BEHAVIOR, DISTURBANCE RESPONSES AND DISTRIBUTION OF BOWHEAD WHALES *Balaena mysticetus* IN THE EASTERN BEAUFORT SEA, 1983

Edited By
W. John Richardson

LGL Ecological Research Associates, Inc.
1410 Cavitt Street
Bryan, Texas 77801

for
U.S. Minerals Management Service
12203 Sunrise Valley Dr.
Reston, VA 22091

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DISCLAIMER

PROJECT RATIONALE, DESIGN AND SUMMARY, 1983*

By

W. John Richardson[1] and Bernd Würsig[2]

[1]LGL Ltd., environmental research associates
44 Eglinton Ave. W.
Toronto, Ont. M4R 1A1, Canada

[2]Moss Landing Marine Laboratories
P.O. Box 223
Moss Landing, CA 95039

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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 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 3857 individuals (I.W.C. 1983).

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 (Ljungblad et al. 1982a; Braham et al. 1984).

From May 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. Offshore drilling from drillships and artificial islands has been underway in the central part of the summering area since about 1976. Seismic exploration and nearshore drilling began there earlier and still continue. 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 (Richardson et al. 1983a).

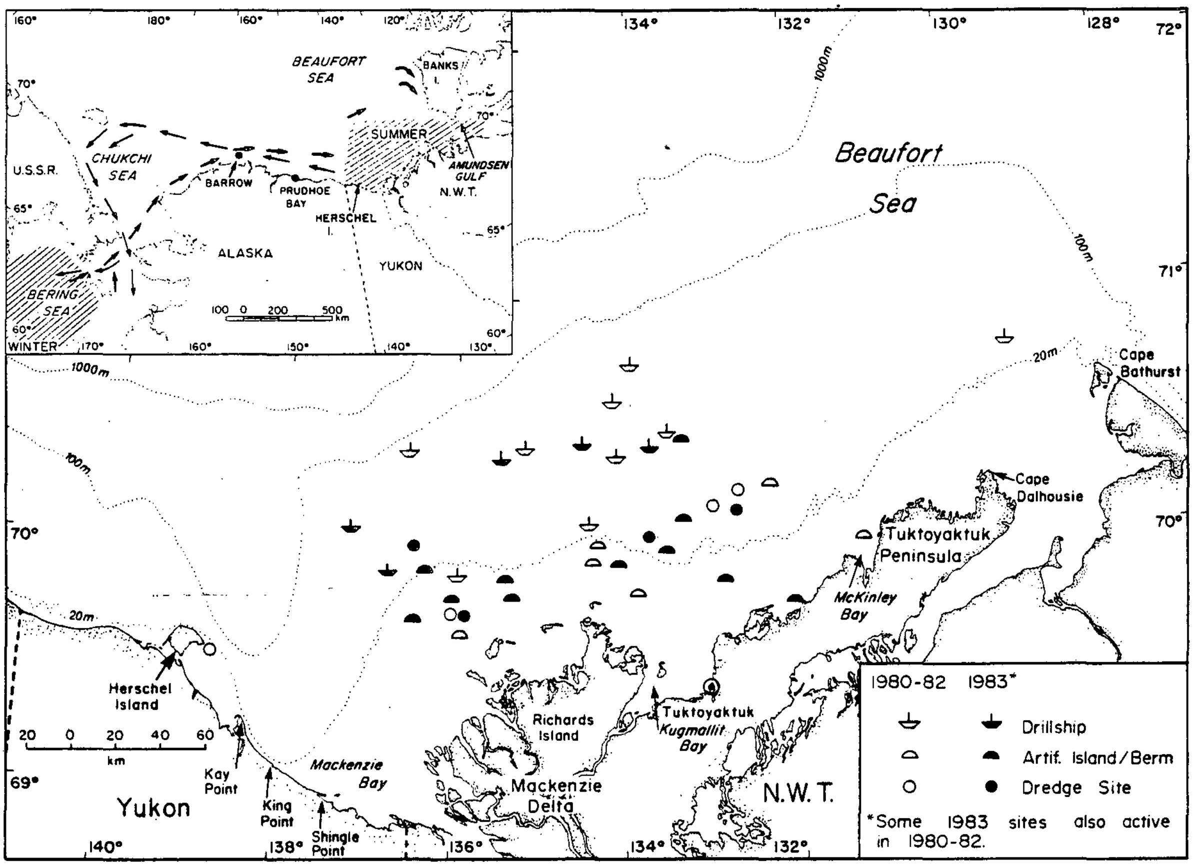

FIGURE 1. The eastern Beaufort Sea—study area for this project—showing the main sites of offshore industrial activity in August and early September 1983 (solid symbols) and 1980-82 (open symbols). Some of the 1983 sites were also active in 1980-82. **Inset:** Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

POTENTIAL FOR DISTURBANCE

The scientific literature contains some descriptions of the reactions of baleen whales to boats, aircraft, drillships, and other activities associated with offshore oil exploration. However, there have 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. (1983b).

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 offshore activities associated with the oil industry, including boat and aircraft traffic, seismic exploration, dredging and drilling (Acoustical Society of America 1981; Greene 1982, 1983; Richardson et al. 1983b). 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; Würsig et al. 1982). 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 (Greene 1982, 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; Greene 1982, 1983; Reeves et al. 1983). 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, sometimes over distances of kilometres (e.g. Tyack and Whitehead 1983; Watkins 1981). 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.

APPROACH IN THIS STUDY

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.

Objectives and Tasks

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. This report includes our results from 1983, the fourth year of the study. Results from 1980-81 and from 1982 appear in Richardson (1982, 1983). The work was done for two branches of USDI -- the Bureau of Land Management in 1980-81, and the Minerals Management Service in 1982-83. Besides examining bowhead behavior in the (1) presence and (2) absence of disturbance, we have also studied (3) the characteristics of the underwater noise from offshore industrial activities, (4) the distribution of bowheads in relation to industrial activities, and (5) the zooplankton in areas where bowheads did and did not feed. All five tasks were considered important in assessing the effects of offshore hydrocarbon exploration on bowhead whales. The rationale for each task was discussed in Richardson (1982, 1983).

Fieldwork in 1983 involved continued work on all tasks except zooplankton:

1. Disturbance responses: Priority was to be placed on disturbance experiments involving noise from seismic exploration, drilling, helicopters and dredging. In practice, it was possible to conduct an airgun experiment, drillship and dredge noise playback experiments, aircraft overflights at different altitudes, and one boat disturbance trial. We were also able to observe bowhead behavior in the presence of seismic noise and near offshore industrial sites.

2. Studies of normal behavior were assigned low priority in 1983, but considerable additional information was obtained because such observations are often possible when circumstances do not permit studies of reactions to industrial operations.

3. Characteristics of the industrial noises to which bowheads were exposed in 1983 were analyzed.

4. Distribution of summering bowheads in relation to industrial activities was determined by combining our observations during this behavioral study with results from three other bowhead studies conducted in the eastern Beaufort Sea in 1983.

Limited studies of zooplankton at locations where bowheads did and did not feed were conducted as part of this project in 1980-81 (Griffiths and Buchanan 1982) but not in 1982-83.

Study Area

The study area has been 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.

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 varies 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; Richardson et al. 1983a). 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 1983, three to five 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, five drillships, six seagoing dredges, ten helicopters and many support vessels were in use offshore. Offshore seismic exploration occurs in the study area each summer. At most times in recent open water seasons, two or three 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

The general approach in 1983 was similar to that in 1980-82. Whenever possible, we conducted experimental tests of reactions of bowheads to industrial activities. 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. Behavior of undisturbed bowheads was studied before and after disturbance experiments, and on other occasions when experiments were not possible.

Logistic support in 1983 consisted of observation aircraft and the same 12.5-m boat (MV 'Sequel') used in 1981-82. Two aircraft were used: a Twin Otter on 1-12 August and an Islander on 14 August-1 September. Most behavioral observations were from the aircraft. The aircraft crew also dropped sonobuoys to record underwater sounds from industrial sources and bowheads. The main functions of the boat were to conduct disturbance experiments and to record underwater sounds. Both the boat and the aircraft crew were based at Tuktoyaktuk, N.W.T., as in past years.

Shore-based observations were attempted at Herschel Island and King Point (Fig. 1) in 1980-81 but not in 1982 or 1983. Many whales had been seen near King Point in 1976 (W.R. Koski in Fraker and Bockstoce 1980), but virtually none were there in 1980-82. As events developed, 1983 proved to be the one year when shore-based observers could have collected valuable data on disturbance responses of bowheads. Bowheads occurred at King Point in mid and late August 1983, and much of our aircraft- and boat-based work was in this area.

In last year's report, we analyzed the distribution of summering bowheads during 1980-82 relative to industrial activities in those years (Richardson et al. 1983a). (Systematic information about bowhead distribution in the eastern Beaufort Sea was not obtained before 1980.) The objective of the analysis was to assess whether there was any evidence of long-term displacement of bowheads from the area of oil exploration. It was recognized that a 3-yr series of data beginning after offshore oil exploration began would probably be inconclusive, and this was in fact the case. Whales became progressively less common in the main industrial area from 1980-82, but this could have been attributable either to disturbance or to natural variation.

In 1983, this study plus three other investigations (McLaren and Davis 1984; Cubbage et al. 1984; D.K. Ljungblad pers. comm.) provided data on the distribution of bowheads summering in the eastern Beaufort Sea. One objective of this study was to draw together the distributional information arising from all four studies. The combined evidence about bowhead distribution was compared with the distribution of industrial activities in 1983, and with the 1980-82 results.

SUMMARY OF RESULTS

This section consists of slightly amended versions of the Abstracts from the following four self-contained sections of this volume. Readers planning to read the Abstracts later in the volume may wish to skip this section.

Normal Behavior of Bowheads, 1983

The report with the above title (Würsig, Dorsey, Richardson, Clark, Payne and Wells 1984) describes the 'undisturbed' behavior of bowhead whales summering in the southeastern Beaufort Sea. The emphasis is on the 1983 results, but the report contains considerable integration of results from 1980-83. Detailed accounts of results from 1980-81 and 1982 appear in Würsig et al. (1982, 1983).

Behavior of bowhead whales was observed from an aircraft during 15 of 28 flights in the period 1 August to 1 September 1983, mainly near shore in the Beaufort Sea between Herschel Island (Yukon Terr.) and Richards Island (Northwest Terr.), Canada. Detailed behavioral observations were made while we circled over whales for 38.4 h. Bowheads were 'presumably undisturbed' during 37.0% of the observation time (14.2 h), and these observations of 'normal behavior' are described in the present report. This represents the fourth consecutive year of detailed behavioral observations of bowhead whales in the eastern Beaufort Sea in summer. Methods were similar during all four years.

During most flights in 1983, bowheads were observed near shore in water 5-35 m deep. Whales dove for brief periods, socialized often, and--at least after mid August--spent time skim-feeding at the surface or apparently feeding near the bottom. These behaviors were somewhat similar to behaviors seen in shallow water in 1980 and 1981. Behavior in 1983 differed from that in 1982, when whales spent most time apparently feeding in the water column in water >100 m deep.

Social interactions--nudges, pushes, chases, and close proximity--were observed at a rate similar to that in 1981, less than that in 1980, and greater than that in 1982. The rate of social activity in 1983 up to and including 18 August was higher than after this date. This decrease in late August was consistent with data from 1980 and 1981 (with too little information on socializing in 1982 for analysis). There was no consistent relationship between rate of socializing and depth of water. As in previous years, socializing whales tended to turn while at the surface more frequently than did non-socializing whales. We observed no apparent mating in 1983. However, during one flight groups of whales interacted with each other by rolling and nudging in a fashion similar to that seen in mating groups of bowhead whales in spring and right whales in winter. On 31 August, two whales repeatedly slapped each other with their pectoral flippers and flukes, and this observation represented the most obviously aggressive interaction we have noted in four seasons.

We saw 347 underwater blows in 1983, including both 'presumably undisturbed' and 'potentially disturbed' whales. The rate of underwater blowing was positively correlated with the rate of socializing. This suggests that underwater blows are in some manner linked to social behavior. However, we do not know whether underwater blows represent aggression, as believed in southern right whales, or whether they have some other function.

Aerial activity occurred sporadically, and included brief bouts of tailslaps, flipper slaps, and/or breaches. However, on 22 August, we observed two longer bouts lasting about 12 min and 75 min. The latter was the longest uninterrupted bout of aerial activity seen in four years of observations.

As in earlier years, some whales were recognizable by distinctive features such as unusual white pigmentation, or scars and marks on the back. This allowed us to identify individuals for up to several hours. We obtained no known resightings on different days. In 1983, few whales near shore had distinctive white chin patches or patches of white on the tail or tail stock, and a sample of about 20 of these whales that we measured via photogrammetry were only 7-12 m long. Thus, most whales near shore were yearlings and older subadults.

The mean blow interval for presumably undisturbed non-calves in 1983 was 17.0 ± s.d. 13.49 s, n = 866, which was significantly higher than combined data for 1980-1982. Number of blows per surfacing and duration of surfacings were significantly correlated, as in previous years. Mean number of blows per surfacing for non-calves was 3.2 ± s.d. 2.37 blows, n = 229; and mean surface time for non-calves was 1.05 ± 1.484 min, n = 248. These values were much lower than those for 1982, but not significantly lower than those for 1980 and 1981. The mean dive time for non-calves was 1.88 ± 2.357 min, n = 140, shorter than in any of the three previous years.

Several factors were related to surfacing-respiration-dive characteristics. Durations of surfacings and number of blows per surfacing were longer for socializing whales than for non-socializing whales. Blow intervals of skim-feeding whales averaged more than twice as long as for non-feeding whales. Mean duration of surfacing, number of blows per surfacing, and proportion of time at the surface were higher in skim-feeders than in others, while mean duration of dives was slightly lower for skim-feeders than for others. Blow rates, however, were approximately equal for skim-feeders and other whales.

Only 4 or 5 calves were seen in 1983, all in water >1000 m deep on 7 August. Two calves interacted at the surface for at least 5 min. This represents our only observation in four years of apparent play between calves. One apparent subadult associated with a mother-calf pair for at least 40 min. Because we sighted calves only in deep water far north of Herschel Island and not with the many small whales close to shore in 1983, we surmise that the population was at least partially segregated into (1) mature animals, including females and calves, far offshore and perhaps in other areas not searched by us, and (2) subadult whales near the Yukon shore.

Sounds of bowheads were analyzed from 33.7 h of sonobuoy recordings (11.0 h from presumably undisturbed whales). The types of sounds recorded were no different from previous years, and, as in previous years, the majority of sounds (85%) were tonal, frequency modulated calls lasting 1-2 s. Most loud pulsive calls were heard during socializing, consistent with results from 1980-1982. Blow sounds were associated with periods of much underwater blowing, and slap sounds occurred during periods with aerial behavior, especially on 22 August.

We have observed considerable year-to-year variation in the distribution and behavior of bowhead whales from 1980 to 1983. Aside from the aforementioned relationship between activities and water depth, no consistently repeating pattern is discernible. A consideration of year-to-year variations in the distribution and behavior of other cetaceans demonstrates that variations in distribution and abundance of prey species may often be responsible.

Disturbance Responses of Bowheads, 1983

The report with the above title (Richardson, Wells and Würsig 1984b) describes the behavior of bowhead whales in the presence of actual or simulated industrial activities. The report presents the 1983 data in detail, with some integration of results from 1980-83. The 1980-82 results were given in detail by Fraker et al. (1982) and Richardson et al. (1983c).

Studies of the behavioral responses of bowhead whales to offshore oil and gas exploration were conducted in the Canadian Beaufort Sea from 1 August to 1 September 1983. This study, on behalf of the U.S. Minerals Management Service, was a continuation of similar studies in the same area in late summer during 1980-82. The general objective was to assess short-term behavioral responses of bowheads to noise and other stimuli associated with boat and aircraft traffic, seismic exploration, dredging and drilling. In 1983, we emphasized reactions to aircraft, seismic exploration and drilling, but also collected data on reactions to boats and dredging.

Methods in 1983 were very similar to those in previous years. Both experimental and opportunistic methods were used. During experiments, we tried to observe whales before, during and after simulated industrial activity. In 1983, we conducted the following disturbance experiments: 3 aircraft, 1 boat, 1 airgun, 3 drilling noise playbacks, and 1 dredge noise playback. We also observed whales opportunistically in the presence of aircraft at low altitudes, seismic exploration, a drillship, and a dredge; we compared behavior in these circumstances with behavior in the absence of potential sources of disturbance. Most observations were from an Islander or a Twin Otter aircraft circling at altitudes of 457 or 610 m (1500 or 2000 ft). Underwater sounds from whales and industrial sources were recorded via sonobuoys dropped from the aircraft and via hydrophones deployed from a boat. The boat was also used to conduct the boat, airgun and playback experiments.

Reactions to aircraft were evaluated mainly by assessing responses to the Islander observation aircraft. New information in 1983 included (1) three experiments in which we circled above the same group of whales at two different altitudes, and (2) subjective interpretation of apparent reactions to the aircraft. Although no controlled experiments with helicopters were possible, we twice observed bowheads while a helicopter flew at low altitude over the whales.

As in 1980-82, reactions to the observation aircraft were conspicuous when it was below 457 m above sea level, occasional at 457 m, and undetectable at 610 m. However, the responses of some whales to the aircraft circling at 457 m seemed more marked in 1983 than in earlier years, possibly because of lower ambient noise levels and/or greater lateral propagation of aircraft noise in the shallow water where most 1983 observations were obtained. During 1 or 2 of 3 experiments when the aircraft circled at two altitudes, mean blow interval was shorter, mean number of blows per surfacing lower, and mean duration of surfacings shorter when the aircraft was at 305 m than when it was at 457 or 610 m. Considering all 7 such experiments in 1981-83, only mean blow interval has been significantly different depending on aircraft altitude (lower mean at lower altitude, $p<0.001$). During experiments in 1983, the frequency of pre-dive flexes was also reduced when the aircraft was at 305 m. No reactions to the two helicopter overflights were detected, but conditions were not favorable for detailed behavioral observations.

In general, sensitivity of bowheads to aircraft seems to vary with season, whale activity, and perhaps water depth. Bowheads seem more sensitive to aircraft than are other species of whales.

The one boat disturbance experiment in 1983 employed 'Sequel', the same 12.5-m boat used in 1981 and 1982. Results were similar to those from previous boat disturbance trials. Bowheads began to orient away when the boat was within 4 km. They swam rapidly away from the track of the oncoming boat as it came closer. Both blow intervals and durations of surfacing were reduced ($p<0.05$) when the boat was within 4 km. As in 1980-82, reactions to the boat were stronger than to any other type of disturbance tested.

We observed bowheads in the presence of noise from seismic vessels on four days in 1983. One controlled test of reactions to a single 40 in^3 airgun was done in 1983, replicating two similar tests in 1981. In 1983, bowheads 26-99 km from full-scale seismic vessels or 3-4 km from the single airgun exhibited normal activities. There was no evidence that they moved away from the noise sources. Received levels of seismic or airgun noise were, at 18 m depth, ~107 to at least 138 dB//1 μPa in 1983. Levels received by whales at the surface would have been a few dB lower. Spectral and temporal characteristics of noise received from the one airgun were similar to those from more distant seismic ships.

The 1980-82 results suggested that seismic noise may have subtle effects on surfacing and respiration behavior of bowheads. However, the 1983 results did not confirm that any behavioral variable is affected consistently by seismic or airgun noise. When all opportunistic and experimental data from 1980-83 were pooled, surface and dive times, number of blows per surfacing, and blow intervals did not differ significantly in the presence and absence of seismic or airgun noise. Considering only the three airgun tests, mean blow interval was longer with airgun noise ($p<0.01$). Mean surface time and mean number of blows per surfacing were slightly lower in the presence of airgun noise during each airgun experiment, but the overall trends were not statistically significant. We conclude that noise from distant seismic ships (> 6 km away, received level <160 dB) has no pronounced effect on overt behavior of bowheads despite the high levels of seismic noise occurring to ranges far beyond 6 km. Experiments are needed to determine if subtle effects occur at ranges >6 km, or if pronounced reactions occur when seismic vessels are <6 km away.

There was no drilling from artificial islands in the Canadian Beaufort Sea during our 1983 field season, but 4-5 drillships were working. There were very few bowheads in the main industrial area in August 1983. We saw no bowheads closer than 12 km from a drillship in 1983, but industry personnel reported one bowhead ~3.7 km from a drillship. Bowheads have been seen closer to drillships in previous years.

Two drillship noise playback experiments were completed successfully in 1983, replicating two similar tests in 1982. Drillship noise levels received by the whales during the 1983 tests were 112 dB//1 μPa in the 10-1000 Hz band; such levels occur ~5 km from the actual drillship. As in 1982, calling rate decreased and bowheads tended to orient away from the playback site during playbacks. However, some whales did not orient away, and the dispersal was not nearly as rapid or consistent as occurs when a boat approaches. Aside from calls and orientation, other behaviors did not change in any consistent manner during drillship playbacks.

In 1980, bowheads frequently were seen <5 km from a dredging operation. In 1983, 1-2 bowheads were seen within a few kilometres of the same suction dredge for >2 days. We also conducted one playback experiment using noise from that dredge. No noticeable change in general activities occurred during the playback. Bowheads were slightly more likely to orient away from the playback site during the playback than during control periods. This trend was consistent with results from drilling noise playbacks, but was of marginal statistical significance. No other behavioral variables differed significantly during playback and control periods.

Overall, the behavior of bowheads can be affected markedly (but temporarily) by the close approach of ships or aircraft. Reactions to industrial activities that continue for hours or days, such as seismic exploration, drilling and suction dredging, are less obvious. Bowheads sometimes occur close enough to drillships, dredges and especially seismic boats to be exposed to considerable industrial noise. When seen near these ongoing operations, bowheads are not swimming consistently away. However, playback experiments showed a weak tendency for bowheads to orient away from sources of drillship or dredge noise when this noise first became evident. Whether whales that remain near industrial operations are subject to stress or other negative effects cannot be determined from short-term behavioral observations. The possibility of long-term displacement is examined in a different section of this report.

Characteristics of Waterborne Industrial Noise, 1983

The report with the above title (Greene 1984) documents the underwater sounds to which bowhead whales were exposed during the experiments and observations summarized above. Corresponding results from 1980-81 and from 1982 were reported by Greene (1982, 1983). The report also includes analyses of noise from various industrial sources recorded when no bowheads were nearby. A new feature of the 1983 results was simultaneous recordings of noise at two or more depths in the water column.

Underwater industrial noises in the Canadian Beaufort Sea were recorded in August 1983 in support of a study of the behavior of bowhead whales near actual and simulated oil industry activities. Bowheads are believed to be more likely to react to underwater sounds than to other stimuli associated with industrial activities. 1983 was the fourth year of research, which has always been in August. Sounds were again recorded via two systems: (1) sonobuoys dropped and monitored from the aircraft used for behavioral observations, and (2) hydrophones suspended beneath a sparbuoy drifting near a boat. In 1983, the boat system included hydrophones deployed at depths of 3, 9 and 18 m. This permitted us to compare ambient noise, noise from aircraft, and noise from in-water sources as received simultaneously at three depths. Unless otherwise noted, levels quoted below were at 9 or 18 m depth.

The ambient noise data revealed that very low levels of background noise sometimes occur in the Beaufort Sea. The lowest levels observed in 1983, about 0-10 dB below the 'Knudsen sea state zero' curve, were recorded in water 12 m deep with the hydrophone on the bottom. At frequencies below about 20 Hz, noise levels were greater at depth 3 m than at 9 or 18 m. The greater levels at 3 m probably represented hydrostatic pressure variations due to surface waves. At higher frequencies there was no apparent distinction in levels at the three depths.

Measurements of aircraft noise in 1983 included a Sikorsky 61 helicopter and the Twin Otter and Islander fixed-wing aircraft used for behavioral observations. For a large helicopter, the Sikorsky 61 appeared relatively quiet, although it did not pass directly over our hydrophones. Its strongest tone, at 102 Hz, was 95 dB//1 μPa during a pass at altitude 152 m. The strongest tone from a Bell 212 helicopter at that altitude in 1981 was 109 dB at 20 Hz. A Twin Otter at altitude 457 m, circling at reduced power, produced an 82 Hz tone of level 100 dB. All of these values are averages over 4 s.

The Islander flew over the hydrophones at several altitudes and two power settings. Received noise levels were less with circling than with cruise power, less at high than at low altitudes, and less at 9 or 18 m depth than at 3 m depth. Differences were a few dB in each case. Also, in shallow water (15 m) the Islander sometimes could be heard continuously as it made a circle of radius about 2 km. In deeper water, aircraft noise is detectable in the water for only a brief period when the aircraft is almost directly overhead.

Boat noise recorded in 1983 included the survey boat 'Arctic Sounder' (anchored; generators only), the crewboat 'Imperial Sarpik' underway at high speed, and the project's chartered boat 'Sequel'. As expected, 'Arctic Sounder' was relatively quiet, with tones from the generators dominating its sound spectrum. 'Imperial Sarpik' was noisy, with a dominant tone at 195 Hz (100 dB level at range 2.8 km). 'Sequel' showed a strong family of tones, evidently originating from its shaft rotation rate and possibly caused by a damaged propeller blade; we did not observe these tones in 1981 or 1982.

The geophysical survey ship 'Canmar Teal', recorded while underway at range 4.6 km, showed strong tones at 52, 291 and 301 Hz. The received level of the 52 Hz tone was 85, 96 and 99 dB at hydrophone depths 3, 9 and 18 m, respectively, making 'Teal' potentially as noisy as 'Sarpik'. These noises were from the ship itself, not the seismic gear. The hopper dredge "Cornelius Zanen' underway at ranges from 2.4 to 7 km provided noise levels from 127 to 100 dB in the 20-500 Hz band. This large vessel produced noise levels comparable to those of other large vessels we have studied.

Most seismic survey signals analyzed in 1983 were recorded via sonobuoys, which can overload and distort with pressure levels as low as 124 dB, depending on frequency and type of sonobuoy. However, received signal levels from sources 26-80 km away varied without strong dependence on range, indicating that other factors (e.g. water depth, properties of the ocean bottom) strongly affect signal strength at these distances.

Seismic signals from 'Canmar Teal' at ranges 3 to 10.4 km were received via hydrophones at depths 3, 9 and 18 m. 'Teal' was using a small array of three airguns of total volume 5.2 L (320 in^3). The signal at 3 m was generally 4 to 10 dB less than that at 9 m. Levels at 9 and 18 m were not consistently different. This depth effect was consistent with that for boat noise; the shallow hydrophone received lower sound levels. In contrast, the shallow hydrophone received the highest level of aircraft noise.

Noise from three dredges was recorded while they were dredging in 1983. The noise from 'Beaver Mackenzie' was different than it had been during measurements in 1980 and 1981; the signals were weaker and the characteristic tones were missing. This dredge has evidently been modified to some extent since 1981. Hopper dredge 'Cornelius Zanen' picking up a load at Ukalerk radiated noise at levels comparable to those from a similar dredge, 'Geopotes X', measured in 1982. The 10-500 Hz band levels usually were between 140 and 145 dB//1 μPa for ranges from 0.63 to 1.19 km. The suction hopper dredge 'Aquarius', moored in place at Nerlerk and transferring sand from the bottom to construct a berm, did not radiate as much noise, but neither was it underway. At range 0.2 km, its level in the 20-500 Hz band was 139 dB//1μPa at depth 3 m, 143 dB at depth 9 m and 140 dB at depth 18 m. For ranges from 0.20 to 14.8 km, the relationship between received levels and range followed cylindrical spreading at all three hydrophone depths, with additional linear losses of 0.82 dB/km for depth 3 m, 0.43 dB/km for depth 9 m and 0.27 dB/km for depth 18 m.

The noise levels from the Kadluk construction site were about the same when recorded at ranges 0.93, 1.8, and 3.8 km. At depth 3 m the levels were close to 114 dB and at 9 m the levels were close to 117 dB in the 40-1000 Hz band. About 9 h passed between the times of recording at the 3.8 and 1.8 ranges, and no doubt the activities changed. At the 0.93 km range the noise levels varied considerably. To avoid noise from a work boat nearby, we chose a quiet time to analyze.

Distribution of Bowheads and Industrial Activity, 1983

The report with this title (Richardson, Norton and Evans 1984a) summarizes the distribution of bowheads summering in the eastern Beaufort Sea in 1983 relative to the distribution of industrial activities. Results are compared with a corresponding analysis of data from 1980-82 (Richardson et al. 1983a).

Methods. — Sightings of bowheads during this and other studies conducted in the Canadian Beaufort Sea from 1 August to 10 September 1983 are compiled here onto a series of maps by 10-d periods. Survey routes are also shown on these maps. For each 10-d period, we include a map showing the sites of offshore drilling, dredging, etc., along with the approximate number of boat trips along each route. Additional maps show locations of seismic lines and low-energy sounding, helicopter traffic, and ice conditions.

We use the phrase 'main industrial area' to refer to the region off the Mackenzie Delta where there is island construction, drilling, dredging, and intensive boat and helicopter traffic. Seismic exploration occurs over a wider area, and noise from distant seismic exploration is detectable over a still wider area.

Results in 1983. -- In 1983, as in 1982, most bowheads remained outside the main industrial area. In early August, bowheads were found far offshore just east of the Alaska-Yukon border and far north of Herschel Island. These whales were far outside the main industrial area, but were exposed to noise from distant seismic exploration. There were only a few sightings in more easterly parts of the Beaufort Sea.

In mid and late August, there was a dense concentration of several hundred bowheads, most if not all subadults, in shallow water along the Yukon coast southeast of Herschel Island. These whales were not exposed to much industrial activity. In mid and late August there were also some bowheads in shallow water in the main industrial area, plus a few far offshore near the Alaska-Yukon border. In addition, during late August bowheads were widely dispersed off Cape Bathurst and the Tuktoyaktuk Peninsula, mainly outside the industrial area.

In early September, there were many widely dispersed whales off the Tuktoyaktuk Peninsula, outside the main industrial area but probably exposed to distant seismic noise. Whales had left the Yukon coast by 6 September, and few were present in the main industrial area.

Discussion. -- Qualitatively, bowhead numbers in the main industrial area in 1980-83 were 'many, some, very few and few', respectively. We consider the difference between 1982 (very few) and 1983 (few) to be insignificant. Thus, the trend for reduced utilization of the main industrial area identified from the 1980-82 data continued in 1983.

Intense offshore industrial activity began in the central part of the main industrial area in 1976. In that area, limited data on bowheads were obtained in 1976-79. Bowheads were numerous there in the summers of 1976 and 1977, not numerous in 1978 or 1979, very numerous in 1980, less so in 1981, and not numerous in 1982 or 1983. The reappearance of many whales in 1980, after being scarce for two years, makes it questionable whether the trend toward reduced utilization of the main industrial area was attributable to industrial activity. However, the intensity of offshore industrial activities has increased gradually since 1976, and industry may have begun to affect bowhead distribution since 1980.

In 1980-83, seismic exploration occurred over much of the Canadian Beaufort Sea -- both within and beyond the main industrial area. Numerous bowheads were in areas with seismic exploration in 1980-82. Fewer bowheads were in such areas in 1983, but many whales were apparently exposed to noise from distant seismic vessels. There was a possible trend for reduced numbers of bowheads in areas where they were exposed to intense seismic noise in previous years, but there were important exceptions to this trend.

Bowhead distribution in summer may or may not be influenced by industrial activities, but some whales still do enter the main industrial area and other areas with seismic exploration. Aside from possible industrial effects, bowhead movements probably depend strongly on the distribution and abundance of zooplankton. Until zooplankton dynamics and resultant effects on bowheads are better understood, it will be difficult to assess whether changes in bowhead distribution are partly in response to industrial activities.

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NORMAL BEHAVIOR OF BOWHEADS, 1983*

By

Bernd Würsig[1], Eleanor M. Dorsey[2], W. John Richardson[3],
Christopher W. Clark[4], Roger Payne[2] and Randall S. Wells[5]

[1] Moss Landing Marine Laboratories
P.O. Box 223
Moss Landing, CA 95039

[2] Center for Long Term Research
Weston Road
Lincoln, MA 01773

[3] LGL Ltd., environmental research associates
44 Eglinton Ave. W.
Toronto, Ont. M4R 1A1, Canada

[4] Rockefeller University Field Research Center
Tyrrel Rd., Millbrook, NY 12545

[5] Joseph M. Long Marine Laboratory
University of California
Santa Cruz, CA 95064

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* Würsig, B., E.M. Dorsey, W.J. Richardson, C.W. Clark, R. Payne and R.S. Wells. 1984. Normal behavior of bowheads, 1983. p. 23-99 In: W.J. Richardson (ed.), Behavior, disturbance responses and distribution of bowhead whales *Balaena mysticetus* in the eastern Beaufort Sea, 1983. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. 361 p.

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ABSTRACT

Behavior of bowhead whales was observed from an aircraft during 15 of 28 flights in the period 1 August to 1 September 1983, mainly near shore in the Beaufort Sea between Herschel Island (Yukon Terr.) and Richards Island (Northwest Terr.), Canada. Detailed behavioral observations were made while we circled over whales for 38.4 h. Bowheads were 'presumably undisturbed' during 37.0% of the observation time (14.2 h), and these observations of 'normal behavior' are described in the present report. This represents the fourth consecutive year of detailed behavioral observations of bowhead whales in the eastern Beaufort Sea in summer. Methods were similar during all four years.

During most flights in 1983, bowheads were observed near shore in water 5-35 m deep. Whales dove for brief periods, socialized often, and--at least after mid August--spent time skim-feeding at the surface or apparently feeding near the bottom. These behaviors were somewhat similar to behaviors seen in shallow water in 1980 and 1981. Behavior in 1983 differed from that in 1982, when whales spent most time apparently feeding in the water column in water >100 m deep.

Social interactions--nudges, pushes, chases, and close proximity--were observed at a rate similar to that in 1981, less than that in 1980, and greater than that in 1982. The rate of social activity in 1983 up to and including 18 August was higher than after this date. This decrease in late August was consistent with data from 1980 and 1981 (with too little information on socializing in 1982 for analysis). There was no consistent relationship between rate of socializing and depth of water. As in previous years, socializing whales tended to turn while at the surface more frequently than did non-socializing whales. We observed no apparent mating in 1983. However, during one flight groups of whales interacted with each other by rolling and nudging in a fashion similar to that seen in mating groups of bowhead whales in spring and southern right whales in winter. On 31 August, two whales repeatedly slapped each other with their pectoral flippers and flukes, and this observation represented the most obviously aggressive interaction we have noted in four seasons.

We saw 347 underwater blows in 1983, including both 'presumably undisturbed' and 'potentially disturbed' whales. The rate of underwater blowing was positively correlated with the rate of socializing. This suggests that underwater blows are in some manner linked to social behavior. However, we do not know whether underwater blows represent aggression, as believed in southern right whales, or whether they have some other function.

Aerial activity occurred sporadically, and included brief bouts of tailslaps, flipper slaps, and/or breaches. However, on 22 August, we observed two longer bouts lasting about 12 min and 75 min. The latter was the longest uninterrupted bout of aerial activity seen in four years of observations.

As in earlier years, some whales were recognizable by distinctive features such as unusual white pigmentation, or scars and marks on the back. This allowed us to identify individuals for up to several hours. We obtained no known resightings on different days. In 1983, few whales near shore had distinctive white chin patches or patches of white on the tail or tail stock, and a sample of about 20 of these whales that we measured via photogrammetry were only 7-12 m long. Thus, most whales near shore were yearlings and older subadults.

The mean blow interval for presumably undisturbed non-calves in 1983 was 17.0 ± s.d. 13.49 s, n = 866, which was significantly higher than combined data for 1980-1982. Number of blows per surfacing and duration of surfacing were significantly correlated, as in previous years. Mean number of blows per surfacing for non-calves was 3.2 ± s.d. 2.37 blows, n = 229; and mean surface time for non-calves was 1.05 ± 1.484 min, n = 248. These values were much lower than those for 1982, but not significantly lower than those for 1980 and 1981. The mean dive time for non-calves was 1.88 ± 2.357 min, n = 140, shorter than in any of the three previous years.

Several factors were related to surfacing-respiration-dive characteristics. Durations of surfacings and number of blows per surfacing were longer for socializing whales than for non-socializing whales. Blow intervals of skim-feeding whales averaged more than twice as long as for non-feeding whales. Mean duration of surfacing, number of blows per surfacing, and proportion of time at the surface were higher in skim-feeders than in others, while mean duration of dives was slightly lower for skim-feeders than for others. Blow rates, however, were approximately equal for skim-feeders and other whales.

Only 4 or 5 calves were seen in 1983, all in water >1000 m deep on 7 August. Two calves interacted at the surface for at least 5 min. This represents our only observation in four years of apparent play between calves. One apparent subadult associated with a mother-calf pair for at least 40 min. Because we sighted calves only in deep water far north of Herschel Island and not with the many small whales close to shore in 1983, we surmise that the population was at least partially segregated into (1) mature animals, including females and calves, far offshore and perhaps in other areas not searched by us, and (2) subadult whales near the Yukon shore.

Sounds of bowheads were analyzed from 33.7 h of sonobuoy recordings (11.0 h from presumably undisturbed whales). The types of sounds recorded were no different from previous years, and, as in previous years, the majority of sounds (85%) were tonal, frequency modulated calls lasting 1-2 s. Most loud pulsive calls were heard during socializing, consistent with results from 1980-1982. Blow sounds were associated with periods of much underwater blowing, and slap sounds occurred during periods with aerial behavior, especially on 22 August.

We have observed considerable year-to-year variation in the distribution and behavior of bowhead whales from 1980 to 1983. Aside from the aforementioned relationship between activities and water depth, no consistently repeating pattern is discernible. A consideration of year-to-year variations in the distribution and behavior of other cetaceans demonstrates that variations in distribution and abundance of prey species may often be responsible.

INTRODUCTION

This study was a continuation of research on normal, undisturbed behavior of the bowhead whale, Balaena mysticetus, summering in the eastern Beaufort Sea. Results from the summers of 1980, 1981 and 1982 were described by Würsig et al. (1982, 1983). As in 1980-82, the observations of bowhead behavior in the summer of 1983 were part of a broader analysis of the potential effects on these whales of offshore oil and gas exploration and development in the Beaufort Sea. Results from previous summers showed that bowhead behavior differs among years. Thus, to interpret the 1983 studies of the possible effects of industrial activities on behavior, it was necessary to examine normal behavior during the same season. The other tasks in 1983 were studies of the responses of bowheads to various offshore industrial activities (Richardson et al. 1984b), studies of the characteristics of waterborne industrial noise (Greene 1984), and an analysis of the distribution of summering bowheads in relation to industrial activity (Richardson et al. 1984a). For reviews of previously existing knowledge of the behavior of bowhead whales, see Fraker and Richardson (1980) and Würsig et al. (1982, 1983).

Objectives

The two main objectives of the 'Normal Behavior' task for 1983 were (1) to provide a description of presumably undisturbed behavior immediately prior to experimental disturbance trials, against which the results of these trials could be compared, and (2) to provide additional information about normal behavior, with emphasis on aspects not studied in detail in 1980-82.

Additional pre-disturbance 'control' information was considered essential because the 1980-82 studies showed that bowhead behavior is quite variable. To recognize and evaluate disturbed behavior, it is desirable to obtain observations of 'presumably undisturbed' behavior from the same individual whales immediately before and after the period of potential disturbance.

The second main objective of the normal behavior study in 1983 was, in periods when studies of disturbance effects were not possible, to observe aspects of 'presumably undisturbed' behavior that had not been studied in sufficient detail in previous years, or that showed significant variation from year to year. Because of the variability in behavior among years, it is instructive to assess behavior of presumably undisturbed whales during several years. An understanding of year to year variability is important in assessing whether whales might be more susceptible to disturbance in some situations or years than others.

Approach

The general approach in 1983 was very similar to that in 1980-82. 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, Design and Summary, 1983' (Richardson and Würsig 1984). As in 1982, no shore-based observations were collected in 1983.

Field work extended from 1 August to 1 September 1983 and, as in previous years, was based at Tuktoyaktuk, Northwest Territories (Fig. 1), a coastal settlement with facilities for personnel, aircraft and boats. Observations of behavior were conducted from the air and from a boat. Aircraft-based observers had the advantage of high mobility and a good vantage point and consequently collected most of the behavioral data. Sonobuoys were dropped from the aircraft to allow us to hear and record bowhead sounds; boat-based observers had hydrophones for this purpose. Sonobuoys also allowed us to determine when industrial noises were present in the water. Observations of bowheads in the presence of industrial noise may not represent undisturbed behavior and have been excluded from this 'Normal Behavior' section.

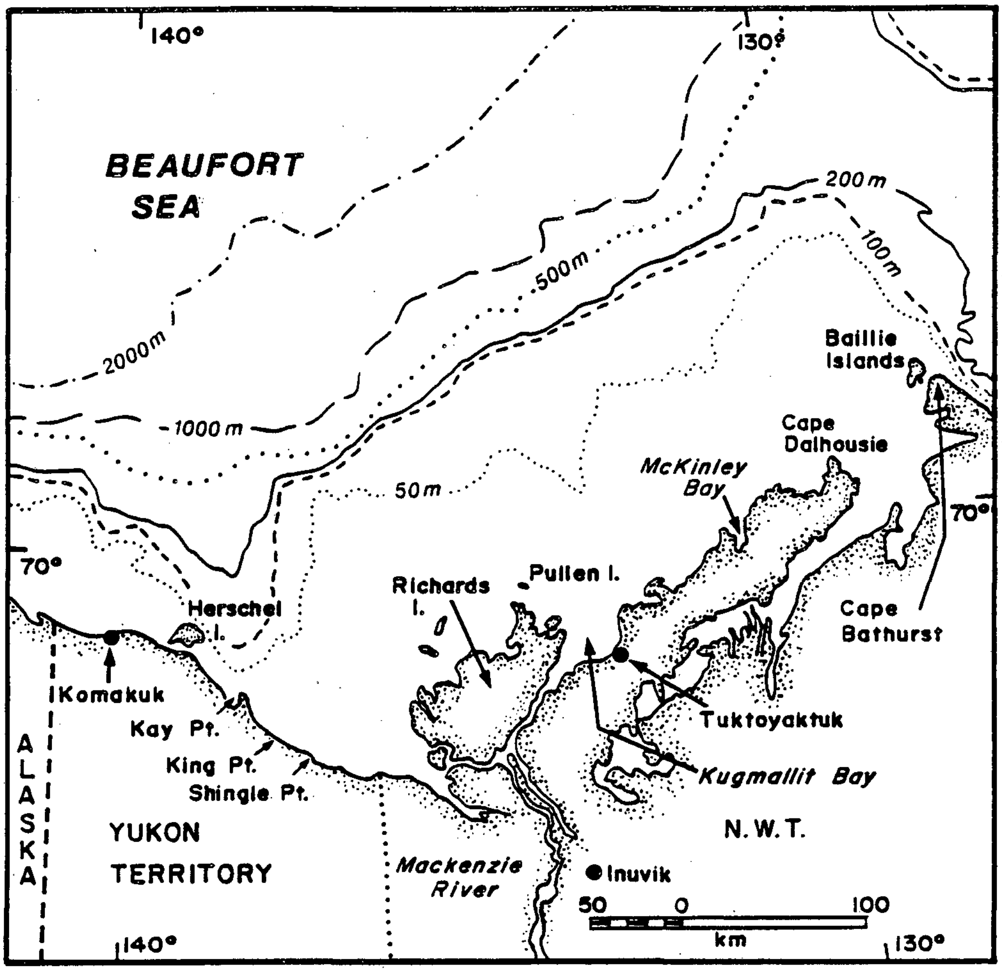

FIGURE 1. The eastern Beaufort Sea region, showing bathymetry and locations mentioned in the text.

METHODS AND DATA BASE

Aerial Observations

As in the previous two years, most of the behavioral observations were made from the air. From 1-12 August, when the aircraft that we normally use was unavailable, we used a de Havilland Series 300 Twin Otter aircraft. The Twin Otter has two turboprop engines, high wing configuration, low stall speed, and bubble windows. After 12 August, when most of the 1983 observations were made, we used the same Britten-Norman Islander aircraft that was used for behavioral observations in 1980-1982. The Islander has two piston engines, high wing configuration, and low stall speed. Both aircraft were equipped with radar altimeters and Very Low Frequency (VLF) navigation systems, which continuously computed position, usually within 1.8 km of the real position. 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 1984). A hand-held color video camera (Sony HVC-2000) connected to a portable videocassette recorder (Sony SL-2000) was used through the side windows 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 to record waterborne sounds.

In 1983 we made 28 flights between 1 August and 1 September, and we made behavioral observations of bowheads during 15 of the flights. Except when the aircraft required maintenance, we flew twice per day whenever weather conditions permitted. However, as in previous years, inclement weather precluded useful observations on about half of the days. Each flight typically lasted 4 to 5.5 hours. Total flight duration in 1983 was 113.6 hours, and we observed bowhead whales for 38.4 hours.

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. In previous years, bowheads rarely appeared to be disturbed by the aircraft when it remained at or above 457 m (see Richardson et al. 1983b). However, whales observed on 17 August 1983 appeared to be disturbed by the aircraft circling at 457 m, so subsequent observations were from 610 m whenever conditions allowed (Richardson et al. 1984b). The greater sensitivity to aircraft in 1983 may have been partly attributable to the shallow water at most observation locations; lateral underwater propagation of aircraft noise is greater in shallow than in deep water (Greene 1984).

The aircraft crew 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. As in earlier years, 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, recorded 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 circle on the left side of the aircraft, 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 13 types:

1. Location of sighting (and therefore water depth);
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 swimming speed of each whale;
6. Distances between individuals (estimated in adult whale lengths);
7. Duration 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;
11. Underwater blow (releasing a large burst of bubbles underwater);
12. Aerial activity: breaches, tailslaps, flipper slaps, lunges, rolls;
13. Type of dive: fluke out, peduncle arch, pre-dive flex.

Water depths were determined by consulting Canadian Hydrographic Service chart #7650 (1980 printing) and Dome Petroleum Ltd. chart E-BFT-100-03. Descriptions of the behaviors mentioned above appear later in this report. In 1983, we looked for but did not see several other types of behavior recorded in earlier years: play with surface debris or logs, probable mating, and probable nursing.

The 15 flights during which we made behavioral observations in 1983 are summarized in Table 1. The distributions of behavioral observations by flight, hour of day, and water depth are presented in Figures 2, 3 and 4. Most observations in 1983 were in shallow water, comparable to water depths where bowheads were observed in 1980 and very different from depths where whales were seen in 1982.

The observation times in Figures 2, 3 and 4 are divided into periods with and without known sources of potential man-made disturbance in the observation areas. 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 the periods of potential disturbance are described separately in the 'Disturbance' section (Richardson et al. 1984b). 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. and if no vessels or other industrial activities were close enough to create detectable waterborne sound. Some observations were collected when

Table 1. A summary of aerial observations of bowhead behavior, 1983.

	Time Observing Bowheads					Est. Number of Whales				
Date	Start MDT	Stop MDT	Total hours	Distance From Shore & Location	Depth of Water (m)	Adults	Calves	Est. Area Under Obs. (km^2)	Potential Disturbance (and distance from it)	General Behavior
7 Aug Flt #1	16:52	17:33	0.7	109 km NNE of Herschel I.	950	2	0	20	Seismic (79 km)	Unknown
	17:40	18:59	1.3	128 km NNE of Herschel I.	1370	6	4	20	Seismic, which stopped at 18:50 (95-99 km)	Two calves interacting actively; trio of mother, calf, and subadult travelling rapidly
7 Aug Flt #2	21:44	22:13	0.5	217 km N of Herschel I.	1670	1	1	1	None	Slow travel by lone mother-calf pair, in small ice-free area
9 Aug	13:34	17:03	3.5	41 km N of Herschel I.	190	12	0	10	Seismic started at 13:47 (57 km)	Much socializing
15 Aug	10:31	11:32	1.0	28 km NE of King Point	12	6	0	10	None	Lone whales moving medium speed
	12:04	13:21	1.3	43 km NE of King Point	7	6	0	10	None	Some socializing
	13:46	14:28	0.7	13 km N of King Point	30	14	0	10	None	Some socializing, but most whales >5 whale lengths apart
17 Aug Flt #1	09:53	10:09	0.3	61 km NE of King Point	11	2	0	10	Aircraft <457 m overhead	Unknown
	11:35	13:12	1.6	7 km E of Kay Point	30	15	0	10	Aircraft <457 m for first hour	Much socializing
17 Aug Flt #2	18:59	22:01	3.0	2-5 km E and NE of Kay Pt.	16-25	7-10	0	30	Drillship playback experiment (0.7-3 km)	Mostly lone whales with unknown behavior
18 Aug Flt #1	11:27	12:36	1.2	16 km NNW of Kay Point	20	9	0	30	None	Very little socializing
	12:36	14:38	2.0	17 km NNW of Kay Point	12	13	0	30	Drillship playback experiment (0.4-1.7 km)	Some socializing, some lone whales
18 Aug Flt #2	19:55	21:41	1.8	6 km NNW of Kay Point	10	7-20	0	25	Boat experiment (9 to <1 km)	Socializing, repeated tail slaps by one whale

Continued...

Table 1. Concluded.

Time Observing Bowheads						Est. Number of Whales				
Date	Start MDT	Stop MDT	Total hours	Distance From Shore & Location	Depth of Water (m)	Adults	Calves	Est. Area Under Obs. (km^2)	Potential Disturbance (and distance from it)	General Behavior
22 Aug Flt #1	10:04	11:34	1.5	13 km ENE of King Point	18	3-6	0	40	Aircraft experiment	Aerial activity, possible bottom feeding, otherwise unknown
22 Aug Flt #2	13:46	18:03	4.3	19 km N of King Point	32	9-11	0	15	Drillship playback (0.8-1.8 km) and aircraft experiments	Mostly lone whales with little or no forward movement, but some brief socializing
26 Aug Flt #1	16:15	18:45	2.5	1-2 km off King Point	8	5-8	0	10	Boat approaching (6 to 1.5 km)	Skim-feeding
26 Aug Flt #2	20:58	23:24	2.4	2-3 km N of King Point	18	8	0	10	Dredge playback experiment (0.5-2.0 km)	Lone whales hanging at surface between long dives; occasional socializing
28 Aug	09:38	10:02	0.4	26 km ENE of King Point	5	4	0	10	None	Travelling medium speed
	10:04	13:40	3.6	17 km E and ENE of King Point	11-12	6	0	25	Airgun expt. (3-4 km)	Some bottom feeding; lone whales moving medium speed
31 Aug	14:19	17:15	2.9	82 km WNW of Pullen I.	19	6	0	10	Seismic (52 km)	Bottom feeding and some socializing
1 Sept	15:26	15:29	0.1	82 km WNW of Pullen I.	19	4	0	20	Seismic (31 km) and aircraft	Unknown
	16:28	18:17	1.8	82 km WNW of Pullen I.	19	5	0	20	Seismic (26-30 km) and aircraft	Some bottom feeding, some socializing, long dives

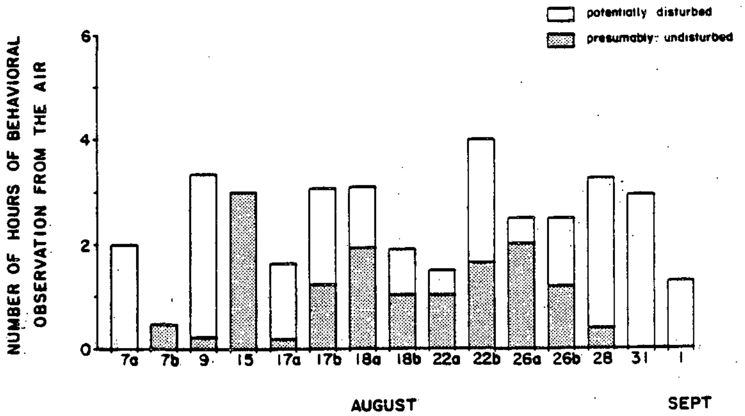

FIGURE 2. Distribution of behavioral observation time from the air by flight in 1983. Time spent over presumably undisturbed whales is distinguished from time spent over potentially disturbed whales.

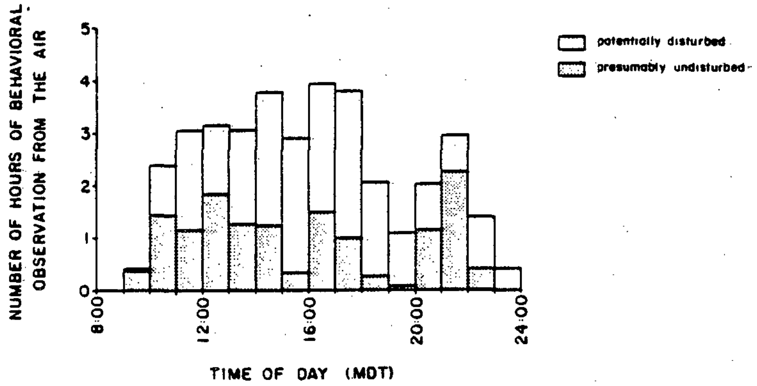

FIGURE 3. Hourly distribution of behavioral observation time from the air, 7 August - 1 September 1983. Time spent over presumably undisturbed whales is distinguished from time spent over potentially disturbed whales.

