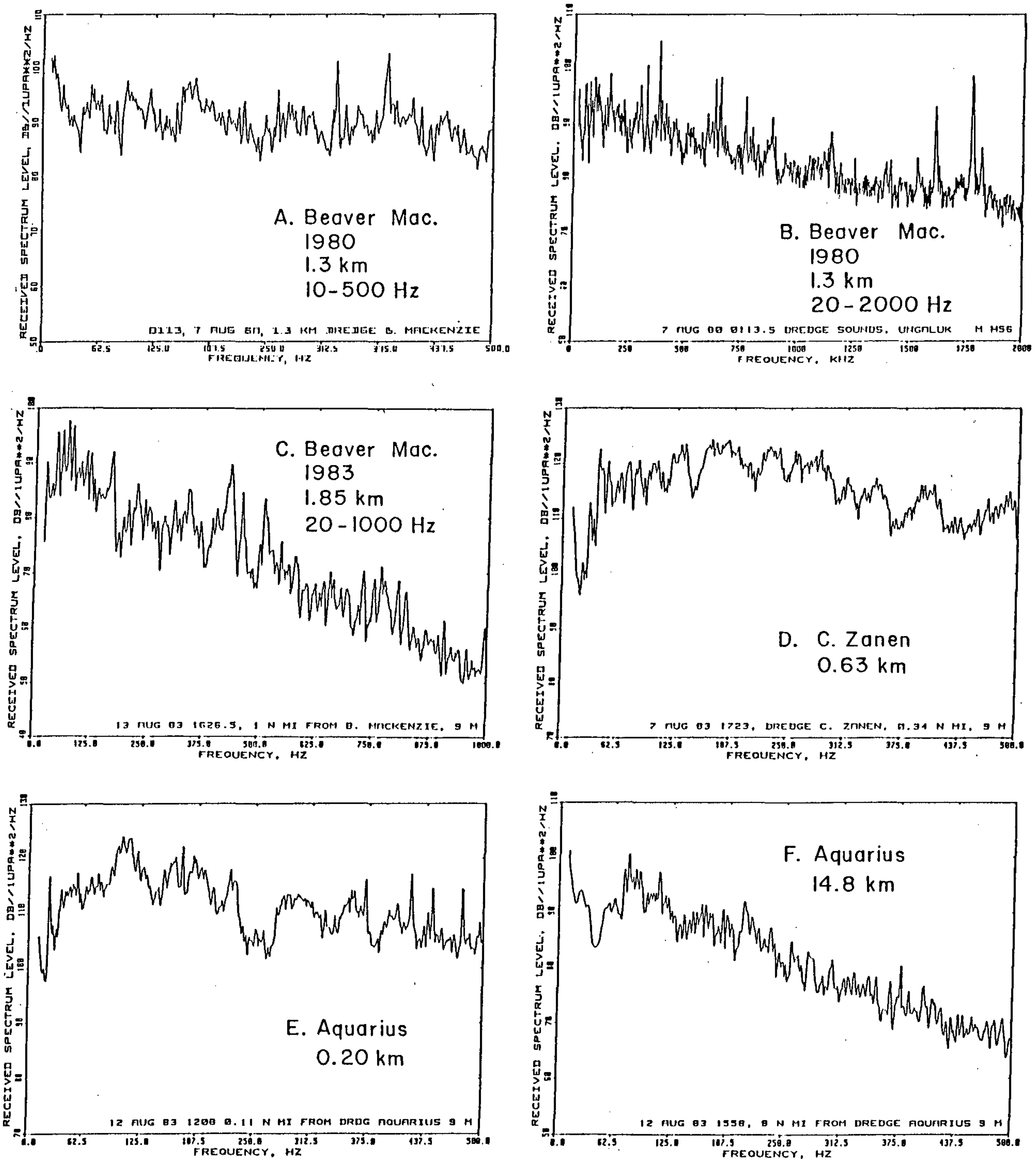


FIGURE 16. Sound pressure spectra from working dredges.

from the rig leaving low frequency tonal components...observed out to 4-6 miles under low ambient noise conditions'.

Measurements

During the project we measured sounds at three operating island sites: (1) at the Tarsiut caisson retained island (CRI); (2) at Kadluk while a different caisson was being installed on a berm, and (3) at the Amerk CRI during drilling.

When the sound boat 'Sequel' reached Tarsiut on 6 August 1982, drilling had already been completed and 'wiper tripping' was in progress. Anchored at range 1.1 km, water depth 21 m, hydrophone depth 9 m, we recorded sounds from the area for over 12 h. The movement of support craft (especially tugs and workboats; a crane barge remained in place alongside the caisson) undoubtedly contributed to the sounds recorded. The 20-1000 Hz band levels varied from 121 to 130 dB. Further data were obtained on 15 August 1982, when activities reportedly included pile driving on one corner of the island; 20-1000 Hz band levels diminished from 119-125 dB at 0.46 km to 100 dB at 18.5 km. We did not distinguish any sounds that we could associate with pile driving.

On the evening of 16 August 1983, 'Sequel' anchored 3.8 km east of the caisson being installed on a berm at Kadluk. This particular caisson was an octagonal structure that had been floated over a berm and ballasted down. On 16 August 1983 it was being filled with sand to form the caisson-retained island. However, at the time of our measurements, filling was not in progress. Kadluk was the first site where this particular caisson had been installed. We recorded sounds at ranges of 3.8, 1.8, and 0.93 km, where water depths were 12, 13, and 13 m. Numerous support boats, a crane barge, and dredge 'Cornelis Zanen' were all in the vicinity. The 20-1000 Hz band levels were 116, 119, and 117 dB, respectively, for ranges 3.8, 1.8, and 0.93 km, hydrophone depth 9 m. We attribute the lack of dependence on range to the varying presence and activities of the operating vessels around the Kadluk area. Measurements at ranges that were large compared to the separations of the working vessels would be expected to show the usual sound attenuation with increasing distances.

On 29 August 1984 we maneuvered 'Sequel' to a range of 0.2 km from the same caisson, now installed at Amerk (Fig. 1). A crane barge and workboat were moored at the caisson, and a second workboat was underway slowly nearby. After confirming by radio that drilling was underway, we recorded the sounds at ranges 0.22, 0.39, 1.85, 3.7, 7.8 and 13.2 km. The corresponding sound levels in the 20-1000 Hz band were 130, 128, 128, 126, 118, 113 and 112 dB. However, it appears likely that the levels for ranges 7.8 and 13.2 km were predominantly background noise. The other five levels have been plotted on Figure 12 for comparison with the drillship sound level measurements vs. range. The CRI drilling sounds were comparable in level to those from drillship 'Explorer II'.

Figure 17 contains six spectra associated with operations at caisson retained island operations. Figure 17A is from Tarsiut at range 0.46 km on 15 August 1982, and Figure 17B is from Tarsiut at range 1.1 km on 7 August 1982 (hydrophone depth 9 m). The former shows a strong tone at 120 Hz; such a tone is usually associated with electric power generation. Figure 17C is a spectrum for a hydrophone at depth 9 m at range 0.93 km from the caisson

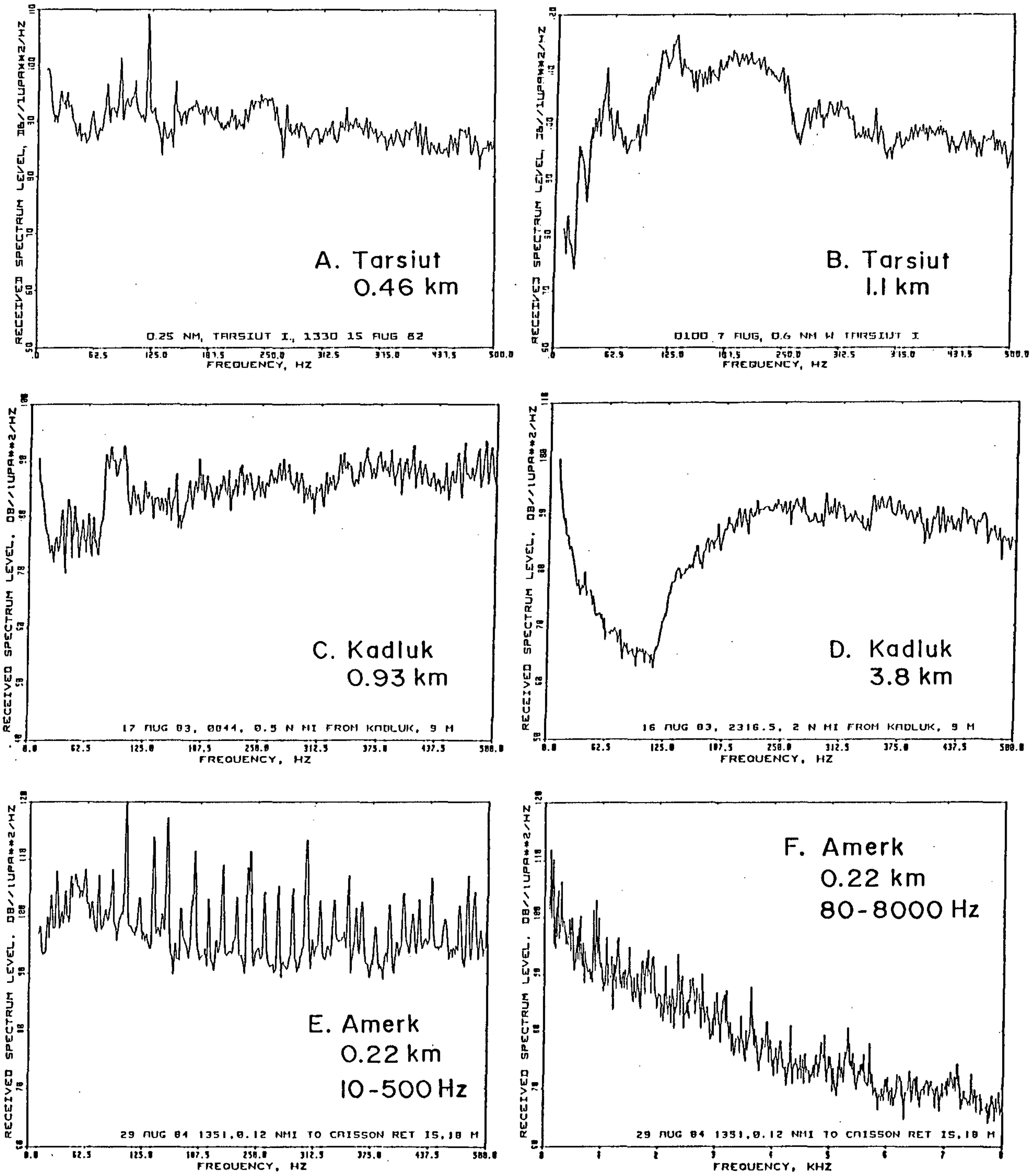


FIGURE 17. Sound pressure spectra from operations at caisson islands.

being installed at Kadluk (water depth 12 m). This case is unusual in that levels increased with increasing frequency, up to 350 Hz. Figure 17D is a spectrum for a hydrophone at depth 9 m at range 3.8 km from the same operation. It shows a dip in received level at frequencies up to 100 Hz; we often noted such a dip in shallow water sound measurements, presumably because low frequency, long wavelength sound energy is rapidly attenuated in shallow water. Figure 17E is a spectrum to 500 Hz for the CRI during drilling at Amerk, range 0.22 km, water depth 26 m, hydrophone depth 18 m. Figure 17F is the same sound analyzed to 8 kHz; the tonal spikes can be seen easily up to 5.7 kHz. The frequency resolution is only 27.4 Hz in Figure 17F, compared to 1.7 Hz in Figure 17E, so the tones are not displayed as prominently in Figure 17F.

Discussion

The activities at the three caisson retained island sites were widely diverse. The levels of sounds during drilling at Amerk were comparable to the levels during drilling by the drillship 'Explorer II'. Comparing the 20-1000 Hz band levels of the three caisson island activities at range 1.8 km, the drilling operation at Amerk produced a sound level of 126 dB, the caisson installation at Kadluk produced 119 dB, and the general activities at Tarsiut produced 113 dB. However, at range 0.93 km the corresponding levels were 128, 117, and 124 dB, making Tarsiut noisier than Kadluk. At all three sites, the radiated sound levels could vary considerably because of the varying activities of the surrounding support vessels. However, such vessel support is standard practice at offshore exploration sites and it must be expected to contribute to the overall industrial noise for such sites.

GENERAL DISCUSSION

As an aid in comparing the measured sound levels with one another and with ambient levels, Figure 18 summarizes 20-1000 Hz band levels vs. receiver range. Only representative sound sources have been included (see also Figs. 5, 13, 15). However, we will discuss other sounds in relation to those plotted.

The strongest levels on the graph are airgun array signals from 'GSI Mariner' at ranges 12-17 km. These signals are transitory, usually lasting less than a second and occurring once each 12-15 s. Other 'GSI Mariner' airgun array signal levels are plotted for ranges 62-73 km on 18 August 1982. We noted considerable variability in airgun signals from longer ranges, as shown by these examples, and attribute it to the important influences of water depth and bottom sediment properties on sound propagation. Aspect with respect to the long axis of the airgun array was probably also a factor (Barger and Hamblen 1980; Malme et al. 1983).

Sounds from the sleeve exploders on 'Arctic Surveyor' were received at nominal ranges of 8, 13, and 28 km in water 15-30 m deep, hydrophone depth 9 m. Figure 18 includes the curve derived from multiple regression analysis of the measured levels relative to range. The curve shows that the sound levels diminished with increasing range in two ways: by cylindrical spreading (10*log(range)) and by a combination of absorption and scattering losses amounting to 1.4 dB per kilometre. The latter linear term is very important for longer range sound transmission. Data not shown here (see Greene 1982, p. 338) revealed that the linear term was generally larger for shallow depths

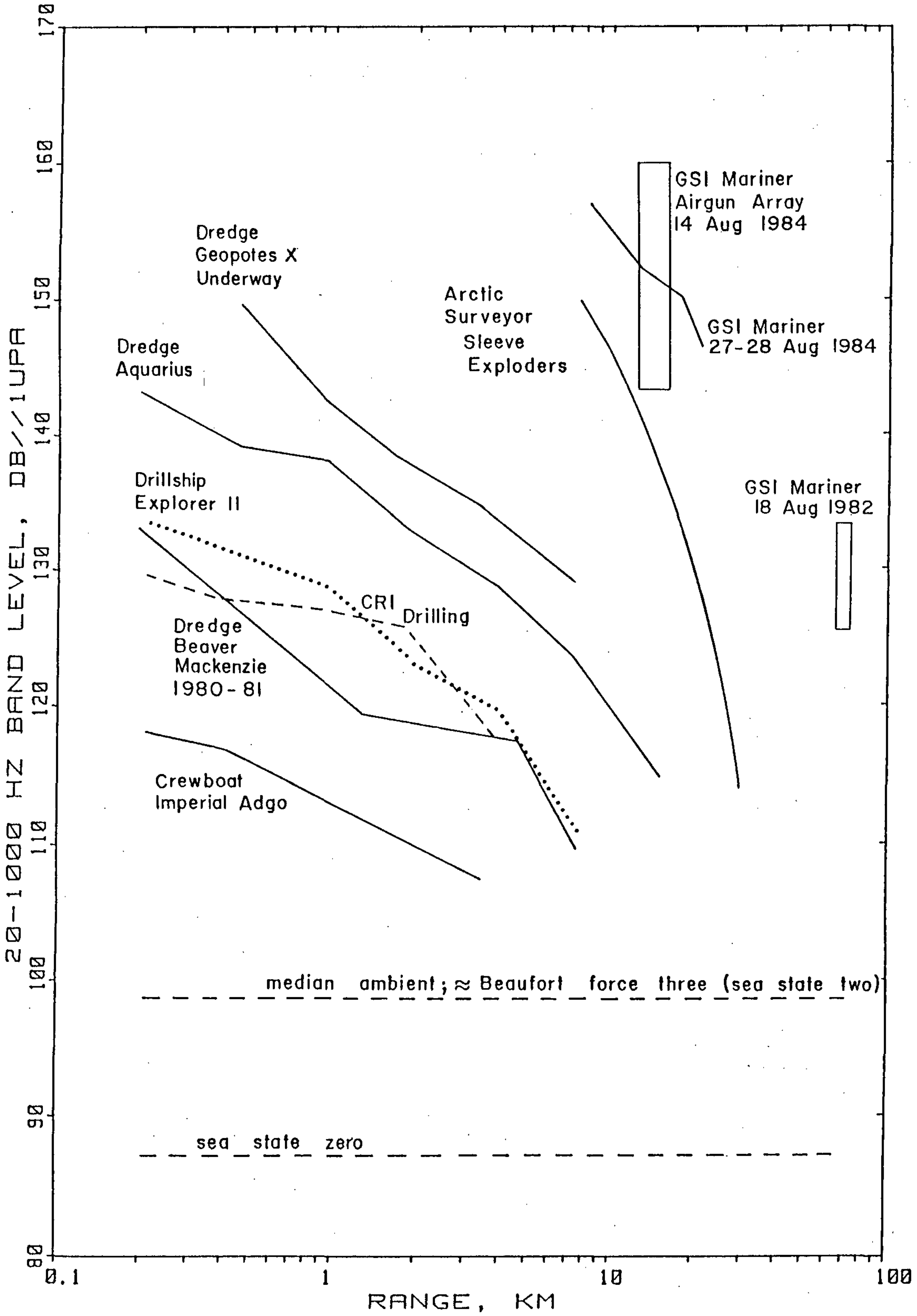


FIGURE 18. Summary of levels vs. range for various industrial sounds. The boxes circumscribe the ranges and levels received from 'GSI Mariner' during various short spans of time.

and/or higher frequencies. For example, for a 1000 Hz tone for 'Geopotes X' in water 25 m deep, the absorption/scattering loss term was 2.53 dB per kilometre.

The strongest continuous type of signal received during the project came from hopper dredge 'Geopotes X' underway. The ship was apparently operating that season with a damaged propeller, which probably accounts for the high levels. Also shown on Figure 18 is the curve connecting the measured levels of sound from crewboat 'Imperial Adgo' operating over shallow water (18.5 m). Sound levels from crewboat 'Imperial Sarpik' and the sound boat 'Sequel' were similar. These were among the quietest industrial noises recorded. Only 'Arctic Sounder', anchored and running only its electric generator, was quieter. Other boat and ship sound levels, including those from supply boats and other dredges underway, fell between the levels for 'Geopotes X' and 'Imperial Adgo'.

The sound levels near drillship 'Explorer II' while drilling are also presented in Figure 18. The sounds near conical drilling unit 'Kulluk' while drilling were stronger by 10-15 dB, but sounds from 'Explorer I' while logging were 5-10 dB weaker. Sounds from Amerk caisson retained island while drilling were on the same order as sounds from 'Explorer II'. In all these cases, some of the sounds probably came from ancillary vessels nearby, and some of the differences may have been attributable to the variable types and activities of those vessels.

The received levels for sounds from transfer dredges 'Aquarius' and 'Beaver Mackenzie' are graphed on Figure 18. Sounds from hopper dredges like 'Cornelis Zanen' picking up a load were received at somewhat higher levels (by about 5 dB) than the sounds from 'Aquarius' at comparable ranges. We attributed the higher levels from hopper dredges to the contributions from the propulsion machinery. 'Beaver Mackenzie' in 1983 was significantly quieter than it had been in 1980-81.

Below the industrial sound levels in Figure 18 we have plotted the median of the ambient noise levels measured during the 1984 season (excluding measurements near industrial sites) and the expected 20-1000 Hz band level for sea state zero. The 1980-84 median level (99 dB) was 1 dB less than the expected level for Beaufort Wind Force 3 (Sea State Two). These ambient levels are not range dependent and are, therefore, plotted as straight lines independent of range.

The sound levels received from overflying aircraft are not plotted because they were not analyzed for range dependence. However, the received levels can be compared with the plotted levels for other sources. For example, the maximum noise level below the Islander at altitude 152 m was 117-123 dB at a hydrophone 3 m deep; those levels are comparable to 'Imperial Adgo' at range 0.2 km and to drillship sounds at ranges near 4 km. Levels of aircraft noise decreased with increasing aircraft altitude and increasing hydrophone depth. At depth 9 m, Twin Otter and Islander sounds from altitude 457 m were 101-106 dB, or just above the 1984 median ambient noise level. These levels are averages for the 4 s when the aircraft sound was strongest. The maximum level was received for only a few seconds.

Sound levels from caisson retained islands at Kadluk and Tarsiut are not plotted on Figure 18, but Tarsiut levels were generally similar to levels from drillship 'Explorer II', CRI drilling, and dredge 'Beaver Mackenzie' in 1980-81. Kadluk sound levels were also about the same.

The following are the fitted equations for received level in the 20-1000 Hz band (dB//1 µPa) vs. range (km) for three industrial sound sources in the shallow Beaufort Sea. Cylindrical spreading (10*log R) was forced.

Drillship 'Explorer II' drilling:

$$RL = 128.4 - 0.985*R - 10*\log(R) \qquad se = 1.06 \text{ dB}, r^2 = 0.892, n = 6.$$

Hopper dredge 'Geopotes X' underway:

$$RL = 143.9 - 0.916*R - 10*\log(R) \qquad se = 2.27 \text{ dB}, r^2 = 0.634, n = 5.$$

Dredge 'Beaver Mackenzie' dredging (at Alerk):

$$RL = 127.1 - 1.197*R - 10*\log(R) \qquad se = 1.57 \text{ dB}, r^2 = 0.847, n = 6.$$

For dredge 'Aquarius' dredging at Nerlerk (depth 46-60 m), we derived an equation for received level in the 20-500 Hz band (dB//1 µPa) as a function of both range in km and hydrophone depth in m (from Greene 1984, p. 293):

$$RL = 119.9 - 0.42*R - 1.31*D - 10.8*\log(R) + 29.6*\log(D)$$
$$se = 2.1 \text{ dB}, r^2 = 0.96, n = 21.$$

We can make several summary statements about industrial sounds in the Beaufort Sea:

1. Sounds from an aircraft overhead diminish in strength with increasing receiver depth. Sounds from an aircraft not directly overhead increase in strength with increasing receiver depth. Low flying aircraft induce stronger peak levels of sound underwater than do high flying aircraft. The peak levels of aircraft sound are short-lived, especially when the aircraft is low. Sounds from passing aircraft are audible longer in shallow water than in deep water.

2. Sounds from underwater sources are weaker near the surface. For the low frequencies (<100-200 Hz) dominating the industrial sound sources that we studied, this shallow depth effect is most noticeable within 9 m below the surface.

3. The impulsive sounds from distant seismic surveys can travel via both water and bottom paths. In shallow water, the waterborne sound reaching ranges of several kilometres or more is limited to frequencies above about 100 Hz, and sometimes to even higher frequencies. Generally, the summation of multiple reflections over a long path leads to the appearance of higher frequencies first, followed by decreasing frequencies, in the waterborne sound. Longer distances mean more multipaths and, hence, a longer-lasting signal. Sound may also travel via bottom paths, bending upward and reflecting at the surface many times on its way to the receiver.

Low frequencies travel via these bottom paths and generally the lowest frequencies arrive first, followed by increasing frequencies.

4. Sounds from offshore sites generally include sounds from numerous support vessels--supply boats, tugs, crane barges, and camp barges. Drilling vessels are also sometimes protected by icebreakers. The sounds from these vessels are an integral part of the noise fields around the offshore sites, but these sounds can be highly variable, depending on activities.

5. Ambient noise levels in the Beaufort Sea vary from below the levels expected for sea state zero (deep water) to above levels expected for Beaufort Wind Force 8. The median level for the 20-1000 Hz band, excluding measurements near industrial sites, was 99 dB. This is equivalent to the expected level for Beaufort Wind Force 3. It should be noted that measurements were generally not made during bad weather, either from the sound boat or the airplane, and the true median level would be higher.

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Over the five year program, more people contributed to the acoustics effort than can be acknowledged here. Exceptional contributions came from Mark Fraker, field project leader in 1980; Peter Thomas, biologist on the sound boat in 1980-83; Len Pearson, captain of 'Sequel' and an important contributor in 1981-84; and Gary Miller, biologist on 'Sequel' in 1983-84. Dr. Bernd Würsig, biologist with the air crew, organized supply drops to 'Sequel', and helped with instrumentation problems, including the major reconstruction of a tape recorder. Dr. W. John Richardson of LGL, principal investigator, led all phases of the research. I am particularly grateful for his guidance during report preparation and editing. Dr. R. Davis of LGL provided helpful comments on the draft report.

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Dave Heffler and Fred Jodray at Bedford Institute of Oceanography provided the 40 in^3 airgun used from 'Sequel' in 1981, 1983 and 1984.

The staff at the LGL office in King City devoted extra effort to the production of this report. C. Holdsworth and R. Evans looked after details, B. DeLong did the graphic art, and B. Griffen and R. Stark typed the text and tables.

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OCS STUDY

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BEHAVIOR, DISTURBANCE RESPONSES AND DISTRIBUTION OF BOWHEAD WHALES *Balaena mysticetus* IN THE EASTERN BEAUFORT SEA, 1980-84

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DISTRIBUTION OF BOWHEADS AND INDUSTRIAL ACTIVITY, 1980-84*

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TABLE OF CONTENTS

ABSTRACT

This section summarizes seasonal and year-to-year trends in the summer distribution of bowheads during 1980-84. It identifies locations where bowheads tended to concentrate, documents the locations of offshore industrial operations within the summering area, and discusses whether any year-to-year changes in distribution are attributable to oil exploration. Sightings of bowheads during all studies in the Canadian Beaufort Sea in mid-late summer of 1980-1984 are mapped by 10-d period. Other maps show sites of offshore drilling, dredging, boat and helicopter traffic, seismic lines, and ice conditions. The 'main industrial area' is off the Mackenzie Delta, and includes island construction, drilling, dredging, and intensive boat and helicopter traffic. Seismic exploration occurs over a wider area.