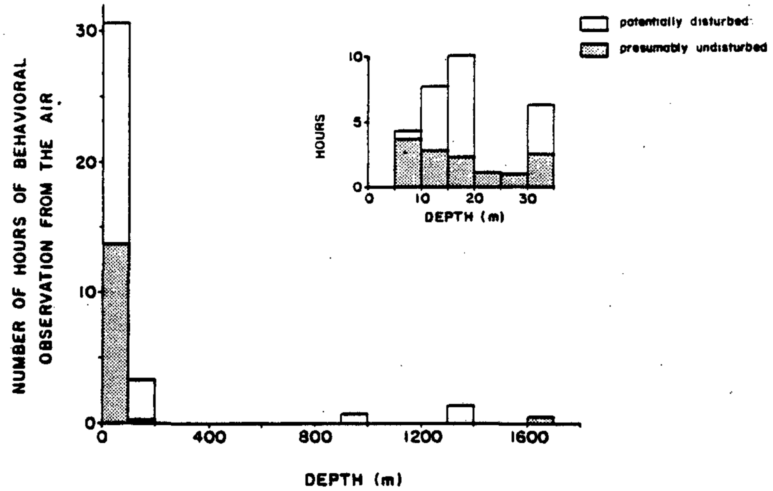

FIGURE 4. Distribution of behavioral observation time from the air by depth of water in 1983. Time spent over presumably undisturbed whales is distinguished from time spent over potentially disturbed whales. All behavioral observations at depths <100 m were actually at depths <35 m.

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 engines off for at least 30 min. In 1983, of 38.4 h spent observing bowheads, 14.2 h (37.0%) were 'presumably undisturbed'.

The 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, these transcribed observations 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 now contain the following:

Year	Surfacing Records	Dive Records	Total Records
1980	562	223	785
1981	778	223	1001
1982	312	141	453
1983	1401	242	1643

These counts include both presumably undisturbed and potentially disturbed whales. In 1983, there were 545 surfacing and 154 dive records from presumably undisturbed periods.

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

Boat-Based Observations

Behavioral observations were again made from the 12.5 m diesel vessel 'Sequel' based at Tuktoyaktuk. The 'Sequel' cruised at about 13-15 km/h and required about 24 h to travel from Tuktoyaktuk to the usual locations of bowheads in 1983. The boat crew consisted of two biologists making behavioral observations, one acoustician to obtain underwater recordings and to play back industrial noise, and the captain.

RESULTS AND DISCUSSION

Descriptions of Behaviors

Descriptions of behaviors have been given in detail in earlier reports (Würsig et al. 1982, 1983), and we here summarize only those descriptions necessary for an understanding of our analyses of the 1983 results. Unless otherwise noted, the descriptions apply specifically to undisturbed bowheads exclusive of calves.

Surface-Dive Sequence

The respirations of bowhead whales are usually not spaced at even intervals but are clustered together in groups. The groups of breaths are separated by longer periods without breathing ('apneas'). Behavior at the surface during these breath groups depends upon overall activity. When 'making a passage', i.e. migrating or otherwise travelling for relatively long distances, the breaths in breath groups are separated by short dives. These short dives have been called series dives (Rugh and Cubbage 1980) to distinguish them from the long dives between breath groups, called sounding dives. When bowheads are not travelling, but are engaged in other behavior like feeding or socializing, they usually remain at the surface between breaths in a breath group, and dive for varying lengths of time between these surfacings. Most of the bowheads we observed in this study behaved in the latter manner. As a result, we discuss only one type of dive, the sounding dive.

On occasions when a whale made short dives between respirations, we did not consider its surfacing to be interrupted if it remained visible from the air. Observers working from low vantage points on ice, shore or a boat, however, would treat such an occasion differently, because the whale would usually be out of their sight as soon as it went below the surface. Thus the definition of a surfacing and a dive used in this study is in part a function of our aerial vantage point. We consider a shallow and brief submergence during which the whale is in sight from the air as part of a surfacing. This is necessary because our aerial vantage point does not always allow us to determine whether a whale is at the surface or slightly below it. One must use caution when comparing data collected from different vantage points.

Blow

A blow is an exhalation of air by a whale. It can occur either above or below the surface. Most surface blows were probably immediately followed by an inhalation. Underwater blows occurred with high frequency in 1983, and are discussed later.

Pre-dive Flex

The pre-dive flex is a distinctive concave bending of the back, with the back about 0.5 to 1 m below the level of the rostrum tip and the tail. Rostrum and tail usually lift slightly out of water during the flex, and considerable whitewater may be created at these two points. The whale then straightens its back and lies momentarily still before arching the back convexly as it begins to pitch 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. (All ± figures quoted in the text are ± 1 standard deviation.)

During 1983, pre-dive flexes occurred in presumably undisturbed non-calves before 43 of 277 dives (15.5%), and there did not appear to be a change in the frequency of pre-dive flexes over the study period. Furthermore, there was no significant difference between the durations of dives that were and were not preceded by pre-dive flexes. This situation was different from that of 1982, when pre-dive flexes occurred more often later in the month of August than earlier, and when dives following pre-dive flexes were about twice as long as those without pre-dive flexes (Würsig et al. 1983). The differences may be related to the lower incidence of pre-dive flexes in 1983, the very shallow water, and the generally short dives.

There was no significant difference in the durations of surfacings with and without pre-dive flexes in 1983, but there were significantly more blows during surfacings with pre-dive flexes (surfacings with flex: mean = 5.1 ±

s.d. 2.77 blows, n = 32; surfacings without flex: mean = 2.9 ± 2.19 blows, n = 177; t = 4.89, df = 207, $p<0.001$).

Dive

During the dive, the whale arches (makes its body 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 dive is steep, the tail is usually raised above the surface; if not, the tail may remain below or just touch the surface. Seventy-six of 390 dives (19.5%) of presumably undisturbed non-calves were preceded by raised flukes. Of the 43 dives preceded by a flex and the 76 dives preceded by raised flukes, 18 were preceded by both actions. These two pre-dive behaviors occurred together more frequently than would be expected by chance (chi-square = 9.51, $p<0.005$, df = 1), just as they did in 1982.

There was no difference in the duration of dives depending on whether or not flukes were raised preceding the dive. However, the mean duration of surfacings was shorter when ended by raised flukes (mean = 0.80 ± s.d. 0.492 min, n = 40) than when flukes were not raised (mean = 1.11 ± 1.614 min, n = 204; t' = 2.27, $p<0.05$). [In this report, t' represents the Student's t statistic calculated assuming unequal population variances.] Surfacings preceding raised flukes also showed shorter blow intervals (mean = 13.97 ± 8.434 s, n = 144) than surfacings not ending in raised flukes (mean = 17.97 ± 14.796 s, n = 614; t = 3.13, df = 756, $p<0.002$). There was no significant difference in number of blows during surfacings with and without raised flukes.

Social Interactions

Behavior was termed social when whales (1) appeared to be pushing, nudging, chasing each other, or otherwise interacting, or (2) were within one-half body length of one another but not obviously interacting. In the 1983 analysis, we coded and analyzed these two situations separately, with the realization that animals merely in close proximity may not be socializing to the same degree as those that are physically interacting. We also recognize that whales far apart could have been interacting by sound, but we have no way of evaluating such communication at present, and therefore do not include it as socializing here. Details of socializing are given in a later section.

Recognition of Individuals

Except in their first few months of life, bowhead whales are usually black or dark gray with white chin patches. Many individuals also have smaller white dots or lines (some of these presumably are scars) on their backs, and a variable amount of light skin on the tail peduncle and on the tail itself. Davis et al. (1982, 1983) showed that clear photographs allow for identification of many individuals.

In 1983, as in past years, we were at times able to identify whales by sight, within an observation flight, from distinctive chin patch shapes or white marks on the back or tail, and we were then able to determine dive durations for these individuals. However, few of the whales encountered close to shore in 1983 had extensive patches of white pigmentation on the chin or at the fluke/caudal region. Davis et al. (1983) showed that small juvenile whales tend to have fewer such white marks than do large adult whales. We saw few white marks and almost no calves amongst the whales close to shore and had the general impression that most of those whales were smaller than adults previously seen. Hence, we believe that these whales were mostly subadults. This impression was confirmed in a small sample of whales that we measured by the vertical photography method of Davis et al. (1983). The segregation by age is discussed below in the section on mothers and calves.

Respiration and Surfacing 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 and surfacing behavior under undisturbed conditions is a prerequisite for interpretation of disturbance responses.

The measurement of each of these four quantities depends upon how a surfacing and a dive are defined. In all four years of this study, a surfacing was defined as the period of time when a whale was at the surface or visible just below the surface. Thus, the shallow 'dives' that often occurred for a few seconds between blows were not counted as dives or as interruptions of a surfacing or of a blow interval. 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 because the water was usually more turbid than in previous years, which meant that whales were less easily visible while underwater. Periods of submergence lasting less than 15 s were not counted as dives unless before submerging the whale lifted its flukes out of the water, arched strongly or performed a pre-dive flex. The ability to see a whale just under the surface of the water depends not only on the clarity of water, but also on the vantage point from which the observations are made; thus, some of our definitions would not be appropriate for observations from shore, ice, or a boat.

Calves, because of their small size, are much more difficult to observe than are adults when just under the surface of the water. We have analysed the few observations of calves in 1983 separately and will present that analysis after consideration of the non-calf observations. The remainder of this section considers undisturbed whales excluding calves, i.e. all adults and subadults that we observed.

In 1983, we measured the blow interval, number of blows per surfacing, surface time, and dive time for undisturbed non-calves 866, 229, 248, and 140 times, respectively. Figures 5 through 8 present the frequency distributions of these observations. Figures 9 to 12 present the mean value for each of these four variables during each of our observation flights. Table 2 summarizes each of these variables for 1983.

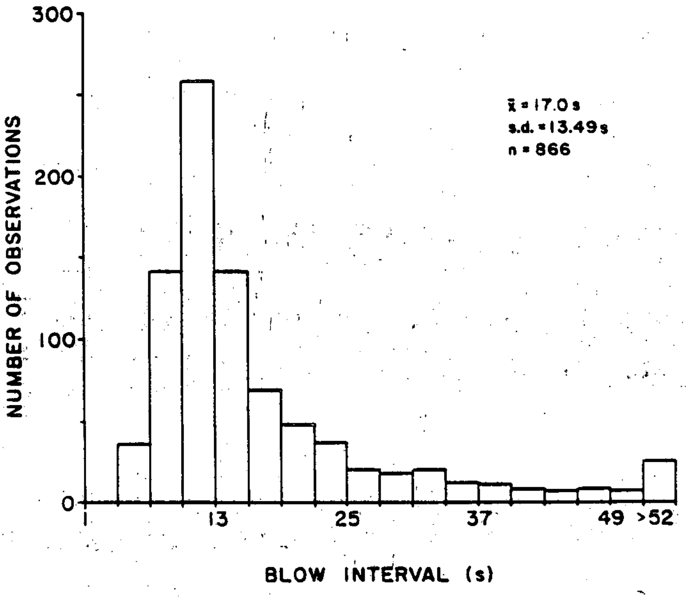

FIGURE 5. Frequency distribution of blow intervals for presumably undisturbed non-calves in 1983.

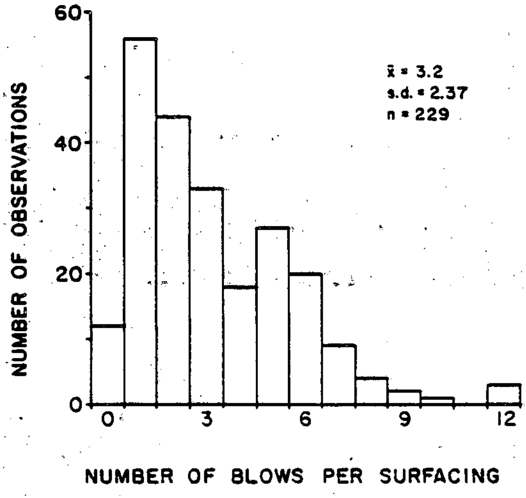

FIGURE 6. Frequency distribution of number of blows per surfacing for presumably undisturbed non-calves in 1983.

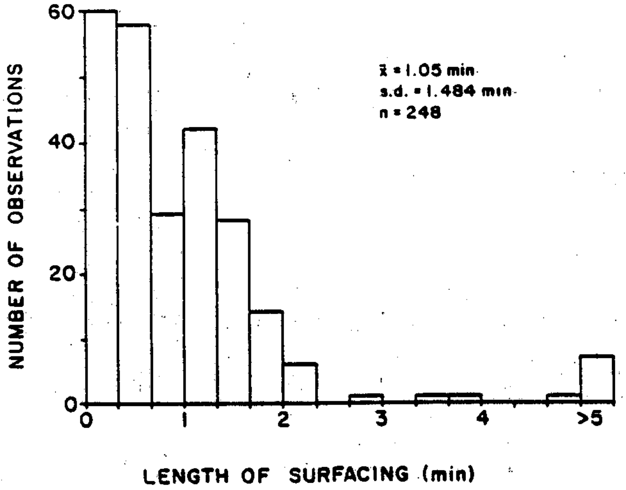

FIGURE 7. Frequency distribution of length of surfacing for presumably undisturbed non-calves in 1983.

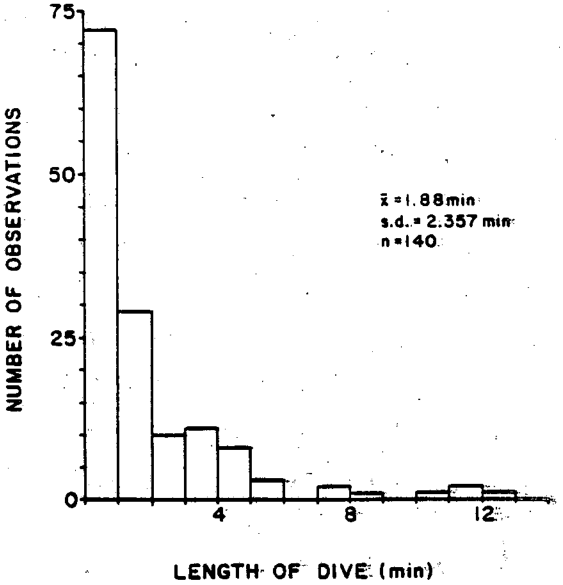

FIGURE 8. Frequency distribution of length of dive for presumably undisturbed non-calves in 1983.

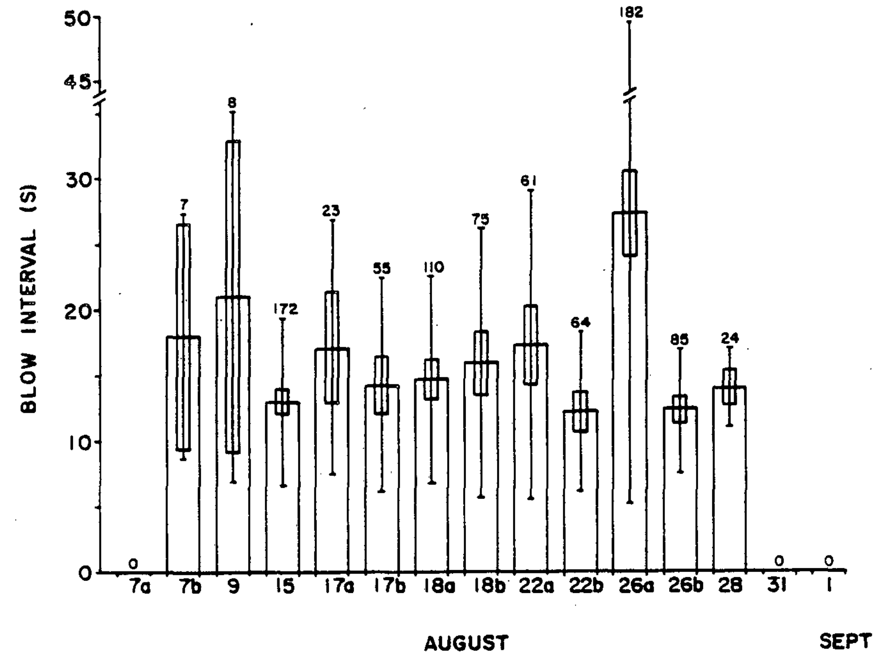

FIGURE 9. Mean interval between blows for presumably undisturbed non-calves during each observation flight in 1983. The vertical line in each column represents one standard deviation on either side of the mean, the box represents the 95% confidence interval for the mean, and the number at the top is the sample size.

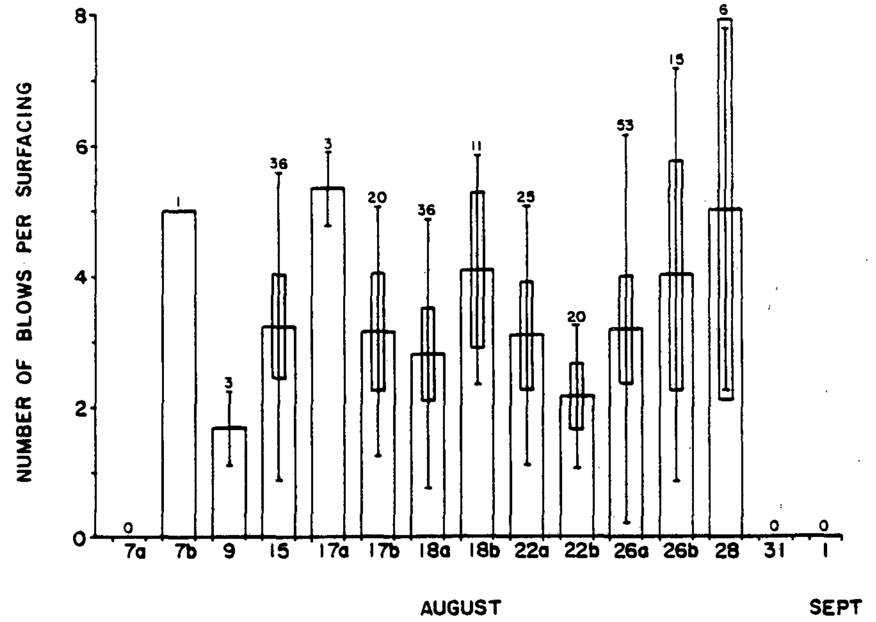

FIGURE 10. Mean number of blows per surfacing for presumably undisturbed non-calves during each observation flight in 1983. Presentation as in Fig. 9.

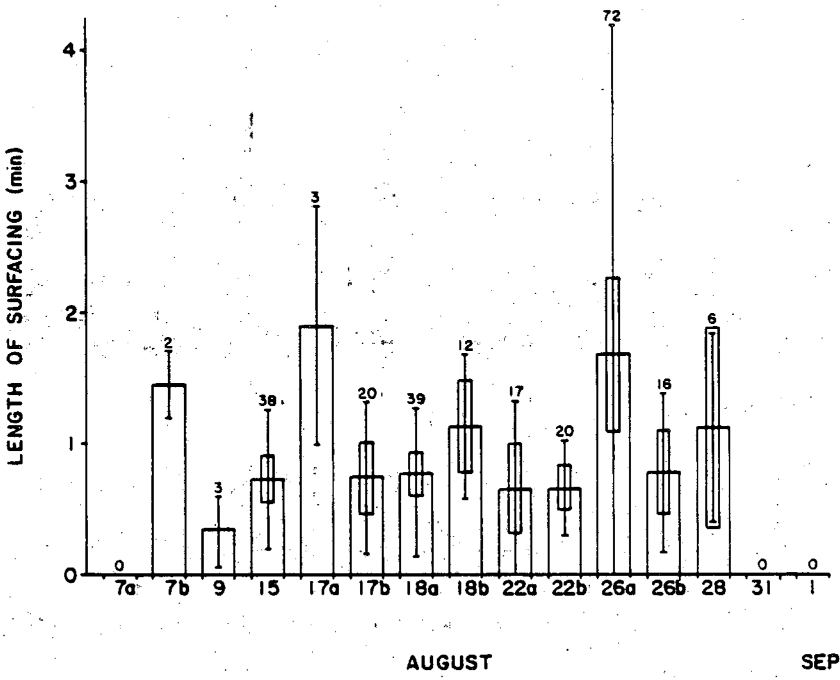

FIGURE 11. Mean length of surfacing for presumably undisturbed non-calves during each observation flight in 1983. Presentation as in Fig. 9.

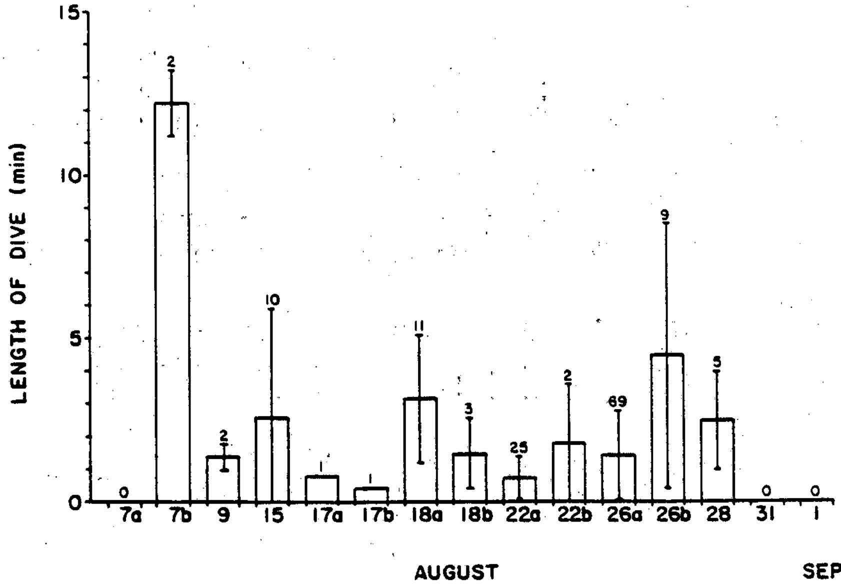

FIGURE 12. Mean length of dive for presumably undisturbed non-calves during each observation flight in 1983. The vertical line in each column represents one standard deviation on either side of the mean, and the number at the top is the sample size.

Table 2. Summary statistics for the principal surfacing, respiration and dive variables in presumably undisturbed bowheads in 1983. 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	17.0	13.49	866	3.2	2.37	229	1.05	1.484	248	1.88	2.357	140
Calves	11.5	5.07	4	1.1	0.90	7	0.36	0.478	8	1.98	2.720	7
Adults with calf	18.0	9.29	7	5.0	-	1	1.45	0.259	2	12.18	1.002	2
All others	17.0	13.52	859	3.2	2.37	228	1.05	1.489	246	1.73	2.015	138
Skim-feeding whales	31.7	23.79	120	6.9	3.99	10	5.20	3.636	15	0.93	1.001	16
Bottom-feeding whales	11.6	6.02	5	6.0	-	1	-	-	0	0.40	-	1
Non-feeding whales	14.5	8.95	651	2.9	2.17	199	0.76	0.586	212	2.03	2.510	115
Socializing whales, type #1[a]	15.6	9.70	85	4.3	2.46	13	1.22	0.711	14	0.62	0.235	3
Socializing whales, type #2[b]	10.7	5.02	15	3.0	-	1	1.11	0.474	3	2.34	2.722	2
Non-socializing whales	17.3	13.92	766	3.1	2.36	215	1.04	1.527	231	1.90	2.381	135
Non-socializing whales, excluding skim-feeders	14.6	8.90	646	2.9	2.10	205	0.75	0.584	216	2.03	2.482	119
Single whales excluding skim-feeders	14.0	7.89	521	3.0	2.15	151	0.71	0.540	151	2.12	2.466	74
Whales in groups excluding skim-feeders	15.9	10.93	225	3.0	2.12	68	0.91	0.683	82	1.83	2.451	50
Depth (m) <16	19.4	16.58	459	3.4	2.66	111	1.32	1.934	131	1.69	1.757	87
16-50	14.0	7.71	392	3.0	2.07	114	0.75	0.568	112	1.83	2.456	49
101-250	21.0	14.13	8	1.7	0.58	3	0.34	0.275	3	1.36	0.389	2
>250	18.0	9.29	7	5.0	-	1	1.45	0.259	2	12.18	1.002	2

[a] Socializing by activity: touching, chasing, otherwise interacting.
[b] Socializing by proximity only: within 1/2 body length.

Blow Interval

The frequency distribution for blow intervals in 1983 (Fig. 5) was very similar to that obtained in all three previous years. However, in 1983 there was more variability between observation flights (Fig. 9) than in the previous years, when blow intervals were quite consistent from flight to flight. The overall mean blow interval for all undisturbed non-calves was significantly longer in 1983 (mean = 17.0 ± s.d. 13.49 s, n = 866, range 4-173 s) than in 1980, 1981, and 1982 combined (mean = 13.5 ± 8.46 s, n = 2822)(t' = 7.21, $p<<0.001$). As will be explained below, much of the variability in blow intervals within 1983 and much of the increase in mean blow interval over previous years can be attributed to a single flight, the first flight on 26 August (Fig. 9), when most of the whales were skim-feeding.

Blows per Surfacing and Duration of Surfacing

In spite of the increased variability in blow intervals in 1983 compared to previous years, the number of blows per surfacing and the duration of surfacing were again very highly correlated (Fig. 13), as they had been in each of the three previous years. Both of these variables were significantly lower in 1983 than in 1980-82 combined. The mean surface time for non-calves in 1980-82 was 1.3 ± s.d. 0.960 min (n = 368), whereas in 1983 it was 1.05 ± 1.484 min (n = 248, range = 0.03-13.17 min) (t' = 2.34, $0.01<p<0.02$). The mean number of blows per surfacing for non-calves in 1980-82 combined was 4.9 ± 3.61 blows (n = 322), whereas in 1983 it was 3.2 ± 2.37 blows (n = 229, range = 0-12 blows)(t' = 6.67, $p<0.001$). This latter difference is attributable mostly to the high value for number of blows per surfacing in 1982. The mean number of blows per surfacing in 1981 was almost identical to that in 1983, and there was no significant difference between the 1983 mean and the 1980-81 combined mean.

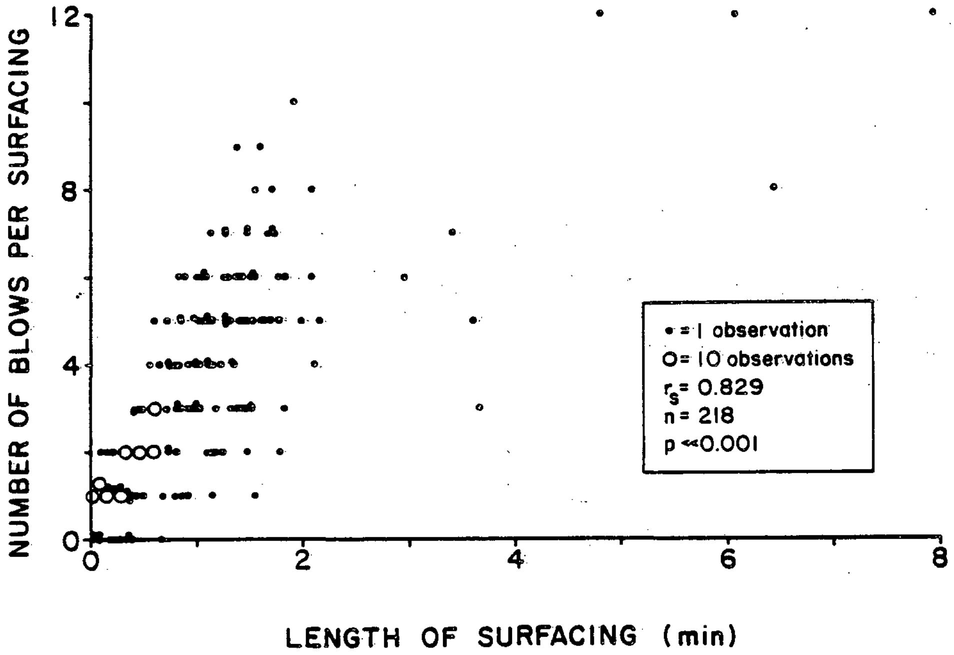

FIGURE 13. Correlation of number of blows per surfacing with length of that surfacing for presumably undisturbed non-calves in 1983. r_s is the Spearman rank correlation coefficient.

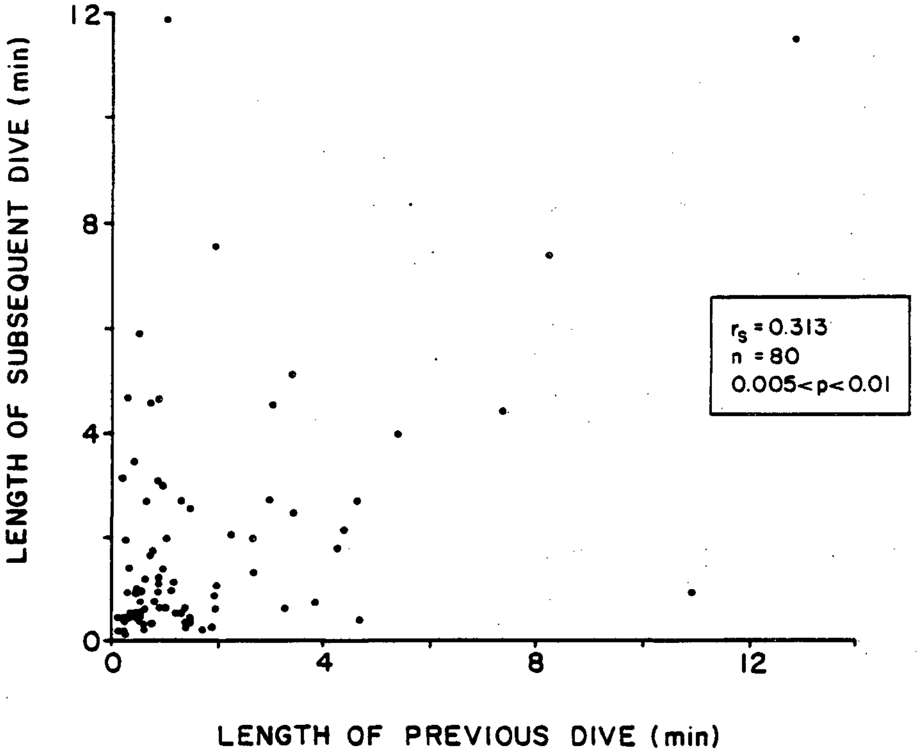

FIGURE 14. Correlation of length of dive subsequent to surfacing with length of dive previous to that surfacing for presumably undisturbed non-calves in 1983. r_s is the Spearman rank correlation coefficient.

Duration of Dives

Our estimates of mean dive duration are biased downward to a degree that has varied somewhat from year to year (Würsig et al. 1983). The reason for this bias is that it is more difficult to find and recognize a whale when it re-surfaces after a long dive than after a short dive. In 1982, the conditions for measuring durations of long dives were better than in previous years 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. Thus the mean dive duration in that year was probably less of an underestimate of the real mean duration than in 1980 and 1981. In 1983, there was again an especially strong sampling bias against long dives. We usually encountered whales in larger groups than in 1982, and most whales we circled in 1983 had few or no distinguishing marks.

The frequency distribution of dive times recorded in 1983 (Fig. 8) was strongly skewed toward short dives; 51% of those recorded were <1 min in duration. In this respect the frequency distribution for 1983 was much more similar to that for 1980 and 1981 (Würsig et al. 1982, Fig. 11) than to that for 1982 (Würsig et al. 1983, Fig. 7). The stronger sampling bias in 1980-81 and 1983 than in 1982 was partly responsible. However, we believe that the relative increase in short dives observed in 1983 as compared to 1982 was due also to an increase in the number of short dives made by the whales. As in past years, all statistical comparisons of dive times in 1983 were done non-parametrically.

The overall mean dive time for non-calves in 1983 was 1.88 ± s.d. 2.357 min (n = 140, range = 0.13-12.88 min). This was shorter than the mean dive time observed in any of the three previous years. In addition to a real increase in short dives and a strong sampling bias in favor of short dives in 1983, a third factor may have contributed to this low value: an increase in water turbidity compared to previous years. Most 1983 observations were of whales in shallow turbid water close to shore. This probably resulted in whales disappearing from sight while 1-2 m closer to the surface than in previous years. Some shallow submergences that would not have been considered dives in clearer water in earlier years might have been counted as dives in 1983.

As in previous years, the length of the dive before a surfacing was significantly correlated with the length of the dive after that surfacing (Fig. 14). This indicates that a whale tends to make a series of dives of similar length rather than alternating short and long dives. However, the correlation in 1983 was not as close as that in 1982 (Spearman rank correlation coefficient $r_s = 0.313$ vs. 0.695) perhaps partly because of the narrow range of dive times in 1983. The number of blows per surfacing in 1983 was significantly correlated with the length of the previous dive $r_s = 0.225$, df = 96, $0.02<p<0.05$) but not with the length of the subsequent dive ($r_s = 0.114$, df = 98, $p>0.2$). The length of surfacing was not significantly correlated with the length of either the previous dive ($r_s = 0.033$, df = 114, $p>0.50$) or the subsequent dive ($r_s = 0.101$, df = 108, $p>0.20$).

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). The resulting number of blows per minute is a function of the surface time, dive time, and number of blows per surfacing, and provides a variable that describes the respiratory activity of a whale during a longer period of time than any of the constituent variables considered separately. The mean blow rate for undisturbed non-calves in 1983 was 1.12 ± s.d. 0.709 blows/min (n = 70 blow rates by 32 whales, range = 0-2.82 blows/min). The 1983 value falls between the mean blow rates for 1982 (0.70 ± 0.470 blows/min, n = 25) and for 1980-81 (1.28 ± 1.140 blows/min, n = 43). Figure 15 presents the frequency distribution for blow rates in 1983.

Proportion of Time Visible from the Air

The proportion of time that a whale was visible from the air was calculated from all surfacings of known length in 1983 that were followed by dives of known length. As in 1982, we did not consider shallow submergences between blows to be dives. Figure 16 presents the frequency distribution of time visible from the air for presumably undisturbed non-calves in 1983. The mean proportion of time visible in 1983 was 0.41 ± s.d. 0.279 (n = 110

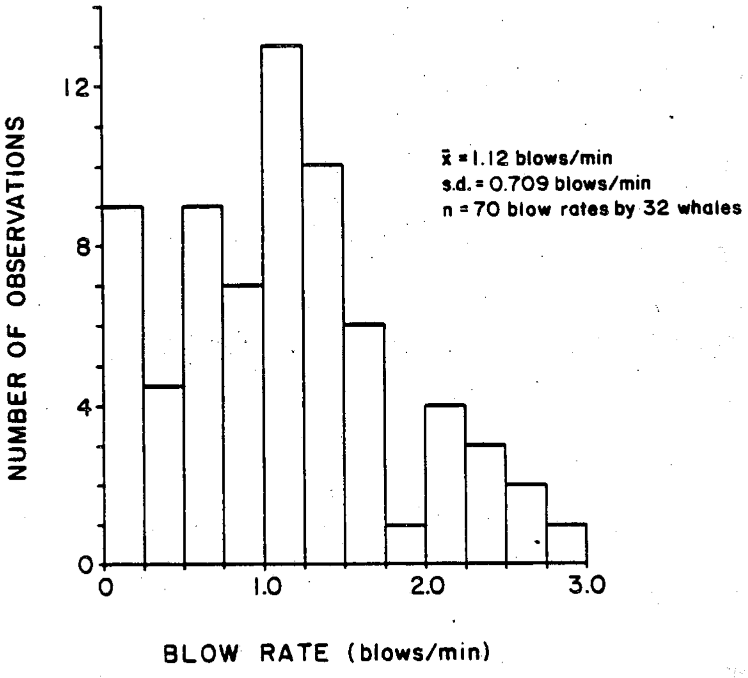

FIGURE 15. Frequency distribution of blow rates of presumably undisturbed non-calves in 1983.

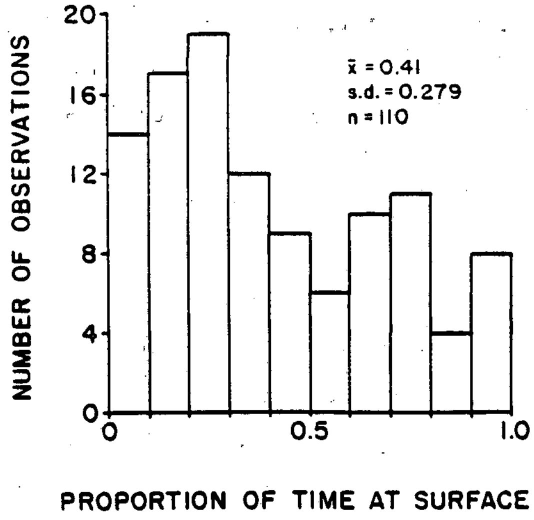

FIGURE 16. Frequency distribution of proportion of time visible from the air for presumably undisturbed non-calves in 1983.

surface-dive cycles, range = 0.007 - 0.969). This is significantly higher than the mean value obtained in 1982 (mean = 0.24 ± 0.170, n = 31) (t' = 4.20, $p<0.001$). As presented below, skim-feeding whales in 1983 had considerably higher values for proportion of time visible than other whales. Even if the skim-feeding whales are excluded, however, the 1983 mean proportion of time visible is still significantly higher than the 1982 value (1983 mean excluding skim-feeders = 0.35 ± 0.234, n = 95; t = 2.42, $0.01<p<0.02$).

Depth of Water

From 1980 through 1982 there was a progressive increase in the average distance from shore and the average depth of water at the locations where we observed bowheads. Most of the 1982 observations were in markedly deeper water than during 1980 or 1981. In 1982, mean values of the four primary surfacing, respiration and dive variables were higher than in 1980-81. Analyses of the data did not support the hypothesis that there was, within any one year, a positive correlation between depth of water and any of the four variables (Würsig et al. 1983). However, in no one year were whales observed regularly over a wide enough range of depths to allow a good test of the hypothesis that behavioral variables are related to water depth.

In 1983, most of the whales observed were very close to shore and were in water as shallow as in 1980, with just a few observations in water deeper than 35 m (Fig. 4). If depth has a major influence on the surfacing, respiration, and dive patterns of these whales, then we would expect the values for these variables in 1983 to have been lower than in 1982 and comparable to what we saw in 1980 and 1981. As explained above, this was true only for the length of surfacing. Blow intervals were considerably longer in 1983 than in any previous year or, if skim-feeding whales are excluded, were approximately equal to the 1982 mean for blow intervals. Number of blows per surfacing and dive time were both lower than in any previous year. This suggests again that factors other than depth of water determine how these whales dive, surface, and respire.

An analysis of the effect of depth of water within 1983 is not meaningful because of the highly skewed distribution of observation time with depth (Fig. 4). Sample sizes for the surfacing, respiration, and dive variables in water deeper than 50 m are extremely small; only two depth categories, <16 m and 16-50 m, have enough observations for statistical treatment (Table 2). Although both blow intervals and surface times were significantly longer in water <16 m than in water 16-50 m deep ($t' = 6.23$, $p<0.001$, and $t' = 3.22$, $0.001<p<0.01$, respectively), these differences are not evident if skim-feeding whales are excluded from analysis.

Time of Day

Figures 17 through 20 present the mean values for each of the four main respiration, surfacing, and dive variables in relation to time of day. Both blow intervals (Fig. 17) and surface times (Fig. 19) show an apparent peak at 16:00-19:00 Mountain Daylight Time (MDT). Of the 2.8 hours of observation within that time of day, however, over 70% were from the first flight of 26 August, when many whales were skim-feeding and when most of the skim-feeding observations in 1983 occurred. As discussed below, skim-feeding whales had considerably higher values for blow intervals and for surface times. The peaks in Figures 17 and 19 at 16:00-19:00 MDT were apparently not related to time of day, but rather to skim-feeding, our observations of which happened to be concentrated during that time of day.

Aside from those apparently spurious relationships, there were no clear relationships between any of the four variables and time of day. This result is consistent with our findings in 1980-1982 (Würsig et al. 1982, 1983).

Calves and Mothers

In 1983, we saw calves less frequently than in any of the three previous years, considering both presumably undisturbed and potentially disturbed periods (Table 3). There were just over one-third as many calf sightings in 1983 as in any preceding year, based on both the number of observation flights and the number of hours of observation time. The proportion of all

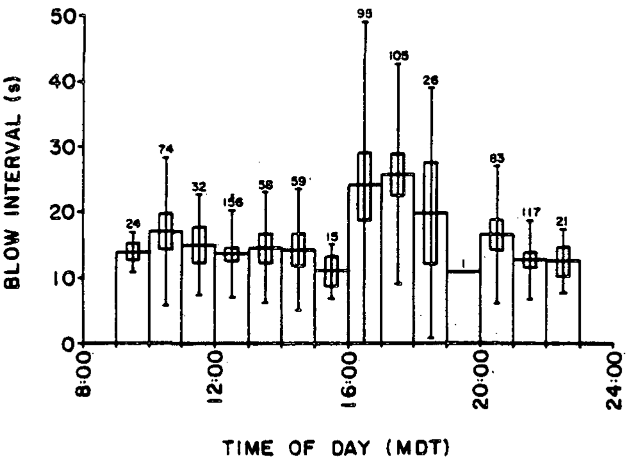

FIGURE 17. Mean interval between blows in relation to time of day for presumably undisturbed non-calves in 1983. Presentation as in Fig. 9.

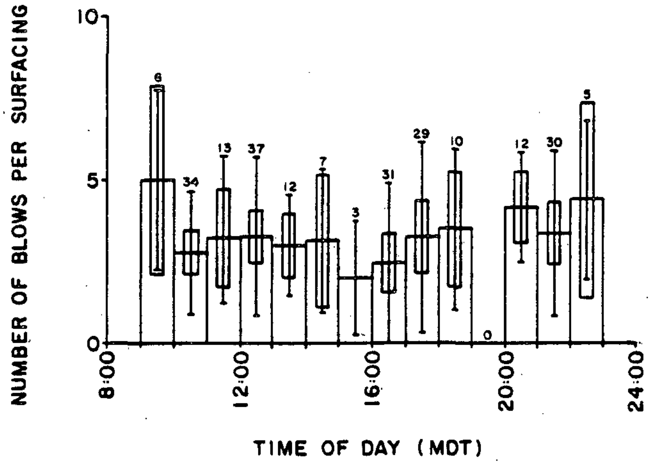

FIGURE 18. Mean number of blows per surfacing in relation to time of day for presumably undisturbed non-calves in 1983. Presentation as in Fig. 9.

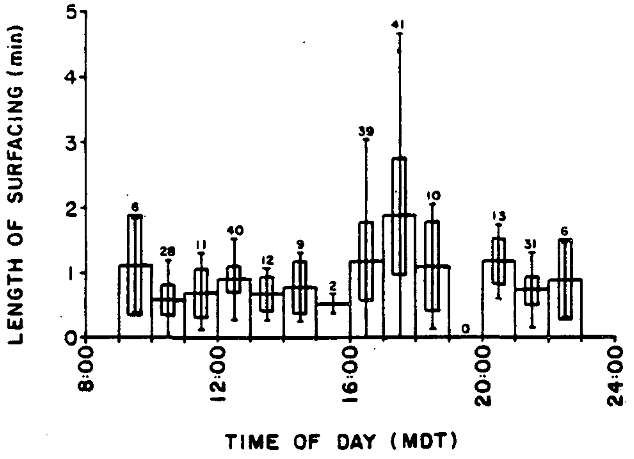

FIGURE 19. Mean length of surfacing in relation to time of day for presumably undisturbed non-calves in 1983. Presentation as in Fig. 9.

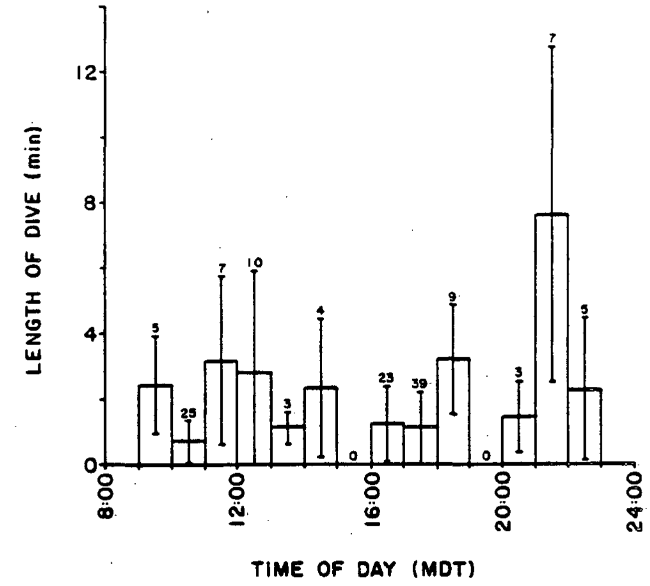

FIGURE 20. Mean length of dive in relation to time of day for presumably undisturbed non-calves in 1983. Presentation as in Fig. 12.

Table 3. Calf sightings and observation time in 1980-83. Both presumably undisturbed and potentially disturbed periods are included. The number of sightings of calves is an approximate count because multiple counts of the same calf were possible where the calf and its mother were not recognizable.

	1980	1981	1982	1983
Number of calf sightings	12	16	16	5
Number of flights*	14	18	14	15
Calf sightings per flight	0.86	0.89	1.14	0.33
Hours in plane over whales	30.4	30.8	36.5	38.4
Calf sightings per hour	0.39	0.52	0.44	0.13
Calf time at surface with mother (min)	20.4	17.5	63.1	8.6
Calf time at surface unaccompanied by mother (min)	1.6	12.7	38.2	11.5
Total calf time at surface (min)	22.0	30.2	101.3	20.1
% of calf surface time unaccompanied by mother	7.3%	42.1%	37.7%	57.2%
Whale-hours of observation at surface	10.03	14.98	10.95	17.91
Calf-hours of observation per whale-hour of observation	0.037	0.034	0.154	0.019
Calf time at surface per sighting (min)	1.57	1.89	6.33	4.02

* Only flights with behavioral observations considered.

whale-hours of observation at the surface that were of calves was lower in 1983 than in any previous year. The total length of time that calves were in sight at the surface in 1983 was slightly lower than the lowest previous value, in 1980, and calves were seen without an adult for a higher percent of the time than in any previous year. The length of time that calves were seen at the surface per sighting in 1983 was considerably higher than in 1980 or 1981, but not as high as in 1982.

Segregation of Bowheads by Age Class

The few calves seen during behavioral observations in 1983 were all sighted during the first two observation flights, both on August 7. These were the only two flights in 1983 that were far from shore and over very deep water; the calves were seen over depths of about 1370 m and 1670 m in areas with much ice. No other behavioral observations were made in water deeper than 190 m, and most of the other observations were of bowheads in water less than 30 m deep, very close to shore (Table 1). The bowheads observed near shore in 1983 appeared to be lacking not only calves but also whales with large white chin patches and white pigmentation on the tailstock and flukes. Davis et al. (1983) have shown that both types of white pigmentation occur more frequently on larger whales, suggesting that the white patches develop with age. Our impression in 1983 was that we were seeing mostly whales that were not fully grown, except during the two 7 August flights over deep water.

In 1983, we measured a limited number of whales using the photogrammetric technique developed by Davis et al. Sixteen whales photographed close to the Yukon coast near King Point on 26-27 August were 8-12 m long, and four or five whales WNW of Pullen Island on 1 September were 7-12 m long (W.R. Koski, LGL Ltd., unpubl. data). These lengths are typical of yearlings and other subadult whales; adults with calves are 13 m or more in length (Davis et al. 1983).

This suggests that the bowheads in the study area in 1983 were at least partially segregated by age into two groups — (1) fully mature animals including females with calves in deep water offshore, and perhaps also in other areas that we did not search, and (2) immature animals, probably of a variety of ages, but not including young of the year, in shallow water near the Yukon shore. Most of our observations were of the nearshore group because they were closer to our base at Tuktoyaktuk and provided dense concentrations of whales for observation and experiments (Richardson et al. 1983b).

Simultaneous with our study, Cubbage et al. (1984) measured a larger sample of whales over a wider area, although they obtained few measurements on the major concentration along the Yukon coast. Cubbage et al. also found that bowheads west of Tuktoyaktuk tended to be small (mostly <13 m). A higher proportion of those off the Tuktoyaktuk Peninsula were >13 m long, and almost all of those farther east in Franklin Bay and Amundsen Gulf were >13 m. In summary, we found that bowheads close to the Yukon coast were small, and Cubbage et al. (1984) found that there was a general trend for increasing size from west to east across the summer range.

In past years we have not had the impression that the bowheads we encountered were segregated by age to the same extent as in 1983. However, we have at times noted clumping of mother-calf sightings and of 'nondescript whale' sightings. Our ability to detect such segregation is weak, however, because we usually do not have length measurements for whales we observe. Davis et al. (1982, 1983) measured bowhead whales photogrammetrically in the eastern Beaufort Sea in the summers of 1981 and 1982. In both years they found geographic variation in the distribution of length classes over several hundred kilometres. In 1982 they also had evidence of temporal variation, on a scale of days or weeks, in the distribution of length classes within a single area.

Behavior of Mothers and Calves in 1983

In 1983, for the first time in this study, we observed interactions between two calves. More than half of the 'calf time at the surface unaccompanied by mother' (Table 3) consisted of a single 5-min observation of two calves interacting quite boisterously. This occurred in the presence of seismic noise during the first flight on 7 August. The two calves were about the same length, but one was distinctly darker than the other. While remaining within about a calf's length of each other, they rolled onto their sides or back, circled tightly as if chasing each other's tails, made slicing movements with their tails, and--while just under the surface--performed other boisterous movements that produced white water. During this 5-min period, an adult moved toward the calves from 12-15 adult lengths away. However, we did not see it join the calves. Toward the end of the period, when the first adult was still in sight, a second adult surfaced for 43 s within a half body length of the two calves. The calves continued interacting boisterously when the second adult appeared, but when the adult dove again, one of the calves dove 17 s later and did not reappear. The remaining calf apparently then stayed by itself for at least 13 min, tail slapping and rolling at the surface for part of that time. We did not observe this calf joining an adult.

Another behavior pattern that we saw for the first time in 1983 was the persistent association of a subadult with a mother-calf pair. During the first flight on 7 August, also in the presence of seismic noise, we encountered a recognizable trio consisting of a large whale with very large white chin patches, a light calf, and a darker whale of intermediate size. They maintained their positions relative to one another over several surfacings. In at least 5 of 6 surfacings observed in about 40 minutes, the subadult swam behind the adult, usually by about 1/2 body length, while the calf swam on the left side of the adult, either touching or within 1/2 body length.

All other sightings of calves in 1983 were of lone calves or adult-calf pairs, except for one group of a calf and two adults. We saw only one potential nursing dive in 1983, when a calf briefly submerged at its mother's side; the mother reacted by turning its body in such a way as to move its belly away from the calf. This may have been an attempt on the mother's part to forestall nursing.

Mothers and Calves Compared to Other Bowheads

Of the two flights when we encountered mothers and calves in 1983, only one (the second flight on 7 August) was during presumably undisturbed conditions. Our only observations during that flight were of a single mother-calf pair amongst ice pans, and we were able to obtain very few data (Table 2). Because of the small sample sizes, we will not discuss these data in detail. The two measured dives by undisturbed mothers were noticeably longer than for any other category of undisturbed bowhead in 1983, but they were in very deep water, about 1670 m. All other timed dives by undisturbed non-calves in 1983 were in water less than 35 m deep. We do not have enough data for mothers in 1983 in order to consider whether long dives occurred because they were mothers or because they were in deeper water, or for some other reason.

Feeding Behavior

During the four years of this study we have observed several types of feeding behavior. We have seen bowheads skim-feeding with open mouths at or just below the surface, sometimes in echelon formation. Feeding at or near the bottom has been indicated by whales surfacing with muddy water emanating from their mouths. And we have hypothesized feeding in the water column when whales made long dives interrupted by short surfacings with little forward motion and occasional defecation. Würsig et al. (1982) provide detailed descriptions of these behaviors.

During 1983, we saw no indications of feeding (except for 6 defecations on 15 and 17 August) until 22 August, when a whale that was aerially active for 75 min (see below) surfaced twice with mud pouring from its mouth. We observed much skim-feeding on 26 August, and more apparent bottom feeding on 28 and 31 August and 1 September. Skim-feeding occurred in 8 m depth, only several hundred metres from shore at King Point, Yukon. Apparent bottom feeding, on the other hand, occurred in water from 11 to 19 m deep, and from 11 km from shore (off King Point on 28 August) to about 82 km WNW of Pullen Island (on 31 August and 1 September). No skim-feeding whales seen in 1983 were in echelon formation. In 1983, dives were generally short, and we obtained no direct evidence that feeding in the water column took place.