In 1980, bowheads were more numerous close to shore than in the subsequent four years. Some were <5 km from an island construction operation off the central Mackenzie Delta. By late August, very large numbers (probably well over half the population) were widely distributed off the Tuktoyaktuk Peninsula, many in water <20 m deep. Numbers off the Delta were somewhat reduced by late August, but still high. In 1981, most bowheads

remained farther offshore. In early August many moved south onto the outer continental shelf off the Mackenzie Delta, with lesser numbers off the Tuk Peninsula. None were seen where whales were abundant in early August 1980. In mid August the whales were widely distributed in waters >50 m deep, but there was a concentration off the central Delta, with some whales <10 km from industrial sites.

In 1982, most bowheads were far enough offshore or west to be outside the main industrial area. In mid-late August, there were concentrations near Herschel Isl and near the shelf break. In 1983, most bowheads again remained outside the main industrial area. In early August, bowheads were found far off the western Yukon, sometimes exposed to noise from distant seismic exploration. In mid and late August, several hundred subadult bowheads were along the Yukon coast, distant from industrial activity. Some bowheads were near the edges of the industrial area in late Aug-early Sept. In 1984, bowheads were somewhat more common in the main industrial area than in 1982 and 1983, although less so than in 1980 and 1981. Most of those in the industrial area were around its periphery, not in the central part where bowheads were abundant in 1980 and, to a lesser extent, 1981. From mid Aug to early Sept, many were along the Yukon coast and along the edge of the turbid Mackenzie River water in Mackenzie Bay.

Discussion.--From 1980 to 1982, bowhead distribution overlapped progressively less with the main industrial area. Peak numbers there in 1983 were slightly greater than in 1982, and there was some further increase in 1984. Most of those in the industrial area in 1983-84 were near its edges, unlike the situation in 1980. Intense offshore industrial activity began north of the Mackenzie Delta in 1976. Very limited data from 1976-79 indicate that bowheads were numerous in the central part of the main industrial area in August of 1976 and 1977 but not 1978 or 1979, i.e. in 3 of 5 years from 1976-80, and in 0 of 4 years from 1981-84. The reappearance of many whales in 1980 makes it questionable whether the apparent trend toward reduced utilization of the main industrial area was attributable to industrial activity. However, offshore industrial activities have increased gradually since 1976; industry may have begun to affect bowheads after 1980.

In 1980-84, seismic exploration occurred both within and beyond the main industrial area. Bowheads were often seen in areas with seismic noise, and in areas where whales had been exposed to seismic noise the preceding year. Thus, we found no evidence that bowheads avoided areas of previous exposure to seismic noise.

Bowhead distribution varied markedly from summer to summer in the feeding grounds of the Canadian Beaufort Sea. This variation occurred outside as well as within the main industrial area. At present, it is not possible to determine whether the scarcity of bowheads in the central part of the main industrial area in 1982-84 was related to industrial activities. Assumed variation in food availability (zooplankton concentrations) may also have been involved. Zooplankton is probably controlled by oceanographic and meteorological factors that vary seasonally and annually. Until the influences of these natural factors on zooplankton and bowhead distribution are understood, it may be impossible to determine whether any of the variation in bowhead distribution is a result of industrial activities.

INTRODUCTION

The main focus of this volume is a study of short-term behavioral reactions of bowhead whales to offshore industrial activities. An observable behavioral response provides an immediate indication that whales are sensitive to the industrial activity. However, it is difficult to determine whether brief behavioral reactions have any long-term negative consequences. Long term reactions might, in theory, include such interrelated factors as increased stress, reduced overall food intake during the summer feeding season, reduced reproductive success or survival rate, and displacement from parts of the traditional range. Of these, the potential effect that might be detected most easily is displacement.

The literature contains little quantitative information about prolonged displacement of other species of baleen whales by human activities. Gray whales apparently were displaced from a wintering lagoon when ship traffic and other human activities intensified, and returned several years later when ship traffic decreased (Gard 1974; Reeves 1977; Bryant et al. 1984). In other cases, suggested displacements have not been demonstrated convincingly (reviewed by Richardson et al. 1983b). These possible cases include other gray whale wintering areas and migration routes (Rice 1965; Rice and Wolman 1971; Wolfson 1977; Dohl and Guess 1979), humpback whale wintering and feeding areas (Norris and Reeves 1978; Jurasz and Jurasz 1979; MMC 1979/80), and whales in areas of heavy ship traffic off Japan (Nishiwaki and Sasao 1977). Most of these data are equivocal regarding whether whales are displaced by industrial activities. However, it is clear that whales often return each year to areas where they have been hunted or exposed to heavy vessel traffic.

By 1980, when detailed studies of Western Arctic bowheads in their Canadian summering areas began, full-scale offshore oil exploration had been underway for some years. Drilling from artificial islands in very shallow nearshore waters off the Mackenzie Delta began in 1972. In 1976, drillships began operating offshore, and island-construction also extended offshore into waters where bowheads occur. The intensity of offshore industrial activity has generally increased since 1976. By 1983 and 1984, five drillships, two active drilling caissons, 5-6 suction and hopper dredges, 9-10 helicopters, 3-4 seismic exploration boats, four industry-owned icebreakers, about 10 supply ships and many other support vessels were operating offshore in the southeastern Beaufort Sea (Fig. 1).

Before 1980, the only data about summer distribution of bowheads were from commercial whalers operating in the area around 1890-1914, and recent incidental sightings. Those records showed that bowheads migrate eastward into the Canadian Beaufort Sea in May and June, mainly along routes far offshore in the pack ice (Fraker 1979; Braham et al. 1980). Most sightings in early summer were in western Amundsen Gulf and the extreme eastern part of the Canadian Beaufort Sea -- east of the area of offshore oil exploration (Townsend 1935; Sergeant and Hoek 1974; Fraker et al. 1978; Fraker 1979; Fraker and Bockstoce 1980). Some bowheads occurred as far east as western Victoria Island (118°W) in May-August (Sergeant and Hoek 1974; Hazard and Cubbage 1982).

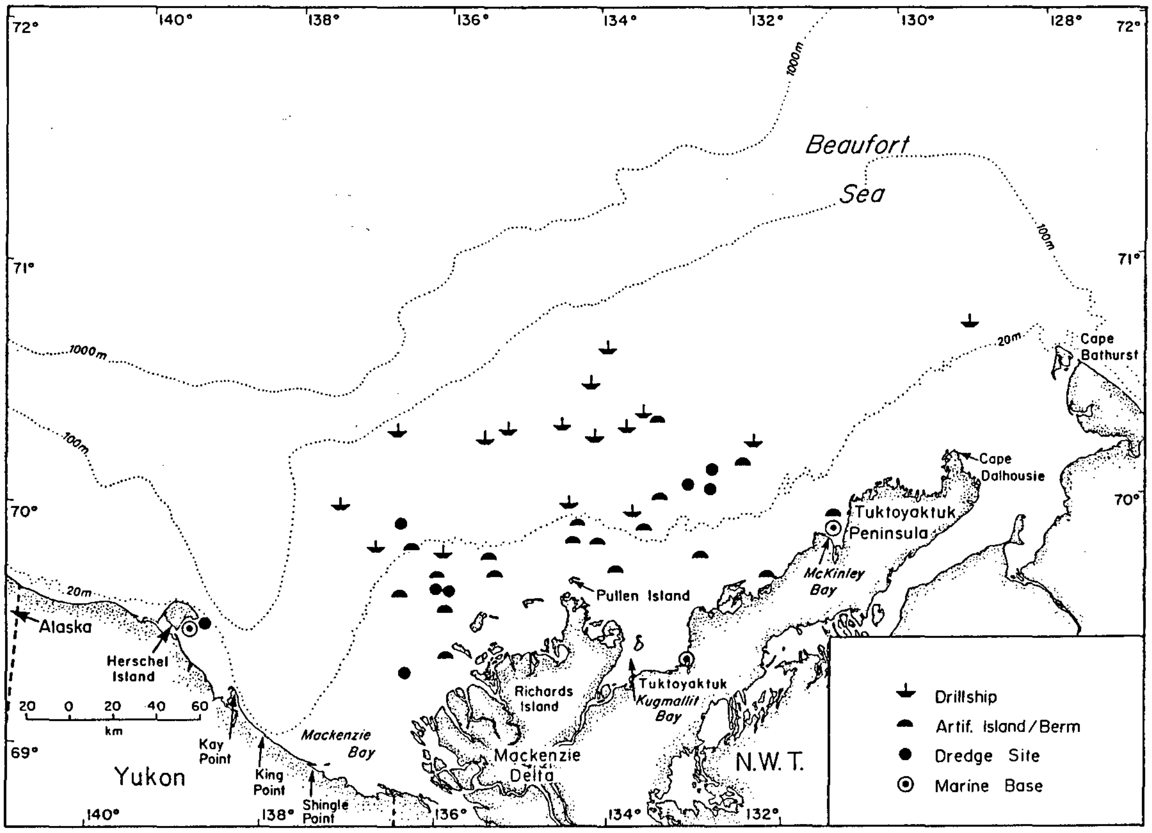

FIGURE 1. The eastern Beaufort Sea, study area for this project, showing the main sites of offshore industrial activity in August and early September, 1980-84. **Inset:** Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

During both the whaling era and the 1970's, the distribution of bowheads seemed to spread gradually westward off the Tuktoyaktuk Peninsula, Mackenzie Delta and Yukon coast in August (Townsend 1935; Sergeant and Hoek 1974; Fraker et al. 1978). The westward trend was considered real although (1) changing ice conditions were known to cause biases in detectability, and (2) most bowheads seen during August 1976-78 were oriented eastward (Fraker and Bockstoce 1980). In September, bowheads moved westward between Cape Bathurst (128°W) and the Alaska border (Sergeant and Hoek 1974), sometimes concentrating near the Yukon coast (Fraker and Bockstoce 1980). The last sightings in Canadian waters were in early October (Fraker and Bockstoce 1980).

Aerial surveys provide the type of comprehensive information about bowhead distribution that can be used to detect changes in distribution. Systematic surveys of parts of the Beaufort Sea were conducted in late summer of 1980-84. Coverage was incomplete and variable, but provided a far more detailed view of bowhead distribution and movements than was evident up to 1980. The surveys also showed major year to year differences in summer distribution, and in number of bowheads within the area of offshore oil exploration (Renaud and Davis 1981; Davis et al. 1982; Harwood and Ford 1983; Harwood and Borstad 1984; McLaren and Davis 1985).

Besides the systematic surveys, numerous other studies of bowheads have been conducted in the eastern Beaufort Sea since 1980. These included the behavioral study reported in this volume (1980-84), photogrammetric studies (1982-84), Alaskan aerial surveys that sometimes extended into Canadian waters (1980-84), and an attempt at radio-tagging (1980). All these studies included aerial surveys or reconnaissance; all bowhead sightings were recorded, although many of these distributional data were not included in resulting project reports. These non-systematic data included many locations and periods for which no systematic survey coverage was obtained.

The objectives of this report are twofold:

1. Draw together in a standardized way the available published and unpublished information about bowhead distribution in relation to industrial activities in the eastern Beaufort Sea during the summers of 1980 to 1984.

2. Assess whether there are any consistent trends in the summer distribution of bowheads during this period, and whether any such trends can be related to industrial activities.

For each 10-day period in the late summers of 1980-84, we present a map of the aerial survey routes (systematic and non-systematic) and the sightings of bowheads. For each of the five years, we also include maps showing the active offshore industrial sites, vessel and helicopter traffic, seismic exploration, and ice conditions. The very limited available data on bowhead distribution in the summers of 1976-79 are also summarized. We then assess whether there were any consistent trends in the summer distribution of bowheads in recent years, and whether the trends are related to industrial activities. We use the term "main industrial area" to refer to the zone with drilling, island construction, and intensive support by vessels and helicopters. Some seismic exploration is in the main industrial area, but seismic vessels often operate outside that zone.

This analysis of possible medium- to long-term effects complements our study of short-term behavioral reactions to industrial activities (Richardson et al. 1985a,b), and should be helpful in assessing whether offshore oil exploration in the Alaskan waters is likely to displace bowheads from parts of their traditional Alaskan range. The present final report is self-contained and includes the data and interpretations pertaining to all years. However, earlier versions of this report (Richardson et al. 1983a, 1984a) include more details for 1980-82 and for 1983, respectively, particularly concerning industrial activities in those years.

The scarcity of information about natural factors affecting the distribution of summering bowheads, or their zooplankton prey, is recognized as a serious problem in attempting to interpret the data on bowhead distribution. Variables that could be important in affecting bowhead distribution, directly or through effects on zooplankton, might include the variable outflow from the Mackenzie River, the variable extent and location of the Mackenzie plume, the variable distribution of ice, and variable hydrographic phenomena at the shelf break, ice edge and elsewhere (Griffiths and Buchanan 1982; Borstad 1984; LGL, ESL and ESSA 1984). Ongoing and planned work to address these factors will, when completed, be important in understanding the distribution of bowheads as documented below.

METHODS AND DATA SOURCES

Bowhead Sightings

Information about bowhead distribution in the eastern Beaufort Sea is available from early August to early or mid September of 1980-84, plus parts of July in 1981 and 1984 (Table 1). We include maps of bowhead distribution for four 10- or 11-day periods: 1-10, 11-21 and 22-31 August, and 1-10 September. A map for late July 1981 is also included. Almost all bowheads seen in the area of intense industrial activity off the Mackenzie Delta were seen in these periods. Our study area was the Canadian Beaufort Sea from Cape Bathurst (127°W) to the Alaska border (141°W), and north to 72°N (Fig. 1). The map for each 10-d period shows all flight lines and bowhead sightings within the study area during the studies listed in Table 1.

Field procedures during the various surveys are described in the reports cited in Table 1. During almost all surveys, Very Low Frequency (VLF) navigation systems were used to determine flight routes and sighting locations. Many flights were not systematic surveys with defined transect widths. Hence, we mapped all sightings, whether or not they were classified as on- or off-transect in the original reports. Symbols of progressively increasing prominence are used to show sightings of 1-3, 4-7, 8-15, 16-30 or 31-80 bowheads. When two or more sightings were so close together that their symbols overlapped broadly, only the larger of the two symbols was shown. This procedure reflects the fact that some whales undoubtedly were seen more than once during single 10-d periods.

The map for each 10- or 11-d period differentiates sightings and routes during the first 5 days from those during the next 5 or 6 days. In some 10-d periods, there were so many aerial surveys in certain areas that it was impractical to show every flight line. These 'intensive coverage areas' are demarcated with a heavy line. Within these areas only the bowhead sightings, not the flight routes, are shown.

We emphasize that the non-systematic surveys provide only a qualitative indication of the relative abundance of bowheads in different areas, and must be interpreted with caution. Survey procedures differed among projects, and detectability of whales was better during some flights than others. Survey effort in different parts of the study area ranged from nil to intensive, and non-systematic surveys tended to be concentrated in areas with many bowheads. Some whales are undoubtedly mapped more than once in a 10-d period, especially in areas where there was much coverage.

Offshore Industrial Sites and Vessel Movements

For each year from 1980 to 1984, we mapped the offshore locations where industrial activities were concentrated in the 1 August to 10 September period. The main site-specific activities were dredging, island construction or maintenance, drilling from drillships or islands, and island clean-up. These activities are shown by various symbol types. Construction of underwater berms and of islands were not differentiated. Offshore sites were mapped even if active for only a few days.

Table 1. Systematic and non-systematic aerial surveys of bowhead whales in the Canadian Beaufort Sea, 15 July to 20 September of 1980 to 1984. Survey effort is summarized in terms of d, days of surveying; f, number of offshore flights; h, hours of surveying; km, kilometres of straight-line transects.

	1980	1981	1982	1983	1984
Systematic surveys	- **Renaud & Davis (1981)** - 6 Aug-4 Sept - 7 d/6258 km - 3 surveys off Tuk Pen (133° to 129°W)	- **Davis et al. (1982)** - 18 July-14 Sept - 28 d/37,745 km[g] - 4 surveys, AK border to Amund Gulf (138°-141° to 117°-126°)	- **Harwood & Ford (1983)** - 18 Aug-13 Sept - 9 d/7442 km - 2 surveys, AK border to C. Dalhousie (140°-141° to 129°-130°W)	- **McLaren & Davis (1985)** - 19 Aug-11 Sept - 9 d/7045 km - 2 surveys, AK border to C. Dalhousie (141° to 129°W)	- **Harwood & Borstad (1984)** - 18 Aug-18 Sept[a] - 10 d/11,170 km[a] - 2 surveys[a], AK border to Franklin Bay (141° to 126°W)
Behavior & disturbance	- **Richardson (1982)**[b] - 3-31 August - 16 f/101 h - Mostly N of Mack Delta & Tuk Pen	- **Richardson (1982)**[b] - 27 July-8 Sept - 27 d/32 f/117 h - Mostly N of Mack Delta & Yukon	- **Richardson (1983)**[b] - 1-31 August - 19 d/27 f/122 h - Widespread off Delta & Yukon	- **Richardson (1984)**[b] - 1 Aug-1 Sept - 18 d/28 f/114 h - Mostly N of Mack Delta & Yukon	- **Richardson (this vol.)**[b] - 1 Aug-3 Sept - 23 d/33 f/140 h - Widespread; much in Mack Bay
Alaskan surveys extending into Canada[d]	- **Ljungblad (1981)**[d] - 28 July-24 Oct - 8 f/8 d[e] - Mostly off Yukon; some off Tuk	- **Ljungblad et al. (1982)**[d] - 15 Aug-20 Sept - 10 f/10 d - Mostly off Yukon	- **Ljungblad et al. (1983)**[d] - 2 Aug-15 Oct - 16 f/16 d[e] - Mostly off W Yukon	- **Ljungblad et al. (1984a,b, unpubl.[c])**[d] - 2 Aug-5 Oct - 29 f/23 d[e] - Mostly off W Yukon	- **Ljungblad (unpubl.)**[c],[d] - 17 July-11 Oct - 24 f/21 d[e] - Mostly off W Yukon
Photogrammetric & other studies	- **Hobbs & Goebel (1982)** - 21 July-12 Sept - 13 f/13 d[f] - Mostly off Tuk Pen & C. Bathurst	- part of Davis et al. (1982); see above	- **Davis et al. (1983)** - 12 Aug-5 Sept - 15 d/72+ h/>8781 km - AK border to C. Parry (141°-125°)	- **Cubbage et al. (1984)** - 7 Aug-6 Sept - 24 f - AK border to Amund Gulf (141°-122°)	- **Davis et al. (in prep.)** - 14 Aug-14 Sept - 23 d/90+ h - AK border to Franklin Bay (141°-126°)
	- **Norton Fraker & Fraker (1981)** - 24 July-9 Aug - 3 f/3 d - N of Delta near Issungnak				- **D. Rugh (U.S. Nat. Mar. Mamm. Lab.)**[c] - 13-17 Aug - 4 d/4 f - AK border to C. Bathurst (141°-128°)

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[a] Harwood and Borstad (1984) also summarize four July surveys (5 July-2 August 1984, 12 d, approx. 6400 km) of the Alaska border to Cape Bathurst area (longitudes 139°- 141° to 128°-131°W).

[b] Distributional data obtained during the behavioral study have not been presented in detail elsewhere.

[c] Unpublished distributional data are mapped here through the cooperation of the investigators cited above.

[d] Flights that extended east of 141°W are considered here.

[e] Flights after 20 September not counted.

[f] Excludes flights also mapped by Ljungblad (1981).

[g] Includes coverage in Amundsen Gulf as well as Beaufort Sea *per se*.

For 1 August to 10 September in each of 1980 to 1984, the approximate number of vessel trips along each route is shown by line thickness. We included supply and crew boats, tug/barge trains, dredges, icebreakers, and drillships moving between sites. Seismic, sounding and scientific research vessels were excluded. The information came from records kindly made available by the oil companies and other vessel operators (see Acknowledgments). All major offshore operators allowed us to use their records. The maps do not record every vessel movement, and the mapped routes are approximations. Data for 1982-84 were more complete than those for 1980-81. However, the maps are indicative of the relative amounts of traffic in various offshore areas and periods. The vessel maps in this report include the entire 1 Aug-10 Sept period. For vessel traffic by 10-d periods in 1980-83, see Richardson et al. (1983a, 1984a).

For 1976 to 1979, we mapped the offshore sites that were active in the 1 August to 10 September period. On those maps, we indicate the routes that we know or believe were used by vessels. However, we did not attempt to determine how many vessels travelled along each route in 1976-79.

Seismic Exploration and Sounding

A third type of map shows the lines along which seismic vessels operated in the 1 August to 10 September periods of 1980 to 1984. Noise impulses emitted by seismic vessels are the most intense sounds routinely introduced into the sea by the oil industry (Richardson et al. 1983b, 1985b; Greene 1985). Surveys by three types of vessels are distinguished: Solid lines depict geophysical surveys shot by vessels using large arrays of airguns. Dashed lines depict surveys by the 'Arctic Surveyor', a vessel with an array of 12 sleeve exploders (1980-81) or 12 open bottom gas guns (1982-84). Dotted lines show surveys by 'Canmar Teal', a vessel using a small array of airguns. Sounding and other activities involving single airguns and other low-energy sources are not mapped here. The characteristics of the noise sources and of the resulting sounds are summarized by Greene (1982-85) and Richardson et al. (1985b). For locations of the 1980-83 seismic surveys by 10-d periods, and for locations of low-energy sounding operations, see Richardson et al. (1983a, 1984a).

The locations of seismic lines were kindly provided by Geophysical Service Inc., Western Geophysical Inc., Dome Petroleum Ltd., Esso Resources Canada Ltd., and Gulf Canada Resources Inc. Supplementary information was obtained from our sightings of seismic vessels at sea (Richardson et al. 1985b). Some seismic lines in the Alaskan Beaufort Sea extended east to 141°W longitude, the nominal western edge of our study area, and some extended a few kilometres farther east. These seismic lines are close to the western edge of our maps, and we did not attempt to include them. Seismic lines that crossed 141°W but also extended far to the east are included.

Helicopter Movements

A fourth type of map presented for each of 1981 to 1984 shows the offshore industrial sites (as on the vessel traffic map) plus the number of helicopter trips along each offshore route. The information was obtained from Dome, Esso and Gulf records, and included data for helicopters chartered by those oil companies. No other operators fly helicopters over the eastern

Beaufort Sea on a routine basis. However, a few single-engine helicopters occasionally travel offshore; we have not attempted to map their movements.

No adequate records of helicopter traffic in 1980 were available, and no map was prepared for that year. In 1980, as in other years, helicopters undoubtedly travelled from Tuktoyaktuk to all of the mapped offshore sites, as well as between some pairs of offshore sites.

Offshore flights by fixed-wing aircraft are excluded from the helicopter traffic maps. Whale survey flights are mapped on the whale distribution maps. Most commercial and ice reconnaissance flights are at altitudes above 457 m (1500 ft), and thus are too high to affect whales significantly (cf. Richardson et al. 1985a,b).

Ice Conditions

Ice conditions in early August and early September of 1980-84 are mapped. These maps show the areas with over 1% cover and over 80% cover. The maps are based on Weekly Composite Charts compiled by Ice Forecasting Central, Environment Canada. Their maps are based on satellite photographs and ice reconnaissance flights. Locations of pack ice sometimes changed by many kilometres within a few hours. Thus, the generalized maps presented here provide only a rough indication of ice cover.

RESULTS

Bowhead Distribution and Industrial Activities in 1980 (Fig. 2-9)

Industrial Activities, 1980

The general level of industrial activity in 1980 was slightly greater than in 1976-79 but lower than in 1981-84. Esso Resources Canada Ltd. and Dome Petroleum Ltd. were the only two oil companies operating offshore in 1980.

All drilling during the 1980 study period was from the four Dome drillships, which were at four sites north of the Mackenzie Delta for most or all of the 1 Aug-10 Sept period (Fig. 6). The one suction dredge that operated offshore built or improved artificial islands at Issungnak (27 Jul - 24 Aug; depth 18 m) and later Alerk (25 Aug-Oct; depth 13 m; Fig. 6). Most vessel movements were in support of these drilling and island building activities in the central part of the study area. However, there were several supply trips to points farther east and west (Fig. 6).

At least five twin-engine turbine helicopters were used offshore in 1980 --fewer than in 1981-84 (Table 2). Details concerning routes and number of flights were not available. However, most flights were from Tuktoyaktuk to the offshore sites shown on Fig. 6, with lesser numbers of trips (a) between those sites and (b) between McKinley Bay (Fig. 1) and the drillships.

Seismic exploration occurred off the eastern part of the Mackenzie Delta and much of the Tuktoyaktuk Peninsula throughout the 1 Aug-10 Sept period. Seismic occurred northwest of the Delta in mid and late August, and far to

Table 2. Number of helicopters operating offshore from Tuktoyaktuk on behalf of the oil industry in the summers of 1980-84.

Type of Helicopter	1980	1981	1982	1983	1984
Light twin (AS-355, BO-105)	0	0	1	2	2
Medium twin (B212, B412, S76)	4+	6+	5+	5	4
Large twin (AS-332, B214ST, S61)	1	1	2-3	3	2-3
Total	5+	7+	8+	10	8-9

the east off Cape Bathurst in early Sept (Fig. 8). There was additional seismic exploration at unknown locations and times during the summer of 1980.

Bowhead Distribution, 1980

Many bowheads occurred close to shore off the eastern Mackenzie Delta and western Tuk Peninsula in August 1980 (Figs. 2-4)--more so than in 1981-84. Survey coverage of the more remote areas was not comprehensive in 1980. Hence, large scale movements of the whales in 1980 are not well documented. There was almost no ice in the areas surveyed during August, but ice moved closer to shore in early September (Fig. 9).

The whereabouts of the bowheads during late July 1980 is not known. None were seen during an intensive but restricted survey north of the Delta around Issungnak on 24 July (Norton Fraker and Fraker 1981). There were no definite sightings during the four flights elsewhere in the study area (Ljungblad 1981; Hobbs and Goebel 1982).

In early August 1980, many bowheads moved into shallow water north of the Delta (Fig. 2). From 2 August onward, aerial surveyors and industry personnel saw many bowheads within 5 km and a few within 1 km from the suction dredge and support vessels at Issungnak (Norton Fraker and Fraker 1981; Richardson et al. 1985a,b). The whales were socializing, diving, and feeding in this area. There were few bowheads off the Tuk Peninsula in early August (Renaud and Davis 1981; Fig. 2).

Many bowheads moved into the area of heaviest industrial activity in early August. Seismic exploration was occurring both north of Issungnak and off the Tuk Peninsula. Besides traffic in support of the construction operation at Issungnak, vessel and helicopter traffic to at least 3 of the 4 drillships passed through the area where bowheads were concentrated (Fig. 2 vs. 6).

In mid August 1980, bowheads were still numerous near Issungnak, but many appeared farther east off the Tuk Peninsula around 14 August (Fig. 3). During flights on 19, 20 and 21 August, Hobbs and Goebel (1982) saw 114, 157 and 245 bowheads, mostly in shallow waters off the Tuk Peninsula. Many whales were feeding in waters as shallow as 10 m (Würsig et al. 1982). Aerial

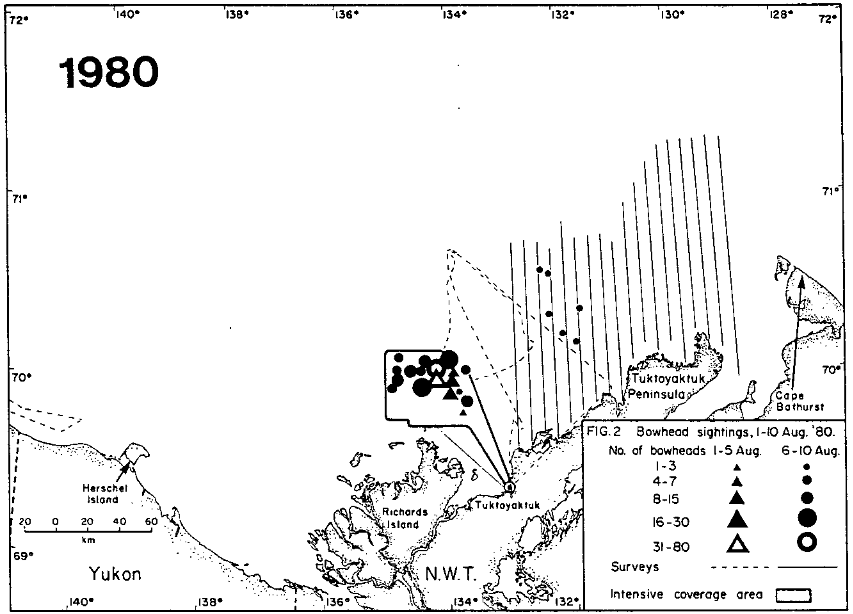

FIG. 2 Bowhead sightings, 1-10 Aug. '80.

No. of bowheads	1-5 Aug.	6-10 Aug.
1-3	▲	●
4-7	▲	●
8-15	▲	●
16-30	▲	●
31-80	△	○

Surveys - - - - - ——

Intensive coverage area ▭

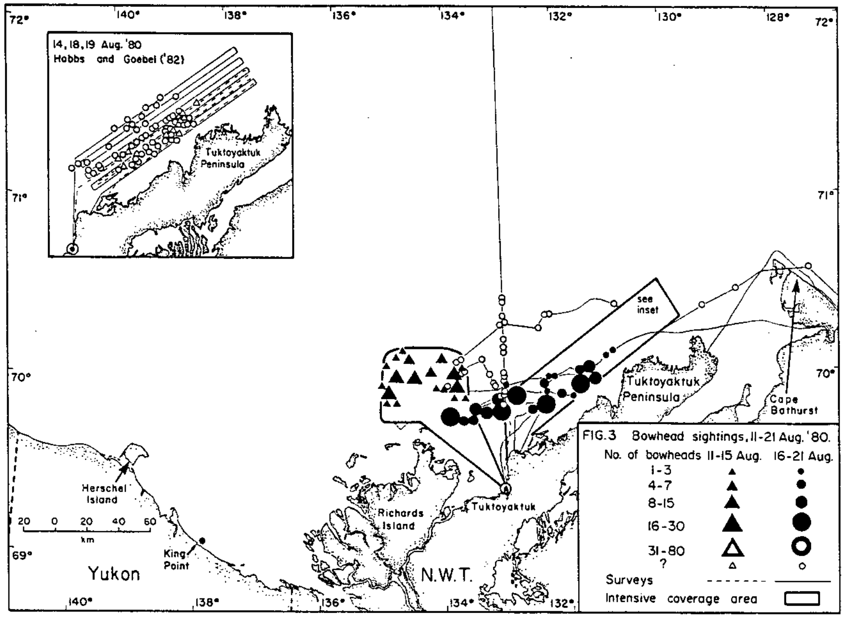

FIG. 3 Bowhead sightings, 11-21 Aug. '80.

No. of bowheads	11-15 Aug.	16-21 Aug.
1-3	▲	●
4-7	▲	●
8-15	▲	●
16-30	▲	●
31-80	△	○
?	△	○

Surveys - - - - - ——

Intensive coverage area ▭

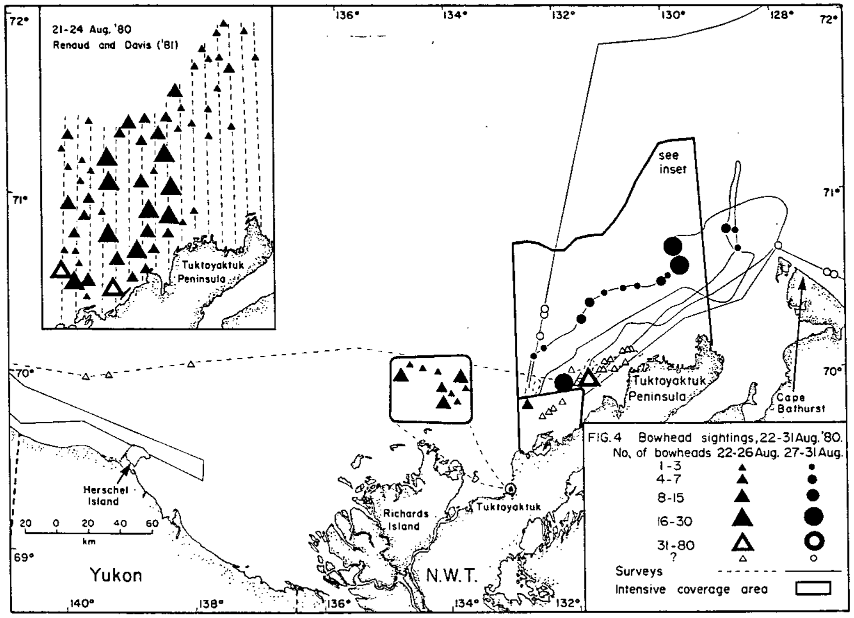

FIG. 4 Bowhead sightings, 22-31 Aug. '80.

No. of bowheads	22-26 Aug.	27-31 Aug.
1-3	▲	●
4-7	▲	●
8-15	▲	●
16-30	▲	●
31-80	△	○
?	△	○

Surveys - - - - - ——

Intensive coverage area ▭

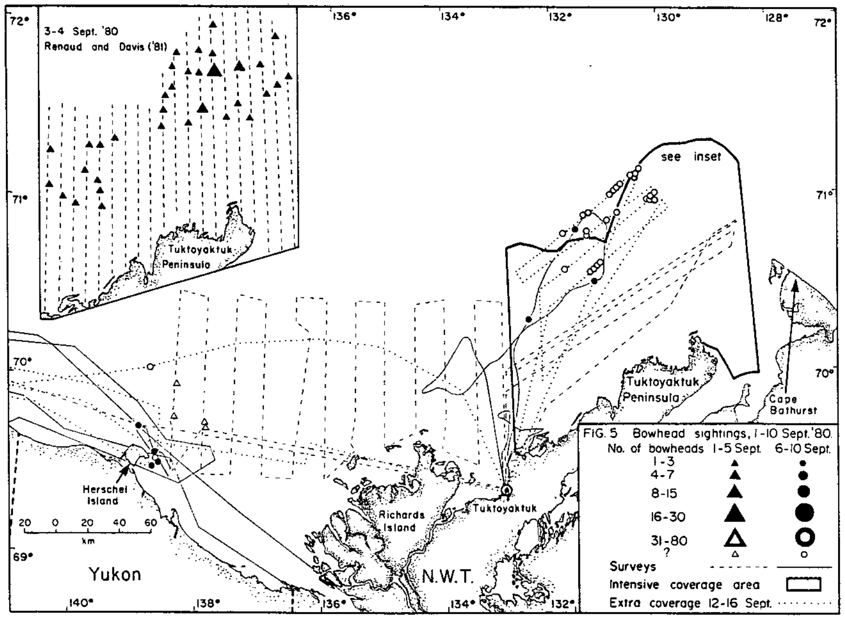

FIG. 5 Bowhead sightings, 1-10 Sept. '80.

No. of bowheads	1-5 Sept.	6-10 Sept.
1-3	▲	●
4-7	▲	●
8-15	▲	●
16-30	▲	●
31-80	△	○
?	△	○

Surveys - - - - - ——

Intensive coverage area ▭

Extra coverage 12-16 Sept. ....

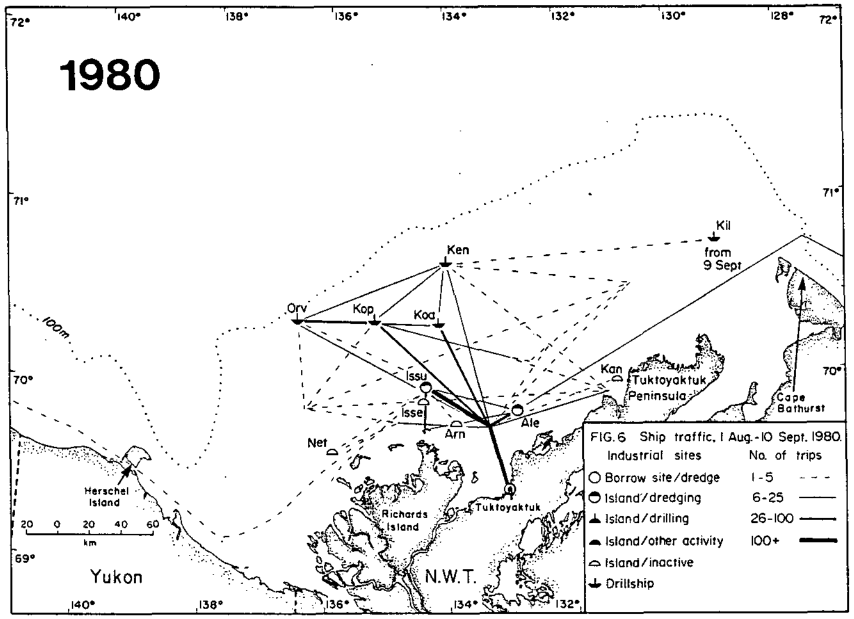
FIG. 6 Ship traffic, 1 Aug.-10 Sept. 1980.

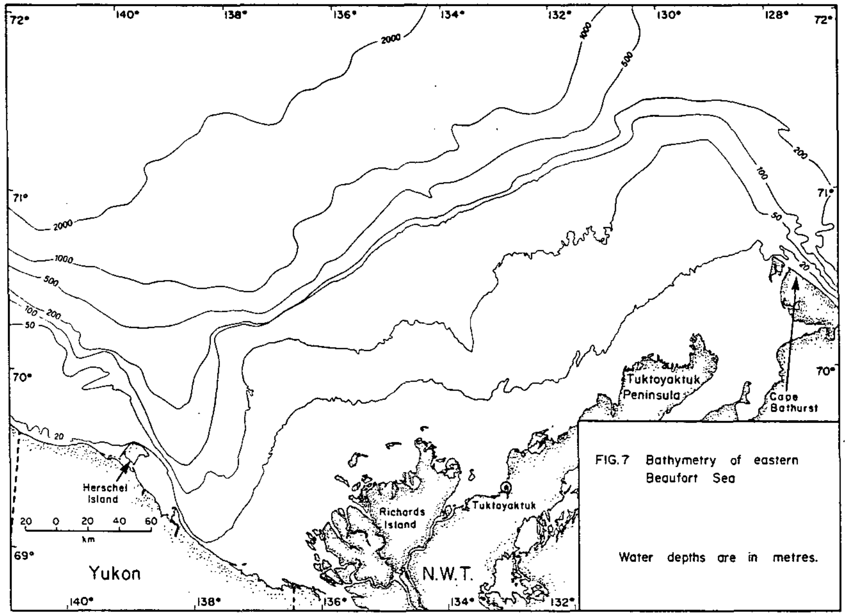
FIG. 7 Bathymetry of eastern Beaufort Sea

Water depths are in metres.

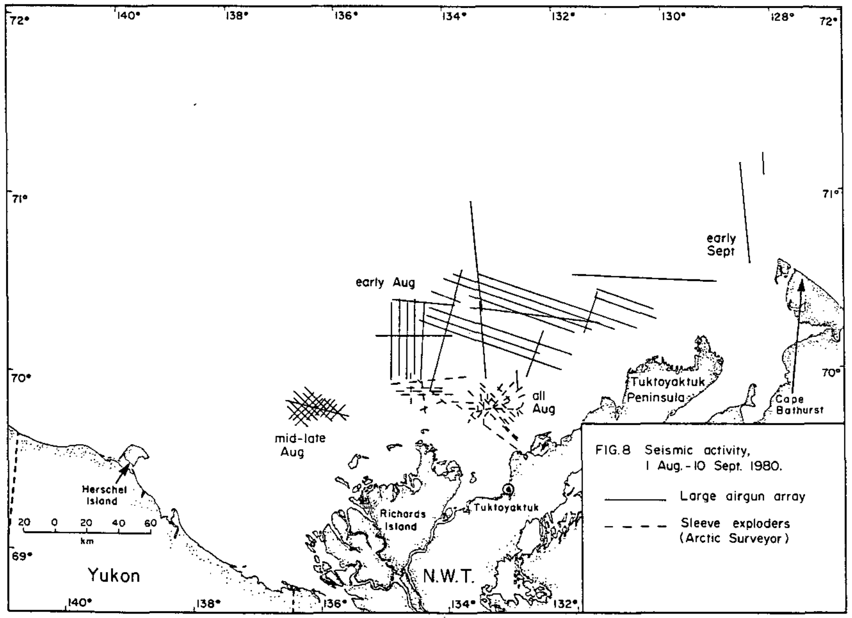
FIG. 8 Seismic activity, 1 Aug.-10 Sept. 1980.

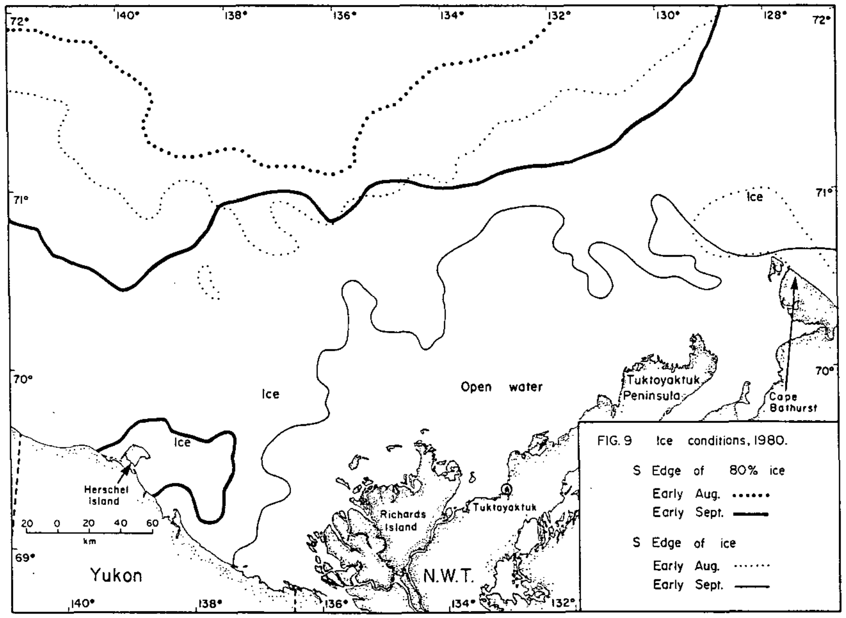
FIG. 9 Ice conditions, 1980.

coverage elsewhere in the study area was virtually nil, but observers who were at King Point, Yukon coast, from 16 Aug to 13 Sept saw only one bowhead throughout that period, on 18 Aug (Würsig et al. 1982).

During mid August, island construction and frequent vessel traffic continued around Issungnak; industrial activity was much less intense off the Tuk Peninsula (Fig. 6). One or two seismic boats worked north of Tuktoyaktuk (132°45'-133°40'). Some whales were exposed to strong noise pulses from a seismic vessel as close as 8-13 km away on 20-21 Aug (Richardson et al. 1985a,b).

During late August 1980, very large numbers of bowheads were off the Tuk Peninsula; densities near Issungnak were reduced from those in early August (Fig. 4). Renaud and Davis (1981) estimated that 755 bowheads were off the Tuk Peninsula within the 50 m contour on 21-24 Aug, with no allowance for missed whales. More whales appeared to be moving east than west, and numbers were significantly higher off the west than the east part of the Tuk Peninsula (Fig. 4, inset). Many bowheads were feeding at or near the surface off the Tuk Peninsula; others were socializing (Würsig et al. 1982). The size of this concentration was unique in the 5 years of study. Based on conservative correction factors for missed whales at and below the surface (Davis et al. 1982), >50% of the Western Arctic bowhead population apparently was in the shallow waters (≤50 m) off the Tuk Peninsula. Industrial activities were similar to those in mid August. Numerous whales were near Alerk, where there was dredging and seismic exploration, but the majority of those seen were farther north and east where there was less industrial activity.

Hobbs and Goebel (1982) found no bowheads far offshore during a flight northeast to Banks Island on 31 Aug, but 12 were seen in water about 50-250 m deep off the Yukon on 22 Aug (Fig. 4). It is not known whether bowheads were present off the Yukon coast earlier in August. No bowheads were seen in the Alaskan Beaufort Sea in July or August 1980 (Ljungblad 1981).

During early September 1980, bowhead numbers off the Tuk Peninsula were about 1/3 those in late August, and all were in water at least 25 m deep (Fig. 5 vs. 4, insets). Most were oriented southwest or west (Renaud and Davis 1981). Bowheads were still present far off the Tuk Peninsula on 12 Sept (Fig. 5; Hobbs and Goebel 1982). None were seen during surveys off the Mackenzie Delta in early Sept, and only one was reported by industry personnel at Issungnak. Bowheads were present farther west, near Herschel Island, in early Sept (Fig. 6). Observers on Herschel Isl saw bowheads about 5 km offshore on 3-11 Sept; none were seen 19 Aug-2 Sept (Würsig et al. 1982). The last September coverage was on 16 Sept, when Ljungblad (1981) saw three bowheads just east of Herschel Island.

Most bowheads seen in early September were distant from industrial activity. However, a few off the eastern Tuk Peninsula were near seismic lines (Fig. 5,8).

In the Alaskan Beaufort Sea, the first autumn sighting was on 4 Sept east of Barter Island (Ljungblad 1981). Bowheads became numerous there by 14 Sept, and the last sighting in the Alaskan Beaufort was a pilot's report on 17 Oct. On 21 and 24 Oct, Ljungblad found no bowheads near Herschel Island.

Bowhead Distribution and Industrial Activities in 1981 (Fig. 10-18)

Industrial Activities, 1981

The level of industrial activities, especially dredging, increased in 1981. Four dredges worked offshore, including the first two hopper dredges to operate in the study area. The hopper dredges loaded at Herschel Isl, South Tarsiut, Ukalerk and Banks Isl, and brought material to berm construction sites at Tarsiut (23 m deep) and Uviluk (31 m; Fig. 15). One suction dredge alternated between two island construction sites NW and north of Tuktoyaktuk, Itiyok and Alerk, from 20 July to 6 Sept (Fig. 15). Another dredged at South Tarsiut until 12 Aug; barges hauled the material to Tarsiut (Fig. 15).

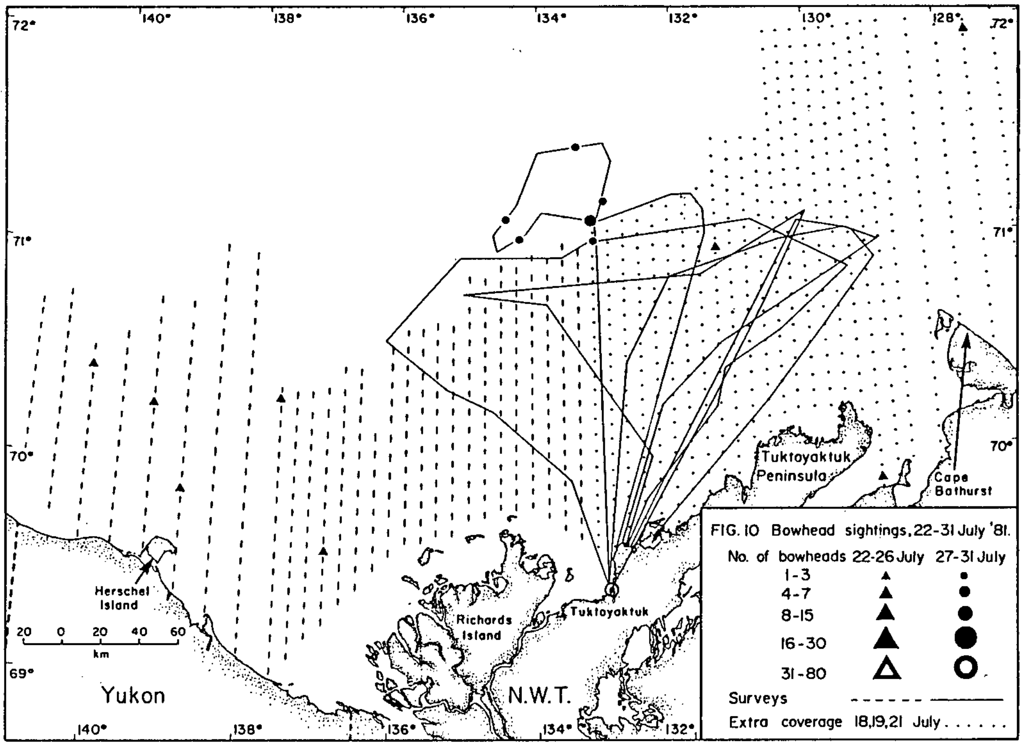

FIG. 10 Bowhead sightings, 22-31 July '81.

All drilling during the 1981 study period was from four drillships working at five drillsites. Drilling at Issungnak island ended before 1 Aug, but the island was still occupied and serviced by vessels and helicopters during August.

Most vessel traffic was in support of island building or drilling. The oil industry used over 30 supply boats, tugs and other vessels, including one icebreaker. Vessel traffic occurred over a wider area in 1981 than 1980, partly because hopper dredges operated west to Herschel Isl and northeast to Banks Isl, and partly to support the drillship operating far to the east at Kilanik (Fig. 15). There was additional traffic to the west because caissons for Tarsiut were assembled at Herschel Isl in late summer.

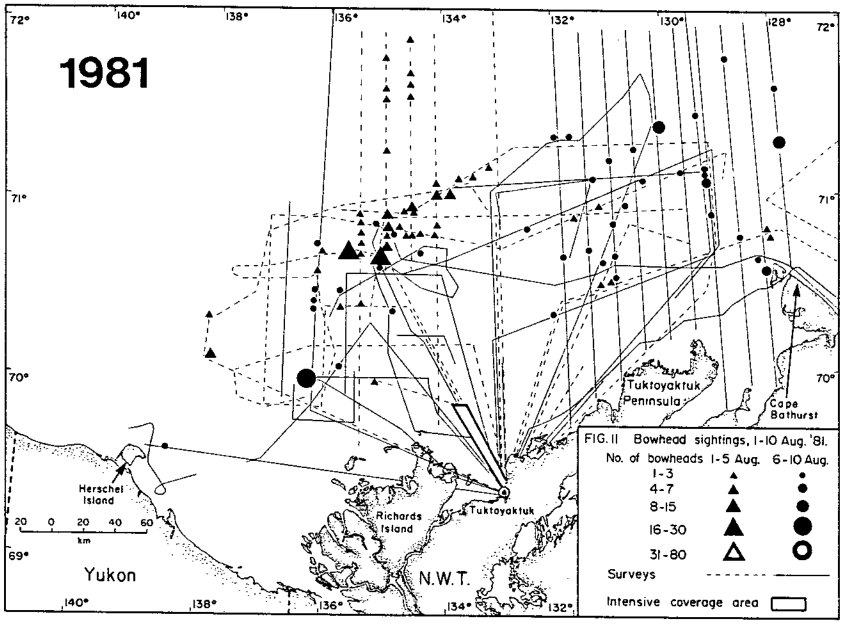

FIG. 11 Bowhead sightings, 1-10 Aug. '81.