Figure 21 and Table 2 present the surfacing, respiration and dive characteristics of **skim-feeding** and 'non-feeding' bowheads during presumably

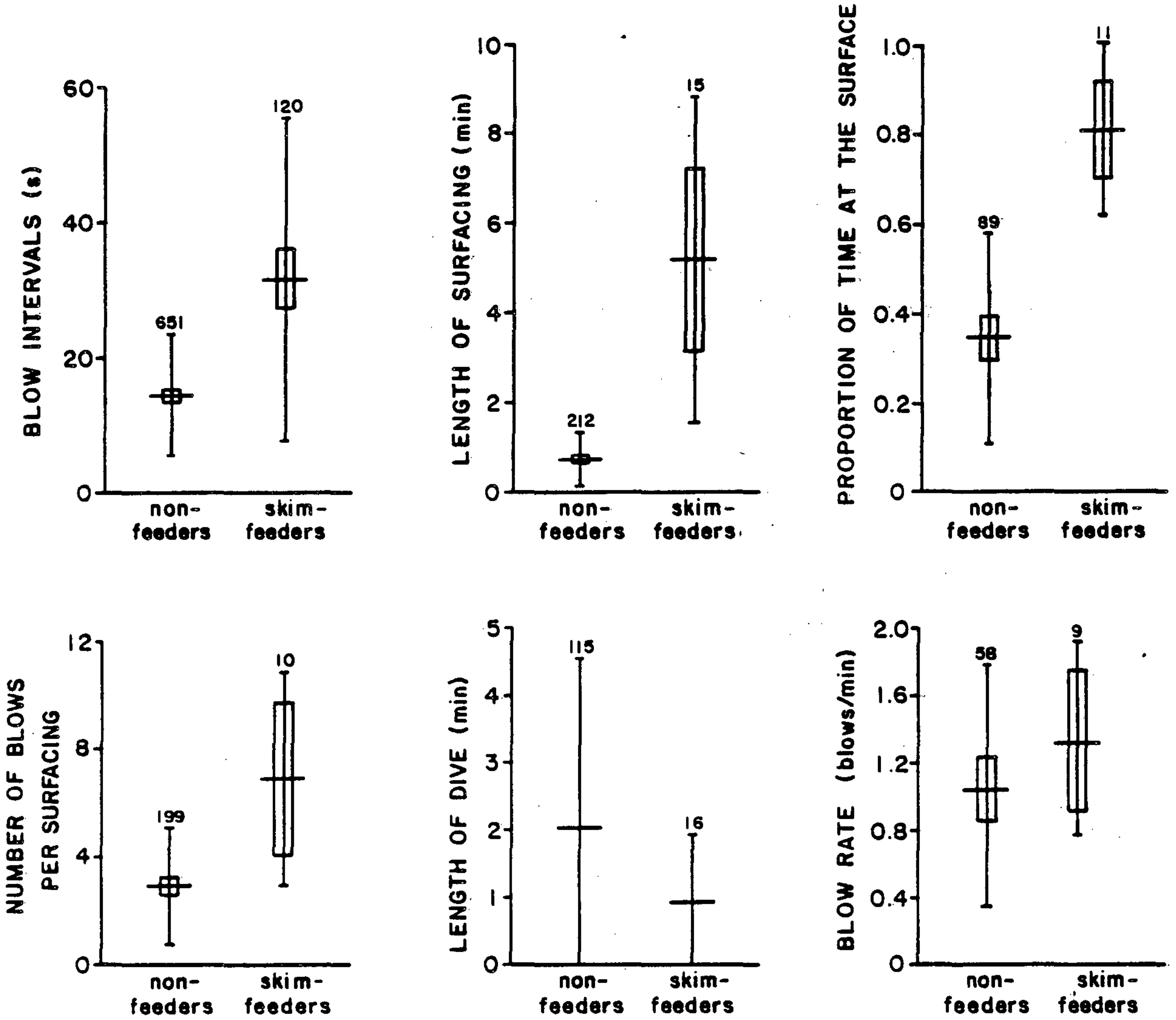

FIGURE 21. Comparison of respiration, surfacing and dive characteristics of skim feeding whales and non-feeding whales in 1983. Only presumably undisturbed non-calves are included.

undisturbed periods in 1983. The mean blow interval of skim-feeding whales was more than twice that of non-feeding whales ($t' = 7.82$, $p<<0.001$). Skim-feeding whales in 1983 had the longest mean blow interval yet observed for any category of whales during this study. In 1980-81, the mean blow interval for skim-feeding whales was also longer than that for 'non-feeders', but the difference was not statistically significant. In 1983, both the mean surface time and the mean number of blows per surfacing were significantly higher for skim-feeding whales ($t' = 4.72$, $p<0.001$, and $t' = 3.12$, $p<0.02$, respectively). Neither of these trends was evident in the quantitative data collected in previous years. (However, our previous data on skim-feeding whales were biased toward short surfacings. In 1981, we were unable to include several whales that skim-fed for several minutes, so long that we missed the beginning or the end of the surfacing. Thus the data collected in 1981 on surface times and number of blows per surfacing for skim-feeders were unrepresentatively low.) The mean dive time of skim-feeding whales in 1983 was lower than in non-feeding whales, but the difference was not statistically significant; a similar trend was evident in 1980-81.

In 1983, skim-feeding whales spent a significantly higher proportion of time at the surface than did whales that were not feeding (skim-feeding mean = 0.81 ± s.d. 0.195, n = 15; non-feeding mean = 0.35 ± 0.234, n = 89; $t = 7.26$, $p<0.001$). The mean value for skim-feeders may be biased upwards since we may have recognized skim-feeding more easily when animals stayed at the surface for long periods, but we do not feel that this bias was very strong. The blow rate was only slightly higher in skim-feeding whales (mean = 1.34 ± 0.557 blows/min, n = 9) than in non-feeding whales (mean = 1.06 ± 0.706 blows/min, n = 58), and the difference was not significant.

On 28 August 1983, while the bowheads under observation were potentially disturbed by a nearby boat, we observed a whale swimming along a windrow of debris. The whale surfaced with mud near its head, as if it had been bottom feeding like other whales that day. It then swam at medium speed in the drift line for all 35 s of its surfacing. During three subsequent surfacings the whale was progressively farther from the windrow. There was no indication that the whale's mouth was open or that it was feeding in the windrow, but we mention the incident because it was the first observation of such behavior in an adult whale. In 1982, we saw a calf play in a windrow of debris for over 12 min, and in that case, also, there was no indication of feeding.

The indications of **bottom feeding** in 1983 were the first we had observed since 1980. Mud was definitely seen to come directly from the mouths of bowheads during 19 surfacings in 1983, at times in considerable quantities. The only baleen whale known to feed on organisms that burrow into bottom sediment is the gray whale (Eschrichtius robustus), and it has been suggested that the relatively short, coarsely fringed baleen of that species is particularly adapted to such feeding. Bowhead whales, in contrast, have very long, very finely fringed baleen that would not suggest similar feeding strategies to those of gray whales. Nevertheless, the amount of mud that we have seen pouring from the mouths of bowhead whales, both in 1980 and in 1983, appeared to be too great to have been picked up incidentally while feeding on water column organisms near the bottom. We are forced to conclude that at times bowhead whales must plow up the bottom considerably while collecting epibenthic prey or perhaps while taking inbenthic prey, as gray whales do. We have suggested this earlier (Würsig et al. 1982), but we wish to emphasize this unexpected conclusion. By all indications, bowhead whales feed in this manner only rarely.

Although apparent bottom feeding occurred in 1983 on 28 and 31 August and on 1 September, underwater industrial sounds were detectable near the whales most of the time. As a result, the samples of surfacing, respiration and dive data for undisturbed bottom feeding whales were too small for meaningful analysis (Table 2).

Social Behavior

Behavior was termed social when whales (1) appeared to be pushing, nudging, chasing each other, or otherwise interacting, or (2) were within one-half body length of one another but not noticeably interacting. The first category is definitely social behavior, while the second category is less clearly so, since those whales may simply be in close proximity without interacting. We found that blow intervals were significantly longer for type

#1 than for type #2 socializing whales in 1983 (t' = 2.93, $p<0.01$) (see Table 2); for other variables, sample sizes from #2 socializing were too small to allow comparisons. Because #1 socializing represents more active socializing, and because there is some evidence that surfacing-dive-respiration characteristics may not be similar for the two categories, we separated the two socializing categories in most tabulations of 1983 data, and we considered only #1 socializing in the statistical analyses. Our analysis of socializing in 1983 is, therefore, slightly different from the analyses of 1980-82 data, when the two socializing categories were not separated. When we compared 1983 results with those from 1980-82, however, we included both types of socializing in order for the data to be comparable.

As in past years, interactions between mothers and calves and between whales skim-feeding in close proximity were not included in the analysis of social interactions. Whales may, of course, communicate by sound and thus may interact over far greater distances than those described here. Since we cannot verify whether acoustic communication is occurring between any particular whales, we restrict our definition of socializing to visible behavior. Because groups of whales usually could not be reidentified positively from one dive to the next, we treated observations of social behavior at intervals of >5 min as independent for the purpose of counting number of interactions. Conversely, we did not score social behavior in the same area more than once in 5 min unless we could distinguish groups.

Frequency of Socializing

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). The overall socializing rate for presumably undisturbed whales was much higher in 1983 than in 1982, and was comparable to that in 1981 (Table 4). In 1983, when both undisturbed and potentially disturbed whales are considered, at least some social activity was observed on every day with behavioral observations. More instances of #1 socializing occurred up to and including 18 August than after that date (Fig. 22). The rate of #1 socializing up to and including 18 August was 4.13

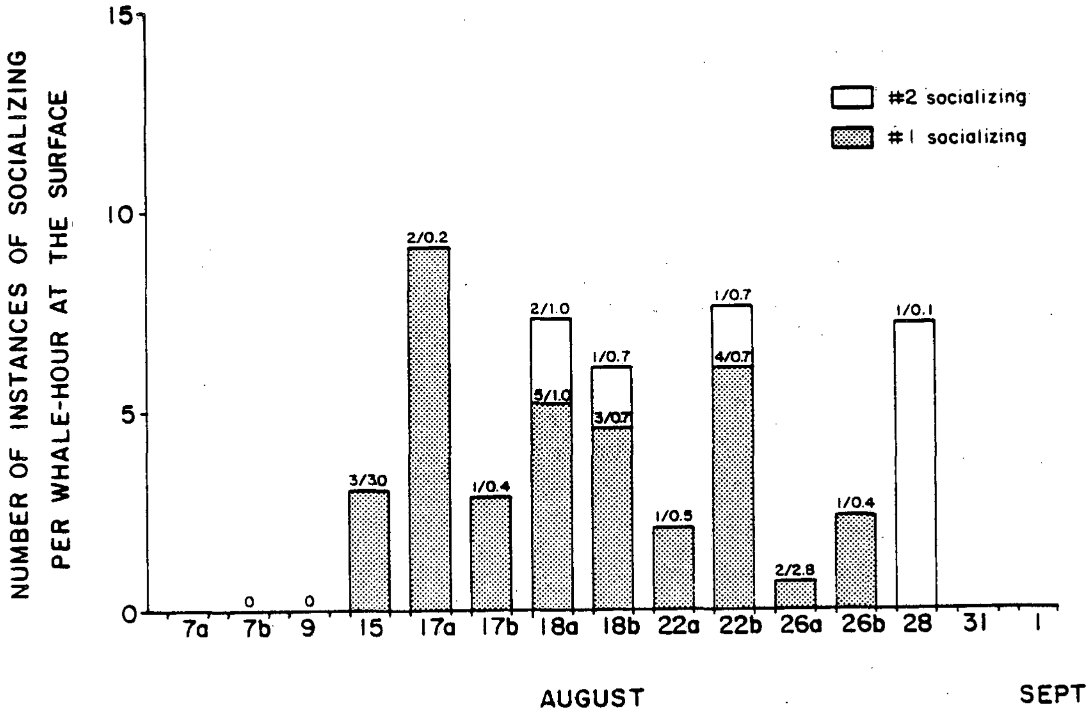

FIGURE 22. Rate of socializing during each flight in 1983. #1 socializing is distinguished from #2 socializing (see text for definitions). Only presumably undisturbed periods are included. The numbers at the top of each column are number of social interactions/number of observation hours.

social interactions per whale-hour at the surface, while the rate later in the study period was only 1.77 interactions per whale-hour (chi-square = 3.87, df = 1, $p<0.05$). The decrease in rate of social activity during late August in 1983 was consistent with a similar trend in 1980 and 1981 (considering both types of socializing).

Table 4. Rate of socializing among presumably undisturbed bowhead whales, 1980-83, calculated according to number of whale-hours of observation at the surface. Both type #1 and type #2 socializing incidents (see text) are included.

	1980	1981	1982	1983
A. Number of instances of socializing	42	39	7	27
B. Whale-hours at the surface	5.9	10.1	6.3	7.9
C. Socializing rate (A/B)	7.1	3.9	1.1	3.4

Figures 23 and 24 show rate of socializing vs. depth of water and time of day for presumably undisturbed bowheads in 1983. There was no discernible relationship between amount of socializing and depth of water (Fig. 23). It appears that #1 socializing occurred more frequently around 12:00 - 15:00 MDT and during evening than during late afternoon (Fig. 24). Sidereal noon occurs at approximately 15:00 MDT in the study area, and the rate of socializing was low from 15:00 to 20:00 MDT. The high rates of #2 socializing from 09:00-10:00 MDT and from 19:00-20:00 MDT are both based on very short observation periods, and may not be representative. Our 1983 results on diurnality of socializing are interesting, because we had evidence from previous years that there was a peak of social activity at or just after sidereal noon (Würsig et al. 1983), and this was not the case in 1983. However, for the 1980-81 data, the rate of socializing by hour of day was calculated based on time spent circling over whales and not on whale-hours at the surface, as in 1983, so comparisons between years may not be valid here.

Types of Social Behavior Observed

Most incidents of socializing in 1983 consisted of brief interactions between two whales, with one nudging the other or orienting towards the other

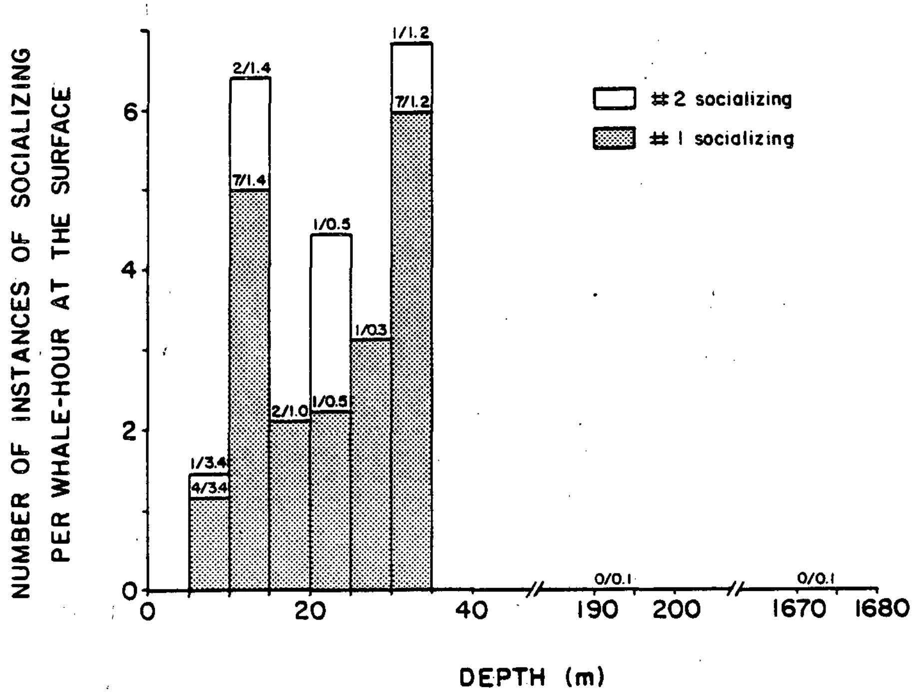

FIGURE 23. Rate of socializing in relation to depth of water in 1983. #1 socializing is distinguished from #2 socializing. Only presumably undisturbed periods are included. Presentation as in Fig. 22.

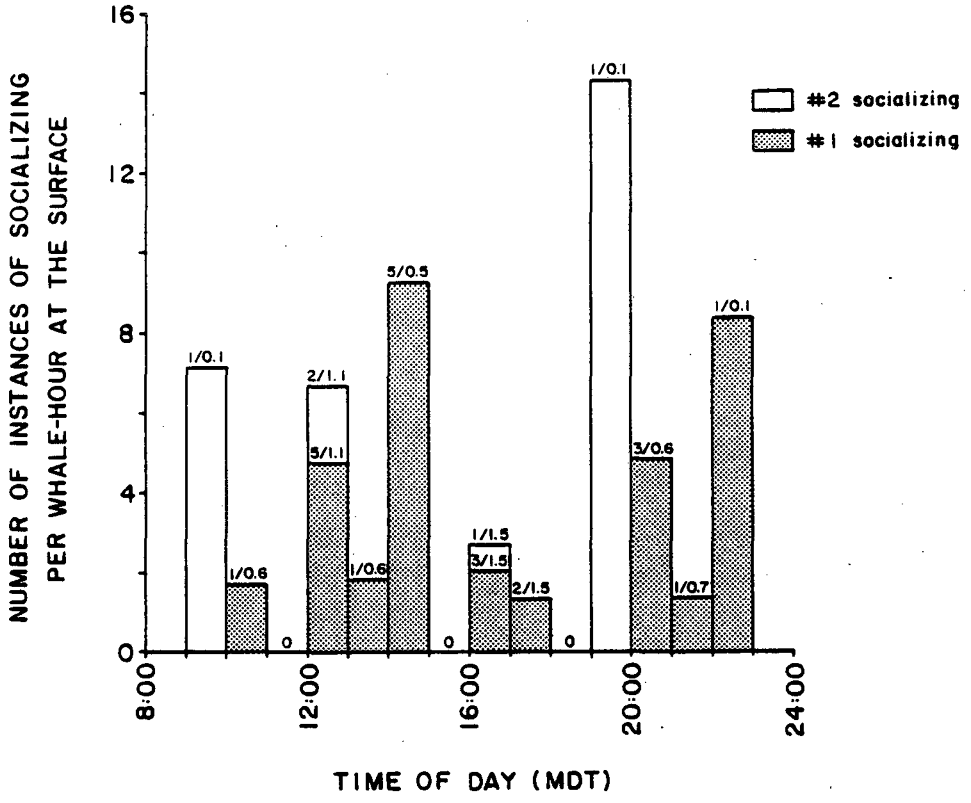

FIGURE 24. Rate of socializing in relation to time of day in 1983. #1 socializing is distinguished from #2 socializing. Only presumably undisturbed periods are included. Presentation as in Fig. 22.

at close distance. However, we also saw six apparent chase sequences, when one whale swam rapidly behind a second whale along the same route. None of these chases lasted longer than 10 s, and only one occurred under presumably undisturbed conditions in 1983.

On 9 August 1983, we observed several groups of interacting whales in water 190 m deep, 41 km north of Herschel Island. Seismic noise was present most of the time (Richardson et al. 1983b). We identified few whales by natural marks and therefore obtained few dive times and no precise count of the number of socializing groups. However, there were about 12 whales in three to four groups within our approximately 10 km^2 circle of observation. Although the instances of socializing at the surface generally lasted for only about 1 min, whales surfaced and dove while interacting, and we suspect that socializing continued underwater. A further impression was that there was usually one whale toward which the two or three other whales oriented, and these whales nudged or pushed the focal whale. The activity in these groups was never as boisterous as in the mating groups of bowheads observed during spring migration (Everitt and Krogman 1979) or southern right whales (Eubalaena australis) observed during winter (Payne and Dorsey 1983; Payne in prep.). In the latter case, the focal animal of such groups is usually a female and the other animals are males attempting to mate with her. We saw no evidence for copulation in the socializing bowheads that we observed in the summer of 1983 (although we observed apparent mating activity in 1981). We also saw no signs of whales attempting to avoid copulation, for example by rolling belly up in an active group. Therefore we do not know whether the socializing that we observed in 1983 was of a sexual nature.

On 31 August 1983, we witnessed a particularly violent interaction between two whales that had apparently been bottom feeding. At least four other whales were bottom feeding in the area, which was about 82 km WNW of Pullen Island, in 19 m depth. All whales observed that day were exposed to seismic blasts. One whale surfaced beside a second whale and began slapping one of its pectoral flippers onto the mid-body of the second whale. There were three such slaps, after which the second whale rolled on its axis and then slapped its flukes onto the mid-body of the first whale six times in 1.33 min. The last two fluke slaps were particularly high and forceful, and hit the first whale squarely on the back. We could not see what immediate reaction the first whale had, if any, because we lost sight of the action for 12 s after the last slap. When we resighted the whales, they lay side by side and then slowly sank below the surface together. We do not know how to interpret this apparent aggression between the two whales; we have not seen such behavior in other cases when whales were exposed to seismic noise.

While interacting with nearby whales, socializing whales often turn while at the surface. In contrast, non-socializing whales often come to the surface and dive again without changing direction. The data from 1980-82 showed significantly more turns for socializing whales than for non-socializing whales. In 1983, during presumably undisturbed periods, socializing whales also made turns during a higher proportion of surfacings than did non-socializing whales. However, the difference was not statistically significant in 1983 (chi-square = 2.49, df = 1, $0.10<p<0.25$).

	#1 socializing whales	non-socializing whales
surfacings with turns	7	60
surfacings without turns	6	147
total surfacings	13	207
% surfacings with turns	54%	29%

Socializing Whales Compared to Non-socializing Whales

The surfacing, respiration, and dive characteristics for socializing and non-socializing whales, considering only presumably undisturbed non-calves, are presented in Table 2 and Figure 25. As explained above, the socializing whales are divided into two categories, #1 and #2 socializing. The non-socializing whales are also presented in two ways, both with and without the inclusion of skim-feeding whales. In past years, we have compared socializing whales to all non-socializing whales without regard to feeding behavior. However, in 1983, the behavior of skim-feeding whales differed dramatically from that of non-feeding whales, especially in the mean interval between blows. The following statistical analyses therefore compare only #1 socializing whales with non-socializing whales that were not skim-feeding.

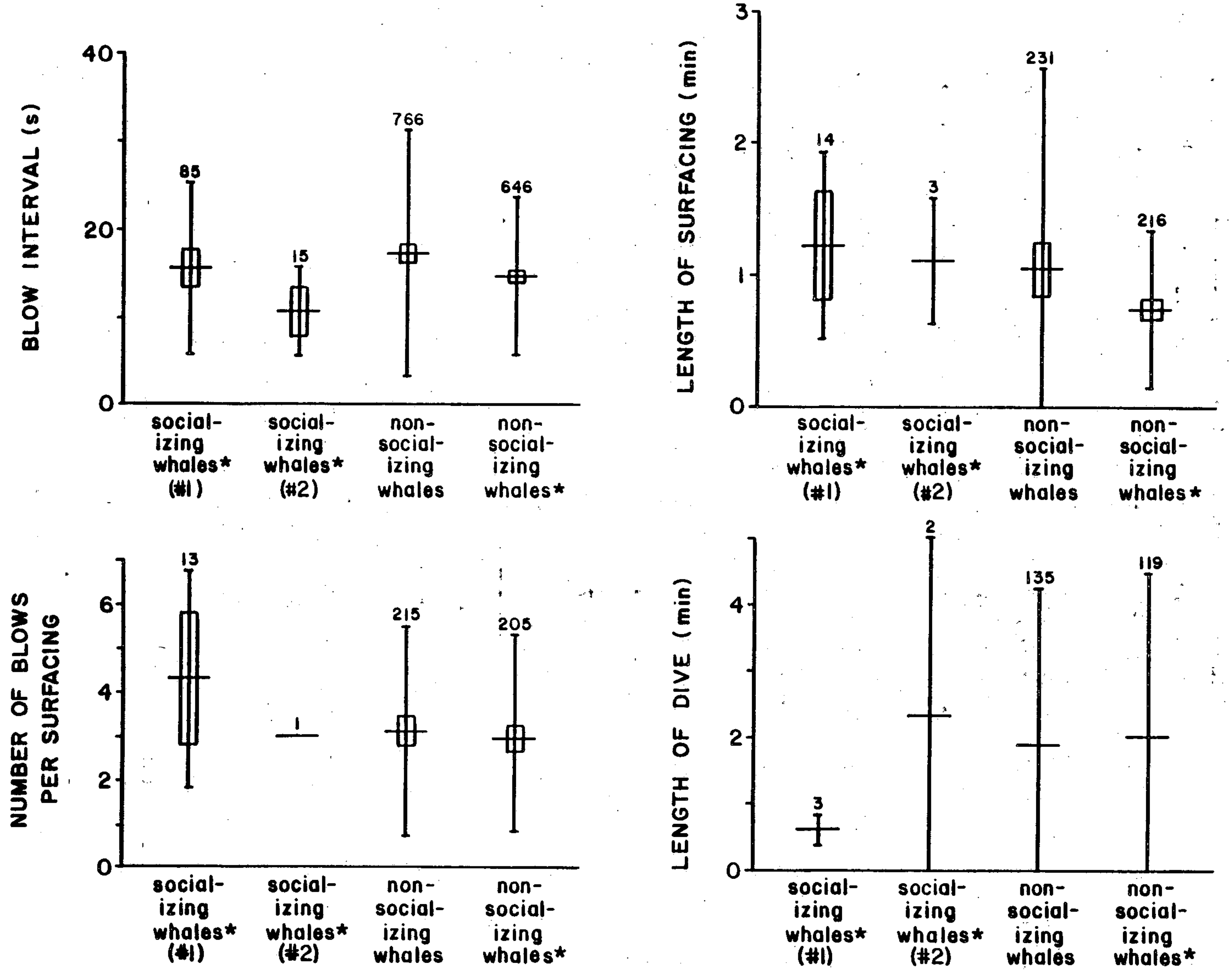

FIGURE 25. Comparison of respiration, surfacing and dive characteristics of socializing whales in two categories (#1 and #2 socializing) and non-socializing whales in 1983. * = skim-feeding whales excluded. Only presumably undisturbed non-calves are included.

Blow intervals were not significantly different for #1 socializing whales and non-socializing whales (skim-feeding whales were excluded from both categories). Mean duration of surfacing, however, was significantly longer for #1 socializers than for non-socializers ($t = 2.88$, $df = 228$, $p<0.005$), and the mean number of blows per surfacing was also significantly greater for #1 socializers than for non-socializers ($t = 2.31$, $df = 216$, $p<0.05$). Although #1 socializing whales had a shorter mean dive time than non-socializers, the sample size for the former group was very low, and the difference was not statistically significant. The sample sizes for proportion of time at the surface and for blow rates in socializing whales were too small for meaningful comparison with non-socializing whales.

Lone Whales vs. Whales in Groups

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 of two or more 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 with any effect of group size.

The mean blow interval was significantly longer for whales in groups than for single whales ($t' = 2.36$, $0.01<p<0.02$), and the mean surface time was also longer in groups of whales ($t = 2.40$, $0.01<p<0.02$) (see Table 2). Because longer blow intervals tended to accompany the longer surface times for whales in groups, there was no difference in number of blows per surfacing between whales in groups and single whales. Lengths of dives by whales in groups appeared slightly shorter than those by single whales, but the difference was not statistically significant.

Correlation of Socializing with Underwater Blows

We observed 347 underwater blows during 1983; 216 of these occurred during potentially disturbed times and 131 during presumably undisturbed times. We often noted underwater blows within or near socializing groups of whales in 1983, so we looked for a correlation between the two behaviors. We felt it necessary to use a new basis for the calculation of underwater blow rates. Because one might expect the rate of underwater blows to vary directly with the number of whales in an area, and because underwater blows —by definition—can occur only when a whale is underwater, we standardized using 'number of whale-hours underwater'. This quantity is intended to be the sum of durations of all dives by whales being circled by the aircraft during a behavioral observation session. Since we were never able to measure all dives of the whales under observation, we estimated the number of whale-hours underwater in the following way. The number of hours of behavioral observations from the aircraft was multiplied by the estimated number of whales in the circle of observation to get the total number of whale-hours of observation, both at and below the surface. From this figure we subtracted the number of whale-hours at the surface (determined by summing the durations of all observed surfacings) to obtain the number of whale-hours underwater. The number of underwater blows observed was then divided by this value to obtain the underwater blow rate.

Figure 26 presents the underwater blow rate for presumably undisturbed whales during each observation flight in 1983. During the first flight on 17 August, the rate of underwater blows was very high (Fig. 26). The highest observed rate of socializing occurred during that same flight (Fig. 22). Over all observation flights, the correlation between the rate of underwater blows and the rate of #1 socializing was indeed positive and highly significant (Fig. 27).

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 (*Megaptera novaeangliae*) (Hain et al. 1982). We did not see any direct evidence of

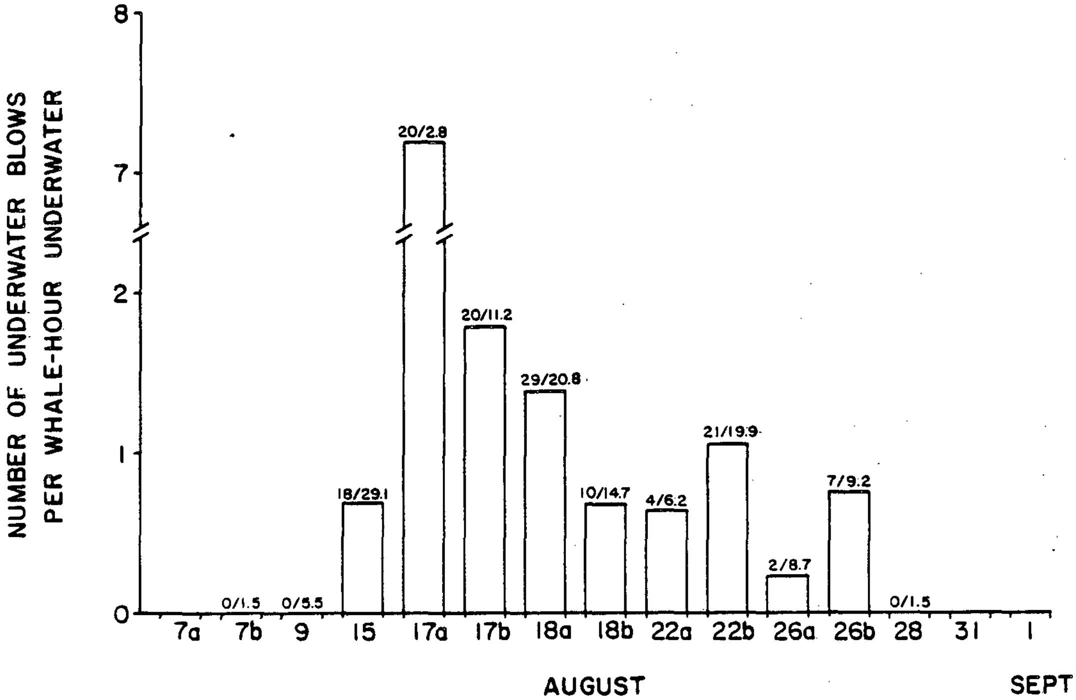

FIGURE 26. Rate of underwater blows during each flight in 1983. Only presumably undisturbed periods are included. The numbers at the top of each column are number of underwater blows/number of whale-hours underwater.

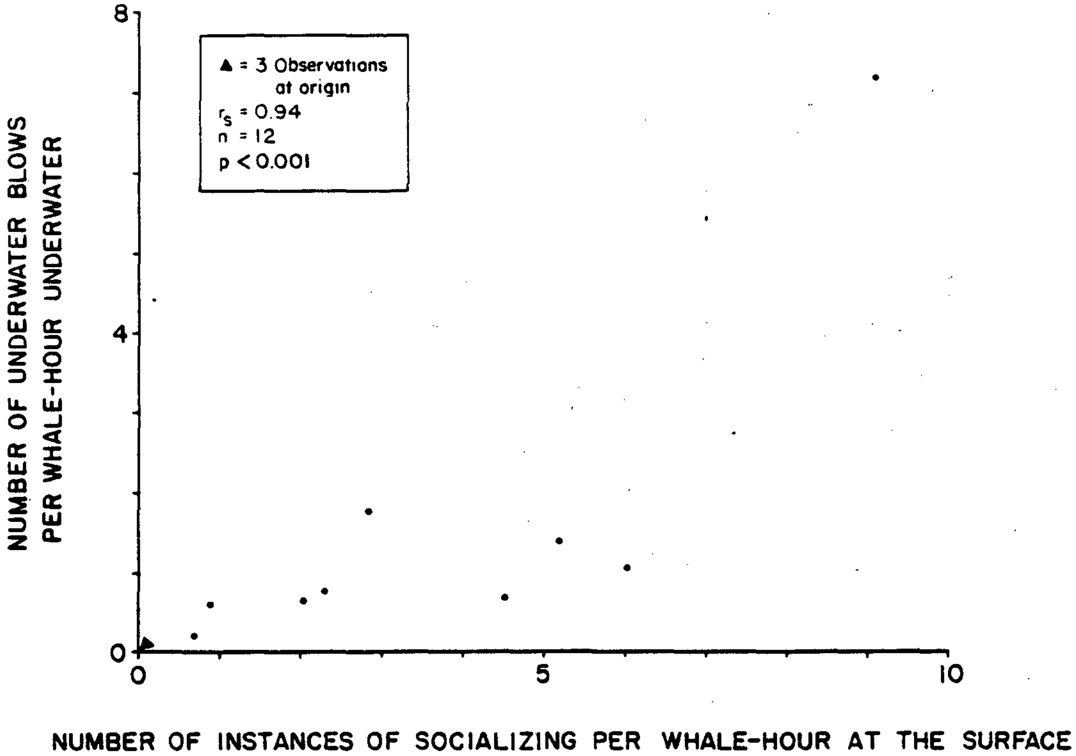

FIGURE 27. Correlation between the rate of #1 socializing and the rate of underwater blows during each observation flight in 1983. Only presumably undisturbed periods are included.

feeding in connection with underwater blowing that year, but 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. In both 1980 and 1981, the rate of underwater blows, when calculated by hour of day, appeared to be lowest when the rate of socializing was the highest, around sidereal noon (Würsig et al. 1982). Thus the incidence of underwater blows appeared to be negatively correlated with socializing in 1980 and 1981. The calculation of underwater blow rates in those two years, however, was based only on number of observation hours and did not consider the number of whales in the area. In 1982, underwater blows were seen too rarely for analysis (Würsig et al. 1983). We thus do not feel that we have properly analyzed the relationship between underwater blows and socializing except in the present analysis of data from 1983.

We have not had time to re-analyze the data on underwater blows from past years to see if the correlation with socializing existed then as well. The total numbers of underwater blows observed in the four years, considering both disturbed and undisturbed periods, and without determining the rates based on whale-hours underwater, were as follows:

1980	1981	1982	1983
158	66	6	347

The fact that socializing rates showed a similar pattern -- a progressive decline from 1980 to 1982 followed by an increase in 1983 (Table 4) -- suggests, on a crude level, that the 1983 relationship between underwater blows and socializing may hold for past years as well.

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, more than half (23) were produced by whales that were within five body lengths of one or more other whales, and 14 of those were produced by whales that were actively socializing just before the underwater blow. In at least one case it appeared that the interacting continued underwater after the whales dove. Of the 88 underwater blows where we did not observe the whale that produced it, 23 appeared 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. We suspect that at least some of those blows marked the locations of groups of whales socializing underwater and out of sight.

The strength of the correlation between rates of underwater blows and of socializing in 1983, coupled with the observation of underwater blows within actively socializing groups of whales, strongly suggests that underwater blows were a form of social interaction, at least for much of the time in 1983. 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, Darling et al. (1983) have reported both forceful underwater blows and curtains of bubbles produced by exhaling underwater while moving forward, in apparently aggressive social contexts. We do not know whether the underwater blows we observed in bowhead whales were also of an aggressive nature.

Aerial Activity

Aerial activity, consisting mainly of breaching, tailslapping and pectoral flipper slapping, occurred sporadically throughout our 1983 observations. General descriptions of these aerial activities are given by Würsig et al. (1982). Aerial behavior presents certain difficulties for the definition of surfacings and dives. We excluded breaches from our surfacing analysis because we considered a breach to be an abnormal surfacing of uncertain duration. We also could not be certain whether or not a blow accompanied a breach, so we measured blow intervals only for blows between breaches. (One of us [RP] has noted from films of breaching southern right whales that a blow accompanied every breach that was examined in slow motion. Our aerial vantage point in this study, however, made detection of blows in breaching bowheads impossible.) A breach was considered to represent the end of a preceding dive, but the dive following a breach was not coded for analysis. Tailslaps, flipper slaps and rolls were not considered to be interruptions of a surfacing if the whale remained in sight.

In 1983, we observed 19 bouts of aerial activity, ranging from single events to the long series of activities on 22 August, described below. Aerial activity bouts consisted of eight single tailslaps, six single breaches, one bout with two and one with three breaches, one bout with three pectoral flipper slaps, and two long bouts on 22 August. The incidence of aerial activity in 1983 was slightly higher than that of previous years (Table 5). Aerial activity occurred too infrequently to allow many comparisons of presumably undisturbed and potentially disturbed situations, so all sightings are included in Table 5. However, the longest bout of aerial activity by a whale on 22 August began during presumably undisturbed conditions and continued during potentially disturbed conditions (aircraft at 305 m a.s.l.). Possible differences in aerial activities due to the aircraft are discussed by Richardson et al. (1984b).

Table 5. Frequency of aerial activity, 1980-83, based on whale-hours of observation at the surface. Both presumably undisturbed and potentially disturbed periods are included.

	1980	1981	1982	1983
Bouts of aerial activity	6	14	9	19
Whale-hours at the surface	10.03	14.98	10.95	17.91
Bouts/whale-hour	0.60	0.93	0.82	1.06

On 22 August 1983, we encountered an aerially active whale in water approximately 18 m deep about 13 km ENE of King Point, Yukon. We observed the whale for 11.8 min, during which it tailslapped 49 times and breached 6 times. The whale was tailslapping when we first arrived overhead at 610 m a.s.l., and breaches occurred during the latter part of our observations. Although there may have been many aerial activities by the whale before we arrived, the sequence we observed consisted of 38 tailslaps, 1 breach, 7 tailslaps, 2 breaches, 4 tailslaps, 3 breaches. As the whale surfaced after the last breach sequence, a second whale began breaching 300 m distant. The first whale moved away from the second one at medium speed, and we lost it after a dive and another surfacing during which it moved at medium speed. It was not aerially active during the last two surfacings, and it may have

stopped its aerial activity and moved away due to the onset of aerial activity by the second whale.

The first group of tailslaps by the first whale occurred during a 3.5 min period which was interrupted by only 8 brief surfacings of the head in order to breathe; the mean interval between tailslaps was 5.6 + s.d. 2.56 s (n = 37). The six breaches by this whale occurred during a 4.5 min period, and the interval between breaches was 0.89 + 0.584 min. Nineteen blows were observed within 11.8 min of observation, for a blow rate of 1.61 blows/min. However, if respirations occurred during each of the breaches as well, the blow rate would be 2.12 blows/min. The mean blow interval for blows occurring between breaches was 19.60 + 9.125 s (n = 15).

The second whale was aerially active during the entire 75 min that we observed it. It breached 64 times, tailslapped 36 times, and pectoral flipper slapped 48 times. While breaches and tailslaps predominated at the beginning, pectoral flipper slaps--produced as the whale rolled on its longitudinal axis at the surface--occurred more often towards the end of observations. The breaches were distinctly clumped into short series with the pauses between breach series lasting over 1 min and the intervals between breaches within a series lasting only about 0.5 min. There were 15 breach series, with 3.1 ± s.d. 1.41 breaches/series. Fourteen longer intervals separated these series of breaches; they ranged from 1.2 to 3.9 min in length, with the exception of one 16.25 minute interval (mean = 2.72 ± 0.903 min). The mean interval between breaches within a series was 0.48 ± 0.095 min (n = 47).

Tailslaps occurred sporadically throughout observations of this second whale. While 10 tailslaps occurred singly, there were 8 series of two or more tailslaps uninterrupted by a blow. The average number of tailslaps in a series was 3.25 ± s.d. 0.707 s and the interval between tailslaps within a series was 4.8 ± 2.46 s (n = 18). Pectoral flipper slaps, associated with the whale rolling at the surface, occurred only towards the end of observations. There were three occasions with a single flipper slap during a surfacing, 6 series of two or more slaps uninterrupted by blows, and 12 occasions when 2 flipper slaps were separated by a blow. The average number of flipper slaps in a series was 4.5 ± 2.35 (n = 6), and the interval between slaps within a series was 3.6 ± 3.12 s (n = 27). Double flipper slaps separated by a blow occurred at a mean interval of 22.1 ± 9.97 s (n = 12).

The second whale that was aerially active blew at least 89 times within the 75.0 min of observation, and possibly as many as 153 times if it blew during all breaches. The blow rate was thus between 1.19 and 2.04 blows/min. The mean blow interval for blows between breaches was 19.50 - s.d. 14.399 s (n = 60). This whale apparently also fed at the bottom; mud emanated from its mouth during at least two surfacings, and mud was visible near the whale during three other surfacings.

Although this whale was alone during most of the observed sequence, it was joined by another whale about 10 min before the end of observations, and it continued aerial activity while the other whale was near by. We detail the actions of the two whales in case they might provide insight into the function of aerial activity. The newcomer swam at the surface toward the breacher during a breach series and made a dive in the direction of the breacher while only 4 body lengths away. After the breach series ended, the newcomer made three short surfacings within 1 body length of the breacher, which was hanging at the surface. The breacher made a single flipper slap during one of the newcomer's surfacings close by. The two dove while converging head to head, and one of the two surfaced briefly just afterwards. While the newcomer was out of sight underwater, the breacher then made another series of breaches, followed by several tail slaps and flipper slaps while hanging at the surface for over two min. Toward the end of that time, the newcomer surfaced behind the breacher and swam to within 1/4 body length beside the breacher, which again flipper slapped once. The two whales then dove simultaneously side by side with flukes raised, but the newcomer surfaced again briefly 4 s later. After that, one of the two whales surfaced briefly and submerged again, and the breacher next surfaced with mud near its chin and then made two more breaches, followed by a spyhop, a tailslap, and then a flipper slap. After the breacher dove again, we saw an underwater blow near where it went down. We saw only two more short surfacings by a whale that may have been the newcomer before we had to leave the area to refuel.

Overall, the blow intervals of whales engaged in all types of aerial activity were significantly longer than those of whales not aerially active (23.3 ± s.d. 22.89 s, n = 84 vs. 16.3 ± 11.88 s, n = 782; t' = -2.75, p<0.01). However, this apparent difference may be an artefact if an undetected respiration occurred during some or all breaches. Number of blows per surfacing and length of surfacing did not differ significantly on occasions with and without aerial activity. However, the mean duration of dive during aerial activity was briefer than that during non-aerial behavior (0.52 ± 0.293 min, n = 20 vs. 2.01 ± 2.283 min, n = 116; Mann-Whitney test, z = 4.02, p<<0.001).

Many of the breaches and tailslaps by the second aerially active whale on 22 August were detected by a sonobuoy located about 300-600 m from the whale. A lower proportion of the pectoral flipper slaps were detectable by the sonobuoy (see following section).

Bowhead Sounds

In recent years the acoustic behavior of the bowhead whale has been studied during spring and fall migration (Ljungblad et al. 1980, 1982, 1983; Clark and Johnson in press) and during summer (Würsig et al. 1982, 1983). It appears that the full range of call types produced by these animals during spring, summer and autumn has been documented, although winter studies and a detailed quantitative analysis of their sound repertoire are still needed. Because of the difficult field conditions during most acoustic observations, our limited understanding of the biological significance of the various sound types is based upon their association with a general social context rather than a specific context. For example, both Würsig et al. (1982) and Ljungblad et al. (1983) present data associating (1) swimming or migrating whales with low (<250 Hz), frequency modulated (FM) upsweeps, and (2) socially active whales with either complex-pulsive calls or high (>400 Hz) FM calls. Both of these general contexts, swimming and socializing, include a range of behaviors that are probably not mutually exclusive. Nonetheless, these are important results, and they are in general agreement with the notion that low FM sounds function for long range communication in baleen whales, while higher frequency, broadband and pulsive sounds are used in social activities when whales are in close proximity to one another (Payne and Webb 1971; Clark 1982, 1983).

In August and September 1983, sonobuoys were deployed in the eastern Beaufort Sea on most occasions when bowhead whales were under observation, and tape recordings were made throughout most observation periods. The sonobuoy hydrophone was always set to deploy to 18 m below the surface. Water depths where sonobuoys were dropped ranged from about 12 m to 950 m, so on some occasions the hydrophone dragged on the bottom. During the first two days of recording, 7 and 9 August, water depths were 950 m and 210 m, respectively. Water depth at the sonobuoy during subsequent recording sessions was 12-35 m, including periods of potential disturbance.

All recordings were analyzed according to the methods used in previous years (see Würsig et al. 1982, 1983). Each tape was played back at normal speed while one of us (CWC) listened to the direct acoustic output from the tape and observed its continuous spectrographic representation on a memory oscilloscope. Spectrographic output was obtained by playing the taped analog signal into a Spectral Dynamics SD301C realtime analyzer which was coupled to a Tektronix 5111 memory oscilloscope. By this procedure the observer could simultaneously hear the sounds and see their spectrographic images. Such a method greatly facilitated both the detection of faint signals as well as the categorization of the sounds.

Using both the visual pattern of the spectrographic display and an aural judgment, each sound was categorized (by CWC) as one of the seven previously identified sound types (see Fig. 28 on page 117 of Würsig et al. 1982). The number of sounds of each type was tabulated for each minute of sound recording. In addition, a subjective decision was made as to whether the sound was loud or faint. This acoustic analysis was performed on all 33.7 h of tape recordings without knowledge of the experimental conditions or behavioral observations during the period of recording. (However, much information about potential disturbance was unavoidably available to CWC, since industrial sounds were often detected by the sonobuoys.) Later, all recording periods were divided into subsets according to experimental condition.

Table 6 presents the sound recording data for 1983 during periods when there were no known potential disturbances. Next to each date is a listing of the number of whales within an approximate 2 km radius of the sonobuoy, the general behavior of the animals, the calculated rate of calling expressed as total loud calls per whale-hour, and a tabulation of the number of loud and total sounds of each type. Call rate was computed by dividing the total number of loud calls by the duration of the observation period and by the number of whales seen within about a 2 km radius of the sonobuoy. Bowhead calls during potentially disturbed conditions are summarized in Richardson et al. (1984b).

Blow and Slap Sounds

The following discussion of blow and slap sounds includes both presumably undisturbed and potentially disturbed periods. A total of 484 blow sounds and 39 slap sounds were recorded in 1983 (213 blow sounds and 23 slap sounds during presumably undisturbed periods; Table 6).

During both flights on 17 August 1983, some of the blow sounds recorded by sonobuoy coincided with visual observations of underwater blows near the sonobuoy. The blow sound was almost always heard on the recording several seconds before it was announced by the observers in the observation aircraft. The delay could be due, in part, to the time it took the exhalation to reach the surface. Underwater blows from socializing whales were especially frequent on 17 August (Figs. 22, 26). During the first flight on 17 August, 66 of the 118 recorded blow sounds were coincident with visually confirmed underwater blows. The whales being observed were very close to the sonobuoy on this occasion.

The underwater blow sounds were acoustically distinct from the typical blow sounds made by a whale exhaling and then inhaling with its nostrils above the surface of the water. The typical blow sounds are noisy with unstructured broadband energy at 300-800 Hz and durations of about 1 s. On the recordings of 17 August, two types of underwater blow sounds were heard. The first and most common type sounded similar to the noise made by the exhalation from a scuba respirator, that is, a sustained 1-2 s high

Table 6. Daily summary of bowhead sounds recorded during presumably undisturbed periods in 1983. For each period, the upper row of values represents loud sounds and the lower row represents all sounds. Call rate was computed on the basis of the number of loud calls and the number of whales within about 2 km of the sonobuoy. A question mark after number of whales and behavior signals a recording session that extended after the aircraft crew ended behavioral observations and left the area of the sonobuoy.

								# Sounds of Each Type								
								Calls							Other	
Date	Recording Time (MDT)	Depth (m)	# of Whales	Behavior	Call Rate (calls/ whale-h)	Whale-h of Recording	Total Calls (loud & all)	Up	Down	Constant	Double or Inflected	High	Harmonic	Pulsive	Blow	Slap
9 Aug 1983	13:37-13:48	210	12	socializing	0.0	2.2	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0	0
15 Aug 1983	11:01-11:51	15	6	lone whales moving medium speed	0.2	5.0	1 11	1 8	0 1	0 0	0 1	0 0	0 0	0 1	0	0
	11:51-14:56	15	6?	lone whales moving medium speed?	1.7	18.5	31 53	4 12	3 8	3 6	8 10	0 1	13 16	0 0	6	0
17 Aug 1983	13:00-13:19	30	15	socializing	2.3	4.8	11 24	4 10	2 4	2 4	1 1	1 2	1 3	0 0	45	0
	20:49-21:32	30	15?	unknown behavior	0.3	10.8	3 21	1 14	0 0	0 1	0 3	0 0	0 1	2 2	28	2
	21:06-22:36	25	10	mostly lone whales, unknown behavior	0.5	15.0	7 44	3 21	1 7	0 1	0 4	0 1	3 8	0 2	40	0
18 Aug 1983	14:14-14:39	12	13	some socializing some lone whales	0.4	5.4	2 2	0 0	0 0	0 0	0 0	0 0	2 2	0 0	8	0
	14:39-15:08	12	13?	some socializing some lone whales?	0.5	6.3	3 3	2 2	0 0	0 0	1 1	0 0	0 0	0 0	5	0
	20:24-20:57	12	?	no data	-	-	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0	0
22 Aug 1983	10:23-11:05	20	6	some aerial activity, possible bottom feeding, otherwise unknown	2.6	4.2	11 43	3 8	3 13	0 1	2 11	1 5	2 5	0 0	35	21
	14:07-14:21	35	9-11	mostly lone whales; little or no forward movement	0.9	2.3	2 4	2 4	0 0	0 0	0 0	0 0	0 0	0 0	6	0
	15:31-16:45	35	9-11	mostly lone whales; little or no forward movement	1.0	12.3	12 48	10 24	0 1	0 4	0 0	0 7	1 8	1 4	40	0
26 Aug 1983	17:04-17:49	17	5-8	skim-feeding	0.0	4.9	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0	0
TOTAL						91.6	83 253	30 103	9 34	5 17	12 31	2 16	22 43	3 9	213	23

frequency, broadband noise mixed with a chorus of lower frequency, short duration broadband gurgles. The longer durations of these hissy, gurgly underwater blows were presumably attributable to the time it took the bubbles from each exhalation to reach the surface. The second type of underwater blow sound was heard only during the first flight on 17 August. It was more structured than the hissy, gurgly blow sound and consisted of a series of broadband pulses repeated 10–20 times a second. These pulsatile blow sounds would have been categorized as harmonic or pulsive calls had there not been visual observations of underwater blows several seconds after many of these sounds were heard. These observations are similar to those of Clark (1983) for southern right whales; in large groups with social and sexual activity, right whales often exhaled underwater and thereby produced pulsive sounds.

Thirty-seven of the 39 slap sounds (including both presumably undisturbed and potentially disturbed periods) were recorded during the morning flight of 22 August 1983, when the second of two whales was engaged in a prolonged bout of breaching, tailslapping and pectoral flipper slapping (see Aerial Activity section, above). During the 75 min of recording, 40 breaches, 29 tailslaps and 40 pectoral flipper slaps were seen. Of these, 15 breaches, 13 tailslaps and 9 pectoral flipper slaps were distinctly audible on the recordings. Within most bouts of aerial activity, some breaches or slaps were audible, but others were not. For example, between 10:52:13 and 10:54:35, there was a series of six breaches by one whale. Of the six, only the first three in the series were clearly audible. Similar results were found for both tailslaps and pectoral flipper slaps. Apparently, there was considerable variability in the acoustic level of different breaches, tailslaps and flipper slaps within a single series. Greene (1984, this volume) documents the spectral and temporal characteristics of sounds from a breach and tailslap recorded on 22 August. The predominant frequencies were lower for the breach.

Call Types

Excluding blow and slap sounds, the majority (85%) of sounds recorded in 1983 were tonal, frequency-modulated calls lasting 1-2 s. All the types of sounds previously reported and illustrated by Würsig et al. (1982, p. 117) were also recorded in 1983. We did not hear any of the 'twittering' sounds reported by Würsig et al. (1983, p. 86). However, in 1983 we did very little recording near calves, the context in which the 'twittering' sounds were heard in 1982.

Context of Call Types

The behaviors and contexts observed in 1983 were quite variable. They included lone whales with little to no forward movement, swimming, skim-feeding, bottom feeding and socializing. Because of the variation in contexts and the low sample sizes, it is difficult to reach any firm conclusions associating context and call types (see Table 6). However, we observed socializing during 22 of the 27 cases when we recorded loud pulsive calls in 1983, considering both presumably undisturbed and potentially disturbed periods. Nine pulsive calls, both loud (3) and faint (6), were recorded under undisturbed conditions and none of these was known to be associated with socializing. However, of the 5 loud pulsive calls recorded during all periods when whales were not socializing, 1 was heard during a period of aerial activity just after two whales were seen head to head, two were heard during a period of unknown behavior, and only 2 were heard when there were lone whales in the area. Thus pulsive calls again tended to be associated with socializing animals in 1983, as reported earlier by Würsig et al. (1982) and Ljungblad et al. (1983). For all other call types, there were no distinguishable associations with any particular behavior.

Interspecific Interactions

White whales (Delphinapterus leucas) were seen near bowhead whales on 17, 22 and 26 August. The closest approach occurred on 17 August when two white whales were approximately 45 m from a bowhead whale and oriented toward it. However, we did not see any interaction by the two species. This was the closest that we have observed members of the two species in all four years of this study. 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 (Phoca hispida) and gray whales, which were seen near bowhead whales in previous years, were not seen near them in 1983.

Birds were seen near bowheads on ten separate occasions in 1983. They may have been attracted to areas of whale activity in search of food, but we had no direct evidence of interaction between bowheads and birds in 1983. Gulls (probably glaucous gulls, Larus hyperboreus) were seen to pass over skim-feeding whales three times on 26 August. Flocks of phalaropes (probably red-necked (= northern) phalaropes, Phalaropus lobatus) were seen sitting on the water near whales on 17 and 18 August. On 17 August, there were two occasions when phalaropes landed in the location where a whale had been only seconds before. We do not know whether these whales were feeding in the water column, but defecation by one of these whales near where phalaropes landed indicates that feeding had taken place sometime previously. Gulls and small birds, probably phalaropes, each flew over a whale not known to be feeding on 18 August, and later that day about 60 phalaropes were seen in an area with about 30 bowheads.