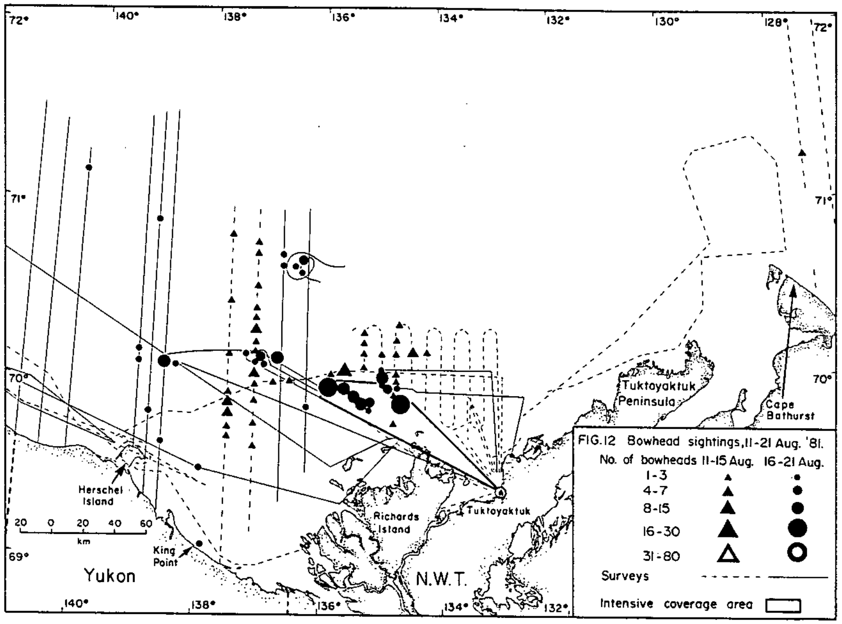

FIG. 12 Bowhead sightings, 11-21 Aug. '81.

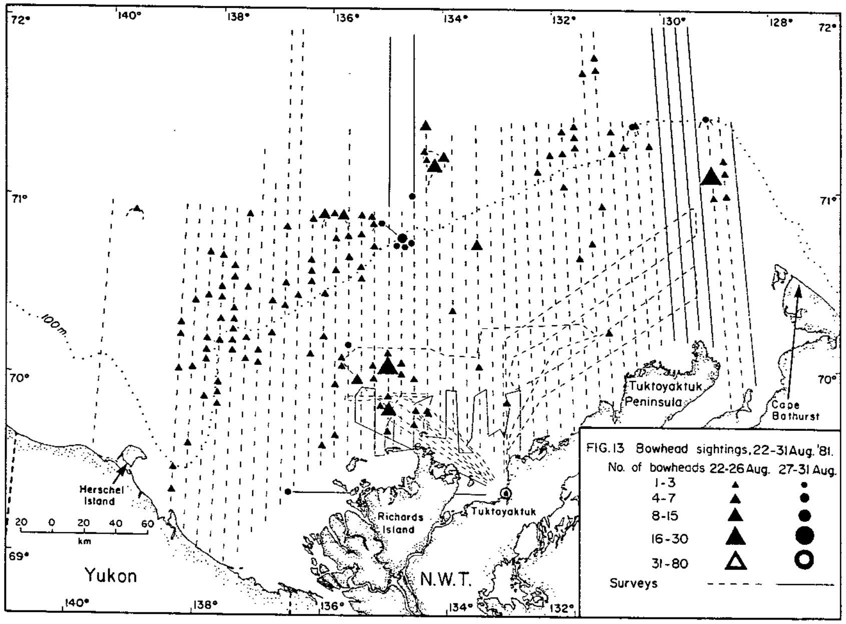

FIG. 13 Bowhead sightings, 22-31 Aug. '81.

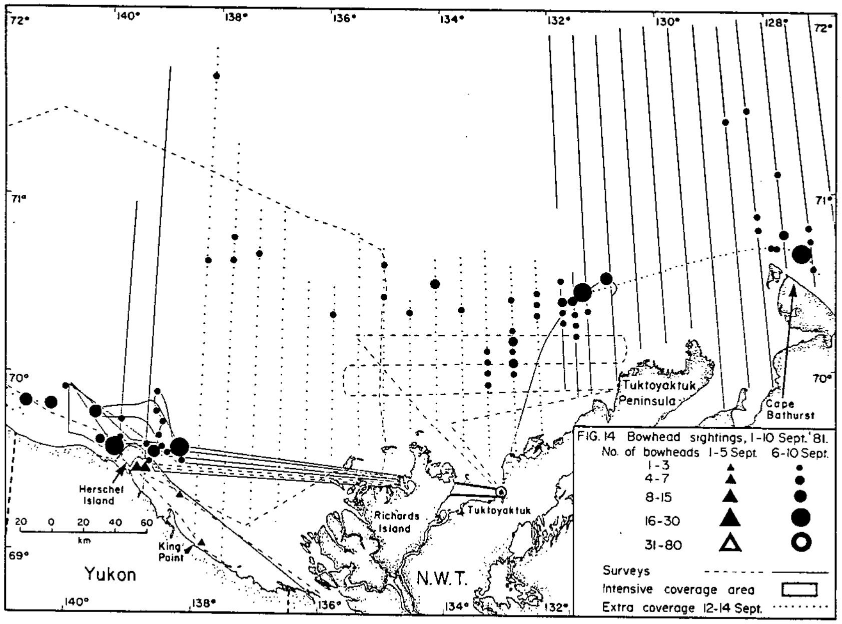

FIG. 14 Bowhead sightings, 1-10 Sept. '81.

1981

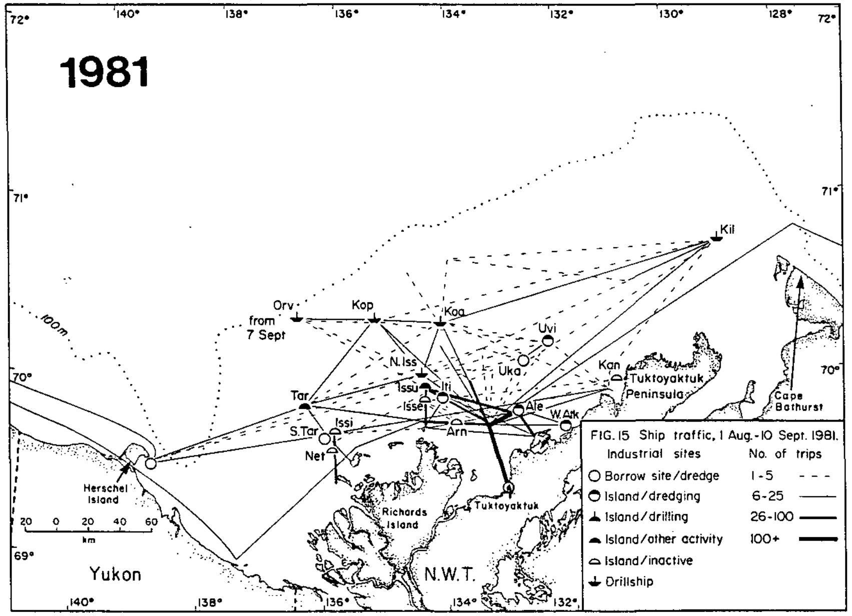

FIG. 15 Ship traffic, 1 Aug.-10 Sept. 1981.

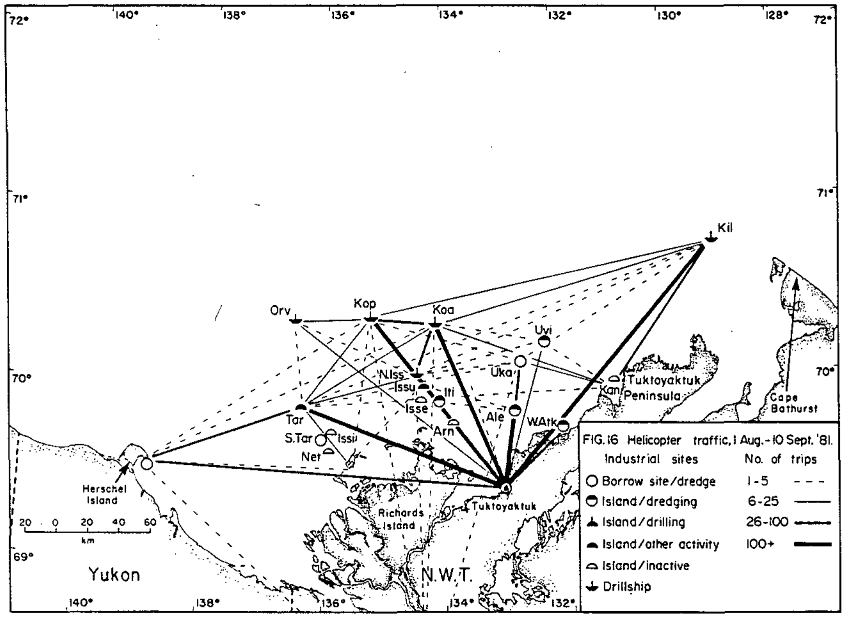

FIG. 16 Helicopter traffic, 1 Aug.-10 Sept. '81.

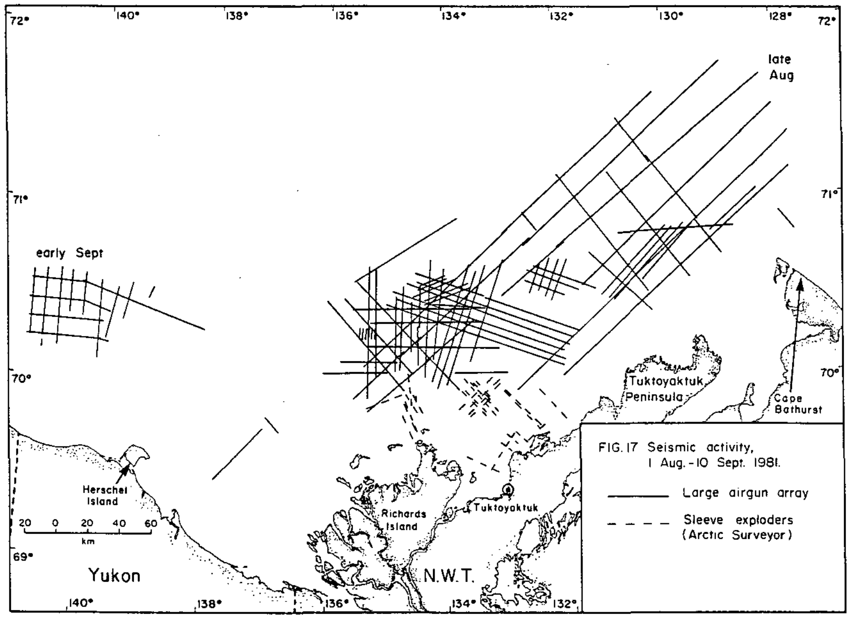

FIG. 17 Seismic activity, 1 Aug.-10 Sept. 1981.

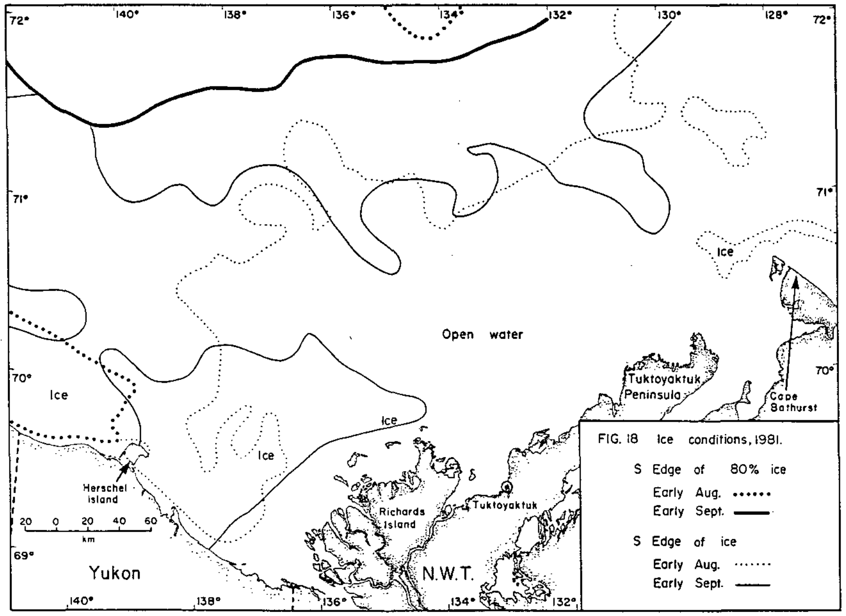

FIG. 18 Ice conditions, 1981.

Helicopters travelled from Tuktoyaktuk to most offshore industrial sites, and between many sites (Fig. 16). Because industrial activity extended farther west and east than in 1980, helicopters ranged more widely in 1981.

Three high-energy seismic ships were present in 1981. They operated off the Mackenzie Delta and Yukon coast in late July; off the Mackenzie Delta in early August; from the Delta to Cape Bathurst in mid and late August; and off Tuktoyaktuk, the Delta, and the western Yukon in early September (Fig. 17; see Richardson et al. 1983a for data by 10-d period). Some additional seismic lines not on Fig. 17 apparently were also shot in August 1981. Furthermore, at least six vessels performed low-energy sounding off the Delta and Tuk Peninsula in 1981.

Bowhead Distribution, 1981

Large scale features of bowhead distribution are better documented for 1981 than for 1980. Four systematic surveys of most of the southeastern Beaufort Sea were done between late July and early September (Davis et al. 1982). The 1981 coverage began earlier than in 1980, and extended farther west and offshore, often beyond the edge of the continental shelf. In some periods, coverage also extended farther east. There were clear differences in distribution between the two years, although cautious interpretation is necessary because of the differences in survey effort.

Ice cover was extensive in western parts of the Canadian Beaufort Sea in Aug 1981 but not in Aug 1980 (Fig. 18 vs. 9). Surveys often extended well into the pack ice in 1981 but rarely did so in 1980. Bowheads were seen in the ice in August 1981; whether they were present there in August 1980 is unknown.

In late July 1981, few bowheads were on the continental shelf within the eastern Beaufort Sea. An intensive survey (19% coverage) of the entire shelf on 18-25 July detected only six bowheads (N-S grid on Fig. 10; Davis et al. 1982). Allowing for whales between grid lines, below the surface, etc., roughly 250 bowheads were in that area. More whales were in Amundsen Gulf, from 127°W to 120°W (Davis et al. 1982). However, the total estimate of 1250 whales in Amundsen Gulf and the surveyed areas of the eastern Beaufort Sea accounted for only 1/3 of the population, which is believed to be about 3871 whales (I.W.C. 1984). The majority were presumably in the Beaufort Sea north or west of the area surveyed by Davis et al. Limited non-systematic coverage of pack ice north of the 100 m contour confirmed that more bowheads were present far offshore (Fig. 10). There were no surveys of the Alaskan Beaufort Sea at this time. Only the very few bowheads off the Yukon coast were near industrial activities; noise from a seismic ship may have reached them.

During early August 1981, many bowheads moved into the southeastern Beaufort Sea. There was a concentration of whales about 125 km north of the Mackenzie Delta, near the southern edge of the pack ice and along the edge of the continental shelf (Fig. 11). One group of 30 plus many singles and smaller groups were found in open water on the shelf, with others in pack ice farther north. Numbers off the Yukon and Alaska were unknown. Based on a second systematic survey, an estimated 2860 bowheads (with broad confidence limits) were off the Delta, and 400 more were off the Tuk Peninsula (Davis et al. 1982). Numbers in Amundsen Gulf (128°-117°W) were very low on 5-17 Aug --

about 225 as opposed to 1000 in late July. Bowheads arriving in the SE Beaufort Sea during early August probably included animals travelling west from Amundsen Gulf and south from the offshore pack ice.

In early Aug 1981, unlike 1980, few whales were in the area of offshore drilling and island construction. However, some were not far north of the industrial area. Some whales far north from the Delta were exposed to seismic impulses on 5 Aug (Richardson et al. 1985a,b) and probably other dates.

In mid August 1981, the area of greatest known whale abundance was in shallow waters off the Delta, mainly between the 20 and 50 m depth contours, and off the eastern Yukon in slightly deeper water. Surveys did not extend far north of the Delta in mid August, but results from early and late August suggest that the whale concentration extended far offshore throughout August. Coverage off the Tuk Peninsula was minimal in mid August, but on both 6-10 and 22-26 Aug there were widely scattered whales far offshore (Fig. 11, 13).

In mid-August 1981, some groups of bowheads were <15 km from Issungnak island and North Issungnak drillship (Fig. 12, 15). However, most of those seen were north or west of the major industrial sites, contrary to results in mid-Aug 1980.

In late August 1981, some bowheads were in shallow water off the Mackenzie Delta, but most were widely distributed near and beyond the 100 m contour (Fig. 13). On 19-29 Aug, about 580, 1500 and 840 bowheads were estimated to be in the sampled parts of the Yukon, Delta and Tuk Peninsula zones, respectively (total 2918 ± s.e. 1015; Davis et al. 1982). There were apparently fewer whales off the Delta and more far off the Tuk Peninsula than during the 5-17 Aug survey, although confidence limits on all estimates were broad. The number and distribution of bowheads north of the Tuk Peninsula in late August 1981 were very different than in 1980 (Fig. 13 vs. 4). Excluding correction factors, estimated numbers were 755 in 1980 and 150 in 1981.

In late August, bowheads occurred at least as far west as Herschel Isl (Fig. 13). Observers on Herschel Isl from 23 Aug to 13 Sept first sighted bowheads on 29 Aug (Würsig et al. 1982).

In late August, most whales were near or beyond the shelf break, beyond most industrial operations. However, some whales far off the Tuk Peninsula were close to seismic lines (Fig. 13 vs. 17). On 24-26 August, the captain of 'GSI Mariner' saw groups of 2-4 bowheads an estimated 2-5 km from the ship while it was shooting here. Whales in shallow water off the Delta were near various industrial operations (Fig. 13). On 25 Aug, one group was only 6-8 km from a seismic ship; behavior was not noticeably unusual (Richardson et al. 1985a,b).

In early September 1981, most Western Arctic bowheads were apparently still in Canadian waters. Based on their incomplete fourth survey on 7-14 Sept, Davis et al. (1982) estimated that >2500 bowheads were still present. The whales were widely distributed from east of Cape Bathurst (126°W) to west of Herschel Island. Off the Tuk Peninsula, many whales were closer to shore than in late August (Fig. 13,14), contrary to the trend at this time in 1980 (Fig. 4,5). Bowheads seemed more numerous around Herschel Isl in early

September of 1981 than of 1980 (Fig. 14 vs. 5). Observers on the island saw whales until 10 Sept, and Ljungblad et al. (1982) saw bowheads just east of 141°W on 12-17 Sept.

Some whales off the western Tuk Peninsula and Delta in early Sept were probably exposed to seismic impulses, and some were in the general area of drilling and dredging. Whales just east of 141°W definitely were exposed to seismic impulses (Ljungblad et al. 1982).

The first autumn sighting off Alaska was on 7 Sept near the Alaska-Yukon border. Few whales moved west of Barter Island (143°W) until about 28 Sept (Ljungblad et al. 1982). Some bowheads were present east to Barter Island as late as 9 Oct.

Bowhead Distribution and Industrial Activities in 1982 (Fig. 19-26)

Industrial Activities, 1982

The level of industrial activities increased again in 1982. Two suction and four hopper dredges constructed artificial islands or subsea berms at five sites, including Nerlerk in water 45 m deep. Hopper dredges used several borrow sites from Herschel Isl to Banks Isl, but Ukalerk was used most heavily (Fig. 23). Drilling from Tarsiut caisson-retained island continued into early August. Testing extended into September, and several support vessels were usually present in August. Four drillships operated at five wellsites (Fig. 23).

The area of frequent vessel and helicopter movements extended less far to the east and west but somewhat farther north in 1982 than in 1981 (Fig. 23,24 vs. 15,16). There was no drillship northeast of the Tuk Peninsula in 1982, unlike 1981. There were again a few vessel trips west to Herschel Isl, but activity there was reduced from 1981. Vessels went north to Kenalooak, the northmost site yet drilled in the eastern Beaufort (also drilled in 1980). More helicopters (8+) were in use in 1982 than in earlier years (Table 2).

Seismic exploration by two high-energy vessels was primarily off the Mackenzie Delta and Yukon coast. Another vessel using a small array of airguns worked mainly off the Delta and north of Tuktoyaktuk (Fig. 25). Relative to 1981, seismic exploration was more extensive off the Yukon coast and much less so off the Tuk Peninsula. It was extensive off the Delta in both years. Low-energy sounding was done from seven vessels operating off the Delta and western Tuk Peninsula.

Bowhead Distribution, 1982

Bowhead distribution and movements in 1982 differed from both 1980 and 1981. There was much ice off the Yukon coast in 1982, especially after 16 Aug. However, north of the Delta and Tuk Peninsula, the ice edge was much farther offshore than in 1980 or 1981 (Fig. 26).

In early August 1982, bowheads were seen far offshore in open water NW of the Delta, and in pan ice far north and NW of Herschel Island (Fig. 19). Surveys off Alaska found bowheads west to Barter Isl (144°W) in deep water and heavy ice (Ljungblad et al. 1983). Intensive surveys within the main industrial area and limited coverage farther north and east found no bowheads (Fig. 19). Many whales off the Delta and off Alaska were travelling west. The sighting closest to any active offshore site was 21 km north of Tarsiut. However, there was seismic exploration in this area, and on one day seismic noise was measured near whales (Richardson et al. 1985a,b).

Distribution in early August was very different in 1982 than in 1980, when there were many whales in the shallow waters of the industrial area. Distributions in 1981 and 1982 were more similar, but in 1981 whales were more widespread on the outer shelf and shelf break, and most seemed to be travelling south, not west.

In mid August 1982, bowheads were concentrated off Herschel Isl, with many more distributed at lower densities farther offshore from the Yukon (Fig. 20). Most were close to or in pan ice; most either dove for long periods with little travelling, or remained quiescent at the surface (Würsig et al. 1983). Bowheads were common west to Barter Isl, Alaska (Ljungblad et al. 1983). The only sightings in the main industrial area were of two whales south of Tarsiut. Limited coverage north of the industrial area found few whales, and the only ones found to the east were near Cape Bathurst (Fig. 20). Whether there were bowheads near the shelf break north and northeast of the industrial area is unknown. Few whales were in water <50 m deep; those close to Herschel Isl and Cape Bathurst were in areas where deep water occurs near shore.

Although very few bowheads were in the main industrial area, those near Herschel Isl were exposed to seismic impulses. Noise pulses up to 133 dB//1 µPa (up to 40 dB above ambient) were recorded near whales on 16 and 18 Aug (Richardson et al. 1985a,b).

Distributions were very different in mid August 1980, 1981 and 1982. In 1980, whales were abundant in shallow water off the eastern Delta and western Tuk Peninsula. In 1981 they were not found there, but were widespread farther to the W, N and possibly NE. In 1982, they were most abundant off Herschel Isl.

In late August 1982, there were still bowheads off Herschel Isl, but others were distributed far offshore from west of Herschel Isl (140°W) to Cape Bathurst (128°W), particularly near the steep shelf break north of the Mackenzie Delta (Fig. 21). The few found off Alaska were far offshore at 145°W (Ljungblad et al. 1983). Few bowheads were within the main industrial area. Distribution in late August 1982 was more 'clumped' than in 1981, with more whales near Herschel Isl and fewer near the Delta (Fig. 21 vs. 13). Distribution in late August of 1980 was very different.

Based on a systematic survey on 18-24 Aug from 140° to 129°W and north at least to the 100 m isobath, Harwood and Ford (1983) estimated that there were ≥1224 whales off the Yukon, ≥256 off the Delta, and ≥459 off the Tuk Peninsula. These estimates were conservative because (1) non-systematic coverage found bowheads north of the surveyed area, and (2) correction for missed animals was only partial.

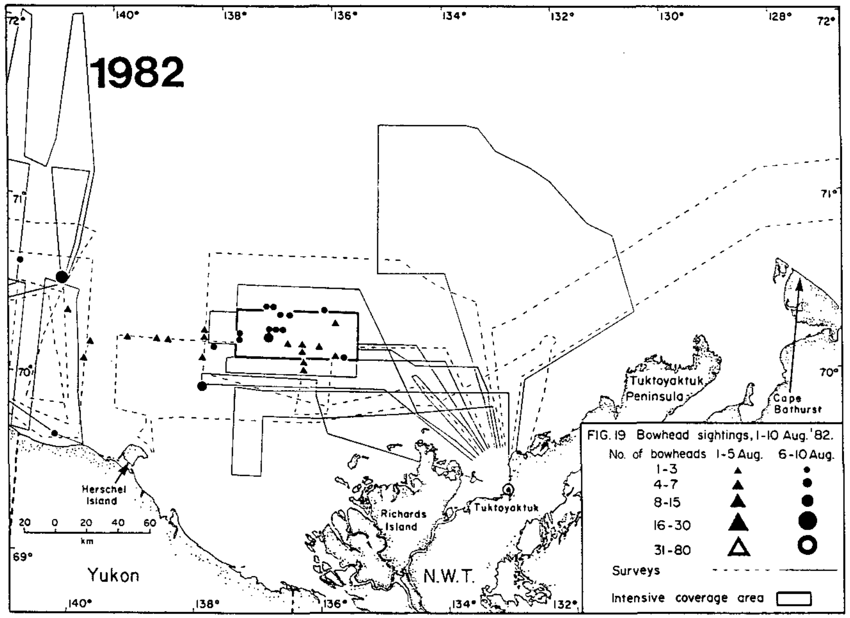

FIG. 19 Bowhead sightings, 1-10 Aug. '82.

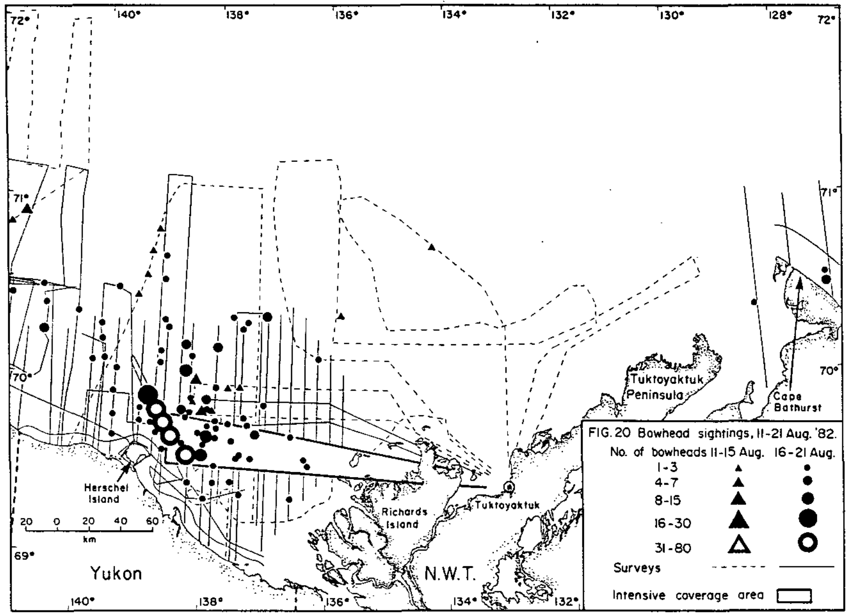

FIG. 20 Bowhead sightings, 11-21 Aug. '82.

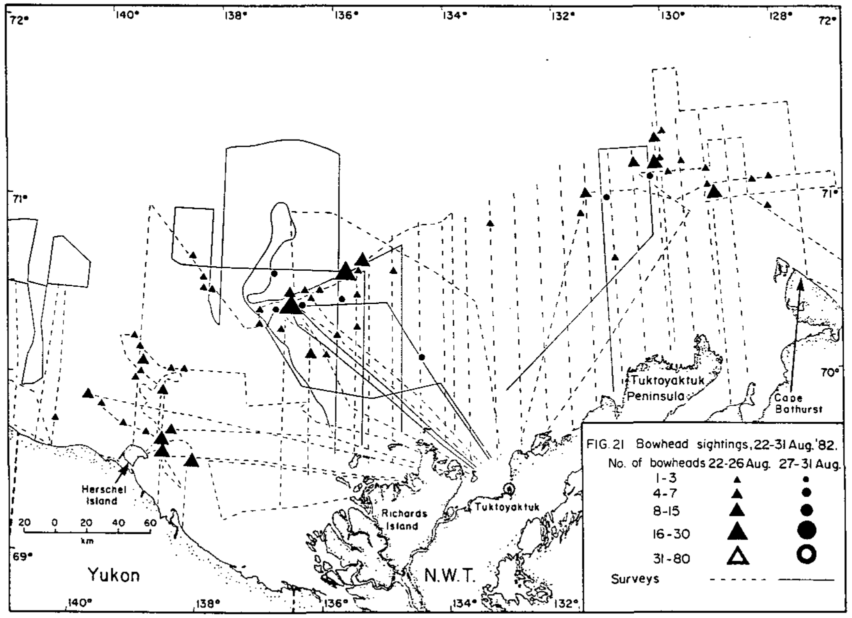

FIG. 21 Bowhead sightings, 22-31 Aug. '82.

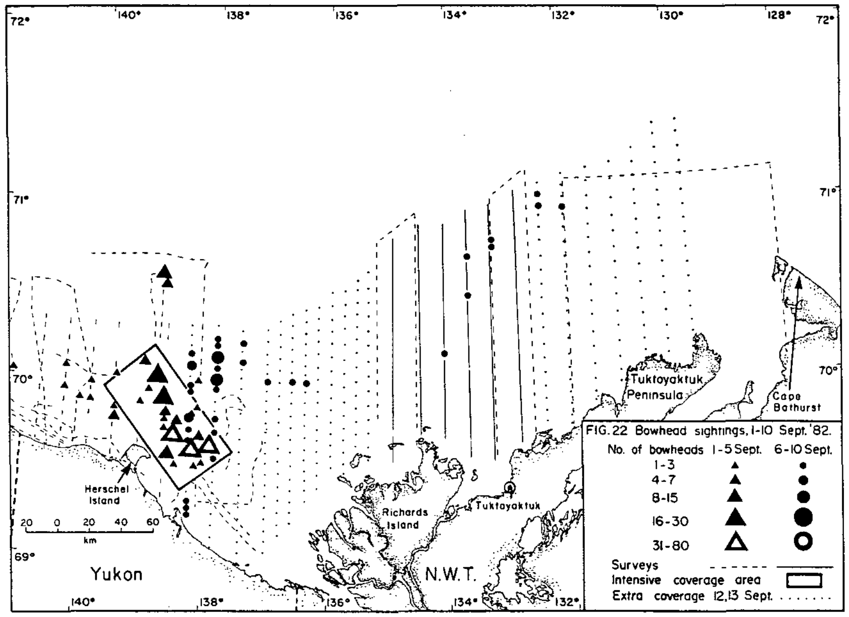

FIG. 22 Bowhead sightings, 1-10 Sept. '82.

1982

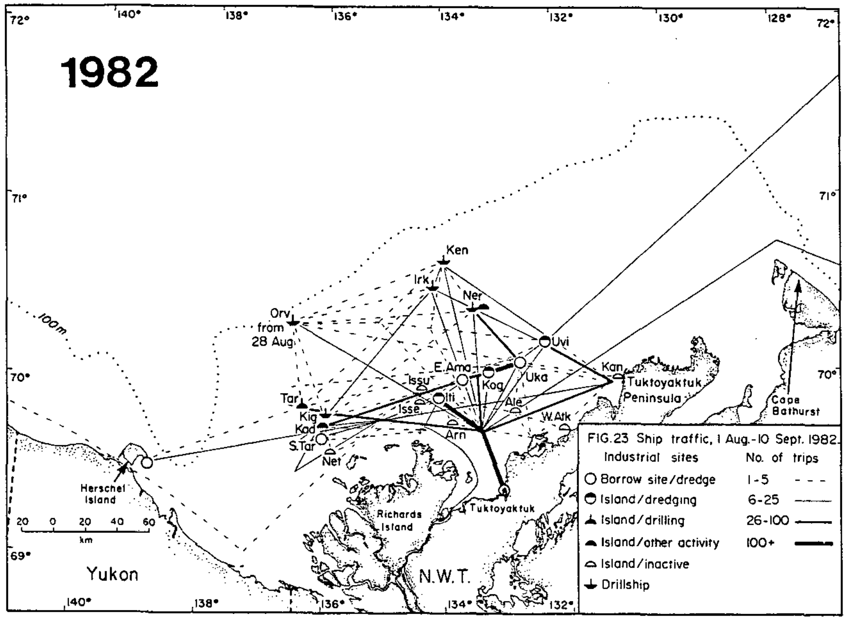
FIG.23 Ship traffic, 1 Aug.-10 Sept. 1982.

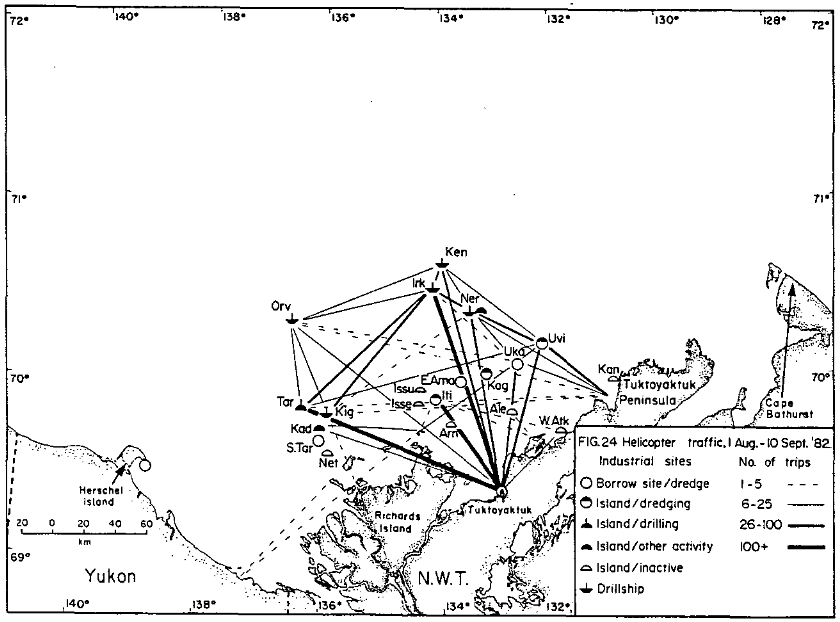
FIG.24 Helicopter traffic, 1 Aug.-10 Sept. '82

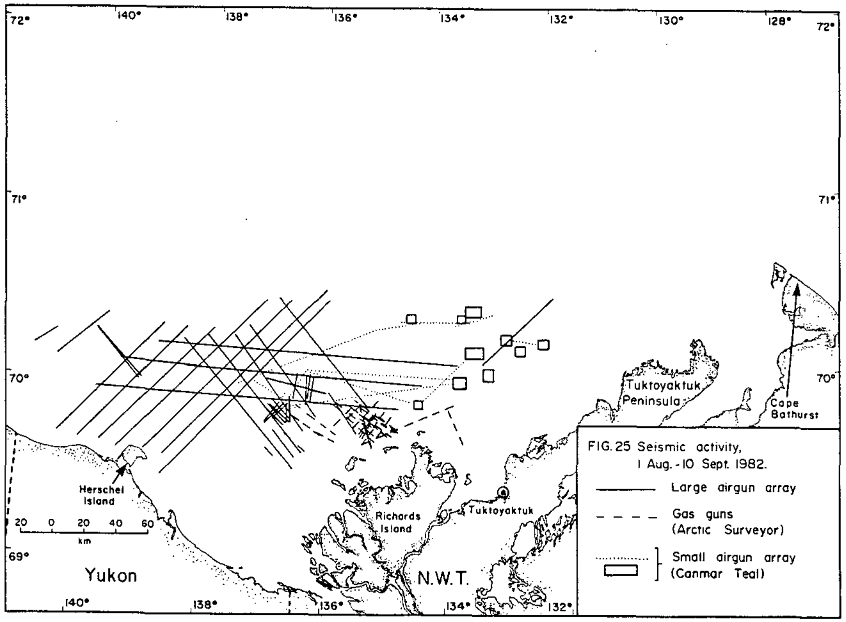
FIG. 25 Seismic activity, 1 Aug.-10 Sept. 1982.

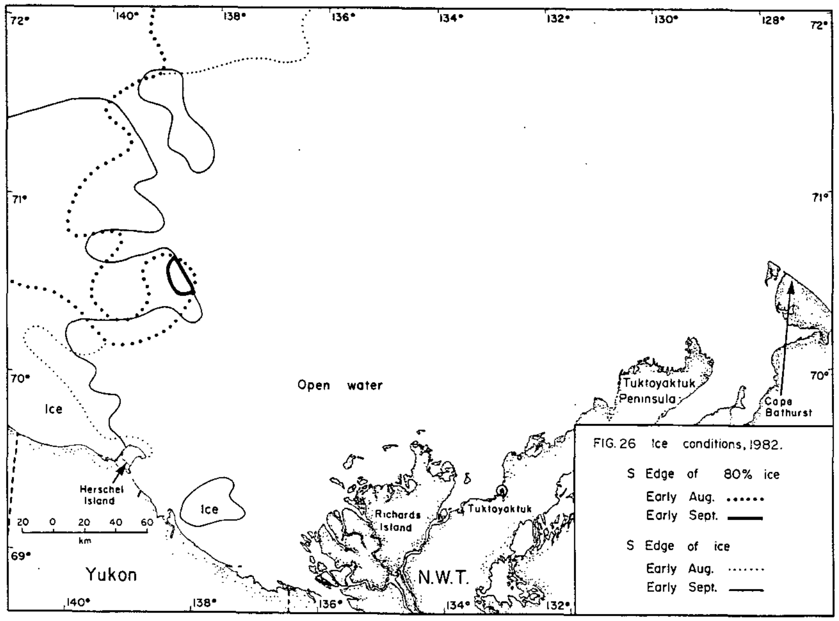
FIG. 26 Ice conditions, 1982.

In early September 1982, bowheads still were abundant off Herschel Isl, mainly over 50-200 m depths (Fig. 22). Few were found north of the Delta or Tuk Peninsula, but surveys did not extend off the shelf or east of 130°W. From systematic surveys on 5-13 Sept, Harwood and Ford (1983) conservatively estimated that ≥1112 whales were off the Yukon, ≥163 off the Delta, and ≥115 off the Tuk Peninsula. Very few were in the area of drilling and island construction. However, the many whales near Herschel Isl were probably exposed to seismic noise, as in mid August.

The one consistent feature of bowhead distribution in early Sept of 1980-82 was the occurrence of whales off Herschel Isl. Bowheads seemed especially numerous there in 1982. Fewer were found off the Delta and Tuk Peninsula at this time in 1982 than in 1980-81.

Aside from low numbers near 145°W, few bowheads moved into the Alaskan Beaufort until 15 Sept in 1982. The main movement through Alaskan nearshore waters began around 20 Sept (Johnson 1983; Ljungblad et al. 1983). A bowhead was seen at Herschel Isl in 7/10 ice on 15 Oct (Ljungblad et al. 1983).

Bowhead Distribution and Industrial Activities in 1983 (Fig. 27-34)

Industrial Activities, 1983

The level of offshore activities increased further in 1983. A new circular drillship began work at Pitsiulak in late August, supported by two new Class 4 icebreakers and two new icebreaking supply ships. Dome's four drillships worked at specific drillsites from 1 Aug to 10 Sept (Fig. 31). In 1983, as in 1982, two suction and four hopper dredges were used to construct seven islands and subsea berms; 2-3 barges with clamshells were also in intermittent use. The main borrow sites were Ukalerk, Issigak, and adjacent to some island and berm construction sites (Fig. 31).

Vessel traffic in 1983 consisted mainly of movements by the four hopper dredges and about 37 other vessels supporting the drilling, dredging and island construction (Fig. 31). Most helicopter traffic was from Tuktoyaktuk to the offshore sites, and between sites (Fig. 32). More helicopters (10) were used in 1983 than previously (Table 2). Considerable vessel and helicopter traffic extended west to Herschel Basin (Fig. 31,32), which became a major staging area in mid-August 1983.

Seismic exploration occurred from Alaska to Cape Dalhousie (129°W; Fig. 33). In Canadian waters, one ship used gas guns, 1-3 used large arrays of airguns, and one used a small array of airguns. Four more seismic ships operated near the Alaska border in late Aug-early Sept; Figure 33 shows their general locations by 'x' symbols, based on daily reports listed in Ljungblad et al. (1984b). Low-energy sounding was done from four vessels off the Mackenzie Delta and Tuktoyaktuk.

Bowhead Distribution, 1983

Bowhead distribution and movements in August-early September of 1983 were markedly different than in the three previous summers. Ice conditions also differed. The usual band of open water north of the Delta and Tuk Peninsula was somewhat narrower in August 1983 than in 1980-82. There was little ice near the Yukon coast in August 1983 (and 1980), unlike 1981-82.

Ice conditions in the Alaskan Beaufort Sea in 1983 were severe (Ljungblad et al. 1984a,b), and ice also moved onto the Yukon coast in early Sept (Fig. 34).

There were no surveys in July, but in early August 1983, bowheads occurred far off the western Yukon (Fig. 27). Most were in deep water (200-2000 m) in or near pack ice. The western edge of their distribution was just into Alaskan waters, near 142°W (Ljungblad et al. 1984a). Our limited surveys north and east of the Delta detected only one bowhead (Fig. 27).

Aerial surveys detected no bowheads in the main industrial area in early August. We received two reports of 1-2 bowheads seen by industry personnel in early August near the east edge of the industrial area. Seismic exploration occurred over a wider area, and sonobuoys showed that some whales off the Yukon were exposed to seismic noise on at least 4 dates in early August (Ljungblad et al. 1984a; Richardson et al. 1985b).

In mid August 1983, we found a concentration of bowheads along the Yukon coast east of Herschel Isl, often <1 km from shore (Fig. 28). We saw 60 whales near the Yukon coast on 17 August, with no allowance for unseen animals. Whether bowheads were near the coast east of Herschel Isl before the first survey there on 14 Aug is unknown.

Survey coverage elsewhere during mid August was extensive but of uneven intensity. Bowheads were almost absent from nearshore waters west of Herschel Isl. A few were seen near the ice far offshore from the Yukon (Fig. 28); none were seen west of 141°W (Ljungblad et al. 1984a). A few were seen in or near the main industrial area during aerial surveys. More were seen there by industry personnel but numbers are unknown, in part because of probable repeated sightings. Survey coverage off the Tuk Peninsula was limited, but Cubbage et al. (1984) sighted a large group of bowheads far off Cape Dalhousie (Fig. 28). In general, bowheads were scarce in most surveyed parts of the SE Beaufort Sea, except along the Yukon coast.

Bowheads near the Yukon coast were not exposed to much human activity, aside from survey aircraft and our disturbance experiments (Richardson et al. 1985b). No seismic boats operated in Mackenzie Bay in mid-August. The only other large groups seen were far north of Herschel Isl and Cape Dalhousie, far from seismic boats and the industrial area. Some bowheads were sighted in the industrial area, but no large concentration of whales was found there.

In late August 1983, the concentration along the Yukon coast persisted until at least 28 Aug (Fig. 29). Distances from shore were <1-15 km, varying from day to day. McLaren and Davis (1985) saw 110 bowheads <4 km from shore on 22 Aug. Whales often dove out of sight, and others were present farther offshore, so numbers present were much greater than 110. Photogrammetric data showed that whales along the coast were mainly immatures <13 m long (W.R. Koski, in Würsig et al. 1985b).

Bowheads were scarce or absent in most offshore areas in late August. The only concentrations were near the westernmost industrial sites, and far to the east (Fig. 29). Based on a systematic survey on 19-24 Aug from the

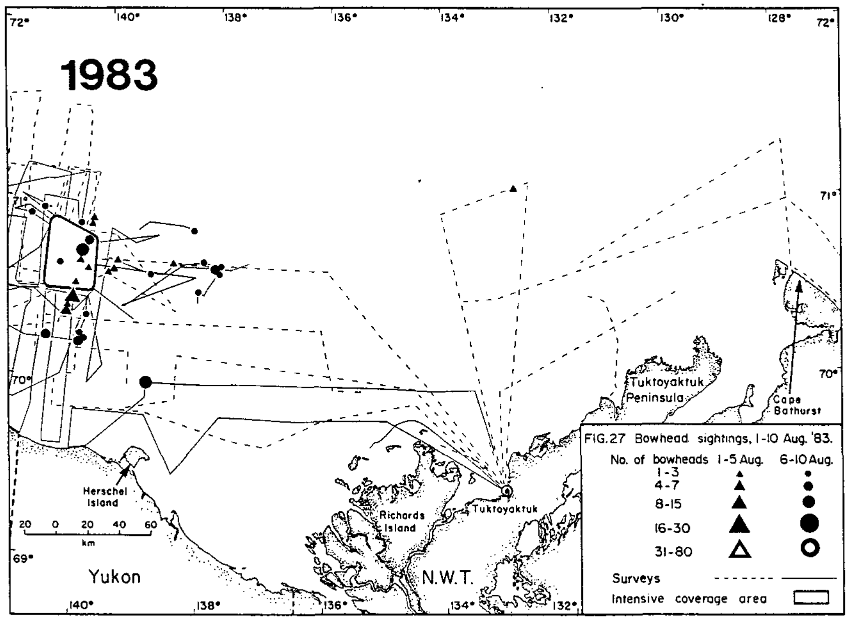

FIG.27 Bowhead sightings, 1-10 Aug. '83.

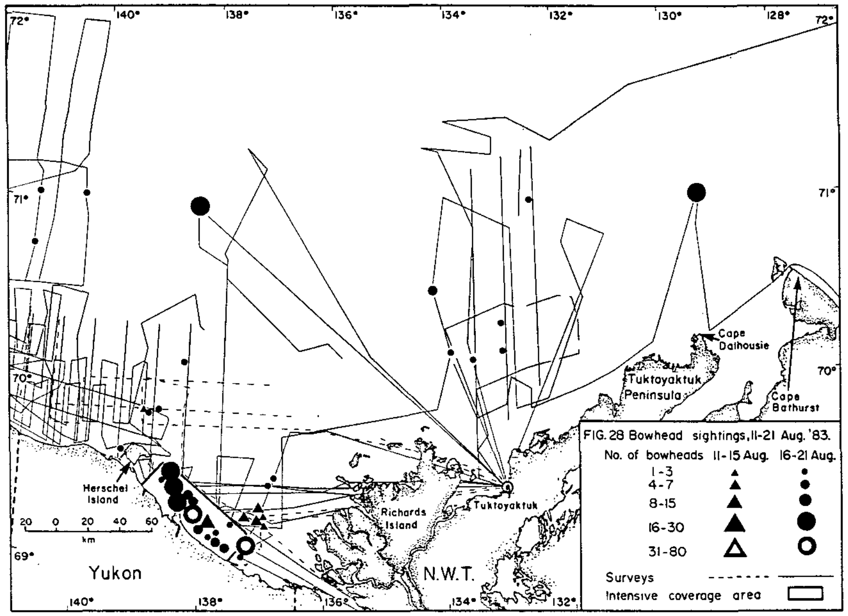

FIG. 28 Bowhead sightings, 11-21 Aug. '83.

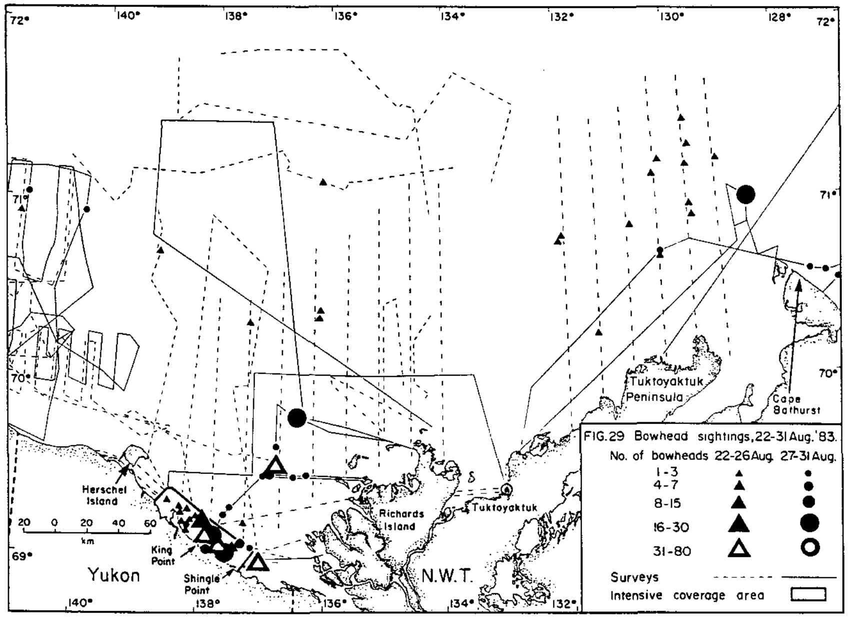

FIG.29 Bowhead sightings, 22-31 Aug. '83.

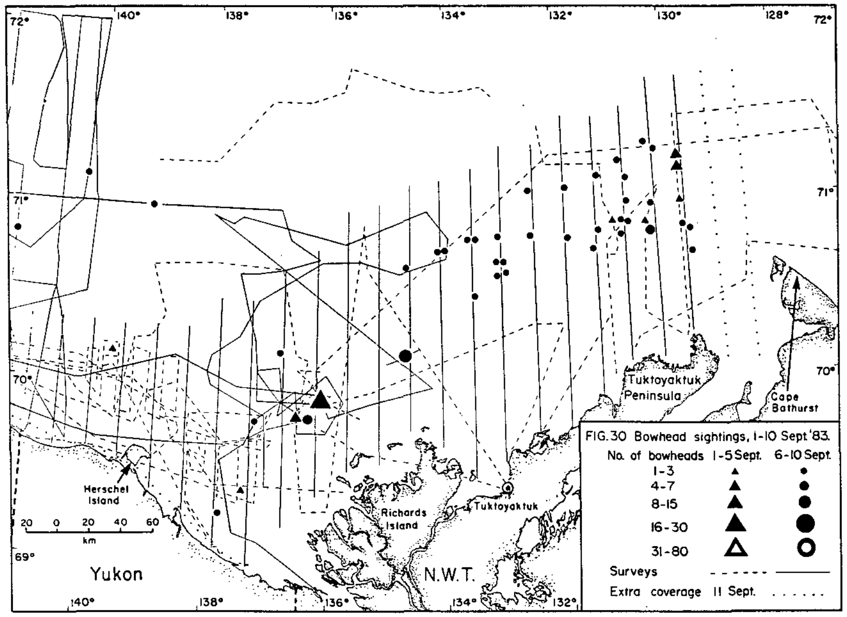

FIG. 30 Bowhead sightings, 1-10 Sept. '83.