Comparisons with Bowheads During 1983 Migration

Würsig et al. (1983) reviewed the information on behavior of migrating bowheads and demonstrated that, during the spring and fall migrations into and out of the Beaufort Sea, bowheads probably engage in the same types of behaviors observed on their summering grounds (feeding, socializing, travelling, and aerial behavior), but with different relative frequencies. We discuss here the little additional information about bowheads during migration that is available at this time.

Durations of dives by bowheads migrating in the spring of 1983 were measured by observers stationed on the ice at Point Barrow, Alaska. The mean dive time obtained was 18.01 ± s.d. 13.986 min (n = 98, range = 1.77 - 76.00 min) (Krogman et al. 1983). This was very much longer than the mean dive time that we observed in presumably undisturbed bowheads summering in 1983

(1.88 ± 2.357 min, n = 140. It was also longer than the mean dive time that we observed in 1982 (12.08 ± 9.153 min, n = 51), when we saw the longest dives in any year of this study. These figures may exaggerate the real difference between the mean dive times for migrating and non-migrating bowheads, because of the bias in our data toward short dives, explained above. However, we believe that the direction of the difference is correct and that migrating bowheads that are actively travelling do indeed make longer dives on average than do summering bowheads.

Reports on behavior of bowheads during fall migration have been limited. One of us (BW) was involved in a study of bowhead whales in the Alaskan Beaufort Sea during the fall migration of 1983. Quantitative data from that study are not yet available, but some behavioral observations are of interest. The ice closed in near shore relatively early, in late August and early September, and most of the whales observed in September were moving rapidly. Very little feeding behavior was observed in areas where feeding occurred in previous years during fall migration (D. Ljungblad, pers. comm.). Socializing was observed only occasionally, consisting of nudges and low-intensity chases. No apparent mating and no groups actively milling at the surface were seen. However, observers working farther from shore at the same time noted some instances of quite boisterous socializing (G. Silber, pers. comm.).

1983 Compared to Previous Years

Striking variations in behavior from year to year have been one of the major generalizations derived from this study to date. In preceding sections of this report, comparisons between 1983 and previous years have been mentioned for many behaviors. Here we review those comparisons to summarize the ways in which 1983 was different from and similar to 1980, 1981, and 1982.

Year-to-year differences in locations where we encountered bowhead whales were one of the more dramatic annual variations observed. Richardson et al. (1983a, 1984a) review the results of systematic and opportunistic surveys of bowhead distribution in the study area. 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 where bowheads were observed in August and early September. In 1983 we again found bowheads in very shallow water close to shore, but in a different part of the study area. In 1983, the nearshore whales were along the Yukon coast, west of the area where they were so common in 1980.

Another difference between 1983 and 1980 was the age composition of the 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), but in 1983 we did not see such whales in the nearshore group. In 1983, mothers and calves were encountered only in very deep water over 100 km north of the immature group (this study) and in offshore areas much farther east (McLaren and Davis 1984; J. Cubbage pers. comm.). As indicated earlier, there appeared to be stronger segregation of bowheads by age class than in the three previous years. Probably because of that segregation and because we rarely flew far offshore in 1983, our calf sighting rate was lower in 1983 than in any of the previous years of study (Table 3).

Feeding is presumed to be the predominant activity of bowheads summering in the Beaufort Sea. The frequencies of various types of feeding have 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. 1983 was probably most like 1980, as the feeding behavior observed near shore was bottom feeding and skim-feeding. Contrary to 1980 and 1981, none of the skim-feeding observed in 1983 was by whales in echelon formation. Water-column feeding was not detected in 1983, but may have occurred. There was a progressive decrease in the observed rate of defecation from 1980 to 1982. The 1983 value was similar to that in 1981 and therefore intermediate between 1980 and 1982.

We have seen some social behavior every year, with a progressive decrease in the rate of socializing from 1980 through 1982. The rate of socializing in 1983 was back up to the approximate level in 1981, and was thus intermediate between the levels in 1980 and 1982 (Table 4). In 1983, as in 1980 and 1981, the rate of socializing was lower in the second half of August than in the first half. (In 1982, the rate was too low to analyze in relation to date.) 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 interacting appears to occur, to fall migration, when there is little social behavior.

There has been considerable variation in the number of underwater blows seen each year, with by far the highest number in 1983. At least in 1983, there was a strong correlation between rates of underwater blowing and of socializing.

The rate of aerial activity in terms of 'bouts per whale-hour at the surface' has not varied very much from year to year. The 1983 value was slightly higher than that for the highest previous year, 1981. It is interesting that the rate of aerial activity should have been so stable over four years when so many other activities have varied to a much greater extent.

Over the four years of this study, several distinct types of behavior have been seen at such low frequencies that it is not meaningful to compute yearly rates. Considering social behavior, we have observed only two instances of probable mating activity, both in 1981; one instance of aggressive tail lashing by a mother with a calf toward two other adults, also in 1981; and a single incident, in 1983, of apparently aggressive physical contact (one whale striking another forcefully with its pectoral flipper, and the second whale then striking the first with its tail flukes). Considering behavior of calves, we have seen interaction between two calves only once, in 1983; and play by a calf with a substance in the water twice (with fluoroscein dye in one case and with a windrow of debris in the other), both cases occurring in 1982. We have observed log play by non-calves three times, twice in 1981 and once in 1982. 1983 did not appear to have either a lower or a higher incidence of rare behaviors.

The types of sounds recorded underwater in the presence of bowheads have been almost the same in all four years of this study. Call rates, however, varied considerably between years. There were indications that changes in depth of water and social context were related to the variations in call rates. For example, in 1982, when there was a six-fold increase in average water depth during recording sessions compared to 1980-81, there was a dramatic increase in the total number of calls recorded. 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 decreased as compared to 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.

We have wondered whether there might be some cyclicity to the changes that we have observed from year to year in the behavior of bowhead whales. Their close relatives, southern right whales, show a cycle in the constituency of the mature females present on calving grounds in the winter (Payne in prep.). This occurs because most females bear calves only once every three years and are absent from the calving grounds in Argentina during the two years in between calves (except for a brief stay early in the winter by some females the year after giving birth to a calf). There is, therefore, a different population of mature females on the calving grounds each year for three years, after which the pattern is repeated.

In 1980-82, a number of the year-to-year changes in the behavior of bowhead whales appeared to be progressive, as detailed above. Depth of water frequented, rate of socializing, number of underwater blows, and rate of defecation all changed progressively from 1980 to 1982, and feeding behavior changed considerably from year to year, though not with any consistent trend. In some respects, the bowheads in 1983 behaved like those in 1980. Many whales were in very shallow depths as in 1980, feeding behavior was most similar to that in 1980, and the number of underwater blows was again very high, even higher than in 1980. In other aspects of behavior, however, 1983 did not appear to be a repeat of 1980. A different shallow water area was occupied than in 1980. The rates of socializing and of defecation in 1983 were both much closer to 1981 rates than to 1980 rates. The calves seen far offshore were not observed exclusively next to their mothers as was true of calves in nearshore waters in 1980, but spent time away from their mothers as in 1981 and 1982. The nearshore whales in 1983 appeared not to include calves, mothers and other full grown whales, contrary to the situation in 1980. In summary, after four years of study, there is no consistent evidence that the considerable year-to-year variation in behavior of bowheads forms a repeating pattern.

Annual Variations in Behavior of Other Cetaceans

Not all whales show as much year-to-year variability in behavior and distribution as we have seen in bowhead whales over the four years of this study. Dorsey (1983; Dorsey et al. 1983) studied the behavior of individually recognized minke whales (Balaenoptera acutorostrata) on summer feeding grounds in Washington state for four consecutive years. The uniformity in distribution and behavior of this species from year to year provides a striking contrast to the variability we have observed in summering bowhead whales. The minke whales were studied in an area of only about 600 km^2, two orders of magnitude smaller than the area covered in this study of bowheads, but within that area, minke whales were found every year, consistently, at about the same time. There are three smaller regions within that area where minke whales tend to concentrate. Some of the recognized individuals were seen in the study area for all four years, and most of those were sighted in only one sub-region each year and in the same sub-region every year. Two main types of feeding behavior were observed, with no major change in the frequency of the two types from year to year. The minke whales were observed feeding on small schooling fish, like Pacific herring (Clupea harengus). Unfortunately, there is no information about variability in supply and distribution of the fish over the years of this study.

Bowhead distribution within the eastern Beaufort Sea and the frequency and type of feeding were two of the main attributes that varied from year to year. 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 examined, and factors affecting zooplankton dynamics in that area have not been studied in any detail. Studies on other baleen whales, however, provide quite direct evidence for changes in whale 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.

An example of humpback whales returning to the same area in consecutive years to feed on stable prey comes from research by Mayo (1982, 1983). He worked on Stellwagen Bank, a small shoal located near the tip of Cape Cod in the Gulf of Maine. He studied the summer movements of humpbacks within and between years as they fed on sand lance (Ammodytes americanus), a small schooling fish present on Stellwagen Bank in large concentrations during Mayo's study. Mayo recognized virtually all of the individual whales that fed on Stellwagen Bank and observed almost every day of the feeding season. Many individuals returned in consecutive years and 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 to this finding is work by Whitehead (1982) who made detailed studies of the distribution of humpback whales on their feeding grounds near Newfoundland, farther north in the western North Atlantic than Mayo's study. Capelin (Mallotus villosus) is the principal prey here. Sighting rates for humpbacks in one small nearshore area roughly quadrupled over three years. This increase was much too rapid to have been caused by population growth; even assuming maximum possible recruitment and zero mortality, the humpback population could grow by only 15% per year. There was a second area farther offshore from Whitehead's study area where humpbacks had been plentiful, but from which they disappeared over the same three years. Capelin stocks offshore from Whitehead's study area collapsed at the same time that spawning schools of capelin and humpbacks became so plentiful inshore. Whitehead concluded that the pronounced change in summer distribution of humpback whales in that region was in direct response to the failure of the offshore capelin stocks.

A similar study by Bryant et al. (1981) showed that the most probable explanation for the disappearance of humpback whales from Glacier Bay, Alaska, in 1980 was the fact that Glacier Bay had a low krill population in that year.

Thus, in a situation where the prey species remained in the same place in high abundance, humpback whales returned each year to the same area. Where the prey of the humpbacks moved dramatically, the whales also moved. These examples are all from whales that summer and feed near shore, 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.

In the early days of research on mysticetes, data obtained from the 'Discovery' expeditions showed that the changing distributions of the rorquals then being caught in the Antarctic Ocean were related to the variable distributions of their principal prey, the krill <u>Euphausia</u> <u>superba</u> (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. This unpredictability may well confer a selective advantage on the krill by making it difficult for local krill-dependent predator populations to build up.

Beklemishev (1960) correlated the distribution of Antarctic blue whales (<u>Balaenoptera</u> <u>musculus</u>), fin whales (<u>B</u>. <u>physalus</u>), and humpback whales with overall krill distribution and then pointed out that the krill distribution is affected by atmospheric cyclones in the following way. Water rises 'very intensively' in the centers of cyclones because of the low atmospheric pressure and sinks along their peripheries. The longer a cyclone stays in a given place, the more intensive is the upwelling it induces near its center. Thus 'the krill is more abundant, and there are more blue and humpback whales in regions where the cyclones are more frequent and stay longer... The position of individual regions rich in krill and whales is largely determined not only by the local Antarctic conditions but also by the tracks of the ...

cyclones as well.' This presumably means that the annual differences in krill distribution are affected by annual differences in the tracks taken by major storms. According to Beklemishev, fin whales are less closely restricted to the areas of upwelling than are blue and humpback whales.

Nemoto (1959) analyzed stomach contents of rorquals caught by Japanese whalers in the North Pacific over a six year period. His results clearly show that in rorquals feeding in the open ocean, it is common to see great year-to-year variability in diet, geographic distribution, and time of arrival at and departure from the feeding grounds. To take these in order: Nemoto showed that the principal prey of fin whales in the eastern Aleutian Islands alternated each year between two types. In one year the great majority of food in fin whale stomachs was euphausiids. In the following year, the principal food in fin whales from the same area was Calanus copepods. From an analysis of plankton tows, he demonstrated that this alternation of 'Calanus years' and 'Euphausiid years' was a reflection of alternating abundance of these prey items in the area (Nemoto 1957) and was not just due to choice by the whales.

The geographic distribution of the blue whales varied greatly from year to year in the area that Nemoto studied. He noted, for example, that 'blue whales never migrate to the grounds [whaling ground A, an area southeast of the Kamchatka Peninsula] if euphausiids are not abundant. When euphausiids are abundant [as in] 1954, blue whales arrive at the whaling ground A already in June' (Nemoto 1957, p. 77) i.e., earlier than in other years. He further noted that 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.

It is not surprising to find that annual changes in the distribution of a whale's prey can cause changes in the distribution of the whale. 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). However, it is less immediately apparent whether changes in the availability of prey could affect other aspects of behavior, such as social behavior or aerial behavior. Two well-documented studies of odontocetes show that the occurrence of socializing may depend on when and where feeding has occurred.

Würsig and Würsig (1980) studied the dusky dolphin (Lagenorhynchus obscurus) in Argentine waters and found that when the dolphins are apparently searching for food, they are spread out and there is very little social interaction. Once schools of anchovies (Engraulis anchoita) are located, the dolphins rapidly congregate to feed. Following feeding bouts, the dolphins produce many social displays including aerial acrobatics not often seen under different conditions. In studies of Hawaiian spinner dolphins (Stenella longirostris), Norris and Dohl (1980) found periods of intense social behavior to be clearly distinct from periods of feeding. If patterns of feeding behavior changed from year to year--say, in response to a change in prey distribution--then patterns of socializing presumably would also change.

Based on the above considerations, we suspect that the observed annual variation in bowhead behavior is principally a reflection of the varying distribution of their prey. If we wish to understand and perhaps predict for any given year where bowheads are likely to concentrate and how they are likely to feed, it will be necessary to develop an understanding of factors affecting the distribution of their principal prey. 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 extent of spring runoff from the Mackenzie River, (2) distribution of ice during spring and summer, (3) 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 could affect prey distribution and therefore bowheads (Richardson et al. 1983a).

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 it was before commercial exploitation, so one could argue that the present stock is probably not food-limited. If so, then details of the summer distribution of bowheads might not be predictable even with a detailed understanding of the variability in 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, it is not known whether the populations of potential food competitors (e.g., arctic cod, Boreogadus saida; Lowry and Frost 1981) have increased since the beginning of commercial whaling. Thus, it is possible that bowheads summering in the eastern Beaufort Sea are food-limited at the present time. In any case, the important limitation for bowheads is probably not the total amount of food available relative to the total requirements of the bowhead population. Bowheads apparently must concentrate their feeding in areas with dense patches of zooplankton (Brodie 1981; Griffiths and Buchanan 1982). If the locations of these patches vary within and between years, as is likely, then the distribution of bowheads is also likely to vary. Thus, an understanding of prey variability would be especially important in understanding the variable activities and distribution of bowheads.

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DISTURBANCE RESPONSES OF BOWHEADS, 1983*

By

W. John Richardson[1], Randall S. Wells[2] and Bernd Würsig[3]

[1]LGL Ltd., environmental research associates
44 Eglinton Ave. W.
Toronto, Ont. M4R 1A1, Canada

[2]Joseph M. Long Marine Laboratory
University of California
Santa Cruz, CA 95064

[3]Moss Landing Marine Laboratories
P.O. Box 223
Moss Landing, CA 95039

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ABSTRACT

Studies of the behavioral responses of bowhead whales to offshore oil and gas exploration were conducted in the Canadian Beaufort Sea from 1 August to 1 September 1983. This study, on behalf of the U.S. Minerals Management Service, was a continuation of similar studies in the same area in late summer during 1980-82. The general objective was to assess short-term behavioral responses of bowheads to noise and other stimuli associated with boat and aircraft traffic, seismic exploration, dredging and drilling. In 1983, we emphasized reactions to aircraft, seismic exploration and drilling, but also collected data on reactions to boats and dredging.

<u>Methods</u> in 1983 were very similar to those in previous years. Both experimental and opportunistic methods were used. During experiments, we tried to observe whales before, during and after simulated industrial activity. In 1983, we conducted the following disturbance experiments: 3 aircraft, 1 boat, 1 airgun, 3 drilling noise playbacks, and 1 dredge noise playback. We also observed whales opportunistically in the presence of aircraft at low altitudes, seismic exploration, a drillship, and a dredge; we compared behavior in these circumstances with behavior in the absence of potential sources of disturbance. Most observations were from an Islander or a Twin Otter aircraft circling at altitudes of 457 or 610 m (1500 or 2000 ft). Underwater sounds from whales and industrial sources were recorded via sonobuoys dropped from the aircraft and via hydrophones deployed from a boat. The boat was also used to conduct the boat, airgun and playback experiments.

Reactions to <u>aircraft</u> were evaluated mainly by assessing responses to the Islander observation aircraft. New information in 1983 included (1) three experiments in which we circled above the same group of whales at two different altitudes, and (2) subjective interpretation of apparent reactions to the aircraft. Although no controlled experiments with helicopters were possible, we twice observed bowheads while a helicopter flew at low altitude over the whales.

As in 1980-82, reactions to the observation aircraft were conspicuous when it was below 457 m above sea level, occasional at 457 m, and undetectable at 610 m. However, the responses of some whales to the aircraft circling at 457 m seemed more marked in 1983 than in earlier years, possibly because of lower ambient noise levels and/or greater lateral propagation of aircraft noise in the shallow water where most 1983 observations were obtained. During 1 or 2 of 3 experiments when the aircraft circled at two altitudes, mean blow interval was shorter, mean number of blows per surfacing lower, and mean duration of surfacings shorter when the aircraft was at 305 m than when it was at 457 or 610 m. Considering all 7 such experiments in 1981-83, only mean blow interval has been significantly different depending on aircraft altitude (lower mean at lower altitude, $p<0.001$). During experiments in 1983, the frequency of pre-dive flexes was also reduced when the aircraft was at 305 m. No reactions to the two helicopter overflights were detected, but conditions were not favorable for detailed behavioral observations.

In general, sensitivity of bowheads to aircraft seems to vary with season, whale activity, and perhaps water depth. Bowheads seem more sensitive to aircraft than are other species of whales.

The one boat disturbance experiment in 1983 employed 'Sequel', the same 12.5-m boat used in 1981 and 1982. Results were similar to those from previous boat disturbance trials. Bowheads began to orient away when the boat was within 4 km. They swam rapidly away from the track of the oncoming boat as it came closer. Both blow intervals and durations of surfacing were reduced ($p<0.05$) when the boat was within 4 km. As in 1980-82, reactions to the boat were stronger than to any other type of disturbance tested.

We observed bowheads in the presence of noise from seismic vessels on four days in 1983. One controlled test of reactions to a single 40 in^3 airgun was done in 1983, replicating two similar tests in 1981. In 1983, bowheads 26-99 km from full-scale seismic vessels or 3-4 km from the single airgun exhibited normal activities. There was no evidence that they moved away from the noise sources. Received levels of seismic or airgun noise were, at 18 m depth, ~107 to at least 138 dB//1 μPa in 1983. Levels received by whales at the surface would have been a few dB lower. Spectral and temporal characteristics of noise received from the one airgun were similar to those from more distant seismic ships.

The 1980-82 results suggested that seismic noise may have subtle effects on surfacing and respiration behavior of bowheads. However, the 1983 results did not confirm that any behavioral variable is affected consistently by seismic or airgun noise. When all opportunistic and experimental data from 1980-83 were pooled, surface and dive times, number of blows per surfacing, and blow intervals did not differ significantly in the presence and absence of seismic or airgun noise. Considering only the three airgun tests, mean blow interval was longer with airgun noise ($p<0.01$). Mean surface time and mean number of blows per surfacing were slightly lower in the presence of airgun noise during each airgun experiment, but the overall trends were not statistically significant. We conclude that noise from distant seismic ships ($\geq$ 6 km away, received level <160 dB) has no pronounced effect on overt behavior of bowheads despite the high levels of seismic noise occurring to ranges far beyond 6 km. Experiments are needed to determine if subtle effects occur at ranges >6 km, or if pronounced reactions occur when seismic vessels are <6 km away.

There was no <u>drilling</u> from artificial islands in the Canadian Beaufort Sea during our 1983 field season, but 4-5 drillships were working. There were very few bowheads in the main industrial area in August 1983. We saw no bowheads closer than 12 km from a drillship in 1983, but industry personnel reported one bowhead ~3.7 km from a drillship. Bowheads have been seen closer to drillships in previous years.

Two drillship noise playback experiments were completed successfully in 1983, replicating two similar tests in 1982. Drillship noise levels received by the whales during the 1983 tests were ~112 dB//1 µPa in the 10-1000 Hz band; such levels occur ~5 km from the actual drillship. As in 1982, calling rate decreased and bowheads tended to orient away from the playback site during playbacks. However, some whales did not orient away, and the dispersal was not nearly as rapid or consistent as occurs when a boat approaches. Aside from calls and orientation, other behaviors did not change in any consistent manner during drillship playbacks.

In 1980, bowheads frequently were seen <5 km from a dredging operation. In 1983, 1-2 bowheads were seen within a few kilometres of the same suction dredge for >2 days. We also conducted one playback experiment using noise from that dredge. No noticeable change in general activities occurred during the playback. Bowheads were slightly more likely to orient away from the playback site during the playback than during control periods. This trend was consistent with results from drilling noise playbacks, but was of marginal statistical significance. No other behavioral variables differed significantly during playback and control periods.

Overall, the behavior of bowheads can be affected markedly (but temporarily) by the close approach of ships or aircraft. Reactions to industrial activities that continue for hours or days, such as seismic exploration, drilling and suction dredging, are less obvious. Bowheads sometimes occur close enough to drillships, dredges and especially seismic boats to be exposed to considerable industrial noise. When seen near these ongoing operations, bowheads are not swimming consistently away. However, playback experiments showed a weak tendency for bowheads to orient away from sources of drillship or dredge noise when this noise first became evident. Whether whales that remain near industrial operations are subject to stress or other negative effects cannot be determined from short-term behavioral observations. The possibility of long-term displacement is examined in a different section of this report.

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. Although functions have rarely been documented, calls seem important for communication between baleen whales (e.g. Clark 1983). Detection of other environmental sounds, e.g. from ice, breaking waves, or perhaps prey, may sometimes be important to bowheads.

Most underwater industrial sounds are also at low frequencies, predominantly below 1 kHz (Acoust. Soc. Am. 1981; Greene 1982, 1983). 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.

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) 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 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 1983, with the 1982-83 work being funded by the U.S. Minerals Management Service (MMS). Results from 1980-82 were reported by Fraker et al. (1982) and Richardson et al. (1983c). This report contains the results from 1983, with some integration of all results to date. The study is expected to continue for one further summer (1984), after which a final report will be written.

The main types of industrial activities investigated have been aircraft and boat traffic, seismic exploration, drilling and dredging. All five of these activities are major components of offshore oil and gas exploration on continental shelves. All are either underway or anticipated in the Alaskan Beaufort Sea. New information about reactions of bowheads to each of these five activities was obtained in 1983, supplementing and extending our previous results.

Objectives in 1983

The high priority topics for 1983, as specified by MMS, were experimental and observational studies of reactions of bowheads to seismic exploration, aircraft (particularly helicopters) and drilling. Controlled tests of reactions to a full-scale seismic ship, should one be made available by industry, were considered the top priority. Experimental tests of reactions to dredging noise were a secondary priority, to be attempted after drilling noise tests.

Control observations under 'presumably undisturbed' conditions were a high priority before and after 'potentially disturbed' periods. Otherwise, studies of normal behavior were a low priority, as were further tests of reactions to boats.

Approach in 1983

The study area and period in 1983 were very similar to those in 1980-82. In 1983 we worked from 1 August to 2 September in 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 accompanying section by Richardson et al. (1984) describes the industrial activities underway in the eastern Beaufort Sea in 1983. Depending on date within the 1983 season, the oil industry used 3-4 seismic boats, 4-5 drillships, six dredges, 9-10 twin-engined helicopters, 2-4 icebreakers and many other boats (supply, tug, crew, and sounding vessels; barges). The overall level of offshore activity by the oil industry was higher than in any previous year, though there was no drilling from artificial islands in the summer of 1983.

We again 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 activities that we could not simulate.

Experiments conducted in 1983 consisted of overflights at different altitudes to test reactions to the observation aircraft, a boat disturbance trial, a test of reactions to an airgun, and underwater playbacks of recorded drilling and dredge noise. With the exception of the dredge noise playbacks, these experiments were attempts to replicate and extend similar tests done in past years (Fraker et al. 1982; Richardson et al. 1983c):

Type of Experiment	No. trials in 1980-82	No. trials in 1983
Aircraft altitude expts.	4	3
Boat disturbance expts.	5	1
Airgun experiments	2	1
Drilling noise playbacks	3	3
Dredge noise playbacks	0	1

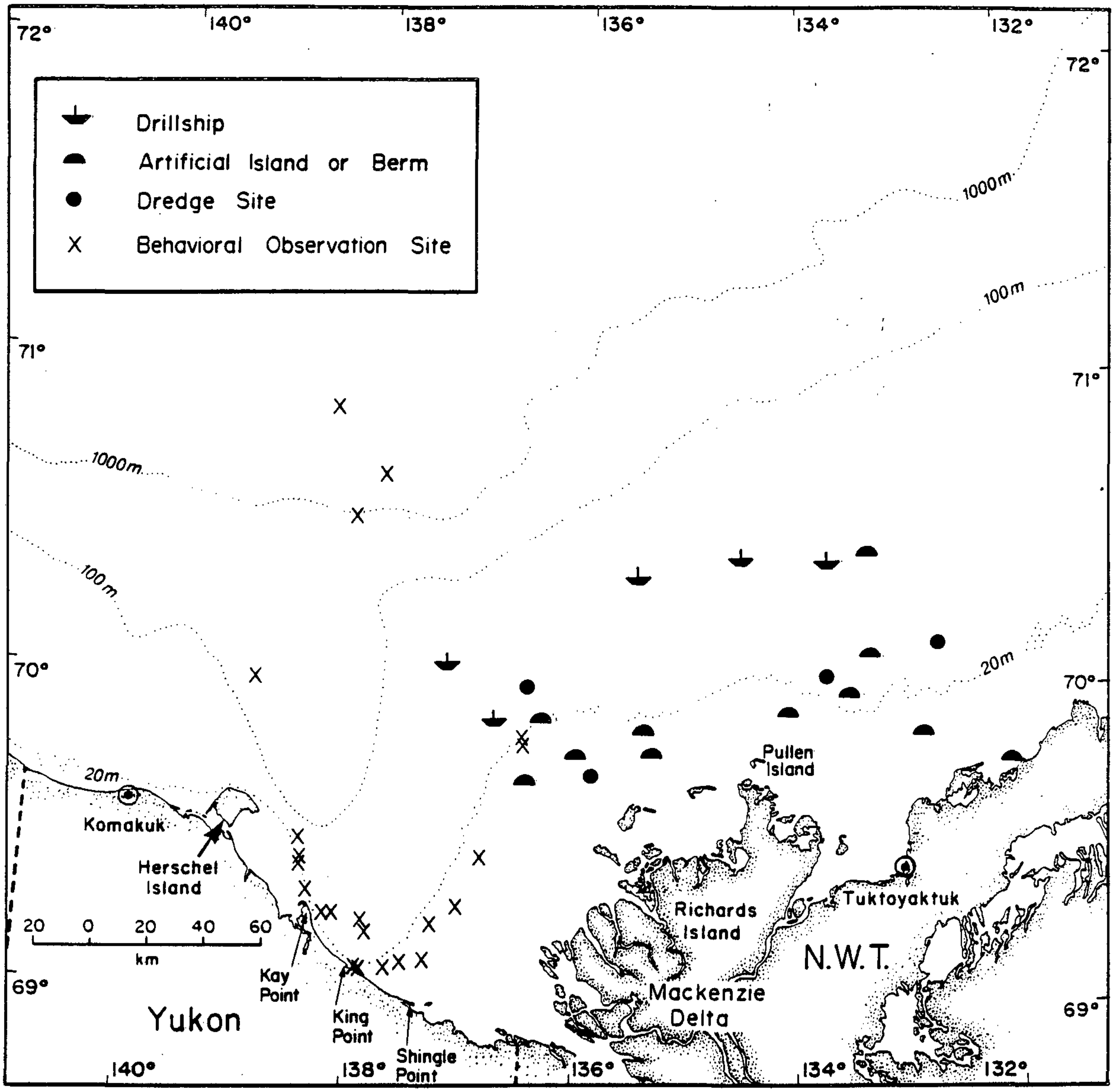

FIGURE 1. Map of the 1983 study area, east-central Beaufort Sea. The locations of our behavioral observations and the main offshore industrial sites in August 1983 are shown. Dredging also occurred at some island sites.

There were no opportunities for controlled tests of reactions to helicopter overflights or to a full-scale seismic vessel. However, opportunistic observations and reports by industry personnel provided further information about bowhead behavior in relation to fixed-wing aircraft, helicopters, seismic noise, drillships and island construction.

The 1983 work was done with similar logistic support as in 1982. Most behavioral observations were from a fixed-wing aircraft circling high overhead. A 12.5-m boat was used to conduct the experiments. Sonobuoys and hydrophones were used to record industrial sounds and bowhead sounds. Characteristics of the industrial sounds studied in 1983 are described in a companion section by Greene (1984). Characteristics of bowhead sounds recorded in 1983 are described here and in the 'normal behavior' section of this report (Würsig et al. 1984).

In 1980 and 1981 we attempted to study bowheads from shore stations at Herschel Island and King Point, Yukon. In previous years, bowheads had sometimes been seen there close to shore (Fraker and Bockstoce 1980). The shore-based work in 1980-81 had only limited success because bowheads were not close enough to shore for detailed observation. Consequently, no shore-based observations were attempted in 1982 or 1983. However, 1983 proved to be a year when observers at King Point would have been able to obtain valuable data. Bowheads were within 1-2 km of King Point on several days in mid and late August 1983 (McLaren and Davis 1984; Richardson et al. 1984), and we conducted some of our boat- and aircraft-based experiments there (Fig. 1).

GENERAL METHODS

The general methods used in 1983 were very similar to those in previous years. Methods specific to each experiment or industrial activity are described later, in the section dealing with that industrial activity.

Aerial Observation Procedures

For most of the 1983 work (14 August-2 September), we used the same Britten-Norman Islander aircraft as in 1980-82 (C-GYTC). This high-wing twin-engined piston aircraft has long-range fuel tanks, OnTrac VLF/Omega navigation system, inverters for AC power, and radar. The radar was valuable in measuring distances from whales to ships, islands, etc.

The arrival of the Islander was delayed by mechanical problems, so in the 1-13 August 1983 period we used a deHavilland DHC-6-300 Twin Otter aircraft. The Twin Otter is a high-wing twin-engined turboprop aircraft. It had a VLF navigation system and long-range fuel tank but no inverters or radar. This aircraft (CG-BDR) was previously employed by Davis et al. (1982, 1983) for systematic surveys, behavioral observations and vertical photography of bowheads. It was equipped with bubble windows for improved visibility. Our procedures in the Twin Otter were the same as in the Islander, 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 very difficult to observe in detail. 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 3.9 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 previous years we had 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. In 1983, we initially used a standard altitude of 457 m. However, during an experiment on 17 August, we believed that the whales were reacting to the Islander aircraft at 457 m (see Reactions to Aircraft section, below). Hence, we adopted a standard altitude of 610 m for subsequent observations.

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) allowed re-identification from one surfacing to the next, and thus determination of dive durations. However, most of our observations in 1983 were of a concentration of bowheads near the Yukon coast southeast of Herschel Island (Richardson et al. 1984). Most of these whales lacked obvious distinctive markings, and virtually no calves were present there. These characteristics are typical of young pre-breeding animals (Davis et al. 1983). We measured a small number of these bowheads by the photogrammetric method of Davis et al., and confirmed that they were relatively small (<13 m) subadult whales (W.R. Koski, LGL Ltd., unpubl. data). The turbid water near the Yukon coast also hindered individual recognition of particular bowheads. Thus, in 1983—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 18 m. The signals were recorded on calibrated equipment aboard the aircraft, as in past years (see Greene 1984 for details).

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 the 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, 1984). 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 113.6 h during 28 offshore flights in 1983. We circled over bowheads for 38.4 h during 15 of those flights. Of the 38.4 h over bowheads, 14.2 h and 24.2 h were under 'presumably undisturbed' and 'potentially disturbed' conditions, respectively. Potentially disturbed cases were defined as in previous years: cases 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 behavioral observations are shown on Figure 1.

Procedures for behavioral observations were the same as in 1981-82. 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 operated sonobuoy receivers and noted whales outside the area being circled. The variables recorded during each surfacing/dive sequence have been described elsewhere (e.g. Würsig et al. 1984).

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, 1401 surfacing and 242 dive records were obtained in 1983:

	Presumably Undisturbed	Potentially Disturbed	Total
Surfacing records	545	856	1401
Dive records	154	88	242

Because the surfacing, respiration and diving behavior of bowhead calves (<1 yr old) differs from that of 'non-calves' (Würsig et al. 1982, 1983), most parts of this report exclude our few 1983 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 1983, we used MV 'Sequel', the same chartered former fishing boat as was used in 1981-82. 'Sequel' is a 12.5 m vessel powered by a single 115 hp GM 471 diesel engine. Maximum speed is about 16 km/h and idling speed (engine idling; propeller engaged) is about 5.6 km/h. In 1983, two biologists were aboard 'Sequel' to observe bowhead behavior. (In 1981-82 only one behavioral observer was aboard.) The crew also included an acoustician and the captain.

The behavioral observers watched for whales when 'Sequel' was underway, while the aircraft circled nearby, and at some other times when 'Sequel' was 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 'Sequel'. Locations and water depths were determined via a Magnavox MX4102 NavSat receiver and an echosounder.

Underwater sounds were recorded from the boat using hydrophones deployed at several standardized depths, usually simultaneously. Signals were recorded on calibrated 2 and 4 channel cassette tape recorders. Greene (1984) describes the field procedures, and outlines how the intensities and spectral characteristics of the recorded industrial sounds were determined.

Experiments in 1983

Five types of experiments were conducted in 1983: aircraft, boat, airgun, drillship noise and dredging noise. All experiments were boat- and/or aircraft-based. For aircraft disturbance experiments, only the observation aircraft was necessary. For the other types of experiments, both the boat ('Sequel') and the observation aircraft had to be present near whales. All experiments were conducted while we were using the Islander aircraft, as in past years. We used the aircraft to locate bowheads, to direct the boat toward them, and to obtain most of the behavioral observations. Experiments using the boat were only possible when whales lingered in an accessible area under favorable weather and ice conditions. These requirements limited the number of experiments that could be done. In 1983, unlike 1982, no bowhead calves were seen during any of the disturbance experiments.

When experiments were possible, the usual procedure was to first 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 drillship and dredge noise playback experiments, the boat was quiet (anchored or drifting) throughout the control, playback and post-playback 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 boat and airgun experiments. Detailed procedures for each type of experiment are described in later sections.

Distances and bearings of whales from 'Sequel' were estimated for many surfacings during experiments. Distances were often estimated relative to sonobuoys or dye markers whose locations relative to 'Sequel' 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 'Sequel'. 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., 'Sequel' and whales or sonobuoy) were much more precise.

In analyzing whale orientations observed from the aircraft during playback 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 Sequel' direction, i.e. 0° = directly away, 180° = directly toward, 90° = tangential to right as viewed from 'Sequel', 270° = tangential to left, etc. The V-test (Batschelet 1981) was used to test the hypothesis that whales were oriented away from 'Sequel' 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 'Sequel' 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). To minimize 'lack of independence' problems in analyses of orientation data obtained by aerial observers, we used only the first observation of each identifiable whale during a given phase of an experiment. This may be a conservative approach in some cases. However, we were unable to recognize most whales for prolonged periods in 1983. 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 exploration for and production of oil and gas. Fixed-wing aircraft are used principally for reconnaissance, while helicopters transport personnel and supplies between shorebases and vessels or facilities offshore. These aircraft may fly at altitudes sufficiently low to create underwater noise at frequencies and intensities that are presumably detectable to bowheads (Greene 1982). 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, usually fixed-wing, are used to census bowheads and to evaluate population structure; reactions to the aircraft could bias the results.

Our results from 1980-82 indicated that bowheads often dove precipitously in response to the observation aircraft when it approached at 305 m a.s.l., and occasionally did so when it approached at 457 m (Richardson et al. 1983c). During four experimental comparisons of whale behavior when the aircraft circled at different altitudes, the mean interval between blows always decreased when the aircraft descended from 610 m to 457 m or 305 m, or from 457 m to 305 m. During periods exclusive of the experiments, the tendency for decreased blow intervals with decreased altitude was not evident. However, in 1981 mean durations of surfacings were slightly but significantly reduced when the aircraft circled at 457-518 m compared to those when it circled at 610 m (Richardson et al. 1983c).

During 1983 we recorded additional cases of apparent reaction to the observation aircraft, and we conducted two additional experiments comparing observations of the same whales from 610 m a.s.l. and 305 m. We also observed the behavior of a group of whales first from 305 m and then 457 m, and observed whales before and after the low altitude passage of a helicopter. We had hoped to conduct controlled tests of reactions of whales to helicopters, but we had no such opportunities in 1983.

Methods

Reactions of bowheads to aircraft were observed from aircraft circling over whales. From 1 to 12 August 1983 we used a Twin Otter aircraft; from 14 August through 1 September we used the same Britten-Norman Islander as during 1980-82. Our aerial observation techniques are described earlier in this report.

As in 1980-82, instances when observers in the aircraft believed that whales were disturbed by the aircraft were recorded during searches for whales and during detailed behavioral observation sessions. The presence or absence of other potential sources of disturbance was determined either through monitoring waterborne sounds via a sonobuoy, or by consulting operations records from the known potential sources of industrial noise in the area. 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 somewhat subjective, but were based on considerable experience concerning the normal behavior of bowheads. Indications of disturbance from past research and this year's efforts included unusual changes in orientation, unusually rapid surfacings or dives, general movement out of the area under observation, changes in general activities, and changes in aerial behaviors such as breaches, tailslaps, and pectoral fin (flipper) slaps.

In 1983, we conducted two experiments specifically to examine the effects of aircraft altitude on the whales' behavior patterns. A third opportunistic set of observations can also be treated as an experiment. (1) Using our Islander observation aircraft, on 22 August we circled over whales from 610 m a.s.l. for 67 min before descending to 305 m and observing whales in the same area for 33 min (Table 1). (2) Later that day we circled whales from 610 m for 74 min and then descended to 305 m and continued observations for 76 min. (3) On 17 August, low ceilings initially forced us to fly at 305 m or less. We circled at 305 m for 60 min before improving cloud conditions allowed us to circle the same whales at 457 m for another 42 min. No other sources of potential disturbance were evident during these three experiments. Four comparable experiments during 1981 and 1982 were described in Table 4 of Richardson et al. (1983c).

Table 1. Summary of aircraft disturbance experiments during 1983.

Date	Aircraft Flight	Location	Time (MDT)	Aircraft Altitude (m a.s.l.)	Water Depth (m)	No. of Whales Within Circle
22 Aug	20	69°07'N	09:58–11:05	610	18	6
		137°40'W	11:07–11:40	305		3
22 Aug	21	69°15'N	15:31–16:45	610	32	6
		137°55'W	16:47–18:03	305		6
17 Aug	15	69°16'N	11:29–12:29	305	30	15
		138°10'W	12:30–13:12	457		15

While no experiments involving helicopters under our control have been possible as yet, on 31 August and 1 September 1983 helicopters opportunistically passed beneath us as we circled over whales in water 19 m deep. On 31 August, the helicopter, believed to be a Bell 412, passed at low altitude (approx. 153 m a.s.l.) at ~14:50 MDT as we circled at 610 m near 69°51'N, 136°30'W. Seismic pulses were detected by our sonobuoy, as was other industrial noise from one or both of two industrial sites 11-18 km away (the 'Kulluk' drillship and the Kadluk island construction site). Behavioral observations obtained during the 26 min prior to the passage of the helicopter were compared to those made during the following 30 min. On 1 September, we were circling whales at the same site when a Bell 412 helicopter at 153 m a.s.l. flew over the whales. Due to poor weather conditions, no quantitative behavioral data are available from the time of helicopter passage on 1 September.

Ten variables were considered in the quantitative analyses of whale behavior relative to potential aircraft disturbance. Sample sizes for these variables varied with sea state, lighting, turbidity, and weather. Thus, it was not possible to use all ten variables for every desired comparison. The primary variables, in approximate descending order of frequency of utilization, included blow intervals, number of blows per surfacing, duration of surfacing, duration of dive, occurrence of turns, speed, and occurrence of pre-dive flexes, fluke-out dives, aerial behaviors, and underwater blows. The scarcity of individually-identifiable whales during 1983 (see General Methods) made it difficult to determine dive durations. Hence, low sample size usually precluded analysis of dive duration and derived variables such as blow rates.

Results

Occasions with Apparent Reactions

Table 2 summarizes the four situations in 1983 when observers aboard the aircraft believed that the whales were exhibiting overt responses to the aircraft. In three of these instances the changes in behavior became evident over several minutes. However, as in the past (Richardson et al. 1983c), some seemingly instantaneous responses were also noted. Changes in general activities and movement away from the area under observation were the most frequently reported apparent responses to the aircraft.

Table 2. Instances of apparent disturbance of bowheads by the Britten-Norman Islander (BNI) and Twin Otter (TO) aircraft during 1983.

Date	Aircraft Flight No. and Type	Aircraft Altitude (m a.s.l.)	Water Depth (m)	Whale Activity	Apparent Reaction to Aircraft
9 Aug 1983	8 TO	457	190	Socializing	As aircraft began to circle, whales ceased socializing, travelled rapidly to the NW, and then resumed socializing (seismic noise began during the travel period)
17 Aug 1983	16 BNI	457	<10	Moving individually near shore	Dispersed offshore as aircraft began to circle
17 Aug 1983	16 BNI	457	25	Socializing	Reduction in socializing; dispersal as aircraft began to circle
22 Aug 1983	21 BNI	305	32	No forward movement, or slow to medium travel	Hasty dives, often perpendicularly away from aircraft's track as aircraft circled

On 9 August, our Twin Otter aircraft began circling a concentration of whales in 190 m water depth near 70°00'N, 139°00'W at 13:19. After our first circle at 457 m a.s.l., a group of six whales ceased socializing and began travelling rapidly northwest. The whales later resumed socializing, and from 13:48 to the end of the observations at 17:11 socializing was frequent.

On 17 August our Islander aircraft began circling at 457 m over whales moving individually near Kay Point, Y.T. Observers aboard the M/V 'Sequel', which was drifting quietly nearby, reported that the whales had been relatively stationary within several hundred metres of shore prior to the arrival of the aircraft. Observers aboard both 'Sequel' and the aircraft believed that the whales reacted to the aircraft: the whales moved offshore. Some passed close to 'Sequel' as they swam seaward. The aircraft continued circling inshore of 'Sequel' during a drillship noise playback experiment, until too few whales remained to make continued observations worthwhile. The circle was then shifted offshore to include a socializing group at the periphery of our previous circle. As these whales became the focus of the circle, the amount of socializing decreased, and the whales dispersed. The seemingly greater response when the group was at the center of the circle is curious. Aircraft noise reaching the whales was probably greater during the earlier period when they were at the periphery of the circle, but the apparent response was not evident until they were at the center.

Aircraft altitude during this flight was consistently 457 m a.s.l., an altitude previously considered to be non-disturbing to bowheads. Primarily as a result of the observations on 17 August, we adopted a standard altitude of 610 m a.s.l. during subsequent flights. The only subsequent observations from altitudes below 610 m were during altitude experiments or when low ceiling precluded observations from 610 m.

As in 1980-82, instantaneous apparent responses to the aircraft were again noticed in 1983. During an aircraft altitude experiment on 22 August, whales engaged in zero to moderate forward movement made hasty dives, often oriented perpendicularly away from the track of the aircraft as it circled at 305 m a.s.l. These dives were characterized by a quickening of the sequence of motions that immediately precede a normal dive.

These observations, although mostly subjective, suggest that bowhead whales sometimes respond to an aircraft circling at 305 m a.s.l., and at times even at 457 m. The latter is an altitude previously considered high enough to avoid significant disturbance to bowheads. Observations from 1980-83 indicated that bowheads may respond to an aircraft that is either making a single pass overhead or circling (Richardson et al. 1983c, this study). In 1983, as in 1980-82, there were no detectable overt responses while the aircraft circled at 610 m. Our 1980-82 work showed a relationship between apparent responses and aircraft altitude, with more frequent conspicuous responses when the aircraft circled at 305 m or less, infrequent responses when the aircraft was at 457 m, and no detectable responses when the aircraft circled at 610 m or more. The 1983 results were consistent with this, but some whales appeared to respond to the aircraft more markedly while it circled at 457 m in 1983 than in earlier years.

Observations from Different Altitudes

Two quantifiable differences in bowhead behavior were found in comparisons of pooled data from 457 m a.s.l. vs. 610 m, exclusive of the altitude experiments. When the aircraft circled at 457 m, bowheads turned less frequently ($p<0.01$, Table 3) and the average blow interval was shorter ($p<0.05$, Table 4). Whether these two differences were attributable to aircraft altitude or to other factors that differed between flights is unknown. There were no significant differences between altitudes in the cases of seven other variables ($p>0.1$, Tables 3, 4).

On two occasions in 1983 we circled whales at high altitude, and then descended to circle the same whales at lower altitude. On another occasion we first circled whales at low altitude, and then ascended to circle the same whales at higher altitude. No other potential sources of disturbance were present during any of these altitude experiments.

Table 3. Contingency analyses for behavioral variables recorded when the Islander observation aircraft was at two altitudes during 1983. Excludes calves, skim-feeding bowheads, the three aircraft altitude experiments, and periods of potential disturbance from sources other than aircraft. Variables were scored once per surfacing.

Variable	Aircraft Altitude (m a.s.l.)	No. Surfacings with		chi^2 (df = 1)
		No Turns	Turns	
Frequency of turning	610	71	41 (37%)	6.82 **
	457	48	10 (17%)	
		Zero to Slow	Mod. to Fast	
Speed of motion	610	53	72 (58%)	0.01 ns
	457	25	35 (58%)	
		None	Some	
Frequency of aerial behaviors	610	271	4 (1%)	1.62 ns
	457	112	4 (3%)	
		No Flex	Flex	
Frequency of pre-dive flexes	610	123	17 (12%)	0.01 ns
	457	68	9 (12%)	
		No Flukes Out	Flukes Out	
Frequency of fluke-out dives	610	160	32 (17%)	1.66 ns
	457	82	10 (11%)	

** means $0.01 > p > 0.001$; ns means $p > 0.1$.

Table 4. Summary statistics for the principal surfacing, respiration, and dive characteristics of bowheads observed while the Islander observation aircraft was at two altitudes. Calves and skim-feeding bowheads were considered non-comparable (see Würsig et al. 1983, 1984) and were excluded, as were all whales that were potentially disturbed by sources other than the aircraft. Excludes aircraft altitude experiments. t means Student's t statistic, population variances assumed equal. U means Mann-Whitney U statistic (smaller U).

Aircraft Altitude (m a.s.l.)	Mean	s.d.	n	Mean	s.d.	n
	Blow Interval (s)			**No. Blows/Surfacing**		
610	15.01	9.537	364	3.02	2.284	111
457	13.30	6.858	227	3.20	2.178	56
	t = 2.35; df = 589 *			t = 0.48; df = 165 ns		
	Duration of Surfacing (min)			**Duration of Dive (min)**		
610	0.82	0.619	130	2.14	2.141	81
457	0.73	0.543	58	2.35	3.243	11
	t = 0.89; df = 186 ns			U = 397.5 ns		

* means 0.05 > p > 0.01; ns means p > 0.1

- During the 17 August experiment, mean blow interval was significantly shorter when the aircraft circled at 305 m than at 457 m ($p<0.05$, Table 5). However, the difference was not significant during the other two experiments, or when data from all three experiments were pooled.
- Mean number of blows per surfacing varied in an inconsistent manner in relation to aircraft altitude: higher at high altitude in one experiment, higher at low altitude in another, and similar at both altitudes in the third experiment (Table 5). When data from the three experiments were pooled, mean number of blows per surfacing was significantly lower when the aircraft was at low altitude ($p<0.05$).
- In 2 of 3 experiments, mean duration of surfacings was significantly shorter while the aircraft circled at 305 m ($p<0.05$ for Flight 20; $p<0.001$ for Flight 15; Table 5). Pooled data showed a significantly lower mean value at low altitude ($p<0.01$).
- Dive durations did not differ significantly when the aircraft circled at 305 m vs. 457-610 m (Table 5).

Table 6 summarizes the results of comparisons of surfacing and respiration data from all seven aircraft altitude experiments conducted during 1981-83. During 6 of 7 experiments, intervals between blows were at least slightly reduced when the aircraft circled at lower altitudes. The overall trend was highly significant ($p<0.001$). 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 (Table 6). Too few dive duration data were available for analysis.

Table 7 summarizes the results for five additional behavioral variables measured during the 1983 experiments. Frequency of pre-dive flexes was lower during the 305 m a.s.l. phase of both experiments in which it was measured, and this relationship was significant when the data were pooled ($p<0.005$). Few data on pre-dive flexes were available from 1981-82. Frequency of turns, speed of motion, and frequency of fluke-out dives were not significantly related to aircraft altitude (Table 7). Neither was the frequency of underwater blows (Table 8).

Table 5. Summary statistics for the principal surfacing, respiration, and dive characteristics of non-calf bowheads observed during aircraft altitude experiments in 1983. Test statistics for altitude comparisons are presented for each experiment. t' is the Student's t statistic when population variances are not assumed to be equal. U is the Mann-Whitney U statistic.

Date	Flight	Altitude (m a.s.l.)	Blow Interval (s)			No. Blows per Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
			Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n
22 Aug	20	610	17.33	11.785	61	3.08	1.977	25	0.65	0.658	17	0.71	0.663	25
		305	21.92	15.141	25	2.71	2.701	14	0.25	0.272	8	0.76	1.113	7
			t = -1.51, df = 84, ns			t = 0.49, df = 37, ns			t' = 2.20*, df = 24.46			U = 75.50, ns		
22 Aug	21	610	11.93	5.696	59	2.15	1.089	20	0.66	0.362	20	1.77	1.815	2
		305	11.61	4.821	41	4.50	2.887	4	0.88	0.587	4	4.78	6.364	2
			t = -0.30, df = 98, ns			t = -2.92**, df = 22			t = -0.98, df = 22, ns			(n too small)		
17 Aug	15	457	19.25	11.690	49	3.00	1.840	14	0.95	0.762	14	0.77	-	1
		305	14.79	9.884	43	1.46	1.422	44	0.41	0.359	46	0.32	0.056	5
			t = 1.96*, df = 90			t = 3.29**, df = 56			t = 3.67***, df = 58			(n too small)		
Pooled Experiments		≥457	16.00	10.460	169	2.75	1.718	59	0.74	0.597	51	0.79	0.767	28
		305	15.23	10.628	109	1.94	2.031	62	0.42	0.385	58	1.18	2.462	14
			t = -0.59, df = 276, ns			t = -2.36*, df = 119			t = -3.35**, df = 107			U = 128.5, ns		

* means 0.05 > p > 0.01; ** means 0.01 > p > 0.001; *** means p < 0.001; ns means p > 0.1.

Table 6. Statistical comparisons of surfacing and respiration characteristics of bowheads during aircraft altitude experiments in 1981-83. Dive duration is excluded because of low sample sizes. Plus signs indicate that the mean value was greater when the aircraft was at low altitude; minus signs indicate that the mean was greater at high altitude. Data for 1981-82 are from Richardson et al. (1983c).

	Experiments							
Parameter	6 Sep '81 610 m, 457 m 305 m	8 Sep '81 610 vs. 305 m	8 Aug '82 457 vs. 305 m	31 Aug '82 457 vs. 305 m	17 Aug '83 305 vs. 457 m	22 Aug '83 Flt. 20 610 vs. 305 m	22 Aug '83 Flt. 21 610 vs. 305 m	Pooled[a]
Blow Interval								
Type of Test	ANOVA	t	t	t	t	t	t	
Test Statistic	-6.04	-2.45	-0.67	-2.59	-1.96	+1.51	-0.30	
df	2,122	148	44	91	90	84	98	
Probability	-0.003	-0.015	-0.51	-0.011	-0.050	+0.13	-0.76	-,<0.001
z[a]	-2.97	-2.43	-0.66	-2.58	-1.96	+1.51	-0.30	-3.54
No. Blows/Surfacing								
Type of Test	t (610 m vs. 457 m)	t	t	t	t	t	t	
Test Statistic	-0.17	-0.88	+3.11	+0.53	-3.29	-0.49	+2.92	
df	9	13	10	7	56	37	22	
Probability	-0.87	-0.39	+0.011	+0.61	-0.0019	-0.63	+0.0078	+0.68
z	-0.16	-0.86	+2.54	+0.51	-3.13	-0.48	+2.66	+0.41
Duration of Surfacing								
Type of test	ANOVA	t	t	t	t	t'	t	
Test Statistic	± 0.063[b]	-1.74	+1.65	+1.09	-3.67	-2.20	+0.98	
df	2,10	16	10	7	58	24.46	22	
Probability	0.95	-0.10	+0.13	+0.31	-0.00063	-0.036	+0.35	-,0.15
z	(0.06)	-1.65	+1.51	+1.02	-3.46	-2.10	+0.93	-1.44

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[a] Pooled z and p values are based on the unweighted z method (Rosenthal 1978); z is the normal (0,1) statistic.