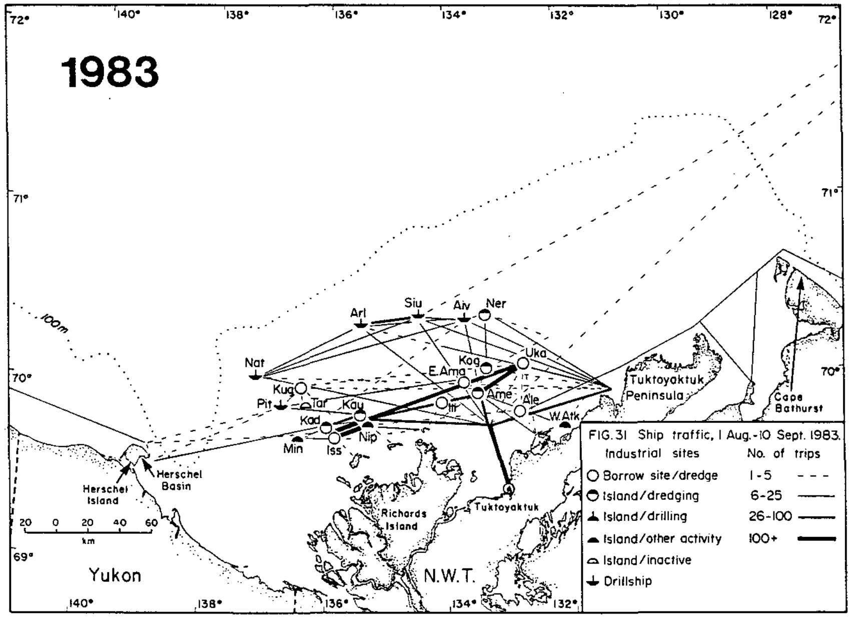

FIG. 31 Ship traffic, 1 Aug.-10 Sept. 1983.

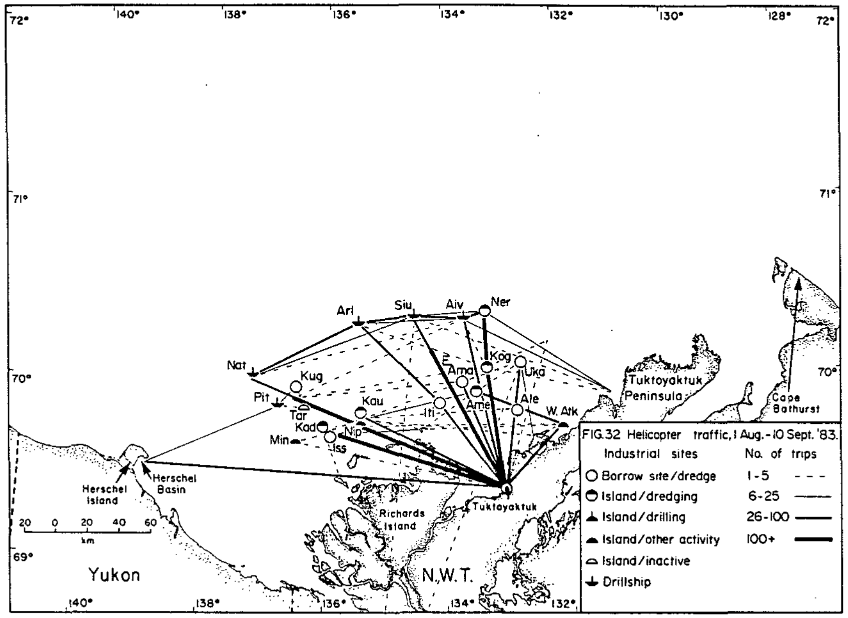

FIG. 32 Helicopter traffic, 1 Aug.-10 Sept. '83.

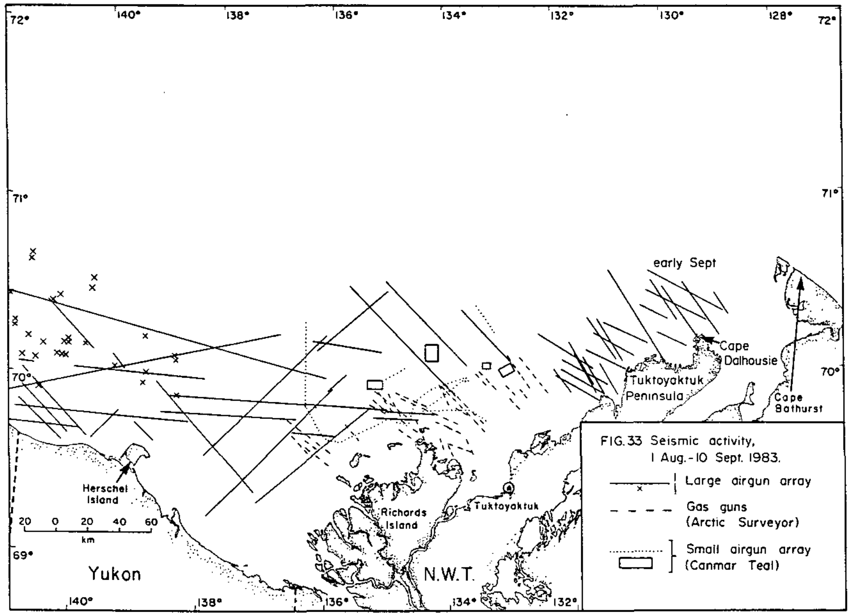

FIG. 33 Seismic activity, 1 Aug.-10 Sept. 1983.

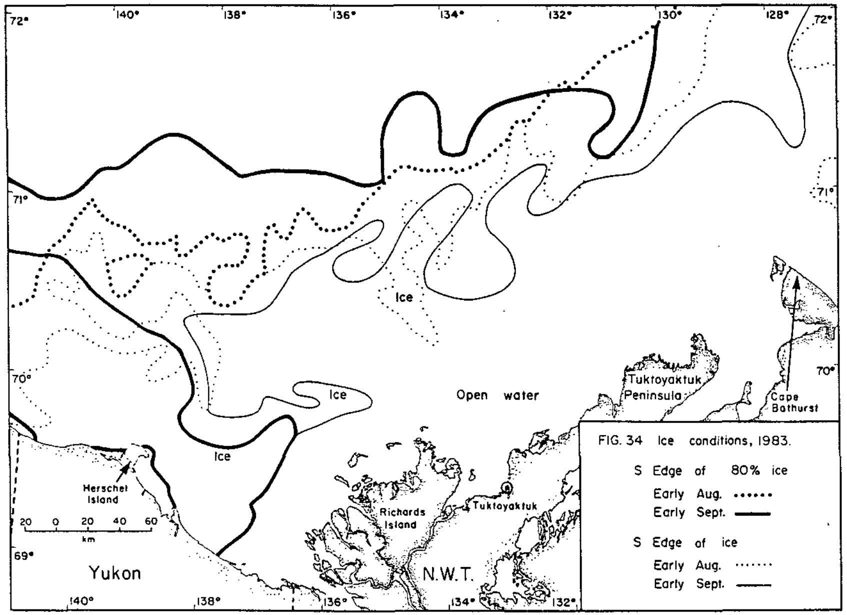

FIG. 34 Ice conditions, 1983.

Alaska border to Cape Dalhousie (141°-129°W) and north beyond the 200 m contour, McLaren and Davis (1984) estimated that about 1057 bowheads were in the surveyed area, excluding the concentration (apparently several hundred) along the Yukon coast. A few bowheads were seen in Alaskan waters west to 147°W in late August, but numbers there seemed very low (Ljungblad et al. 1984a,b). Larger numbers were found east of Cape Bathurst (Cubbage et al. 1984).

Bowheads apparently moved into the western edge of the industrial area in the last week of August. Some were 10-12 km from the conical drillship at Pitsiulak, and directly below the helicopter route to that site; they were also exposed to strong seismic noise, at least on 31 Aug-1 Sept (Richardson et al. 1984b). There were apparently few bowheads in other parts of the industrial area in late August.

In early September 1983, there were a few sightings in the main industrial area, especially just inside its western edge near Pitsiulak. These whales may have come from the Yukon coast, where no whales were found on 6 Sept. Few other bowheads were seen in the western half of our study area (Fig. 30). Reduced detectability because of ice (Fig. 34) may have been partly responsible. However, the majority of the population was apparently farther east. From a systematic survey on 6-11 Sept, McLaren and Davis (1985) estimated that about 1700 bowheads were north of the Delta and Tuk Peninsula, excluding waters beyond the 500 m (approx.) contour. More bowheads, not taken into account in the above estimate, were found farther east in Franklin Bay (126°W; Cubbage et al. 1984). Bowheads were also present this far east in early September of 1981 (Davis et al. 1982). Some bowheads off the Tuk Peninsula were probably exposed to noise from seismic vessels (Fig. 30,33).

Bowheads seen during the 6-11 Sept survey were oriented primarily southwest or west (McLaren and Davis 1985), and migration into Alaskan waters was underway by 3 Sept (Ljungblad et al. 1984a). Bowheads were last seen in Canadian waters on 2 Oct (140°; Ljungblad et al. 1984a).

Bowhead Distribution and Industrial Activities in 1984 (Fig. 35-42)

Industrial Activities, 1984

The region of offshore activities in late summer of 1984 was similar to that in 1983; the levels of various activities were similar or slightly reduced. Five drillships worked throughout the study period, drilling at six sites (Fig. 39). Drilling also began at Amerk caisson-retained island in late August. Four hopper dredges and several barges with clamshells were used to construct six islands or subsea berms. The main borrow sites included Ukalerk, Isserk, and Issigak, plus abandoned artificial islands at Tarsiut, Kadluk, Adgo and Sarpik (Fig. 39).

Patterns of vessel and helicopter traffic in 1984 were similar to those in 1983 (Fig. 39, 40). However, there was more traffic to Herschel Basin because support vessels, including the tanker 'Gulf Beaufort', were anchored there throughout the 1984 season.

Seismic exploration extended from the Alaska border to Cape Bathurst. However, at most times seismic vessels operated in rather confined areas (Fig. 41), partly because ice occurred relatively close to shore in 1984

(Fig. 42). Two or three vessels with large arrays of airguns plus one with gas guns were operating. In 1984, no Alaska-based vessels operated near the Alaska-Yukon border during our study period.

Bowhead Distribution, 1984

Surveys in early and mid July 1984 showed that few bowheads were over the shelf off the Yukon, Delta or Tuk Peninsula (Harwood and Borstad 1984). By late July, bowheads had begun to move into this area, especially off the eastern Yukon, Tuk Peninsula and Cape Bathurst. Most were in water 51-100 m deep and pack ice, not in nearshore ice-free waters (Harwood and Borstad 1984). Only one bowhead was seen in the main industrial area during four aerial surveys, but industry personnel reported 9 sightings totalling 16 bowheads there in July (Harwood and Borstad 1984). The whereabouts of the rest of the population in July is unknown. Bowheads were not seen in the Alaskan Beaufort (D. Ljungblad pers. comm.). There were no surveys in Amundsen Gulf or far offshore in the eastern Beaufort.

In early August 1984, there were still low numbers of bowheads off the eastern Yukon, but larger numbers in open water off the eastern Tuk Peninsula and Cape Bathurst (Fig. 35). None were seen west of Herschel Isl (Fig. 35, D. Ljungblad pers. comm.). We saw none in the main industrial area, but some were not far east of the easternmost drillship. The few whales east and north of Herschel Isl sometimes were exposed to seismic noise (Fig. 35 vs. 41; Richardson et al. 1985b).

In mid August 1984, large numbers of bowheads moved into shallow waters west of the Delta and along the Yukon coast (Fig. 36). Numbers along the shore SE of Herschel Isl were lower than in mid Aug 1983. However, whales also concentrated in some areas where they had not been in 1983--along the shore near and west of Herschel Isl, and in a narrow NNE-SSW band west of the Delta. The latter band was along a sharp discontinuity between turbid water of the Mackenzie River plume and less turbid marine water. Bowheads were still present at Cape Bathurst and low numbers were scattered elsewhere (Fig. 36). The westernmost sightings were just into Alaskan waters (141°25'W; D. Ljungblad pers. comm.).

Only a few bowheads were seen during surveys of the main industrial area north of the Delta. Some of the many whales along the plume edge west of the Delta were just beyond the westernmost artificial islands and along a major helicopter route (Fig. 40). They also were often exposed to strong seismic noise (Fig. 41; Richardson et al. 1985b). The concentrations along the Yukon coast were exposed to much less industrial activity.

In late August 1984, distribution was little changed. The largest concentrations were still along the Yukon coast and the plume edge west of the Delta (Fig. 37). Some whales in the latter area were exposed to helicopter overflights, seismic impulses, and noise from island construction at Minuk (Fig. 39-41; Richardson et al. 1985b). There also were several sightings near the east and NE edges of the main industrial area in late August. Whales were still present near Cape Bathurst, and probably were exposed to seismic noise there (Fig. 41). There were few or no sightings in other offshore parts of the study area (Fig. 37), and few bowheads were west of the Alaska border (westernmost sightings at 143°W; D. Ljungblad pers.

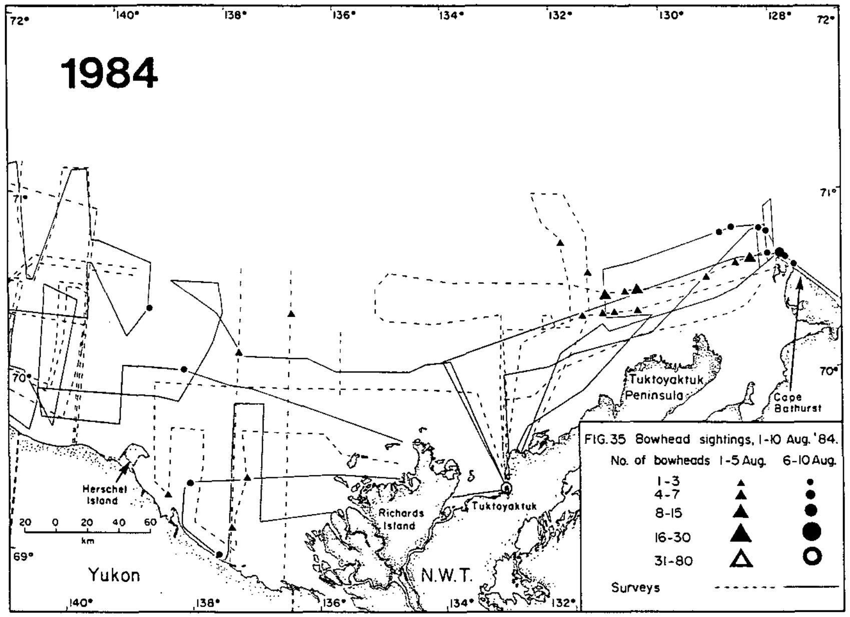

FIG. 35 Bowhead sightings, 1-10 Aug. '84.

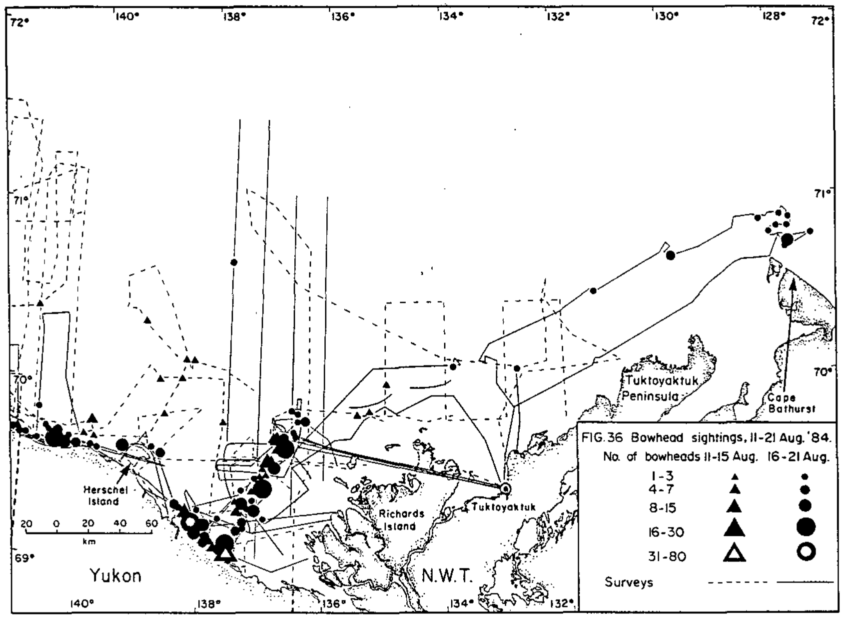

FIG. 36 Bowhead sightings, 11-21 Aug. '84.

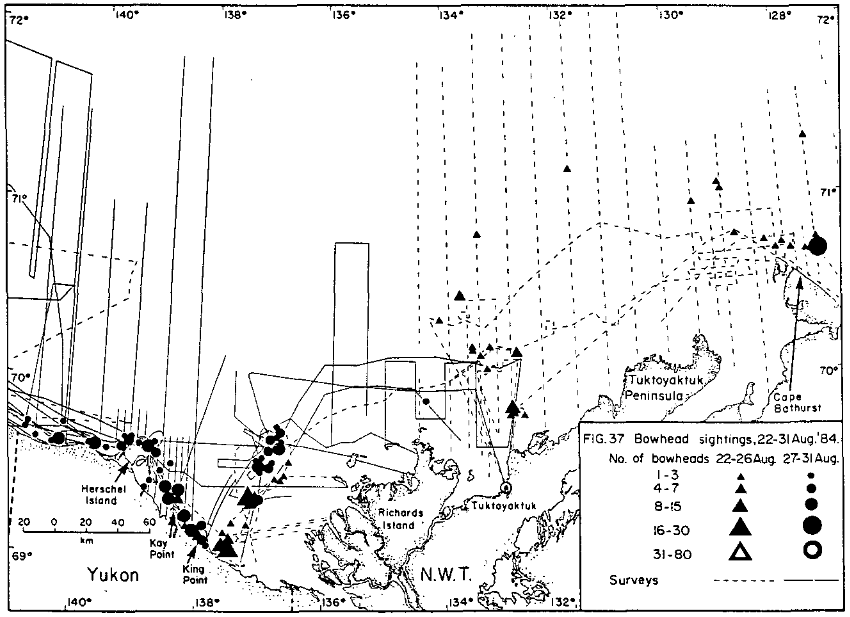

FIG. 37 Bowhead sightings, 22-31 Aug. '84.

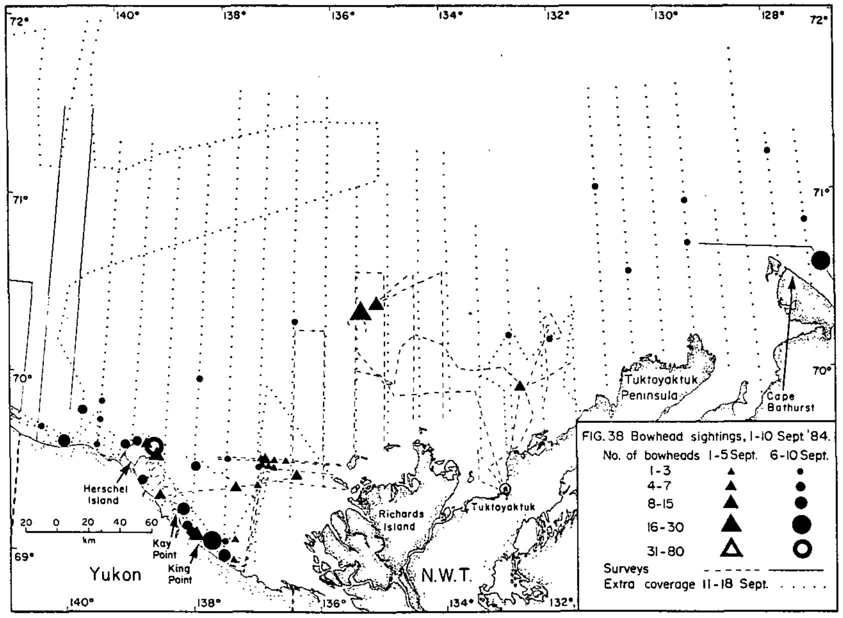

FIG. 38 Bowhead sightings, 1-10 Sept '84.

1984

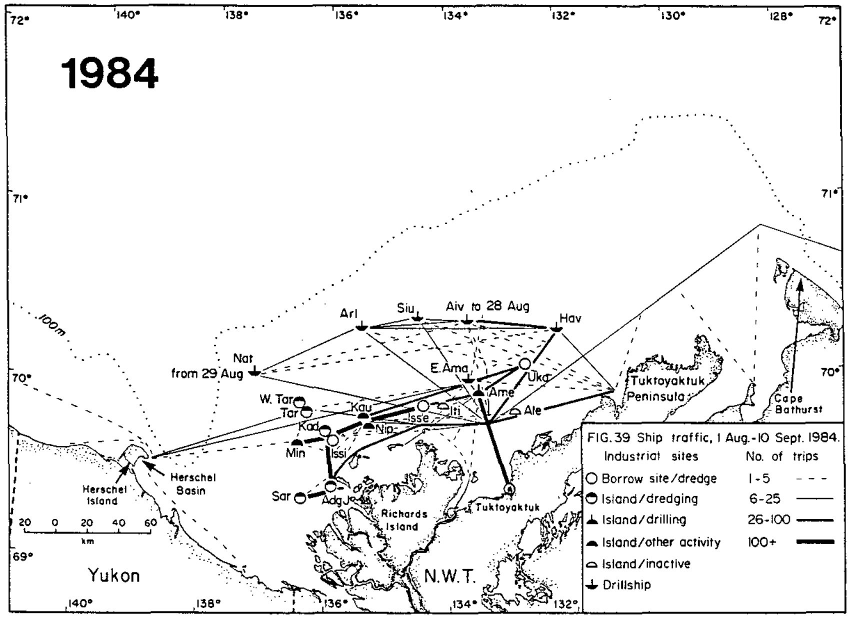
FIG. 39 Ship traffic, 1 Aug.-10 Sept. 1984.

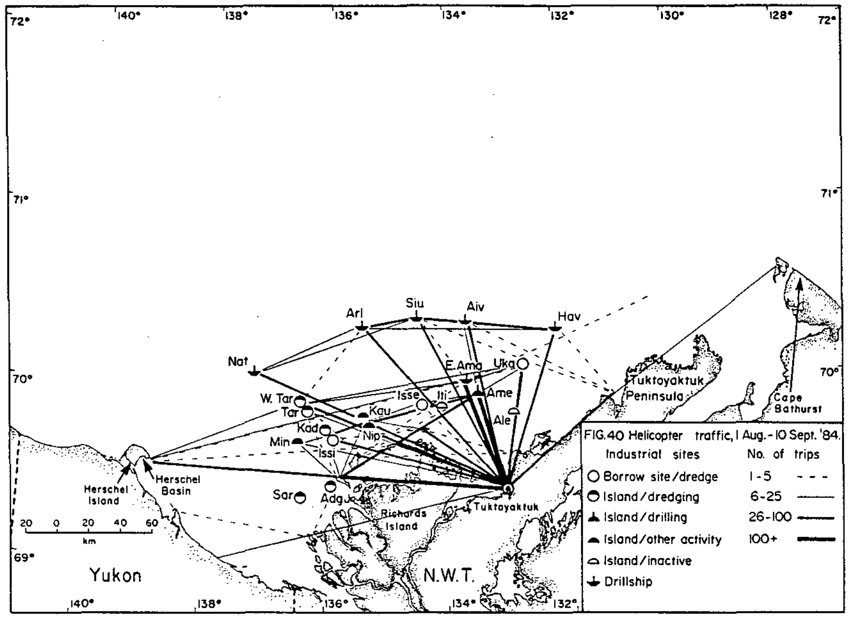
FIG. 40 Helicopter traffic, 1 Aug.-10 Sept. '84.

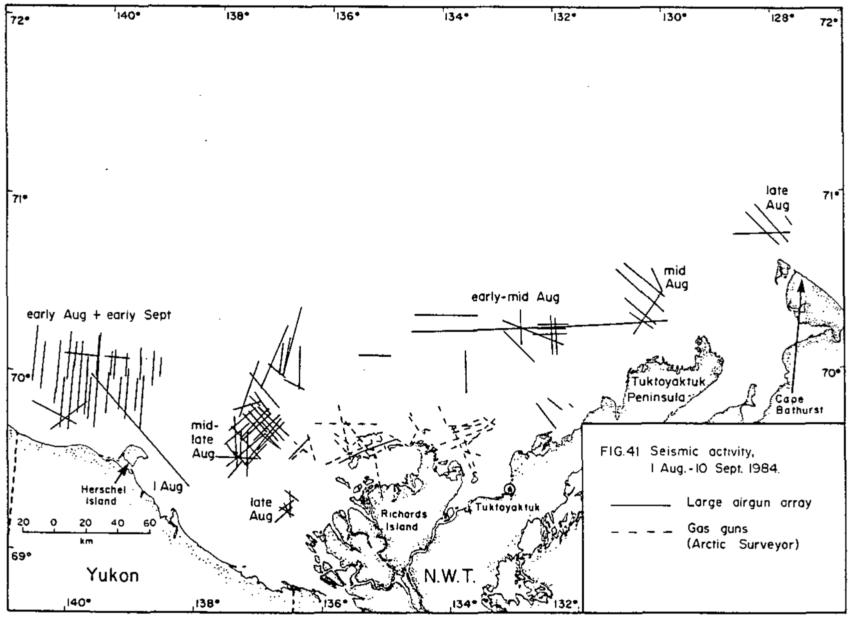
FIG. 41 Seismic activity, 1 Aug.-10 Sept. 1984.