[b] Two values are possible because the trend from 610 m a.s.l. to 457 to 305 m was not linear.

Table 7. Contingency analyses for behavioral variables recorded during aircraft altitude experiments on 17 and 22 August 1983. Excludes calves and periods of potential disturbance from sources other than the aircraft. Variables were scored once per surfacing.

Date (and Flight)	Aircraft Altitude (m a.s.l.)	Frequency of Turning			Speed of Motion			Frequency of Pre-dive Flexes			Frequency of Fluke-out Dives			Frequency of Aerial Behaviors		
		No Turns	Turns	chi^2	Zero-Slow	Mod-Fast	chi^2	No Flex	Flex	chi^2	No Flukes	Flukes	chi^2	None	Some	chi^2
17 Aug.	457	11	2	0.07, ns	11	7	(4.37*)^a	19	4	(5.28*)^a	20	3	0.25, ns	41	0	a
(Fl. 15)	305	35	8		18	2		45	1		49	5		70	1	
22 Aug.	610	13	10	(0.08)^a, ns	7	2	a	21	8	2.66, ns	12	15	0.49, ns	12	19	2.40, ns
(Fl. 20)	305	3	3		3	1		14	1		5	10		10	6	
22 Aug.	610	16	5	(1.14)^a, ns	16	3	2.49, ns		N/A^b		28	10	0.27, ns	53	1	a
(Fl. 21)	305	2	2		13	8					19	9		46	1	
Pooled: 15, 20, 21	≥457	40	17	0.39, ns	34	12	0.03, ns	40	12	10.14**	60	28	1.14, ns	106	20	6.63*
	305	40	13		34	11		59	2		73	24		126	8	

[a] chi^2 analysis may not be meaningful because of low expected values.

[b] Conditions during Flight 21 precluded collection of accurate data for pre-dive flexes.

* means $0.05 > p > 0.01$; ** means $0.01 > p > 0.001$; ns means $p > 0.1$.

Aerial behaviors were infrequent except during the Flight 20 experiment on 22 August, when aerial behaviors were exhibited by several individuals (Würsig et al. 1984). The most active whale exhibited many breaches and tailslaps during both phases of the experiment, but significantly more rolls ($p<0.01$) and flipper slaps ($p<0.01$) after the aircraft descended from 610 m a.s.l. to 305 m (Table 9). However, the whale began these last two behaviors several minutes before the descent, so it is not possible to attribute their initiation or increase in frequency to the lower altitude of the aircraft. Rolls and flipper slaps occurred in bouts, as did breaches and tailslaps; periods of inactivity were followed by a flurry of repeated behaviors. The active whale was alone throughout the high altitude phase of the experiment, but was occasionally paired with another individual with which it socialized while the aircraft circled at 305 m. The overall altitude-related difference in frequency of aerial behaviors (Table 7) is based mainly on the data from Flight 20, and should be viewed with caution. The infrequency of aerial behaviors makes it difficult to determine whether they ever represent reactions to aircraft.

Bowhead calls were detected during both high and low altitude phases of all three experiments in 1983 (Table 10). On 17 August, call rate increased when the aircraft climbed. In contrast, during both tests on 22 August, call rate increased when the aircraft descended. Overall, the seven types of calls that we distinguished occurred in similar proportions during the high and low altitude phases of the 1983 experiments. No interpretable data on call rates were obtained from the altitude experiments in earlier years. 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 1981-83. During uncontrolled observations in 1983, the average blow interval was also lower when the aircraft circled at lower altitudes, and turns were less frequent. During experiments in 1983, the number of blows per surfacing, duration of surfacing, and frequency of pre-dive flexes tended to be lower when the aircraft was low.

Table 8. Comparison of rates of underwater blowing by bowheads during aircraft altitude experiments in 1983. Data are pooled from all three experiments.

Aircraft Altitude (m a.s.l.)	No. of Underwater Blows per Whale-hour of Observation when Whales Underwater					
	Flt. 15	Flt. 20	Flt. 21	Mean	s.d.	n
457-610	7.45	0.64	1.53	3.21	3.70	3
305	3.79	1.42	0.94	2.05	1.53	3
	Paired t = 0.88, df = 2, ns					

Table 9. Frequencies of aerial behaviors by 5-min period for Whale 2 during aircraft altitude experiment on 22 August 1983, Flight 20.

Aircraft Altitude m (a.s.l.)	Mean	s.d.	n[a]	Mean	s.d.	n
	Breaches			**Tailslaps**		
610	4.0	2.54	10	3.0	2.91	10
305	3.2	0.84	5	1.4	1.52	5
	t = 0.68, df = 13, ns			t = 1.14, df = 13, ns		
	Rolls			**Flipper Slaps**		
610	0.7	1.34	10	0.4	1.26	10
305	4.0	2.83	5	9.0	9.03	5
	t = -3.13**, df = 13			t = -3.07**, df = 13		

[a] n = number of 5-min periods.

** means 0.01 > p > 0.001; ns means p > 0.1.

Table 10. Numbers and types of bowhead sounds recorded during aircraft altitude experiments, 1983. Data compiled by C.W. Clark.

Date	Observation Time (MDT)	Aircraft Altitude (m)	Whales' Activity	Received Level of Calls[a]	Approx. No. Whales	Whale-h of Observation	No. Sounds of Each Type								Calls per Whale-h
							Up	Down	Constant	Inflected	High	Harmonic	Pulsive	Total	
17 Aug '83	12:10-12:29	305	Socializing	Loud	15	4.8	0	0	0	0	0	0	0	0	0.0
				All	–	–	2	1	1	1	1	3	0	9	–
	12:30-13:19	457	"	Loud	15	12.3	4	3	2	1	1	3	0	14	1.1
				All	–	–	19	8	10	2	7	5	1	52	–
22 Aug '83 (Flight 20)	10:23-11:05	610	Aerial	Loud	6	4.2	3	3	0	2	1	2	0	11	2.6
				All	–	–	8	13	1	11	5	5	0	43	–
	11:07-11:40	305	"	Loud	4	2.2	1	2	0	3	1	2	1	10	4.5
				All	–	–	11	12	5	6	4	8	2	48	–
22 Aug '83 (Flight 21)	15:31-16:45	610	Little movement	Loud	9-11	12.3	10	0	0	0	0	1	1	12	1.0
				All	–	–	24	1	4	0	7	8	4	48	–
	16:45-18:03	305	"	Loud	9-11	13.0	16	1	7	1	4	7	1	37	2.8
				All	–	–	51	12	25	4	4	19	3	118	–
All 1983 at altitude 457-610 m			As above	Loud	–	28.8	17	6	2	3	2	6	1	37	1.3
				All	–	–	51	22	15	13	19	18	5	143	–
All 1983 at altitude 305 m			As above	Loud	–	20.0	17	3	7	4	5	9	2	47	2.4
				All	–	–	64	25	31	11	9	30	5	175	–

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[a] This column gives the number of calls that were loud (as received at the sonobuoy) as well as the total number of calls detected.

Helicopter Overflights

On 31 August, a helicopter (probably a Bell 412) flew at ~153 m a.s.l. beneath us as we observed bowheads. No overt responses were noticed at the time of helicopter passage. Surfacing and respiration characteristics in the 26 min prior to the passage of the helicopter were compared to those in the 30 min following passage (Table 11). No significant differences were found, even though a Turbo-Commander fixed-wing aircraft flew over the whales at ~153 m a.s.l. several times during the 30-min period after the helicopter passed. Insufficient data on other behavioral variables were available for comparisons. Other confounding factors included the presence of seismic and other industrial noise from nearby sites.

A similar situation existed on 1 September when a Bell 412 helicopter passed at 153 m a.s.l. through the same observation area. As before, no overt responses attributable to the passage of the helicopter were noticed. Because of low clouds, we could not obtain quantitative data during the period of helicopter passage.

Table 11. Summary statistics for the principal surfacing and respiration characteristics[a] of bowheads observed during helicopter overflight on 31 August 1983.

Variable	Time re Helicopter	Mean	s.d.	n	Test Statistic
Blow Interval (s)	Before	16.25	6.496	16	t = 0.65
	After	14.86	7.012	28	df = 42
					ns
No. Blows/Surfacing	Before	4.33	3.215	3	t = -0.22
	After	4.80	2.775	5	df = 6
					ns
Duration of Surfacing (min)	Before	0.85	0.769	4	t = -0.67
	After	1.17	0.691	5	df = 7
					ns

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[a] Too few data available for analysis of duration of dives or other behavioral variables.

The whales observed on 31 August and 1 September were on the direct line between the 'Kulluk' drillship and the helicopter base at Tuktoyaktuk. During those two days there probably were several additional helicopter flights over or very near the whales.

Discussion

Variation in Sensitivity to Aircraft

Responses of bowheads to aircraft are quite variable. Richardson et al. (1983b) and Malme et al. (1983) reviewed the literature on responses of whales to aircraft. Their conclusions agree with those of this study: while whales often show a graded response relative to aircraft altitude, the response is not absolutely predictable, either qualitatively or quantitatively. Under similar conditions, responses may range from no overt reaction to a dramatic disruption of activities and dispersal. Between these extremes is a range of variations in apparent response, often involving subtle behavioral variables. However, our findings and the limited literature suggest that aircraft affect some aspects of behavior more consistently than other aspects.

Disruption of activity and/or dispersal do not always occur in response to an aircraft overhead. Although those responses were observed on several occasions in 1983 and once in 1982 (Richardson et al. 1983c), the most dramatic cases were during Flight 16 on 17 August 1983. The whales were initially very close to shore, in quite shallow water off Kay Point. They dispersed into deeper water when the observation aircraft began circling at 457 m a.s.l. Later in Flight 16, whales showed decreased socializing and again dispersed in apparent response to the aircraft. The latter whales had recently been subjected to approach by a vessel and playback of drillship noise; some may have been among the animals that dispersed from the location closer to shore when the aircraft began circling. The unusually pronounced reactions noticed during Flight 16 may have been related to the multiple sources of potential disturbance (aircraft, boat, playback) during this flight. Increased sensitivity due to the cumulative effects of several disturbances has been suspected previously (Fraker et al. 1982; Richardson et al. 1983c).

These observations from 1983 also suggest that shallow water or proximity to shore may also increase sensitivity to potential disturbances. Ljungblad et al. (1983) reported that, during early August, 97% of the bowheads seen in deep water and heavy ice appeared to react to the survey aircraft at 280 m a.s.l. In contrast, in late September, 92% of the bowheads seen in ice-free, shallower water (but still many kilometres from shore) showed no detectable response. These observations suggest that factors restricting horizontal movement (i.e. ice or shore) may influence sensitivity to disturbances. Seasonal variations in response have also been reported: whales observed in late spring frequently dived as the aircraft approached, while in autumn they tended to remain at the surface even as the aircraft circled for extended periods (Ljungblad et al. 1980).

The responsiveness of bowheads to aircraft may also depend on behavioral state. Bowheads engaged in socializing appear less sensitive to aircraft than are bowheads engaged in other activities. Though the socializing group seen on 9 August 1983 was temporarily disrupted, the whales eventually resumed socializing, even in the continued presence of the aircraft and with seismic noise. Whales observed on 17 August 1983 (Flight 15) continued socializing in spite of our aircraft circling at 305 m. 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, observations by Ljungblad (1981) suggested that mating groups of bowheads in Bering Strait were less prone to disturbance than were migrating whales.

Reactions of right and gray whales to aircraft may also be less pronounced when socializing. Payne et al. (1983) noticed that interacting groups of southern right whales (Eubalaena australis) showed little reaction to a Cessna 180 circling at 65-150 m a.s.l. In contrast, isolated individuals often reacted to the aircraft. Malme et al. (1983) observed the responses of socializing gray whales to a single-engine aircraft circling first at 400 m and then at ~60 m. Socializing continued when the aircraft was at 400 m. Upon descent, all observable socializing ceased and the whales dispersed, but they resumed their activities after the aircraft left.

Bowheads may also be less sensitive to aircraft when feeding, especially in groups. For example, Fraker et al. (1982) 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 to be 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).

Characteristics of Responses to Aircraft

Disruption of activities and dispersal were mentioned above as occasional but inconsistent responses of bowheads to aircraft. Other behavioral responses also occur at certain times.

Aerial behaviors have occasionally been reported as possible responses to aircraft (Richardson et al. 1983c). Our observations during 1983 are equivocal on this point. In several cases (e.g., Flights 4, 5, and 20) aerial behaviors were already in progress before the aircraft arrived. In two of these cases, the behaviors changed qualitatively while the aircraft was present (Flight 4—flipper-slapping whale began breaching after we flew over at 305 m a.s.l.; Flight 20—breaching and tailslapping whale began flipper-slapping). However, in neither case was the change definitely attributable to the presence of the aircraft. Ljungblad et al. (1983) reported that bowheads occasionally slapped their tails as an aircraft circled at 600 m, possibly as an overt display toward the aircraft. In any case, aerial behaviors are not a consistent response to the presence of aircraft.

Changes in orientation have also been suggested as responses to the presence of aircraft. However, as in 1982, we found no relationship between aircraft altitude and frequency of turns during our altitude experiments in

1983. Perhaps the initial response when an aircraft first passes over is more pronounced than is evident in our altitude experiments, in which most data are collected after the aircraft has 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 his light aircraft came overhead; however, most did not show such a clear reaction.

Sudden or hasty dives are the most frequently reported responses by bowhead whales approached by aircraft. This response is more evident when aircraft are at lower altitudes (Fraker et al. 1982; Ljungblad et al. 1983; Richardson et al. 1983c). The pooled results of the 1983 experiments indicated that, when the aircraft was low, the whales made significantly fewer blows and remained at the surface for significantly shorter periods. Overall results from 1981-1983 indicated that, when the aircraft was low, blow intervals were significantly reduced, and there was a tendency towards shorter durations of surfacings. The general pattern appears to be one of reducing exposure at the water's surface.

These results are consistent with our subjective impression of a 'quickening' of the motions preceding a dive in apparent response to low-flying aircraft. The results are also consistent with the significant reduction in frequency of pre-dive flexes during low altitude observations in 1983. Pre-dive flexes occur 3-7 s before many dives by presumably undisturbed whales, and they prolong the time at the surface.

Subtle responses, such as reduced blow intervals, surface durations, or numbers of blows per surfacing, have typically been measured during prolonged periods of circling over the same whales, whereas hasty dives have been reported by observers making single passes over whales. Responses to single passes vs. circling aircraft need to be examined more closely. During actual offshore operations by the petroleum industry, whales are more likely to be exposed to single passes rather than to circling aircraft. Responses by whales may be related both to aircraft altitude and to temporal characteristics of the exposure. Bowheads in Baffin Bay almost always dove when overflown by a Twin Otter at 90 m a.s.l., but usually did not dive during the first pass at 150 m; there was little observable response to the aircraft at 300 m (W.R. Koski, LGL Ltd., pers. comm.). During our Flight 16, the socializing whales that reduced their socializing and dispersed as the Islander began circling them had been socializing at the periphery of our circle for quite some time before circling began. These whales had been subjected to several overflights by the aircraft, but showed no obvious response until they became the focus of the circle.

Reactions in Relation to Aircraft Noise Characteristics

Our sonobuoys show that aircraft noise is prominent in the water directly below the observation aircraft. However, when the aircraft flies over, the noise received at the sonobuoy hydrophone 18 m deep is strong for only a few seconds. Even under near calm conditions, when masking by ambient noise is least, the aircraft is usually audible for <30 s when monitored via hydrophones 9 or 18 m deep (Greene 1982). This means that the sound usually would be detectable at 9-18 m depth no more than a few hundred metres ahead, behind or to the side of the aircraft. Consequently, when an observation aircraft circles to observe bowheads, little if any aircraft noise would be detectable at 9 or 18 m depth at the center of the circle.

However, whales closer to the surface--especially in shallow water--will be exposed to higher levels of aircraft noise. To understand why this is so, the propagation path for noise travelling from an aircraft to a bowhead must be taken into account. This path is partly or largely through air. Hence, distance from source, water depth, and depth of receiver all affect aircraft noise differently than noise from in-water industrial sources (Urick 1972; Young 1973; Greene 1982, 1984; Richardson et al. 1983b). Of particular relevance here, underwater noise levels below an aircraft are higher just below the surface than at deeper depths (e.g., a few decibels higher at 3 m than at 9 m depth--Greene 1984). Also, underwater noise is detectable farther ahead, behind and to the side of the passing aircraft when the water is shallow than when it is deep (Urick 1972; Greene 1984).

The reduction in received level with increasing depth may be one reason why whales tend to dive hastily when an aircraft approaches. However, it is also possible that the diving response when an aircraft first approaches is a startle reaction to either the sound or the sight of the aircraft. If so, the immediate reaction may have little or no connection with the reduced noise level that can be achieved by diving.

The greater lateral propagation of underwater sound when the water is shallow may have been responsible for the seemingly greater sensitivity of bowheads to our observation aircraft in 1983 than in earlier years. Many observations in 1983 were in very shallow water. Some of the most conspicuous responses to the aircraft in 1983 were in water <10 m deep and <1 km from shore (17 August 1983, Table 2). Besides the effect of the shallow water, the background noise level was also rather low on this occasion (92 dB in the 10-1000 Hz band). The low background noise would result in a higher-than-normal signal to noise ratio for aircraft noise relative to background noise. Thus, the low background noise level as well as the shallow water probably was a factor in the unusually high sensitivity of bowheads to the aircraft on this occasion.

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 1982, 1984). Consequently, one might wonder why whales generally react less to aircraft at high than to those at low altitudes. One possibility is that much of the response is actually to the sight of the aircraft, or perhaps its shadow, rather than to noise. While sight may be important, the playback results of Malme et al. (1983) indicate that gray whales respond to helicopter noise *per se*, at least when the noise from a single pass is repeated at frequent intervals (see below). Another possibility is that whales 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, 1984).

Reactions to Helicopters

Helicopters are the most frequent sources of potential aircraft disturbance in offshore oil operations. With the exception of a single opportunistic overflight by a Bell 412 helicopter during 1983 (Table 11), our behavioral data on responses of bowheads to aircraft have involved only fixed-wing aircraft. No significant changes in behavior were found in response to the one helicopter overflight. However, there were other sources of potential disturbance at the time, and the results are inconclusive. Dahlheim (1981) stated that, during early spring, bowheads were rarely disturbed by two Sikorsky H52-A turbine-powered helicopters flying surveys at 152-228 m. Berzin and Doroshenko (1981) indicated that some bowheads in the Sea of Okhotsk during August paid 'no attention' to a MI-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.

Malme et al. (1983) conducted controlled experiments on the responses of gray whales to helicopter sounds. The underwater sound of a Bell 212 helicopter recorded in the Beaufort Sea (Greene 1982) was projected at random intervals of 10 s to 2 min. Shore-based theodolite tracking of migrating whales showed a significant response to the sounds. The helicopter noise resulted in deflections of the whales' courses in apparent avoidance of the sounds, and the whales slowed down both before and after passing the sound source. However, the tests by Malme et al. were not designed to determine whether gray whales would respond to noise from a single helicopter overflight, which would be a more realistic case. It is also unknown whether underwater playbacks of recorded helicopter noise are an adequate simulation of noise during an actual helicopter overflight.

Without observations of bowheads during controlled helicopter overflights or helicopter noise playbacks, we can only speculate on relative responses to helicopters vs. fixed wing aircraft. Greene (1982) found that 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. 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 detectable underwater noise for only a brief period--little different than that from the Islander or Twin Otter (Greene 1982). 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 1982). It seems doubtful that a single pass by a helicopter would elicit a prolonged reaction by bowhead whales, but this remains to be tested.

REACTIONS OF BOWHEADS TO BOATS

Vessel traffic is a major source of potential noise 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, tugs and barges, dredges, seismic vessels, icebreakers, and drillships moving between sites (see Richardson et al. 1983a, 1984 for a discussion of the intensity of this activity). Most of the vessel traffic is within the area where oil exploration is now occurring (Fig. 1). Bowhead whales summering in this area are exposed to potential vessel disturbance, and there is also the possibility of collisions.

Our 1980-82 work showed that short-term behavioral reactions to boats were more conspicuous than were reactions to any of the other industrial activities studied (Fraker et al. 1982; Richardson et al. 1983c). Bowheads responded to boats in two main ways. (1) Whales altered their surfacing and diving pattern by decreasing the mean duration of surfacing, mean number of blows per surfacing, and mean dive duration. In 1980, even a stationary 16-m boat idling 3-4 km from whales led to reductions in mean duration of surfacing and mean number of blows per surfacing. (2) Whales within 1-3 km of an approaching boat swam rapidly away and scattered. Bowheads directly on the boat's track initially tried to outdistance it, but usually turned to move off the track as the boat closed to within a few hundred metres. This flight reaction ceased after the vessel was 1-2 km beyond the whales, but increased spacing between whales sometimes persisted longer. As far as we could determine, none of the observed boat disturbances resulted in long-distance displacement. However, the effects of more frequent boat disturbances, or disturbances when whales and ships are both confined within ice leads or near shore, remain unknown.

Boat disturbance studies were not identified as a priority in 1983. However, one boat disturbance experiment was conducted using 'Sequel', the same chartered vessel used for similar work in 1981-82. Also, opportunistic observations of whales were obtained from 'Sequel' again in 1983.

Methods

'Sequel', a 12.5-m former fishing boat, is described in 'General Methods'. Methods of observation from 'Sequel' in 1983 were the same as in 1981-82, except that there was an additional observer in 1983. When bowheads were encountered, observers on the flying bridge 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. Observers aboard 'Sequel' recorded whale orientations in clock-face co-ordinates (see Fraker et al. 1982, p. 165-166, for details). Whales oriented from 10 through 2 o'clock were considered to be oriented 'away' from the boat; 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 analyses in 1983.

Distance and orientation data were collected from 'Sequel' on 16, 17, 18, 19, 22, 23, 26, and 28 August 1983, including observations during a boat disturbance experiment on 18 August. These data were pooled and used for analysis of whale orientations relative to distance from 'Sequel' under four conditions: (1) engine turned off within past 30 min, (2) engine off for over 30 min, (3) boat underway at idle speed, ~5.6 km/h, and (4) boat underway at 'high' speed, ~14-16 km/h. These data were also pooled with similar data from 1981-82, using the same 'engine off' categories, but combining the 'underway' data into a single 'engine engaged' category.

On 18 August, a boat disturbance experiment was conducted north of Kay Point, Y.T., near 69°21'N, 138°26'W. 'Sequel' had been anchored for over 2.5

h prior to the arrival of the observation aircraft. The aerial observers located 15-20 whales 9 km to the south of 'Sequel' and several kilometres from shore. We observed the whales for 47 min, and then directed 'Sequel' to head toward the whales. Water depth was 10 m, sea state was 3, and the observation aircraft was at 610 m a.s.l. The stages of the experiment are described in Table 12. The vessel moved towards and through the concentration at 16 km/h, and then anchored 4 km south of the concentration. Behavior of whales within ~9 km of the boat was recorded by the aircraft crew. For analyses of orientations, distances and bearings, we attempted to tally individual whales only once during each stage of the experiment. However, it was rarely possible to identify a given whale from one surfacing to the next, so some individuals were undoubtedly tallied more than once.

Results

Boat-based Observations

Bowheads observed from 'Sequel' in 1983 tended to orient away from the boat under a variety of conditions (Fig. 2). Of the distant whales (arbitrarily defined as >900 m from 'Sequel'), significantly more oriented away from rather than toward the boat as it moved rapidly (100% away, $p<0.05$). Slightly more oriented away than toward even when the engine had been off for >30 min (64% away, $p<0.05$). Distant whales appeared to orient randomly relative to the boat as it idled ahead, but the sample was small. Whales within 900 m of 'Sequel' oriented randomly relative to the boat when the engine had been off for >30 min, but tended to orient away during the first 30 min following shutdown (77% away, $p<0.05$) and when the boat was underway at high speed (84% away, $p<0.01$).

Pooled orientation data collected from 'Sequel' during 1981-83 showed roughly similar trends (Fig. 3). Whales more than 900 m from 'Sequel' showed a tendency to orient away during 'engine off' periods. However, the tendency for distant whales to orient away while the boat was underway was not significant (note the low sample size--Fig. 3). Whales within 900 m of 'Sequel' showed a graded response: whales were randomly oriented when the boat had been quiet for >30 min. There was a non-significant tendency for

Table 12. Description of events in a boat disturbance experiment involving the boat 'Sequel' on 18 August 1983.

Time (MDT)	Event
19:54-20:41	'Quiet Boat'--'Sequel' anchored since 17:07 approximately 9.3 km due north of a concentration of about 15-20 whales. The whales are several kilometres north of Kay Point, Y.T.
20:41-20:57	'Far Boat'--'Sequel' starts engine, and motors rapidly (approx. 16 km/h) to the south, towards the concentration. The whales are >4 km away.
20:57-21:06	'Near Boat'--'Sequel' continues rapidly to the south, 2-4 km from the whales.
21:06-21:28	'Close Boat'--'Sequel' continues moving rapidly, and passes through the whale concentration. All whales are within 2 km of the boat.
21:28-21:41	'Post Boat'--'Sequel' stops and anchors about 4.3 km south of the previous center of the concentration of whales. Insufficient data collected during this phase to allow comparisons.

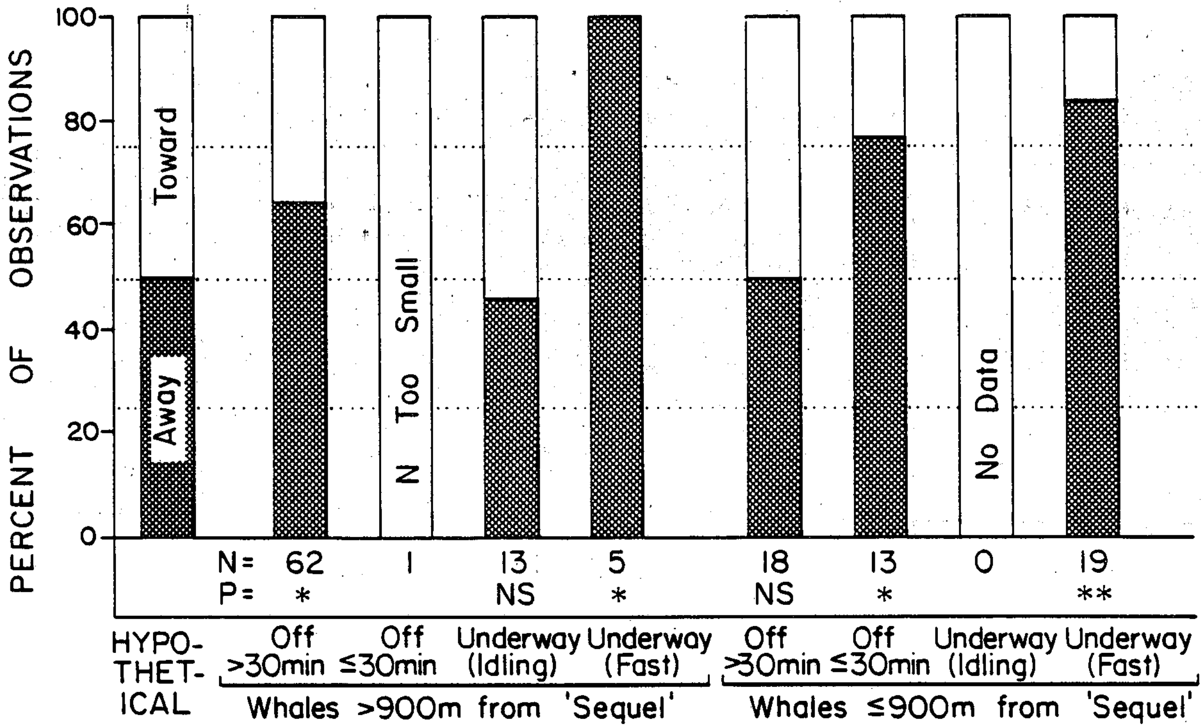


FIGURE 2. Orientations of bowheads observed from the boat 'Sequel' during 1983. Includes data from a boat disturbance experiment on 18 August as well as opportunistic observations. Hypothetical orientations are those expected if whales were randomly oriented with respect to the boat; whales moving tangentially are excluded (see text). Significance determined by one-sided binomial tests; ns means $p > 0.1$, * means $0.05 \geq p > 0.01$, ** means $0.01 > p > 0.001$.

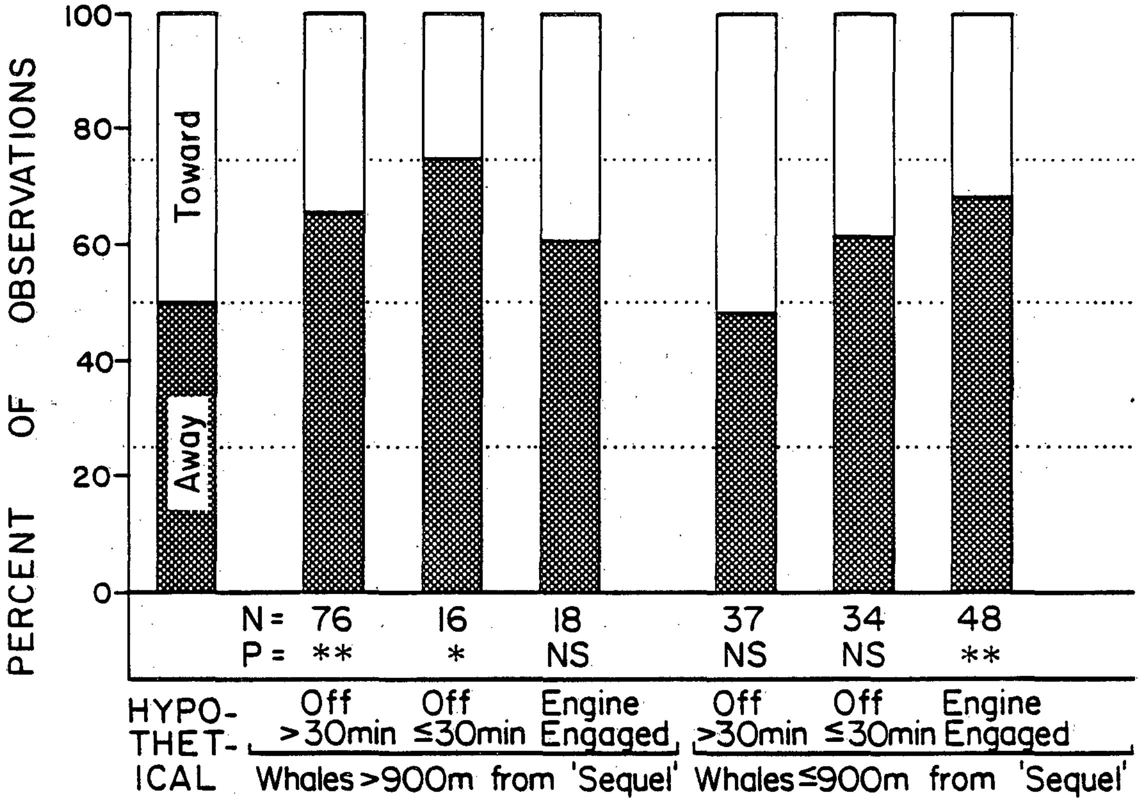


FIGURE 3. Orientations of bowheads observed from the boat 'Sequel' during 1981-83. Includes data from three boat disturbance experiments as well as opportunistic observations. Plotted as in Fig. 2.

orientation away from the boat immediately following shutdown, and a somewhat stronger tendency when the boat was underway ($p<0.01$).

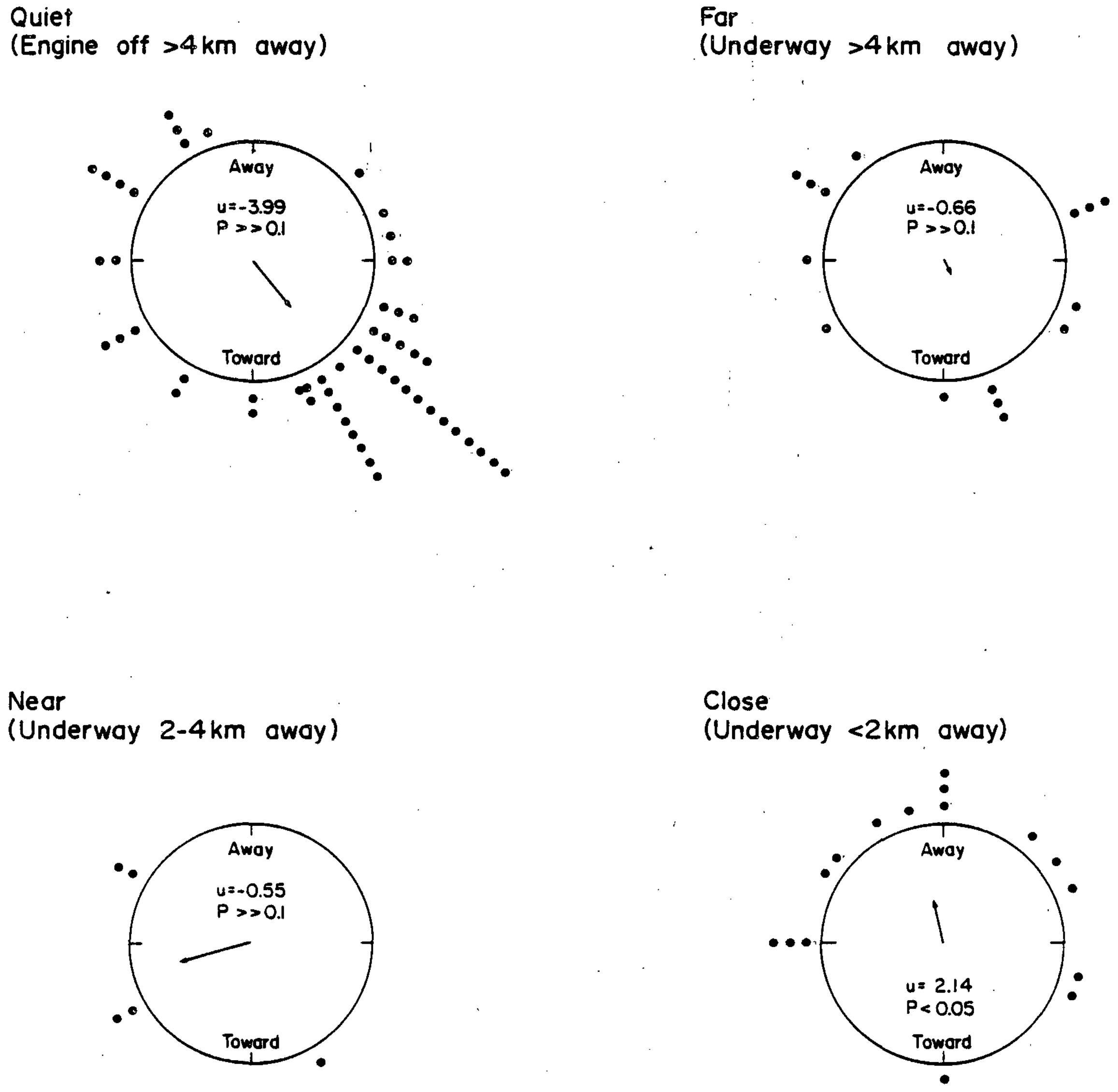
In general, the tendencies to orient away from the boat were stronger in 1983 than in 1981-82, when whales appeared to orient randomly relative to 'Sequel' regardless of distance or engine condition (Richardson et al. 1983c). The 1983 data were responsible for the trends exhibited in the pooled data. The reasons for differences between the 1983 and 1981-82 data are not known. Observations from the crew boat 'Imperial Adgo' in 1980 showed that reactions to it were stronger than those to 'Sequel' in 1981-83, probably because 'Adgo' is a more powerful, faster (41 km/h) and noisier boat.

Boat Disturbance Experiment

As in similar experiments in 1981-82, bowheads observed from the circling aircraft responded strongly to Sequel's approach by swimming rapidly away from the vessel. The distributions of whale orientations relative to 'Sequel' differed significantly between the two most extreme stages of the experiment, 'quiet boat' vs. 'close boat' (Fig. 4; Kuiper's $K = 539.4$, $n_1 = 16$, $n_2 = 55$, $p<0.002$). While the boat was >2 km from the whales, there was no evidence of orientation away from the boat (V-tests, $p >> 0.1$; Fig 4). However, when the boat was approaching the whales and within 2 km, the whale orientations relative to 'Sequel' were significantly clustered in the 'away' direction ($p<0.05$, Fig. 4).

As in 1981-82, it was difficult to define the greatest distance at which whale orientations were affected by the boat. Whales 2-4 and 4-9 km from the approaching boat (Fig. 4) did not orient consistently away from it. However, orientations of these whales were significantly different than those of whales when the boat's engine was off (Kuiper test, $K = 479.6$, $n_1 = 55$, $n_2 = 20$, $p<0.05$).

Reactions of whales to 'Sequel' during the 1983 experiment were also evident in comparisons of behavioral variables other than orientations. Significantly more whales moved at moderate to fast speed when the boat was within 4 km than when the boat was >4 km away and either stopped or moving



Quiet
(Engine off >4 km away)

Far
(Underway >4 km away)

Near
(Underway 2-4 km away)

Close
(Underway <2 km away)

FIGURE 4. Orientations of bowheads during four phases of a boat disturbance experiment, 18 August 1983. See Table 12 for further definition of the four phases. 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 u and p values summarize V-tests (Batschelet 1981) of the hypothesis that there was significant orientation away from 'Sequel'.

($p<0.05$, Table 13). Significantly reduced blow intervals ($p<0.05$) and durations of surfacing ($p<0.05$) were found for whales within 4 km of 'Sequel' compared to those for whales farther away (Table 14).

The results of the surfacing and respiration comparisons for all three experiments involving 'Sequel' during 1981-83 were pooled using the unweighted z method (Rosenthal 1978). No consistent trends were evident across all three experiments (Table 15). However, the pooled results revealed reduced durations of surfacing as the boat approached.

Discussion

The results of our previous research on responses of bowheads to vessels have been described by Fraker et al. (1982) and Richardson et al. (1983c). Recent literature reviews by Malme et al. (1983) and Richardson et al. (1983b) describe the responses of various baleen whales to vessel traffic. Here we concentrate on our results from 1983.

The responses of bowheads to 'Sequel' in 1983 were qualitatively similar to, but quantitatively more marked than, reactions to the same vessel in 1981-82 (cf. Richardson et al. 1983c). The response to 'Sequel' in 1983 was similar to the reaction to 'Imperial Adgo', a 16-m twin-engine crew boat used in 1980 (Fraker et al. 1982).

The marked flight response recorded by observers in the aircraft in 1983 was consistent with reactions of bowheads to various boats in previous years. In general, it appeared that whales began to orient away from the approaching vessel when it was as much as 4 km away. When the vessel was within 2 km, significant proportions of the whales oriented away and increased speed. Changes in surfacing and respiration patterns also became evident. The pooled results from our three experiments with 'Sequel' (1981-83) reveal a significant reduction in mean duration of surfacing.

The response of bowheads to boats is most dramatic within several hundred metres of the boat and, as expected, seems to diminish with increasing range. However, we have seen reactions at least out to 3 or 4 km,

Table 13. Contingency analyses for behavioral variables recorded during boat disturbance experiment on 18 August 1983. Experiment compares two conditions: (1) 'presumably undisturbed', when 'Sequel' was >4 km from whales (the 'Quiet' and 'Far' phases of Fig. 4), vs. (2) 'potentially disturbed', when 'Sequel' was motoring <4 km from whales (the 'Near' and 'Close' phases of Fig. 4). Excludes calves. Variables were scored once per surfacing. All observations were by aircraft-based observers.

Variable	Condition	No. Surfacings with		chi^2 (df = 1)
		No Turns	Turns	
Frequency of turning	1	7	4 (36%)	(1.36)[a]
	2	7	1 (13%)	ns
		Zero to Slow	Mod. to Fast	
Speed of motion	1	17	24 (59%)	5.03*
	2	4	22 (85%)	
		No Flex	Flex	
Frequency of pre-dive flexes	1	15	4 (21%)	(0.67)[a]
	2	16	2 (11%)	ns
		No Flukes Out	Flukes Out	
Frequency of fluke-out dives	1	21	10 (32%)	1.66
	2	16	3 (16%)	ns

* means 0.05 > p > 0.01; ns means p > 0.1.

[a] chi^2 values questionable due to low expected values.

Table 14. Surfacing and respiration characteristics[a] of whales observed during boat disturbance experiment on 18 August 1983. All observations were by aircraft-based observers.

	Distance from Boat (km)	Blow Interval (s)			No. Blows per Surfacing			Duration of Surfacing (min)		
		Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n
Quiet Boat	9	16.22	10.873	46	3.89	1.833	9	1.03	0.593	9
Far Boat	4-9	15.41	9.616	29	5.00	1.414	2	1.43	0.306	3
Near Boat	2-4	11.75	4.989	24	3.00	2.449	4	0.51	0.601	4
Close Boat	<2	13.18	6.460	39	2.25	1.893	4	0.67	0.603	4
		F = 1.81, df = 3,134 ns			F = 0.99, df = 2[b],14 ns			F = 1.89, df = 3,16 ns		
Pooled Data:										
'Presumably Undisturbed'	4-9	15.91	10.346	75	4.09	1.758	11	1.13	0.553	12
'Potentially Disturbed'	<4	12.64	5.941	63	2.63	2.066	8	0.59	0.564	8
		t' = 2.32[c], df = 122.59 *			t = 1.67, df = 17 ns			t = 2.13, df = 18 *		

---

[a] Too few dive data were collected for analysis of duration of dive.

[b] 'Far boat' category excluded because of low sample size.

[c] t' is the Student's t statistic when population variances are not assumed to be equal.

* means $0.05 > p > 0.01$; ns means $p > 0.10$.

Table 15. Statistical comparisons of surfacing and respiration characteristics of bowheads during boat disturbance experiments with 'Sequel' in 1981-83. Dive durations excluded because of low sample sizes. Plus signs indicate that the mean value was greater when the boat's engine was on and it was within 4 km of whales; minus signs indicate that the mean was greater when the boat's engine was off or the boat was more than 4 km from whales.

	Experiments			
Parameter	25 Aug '81	16 Aug '82	18 Aug '83	Pooled[a]
Blow Interval				
Type of Test	t'[b]	t'	t'	
Test Statistic	+1.67	-0.68	-2.32	
df	86.82	35.65	122.59	
Probability	+0.095	-0.51	-0.021	-,0.45
z[a]	+1.67	-0.66	-2.31	-0.75
No. Blows/Surfacing				
Type of Test	t	t	t	
Test Statistic	-1.72	+1.38	-1.67	
df	60	13	17	
Probability	-0.087	+0.19	-0.11	-,0.25
z	-1.71	+1.32	-1.60	-1.15
Duration of Surfacing				
Type of Test	t	t	t	
Test Statistic	-2.29	+0.89	-2.13	
df	66	16	18	
Probability	-0.024	+0.39	-0.045	-,0.05
z	-2.26	+0.86	-2.00	-1.96

[a] Pooled z and p values are based on the unweighted z method (Rosenthal 1978); z is the normal (0,1) statistic.

[b] t' defined as in Table 14.

and perhaps to 5-7 km. Baker et al. (1983) described different responses for humpback whales, depending on the distance of vessels from the whales. Within 2-4 km, humpbacks engaged in 'horizontal avoidance', in which speed and blow intervals increased while dive durations decreased. Within 2 km of vessels, humpbacks began 'vertical avoidance', in which blow intervals and speed decreased, but the whales made longer (but not necessarily deeper) dives.

When bowheads were within 900 m of 'Sequel' (Fig. 3) or 'Adgo' (Fraker et al. 1982), a higher proportion were moving away when the boat was underway than when it was quiet. In contrast, observations from 'Sequel' suggest that distant whales (>900 m from boat) were at least as likely to orient away when the engine was off as when the engine was engaged (Fig. 3). This suggests that bowheads tended to continue to orient away from 'Sequel' for a considerable time after her engine stopped. This speculation must be treated with caution, since observations from 'Adgo' provided no evidence that bowheads tended to orient away when the engines were off (Fraker et al. 1982). Nonetheless, the observations from 'Sequel' are consistent with a recent observation concerning reactions of humpback whales to boats (Baker et al. 1983). Some humpbacks were most likely to move away from the paths of vessels <u>after</u> the vessels had reached their point of closest approach.

Our previous work has shown that the fleeing response does not persist for long after the boat moves away. However, bowheads do tend to orient away from the boat for some time after the boat has passed, and sometimes even after its engine has stopped. Also, increased inter-individual spacing sometimes continues longer than the flight reaction (Fraker et al. 1982). This could indicate some degree of social disruption. The long-term biological effects of one-time or cumulative disturbance of bowheads by boats remain unknown.

Bowheads respond to boats more dramatically and consistently than to any of the other industrial activities studied to date. 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

Geophysical exploration by impulses of sound 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) fired simultaneously several times per minute. There are typically 20-30 airguns in the array, and total gun volume is usually 20-65 L (1200-4000 in^3) of compressed air. Source levels are ~245-250 dB//1 µPa-m (R.C. Johnston and B. Cain, in Richardson et al. 1983b). Received noise levels exceed 150 dB//1 µPa to a radius of several kilometres, and the noise is often detectable 25-90 km away (Ljungblad et al. 1980, 1982a; Greene 1982, 1983, 1984; Malme et al. 1983; Reeves et al. 1983). Characteristics of the received pulses depend on propagation conditions and range. However, received pulses typically are ~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, p. 5-23).

We observed bowheads in the presence of seismic noise on 8 days in 1980-82, at ranges 6-73 km from the seismic vessel (Fraker et al. 1982; Richardson et al. 1983c). Received noise levels were 107-150 dB. There was no evidence that these whales were attempting to move away, and the usual types of calls were heard. Sometimes there were indications of unusually short surfacings and dives, and unusually few respirations per surfacing. However, these differences were small and not always evident. In the absence of control data from the same whales prior to the onset of the seismic noise, it was not certain that the apparent changes in behavior were attributable to the seismic noise.

In 1981, we conducted two controlled experiments with a single 0.66 L (40 in^3) airgun fired 5 and 3 km from bowheads. These experiments simulated the onset of seismic exploration by a full-scale seismic vessel ~20 km away. The general activities of the whales did not change when the airgun started firing. We did find subtle indications of altered surfacing, respiration and dive cycles, consistent with the uncontrolled observations near full-scale seismic vessels. Again, however, the results were not dramatic.

Similarly, bowheads have been seen in Alaskan waters as close as 3 km from operating seismic vessels (Ljungblad et al. 1980, 1982a; Reeves et al. 1983). Bowhead calls have been heard in the presence of seismic noise in Alaskan waters, and there have been no clear indications of whales moving away from approaching seismic boats. Reeves et al. (1983) described bowheads 'huddling' in a compact group in the presence of seismic noise, but they also observed similar behavior in the absence of such noise. Average surface times in Alaskan waters were marginally higher in the presence of seismic noise, contrary to our results from the Canadian Beaufort Sea. However, Reeves et al. found increased surface times on only 1 of 3 days when whales were watched in both the presence and the absence of seismic noise, and it is not clear that the apparent difference was attributable to the seismic noise.

Recent tests on gray whales provide the strongest evidence that whales are sensitive to seismic exploration (Malme et al. 1983). They tested reactions to a full-scale seismic vessel at 1-90 km range, and to a 100 in^3 airgun at ranges from <1 km to ~5 km. 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, which was the lateral 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. There was also some evidence of behavioral reactions to seismic noise with average pulse pressure levels of 140-160 dB (Malme et al. 1983).

In general, uncontrolled observations in Canadian and Alaskan waters have shown that bowhead whales often tolerate strong seismic pulses without displaying any avoidance reaction or other pronounced response. However, subtle behavioral effects have sometimes been suspected in the presence of seismic vessels and during our tests with one airgun. The recent experiments on gray whales demonstrated that avoidance reactions do occur when seismic noise is intense ($\geq$160 dB average pulse pressure), and possibly at lower levels. Seismic noise levels received during our observations of bowheads in the Canadian Beaufort Sea during 1980-82 were 107-150 dB, which may account for the variability and lack of conclusive results.

In 1983, we hoped to use three approaches to test the reactions of bowheads to seismic noise: (1) further opportunistic observations near ongoing seismic operations, (2) additional controlled tests of reactions to a single airgun, and (3) controlled tests of reactions to a full-scale seismic vessel. Approaches (1) and (2) were successful, but (3) was not possible for logistical reasons.

Methods

Opportunistic Observations with Seismic Noise, 1983

On four dates in 1983 we observed bowhead behavior when a seismic vessel was close enough to ensonify the water around the whales. On the first two occasions the vessel was 'GSI Mariner', a 36-m vessel using an array of 27 airguns of various sizes from 10 to 100 in^3 and totalling 1410 in^3, or 23 L. The source level of this array is 38 bar-m, peak to peak, or 246 dB//1 μPa-m (G. Bartlett, GSI, pers. comm.). The other two occasions involved the 'Western Aleutian' and the 'Arctic Surveyor'. 'Western Aleutian' is a 45-m vessel using an array of airguns with source level 250 dB (Reeves et al. 1983). 'Arctic Surveyor' used an array of 12 open bottom gas guns as the energy source during 1983; the source level was about 17-18 bar-m, or 239 dB (T. Buckley, Esso Resources Canada Ltd., pers. comm. to C. Greene).

On 7 August, we observed whales in deep water north of Mackenzie Bay while the 'GSI Mariner' travelled west over shallower water 79-99 km south and later SSW of the whales (Table 16). Initial observations were of two whales in ~950 m of water 79 km from 'GSI Mariner'. A sonobuoy showed that the received level of the seismic pulses was at least 127-131 dB//1 μPa while we were overhead (Table 16; data from Greene 1984). After 44 min of observation, we moved 18 km NE to a group of 4 adults and 3 calves in ~1370 m of water. 'GSI Mariner' was 95 km SSW when we began observations of the second group of whales, and was 99 km SSW 70 min later when seismic shooting stopped. No sonobuoy was deployed at the second location, but the sonobuoy at

Table 16. Observations of bowhead whales in the presence of noise from seismic exploration, Canadian Beaufort Sea, August–September 1983. ? means unknown.

Date	7 Aug		9 Aug	31 Aug	1 Sept
Location – N. Lat.	70°32'	70°40'	70°00'	69°51'	69°50'
W. Long.	138°10'	137°53'	139°00'	136°31'	136°30'
Water Depth (m)					
At Whales	950	1370	190	19	19
At Seismic Vessel	190	190–150	20–?	18	40–33
Sea State	2	2	1	1–3	1–3
Aircraft					
Altitude (m)	457	457	457	610	137–457
Type	Tw Ott.	Tw Ott.	Tw Ott.	Islander	Islander
Duration of Observations (min)					
With Seismic Noise	44	70	204	182	204
Without Seismic	0	20[a]	28[b]	0	0
Seismic Sounds					
Vessel	GSI Mariner		GSI Mariner	Arctic Surv.	Western Aleutian[c]
Range (km)	79	95–99	57–?	53–52	31–26–30
Bearing[d]	S	SSW	SW–?	E	NNW–NE
Aspect[e]	95°	105°	?	50°	55°–120°
Received Level[f]	127–131	see text	110–123	125–107	135–120
Ambient Level[g]	105–108	105	92–99	103–125[h]	98–109
Activity of Whales	?	Calves interacting; some rapid travel	Much socializing	Bottom feeding and some socializing	Bottom feeding and some socializing

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[a] After seismic ended.

[b] Before seismic started.

[c] Also faint pulses suspected to be from 'Arctic Surveyor', 67 km to the east.

[d] Bearing of ship relative to whales.

[e] 0° = whales ahead of ship; 90° = whales abeam; 180° = whales astern.

[f] Received levels are in dB//1 µPa and are conservative because of possible signal saturation problems in the sonobuoy/receiver system (see Greene 1984).

[g] Ambient levels are for the 10-500 Hz band. They were for sounds recorded between seismic pulses.

[h] On 31 August there was intermittent strong noise at 10–20 Hz, accounting for the wide range of levels in the 10-500 Hz band. The range of levels in the 20-500 Hz band was 101–111 dB.

the first location (then 80-81 km from the ship) was monitored while we circled at the second site. The level received at the sonobuoy seemed to decrease to 115-119 dB before shooting stopped, but the decrease may have been a measurement artefact (Greene 1984). The level near the second group of whales was probably slightly less than that at the sonobuoy.

On 9 August, we observed ~12 adult bowheads socializing in water 190 m deep north of Herschel Island while seismic impulses from 'GSI Mariner' were received (Table 16). No seismic noise was present for the first 28 min of observations, but then 'GSI Mariner' started firing her airguns 57 km SW of the whales. Subsequent movements of the ship are unknown, but seismic noise was detected via sonobuoy until our observations ended. Measurements of received levels of the seismic pulses ranged from 110 to 123 dB, but these are conservative figures because of possible overload in the sonobuoy/receiver system.

On 31 August, we found ~15 bowheads bottom-feeding and socializing in water 19 m deep while 'Arctic Surveyor' operated 52 km to the east (Table 16). We watched ~6 whales in detail for 3 h. A sonobuoy amongst the whales showed that received levels of the seismic pulses were at least 119-125 dB for the first 2 h, and then decreased to ~107 dB by the end of our observations.

On 1 September, we found ~5 bowheads at the same location as on 31 August. While we observed these whales, 'Western Aleutian' travelled ESE from a point 31 km NNW of the whales to a point 30 km NE. The closest point of approach was 26 km, mid-way through our observations. Initially, systematic behavioral observations were impossible because low cloud forced us to circle at 150 m a.s.l. However, the last 1.6 h of observation were from 457 m a.s.l. Received levels of the pulses from 'Western Aleutian' were at least 120-135 dB at various times during the observations. Again, these are minimum values because the strong pulses may have overloaded the sonobuoy system. Faint seismic pulses, probably from 'Arctic Surveyor' operating 67 km to the east, were heard simultaneously with the strong pulses from 'Western Aleutian'.

For quantitative comparisons of behavior with and without seismic noise during 1983, we considered two groups of data:

1. Behavior of whales in the presence of seismic noise on 7 and 9 August was compared with the few observations of 'presumably undisturbed' whales on the same dates. All of these observations were far offshore in water 190-1675 m deep. There were no other detailed observations in the 1-14 August 1983 period, and no other dates with observations in deep water.
2. Behavior with seismic noise on 31 August-1 September was compared with behavior of 'presumably undisturbed' whales on 22-28 August. There were no observations without seismic after 28 August. The observations on 22-28 August were in shallow water (<35 m) near the Yukon coast, 100 km from the location of the 31 August-1 September observations (depth 19 m). Observations during a flight on 26 August when there was much skim-feeding (Würsig et al. 1984) were excluded from the 22-28 August 'control' observations.

Airgun Experiment, 28 August 1983

In 1983 we performed one controlled test with a single Bolt 40 in^3 (0.66 L) airgun deployed from 'Sequel'. The airgun was the same type used for two similar experiments in 1981 (Fraker et al. 1982). Water depth was 13 m at Sequel's location while the airgun fired, and 11-12 m at the whales' locations. The airgun was fired at 6 m depth every 15 s for 25 min. The whales were observed from the Islander aircraft circling overhead at 610 m a.s.l. before, during and after the period of airgun firing (3.0 h, 0.4 h and 0.3 h, respectively). 'Sequel' travelled slowly (~6 km/h) around the whales at 2-6 km radius throughout this period (radius 3-4 km while airgun fired).

The airgun operated from compressed air tanks that had been filled to 2200 psi (152 bars) before pre-airgun control observations began. Thus there was no compressor noise during the experiment. By the end of the 25-min period of airgun firing, air pressure had dropped to about 400 psi (28 bars). Airgun sounds were monitored by two sonobuoys near the whales. The sonobuoys were about 2 and 5 km from the boat, with the whales between the sonobuoys. Because of the shallow water, the sonobuoy hydrophones were on the bottom.

Results

Opportunistic Observations in 1983

General activities of whales observed in the presence of seismic noise on four days in 1983 (Table 16) were typical of bowhead activities in the eastern Beaufort Sea. Whales surfaced, dove, socialized, and (on two days) fed near the bottom in the presence of seismic noise. There was no evidence that the whales were moving away from the seismic vessels. On 7 August, when seismic noise stopped while we were watching whales, no obvious change in behavior was noted when the noise ceased. Similarly, on 9 August, when seismic noise began while we were watching whales, no changes in behavior were noticed.

Detailed analysis of behavioral data provided very little evidence that bowhead behavior was affected by the noise from distant seismic vessels. In 1983, surfacing, respiration and dive characteristics in the presence of seismic noise were well within the usual ranges for 'presumably undisturbed' bowheads (Table 17). The mean values of behavioral variables sometimes did differ in the presence and absence of seismic noise. However, when all available data from 1980-83 were considered, the directions of the apparent effects were not consistent, and the overall trends were not statistically significant. Thus, our opportunistic observations of bowheads 6-99 km from seismic ships in 1980-83 provided no clear evidence that surfacing, respiration or dive characteristics were affected by seismic noise:

- Mean blow interval in the presence and absence of seismic noise differed significantly on 7-9 August 1983. Blow intervals tended to be shorter with seismic noise (Table 17). However, the mean value with seismic noise (15.2 s) was similar to the overall mean for undisturbed whales in 1980-83 (14.3 s). The mean value in the absence of seismic noise (19.6 s) was based on a small sample (n=15) and seemed atypical. On 22 Aug - 1 Sept, blow intervals with and without seismic noise were very similar (Table 17). When all 1983 results were pooled, blow intervals did not differ significantly in the presence and absence of full-scale seismic noise ($p>0.1$, Table 18). The same was true when all 1980-83 results were pooled ($p>0.7$, Table 18).

- Mean duration of surfacing and mean number of blows per surfacing tended to be greater in the presence of seismic noise in the 22 August-1 September 1983 period ($p<0.01$, Table 17). There were no significant differences on 7 and 9 August. However, values on all 4 days with seismic noise were well within the usual ranges for

Table 17. Surfacing, respiration and dive characteristics of non-calf bowheads observed in the presence and absence of seismic noise, 1983. ? means unknown.

Date(s)	Seismic Source	Mean	s.d.	n	t-test[a]	Mean	s.d.	n	t-test[a]
		Blows/Surfacing				**Duration of Surfacing (min)**			
7 Aug 1983	79–99 km from GSI Mar.	4.00	2.179	9		0.96	0.559	10	ns
9 Aug 1983	57– ? km from GSI Mar.	2.22	1.707	85		0.71	0.438	97	ns
7 + 9 Aug 1983	Above combined	2.39	1.821	94		0.73	0.453	107	ns
7 + 9 Aug 1983[b]	None	2.50	1.732	4		0.78	0.652	5	
31 Aug 1983	52 km from Ar. Surv.	4.64	2.498	25	**	1.15	0.560	29	**
1 Sep 1983[c]	26–31 km from W. Aleut.	4.67	2.082	3		1.18	0.150	3	
31 Aug + 1 Sep	Above combined	4.64	2.422	28	**	1.15	0.534	32	**
22–28 Aug 1983[b]	None	3.18	2.300	66		0.74	0.566	59	
		Blow Interval (s)				**Dive Duration (min)**			
7 Aug 1983	77–99 km from GSI Mar.	14.75	6.772	56	*	4.32	0.724	3	
9 Aug 1983	57– ? km from GSI Mar.	15.27	8.678	204	(*)	1.37	1.585	13	
7 + 9 Aug 1983	Above combined	15.16	8.295	260	*	1.92	1.869	16	
7 + 9 Aug 1983[b]	None	19.60	11.801	15		6.77	6.276	4	
31 Aug 1983	52 km from Ar. Surv.	14.08	7.608	228	ns	0.27	-	1	
1 Sep 1983[c]	26–31 km from W. Aleut.	11.81	7.282	31	ns	3.21	2.510	2	
31 Aug + 1 Sep	Above combined	13.81	7.592	259	ns	2.23	2.456	3	
22–28 Aug 1983[b]	None	13.76	7.697	234		1.80	2.494	41	

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[a] ** indicates that $0.01 \geq p > 0.001$ for comparison with the corresponding 'No seismic' mean. * indicates $0.05 \geq p > 0.01$, (*) indicates $0.1 \geq p > 0.05$, and ns indicates $p > 0.1$. Test not done when $n < 5$ for either group.

[b] Only data from 'presumably undisturbed' non-calves are included in these lines. Data from the first flight on 26 August 1983, when there was much skim-feeding, are not included in the 22–28 August lines.

[c] Data from 1 September 1983 exclude observations when the observation aircraft was <457 m a.s.l.

Table 18. Statistical comparisons of surfacing and respiration characteristics of non-calf bowheads in the presence and absence of seismic noise. Plus signs indicate that the mean value was greater when seismic noise was present; minus signs indicate that the mean was greater when seismic noise was absent. Pooled z and p values are based on the unweighted z method (Rosenthal 1978); z is the normal (0,1) statistic. ? means unknown.

Parameter	Cases of Full-Scale Seismic, 1983		Airgun '83	Pooled 1983		Pooled 1980-83[a]		
Date with Seismic	7 + 9 Aug '83	31 A + 1 S '83	28 Aug '83	Full-Scale	Full-Scale plus Airgun	Full-Scale	Airgun	Full-Scale plus Airgun
Control Data	7 + 9 Aug '83	22-28 Aug '83	Pre-Gun					
Range from Source	?-99 km	26-52 km	3-4 km					
Source Identity	GSI Mariner	Ar. Surv./W. Al.	1 Airgun					
Blows/Surfacing								
Type of Test	t	t	t					
Test Statistic	-0.12	+2.77	-0.28					
df	96	92	41					
Probability	-0.90	+0.007	-0.78	+,0.07	+,0.18	-,0.56	-,0.10	-,0.18
z	-0.12	+2.70	-0.28	+1.82	+1.33	-0.59	-1.65	-1.33
Surface Time								
Type of Test	t	t	t					
Test Statistic	-0.24	+3.36	-0.62					
df	110	89	42					
Probability	-0.81	+0.001	-0.55	+,0.03	+,0.17	-,0.65	-,0.09	-,0.21
z	-0.24	+3.22	-0.60	+2.11	+1.37	-0.45	-1.72	-1.25
Blow Interval								
Type of Test	t	t	t					
Test Statistic	-1.96	+0.07	+0.79					
df	273	491	168					
Probability	-0.05	+0.94	+0.43	-,0.18	-,0.52	+,0.74	+,0.01	+,0.12
z	-1.96	+0.07	+0.79	-1.34	-0.64	+0.33	+2.56	+1.57

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[a] The 1980-82 data used in the 'Pooled 1980-83' columns are from Richardson et al. (1983c, p. 176).

undisturbed whales (cf. Würsig et al. 1983, 1984). The 22 Aug - 1 Sept differences were in the opposite direction to the general tendency in 1980-82 (Richardson et al. 1983c). The pooled results for 1980-83 show no significant tendency for mean surface times or mean number of blows per surfacing to differ in the presence and absence of full-scale seismic noise ($p>0.5$ in each case, Table 18).

- Too few data on dive duration were obtained in 1983 to allow meaningful comparisons. In 1980-82, there was a weak and inconsistent tendency for dives to be shorter in the presence of seismic noise (Richardson et al. 1983c).

Thus, the overall 1980-83 results from opportunistic observations showed no clear tendency for any surfacing, respiration or dive parameter to differ in the presence and absence of noise from full-scale seismic exploration.

Speeds of whales were not noticeably different in the presence and absence of seismic noise in 1983 (Table 19). These results are similar to those from 1982 (Richardson et al. 1983c).

Turns occurred less often with than without seismic noise in the 22 August-1 September period (Table 20, $\text{chi}^2 = 5.10$, df = 1, $p<0.05$). Low sample size prevented a similar comparison for the 7-9 August period. Results from earlier years showed no relationship between occurrence of turns and seismic noise (Richardson et al. 1983c).

Table 19. Speeds of non-calf bowheads observed in the presence and absence of seismic noise, 1983[a]. ? means unknown.

		No. of Surfacings when Speed was					
Date(s)	Seismic Source	Zero	Slow	Moderate	Fast	Changed	Total
7 Aug 1983	79-99 km from GSI Mar.	0	1	2	4	0	7
9 Aug 1983	57- ? km from GSI Mar.	12	12	9	4	1	38
7 + 9 Aug 1983	Above combined	12	13	11	8	1	45
7 + 9 Aug 1983	None	0	1	0	3	0	4
31 Aug 1983	52 km from Ar. Surv.	4	19	33	2	5	63
1 Sep 1983	26-31 km from W. Aleut.	0	4	3	0	2	9
31 Aug + 1 Sep	Above combined	4	23	36	2	7	72
22-28 Aug 1983	None	21	18	18	1	14	72

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[a] Criteria for inclusion of data same as for Table 17.

Table 20. Occurrence of turns, pre-dive flexes, and 'flukes out' by noncalf bowheads observed in the presence and absence of seismic noise, 1983[a].

		No. of Turns/Surfacing			
Date(s)	Seismic Source	None	One	>1	Total
7 Aug 1983	79-99 km from GSI Mar.	7	3	0	10
9 Aug 1983	57- ? km from GSI Mar.	72	10	1	83
7 + 9 Aug 1983	Above combined	79	13	1	93
7 + 9 Aug 1983	None	5	0	0	5
31 Aug 1983	52 km from Ar. Surv.	27	3	0	30
1 Sep 1983	26-31 km from W. Aleut.	3	0	0	3
31 Aug + 1 Sep	Above combined	30	3	0	33
22-28 Aug 1983	None	46	16	3	65

		Pre-dive Flex		
Date(s)	Seismic Source	No	Yes	Total
7 Aug 1983	79-99 km from GSI Mar.	16	0	16
9 Aug 1983	57- ? km from GSI Mar.	108	7	115
7 + 9 Aug 1983	Above combined	124	7	131
7 + 9 Aug 1983	None	7	0	7
31 Aug 1983	52 km from Ar. Surv.	50	10	60
1 Sep 1983	26-31 km from W. Aleut.	6	1	7
31 Aug + 1 Sep	Above combined	56	11	67
22-28 Aug 1983	None	41	13	54

		Pre-dive 'Flukes Out'		
Date(s)	Seismic Source	No	Yes	Total
7 Aug 1983	79-99 km from GSI Mar.	13	3	16
9 Aug 1983	57- ? km from GSI Mar.	120	9	129
7 + 9 Aug 1983	Above combined	133	12	145
7 + 9 Aug 1983	None	8	0	8
31 Aug 1983	52 km from Ar. Surv.	30	48	78
1 Sep 1983	26-31 km from W. Aleut.	4	5	9
31 Aug + 1 Sep	Above combined	34	53	87
22-28 Aug 1983	None	72	47	119

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[a] Criteria for inclusion of data same as for Table 17.

The occurrence of pre-dive flexes seemed unrelated to the presence or absence of seismic noise in the 22 August-1 September period (Table 20; chi^2 = 1.10, df = 1, $p>0.25$). Low sample size prevented such a comparison for 7-9 August 1983.

In the 22 August-1 September 1983 period, bowheads raised their flukes above the water during 61% of the dives in the presence of seismic noise, but during only 39% of the dives without seismic noise (Table 20; chi^2 = 9.23, df = 1, $p<0.01$). Whether this difference was related to the seismic noise is unknown. The whales seen on 31 August-1 September with seismic noise often brought mud to the surface, and may have been diving deeper than those seen without seismic noise on 22-28 August. On 7-9 August, the sample size without seismic noise was too small to allow a similar comparison.

Bowhead calls were heard during three of the four days in 1983 when underwater sounds were recorded near bowheads that were exposed to seismic noise. The overall calling rate for the four days was 1.3 loud calls/whale-h (Table 21). This was similar to the 0.9 loud calls/whale-h recorded near 'presumably undisturbed' whales in 1983 (Würsig et al. 1984). Call types also were similar in the presence and absence of seismic noise (Table 21). All seven types of calls heard under 'presumably undisturbed' conditions were also heard in the presence of seismic noise. High, harmonic and pulsive calls, which tend to be produced by socializing bowheads (Würsig et al. 1983, 1984), accounted for 29% of the loud calls in the presence of seismic noise and 33% in 'presumably undisturbed' conditions (chi^2 = 0.31, df = 1, $p>0.5$). Thus, there was no evidence that seismic noise affected bowhead calling in 1983. Similar results were obtained in 1980-82 (Richardson et al. 1983c).

Airgun Experiment

About 4-6 whales were observed as 'Sequel' travelled slowly around them at a radius of 2-6 km. Their general activities were surfacing and diving, with travel at medium speed during surfacings. Activities during the 25-min period of airgun firing were similar, except that some mud was brought to the surface of the shallow water and some socializing occurred.

Table 21. Numbers and types of bowhead sounds recorded in the presence and absence of seismic and airgun noise, 1983. Data compiled by C.W. Clark.

Date	Observation Time (MDT)	Seismic Source	Whales' Activity	Level of Calls	Approx. No. of Whales	Whale-h of Observation	No. Sounds of Each Type								Calls per Whale-h
							Up	Down	Constant	Inflected	High	Harmonic	Pulsive	Total	
7 Aug '83	17:15-18:50	GSI Mar.	?	All	2	3.2	0	0	0	0	0	0	0	0	0.0
9 Aug '83	13:48-17:20	GSI Mar.	Socializing	Loud	12	39.4	3	5	6	5	3	0	19	41	1.1
				All	-	-	61	54	29	25	36	1	59	265	-
31 Aug '83	14:54-17:18	Ar. Surv.	Bottom feeding & socializing	Loud	6	14.2	13	9	2	17	0	1	1	43	3.0
				All	-	-	125	29	25	58	6	1	2	246	-
1 Sep '83	16:57-18:26	W. Aleut.	Bottom feeding & socializing	Loud	5	7.4	0	0	0	0	0	0	0	0	0.0
				All	-	-	4	1	1	0	0	0	0	6	-
All 1983	with seismic	As above	As above	Loud	-	64.2	16	14	8	22	3	1	20	84	1.3
				All	-	-	190	84	55	83	42	2	61	517	-
All 1983	'presum. undist.'	None	-	Loud	-	91.6	30	9	5	12	2	22	3	83	0.9
				All	-	-	103	34	17	31	16	43	9	253	-
28 Aug '83	10:37-13:07	None	Bottom feeding, travelling & socializing	Loud	6	15.0	2	0	0	3	0	1	0	6	0.4
				All	-	-	16	12	4	6	1	1	0	40	-
	13:07-13:32	Airgun	"	Loud	6	2.5	0	0	0	0	0	0	0	0	0.0
				All	-	-	5	0	2	0	1	0	0	8	-

The whales were ~3-4 km from the airgun while it fired, and were about midway between two sonobuoys. Received levels of airgun noise were higher at the sonobuoy ~2 km from the airgun than at the sonobuoy ~5 km away (Greene 1984). Noise levels were slightly higher at the start of the 25 min period of firing (when air pressure was highest) than at the middle or end of that period. Each received pulse was a few tenths of a second in duration, and the predominant frequency and received level changed within that interval:

Time within Airgun Firing Period	200 Hz*		70 Hz*	
	2 km	5 km	2 km	5 km
Early	131 dB	129 dB	138 dB	128 dB
Middle	126	122	130	122
Late	127	120	132	118

* Received level (dB//1 µPa) during portion of pulse when predominant frequency was (a) ~200 Hz, and (b) ~70 Hz. Noise data from Greene (1984).

Because of the limitations of the sonobuoy/receiver system, the above figures may be underestimates. The received noise level at the location of the whales was presumably about midway between the levels at the two sonobuoys. Ambient noise levels between seismic pulses were 95-104 dB//1 µPa in the 10-500 Hz band and 88-98 dB in the 20-500 Hz band (Greene 1984). Based on the latter figures, the signal-to-noise ratio for airgun pulses was about 25-35 dB, or possibly more if received levels of airgun signals were underestimated.

Comparisons of behavioral observations before vs. during the period with airgun noise revealed no obvious changes in surfacing and respiration variables ($p>0.1$ in each case, Table 22). However, the sample sizes during the period of airgun firing were small. Interestingly, the directions of the slight differences that did occur were consistent with those in each of the airgun experiments in 1981. During the airgun firing period of all three experiments, mean blow intervals were slightly increased, and mean surface times and mean number of blows per surfacing were slightly reduced. The pooled results from the three experiments were significant in the case of blow intervals ($p=0.01$, Table 18), but very marginal in the other two cases ($p=0.09$ and $p=0.1$, respectively).

Table 22. Surfacing, respiration and dive characteristics of non-calf bowheads observed before, during and after an airgun fired, 28 August 1983. For results of airgun experiments in 1981, see Richardson et al. (1983c, p. 180).

Phase	Mean	s.d.	n	t-test[a]	Mean	s.d.	n	t-test[a]
	Blows/Surfacing				**Duration of Surfacing (min)**			
Pre-Gun	3.58	2.612	36	t = 0.28	0.77	0.515	37	t = 0.62
Airgun	3.29	2.059	7	ns	0.64	0.543	7	ns
Post-Gun	5.00	3.606	3		0.98	0.624	3	
	Blow Interval (s)				**Dive Duration (min)**			
Pre-Gun	12.67	7.044	148	t = 0.79	3.02	3.839	13	
Airgun	13.91	5.773	22	ns	3.13	3.948	2	
Post-Gun	12.83	8.133	12		-	-	0	

[a] t-tests compare values during 'pre-gun' and 'airgun' phases of the experiment.

Analysis of other behavioral variables provided no further indication that bowhead behavior was affected by airgun noise:

- Most whales moved at medium speed during all phases of the 1983 experiment (Table 23). There were few data on speeds during the 1981 experiments. Swimming speed was judged subjectively by the observers in the aircraft, and the results must be treated cautiously.
- In 1983, the frequency of turns was similar before and during the period of airgun firing (Table 24). Results from 1981 were similar. If data from all three experiments are pooled, turns occurred during 28% of surfacings in the pre-airgun control periods and 29% of surfacings while the airgun fired (Table 24; $chi^2 = 0.01$, df = 1, p = 0.9).
- Pre-dive flexes occurred during a minority of the surfacings in all phases of the 1983 experiment. Results were similar in 1981. Considering all 1981 and 1983 data, pre-dive flexes occurred in 18% of surfacings in the pre-airgun periods and 20% of surfacings while the airgun fired (Table 24; $chi^2 = 0.05$, df = 1, $p>0.75$).
- During the majority of dives in both the pre-airgun and airgun phases in 1983, the flukes were raised above the surface as the whales dove (Table 24).

In 1983, few orientation data were collected during and after the airgun firing period. However, there was no evidence that whales oriented away while the airgun fired. The 1981 experiments also provided no indication that orientations of the whales changed in response to airgun noise (Fraker et al. 1982).

In 1983, the rate of loud calls was low during the pre-airgun period (0.4/whale-h; Table 21). If the rate were unchanged during the brief airgun firing period, only 1 loud call would be expected in that period. In fact, no loud calls were detected while the airgun fired. The observed value (0) did not differ significantly from the expected value (1) (Poisson test; $p>0.3$). Similarly, the number and types of faint calls heard during the airgun firing period were consistent with those in the pre-airgun period (Table 21). In 1981, whales called very infrequently during one experiment. During the other experiment, the whales apparently stopped calling during the airgun firing period and resumed thereafter (Richardson et al. 1983c).

Table 23. Speeds of non-calf bowheads observed before, during and after an airgun was fired.

		No. of Surfacings when Speed was					
Experiment	Phase	Zero	Slow	Moderate	Fast	Changed	Total
18 Aug '81 (5 km range)	Pre-Gun	11	8	0	0	0	19
	Airgun	0	0	0	0	1	1
	Post-Gun	2	1	0	1	4	8
19 Aug '81 (3 km range)	Pre-Gun	11	6	1	0	1	19
	Airgun	1	2	0	0	1	4
	Post-Gun	5	3	0	3	2	13
28 Aug '83 (3 km range)	Pre-Gun	2	6	35	5	3	51
	Airgun	0	0	3	0	2	5
	Post-Gun	0	1	2	0	0	3
Total	Pre-Gun	24	20	36	5	4	89
	Airgun	1	2	3	0	4	10
	Post-Gun	7	5	2	4	6	24

Table 24. Occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads observed before, during and after an airgun was fired.

		No. Turns/Surfacing				Pre-dive Flex			Pre-dive 'Flukes Out'		
Experiment	Phase	Zero	One	>1	Total	No	Yes	Total	No	Yes	Total
18 Aug '81 (5 km range)	Pre-Gun	12	6	0	18	12	2	14	Data not available		
	Airgun	0	1	0	1	1	1	2			
	Post-Gun	5	5	0	10	10	1	11			
19 Aug '81 (3 km range)	Pre-Gun	28	13	1	42	20	3	23	Data not available		
	Airgun	7	2	0	9	4	1	5			
	Post-Gun	12	4	1	17	7	4	11			
28 Aug '83 (3 km range)	Pre-Gun	29	7	0	36	43	11	54	30	37	67
	Airgun	5	2	0	7	7	1	8	2	6	8
	Post-Gun	3	0	0	3	2	1	3	0	3	3
Total	Pre-Gun	69	26	1	96	75	16	91	As above		
	Airgun	12	5	0	17	12	3	15			
	Post-Gun	20	9	1	30	19	6	25			

Discussion

Results to Date

We have observed bowheads exposed to noise from seismic exploration on 12 occasions in 1980-83. Ranges were 6-99 km. On three further occasions we observed bowheads exposed to noise from a single airgun 3-5 km away. Noise levels near the whales ranged from barely detectable to ~150 dB//1 μPa.

We found no clear evidence that bowheads moved away from these noise sources. General activities seemed normal in the presence of seismic noise -- surfacing and diving, feeding, socializing, calling, and sometimes travelling. Estimated speeds, frequency of turns, and occurrence of pre-dive flexes usually were similar with and without seismic noise. On these points, our results from 1983 were consistent with those from 1980-82.

In 1980-82 there was sometimes evidence of subtle differences in surfacing, diving and respiration behavior in the presence and absence of seismic noise. However, the trends were weak and not evident on every occasion, and most results came from uncontrolled opportunistic observations (Richardson et al. 1983c).

Our reservations about the significance of the weak trends in the 1980-82 data were apparently justified. Data from 1983 failed to corroborate most of those trends. When 1980-83 results from opportunistic observations and airgun experiments were combined, there was no significant tendency for surface times, number of blows per surfacing, or intervals between blows to differ in the presence and absence of seismic noise (Table 18).

Overall, our results show that behavior of bowheads summering in the Canadian Beaufort Sea is not altered in a conspicuous, consistent manner by noise from seismic vessels 6 km or more away, or by a single airgun simulating such a vessel. Reeves et al. (1983) obtained similar results from bowheads feeding and migrating in the Alaskan Beaufort Sea in late summer and autumn.

This lack of detectable reactions by bowheads is not necessarily inconsistent with the results of Malme et al. (1983), who found that migrating gray whales sometimes react to seismic noise. Definite reactions by gray whales were found only when 'average pulse level' was ≥160 dB//1 µPa, i.e. peak levels ≥170 dB. We have not observed bowheads exposed to such strong seismic signals. Peak received levels were ~150 dB for bowheads 6-8 km from a seismic boat in shallow water (Fraker et al. 1982). Similarly, almost all Alaskan observations of bowheads exposed to seismic noise were ≥6 km from seismic boats, so received levels were probably <160 dB.

Furthermore, observations of the speeds and courses of gray whales were more detailed and better controlled than has been possible for bowheads. Gray whales migrate in large numbers below coastal vantage points from which precise measurements of speeds and courses are possible. In contrast, all observations of bowhead behavior with seismic noise were obtained well offshore via observation aircraft. If bowheads alter their speeds or courses subtly when several kilometres from a seismic boat, it is doubtful that aerial observers could detect these changes. On the other hand, better information about surfacing, respiration and dive patterns with seismic noise has been obtained from aerial observations of bowheads than from shore-based observations of gray whales.

Protocols for Future Experiments

To determine conclusively whether bowheads react to seismic noise, controlled and replicated tests involving high received levels of seismic noise are needed. Opportunistic observations in the presence of noise from seismic vessels have shown that bowheads do not react in any strong and consistent manner to noise from distant seismic vessels. However, bowhead behavior is quite variable, so it is difficult to determine from opportunistic observations whether seismic noise causes subtle behavioral effects. Replication is important because variability in behavior can confound even a controlled test in which particular whales are observed before, during and after disturbance. High received levels are needed because available data from bowheads (especially our three controlled tests with an airgun) and from gray whales (Malme et al. 1983) indicate that conspicuous responses do not occur when received levels are moderate (e.g., 120-140 dB).

One promising experimental approach is to bring a full-scale seismic vessel progressively closer to whales until a reaction is detected. This is one of the methods used successfully by Malme et al. (1983). It is also the method that was planned for the Canadian and Alaskan Beaufort Sea in 1983. The approach was unsuccessful in the Beaufort Sea because no seismic boat was available while we conducted other types of experiments on the many bowheads off the Yukon coast in August 1983, and because ice prevented experiments in Alaskan waters in September.

If the logistical problems can be overcome, experiments with a full-scale seismic boat have the potential to determine at what range and received noise level bowheads first react. One complication with this approach is that a strong reaction probably will not occur until the vessel is within a few kilometres of the whales. (We already know that bowheads as close as 6 km do not react strongly, if at all, to seismic noise.) However, bowheads react to noise from ships up to 4 km away (Fraker et al. 1982; Richardson et al. 1983c; this study). Indeed, bowheads as much as 2.8 km from 'Arctic Surveyor' reacted strongly when this seismic vessel was underway but not firing its seismic gear (Fraker et al. 1982). Reactions of bowheads to ships typically involve changes in course, speed, respiration, and surfacing and diving behavior. If bowheads respond to a seismic vessel underway and firing its seismic gear a few kilometres away, it will be difficult to determine whether the reactions are to the seismic pulses or to the ship itself. At the least, control tests with the seismic ship underway but not firing its seismic gear would be needed to resolve this question.

Another approach would be to fire one or more seismic sources (e.g. airguns) from a stationary and otherwise quiet vessel. This has not been attempted with bowheads, but was done near gray whales (Malme et al. 1983). Gray whales reacted to this airgun noise. Although reactions to conventional ship noise were not determined by Malme et al., gray whales often tolerate close approach by vessels. This, along with the reactions to the airgun, suggests that the reactions of gray whales to the full-scale seismic vessel were to its seismic noise and not to its continuous ship noise. The same might not be true of bowheads, which react strongly to conventional vessels. Hence, tests with an airgun deployed from a stationary and quiet boat near bowheads are desirable. The 40 in^3 airgun that we have used 2-5 km from bowheads would need to be within a few hundred metres of the whales in order to produce received levels of ~160 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 (~50 dB above the ambient level in the 10-500 Hz band). Similarly, gray whales reacted clearly to seismic noise only when received levels were at least 160 dB (~60 dB above ambient levels in the 50-315 Hz or similar band; Malme et al. 1983). 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 (Fraker et al. 1982), the received boat noise was only 109 dB//1 µPa in the 10-500 Hz band, which was barely above ambient (C.R. Greene, unpubl. data). Similarly, we have found weak reactions to drillship noise at levels of about 100-112 dB (Richardson et al. 1983c and this study). Malme et al. (1983) 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.

It is not clear why whales are more tolerant of strong seismic pulses than of certain continuous industrial noises. However, some possibilities can be suggested. Noise pulses from typical seismic exploration programs mask other sounds for only a fraction of a second every 10 or 15 seconds. In contrast, continuous industrial noise, even at a considerably lower level, may mask other sounds completely. The significance of masking to whales is not known. However, it 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). The hearing apparatus of whales must not be harmed by brief but loud low-frequency sounds, 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), so received levels of calls by other whales presumably exceed 160 dB at distances up to 10 m.

Another factor is that received levels of seismic sounds reported above are from hydrophones at 9 or 18 m depth (Greene 1982, 1983, 1984). 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 expected to be reduced because of pressure release effects (Richardson et al. 1983c, p. 171). In 1983, simultaneous measurements at 3, 9 and 18 m depth confirmed this (Greene 1984). Received levels of seismic pulses were 4-10 dB less at 3 m than at 9 m. Levels at 9 and 18 m depth did not differ consistently (Greene 1984).

Thus, whales at the surface are exposed to levels of seismic noise somewhat less than those 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 an airgun experiment on 18 August 1981 (Fraker et al. 1982) presumably were rarely exposed to the level of airgun noise received by our sonobuoy. Similarly, a whale engaged in 'log play' 24-39 km from a seismic vessel on 1 August 1982 did not dive during 1.5 h of observations (Würsig et al. 1983; Richardson et al. 1983c). It probably was not exposed to noise levels quite as high as those one would expect to find 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 at 9 or 18 m depth during most of our observations of bowheads in the presence of seismic or airgun noise (up to 50 dB). 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.

The confirmation that received levels of seismic noise are reduced near the surface (Greene 1984) reinforces our earlier suggestion that, if seismic noise is disturbing, whales may spend more time at the surface or dive for shorter periods. Some of our observations are consistent with this hypothesis (e.g. prolonged log play at the surface with seismic noise; reduced average dive duration with seismic noise in 1980-82). However, whales often dive even with strong seismic noise, and the evidence that they reduce the frequency or durations of dives in the presence of seismic noise is inconsistent. Controlled experiments are needed.

REACTIONS TO DRILLING

Offshore drilling can be from drillships, platforms of various types, and artificial or natural islands. Baleen whales have been seen near drillships and drilling platforms (Kapel 1979; Gales 1982; Richardson et al. 1983b,c). However, little systematic information is available about distances of closest approach or behavioral reactions to actual offshore drilling.

Offshore drilling produces underwater noise, primarily from the engines on the drillship, platform or island rather than from the drill string *per se*. Underwater noise from all offshore drilling systems studied to date has been concentrated at frequencies below 1000 Hz. In the absence of other industrial noise sources, underwater noise from drillships drilling in shallow waters of the Canadian Beaufort Sea has been detected as far as 13 km away. The noise was stronger than that from a suction dredge but less strong than that from the noisiest ship (Greene 1983). Underwater noise from drilling on islands has been recorded under the ice in winter (Malme and Mlawski 1979; Cummings et al. 1981), but not in open water. Noise from semi-submersible drillships and bottom-mounted platforms has also been studied (see Gales 1982 and Richardson et al. 1983b for reviews).

Since 1976, three or four conventional drillships have operated in the Canadian Beaufort Sea each summer and autumn. In 1981-82, we observed bowheads 4-20 km from drillships on several occasions (Fraker et al. 1982; Richardson et al. 1983c). The whales were not moving away from the ship on any of these occasions. Behavior sometimes was indistinguishable from 'normal'. However, on two occasions dive durations were unusually long, and on one the durations of surfacings and the numbers of blows per surfacing were also rather long. Some whales called in the presence of drillship noise, but on one occasion no calls were detected near a group of socializing whales; socializing bowheads and right whales usually call frequently (Würsig et al. 1982; Clark 1983). Whether these results were in any way connected with the proximity of the drillship is unknown. It is also unknown whether as many bowheads were present near drillships as would have been there if the ships were absent.

Besides our own observations of bowheads near drillships, industry personnel reported to us nine sightings 0.2-5 km from drillships in the summers of 1980-82 (Fraker et al. 1982; Richardson et al. 1983c).

Controlled tests of reactions of whales to drilling noise were desirable because of the difficulties in interpreting opportunistic observations near ongoing drilling operations. On two occasions in 1982, we completed experiments in which we broadcast drillship noise into the water 2-6.5 km from bowheads whose behavior was observed before and during the playback period. The signal-to-noise (S/N) ratio for the drilling noise (10-1000 Hz band) was 15 dB for the whales 2 km away, and probably near zero for those 6.5 km away. Calling rate apparently decreased during playbacks, and the whales seemed to increase their rate of dispersal away from the underwater projector during the playback period. However, sample sizes were small and the reactions were not very conspicuous.

Malme et al. (1983) tested reactions of migrating gray whales to underwater playbacks of noise from a drilling platform, a semisubmersible drillship, and a conventional drillship. (For their 'conventional drillship' playbacks, Malme et al. used the same recording used in our playback experiments on bowheads.) For each of the three noise types, gray whales slowed as they approached within 1-2 km of the playback site. In the case of drilling platform noise only, whales changed course to avoid the area within a few hundred metres of the playback site. Malme et al. estimated that the first reactions occurred at ranges where the drilling sounds were barely detectable, i.e. S/N ratios of 4 dB or less. The avoidance response to noise from a drilling platform occurred at ranges where the S/N ratio (80-315 Hz band) was about 19 dB. Noise from the drilling platform was more variable than that from the drillship or semisubmersible, and Malme et al. suggested that this may have been responsible for the greater response to the platform noise.

Our 1982 drillship noise playback experiments suggested that bowheads sometimes react to drillship noise, but the results were not conclusive. Additional experiments were, therefore, a high priority in 1983. In the absence of recordings of noise from drilling on an artificial island surrounded by open water, we again used recorded drillship noise in our 1983 experiments. We were able to expose bowheads to higher noise levels (and higher S/N ratios) in 1983 than in 1982, mainly by finding situations when the sound projector could be deployed closer to the whales. We also obtained larger sample sizes, partly by prolonging each playback and partly by finding an area with a greater concentration of whales than was accessible in 1982. In addition, we again searched for bowheads near drillships. Industry personnel were requested to report to us any sightings of bowheads near drillships.

Methods

Observations near Drillships

On several dates in 1983 we flew near or around one or more of the four conventional drillships operating in the eastern Beaufort Sea. On four dates we searched near 'Kulluk', an unconventional circular drillship that began operating in the Canadian Beaufort Sea in August 1983. When bowheads were seen, a sonobuoy was dropped to record any drillship or bowhead sounds. Behavioral observations were obtained by our usual methods for aerial observations. No drilling from artificial islands or caisson-retained islands was in progress in the Canadian Beaufort Sea during our 1983 field season, so there were no opportunities to search for bowheads near such operations.

Drillship Noise Playback Experiments

On three occasions in August 1983, we broadcast recorded noise of the drillship 'Canmar Explorer II' into the water near bowheads (Table 25). Whale behavior was observed from the Islander aircraft circling at 457 m a.s.l. (17

Table 25. Circumstances of the three drillship noise playback experiments off the Yukon coast, 17-22 August 1983.

	17 Aug '83	18 Aug'83	22 Aug '83
Location of 'Sequel'	69°18'N 138°17'W	69°27' 138°32'	69°15' 138°02'
Water Depth (m) at			
Boat	18	15	36
Whales	16	12	32
Sea State	1	1	3
Aircraft Altitude (m)	457	610	610
Durations (min) of			
Post-Boat	28	-	-
Quiet Boat	-	69[a] + 26	45
Playback, incr. level	10	10	10
Playback, peak level	20	20	20
Playback, decr. level	10	10	10
Post-playback	39 + 63[a]	57	104
Time (MDT)	19:11-22:01	11:27-14:39	13:36-16:45
Source Level of Sound during Peak Period (dB//1 µPa at 1 m)	162	164	164
Approx. distances (km)			
Projector to Sonobuoy	?[b]	1.2	1.2
Projector to Whales	0.7-3.0	0.4-1.7	0.8-1.8
Noise level at Sonobuoy (dB//1 µPa)			
Ambient, 10-1000 Hz[c]	92[d]	81	94
Playback, 10-1000 Hz[e]	-	108-112	112-113
Playback, 275 Hz[e]	-	104-109	107-110
Activity of Whales	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

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

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

[c] 10-1000 Hz band, immediately after playback.

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

[e] The levels for the 10-1000 Hz band and for the 275 Hz tone are given for the period of peak playback level.

August) or 610 m (18 and 22 August). All three experiments were conducted off the Yukon coast southeast of Herschel Island in water 12 to 36 m deep (Table 25). In contrast, during our playback experiments in 1982 the water depth was 125 to 150 m.

The underwater projector was deployed from 'Sequel', as in 1982.

- On 17 August, the experiment was conducted within 1 km of the Yukon coast. While the observation aircraft was overhead, 'Sequel' approached a group of about seven whales at idle speed (5.6 km/h). Her motor was turned off about 1 km away. Because the whales were dispersing from the area, apparently in response to the aircraft, the 17 August playback began only 28 min after 'Sequel' stopped moving.
- On 18 August, 'Sequel' had been anchored for over 2 h before the observation aircraft arrived to begin pre-playback control observations. That control period contained two phases: whales east of 'Sequel' were observed for 69 min; we then observed whales west of 'Sequel' for a further 26 min before beginning the playback. The latter whales were observed during and after the playback period. Hence, our analyses of pre-playback data include only the whales observed west of 'Sequel'.
- On 22 August, 'Sequel' had again been anchored for over 2 h before the aircraft arrived to begin a 45-min period of pre-playback control observations.

The playback procedure was almost identical to that in 1982. The one exception was that drillship noise was projected at peak level for 20 min in 1983 (10 min in 1982). In both years, we used the same tape of noise recorded 185 m from the drillship 'Explorer II' while it was drilling. As in 1982, noise was broadcast by a 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 min, then was constant for 20 min, 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 simulate what a bowhead would encounter as it approached a drillship.

To avoid distortion and determine source level, the output of the projector was monitored by an H56 hydrophone suspended 1 m in front of the projector. Source levels during the periods of peak level were 162-164 dB//1 μPa at 1 m (Table 25).

Ambient and drillship noise reaching the bowheads was recorded on 18 and 22 August via sonobuoys dropped ~1.2 km from 'Sequel' and amidst whales that were 0.4-1.8 km from 'Sequel' (Table 25). On 17 August, we were unable to deploy a functioning sonobuoy in the shallow water amidst the travelling whales. We did monitor the projected drillship sounds via a sonobuoy dropped nearby during a flight earlier in the day, but the exact location of that sonobuoy during the playback period was not known. On 17 August, ambient sound was measured by a hydrophone deployed from 'Sequel'. Thus, we measured the drillship and ambient noise levels amidst the whales during the 18 and 22 August playbacks, and measured the ambient sounds nearby on 17 August.

In 1983 we were able to monitor behavior for longer periods after the playbacks ended than was possible in 1982 (39-104 min in 1983; 0-34 min in 1982). In each case 'Sequel' remained quiet throughout the period of post-playback monitoring.

Results

Observations near Drillships

We saw no bowheads near the four conventional 'Canmar Explorer' drillships in 1983. Throughout our 1983 field season, bowheads were very scarce in the overall area where those drillships operated (Richardson et al. 1984). Industry personnel did report one bowhead about 3.7 km SSW of 'Explorer I' at the Aiverk drillsite on 18 August.

On 31 August and 1 September we found bowheads 12-15 km SE of the Gulf/BeauDril 'Kulluk' circular drillship. An estimated 15 bowheads were present on 31 August, and at least 4 on 1 September. Water depth here was 19 m. The whales were lingering in the area. On both dates they brought clouds of mud to the surface, and engaged in some socializing. BeauDril advised us that 'Kulluk' was not actively drilling on either day. She was running casing during our observations on 31 August, and pouring cement for most of the observation period on 1 September.

The whales observed 12-15 km from 'Kulluk' were exposed to an unusually wide range of industrial activities. Strong seismic sounds were present during both of our observation periods. The whales also were on the direct route between 'Kulluk' and Tuktoyaktuk, so helicopters passed overhead or nearby several times a day. Indeed, a helicopter flew over the whales at about 150 m a.s.l. during our observations on both days. The Kadluk island construction site was only 18 km away, but it is doubtful that much noise reached the whales from that shallow-water site. Besides this high level of 'normal' industrial activity, a fixed-wing aircraft (Turbo Commander) flew several photographic passes over some of the whales at about 150 m a.s.l. during our observations on 31 August, and we flew similar passes on 1 September when a low ceiling prevented us from flying higher.

Underwater noise amongst the whales near 'Kulluk' was dominated by seismic pulses from 'Arctic Surveyor' on 31 August and from 'Western Aleutian' on 1 September (see seismic section, above). Between the seismic pulses, continuous industrial noise was audible. Levels in the 20-500 Hz band were 101-111 dB//1 μPa (with numerous tones) on 31 August, and 95-104 dB on 1 September.

Despite all of the industrial activity near 'Kulluk' on 31 August, some whales were present on 1 September. We do not know that they were the same individuals as on 31 August, but they were at the same location. The whales seen on both days were not moving rapidly, and were diving and surfacing regularly, as if feeding.

Drillship Noise Playback Experiments

Sound Levels to Which Bowheads were Exposed. — The whales whose behavior was observed in detail during drillship playbacks in 1983 were estimated to be 0.7-3 km from 'Sequel' on 17 August, and 0.4-1.8 km away on 18 and 22 August. The source level of the projected noise was very similar in each 1983 experiment (162, 164 and 164 dB//1 μPa-m; cf. 155-164 dB in the 1982 experiments). The average levels received at the sonobuoys an estimated 1.2 km from 'Sequel' on 18 and 22 August were, respectively, 110 and 112 dB//1 μPa in the 10-1000 Hz band (Table 25). Ambient levels in the 10-1000 Hz band just after the playbacks were 81 and 94 dB on 18 and 22 August. Thus, the signal-to-noise ratios for the 10-1000 Hz band at approximate range 1.2

km on 18 and 22 August were 29 and 18 dB, respectively. Drillship noise levels and S/N ratios at half and twice the 1.2 km range were probably about 3 dB higher and lower, respectively, assuming cylindrical spreading.

It is also of interest to know how far from the actual drillship a whale would have to be in order to receive underwater noise at the same level as that received 1.2 km from our projector. When received at 1.2 km range, the average levels of the strongest tone (275 Hz) were 106 and 109 dB on 18 and 22 August (Table 25). These are the levels expected 6 and 5 km from the actual drillship, respectively, based on Greene's (1982) equation for received level of the 275 Hz tone vs. range in shallow water :

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

where R is range in kilometres.

Behavior of the Whales. — The surfacing, respiration and dive behavior of the bowheads during the three playback experiments is summarized in Table 26. Table 27 summarizes speeds of the whales. Table 28 summarizes the occurrence of turns and pre-dive flexes, as well as the frequency with which the flukes were raised above the surface as the whales dove. In each table, the data are separated into observations during four phases of the experiments:

1. before playback began (post-boat phase on 17 August, when 'Sequel' was maneuvering <30 min before; pre-control phase on other days, when 'Sequel' had been quiet for over 30 min),
2. during playback,
3. first 30 min after end of playback (post-playback phase), and
4. over 30 min beyond end of playback (post-control phase).

In the tables, we have excluded observations in the first 5 min of the 10-min increasing level phase and in the last 5 min of the 10-min decreasing level phase. During parts of these excluded periods, the noise level may have been too low to be detectable at the location of the whales.

Tables 26-28 include the results for each of the three 1983 experiments separately, plus the pooled results for the 18 and 22 August 1983 experiments. The 17 August results are excluded from the pooled category because of apparent confounding by reactions to the aircraft (see next paragraph). The tables also include, for comparison, the pooled results from the three drillship noise playback experiments in 1982 (from Richardson et al. 1983c).

The 17 August 1983 experiment was apparently confounded by reactions to the observation aircraft and possibly to 'Sequel', and did not provide a useful test of reactions to drilling noise. On 17 August, whales <1 km from shore swam into deeper water as the aircraft circled overhead and, later, 'Sequel' moved slowly into position for the playback (see Reactions to Aircraft section). The whales continued to disperse during the subsequent post-boat/pre-playback phase. Because of the dispersal of the whales, we began this playback trial early, only 28 min after 'Sequel' stopped maneuvering. The behavior of the whales during the playback phase was similar to that during the post-boat/pre-playback phase: surfacings were short, the number of blows per surfacing was low (Table 26), and speeds were usually moderate (Table 27). After the playback period, most whales were farther from shore, mean duration of surfacing and mean number of blows per surfacing were both higher and nearer normal, and speeds were slightly reduced.

Neither duration of surfacing nor number of blows per surfacing differed significantly among phases of the experiment on 18 August (Table 26). On 22 August, sample sizes were too small for meaningful analysis. The pooled 18+22 August results were non-significant ($p>0.05$). In 1982, sample sizes for both variables were too small for analysis.

Blow intervals differed significantly among the four phases of the 18 and 22 August experiments ($p < 0.05$ and $p < 0.01$, respectively; Table 26). However, the trends were in opposite directions on the two dates -- rather long blow intervals in the playback and post-control phases on 18 August, but rather short blow intervals in those phases on 22 August. When these two disparate sets of results were pooled, the differences were, not surprisingly, non-significant ($p>0.1$; Table 26). Blow intervals also did not differ significantly among phases during the 1982 experiments.

Table 26. Surfacing, respiration and dive characteristics of non-calf bowheads observed before, during and after playbacks of drillship noise, 1982-83. 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	Difference	Mean	s.d.	n	Difference
	No. Blows/Surfacing				**Duration of Surfacing (min)**			
A. 17 Aug '83								
Post-Boat	1.94	1.519	17	Kr-Wal	0.35	0.403	17	Kr-Wal
Mid-Playback	1.60	0.548	5	H = 5.79	0.38	0.319	5	H = 5.30
Post-Playback	3.91	3.506	11	df = 3	0.71	0.739	11	df = 3
Post-Control	3.15	1.899	20	p>0.1	0.74	0.575	20	p>0.1
B. 18 Aug '83								
Pre-Control	2.50	2.070	8	ANOVA	0.66	0.476	8	ANOVA
Mid-Playback	2.73	1.831	15	F = 2.11	0.63	0.556	15	F = 1.55
Post-Playback	5.00	3.162	6	df = 3,29	1.16	0.750	6	df = 3,29
Post-Control	4.25	2.217	4	p>0.1	0.98	0.477	4	p>0.1
C. 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	
D. 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
E. 16-19 Aug '82								
Pre-Control	8.14	4.824	22	-	1.98	0.822	27	-
Playback	2	-	1		1.77	1.131	2	
Post-Playback	-	-	0		-	-	0	

... continued

Table 26. (cont'd)

Date and Phase of Experiment	Mean	s.d.	n	Difference	Mean	s.d.	n	Difference
	Blow Interval (s)				**Dive Duration (min)**			
A. 17 Aug '83								
Post-Boat	15.59	5.804	22	ANOVA	0.73	0.612	5	-
Mid-Playback	14.09	7.765	11	F = 1.03	-	-	0	
Post-Playback	12.50	3.676	36	df = 3,120	0.47	-	1	
Post-Control	14.25	8.213	55	p>>0.1	0.40	-	1	
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	
C. 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	
D. 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	*
E. 16-19 Aug '82				ANOVA				
Pre-Control	14.12	6.019	245	F = 1.35	9.09	7.711	12	-
Playback	12.85	4.966	58	df = 2,307	10.00	-	1	
Post-Playback	15.29	2.215	7	p>0.1	-	-	0	

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

Table 27. Speeds of non-calf bowheads during surfacings before, during and after playbacks of drillship noise, 1982-83. 'Mid-Playback' phase defined as in previous table.

Date and Phase of Experiment	No. of Surfacings when Speed was							2x2 chi^2 Test on Grouped Data
	Zero	Slow	Moderate	Fast	Zero or Slow	Moderate or Fast	Total	
A. 17 Aug '83								
Post-Boat	1	2	9	0	3	9	12	
Mid-Playback	2	1	3	0	3	3	6	
Post-Playback	0	3	2	0	3	2	5	
Post-Control	1	5	6	1	6	7	13	
B. 18 Aug '83								
Pre-Control	1	1	9	0	2	9	11	
Mid-Playback	0	4	18	3	4	21	25	
Post-Playback	1	4	3	0	5	3	8	
Post-Control	0	8	2	0	8	2	10	
C. 22 Aug '83								
Pre-Control	2	1	3	0	3	3	6	
Mid-Playback	7	1	2	0	8	2	10	
Post-Playback	5	2	1	0	7	1	8	
Post-Control	7	9	3	0	16	3	19	
D. 18 + 22 Aug '83								
Pre-Control	3	2	12	0	5	12	17	chi^2 = 0.12
Mid-Playback	7	5	20	3	12	23	35	df = 1
Post-Playback	6	6	4	0	12	4	16	p>0.5
Post-Control	7	17	5	0	24	5	29	
E. 16-19 Aug '82								
Pre-Control	2	10	6	2	12	8	20	chi^2 = 5.18
Playback	1	0	5	2	1	7	8	df = 1
Post-Playback	0	0	0	0	0	0	0	*
F. (D) + (E)								
Pre-Control	5	12	18	2	17	20	37	chi^2 = 2.10
Playback	8	5	25	5	13	30	43	df = 1
Post-Playback	6	6	4	0	12	4	16	p>0.1
Post-Control	7	17	5	0	24	5	29	

Table 28. Occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads before, during and after playbacks of drillship noise, 1982-83. 'Mid-Playback' phase defined as in previous tables.

Date and Phase of Experiment	Number of Turns				Pre-dive Flex			Pre-dive 'Flukes Out'		
	None	One	>1	Total	No	Yes	Total	No	Yes	Total
A. 17 Aug '83										
Post-Boat	13	4	0	17	19	0	19	20	2	22
Mid-Playback	5	0	0	5	6	1	7	9	0	9
Post-Playback	9	2	0	11	10	2	12	11	2	13
Post-Control	19	1	0	20	19	5	24	24	4	28
B. 18 Aug '83										
Pre-Control	6	2	0	8	10	1	11	11	0	11
Mid-Playback	12	3	0	15	23	0	23	28	2	30
Post-Playback	4	2	0	6	9	0	9	9	2	11
Post-Control	3	1	0	4	10	1	11	11	1	12
C. 22 Aug '83										
Pre-Control	0	0	0	0	High sea-state today			5	6	11
Mid-Playback	2	2	0	4	prevented reliable			8	8	16
Post-Playback	1	0	0	1	observations of "flex"			4	2	6
Post-Control	16	5	0	21	vs. "no flex"			28	10	38
D. 18 + 22 Aug '83										
Pre-Control	6	2	0	8	10	1	11	16	6	22
Mid-Playback	14	5	0	19	23	0	23	36	10	46
Post-Playback	5	2	0	7	9	0	9	13	4	17
Post-Control	19	6	0	25	10	1	11	39	11	50
E. 16-19 Aug '82										
Pre-Control	27	5	2	34	35	3	38			
Playback	10	3	0	13	11	0	11	Data not available		
Post-Playback	2	0	0	2	1	0	1	for 1982		
F. Total, (D) + (E)										
Pre-Control	33	7	2	42	45	4	49			
Playback	24	8	0	32	34	0	34			
Post-Playback	7	2	0	9	10	0	10			
Post-Control	19	6	0	25	10	1	11			

Dive duration was rarely measurable, mainly because the whales were not well marked and were difficult to reidentify after a dive. No dives were timed in the pre-control phases of the 18 or 22 August experiments. Dives during the playback periods tended to be shorter than those after playbacks ended (means 1.30 vs. 3.37 min; Table 26). The sample sizes were small ($n = 10$ and 7), but the difference was significant ($0.05>p>0.02$).