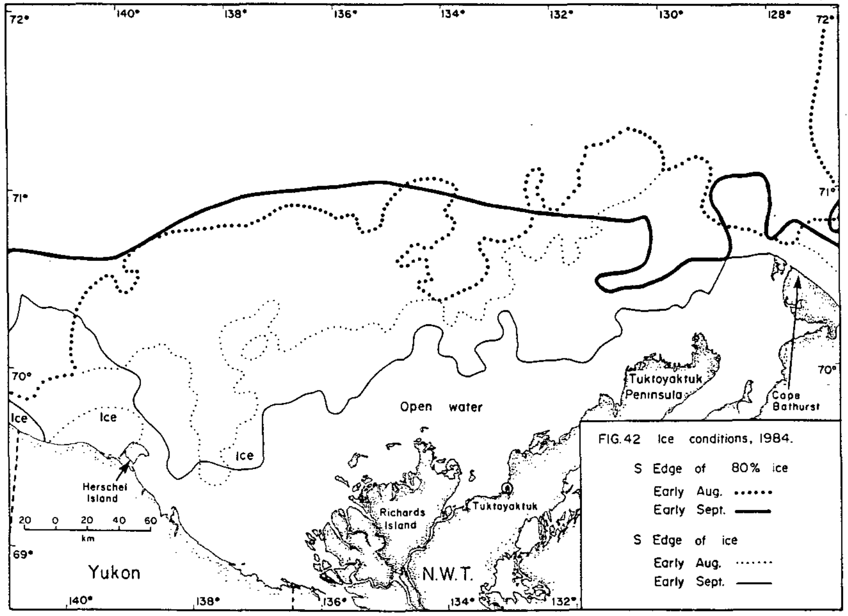
FIG. 42 Ice conditions, 1984.

comm.). However, there were numerous whales east of our study area in Franklin Bay (126°W) at this time (Harwood and Borstad 1984; Davis et al. in prep.).

In early September 1984, bowheads were still concentrated at some locations along the Yukon coast and west of the Delta (Fig. 38). Some of the latter whales were again exposed to helicopter traffic and noise from island construction. Aerial surveyors saw no bowheads within the industrial area north of the Delta, but industry personnel reported some sightings there in Sept (Harwood and Borstad 1984). There was a concentration just north of the industrial area, about 10 km north of the drillship at Arluk (Fig. 38,39). Bowheads were still numerous off Cape Bathurst and farther southeast in Franklin Bay (Davis et al. in prep.).

Offshore coverage in early Sept was meagre, but a systematic survey in mid Sept detected virtually no bowheads far off the Yukon or Delta, and few north of the Tuk Peninsula and Cape Bathurst (Fig. 38; Harwood and Borstad 1984). Bowheads were still concentrated along much of the Yukon coast in mid Sept (Davis et al. in prep.). In general, many bowheads were still in the SE Beaufort Sea, including Franklin Bay, in mid Sept, although others had moved west as far as Prudhoe Bay, AK (LGL unpubl. data). Bowheads were still present near shore SE of Kay Pt on 26 Sept and, in smaller numbers, 3 Oct (D. Ljungblad pers. comm.). On 5 Oct, a few bowheads were seen travelling west in offshore waters near the Alaska-Yukon border (LGL unpubl. data).

Bowhead Distribution and Industrial Activities, 1976-79

Before 1980, bowheads in the Canadian Beaufort Sea were little-studied. Very limited information came from (1) the commercial whaling era (1890-1914), (2) opportunistic observations during recent studies of other topics, and (3) reports by industry personnel (Fraker et al. 1978; Fraker and Fraker 1979; Fraker and Bockstoce 1980), along with (4) opportunistic vessel surveys in 1979 (Hazard and Cubbage 1982).

The area of shallow water off the eastern part of the Mackenzie Delta and western Tuktoyaktuk Peninsula is the one part of the Canadian Beaufort Sea where there was some study of bowheads each year since 1976 (Fig. 43). This area was within the main area of offshore oil exploration in 1976-79 (Fig. 44-47) as well as in 1980-84. Artificial islands had been built in very shallow waters just north of the Delta before 1976, but in 1976 island-building extended out to Isserk in 13 m of water. In both 1976 and 1977 there was much barge traffic between a dredging site at Tuft Point and Isserk. Also, the first three drillships arrived in the Beaufort Sea in 1976 and drilled at several sites (Fig. 44). In 1978 and 1979, dredging and island construction occurred at Issungnak, in water 18 m deep farther offshore than Isserk (Fig. 46, 47). There was much barge traffic between Tuft Point and Issungnak in 1978-79. A fourth drillship arrived in 1979.

In 1976, many bowheads were seen in water <15 m deep during the first half of August, with a few others later (Table 3; Fig. 43; Fraker 1977a). About 35-45 were seen on 10 August alone. Similarly in 1977, there were 26 sightings totalling almost 100 bowheads in water <15 m deep off the Delta and western Tuk Peninsula between 26 July and 17 Sept (Table 3; Fig. 43; Fraker 1977b). Many of these 1976-77 sightings were from vessels travelling farther

Table 3. Bowhead sightings off the eastern Mackenzie Delta and western Tuktoyaktuk Peninsula in the summers of 1976-80[a].

	Incidental Sightings[b]		Systematic Offshore Surveys, 1-15 Aug		Dates Observed	
Year	No. of Sightings	No. of Bowheads	No. of Bowheads	Density[c] (/1000 km^2)	First	Last
1976	15	46	-	-	3 Aug	16 Sept
1977	26	98	-	-	26 July	17 Sept
1978	5	58	1[d]	0.5	26 July	14 Sept
1979	1	6	1	0.5	8 Aug	9 Sept
1980	18	136	139	41.0	2 Aug	11 Sept

[a] Sources: Fraker (1977a,b, 1978), Fraker et al. (1978, 1982), Fraker and Fraker (1979), Fraker and Bockstoce (1980), and P. Norton (unpubl.).

[b] Sightings by industry personnel and biologists, excluding specific studies of bowheads.

[c] Uncorrected density; no allowance for submerged or missed whales.

[d] Plus sightings totalling 4 whales on 26 July 1978.

offshore than was common in previous years. Opportunities for observations thus were increased. Nonetheless, the sightings show that numerous whales occurred in the shallow waters of the Mackenzie estuary in 1976 and 1977.

In 1978, there were fewer incidental sightings in the shallow water off the Delta and western Tuk Peninsula--only 5 sightings of a total of 58 whales. All were seen from 7 to 14 Sept in water 11-18 m deep (Table 3; Fig. 43; Fraker 1978). Opportunities for incidental observations in August 1978 were similar to those in 1977, when many more whales were seen. Also, from 26 July to 8 August 1978, Fraker conducted four systematic aerial surveys north to about the 50-60 m isobath off the eastern Delta. Only 5 whales (uncorrected density 0.9/1000 km^2) were found, all near the 50 m isobath (Fig. 43). Only one was seen during the two August surveys (0.5/1000 km^2). Bowheads clearly did not move into shallow water off the eastern Delta as early in 1978 as in 1976 or 1977.

In 1979, only one bowhead was seen during three systematic surveys off the Delta on 21 July-8 Aug (Fig. 43; Fraker and Fraker 1979). The uncorrected density was 0.3/1000 km^2, or 0.5/1000 km^2 during two August surveys. Industry personnel at Issungnak and elsewhere reported only one sighting in 1979--6+ bowheads in 12 m of water on 9 Sept (Fig. 43; Fraker and Fraker 1979). Similarly, Hazard and Cubbage (1982) saw no bowheads west of 131°W, although they did find bowheads farther east in late July and August.

In summary, the abundance of bowheads in shallow waters off the eastern Mackenzie Delta varied markedly from 1976 to 1979. Bowheads were numerous there in August 1976 and 1977, infrequent until 7 Sept in 1978, and infrequent in 1979 (Fig. 43).

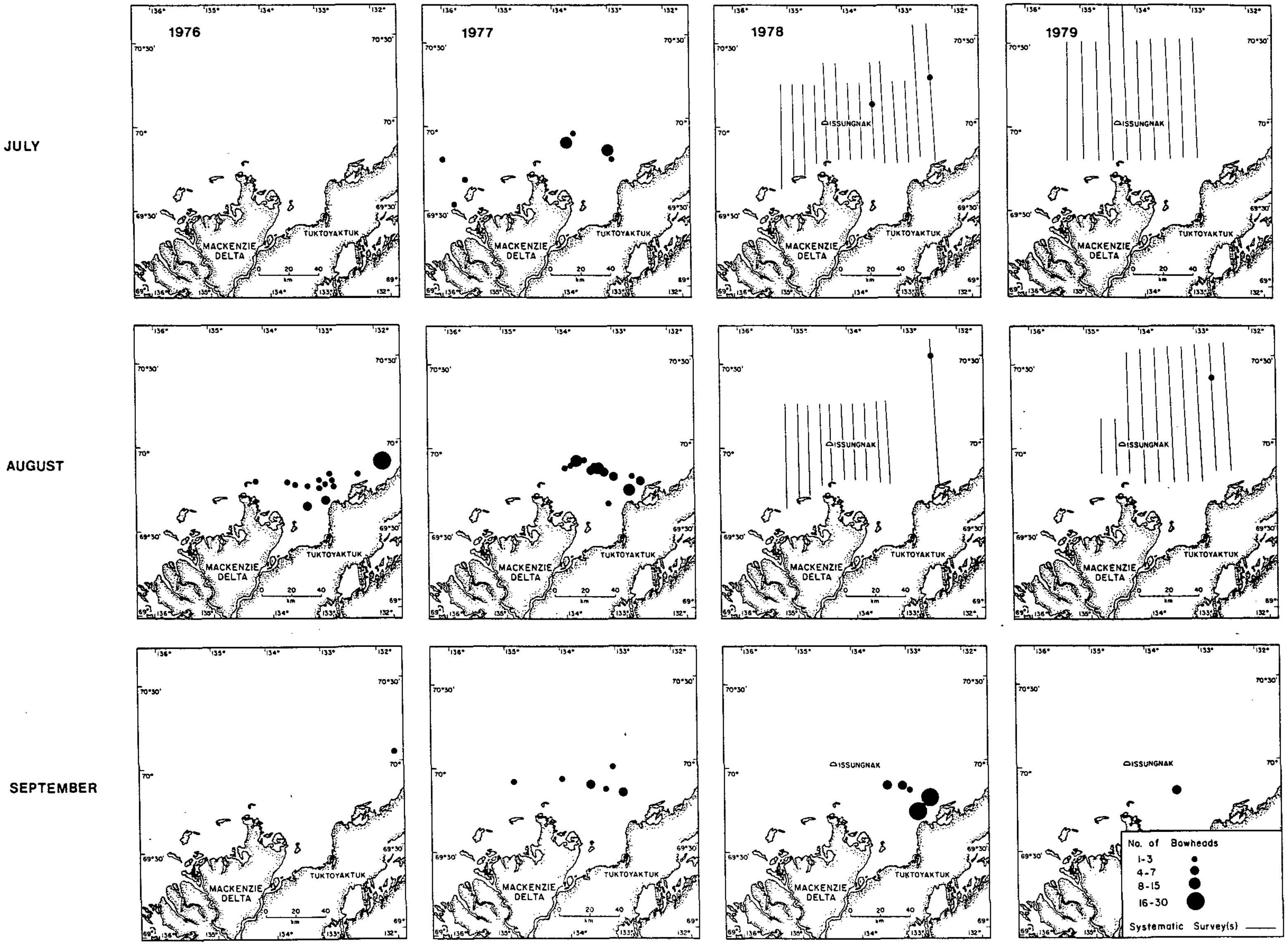

FIGURE 43. Bowhead sightings off the eastern Mackenzie Delta and western Tuktoyaktuk Peninsula in the summers of 1976-79. Sources as for Table 3. There were no systematic surveys in 1976-77. Each survey line shown on maps for 1978-79 was covered once or twice.

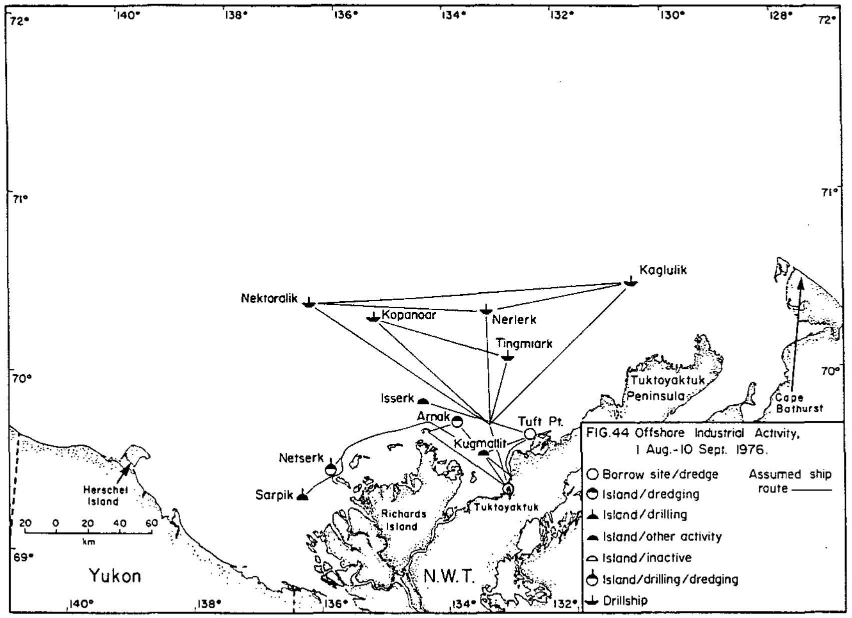

FIG.44 Offshore Industrial Activity, 1 Aug.-10 Sept. 1976.

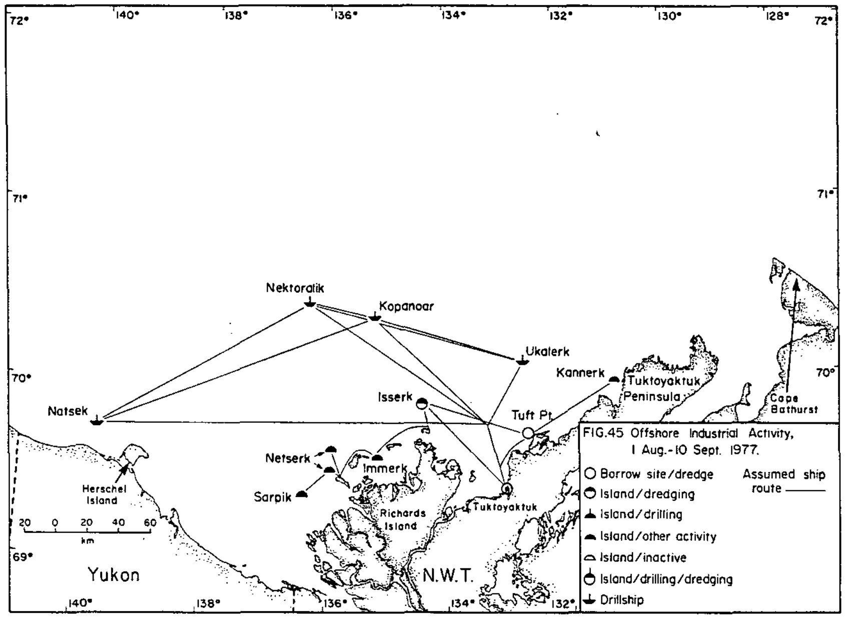

FIG.45 Offshore Industrial Activity, 1 Aug.-10 Sept. 1977.

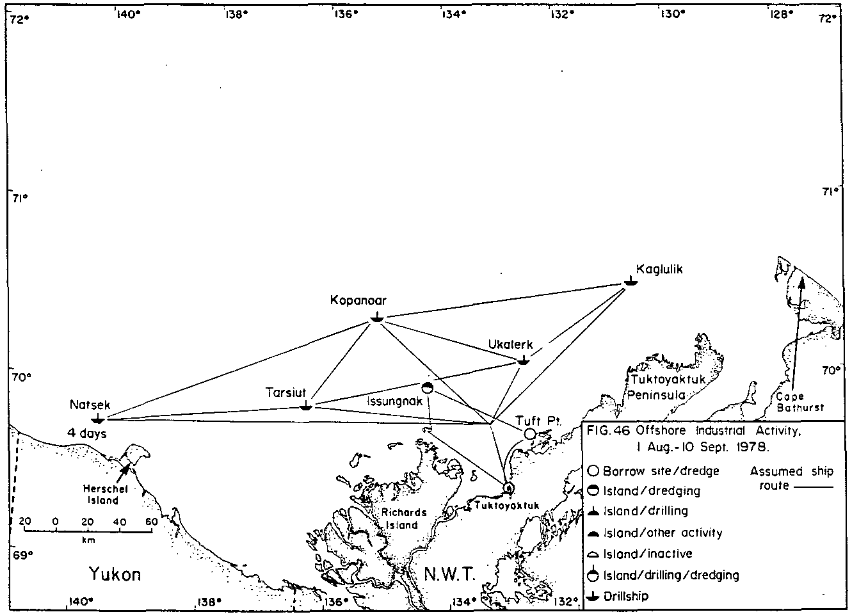

FIG.46 Offshore Industrial Activity, 1 Aug.-10 Sept. 1978.

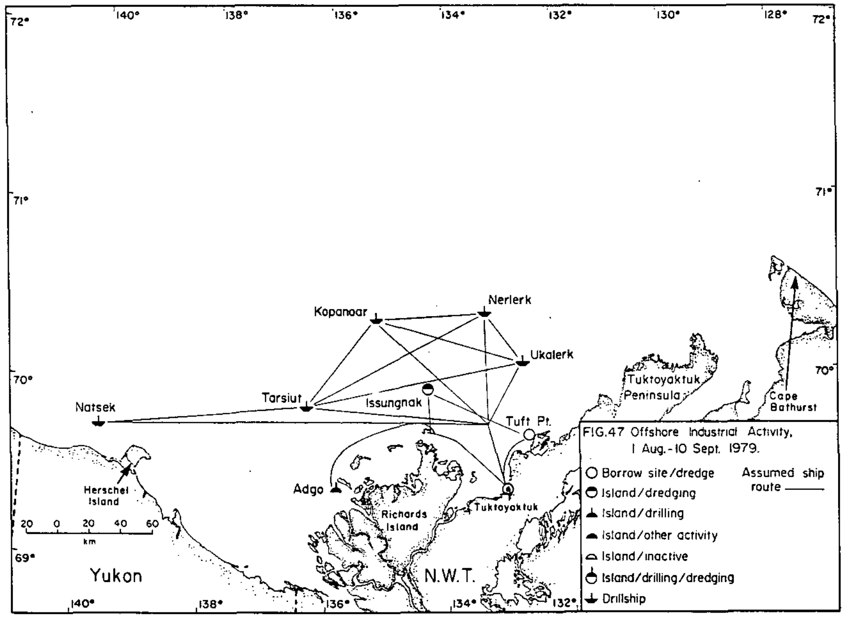

FIG.47 Offshore Industrial Activity, 1 Aug.-10 Sept. 1979.

DISCUSSION

Bowhead distribution in the eastern Beaufort Sea has varied greatly within and between summers. Nonetheless, some patterns are evident. These patterns are summarized before we consider whether there are any trends in distribution and, if so, whether these trends are related to industrial activities.

Seasonal and Annual Trends in Distribution

Few bowheads occurred in the shallow shelf waters off the Tuktoyaktuk Peninsula, Mackenzie Delta and Yukon before 1 August. In August, many bowheads moved into these shallower waters, apparently from the north and east. However, the timing of movement and locations of concentrations varied from year to year.

Summary Maps.--Figures 48 and 49 summarize distribution in early and late August of 1980-84. Areas with no survey coverage are identified. Areas designated as low, moderate and high density are those with, respectively, widely separated sightings of 1-3 whales, many sightings of 1-3 whales, and large groups of whales. The categorization is necessarily subjective. In borderline cases, we considered the amount of survey effort; the greater the amount of survey effort, the less emphasis we gave to any single sighting. The reader can compare Figures 48 and 49 with the detailed sighting and survey coverage maps given earlier to corroborate our categorizations.

Figures 48 and 49 must be interpreted with considerable caution. Survey coverage ranged from nil or sparse to extremely intense (see earlier maps), and survey procedures varied widely. Systematic surveys were not available from the entire study area in any period. In early August of 1982-84 there was considerable non-systematic but essentially no systematic coverage. Where and when available, systematic coverage was very helpful in comparing relative numbers of bowheads. When there was substantial coverage of both the systematic and non-systematic types, major concentrations detected by one approach were generally detected by the other as well. However, when coverage was sparse, moderate concentrations of whales were sometimes missed or, more commonly, greatly underrepresented by one type of coverage.

Both systematic and non-systematic surveys had major limitations. Because systematic surveyors usually did not circle whales, non-systematic coverage commonly detected groups where systematic coverage detected only 1 or 2 whales, or even no whales. On the other hand, the concentration of non-systematic coverage in areas where whales were expected caused considerable complications in estimating relative numbers in different areas. Ideally, this could be allowed for by converting to 'sightings per unit effort'. However, this was not practical here. Effort was not always quantifiable, and it was necessary to combine results from studies with widely varying field procedures.

In summary, caution is necessary in interpreting Figures 48 and 49 even for areas and times when systematic surveys were done. Apparent differences in bowhead abundance between areas and years should be considered proven only when the difference was large and there was considerable survey coverage.

Late July.--Only in 1981 and 1984 were there extensive surveys in late July. In 1981, very few bowheads were in the SE Beaufort Sea; more were in Amundsen Gulf. However, only a minority of the population was detected. Presumably most were far offshore in the pack ice, perhaps with some in unsurveyed Alaskan waters. In 1984, few bowheads were in the SE Beaufort in early-mid July (Harwood and Borstad 1984). Bowheads began to arrive in late July, earlier than in 1981. None were seen in Alaskan waters in July 1984 (D. Ljungblad pers. comm.).

Early August.--Distribution in early August differed greatly among years (Fig. 48). Within the 1980-84 period, only in 1980 did many bowheads move into shallow waters north of the Mackenzie Delta in early August. There was evidence of a similar concentration in early August of 1976 and 1977, but not 1978 or 1979 (Fig. 43). In early August 1981, bowheads were widely distributed on the outer continental shelf, mainly near the ice edge and the shelf break. Many seemed to be moving south on a broad front, although others apparently moved west out of Amundsen Gulf.

In early August of 1982 and 1983, bowhead concentrations were found well offshore in the western part of the study area (Fig. 48C, D). In 1982, many were in open water but moving west. Coincidentally or not, this was toward the ice edge, which was unusually far west. Other bowheads were in the ice, including some far offshore in the pack ice of the Alaskan Beaufort Sea (Ljungblad et al. 1983). In early August 1983, virtually all bowheads seen were in or near the ice beyond the shelf break off the western Yukon (Fig. 48D). In that year bowheads did not extend far into Alaskan waters. In early August 1984, as in late July, there were small numbers of bowheads off the Yukon, but more off the eastern Tuk Peninsula and Cape Bathurst, at or just south of the ice edge.

In general, recent data provide evidence of westward movement out of Amundsen Gulf in early August of some years, as hypothesized by Fraker and Bockstoce (1980). However, the majority of whales that enter the SE Beaufort Sea at this time probably come from the north, not the east. In 1980, many bowheads were in open water well south of the ice by early August, but in 1981-84 most were in or just south of the ice. In 1982, the one recent year when ice was absent east of Herschel Island, both ice and bowheads were concentrated to the west.

Mid August.--In each of the five years studied in detail, the area of peak whale concentration within the Canadian Beaufort Sea was closer to shore in mid August than in early August. In 1980 the shift was slight, since whales were already in shallow water in early August, but in 1981-84 the shift was more dramatic. In mid August 1982, the only large concentration of bowheads within the eastern Beaufort Sea was in an area where water >100 m deep occurs close to shore near Herschel Isl. Adults, immatures and calves were present (Davis et al. 1983). In mid August 1983, a concentration of several hundred bowheads, mainly subadults, was found very close to the Yukon shore SE of Herschel Isl. In mid August 1984, immature whales again concentrated not only there, but also west of Herschel Isl and offshore in Mackenzie Bay, along the edge of the turbid Mackenzie River plume. These coastal concentrations were definitely not present in 1980-82. In general, movement toward shore occurred each year in mid August, but the area of concentration varied among years.