In 1982 we found evidence that whales moved faster during drillship noise playbacks than before those playbacks. The sample sizes were small, but the trend was significant ($chi^2 = 5.18$, df=1, $p < 0.025$; Table 27). However, the pooled 18+22 August 1983 data provided no evidence of such an effect on speed ($chi^2 = 0.12$, df=1, $p > 0.5$; Table 27). Also, the pooled 1982 plus 1983 data were non-significant ($chi^2 = 2.10$, df=1, $p>0.1$).

The three variables summarized in Table 28 also were similar before, during and after playbacks. Considering the pooled 1982 and 1983 data, whales turned during 9 of 42 surfacings preceding playbacks and during 8 of 32 surfacings during playbacks (Table 28; $chi^2 = 0.13$, df=1, $p>>0.1$). Pre-dive flexes were rare before playbacks and not seen during playbacks (Table 28; $chi^2 = 2.92$, df=1, $p>0.05$). The flukes were brought out of the water at the ends of similar proportions of the surfacings preceding and during playbacks (Table 28; $chi^2 = 0.25$, df=1, $p>>0.1$).

Orientation of the Whales. — The 1982 experiments provided weak evidence that bowheads tended to orient away from 'Sequel' during playbacks (Richardson et al. 1983c). The 18 and 22 August 1983 experiments provided further evidence of this weak tendency. 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. Figure 5 shows orientations of bowheads relative to 'Sequel', as observed from the aircraft, and the following paragraphs describe the analyses of these data.

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. 5 and Table 29). During the playbacks, there was evidence of weak orientation away in both years ($p<0.05$ for 1982; $p<0.05$ for 1983; $p<0.01$ 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).

The V-tests and inspection of the data in Figure 5 show a greater tendency for orientation away from 'Sequel' while drilling noise was being broadcast than during the pre- or post-playback periods. However, Table 29 shows that 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 have relied on pooled data from 2-4 experiments in these comparisons. However, Figure 5 shows the data for each individual experiment. The tendency for orientation away was evident in only one of two experiments in 1982, and only one of two experiments in 1983 (Fig. 5, Table 29). A possible reason for the difference in results on 18 and 22 August 1983 is that the ambient noise level was lower on 18 August (Table 25). Consequently, the signal to noise ratio during the playback period was higher on 18 August than on 22 August (about 29 dB vs. 18 dB). This difference was very obvious to the human ear when we listened to the recorded sonobuoy signals. To the human ear, the drillship sound reaching the whales on 18 August completely dominated the underwater sound field, whereas on 22 August water noise was still detectable along with drillship noise during the playback period.

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 about 2-6 km from 'Sequel' in 1982 and about 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° represented directly away, 90° represented tangential to either the right or left, and 180° represented 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

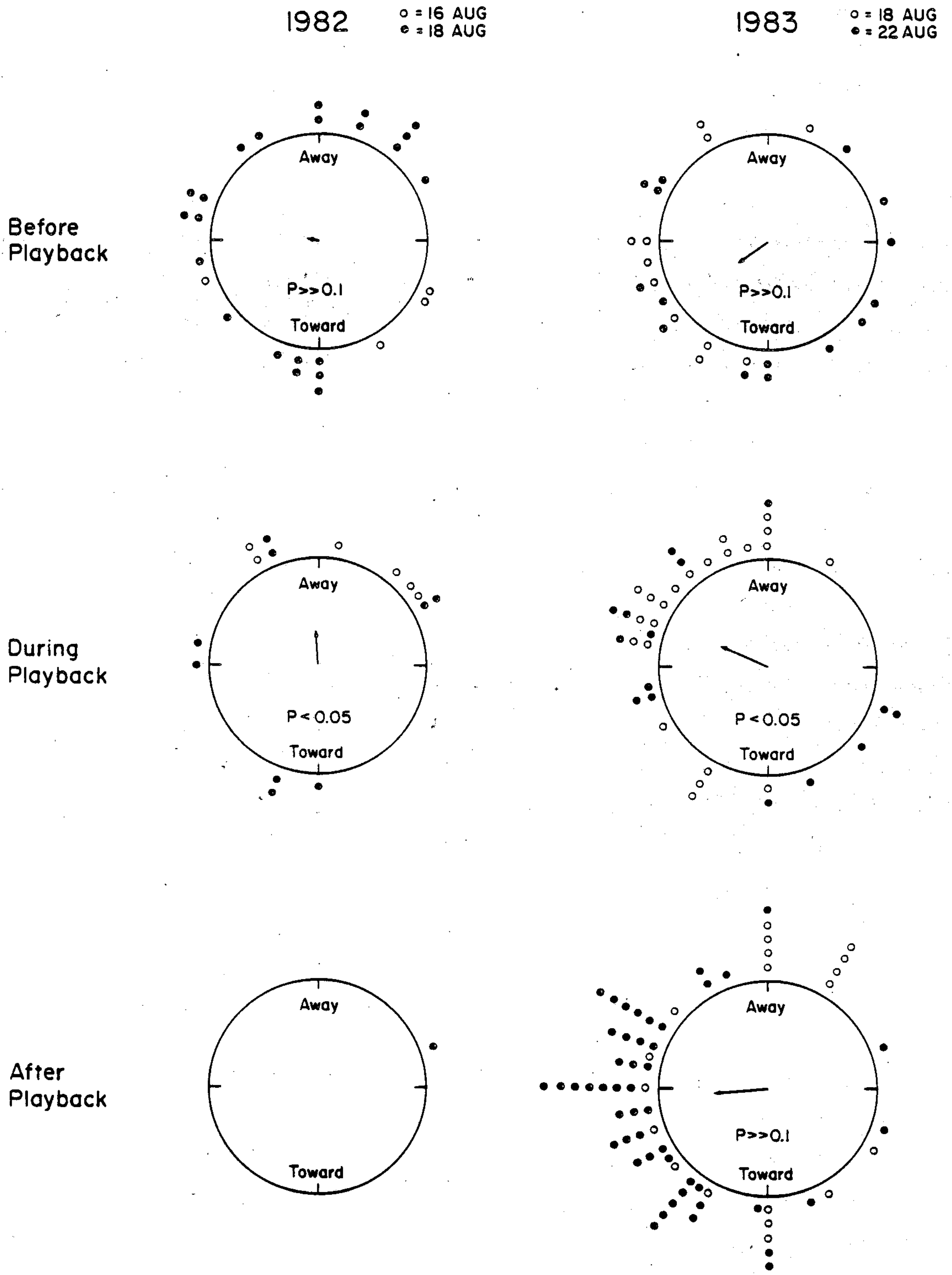

FIGURE 5. Orientations of bowheads during drillship noise playback experiments. Each symbol represents the heading of one whale relative to the playback site as observed from the observation aircraft. The directions and lengths of the mean vectors are shown. The p values are from V-tests of the hypothesis that there was significant orientation away.

Table 29. Vector analyses of bowhead orientations relative to playback site during drilling noise playbacks (0° and 360° = away; 180° = toward). The V-tests assess whether there was significant orientation away from the playback site. The Kuiper tests assess whether orientation differed between adjacent phases. See Batschelet (1981) for descriptions of these procedures.

Date and Phase of Experiment	Mean Vector			V-test vs. 0°		Kuiper Test	
	Direction	Length	n	V	P	K	P
1982							
Pre-Playback	280°	0.103	26	0.484	>>0.1	125.2	>0.5
Playback	357°	0.325	15	4.861	*		
1983							
18 August							
Pre-Playback	260°	0.603	11	-1.204	>>0.1	131.9	>0.1
Mid-Playback	304°	0.607	22	7.438	*	203.1	(*)
Post-Playback	324°	0.140	19	2.149	>0.1		
22 August							
Pre-Playback	190°	0.272	15	-4.025	>>0.1	105.1	>0.2
Mid-Playback	266°	0.337	15	-0.309	>>0.1	249.1	>0.2
Post-Playback	260°	0.678	48	-5.377	>>0.1		
18 + 22 August							
Pre-Playback	234°	0.343	26	-5.229	>>0.1	412.7	*
Mid-Playback	294°	0.476	37	7.129	*	699.1	>0.2
Post-Playback	265°	0.505	67	-3.228	>>0.1		
1982 + 1983							
Pre-Playback	244°	0.210	52	-4.744	>>0.1	832.8	(*)
Playback	306°	0.391	52	11.990	**		

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

significant correlation in either 1983 (Spearman $r_s = 0.09$, $n = 36$, 1-tailed $p>0.01$) 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.

All orientation data discussed above were obtained by observers in the observation aircraft. Boat-based observers recorded too few observations of bowhead orientations during drillship playback experiments to warrant analysis.

In summary, the 1983 playback data, like the 1982 data, indicate that bowheads tend to turn away from locations where drillship noise is originating. However, the effect is weak, and not all whales react in this manner. In 1983 we found evidence that dives were briefer when the water was ensonified by drillship noise 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.

Call rates. — Results from 1982 indicated that bowheads called less during drillship noise playbacks than before or after those playbacks (Richardson et al. 1983c; see also Table 30). Results from 1983 were not as clear, largely because of the lower overall calling rate in 1983. 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 most call types were similar before, during and after playbacks (Fig. 6). However, 'constant frequency' calls became less common during and after playbacks.

Discussion

Our results, mostly from previous years, have shown that bowheads sometimes approach to within a few kilometres of operating drillships, well within the zone where drillship noise is clearly detectable. Behavior there

Table 30. Call rates of bowheads during six drillship noise playback experiments, 1982 and 1983. Data compiled by C.W. Clark.

	Before Playback	Playback Level				After Playback
		Increasing	Peak	Decreasing	All	
Loud Calls/Whale-h						
16 Aug '82	8.3	6.9	0.0	4.0	3.9	1.1
18 Aug '82[a]	2.6	0.0	0.0	0.0	0.0	1.8
19 Aug '82	3.8	0.0	-[b]	-	(0.0)	3.8
17 Aug '83	0.0[c]	0.0	0.0	0.0	0.0	0.0
18 Aug '83	-	0.0	0.2	0.5	0.3	0.7
22 Aug '83	0.9	0.0	0.0	0.0	0.0	0.8
All Calls/Whale-h[d]						
16 Aug '82	49.2	31.5	4.0	17.0	18.8	35.0
18 Aug '82[a]	29.9	23.9	2.3	22.5	16.4	35.0
19 Aug '82	29.4	21.5	-[b]	-	(21.5)	17.1
17 Aug '83	2.7[c]	1.6	1.2	0.4	1.1	2.8
18 Aug '83	-	0.0	0.7	1.4	0.8	0.8
22 Aug '83	1.7	4.8	0.0	0.0	1.2	4.0
Whale-h						
16 Aug '82	5.2	1.3	1.0	1.0	3.3	1.8
18 Aug '82[a]	10.9	1.5	1.3	1.3	4.1	4.0
19 Aug '82	12.9	1.4	-[b]	-	(1.4)	4.2
17 Aug '83	7.0[c]	2.5	5.0	2.5	10.0	7.5
18 Aug '83	-	1.3	4.3	2.2	7.8	11.9
22 Aug '83	2.3	1.7	3.3	1.7	6.7	17.3
Total Calls/h						
16 Aug '82	295.3	188.9	24.0	101.8	112.5	210.0
18 Aug '82[a]	239.2	191.3	18.0	179.6	131.5	280.0
19 Aug '82	264.5	193.3	-	-	(193.3)	154.2
17 Aug '83	40.7[c]	24.0	18.0	6.0	16.5	42.0
18 Aug '83	-	0.0	9.0	18.0	10.0	10.9
22 Aug '83	17.1	48.0	0.0	0.0	12.0	39.9

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[a] Seismic signals were present throughout the experiment on 18 August 1982.

[b] The playback on 19 August 1982 was terminated before the peak level phase because a bowhead calf was detected.

[c] On 17 August 1983, the 'Before Playback' phase was within 30 min after "Sequel's" engine stopped.

[d] '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. The latter limitation also applies to 'Total calls/h'.

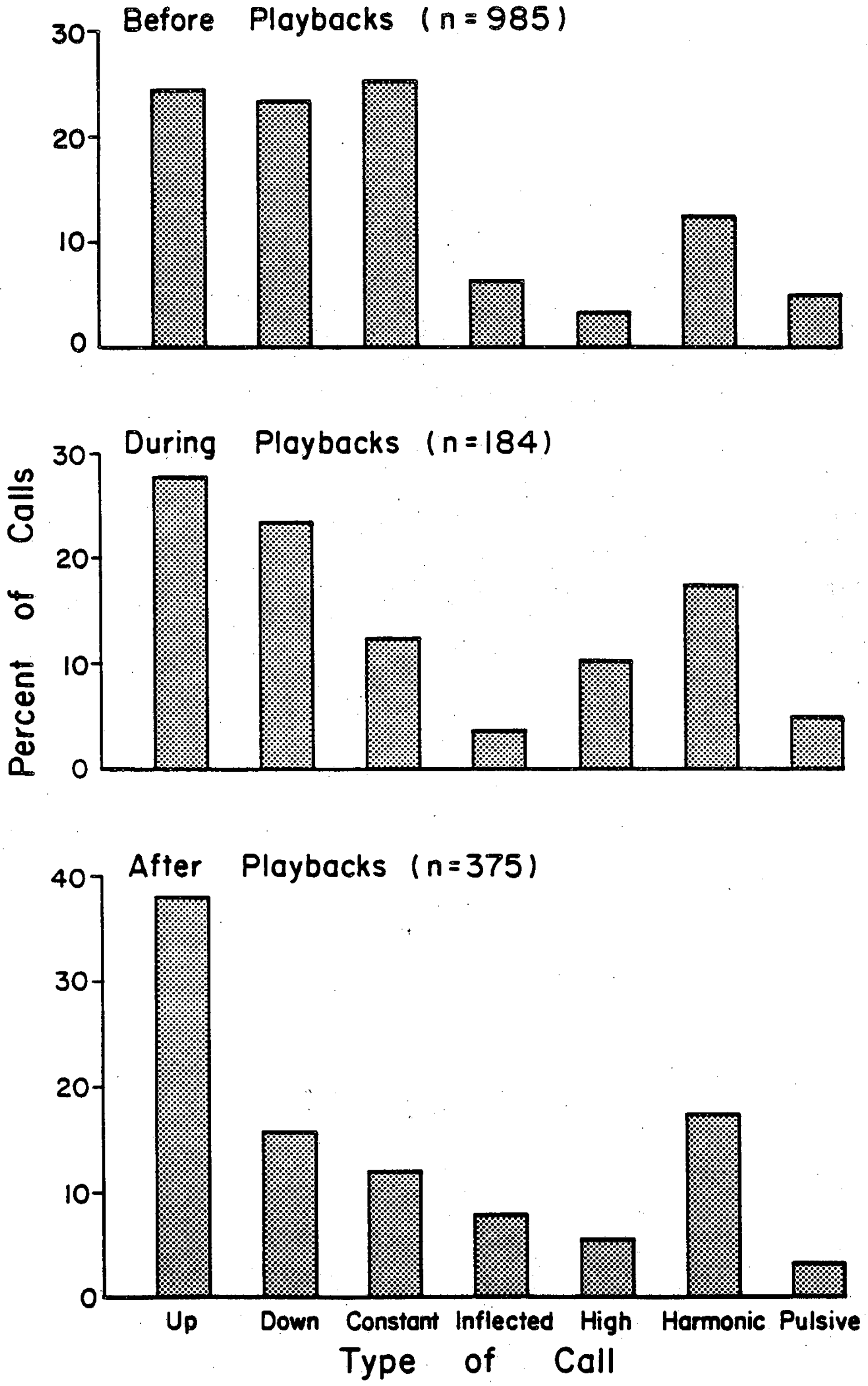

FIGURE 6. Relative frequencies of seven call types before, during and after six drillship noise playbacks, 1982-83. Data compiled by C.W. Clark.

was not conspicuously different from normal, although quantitative differences in surfacing and dive cycles perhaps did occur.

The playback experiments in 1982 and 1983 suggested that some bowheads reacted, although not strongly, to drillship noise at intensities similar to those several kilometres from a real drillship. There seemed to be a weak tendency to move away from the playback site. Results from 1983 were consistent with those from 1982 in this regard. However, contrary to results from 1982, in 1983 we found no change in speed relative to pre-playback periods. Calling rate also tended to decrease during playbacks in both 1982 and 1983.

Our orientation results from summering bowheads are generally consistent with reactions of migrating gray whales to playbacks of drilling noise (cf. Malme et al. 1983). They found a tendency for approaching gray whales to slow down and, with one type of drilling noise, to change course slightly in order to avoid the area within a few hundred metres of the playback site.

The reactions of bowheads and gray whales to playbacks of drillship noise were subtle and not easy to detect. Malme et al. had the advantage of working with large numbers of animals migrating close to shore, where precise theodolite tracking and a 'blind' observation protocol were possible (i.e. behavioral observers did not know when the playback was in progress). Our aerial observers could not obtain such precise data on bowhead movements, and we could not conduct the experiments in a 'blind' fashion. Also, we have not yet been able to test whether bowheads react specifically to drillship noise, or more generally to any novel sound.

The similarity of our results in 1982 and 1983, plus their similarity to results from migrating gray whales, makes it likely that the suspected effect on orientation is real. Nonetheless, it would be desirable to corroborate our results by obtaining precise information about movements of specific bowheads before and during playbacks. This would require shore-based theodolite tracking. We attempted such experiments in 1980-81, but were unsuccessful because bowheads remained too far offshore. The occurrence of bowheads near the Yukon coast in 1983 confirms that shore-based experiments could be done in some years, but not at predictable locations or times.

Why did the whales seem to be affected more strongly by playbacks than by drillships themselves? Bowheads clearly remained near drillships for hours whereas a drillship produces sounds continuously. We increased the playback intensity gradually over 10-13 min in an attempt to avoid startle responses. However, perhaps even a 10-min period of increasing noise is perceived differently than the slower increase that a whale would experience as it swam toward a drillship.

Another possibility is that some whales avoid drillships whereas others do not. This would be consistent with our playback results, in which only some of the whales moved away. It is not known whether bowheads are as numerous near drillships as they would have been in the absence of drillships. In any case, the observations near drillships (Fraker et al. 1982; Richardson et al. 1983c; this study) and the limited reactions to our playbacks show that some bowheads exhibit some tolerance of drillship operations.

It is difficult to predict whether bowheads would react to drilling on an artificial island in the same limited way that bowheads (and gray whales) react to drillship noise. Underwater noise from drilling on an island has not been recorded in the open water season.

REACTIONS OF BOWHEADS TO DREDGING

Dredges are used in the Beaufort Sea area to construct artificial islands from sea bottom materials. 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 floating pipeline. Dredges create continuous underwater noise detectable many kilometres away (Greene 1982, 1983, 1984).

In August 1980, many bowheads occurred around a dredge at Issungnak artificial island in 19 m of water (Fraker et al. 1982). This island was being improved by the suction dredge 'Beaver Mackenzie'. The operation also included a barge, tug boats, and helicopter and crew boat traffic from shore. Underwater industrial noise was readily detectable at least as far as 4.6 km away, with tonal components at various frequencies up to 1776 Hz (Greene 1982). LGL observers saw bowheads as close as 0.8 km from the construction operation, and industry personnel reported some whales <500 m from the dredge.

The 1980 results showed that bowheads sometimes tolerate considerable dredge noise and associated industrial activity. However, previous to 1983 there had been no controlled tests of reactions of bowheads to dredge noise, and it was not known whether any bowheads avoided dredging sites.

In 1983 we conducted one playback experiment with dredge noise, and obtained limited sightings of bowheads near island construction operations.

Methods

On several dates in 1983 we searched for whales near two of Esso's island construction operations -- Amerk in 23 m of water NNW of Tuktoyaktuk, and Kadluk in 12 m of water west of Richards Island (Fig. 1). Most searching was with the observation aircraft. However, 'Sequel' visited each site once to search for whales and record underwater noise.

- At Amerk (69°59'N, 133°31'W), the 'Beaver Mackenzie' suction dredge was constructing an underwater berm throughout our field season. Two or more support boats were usually present, and there was daily helicopter traffic.
- At Kadluk (69°47'N, 136°00'W), two hopper dredges and support vessels were completing an underwater berm in early August. In mid August, a mobile caisson was sunk onto the berm. In mid and late August, hopper dredges unloading via floating pipeline filled the caisson with sand. In late August, support vessels began construction of drilling facilities on the newly formed caisson-retained island.

A dredge noise playback experiment was conducted near the Yukon coast on 26 August 1983. Recorded noise from the 'Beaver Mackenzie' suction dredge was broadcast via a J-11 projector deployed at 9 m depth from 'Sequel' in the same manner as during playbacks of drillship noise (see Reactions to Drilling section, above). 'Sequel' was anchored in water 18 m deep at 69°07'N, 137°55'W, 2.8 km from the Yukon coast. Seas were nearly calm.

'Sequel' had been anchored for 1.8 h before the Islander observation aircraft began circling at 610 m a.s.l. Pre-playback control observations were obtained for 72 min. The 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 32 min.

About eight whales were observed intensively from the observation aircraft, but orientations and general behavior of several other whales were noted when possible. The whales were 0.5-2.0 km from 'Sequel', mostly closer to shore than 'Sequel'. Most were single animals that hung nearly motionless at the surface of the turbid water between dives. There was occasional socializing. Because of the shallow water, it was not possible to drop a sonobuoy amongst the whales.

Results

Observations near Island Construction Operations

Industry personnel reported one or more bowheads near the Amerk dredging site on 12 August. Low ceilings prevented aerial observations. However, '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 10-1000 Hz band at 9 and 18 m depth (Greene 1984).

We saw bowheads 18 km from the Kadluk island construction site on two dates: ~15 bowheads on 31 August, and at least 4 bowheads on 1 September. Our sonobuoys detected continuous industrial noise of undetermined origin at this site. However, it is doubtful that this noise was from Kadluk, given the shallow intervening water (12-19 m) and the presence of closer sources of industrial noise (see Reactions to Drilling section). Other investigators also saw bowheads in the Kadluk area on 3 and 6 September (D.K. Ljungblad pers. comm.; J.C. Cubbage pers. comm.). It is not known whether the same animals remained in the area from 31 August to 6 September.

Dredge Noise Playback Experiment

The bowheads observed during the dredge noise playback experiment on 26 August were about 0.5-2.0 km from the sound projector, i.e. at distances comparable to those during the 1983 drilling noise playbacks. The aerial observers did not notice, in real time, any obvious response of the whales to the playback. The whales remained in the area during and after the playback.

Detailed analysis of surfacing and respiration variables did not reveal any differences among phases of the experiment (Table 31). The estimated speeds were also similar in the pre- and mid-playback periods, although there were indications of higher speeds after the playback ended (Table 32). The frequencies of turns, pre-dive flexes, and 'flukes-out' dives were similar in all phases of the experiment (Table 33). Durations of dives could not be determined during most phases.

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. We saw no conspicuous movement away from 'Sequel' during the playback. However, detailed analysis of the results suggested that there may have been a slight change in orientations:

1. Orientations recorded by aerial observers were less widely scattered during the playback than they were before or after (Fig. 7). There was a weak tendency for orientation away from 'Sequel' both before and during the playback (V-tests, $p < 0.1$ and $p < 0.05$, respectively), but not after the playback ($p >> 0.1$). Orientations during the pre-playback and playback phases were marginally different from one another (Kuiper test, $p < 0.1$; Table 34). Orientations in the playback and post-playback phases were significantly different ($p < 0.05$, Table 34).

Table 31. Surfacing, respiration and dive characteristics of non-calf bowheads observed before, during and after playback of dredge noise, 26 August 1983. The 'Mid-Playback' phase excludes the first 5 min of the increasing level phase and the last 5 min of the decreasing level phase.

Phase of Experiment	Mean	s.d.	n	Difference	Mean	s.d.	n	Difference
	No. Blows/Surfacing				**Duration of Surfacing (min)**			
Pre-Playback	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
	Blow Interval (s)				**Dive Duration (min)**			
Pre-Playback	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	

Table 32. Speeds of non-calf bowheads during surfacings before, during and after playback of dredge noise, 26 August 1983.

Phase of Experiment	No. of Surfacings when Speed was						
	Zero	Slow	Moderate	Fast	Zero or Slow	Moderate or Fast	Total
Pre-Playback	8	4	5	1	12	6	18
Mid-Playback	1	4	3	0	5	3	8
Post-Playback	3	1	9	0	4	9	13

Table 33. Occurrence of turns, pre-dive flexes, and 'flukes out' by non-calf bowheads before, during and after playback of dredge noise, 26 August 1983.

Phase of Experiment	Number of Turns				Pre-dive Flex			Pre-dive 'Flukes Out'		
	Zero	One	>1	Total	No	Yes	Total	No	Yes	Total
Pre-Playback	11	4	0	15	14	5	19	20	14	34
Mid-Playback	3	2	0	5	4	5	9	6	4	10
Post-Playback	1	1	0	2	3	3	6	11	7	18
Contingency test	n too small				chi^2 = 2.64 df = 2 $p > 0.25$			chi^2 = 0.03 df = 2 $p > 0.9$		

Table 34. Vector analyses of bowhead orientations relative to playback site during dredge noise playback (0° and 360° = away; 180° = toward). The data are shown in Fig. 7; all observations were by the aerial observers. The V-tests assess whether there was significant orientation away from the playback site. The Kuiper tests assess whether orientation differed between adjacent phases. See Batschelet (1981) for descriptions of these procedures.

Phase of Experiment	Mean Vector			V-test vs. 0°		Kuiper Test	
	Direction	Length	n	V	P	K	P
Pre-Playback	13°	0.205	26	5.194	(*)	344.2	(*)
Mid-Playback	54°	0.488	31	8.886	*	390.2	*
Post-Playback	94°	0.374	29	-0.782	>>0.1		

(*) means $0.1 \geq p > 0.05$; * means $0.05 \geq p > 0.01$.

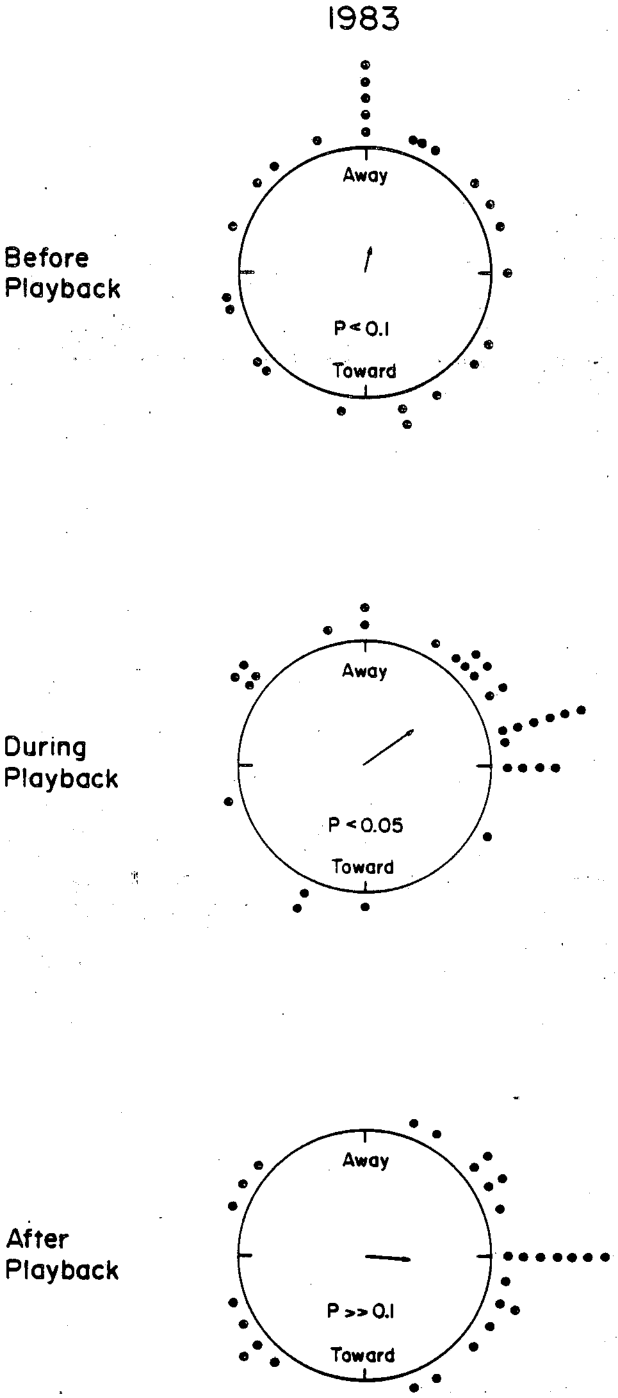

FIGURE 7. Orientations of bowheads during a dredge noise playback experiment, 26 August 1983. Each symbol represents the heading of one whale relative to the playback site as observed from the observation aircraft. The directions and lengths of the mean vectors are shown. The p values are from V-tests of the hypothesis that there was significant orientation away.

2. Of the whales observed from 'Sequel', a higher proportion were headed away during the playback than before the playback (Fig. 8). Each whale was tallied once per surfacing in this analysis. Observers on 'Sequel' saw similar numbers of whales heading away from and towards 'Sequel' before playbacks began (56 vs. 50 sightings; Table 35). If only the period while the aircraft was overhead is considered, the ratio was 18 away and 28 toward. In contrast, during the playback, the ratio was 15 away and 4 toward. Chi-square tests (2x2 design) suggested that the difference was significant ($p < 0.05$). The same was true when the numbers headed away, tangentially and toward were compared via 3x2 chi-square tests (Table 35).

If bowheads did tend to head away from 'Sequel' in response to the dredge noise playback, one would expect a stronger reaction from the whales closest to the boat. This was tested using the same procedure as applied in the analysis of drilling noise playbacks. The Spearman rank correlation between 'deviation of heading from directly away' and 'distance from projector' was only 0.11 ($n = 28$, $p >> 0.1$). Thus, within the rather narrow range of distances considered (~0.7 - 2.0 km), there was no evidence that orientation was more consistently 'away' among the closer bowheads.

In general, there was little reaction to the dredge noise playback. There was, however, an indication that bowheads were slightly more likely to orient away from the noise source during the playback period than during the control periods.

Discussion

Observations of bowheads near island construction sites during 1980 and 1983 show that some bowheads occasionally tolerate these industrial activities and their associated underwater noise. Only a few bowheads approached industrial sites in 1983, but some of those whales apparently remained for at least a day or two. In 1980, larger numbers of bowheads were found near the Issungnak dredge site, sometimes feeding (Fraker et al. 1982). Numerous whales were found within 10 or 15 km of Issungnak for about 3 weeks. On some of those days, several whales were within 5 km of the dredge. However, on other days there were no sightings that close. Thus, it is uncertain how long particular individuals remained within the area ensonified by the dredge noise in 1980. In any case, the sightings near actual island construction operations show tolerance of those operations by at least some bowheads at some times.

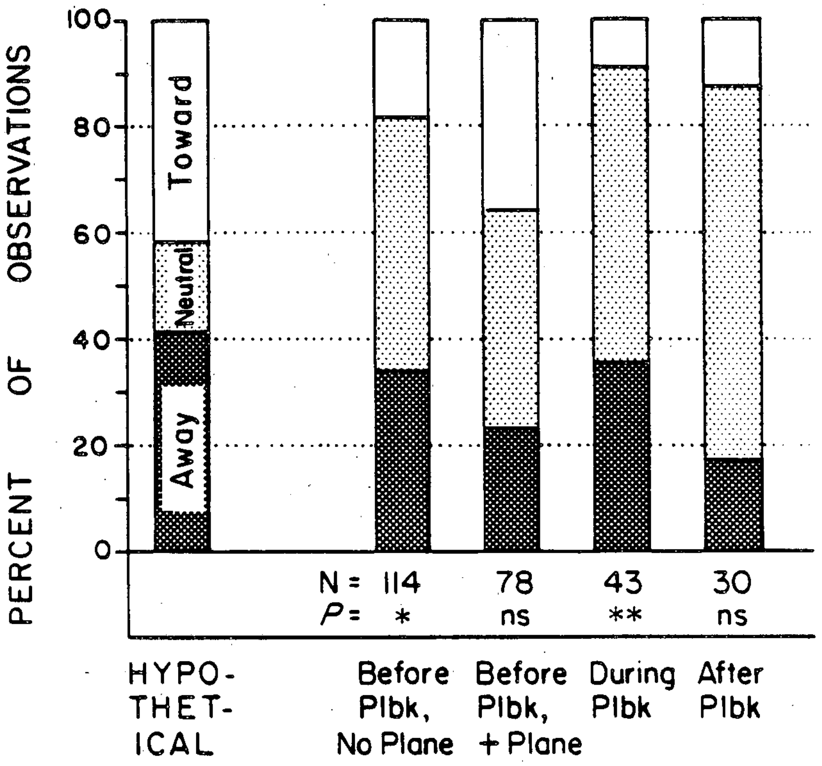

FIGURE 8. Orientations of bowheads observed from 'Sequel' during a dredge noise playback experiment, 26 August 1983. Hypothetical orientations are those expected if whales were randomly oriented with respect to 'Sequel'. Significance determined by one-sided binomial tests of 'number away' vs. 'number toward'; ns means p > 0.1, * means 0.05 ≥ p > 0.01, and ** means 0.01 ≥ p > 0.001.

Table 35. Orientations of bowheads observed from 'Sequel' during a dredge noise playback experiment, 26 August 1983. Each whale was tallied only once for each surfacing. 'Mid-Playback' phase defined as in previous tables. The data are plotted in Figure 8.

	No. of Surfacings with Bowhead Oriented				Comparison of Adjacent Phases	
Phase of Experiment	Away	Tangential	Toward	Total	chi^2	P
Before playback, no plane 19:15-20:58	38	54	22	114		
					6.99	*
Before playback with plane 20:58-22:10	18	32	28	78		
					10.14	**
Mid-Playback 22:15-22:45[a]	15	24	4	43		
					2.98	>0.1
Post-Playback 22:50-23:20	5	21	4	30		

* means 0.05 > p > 0.01; ** means 0.01 > p > 0.001; df = 2 for each test.

[a] Excluding observations during first 5-min of increasing level phase and last 5 min of decreasing level phase.

The results from the one dredge noise playback experiment in 1983 suggest that bowheads do not react strongly to dredge noise. We saw no pronounced response even though the source level of the noise increased rather quickly (within 10 min) in an area where there had previously been no dredge noise. These results are preliminary and require confirmation. Only one trial was possible, and it was not possible to measure the noise levels received by the whales. We believe that noise levels reaching the whales were similar to those during the drilling noise playback experiments, since the location, water depths, and distances from projector to whales were similar. However, our inability to measure the noise level reaching the whales in the dredge noise experiment was an important limitation.

Despite the lack of pronounced response to the dredge noise playback, there was weak evidence of a tendency for bowheads to orient away during the playback. This result must be treated as tentative until it can be replicated. The apparent effect was sufficiently subtle that the aerial observers did not notice it in real time. There was no clear evidence of a concurrent increase in speed of movement (Table 32). Also, the statistical tests of orientations are only approximations because of probable lack of independence. Some whales were undoubtedly tallied more than once, and some were in interacting groups. In these circumstances, it is impossible to judge how many truly independent data points there were in each analysis.

Nonetheless, a slightly higher proportion of the whales oriented away during the playback than before. This result needs confirmation, but it is similar to the results from our drilling noise playback experiments. No other studies of the responses of baleen whales to construction activities have been published.

CONCLUDING REMARKS

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. There sometimes were indications of subtle reactions to drillship noise, and perhaps to dredge and seismic noise. Overall, however, bowheads showed considerable tolerance of ongoing seismic, drilling and dredging operations.

Progress in 1983

Previous to 1983, reactions of bowheads to our observation aircraft were frequent when it was $\leq$ 305 m (1000 ft) a.s.l., infrequent when it was at 457 m (1500 ft), and not detected when it was at $\geq$ 610 m (2000 ft). Results in 1983 were generally consistent with this, but reactions to aircraft at 457 m altitude were more frequent and pronounced in 1983 than before. We suspect that this was largely attributable to the shallow water where most 1983 observations were obtained. Measurements of aircraft noise in 1983 confirmed that lateral propagation of aircraft noise in the Beaufort Sea is greater in shallow than in deep water (Greene 1984). Data from 1983 also confirmed that, directly below the aircraft, aircraft noise levels in the water are greater at shallow depths (e.g. 3 m) than at the deeper depths where most previous measurements of aircraft noise have been made.

We have still not had the opportunity to conduct controlled tests of the reactions of bowheads to helicopters. However, opportunistic observations of bowheads overflown by a helicopter at about 150 m a.s.l. on two occasions revealed no pronounced reactions.

The one boat disturbance experiment conducted in 1983 confirmed our previous finding that bowheads react strongly and consistently to approaching boats. The comparative simplicity of boat disturbance trials could provide a way to assess the relative sensitivity of bowheads to industrial activities in different situations. For example, to determine whether sensitivity varies with season, water depth, distance from shore, activity of the whales, etc., a series of standardized boat disturbance trials could be performed in these different circumstances.

The behavior of bowheads in the presence of noise from seismic vessels 6 km or more away is not dramatically different from behavior in the absence of industrial activities. Observations in 1983 confirmed that activities of bowheads in such circumstances seem normal, with no evidence of avoidance. Results from 1980-82 had suggested that surfacing and respiration behavior sometimes may be altered slightly in the presence of seismic noise. However, when the new 1983 results were combined with previous data, there was no evidence of consistent changes in surfacing or respiration behavior in the presence of noise from seismic vessels ≥ 6 km away.

New noise measurements in 1983 confirmed our earlier speculation that received levels of seismic noise are several decibels less 3 m below the surface than at deeper depths (Greene 1984). Hence, bowheads can, by remaining at or just below the surface, reduce the levels of seismic sounds to which they are exposed.

Although bowheads have been seen near drillships on several occasions, drillship noise playback experiments in 1982 suggested that some bowheads move away when drillship noise is introduced into the water. This tentative conclusion was corroborated by additional drillship playbacks in 1983. Although the reactions of bowheads to drillship noise were not nearly as consistent or dramatic as those to an approaching boat, some bowheads did move away in apparent response to the noise.

Similarly, bowheads have been seen near an operating suction dredge in previous years and again in 1983. In 1983 we obtained the first experimental evidence about responses of bowheads to dredge noise. One playback experiment using noise from that same dredge provided results similar to those during drilling noise playbacks. The whales did not react dramatically, but there were indications of orientation away from the noise source during the dredge noise playback. This result needs corroboration by replicate tests.

Data Gaps

Reactions of bowheads to helicopters have not been documented systematically, although some opportunistic observations have been obtained (Berzin and Doroshenko 1981; Dahlheim 1981; this study). We expect that reactions to helicopters and fixed-wing aircraft are generally similar. However, some helicopters produce rather intense noise with many tones

(Greene 1982, 1984), so reactions of bowheads 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). However, their reactions to the more realistic case of single overflights by an actual helicopter are unknown.

Short-term reactions of bowheads to <u>boats</u> 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. Reactions to icebreakers and hovercraft are unknown.

Bowheads often tolerate intense <u>seismic</u> noise without exhibiting noticeable changes in behavior. However, a number of questions about the effects of this noise remain unanswered.

1. Are there subtle reactions to noise from distant seismic boats?
2. If so, are these effects indicative of any real deleterious effect on the animals?
3. Do bowheads close to a seismic vessel attempt to swim away from it? (We have shown that bowheads $\geq$ 6 km away apparently do not swim away, but movements of gray whales within a few kilometres of a seismic boat were affected [Malme et al. 1983].)
4. Does exposure to intense seismic noise have any negative effect on the hearing system of bowheads?
5. Does exposure to seismic noise affect the probability that bowheads will return to that area in future years? (See Richardson et al. 1983a, 1984 for discussion of available evidence.)

Some of these questions will be difficult or impossible to address by studying short-term behavioral reactions. However, questions (1) and (3) could be answered by controlled, replicated experiments in which bowhead behavior is observed before, during and after exposure to seismic noise. Our three sub-scale experiments with one airgun have provided information relevant to question (1); there were hints of consistent effects, but further replication is needed to confirm them. To address question (3), either a full-scale seismic vessel or a sub-scale system deployed close to the whales will be needed.

Much also remains to be learned about the long-distance propagation of seismic noise through water. There is variation in the rate of attenuation of seismic pulses with increasing range (Greene 1983, 1984). 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, 1983, 1984; Malme et al. 1983). No detailed study of the interactions of these factors 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 are the types of drilling platforms being used for drilling in the Alaskan Beaufort Sea. Malme et al. (1983) found that gray whales reacted more strongly when drilling noise was variable than when it was unchanging over time. There still are no published measurements of underwater noise from drilling on islands in the open water season. Hence, it is not known how the intensity or variability of noise from an island would compare with those from drillships. Noise from summer drilling on islands in the Beaufort Sea should be recorded, analyzed, and used in playback experiments.

We have found that bowheads sometimes tolerate considerable noise from a suction dredging operation. However, our one playback experiment with that type of dredge noise suggested that some bowheads oriented away from the noise source. This result needs confirmation. There is no information about reactions of bowheads to hopper dredges. Unlike suction dredges, hopper dredges often move forward while dredging, and often travel long distances between the sites where the material is picked up and deposited.

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. Bowheads did not respond very dramatically to either drillship or dredge sounds. If they respond in the same way to non-industrial sounds, then the importance of their weak reactions to drillship and dredge sounds would be questionable.

Long-term effects could only be monitored through repeated observations of identifiable individuals, or through documentation of displacement from areas with much industrial activity. To maintain contact with particular whales, radio telemetry or intensive photographic work (Davis et al. 1983) would be necessary. Both approaches were beyond the scope of this study. With regard to displacement, the number of bowheads within the main industrial area has varied dramatically during 1980-83 (Richardson et al. 1983a, 1984). However, it is not known whether any of this variability is attributable to industrial activity rather than to natural factors such as variable food supply, ice conditions, etc.

Implications of Short-term Behavioral Reactions

We reviewed the biological significance of short-term responses to industrial activity in our report on 1982 field work (Richardson et al. 1983c, p. 208-210). In that report we also commented on the probable applicability of our studies in the Canadian Beaufort Sea to bowheads in Alaska. In this section, we summarize the main points, and refer the reader to the earlier report for more details.

Strong responses to boats and aircraft have been found in some situations, and weaker responses to other industrial activities have been detected or suspected. However, even the strong responses do not seem to persist for long. Bowheads do not seem to travel far 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. Disruption of social groupings, especially mother-calf pairs, could be more important. Also, the subtle alterations in behavior that we sometimes detected might be significant as indicators of stress.

Noise, particularly continuous noise, also reduces the maximum range to which a bowhead call or other sound is detectable. The importance of long distance acoustic communication to bowheads is unknown. Hence, it is impossible to assess whether reduction of detection range would affect bowheads negatively. It is possible, but unproven, that detection of noise from ice, or from areas of open water within ice fields, may be important to bowheads. If so, masking of these noises by continuous industrial noise could be important.

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. Hence, we suspect that reactions of whales to industrial activities would be very similar in the two areas. 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 fall.

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CHARACTERISTICS OF WATERBORNE INDUSTRIAL NOISE, 1983 *

By

Charles R. Greene

Greeneridge Sciences, Inc.
5276 Hollister Ave., Suite 408
Santa Barbara, CA 93111

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ABSTRACT

Underwater industrial noises in the Canadian Beaufort Sea were recorded in August 1983 in support of a study of the behavior of bowhead whales near actual and simulated oil industry activities. Bowheads are believed to be more likely to react to underwater sounds than to other stimuli associated with industrial activities. 1983 was the fourth year of research, which has always been in August. Sounds were again recorded via two systems: (1) sonobuoys dropped and monitored from the aircraft used for behavioral observations, and (2) hydrophones suspended beneath a sparbuoy drifting near a boat. In 1983, the boat system included hydrophones deployed at depths of 3, 9 and 18 m. This permitted us to compare ambient noise, noise from aircraft, and noise from in-water sources as received simultaneously at three depths. Unless otherwise noted, levels quoted below were at 9 or 18 m depth.

The ambient noise data revealed that very low levels of background noise sometimes occur in the Beaufort Sea. The lowest levels observed in 1983, about 0-10 dB below the 'Knudsen sea state zero' curve, were recorded in water 12 m deep with the hydrophone on the bottom. At frequencies below about 20 Hz, noise levels were greater at depth 3 m than at 9 or 18 m. The greater levels at 3 m probably represented hydrostatic pressure variations due to surface waves. At higher frequencies there was no apparent distinction in levels at the three depths.

Measurements of aircraft noise in 1983 included a Sikorsky 61 helicopter and the Twin Otter and Islander fixed-wing aircraft used for behavioral observations. For a large helicopter, the Sikorsky 61 appeared relatively quiet, although it did not pass directly over our hydrophones. Its strongest tone, at 102 Hz, was 95 dB//1 μPa during a pass at altitude 152 m. The strongest tone from a Bell 212 helicopter at that altitude in 1981 was 109 dB at 20 Hz. A Twin Otter at altitude 457 m, circling at reduced power, produced an 82 Hz tone of level 100 dB. All of these values are averages over 4 s.

The Islander flew over the hydrophones at several altitudes and two power settings. Received noise levels were less with circling than with cruise power, less at high than at low altitudes, and less at 9 or 18 m depth

than at 3 m depth. Differences were a few dB in each case. Also, in shallow water (15 m) the Islander sometimes could be heard continuously as it made a circle of radius about 2 km. In deeper water, aircraft noise is detectable in the water for only a brief period when the aircraft is almost directly overhead.

Boat noise recorded in 1983 included the survey boat 'Arctic Sounder' (anchored; generators only), the crewboat 'Imperial Sarpik' underway at high speed, and the project's chartered boat 'Sequel'. As expected, 'Arctic Sounder' was relatively quiet, with tones from the generators dominating its sound spectrum. 'Imperial Sarpik' was noisy, with a dominant tone at 195 Hz (100 dB level at range 2.8 km). 'Sequel' showed a strong family of tones, evidently originating from its shaft rotation rate and possibly caused by a damaged propeller blade; we did not observe these tones in 1981 or 1982.

The geophysical survey ship 'Canmar Teal', recorded while underway at range 4.6 km, showed strong tones at 52, 291 and 301 Hz. The received level of the 52 Hz tone was 85, 96 and 99 dB at hydrophone depths 3, 9 and 18 m, respectively, making 'Teal' potentially as noisy as 'Sarpik'. These noises were from the ship itself, not the seismic gear. The hopper dredge 'Cornelius Zanen' underway at ranges from 2.4 to 7 km provided noise levels from 127 to 100 dB in the 20-500 Hz band. This large vessel produced noise levels comparable to those of other large vessels we have studied.

Most seismic survey signals analyzed in 1983 were recorded via sonobuoys, which can overload and distort with pressure levels as low as 124 dB, depending on frequency and type of sonobuoy. However, received signal levels from sources 26-80 km away varied without strong dependence on range, indicating that other factors (e.g. water depth, properties of the ocean bottom) strongly affect signal strength at these distances.

Seismic signals from 'Canmar Teal' at ranges 3 to 10.4 km were received via hydrophones at depths 3, 9 and 18 m. 'Teal' was using a small array of three airguns of total volume 5.2 L (320 in^3). The signal at 3 m was generally 4 to 10 dB less than that at 9 m. Levels at 9 and 18 m were not consistently different. This depth effect was consistent with that for boat noise; the shallow hydrophone received lower sound levels. In contrast, the shallow hydrophone received the highest level of aircraft noise.

Noise from three <u>dredges</u> was recorded while they were dredging in 1983. The noise from 'Beaver Mackenzie' was different than it had been during measurements in 1980 and 1981; the signals were weaker and the characteristic tones were missing. This dredge has evidently been modified to some extent since 1981. Hopper dredge 'Cornelius Zanen' picking up a load at Ukalerk radiated noise at levels comparable to those from a similar dredge, 'Geopotes X', measured in 1982. The 10-500 Hz band levels usually were between 140 and 145 dB//1 μPa for ranges from 0.63 to 1.19 km. The suction hopper dredge 'Aquarius', moored in place at Nerlerk and transferring sand from the bottom to construct a berm, did not radiate as much noise, but neither was it underway. At range 0.2 km, its level in the 20-500 Hz band was 139 dB//1 μPa at depth 3 m, 143 dB at depth 9 m and 140 dB at depth 18 m. For ranges from 0.20 to 14.8 km, the relationship between received levels and range followed cylindrical spreading at all three hydrophone depths, with additional linear losses of 0.82 dB/km for depth 3 m, 0.43 dB/km for depth 9 m and 0.27 dB/km for depth 18 m.

The noise levels from the Kadluk <u>construction site</u> were about the same when recorded at ranges 0.93, 1.8, and 3.8 km. At depth 3 m the levels were close to 114 dB and at 9 m the levels were close to 117 dB in the 40-1000 Hz band. About 9 h passed between the times of recording at the 3.8 and 1.8 ranges, and no doubt the activities changed. At the 0.93 km range the noise levels varied considerably. To avoid noise from a work boat nearby, we chose a quiet time to analyze.

INTRODUCTION

Since 1980 the Minerals Management Service, U.S. Department of the Interior, has 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 comes from the potential for oil exploration and development north of Alaska, and questions about its effects on bowheads. However, the field work has been conducted during August of 1980-83 in the Canadian part of the Beaufort Sea, east of Alaska. Bowheads feed there at that time, and offshore oil development is considerably more advanced in the Canadian than in the Alaskan part of the Beaufort Sea. Thus, the Canadian Beaufort Sea provides a study area with both animals and potential sources of disturbance.

During this project, biologists have studied bowhead behavior in both the absence and presence of industrial activities (Richardson 1982, 1983, this volume). One of the primary suspected sources of disturbance is waterborne sound from industrial activities. Examples are sounds from drillships, dredges, activities at artificial islands, workboats, helicopters and geophysical surveys (seismic soundings with airgun arrays, sleeve exploders, open-bottom gas guns).

The behavioral observations have been made primarily from an airplane, a twin-engine Britten-Norman Islander carrying four biologists. Supplementary observations were provided by one or two biologists on 'Sequel', a 12.5 m closed-cabin fishing boat.

Underwater sound measurements have been made from both the airplane and the boat. The airplane crew deployed sonobuoys in areas where whales were being observed, and tape recorded the signals for later detailed analysis. This procedure was invaluable for characterizing the sounds to which whales were exposed during behavioral observations. Seismic survey signals were particularly pervasive, often coming from ships far enough away that they were not visible to the aircrew. Sonobuoys also permitted monitoring the sounds reaching the whales during disturbance trials when an airgun was fired or when recorded industrial noise was played back underwater from 'Sequel'.

An underwater sound specialist served on the boat crew. In 1983, four hydrophones were suspended at three depths beneath a sparbuoy in order to record ambient noise or sounds from industrial activities. For playback experiments, a J-11 projector, capable of projecting at levels to 172 dB// 1 µPa, was suspended at a depth of 9 m over the side of 'Sequel'. Recordings of drillship and dredge noise were broadcast into the water during playback experiments in 1983 (Richardson et al. 1984). During an airgun disturbance trial, a 0.66 L (40 in^3) airgun was towed about 50 m behind 'Sequel' at a depth ~6 m, comparable to the depth of airgun arrays used for geophysical surveys.

The operating area and sites of particular sound recording and disturbance experiments in 1983 are shown in Figure 1. The behavior of the bowheads observed in the presence of the various industrial sounds and during the disturbance experiments is described in the preceding section by Richardson et al. (1984).

From 1980 through 1982, Polar Research Laboratory, Inc., provided the equipment and personnel for the underwater sound work (Greene 1982, 1983). In 1983, Greeneridge Sciences, Inc. assumed these responsibilities. Senior personnel and basic procedures in the field and laboratory have been unchanged throughout the project. LGL Ecological Research Associates, Inc., has provided the resources for the biological research and has been responsible for the direction of the entire project.

METHODS

The methods used in 1983 were similar to those in 1980-82 (Greene 1982, 1983). This report contains a summary of the aircraft, boat and analysis systems including a description of the changes since 1982.