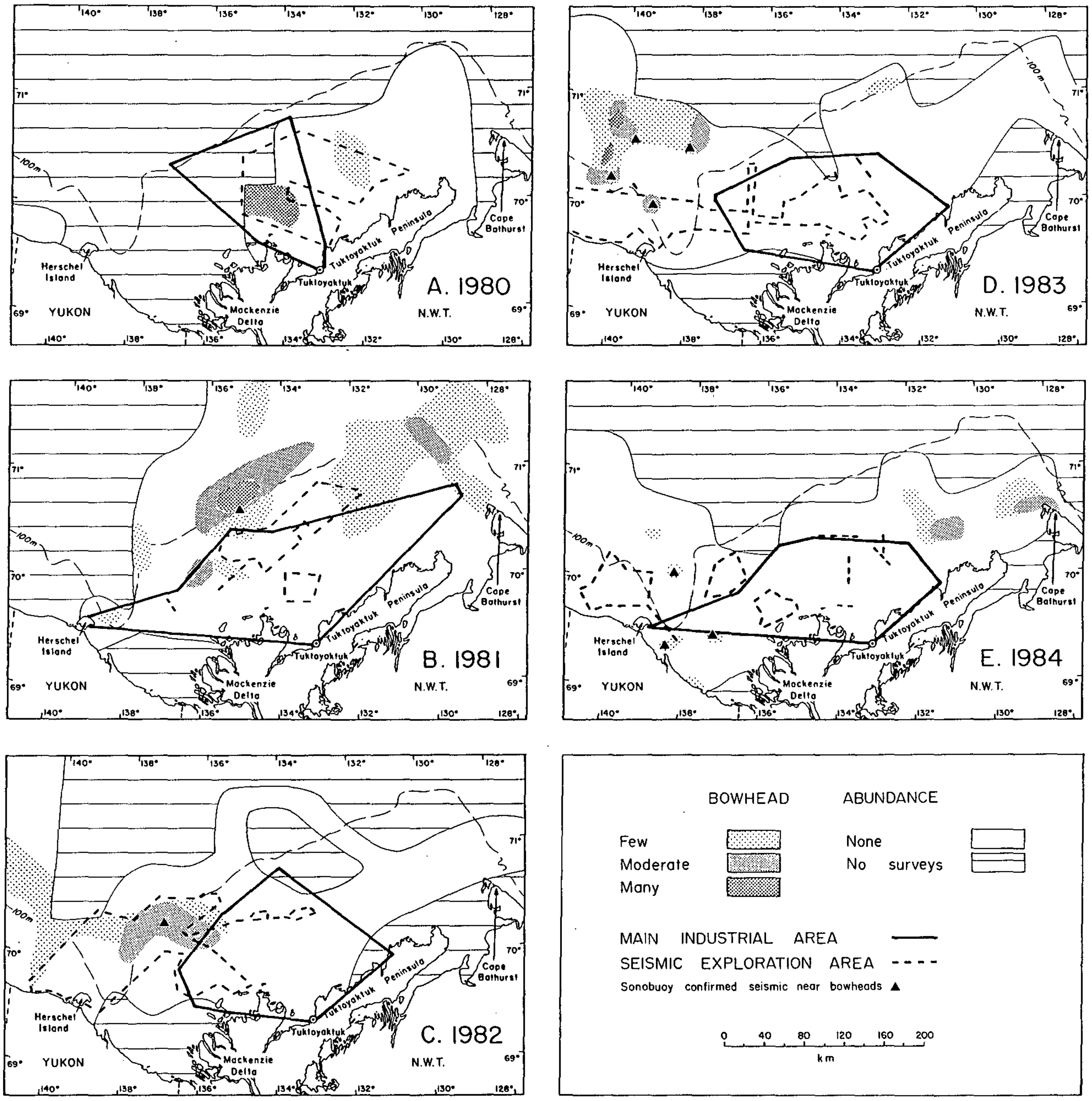

FIGURE 48. Distribution of bowheads on 1-10 August 1980-84 in relation to the area of industrial activity on 1-10 August. Triangles show locations where sonobuoys dropped near bowheads confirmed that bowheads were exposed to noise pulses from seismic vessels.

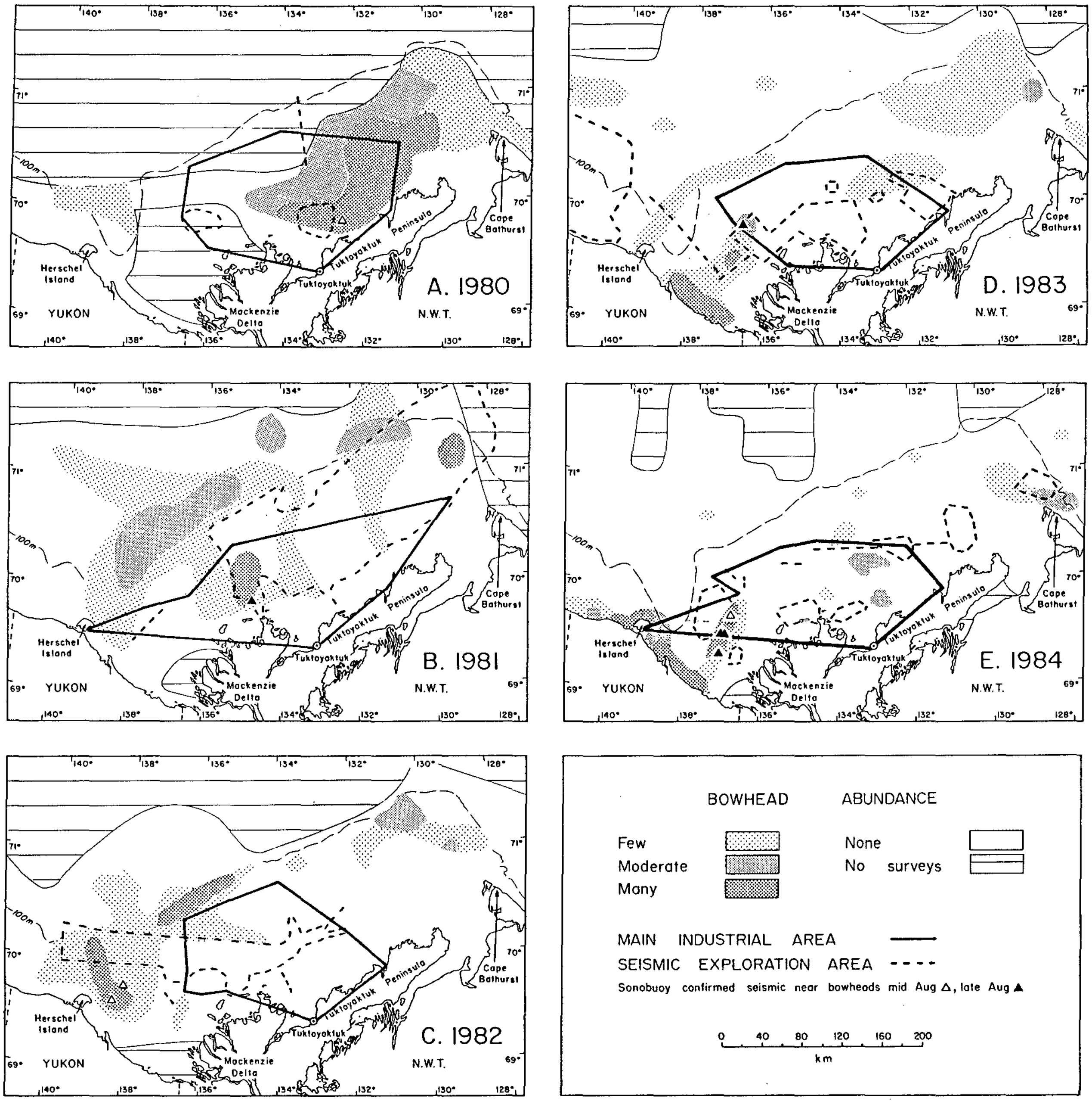

FIGURE 49. Distribution of bowheads on 18*-31 August 1980-84 in relation to the area of industrial activity on 11-31 August. Triangles show locations where sonobuoys dropped near bowheads confirmed that bowheads were exposed to noise pulses from seismic vessels.

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* Systematic surveys for the 'late August' periods of 1980-84 began on 18-21 Aug and ended on 24-29 Aug; all systematic coverage from 18 to 29 Aug was considered here, along with non-systematic coverage on 22-31 Aug.

Late August.--Distributions in late August were related to those in early and mid August, and differed among years. In 1980, there was a large area of concentration off the Tuktoyaktuk (Tuk) Peninsula and eastern Delta (Fig. 49A). This concentration was unique in the 1980-84 period, probably containing well over half the population. The center of abundance had shifted eastward relative to that earlier in August. In 1981, the areas of greatest abundance were in shallow waters off the central Delta and in deeper waters near the shelf break (Fig. 49B). In late August 1982, whales were still concentrated near Herschel Isl, but there were also concentrations near the shelf break, especially where it is steepest off the Delta (Fig. 49C). In late August of 1983 and 1984, the major nearshore concentrations of subadults persisted along the Yukon coast and, especially in 1984, along the turbidity front in Mackenzie Bay. In late August of 1981, 1983 and 1984, bowheads occurred near and beyond the eastern edge of our study area (Fig. 49D,E; Davis et al. 1982, in prep.; Cubbage et al. 1984; Harwood and Borstad 1984). No surveys were conducted east of the study area in 1980 or 1982.

Early September.--Distributions differed somewhat less among years in early September than in August. In 1980, numerous whales remained over the continental shelf off the Tuk Peninsula, although farther offshore than in August. Also, whales appeared close to shore off Herschel Isl. In 1981, whales moved closer to shore off the Tuk Peninsula in early September than they had been in August. There were many whales near Herschel Island, and low densities off the Delta and near Cape Bathurst. In 1982, the largest concentration was near and north of Herschel Isl, but there were a few sightings off the Delta and Tuk Peninsula. In 1983, whales were widely distributed on the outer shelf off the Tuk Peninsula (very similar to the pattern in early Sept 1980), with some off the Delta but virtually none near Herschel Isl. In 1984, unlike 1983, bowheads remained near the Yukon coast and Herschel Isl not only in early September (Fig. 38), but well beyond (D. Ljungblad pers. comm.).

Although some bowheads feed in the eastern Alaskan Beaufort Sea in early September (Ljungblad et al. 1984a), most are still in Canadian waters. Bowhead headings recorded during systematic surveys in early-mid Sept were predominantly westward in 1980, 1982 and 1983, but not in 1981 or 1984. Bowheads were present as far east as Franklin Bay (126°W) in early-mid September of all years with survey coverage (1981, 1983 and 1984). The main movement into Alaskan waters apparently is in mid-September of most years. There have been a few sightings in Canadian waters as late as early-mid October (Ljungblad et al. 1983, pers. comm.).

Geographic Areas Where Bowheads Often Concentrate

Amundsen Gulf and Franklin Bay.--Bowheads apparently concentrate in Amundsen Gulf in early-mid summer, presumably because break-up occurs early there (Sergeant and Hoek 1974; Fraker et al. 1978; Fraker 1979; Fraker and Bockstoce 1980). In 1981, there was evidence that some bowheads moved west out of Amundsen Gulf around 1 August. However, bowheads remain common in Amundsen Gulf and especially Franklin Bay in late summer (Davis et al. 1982, in prep.; Hazard and Cubbage 1982; Cubbage et al. 1984; Harwood and Borstad 1984).

Cape Bathurst.--Around 1900, bowheads were found near Cape Bathurst throughout the summer (Fraker and Bockstoce 1980). Bowheads also were seen there annually from 1979 to 1984, with substantial numbers in 1981 and 1984 (Hazard and Cubbage 1982; this report). Strong currents and sharp water mass boundaries occur there, and deep water occurs close to shore.

Off Tuktoyaktuk Peninsula.--Around 1900, whalers took many bowheads in shelf waters (<50 m) off the Tuk Peninsula in August and early September (Fraker and Bockstoce 1980). Bowheads still occur there at these times. The dates of occurrence, specific locations, and numbers of whales vary among years. Bowheads are often found over the outer shelf and shelf break north of Cape Dalhousie.

Shelf Break off Mackenzie Delta.--In August 1981-82, bowheads often concentrated about 125 km offshore NW or NNW of the Delta, at the edge of the continental shelf. The bottom slope is steeper here than anywhere else in the study area, dropping from 100 to 500 m in <10 km.

Yukon Coast.--During the 1970's, bowheads often were seen along the Yukon coast SE of Herschel Isl in late summer (Fraker and Bockstoce 1980). In 1980-82, there was no such coastal concentration, but in 1983 several hundred bowheads, probably mostly immatures, were there from at least 14 to 28 August. In 1984, bowheads (largely immatures) again concentrated there, and some remained until at least 3 October.

Herschel Island.--Bowheads were seen just N and NE of Herschel Isl in early September 1980-81, and starting in mid-August in 1982 and 1984. Bowheads also were found near Herschel Island in late summer and early autumn around 1900 (Fraker and Bockstoce 1980). This is the second of the two places in the study area where deep water occurs within a few kilometres of shore. Interestingly, very few bowheads were seen northeast of Herschel Isl during 1983.

Near Alaska-Yukon Border.--In mid to late September, bowheads often linger and feed in the 140°-142°W area (Ljungblad et al. 1980, 1982, 1983; Johnson 1983).

Distribution in Relation to Industrial Activities

Behavioral studies suggest that bowheads react only briefly to transient oil industry activities and to the onset of industrial noises, and that bowheads habituate to noise from ongoing drilling, dredging or seismic operations (Richardson et al. 1985a,b). However, the behavioral studies cannot determine whether fewer whales move into an area if industrial activity is present. They also cannot determine whether industrial operations result in a reduced tendency to return to the area in subsequent years. Large-scale survey results collected over a number of years provide a way to address these questions.

In Figures 48 and 49, areas of industrial activity in early and mid-late August 1980-84 are outlined on maps summarizing bowhead distribution in early and late August. Industrial activities are separated into (1) site specific activities such as dredging, island construction and drilling, along with vessel and helicopter traffic in support of those activities, and (2) offshore seismic exploration. The area with activities of type 1 is the 'main industrial area'.

Bowheads and the Main Industrial Area

In 1980, many bowheads were around the Issungnak island construction site north of the Mackenzie Delta in early and mid August (Fig. 48A). Vessel and helicopter traffic to drillships farther offshore also passed through or near that whale concentration. Behavioral and acoustic data confirmed that some whales were exposed to dredge and boat noise (Fraker et al. 1982; Greene 1982; Richardson et al. 1985a,b). By late August, most whales were somewhat east of the offshore construction and drilling sites; however, the western edge of the whale concentration was near Issungnak (Fig. 49A). In general, the only known concentration of bowheads was in the area of most intense industrial activities in early-mid August, and overlapped that area in late August.

In 1981, the main industrial area extended farther east and west but less far offshore. Most bowheads remained north or west of the area of intense industrial activity (Fig. 48B, 49B). The one concentration of whales near industrial sites was north of the Delta in mid and late August. They were, on most days, 10 km or more west of the artificial island and drillship in the Issungnak area. However, some of these whales were exposed to drillship, boat and probably helicopter noise (Richardson et al. 1985a,b).

In 1982, there was very little overlap between whale distribution and the area of intense offshore exploration (Fig. 48C, 49C). There were very few sightings within the main industrial area at any time during the summer.

In 1983, bowheads were virtually absent from the main industrial area in early August (Fig. 48D). There were some sightings there in mid August, but no major concentration. In late August a concentration of whales formed NW of the Delta (Fig. 49D). Some whales were only 10-20 km from the Pitsiulak drillsite and the Kadluk island construction site (Fig. 31), and were along a main helicopter route. These whales were also exposed to seismic noise (Fig. 49D). Overall, however, only a small fraction of the population was in the main industrial area in late August 1983. Much larger numbers were found outside the main industrial area, most notably along the Yukon coast and far to the east (Cubbage et al. 1984; McLaren and Davis 1985). The concentration NW of the Delta persisted into early September, but most bowheads remained outside the main industrial area (Fig. 30).

In 1984, bowheads were very scarce in the main industrial area in July (Harwood and Borstad 1984), and we saw none there in early August (Fig. 48E). From mid August to early September, many bowheads occurred west of the Delta in central Mackenzie Bay (Fig. 49E). Some of these were only 10-15 km west of the westernmost island construction site, and were exposed to occasional dredge noise from that site, seismic noise and helicopter overflights (Richardson et al. 1985b). Lesser numbers of bowheads occurred in eastern parts of the main industrial area (Fig. 49E).

General Trend.--Over the 1980-82 period, bowhead distribution overlapped progressively less with the area of offshore dredging, construction and drilling. This was true in both early and late August. Bowheads were abundant within the main industrial area in 1980, much less abundant there in 1981, and virtually absent in 1982. Maximum numbers in the main industrial area in 1983 were slightly greater than in 1982, and there was some further increase in 1984. Most bowheads in the industrial area in 1983 and 1984 were near its edges, unlike the situation in 1980. Thus, there was a pronounced decrease in utilization of the main industrial area from 1980 to 1982, and a much less pronounced increase from 1982 to 1983 and 1984. There has been no recurrence of the very large numbers seen in the main industrial area in 1980, or even of the lesser numbers seen there in 1981.

Offshore oil exploration north of the Mackenzie Delta became intensive in 1976 (Fig. 44-47). Thus, the appearance of many whales within the main industrial area in 1980 occurred four years after offshore operations in that area became intensive. The fragmentary data from 1976-79 indicate that many bowheads were seen in the middle of the main industrial area in early August of 1976 and 1977, but not in 1978 or 1979 (Fig. 43). Bowheads apparently entered the industrial area in early September of 1978, but in 1979 there were very few sightings at any time.

The presence of many whales in 1980, after a period of apparent scarcity in 1978-79, casts doubt on the suggestion that there is a trend for decreasing utilization of the main industrial area. However, bowheads were apparently abundant in the central part of the main industrial area in 3 of 5 years from 1976 to 1980, but in 0 of 4 subsequent years. The intensity of offshore industrial activities increased gradually from 1976 to 1983-84, and it is possible that industry began to affect bowhead distribution after 1980.

Overall, the data from 1980-84, and also those from 1976-84, provide some evidence of reduced utilization of the main industrial area, particularly the central portion north of the Mackenzie Delta, in recent years. However, some groups of bowheads occurred in the main industrial area in 1983-84, especially near its periphery. It may be of interest that most of the whales there in 1984, and possibly also 1983, were subadults (Davis et al. in prep.). Year-to-year fluctuations in bowhead abundance also occurred in most parts of the summer range outside the main industrial area. There is evidence that some of these variations in distribution may be attributable to variable food supply (see below). We conclude that it is presently uncertain

1. whether recent year-to-year variations in bowhead abundance are indicative of a long-term trend for reduced utilization of the main industrial area, and

2. whether these variations are connected with the gradually increasing level of industrial activity.

Bowheads and Areas of Seismic Exploration

We provide separate discussions of bowhead distribution relative to seismic exploration and the main industrial area. Seismic exploration occurred over a broader area than drilling, dredging and support traffic in 1980-84. Also, noise from seismic exploration was very intense but quite discontinuous, whereas drillsites, dredges and ships in the main industrial area produced continuous but less intense noise (Greene 1985). The discontinuity in seismic noise had two components: (1) seismic noise occurred as pulses spaced several seconds apart, and (2) at any given time seismic vessels operated in only a fraction of the entire zone of seismic exploration.

Seismic exploration occurred in shallow areas off the eastern Mackenzie Delta every year from 1971 to 1984, including 1976, 1977 and 1980 when many bowheads were present. In 1980, 'Arctic Surveyor' operated north of Tuktoyaktuk throughout August (Fig. 8). Bowheads were abundant nearby, and were seen only 8 and 13 km from the ship on two dates (Fig. 49A; Richardson et al. 1985a,b). In early August, when bowheads first moved into the area, another seismic vessel was operating just to the north and northeast (Fig. 8, 48A). In early September, whales far off the Tuk Peninsula were probably exposed to noise from seismic exploration just to the south (Fig. 8).

In August 1981, there was widespread seismic exploration north of the Mackenzie Delta and, from mid-month on, the Tuk Peninsula (Fig. 17). In early August, some whales far off the Delta were exposed to noise from a ship closer to shore; in late August, whales in shallow water off the Delta and in deeper water off the eastern Tuk Peninsula were exposed to strong seismic sounds on some days (Fig. 48B, 49B; Richardson et al. 1985a,b). In mid September, whales off the western Yukon were exposed (Ljungblad et al. 1982).

In 1982, bowheads NW of the Mackenzie Delta in early August were sometimes exposed to seismic noise, as was the concentration off Herschel Isl in mid August (Fig. 48C, 49C; Richardson et al. 1985a,b). There was probably continued exposure in the latter area in early September (Richardson et al. 1983a).

In 1983, fewer whales were found inside areas of seismic exploration than in 1980-82, but whales off the Yukon were often exposed to noise from distant seismic vessels (Fig. 48D, 49D; Ljungblad et al. 1984a,b; Richardson et al. 1984b, 1985b). The same was probably true for bowheads off the eastern Tuk Peninsula in late Aug-early Sept (Fig. 49D). In mid August, a few bowheads just north of Tuktoyaktuk were exposed to seismic and other industrial noise (Richardson et al. 1984b). Whales near the edge of the main industrial area northwest of the Delta definitely were exposed to seismic noise on 31 Aug-1 Sept (Fig. 49D; Richardson et al. 1985b).

In 1984, the concentration of bowheads west of the Delta in mid-late August was often exposed to strong noise pulses from a seismic vessel as close as 10 km away (Fig. 41, 49E; Richardson et al. 1985b). Bowheads scattered east and north of Herschel Isl in early August sometimes were exposed (Fig. 48E), and those near Cape Bathurst in late August probably were (Fig. 49E).

Recurrence in Areas of Seismic Exploration.--Many bowheads were in areas ensonified by seismic noise each summer from 1980 to 1984. Some concentrations were in areas where there was seismic exploration during the previous summer:

1. Many whales occurred in shallow water north of Tuktoyaktuk in 1980, and apparently also in 1976 and 1977. Seismic exploration has occurred there every summer since 1971.

2. Whales occurred off Tuk Peninsula in late Aug-early Sept of 1981-83 despite seismic exploration nearby at those times in 1980, 1981 and to a much lesser extent 1982 (Fig. 49).

3. Bowheads occurred far north of the Yukon in early August of 1982 and 1983 (Fig. 48C,D) despite seismic exploration there in the late July-early Aug of 1981 and 1982 (Fig. 19 and 41 in Richardson et al. 1983a).

4. Bowheads occurred west of the Delta in mid-Aug to early Sept 1984 despite the presence of seismic noise there in late Aug-early Sept 1983 (Fig. 49D,E).

Although these data suggest that seismic exploration has not caused large scale abandonment of parts of the summer range, little is known about recurrence of specific individual whales at places where they were exposed to seismic noise in previous years. Cases of apparent recurrence might involve different whales that were not exposed to seismic noise the previous year.

Natural Factors Affecting Bowhead Distribution

The predominant activity of bowheads in summer is feeding (Würsig et al. 1985a,b). To obtain sufficient energy, bowheads apparently must feed primarily in areas of above-average plankton abundance (Brodie 1981; Griffiths and Buchanan 1982). The latter authors found evidence that copepods are more abundant in areas with bowheads than in nearby areas without bowheads. Copepods and euphausiids are the main food items for bowheads in the Alaskan Beaufort Sea during early autumn (Lowry and Frost 1984), and presumably are also important to bowheads in the Canadian Beaufort Sea. Thus, factors affecting availability of zooplankton in the eastern Beaufort Sea probably have a strong influence on summer distribution of bowheads. Variations in the distributions of some other species of baleen whales are related to variations in their food supplies (for review, see Würsig et al. 1985b).

There has been no detailed study of factors affecting zooplankton abundance in different parts of the eastern Beaufort Sea. Thus, it is impossible to assess whether observed variations in bowhead distribution have any connection with variable zooplankton abundance. However, bowheads sometimes concentrate in areas where high zooplankton abundance would be expected. The early summer concentration in Amundsen Gulf might be related to the early bloom of phyto- and zooplankton that presumably results from the early ice breakup in that area. During late summer, concentrations of zooplankton (and bowheads) may occur because of the hypothesized higher productivity and/or concentrating effects associated with

- turbulence and eddies, e.g. near Cape Bathurst and Herschel Isl,
- hydrographic phenomena such as upwelling near the shelf break,
- occasional upwelling along the Yukon coast and ice edges, and
- hydrographic and nutrient conditions near the edge of the Mackenzie River plume.

(Herlinveaux and de Lange Boom 1975; Buckley et al. 1979; Owen 1981; Griffiths and Buchanan 1982; Borstad 1984; LGL, ESL and ESSA 1984).

Locations of zooplankton concentrations are expected to vary over time. For example, the occurrence of upwelling off the Yukon coast and the position of the estuarine front bordering the Mackenzie plume depend strongly on wind conditions on preceding days (Herlinveaux and de Lange Boom 1975; MacNeill and Garrett 1975). Thus, much of the within- and between-season variation in bowhead distribution may result from variation in areas of peak food availability. It should be noted, however, that this argument is largely speculation. There is very little empirical information about factors affecting zooplankton abundance in the eastern Beaufort Sea, or about the ways in which bowheads respond to variable food abundance and other environmental factors.

The detailed distributional data from 1980-84 and limited data from 1976-79 document pronounced year to year changes in summer distribution of bowheads. There is no evidence of avoidance of areas of seismic exploration. However, since 1980 fewer bowheads have tended to enter the main area of drilling, dredging and support activities, particularly its central zone. From present data it is not possible to determine whether activities in the main industrial area are affecting bowhead distribution. The trend is too imprecise, natural variability in bowhead distribution is too great, and our understanding of the roles of environmental factors, most notably food supply, is too rudimentary.

If many bowheads, particularly adults, return to the central part of the main industrial area in future, this will constitute strong evidence that oil exploration has not excluded bowheads from part of their range. The case will be especially strong if some recognizable individuals return to industrial areas where they were seen in previous years. Conversely, if a distribution similar to that seen in 1980 does not recur, there will be increasing reason for concern about possible long term effects of oil exploration on bowheads. In either case, a better understanding of the interrelated roles of oceanographic and meteorological phenomena in affecting plankton abundance and bowhead distribution may be necessary before firm conclusions about effects of industrial activity on bowhead distribution can be drawn.

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