Aircraft System

Biologists aboard the observation aircraft deployed sonobuoys to detect underwater sounds. One observer listened to the signals and tape recorded them. A maximum of two sonobuoys could be monitored and recorded

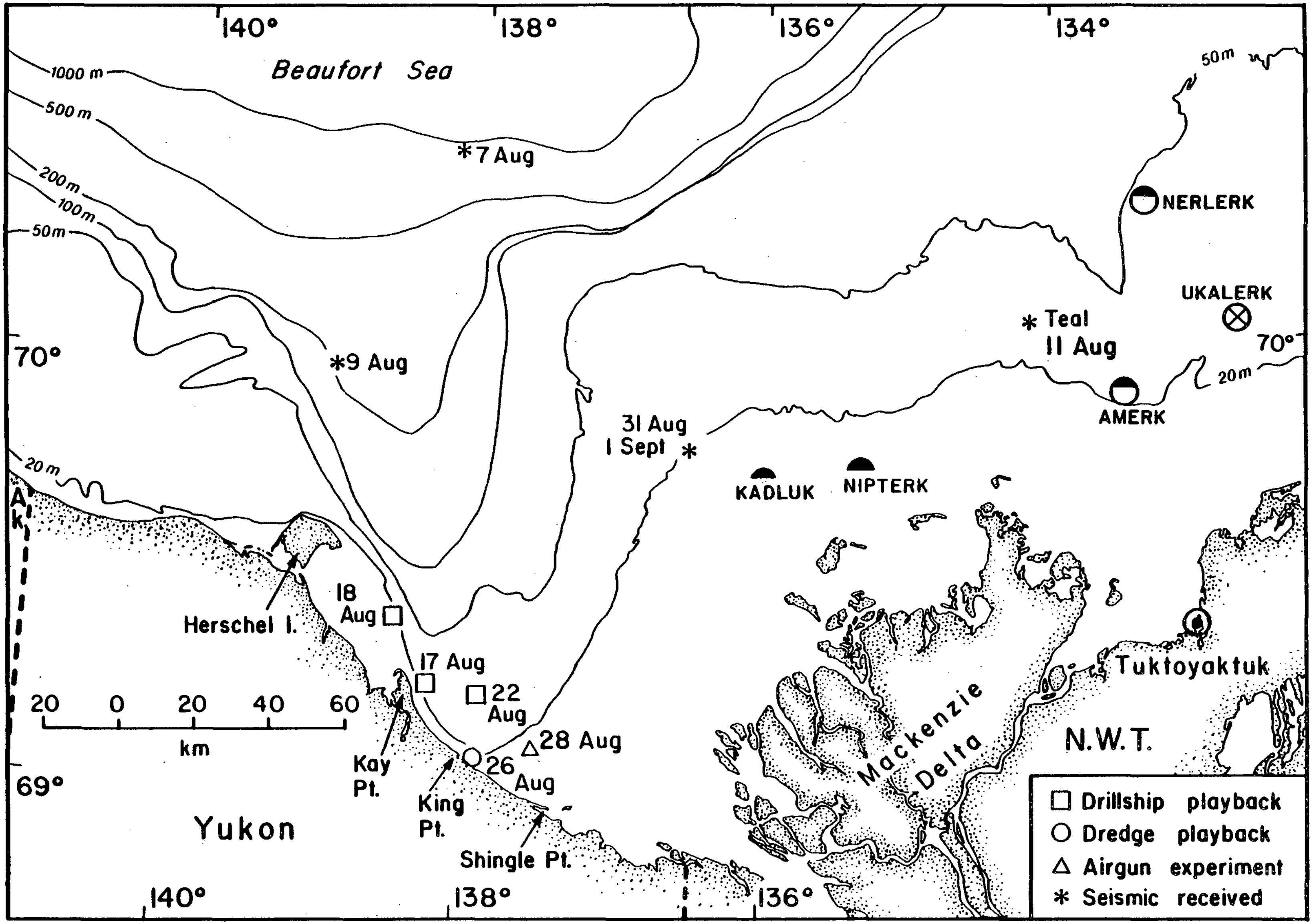


FIGURE 1. Map of the 1983 study area, east-central Beaufort Sea. The major recording and playback sites in August-September 1983 are shown.

simultaneously. In 1983 we used 10 calibrated AN/SSQ-57A sonobuoys and eight AN/SSQ-41B sonobuoys. The latter are functionally similar to the former, but are not calibrated. The Q-41B buoys are built to the same ± 2 dB specification (at 100 Hz) as are the Q-57A buoys, and we assigned corresponding calibration constants for the Q-41B buoys. All sonobuoys were set to deploy the hydrophone to 18 m depth, and to transmit for 8 h.

In previous years we have used the twin-engine Britten-Norman Islander C-GYTC for aerial observations, but in 1983 it was undergoing engine overhaul and was not available until 14 August. Until then we used a de Havilland Twin Otter, which was adequate for observing bowheads but lacked a suitable sonobuoy antenna. As a substitute we used the DME (distance measuring equipment) antenna, which is designed for frequencies several times higher than sonobuoy frequencies. Hence, before 14 August the sonobuoy signals were contaminated by radio static when the airplane was more than 3 or 4 km from the sonobuoy. Sonobuoy positions were determined via VLF navigation systems aboard both the Twin Otter and the Islander.

To receive the sonobuoy signals aboard the aircraft in 1983, the same portable radio receivers used in 1982 were used without modification. However, they were recalibrated. The sensitivity at 10 Hz was about 9 dB less than we had thought. At 20 Hz the difference was about 3 dB, but at 50 Hz and above the results were essentially the same. The tape recorder used in earlier years was used again, a Sony model TC-D5M stereo cassette recorder with servo-controlled capstan drive (for precise control of tape speed).

Boat System

There were two major changes in the underwater sound recording system on 'Sequel' in 1983. One was the use of a vertical string of hydrophones beneath the sparbuoy, with low frequency (5 to 1000 Hz) bender hydrophones at 3 and 9 m and U.S. Navy model H56 wideband hydrophones at 9 and 18 m. We had obtained measurements at a single standard depth of 9 m in 1981-82, based on the desire to be about midway between surface and bottom in the shallow waters of the Beaufort Sea. However, the sonobuoy hydrophones were at 18 m and we desired comparability. Also, we were interested in the effects of receiver depth on signal level for sounds originating in the air and in the water, and the 3 m hydrophone provided a shallow sensor for this purpose. The 3 m depth was chosen because a low frequency pressure sensor too near the surface would be adversely affected by wind-driven waves. In fact this was a problem even at 3 m, where levels were generally high at frequencies up to 20 Hz.

The other change in the boat system was the use of a 4-channel Fostex Model 250 tape recorder. This high quality cassette recorder records the four channels in one pass of the tape. It also runs the tape at twice the normal cassette speed. This higher speed improves high frequency response (useful to at least 18 kHz) but degrades low frequency response unless one uses a different recorder to play the tape back at half the recorded speed. (We did not do this.) Thus, the results from the boat system for frequencies up to 20 Hz are not dependable.

The playback system again utilized a J-11 transducer from the U.S. Navy Underwater Sound Reference Detachment, Orlando. It was deployed from 'Sequel' and operated at a depth of 9 m. A 250 W Bogen amplifier powered the J-11. The sounds to be played back were copied onto two-minute endless loop cassettes, although in the case of the helicopter playback the tape would be played through only once. In 1982 a monitor hydrophone (an H-56) was mounted on a wooden boom 1.9 m in front of the J-11 projector face. During another project we discovered that such a structure might vibrate, giving erroneous readings. In 1983, therefore, we suspended the J-11 and the H-56 monitor hydrophone from a boom and used a 1 m separation. During playback experiments, the signal from the H-56 hydrophone was monitored to prevent overdriving the projector and to measure the source level of the sounds being projected by the J-11.

Boat positions were determined via a Magnavox MX4102 navigation satellite receiver aboard 'Sequel' (accuracy within 300 m). Water depths were determined via an echosounder. Distances from other vessels were determined with Sequel's marine radar.

Data Analysis

Approach. — The 1983 data were analyzed in the same manner as 1980-82 data, but some of the specific equipment used was different. The cassettes were played back on the same recorders used in the field for recording. One channel was analyzed at a time, its signal passing through a low pass, anti-aliasing filter with optional gain before being sampled and digitized by a 12 bit analog-to-digital converter and stored in a computer memory. As in 1982, we always stored 17,408 samples, transferring them to a disk file after they were all in memory. We generally sampled at a rate of 2048 samples per second (s/s), providing a frequency range up to 1000 Hz in spectrum analyses. At that rate, 17,408 samples are taken in 8.5 seconds. In addition, we often sampled the same recordings at 16,384 s/s, providing a frequency range to 8 kHz. Recordings of noise from aircraft flying over a hydrophone were sampled at 4096 s/s, providing a 4.25 s block of samples for the period of maximum noise amplitude. These digitized data were the starting point for various analyses and diagrams, including spectral, waveform and 'waterfall' analyses.

Spectral Analyses. -- Continuous signals like ambient noise and machinery-dominated industrial noise were analyzed for frequency content by computing the average of a series of discrete Fourier transforms (DFT). The 17,408 samples were divided into segments either 2048 or 1024 samples long, with sequential segments overlapping by 50%. The samples in each segment were weighted (Harris 1978) before computing the DFT. The magnitude squared of the DFT is an estimate of the power spectrum, and the power spectra for all the segments were averaged to obtain the distribution of signal power as a function of frequency. From this distribution, called the power density spectrum, we computed the signal power levels for particular frequency bands and the power level in tones (power concentrated at single frequencies). Figures 2-10 are examples of power spectra. When we quote band levels, we consider bands ranging from 10 or 20 Hz to 500 or 1000 Hz. This is the approximate frequency range of most bowhead calls and most industrial sounds.

Waveform Analyses. — Transient signals like seismic survey signals and bowhead calls, breaches and tail slaps were analyzed by examining the waveforms (e.g Fig. 23). From a graph of the signal amplitude vs. time we could measure the amplitude and dominant frequencies of the transient as well as any changes in frequency. (Seismic pulses that have travelled several kilometres in shallow water, for example, begin at a higher frequency and trend downward in frequency.)

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 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 flys overhead. To display spectral amplitudes vs. frequency and time, we use a 'waterfall' spectrogram (e.g. Fig. 11). The same discrete Fourier transform process used to compute average power spectral densities was used to compute the waterfalls. However, instead of averaging the successive results, they were plotted individually with a small (1.27 mm) offset between successive spectra. The following section describes the exact procedure for deriving the waterfall displays.

The waterfall displays in this report included either 80 or 160 amplitude spectra plotted at 1.27 mm intervals (i.e. time scale extends across 101.6 or 203.2 mm, respectively). The amount of time represented by either scale depends on sample rate, number of samples per transform, and amount of temporal overlap between sets of samples for successive transforms.

The sample rate determined the extent of the frequency scale in the waterfall; the upper frequency could not exceed one half the sample rate. For example, when we knew that the frequencies of interest in a signal were less than 500 Hz, as is typical for industrial sources, we sampled at 1024 samples/s.

The transform size (number of samples used per transform) determined the frequency resolution in the spectrum. For example, if the sample rate was 1024 per second and the transform size was 1024, there were 513 useful spectrum values extending from zero to 512 Hz with 1 Hz spacing between 'cells'. However, the larger the transform the longer the time interval it spanned, and it was important not to use so long a time that the frequency variation was smoothed out. The waterfall spectra presented in this report were all based on 128 samples per transform. Thus, for a sample rate of 1024 samples/s, there were 65 frequency cells spanning the range from zero to 512 Hz, and cell spacing was 8 Hz. We did not plot the results for the first two cells (0 and 8 Hz) or the last two cells (504 and 512 Hz), leaving the range from 16 to 496 Hz.

The same window function as used in computing the average power spectrum was applied to each set of 128 samples to be transformed for a waterfall display (Harris 1978). The window caused the analysis resolution to be 1.7 times the cell spacing, or 13.6 Hz in our example.

It is desirable to overlap the samples used in each transform with at least 50% of the samples used in the previous transform. This overlap helps to recover some of the information that would otherwise be lost because of using the window on the data. Higher percentages of overlap help smooth transitions of rapidly changing data, although they have the adverse effect of extending the apparent duration of a short-term event over a longer period of time than it actually spans. In this report most waterfalls were based on 50% overlap, but some were based on 87.5%.

It was necessary to experiment with different methods of displaying the amplitudes of each spectrum. The power spectrum computed directly from the discrete Fourier transform emphasized only the strongest components, and a log function (proportional to decibels) was severely cluttered. We tested several fractional power functions and determined that the square root produced a reasonably detailed display without clutter. The square root of the power spectrum is the amplitude spectrum, and that is what we plotted in the waterfalls.

The amplitudes of all the spectral points in the waterfall were scaled relative to the amplitude of the largest point in the waterfall, which was then plotted with a 'deflection' of 20.3 mm from the zero point of that particular spectrum. (Recall that each spectrum is plotted 1.27 mm from its predecessor.) With this procedure, it is unlikely that amplitudes will be discerned if they are less than 1/100 of (or 40 dB below) the maximum amplitude depicted in the graph. Because all values are plotted relative to the maximum amplitude in that graph, it is not meaningful to compare the amplitudes in one waterfall with those in another.

To make the displays clearer, points which would fall 'behind' a portion of a previously computed spectrum were not plotted. Thus, in some cases interesting smaller amplitudes are 'hidden' from view. However, the benefit of a clearer, uncluttered 'hidden line' display outweighs the disadvantage of not seeing all the points in each spectrum.

Computing Procedure. -- In analyzing most of the 1983 data, we used the same computer system used in previous years for the analog-to-digital conversion, namely, Polar Research Laboratory's NOVA 3 minicomputer and customized A/D converter. For the spectrum analysis and plotting, we used Greeneridge Science's Hewlett-Packard 9816 desk-top computer system. The last few analog-to-digital conversions were done with Greeneridge's 12-bit A/D converter connected directly to the HP 9816. A selected section of cassette tape signal was analyzed on both systems to verify that the results were identical. In addition, selected sonobuoy and 'Sequel' data from 1982 that had been analyzed earlier with the NOVA 3 system were re-analyzed with the HP 9816 system to ensure that the re-coded programs gave identical results.

Use of Calibration Curves. -- The frequency response characteristics of the various pieces of equipment were taken into account when deriving sound pressure levels and sound pressure spectrum levels. The hydrophones used on 'Sequel' had constant frequency characteristics over the frequency range of interest to us, but the sonobuoy receivers and the tape recorders on the aircraft and on 'Sequel' did not. Most important, the sonobuoys are manufactured with a sensitivity that increases with frequency. The frequency response curves of these devices have been used in deriving all power density spectra, band levels, and tone levels given in this report.

It is not as straightforward to derive a calibrated sound pressure using the voltage vs. time waveform from tape recordings of a sonobuoy signal. We have examined waveforms when studying the characteristics of sounds that change rapidly with time, e.g. seismic pulses and bowhead sounds. Waveforms must be corrected according to the frequency content of each part of the signal. This is best done with a filter whose frequency response is the inverse of the frequency response of the sonobuoy, receiver, and recording system. If the signal is essentially tonal, or narrowband, then a manual computation of the sound pressure is feasible. Seismic survey signals, after travelling a few kilometres in the shallow Beaufort Sea, have a narrowband character that changes slowly enough with time to permit at least an approximate computation of the sound pressure level.

Seismic Signal Levels. — In analyzing seismic signals we have followed a consistent but unusual practice since the project began in 1980. This has meant that our results are internally consistent but comparable in only a relative sense to the results of others who use more traditional approaches (cf. Malme et al. 1983). We quantify a seismic signal level on the basis of its peak pressure only, ignoring the duration of the pulse and hence its energy. Specifically, we measure the peak pressure amplitude, square, divide by two, take the logarithm to the base 10, and multiply by 10 to compute the 'effective root mean square pressure level' expressed in dB with respect to one microPascal. This technique would yield the same answer as an rms pressure meter if applied to a constant sinusoidal pressure of long duration. The technique is valid in quantifying the influence of a seismic signal on a bowhead if the animal is sensitive to the peak amplitude of the signal rather than to total pulse energy or to some other function of the amplitude and duration.

There will be no simple or constant difference between the results of our technique and those of the energy measurement technique. The duration of received seismic signals varies widely with water depth, range, and other parameters affecting sound transmission in water and sub-bottom rocks and sediments. These variables could all affect the relationship between results obtained by our technique and other techniques.

Units of Measurement. -- Confusion often arises in interpreting power density spectra. The dimension we use is 'decibels with respect to 1 $\mu Pa^2/Hz$', which is proportional to power per unit frequency. The levels of tones are not correctly displayed on the spectral diagrams because, theoretically, with finite power at a specific frequency, they have infinite power density. We corrected the computed power density to determine the power at the tonal frequency and expressed it as 'dB with respect to 1 µPa' (dB//1 µPa). Noise power levels in various broad bands, e.g. 20-1000 Hz, are also given in dB//1 µPa.

Specialized acoustic terminology used in this report is defined in Greene (1982, p. 272-274).

RESULTS

In this section we present the results of our measurements and analyses organized by type of sound, beginning with a discussion of ambient noise and continuing with aircraft and boat noise, seismic signals, playback sounds of drillship noise, dredge noise, and finally a brief examination of bowhead breach and tailslap sounds.

Ambient Noise

The measurement of ambient noise was not a primary objective of the project, but knowledge of the background, without known sources of man-made noise, is important for comparison with industrial noise. In addition, the 'Sequel' array of hydrophones at 3, 9, and 18 m provided an opportunity to observe ambient noise at different depths. For these analyses, we analyzed segments of noise 8.5 s in duration; frequency resolution was 1.7 Hz.

On 6 August 1983, 'Sequel' was anchored in water 37 m deep at 70°10.3'N, 134°09.0'W, where we hoped to record the sounds of a Sikorsky 61 helicopter flying overhead en route to or from a drillship. The wind varied between 10 and 20 km/h. Spectra for the background noise at 3 and 9 m are presented in Figure 2, which show that-- except for high levels at 20 Hz on the 3 m hydrophone--the background was relatively quiet. The high level at 20 Hz (129 dB//1 µPa) from the 3 m hydrophone is not anomalous; characteristically there were high levels from 10 to 20 Hz. There was an identical bender hydrophone at 9 m, and it did not record these levels. We attribute them to the proximity of the surface and the action of waves. There are two conspicuous but small peaks of unknown origin in the spectrum from the 9 m hydrophone. These possible tones are at 87 and 132 Hz. Two others fall in between, at 99 and 109 Hz. At 9 m, the 10-1000 Hz band level was 100 dB//1 µPa; the 20-1000 Hz band level was also 100 dB.

On 7 August, 'Sequel' was at the Ukalerk dredging site (Fig. 1) and recorded ambient sounds when no ships were evident, although 'Cornelius Zanen' was at the site 0.5 h later. The water depth was 20 m; the coordinates were 69°59.2'N, 133°10.2'W. The 3 m hydrophone signal was dominated by a strong component at 20 Hz (122 dB). Spectra for 9 and 18 m are shown in Figure 3. At 9 m the band levels for 10-1000 and 20-1000 Hz were 100 and 98 dB respectively; at 18 m the corresponding levels were both 101 dB. The source of the closely spaced tones between 54 and 104 Hz, and those at 291, 301, 308, and 317 Hz, is unknown but undoubtedly industrial.

Also on 7 August, but at 70°32'N, 138°10'W, over water about 950 m deep, the Twin Otter was flying and had deployed a sonobuoy (Fig. 1). As

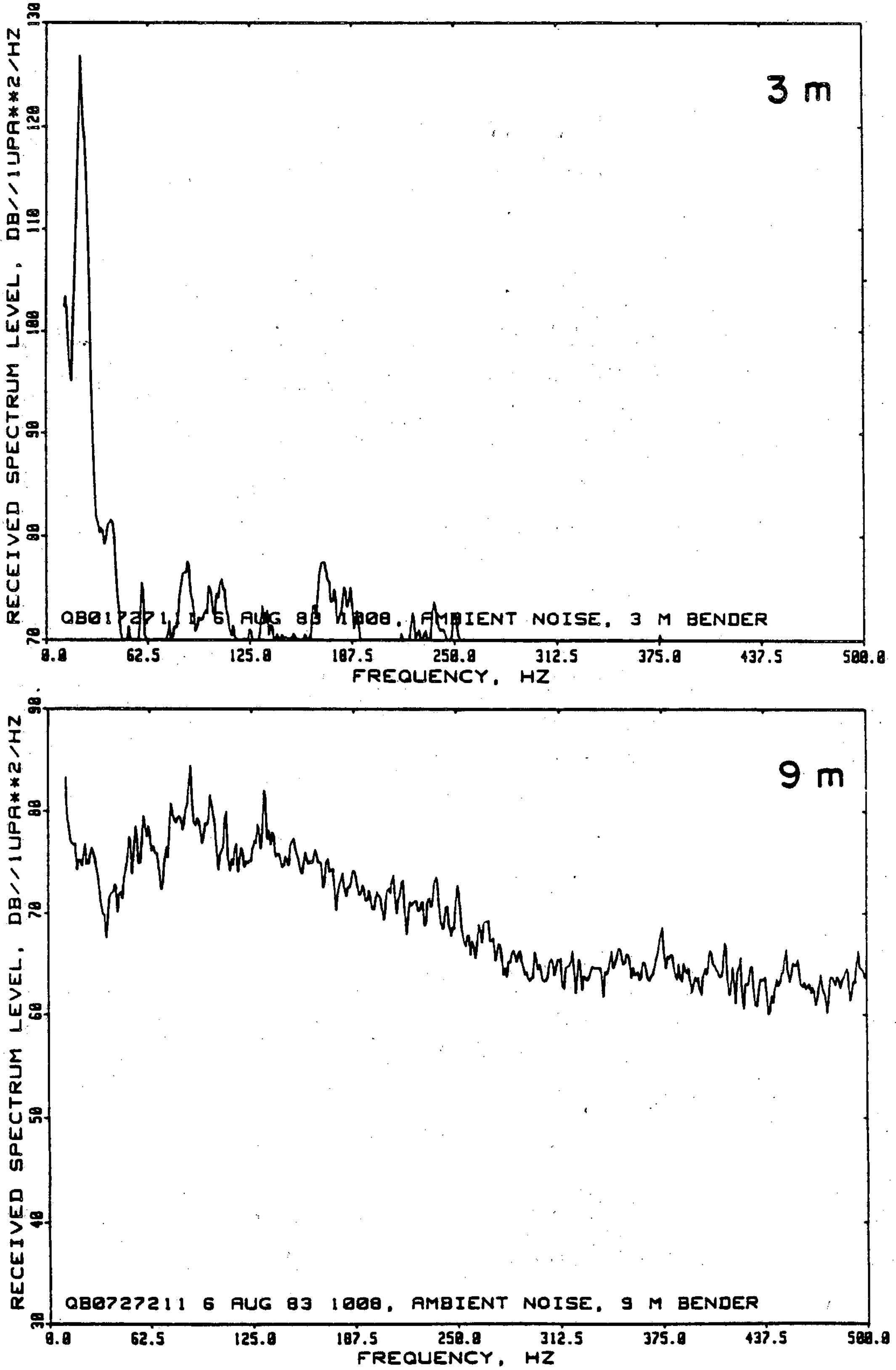


FIGURE 2. Ambient noise spectra at 3 and 9 m depth, 6 August 1983, in water 37 m deep. The frequency resolution is 1.7 Hz. The spectra were averaged over a period of 8.5 s.

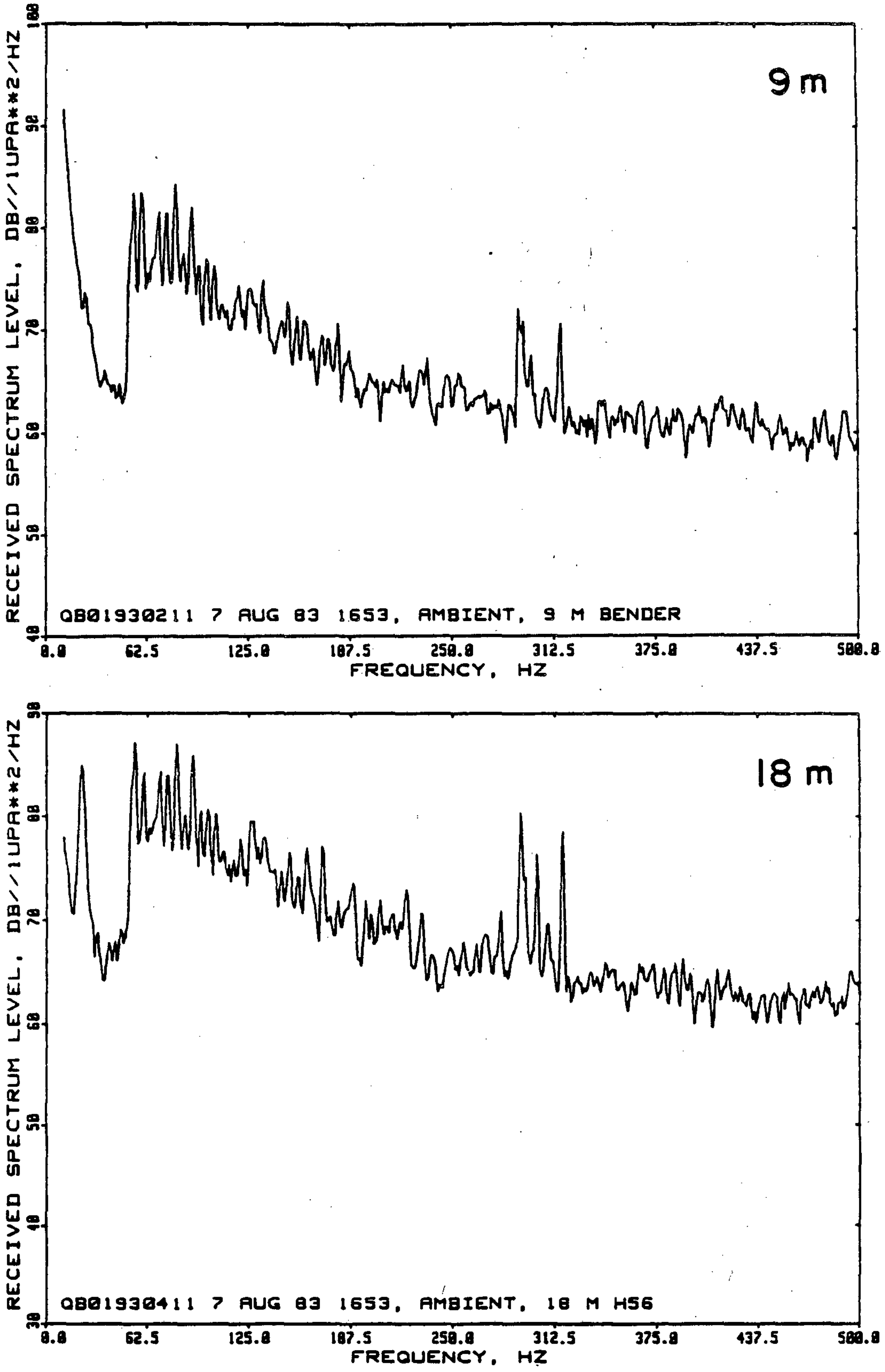


FIGURE 3. Ambient noise spectra at 9 and 18 m depth, 7 August 1983, in water 20 m deep. The source of the tones is unknown.

previously mentioned, the sonobuoy receiver antenna on the Twin Otter was actually the DME (distance measuring equipment) antenna and was unsuitable for the much longer wavelength of the sonobuoy signals. Consequently, when the range from the sonobuoy was more than 3 or 4 km, reception became noisy. This is something of a problem for the lower of the two spectra shown in Figure 4, corresponding to the ambient recorded at 18:43 MDT, when the aircraft was about 18 km from the sonobuoy. However, seismic signals were being received at the time so the system was recording waterborne sounds. These spectra of the ambient noise were computed for intervals between seismic signal arrivals. At 17:17, when the aircraft was near the sonobuoy, the band levels in the 10-500, 10-1000 and the 20-1000 Hz bands were all 105 dB and no tones were conspicuous. At 18:43, when the aircraft was 18 km away, the corresponding band levels were 105, 105 and 103 dB, respectively, and there were no tones.

On 9 August the Twin Otter dropped a sonobuoy at 70°00'N, 138°56'W, water depth 210 m (Fig. 1). Seismic signals thought to be from the 'GSI Mariner' were received beginning at 13:48 until recording ended at 18:43, with short periods near the beginning without seismic signals. Ambient noise was sampled between seismic signals, which occurred about once every 15 s. Spectrum analyses were computed for 9 segments between 13:48 and 16:00; Figure 5 presents the results for 13:48 and 16:00. The peak in the spectrum at 13:48 corresponds to a tone at 83 Hz with a level of 80 dB//1 µPa; it probably came from the Twin Otter itself, which must not have been sufficiently far away to avoid being detected. The 10-500, 10-1000, and 20-1000 Hz band levels were all 95 dB. At 16:00 the corresponding band levels were 99, 99 and 97 dB. These levels are representative of the other seven spectra except that at 15:04 the 10-20 Hz band level was 109 dB, resulting in a 10-1000 Hz band level of 109 dB and a 20-1000 Hz band level of 98 dB. The lowest 10-1000 Hz (and 10-500 Hz) band level in the set of 9 analyses came at 14:24 and was 92 dB.

The first drillship playback experiment in 1983 was conducted on 17 August. The water depth was 16 m at the whales and the hydrophone of a sonobuoy dropped near the whales was dragging on the bottom. It was not useful for ambient noise measurement. However, recordings were made from the

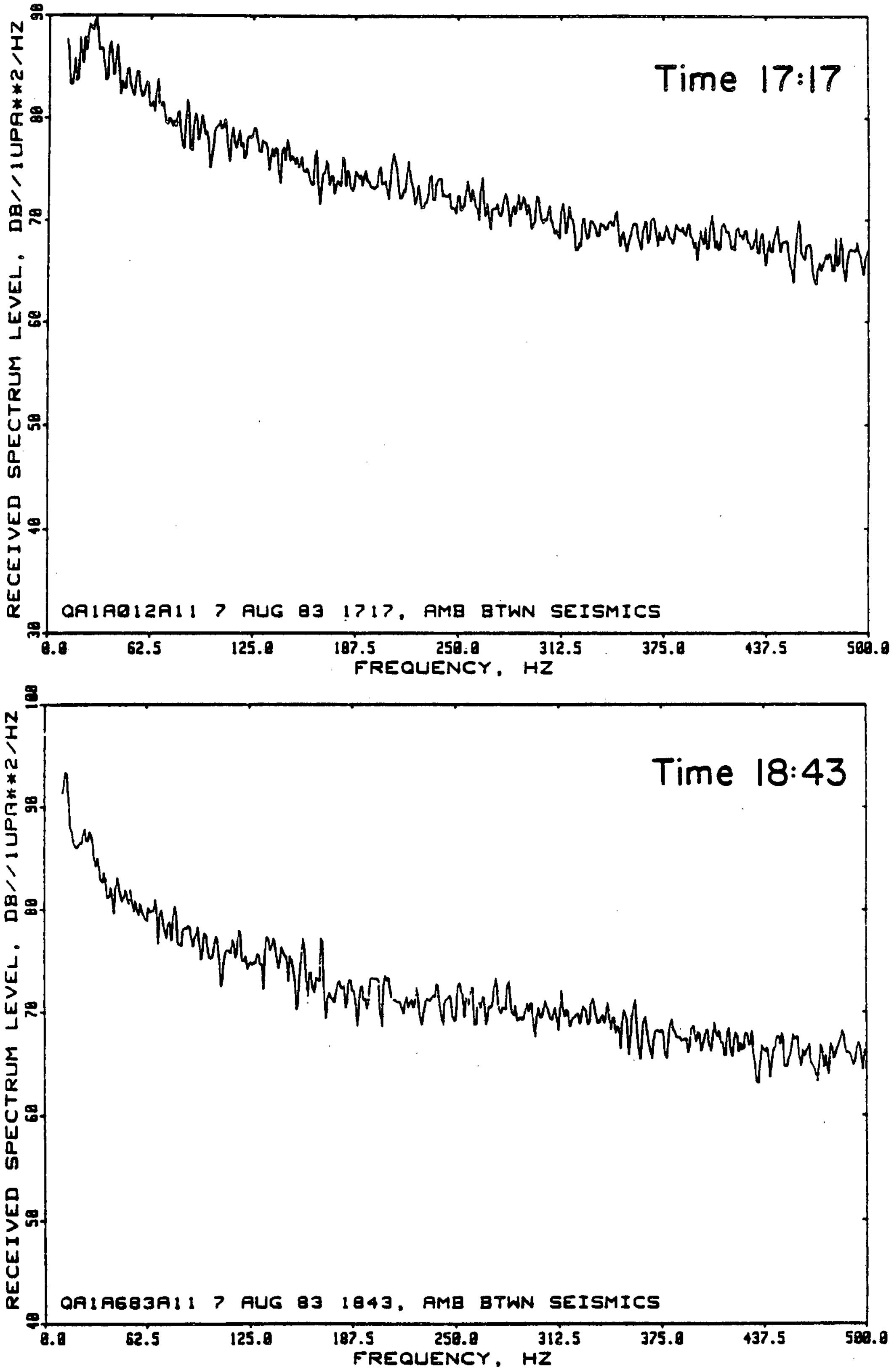
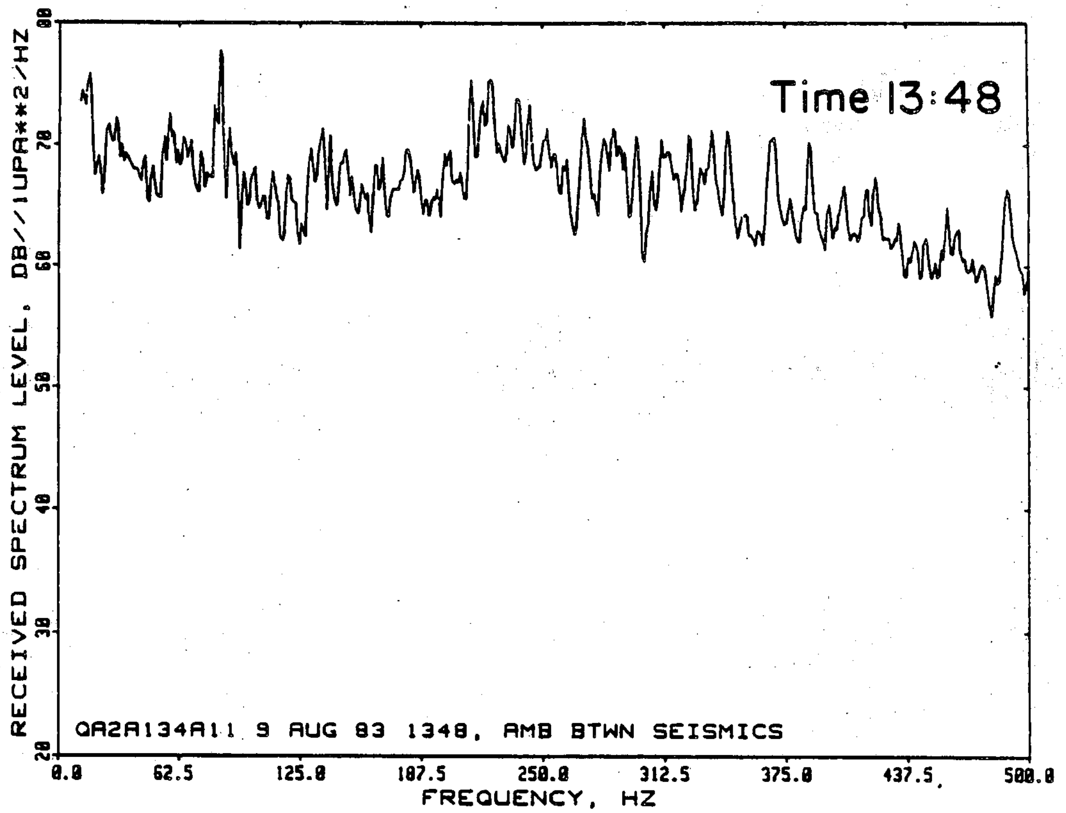


FIGURE 4. Ambient noise spectra at a sonobuoy, 7 August 1983, in water 950 m deep. Radio static noise may be a problem in the lower spectrum.



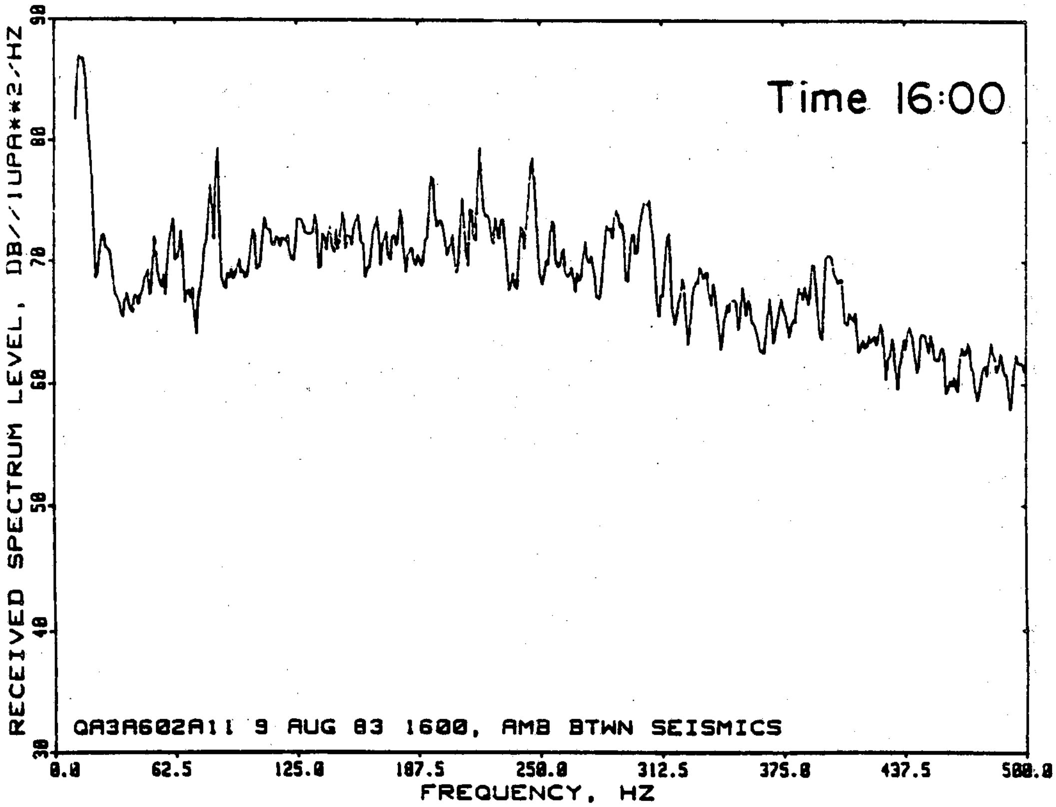


FIGURE 5. Ambient noise spectra at a sonobuoy, 9 August 1983, in water 210 m deep. The tone at 83 Hz is probably from the Twin Otter.

'Sequel' hydrophones after the experiment, and the resulting noise spectrum for depth 9 m is shown in Figure 6A. The 10-1000 Hz band level for this hydrophone was 92 dB//1 μPa.

On 18 August we conducted the second drillship playback experiment, monitoring the sounds near whales with a sonobuoy. The ambient noise spectrum following the test is shown in Figure 6B. The tones, at 69, 103, 138, 155, and 208 Hz, probably came from the Islander observation aircraft circling overhead at altitude 610 m. The band levels for 10-1000 Hz and 20-1000 Hz were 81 and 78 dB//1 μPa, respectively, indicating a particularly quiet time. The location was 69°25'N, 138°26'W, just off the Yukon Coast (Fig. 1). Water depth was 12 m at the sonobuoy; the hydrophone was resting on the bottom. The received levels were 0-10 dB below the 'Knudsen sea state zero (extended)' curve. This curve represents typical noise levels under calm conditions in the open ocean (Knudsen et al. 1948; Greene 1982, p. 280).

The third drillship playback experiment was on 22 August. Two sonobuoys were dropped near 'Sequel' (Fig. 1), one at a location with water depth 19 m a few hours before the test and one at depth 32 m during the test. Ambient noise spectra measured from the two sonobuoys are presented in Figure 7. Again, the tones are probably from the Islander. The band levels for 10-1000 and 20-1000 Hz were 101 and 97 dB before the test and 94 and 93 dB after the test, respectively.

'Sequel' was east of King Point on 22 August at 12:30, 69°15.2'N, 138°01.6'W, water depth 36 m, sea state 3, wind 16-20 km/h. The ambient noise spectrum was unremarkable; there were no significant tones. The band levels vs. hydrophone depth were as shown in Table 1. In this case, received noise level was similar at three depths.

Table 1. Band levels (dB//1 μPa) vs. hydrophone depth near King Pt., Yukon, at 12:30 on 22 August 1983, water depth 36 m, sea state 3.

Depth	10-1000 Hz	20-1000 Hz
3 m	96	93
9	95	94
18	94	93

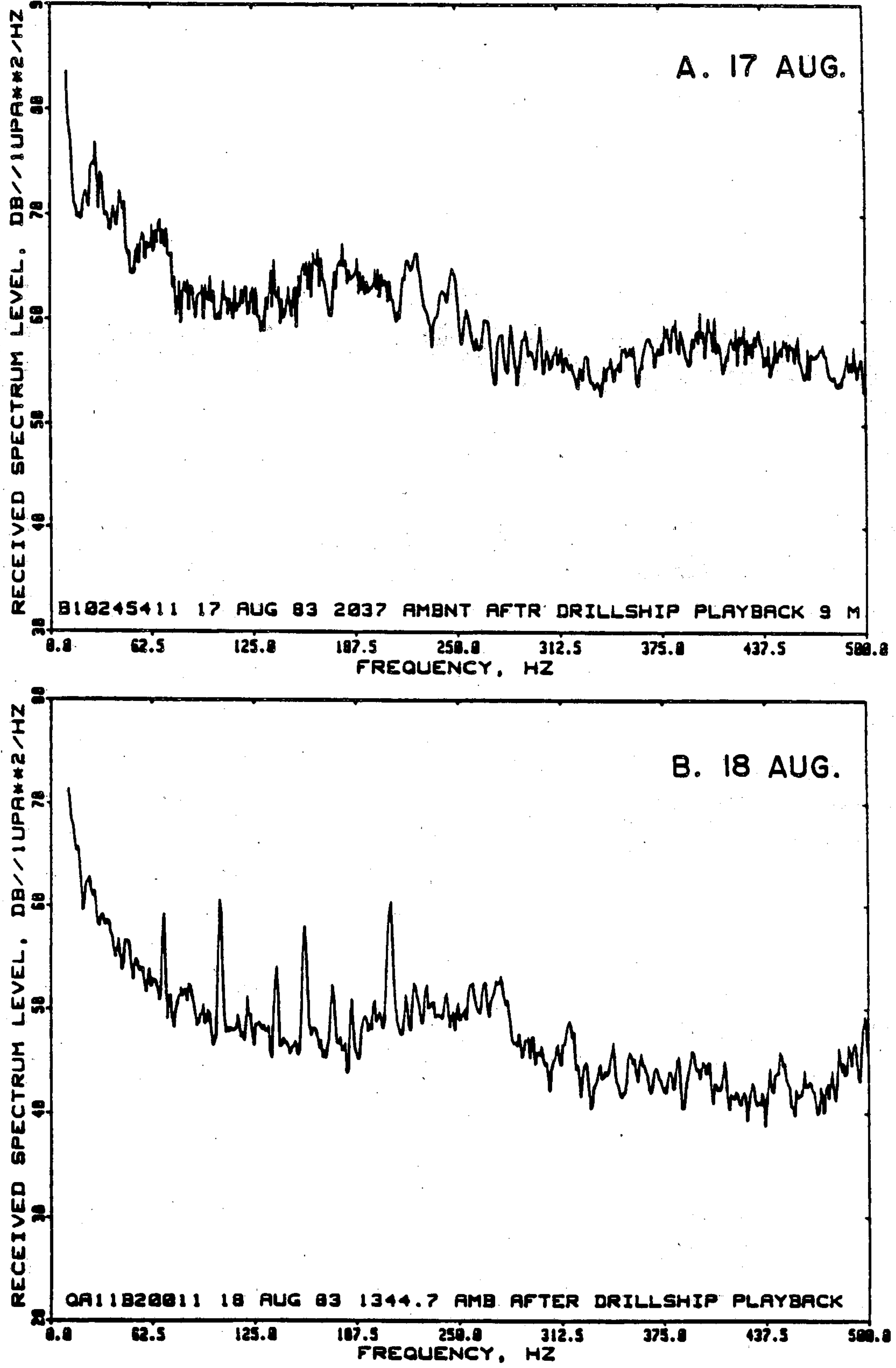


FIGURE 6. Ambient noise spectra following drillship playback experiments on 17 and 18 August. (A), for 17 August, is from a hydrophone 9 m deep at 'Sequel' in water 18 m deep and is relatively free of tonal components. (B), for 18 August, is from the sonobuoy near the whales in water 12 m deep. It contains tones probably caused by sounds from the Islander aircraft. This was the quietest background condition measured in 1983, although the hydrophone was resting on the bottom.

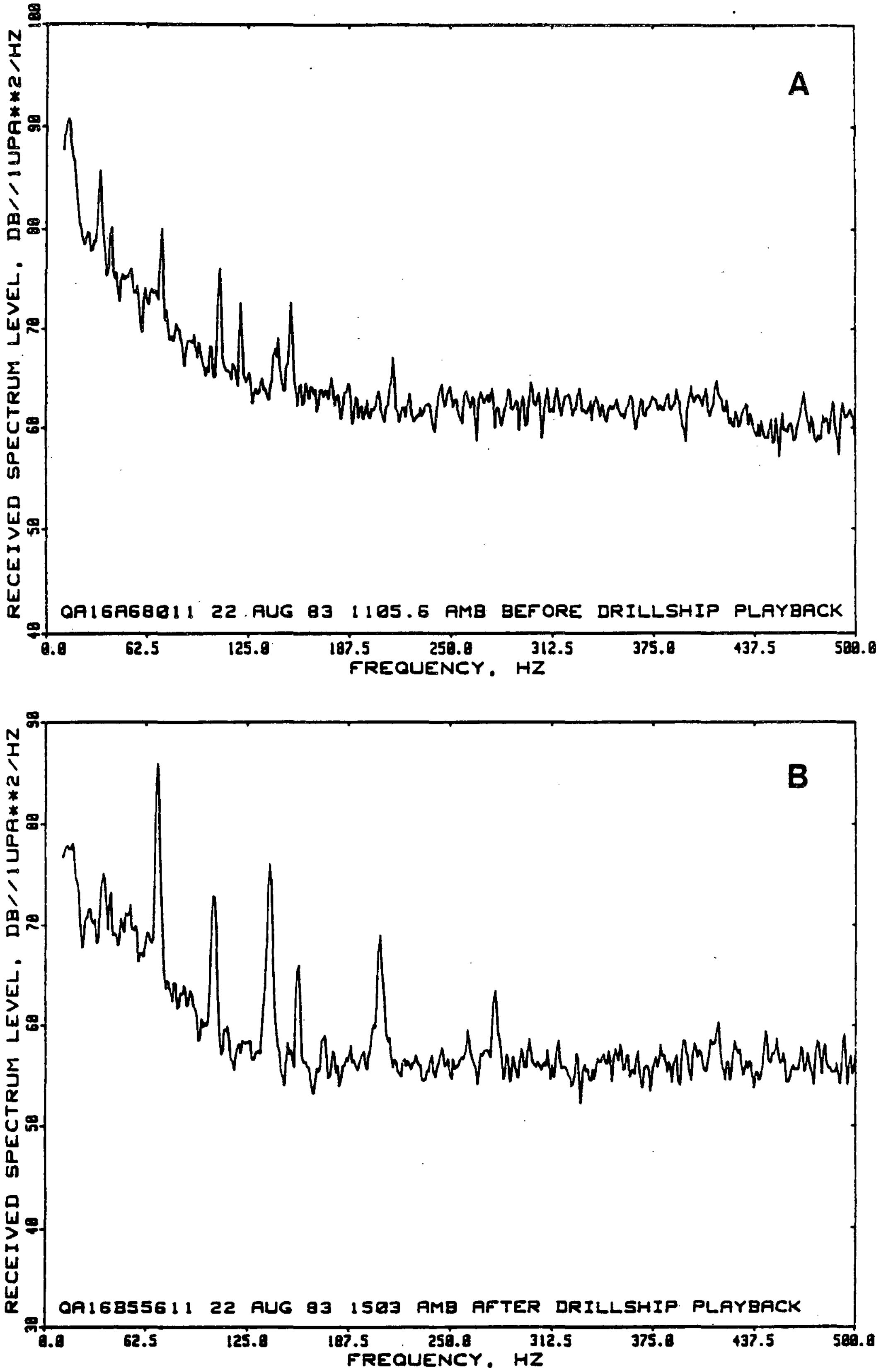


FIGURE 7. Ambient noise spectra at a sonobuoy before and after a drillship playback test, 22 August 1983, in water (A) 19 m deep, and (B) 32 m deep. The tones are from the Islander aircraft.

Ambient noise was measured before and during an airgun experiment on 28 August. Two sonobuoys were deployed, one approximately 2 km from 'Sequel', depth 12 m, and the second about 5 km distant, depth 18 m. Ambient noise spectra for the 'near' and 'far' sonobuoys are shown in Figure 8. The near buoy spectrum contains weak tones at 104 and 285 Hz; their source is unknown. The band levels are presented in Table 2. Similarly, levels were 95-104 dB in the 10-500 Hz band and 88-98 dB in the 20-500 Hz band.

Table 2. Band levels (dB//1 μPa) for the near and far sonobuoys before and during the airgun test, 28 August 1983.

	Near Sonobuoy		Far Sonobuoy	
Time	10-1000 Hz	20-1000 Hz	10-1000 Hz	20-1000 Hz
13:09	103	98	98	90
13:19	104	97	95	88

The Islander deployed a sonobuoy on 31 August at 69°51'N, 136°31'W, water depth about 19 m (Fig. 1). A drillship ('Kulluk') was 12 km in one direction, and an island construction operation was 18 km in the opposite direction. A seismic pulse was detected every few seconds. We analyzed ambient noise between seismic signals five times between 14:55 and 16:48. Examples of the results are shown in Figure 9, which contains spectra for 14:55 and 16:48. The tones appear to be from the Islander. The band levels were 103-125 dB//1 μPa in the 10-500 and 10-1000 Hz bands, and 101 to 111 dB in the 20-1000 Hz band. The spectrum for 16:48 shows an instance of high noise at very low frequencies; the band levels for that time were 116, 116 and 104 dB for the 10-500, 10-1000 and 20-1000 Hz bands, respectively.

On 1 September the Islander deployed a sonobuoy in about the same location, and again we analyzed the ambient noise received between seismic signals. Typically there were, at frequencies above 200 Hz, tones from unknown sources. The band levels ranged from 98 to 109 dB//1 μPa in the 10-500 and 10-1000 Hz bands, and from 96 to 104 dB in the 20-1000 Hz band.

In summary, the ambient levels observed in the 10-1000 Hz band ranged from a low of 81 dB//1 μPa to a high of 125 dB, with levels of 95-105 being

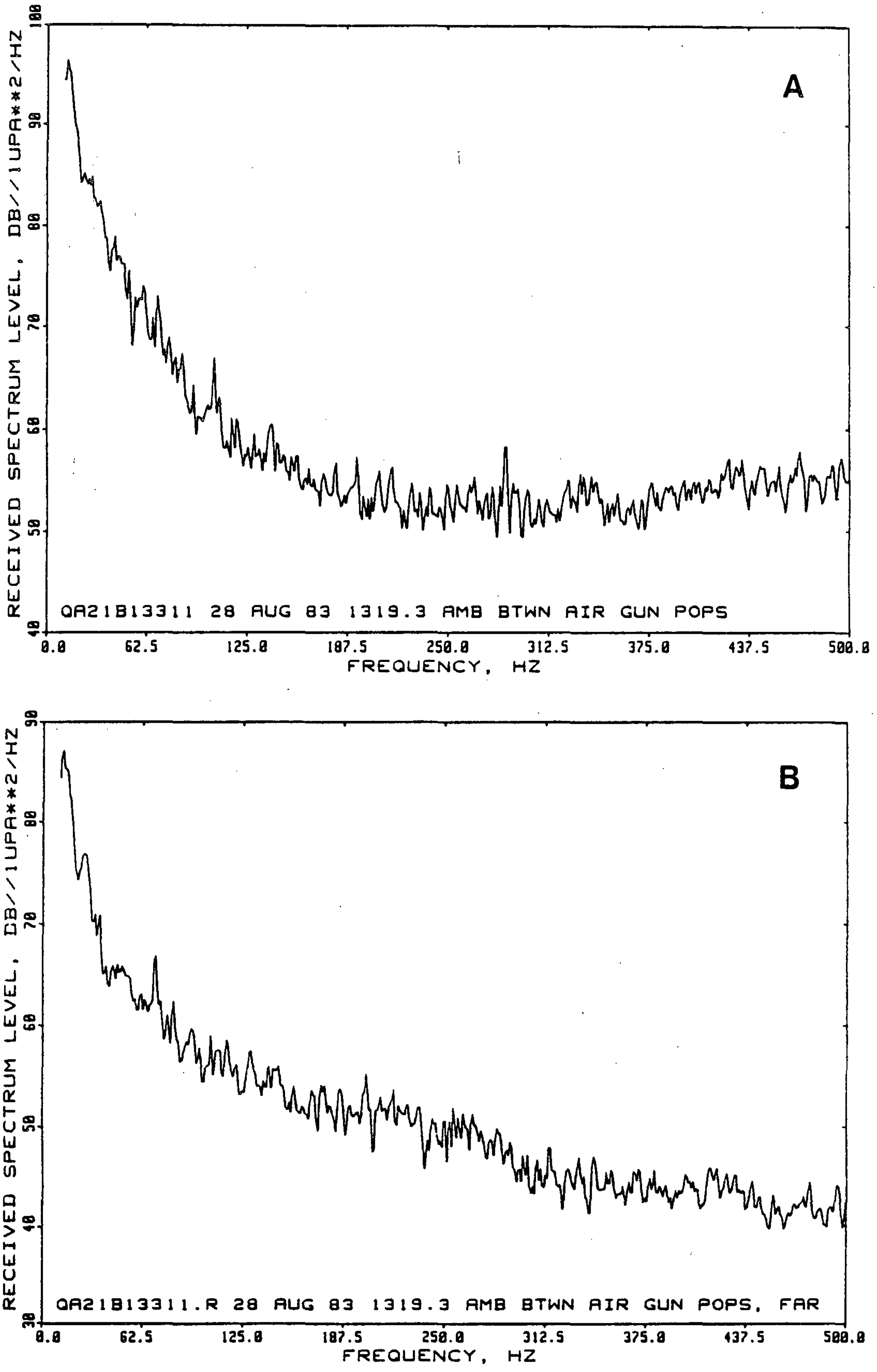


FIGURE 8. Ambient noise spectra at sonobuoys (A) 2 km and (B) 5 km from 'Sequel' during the airgun test, 28 August 1983.

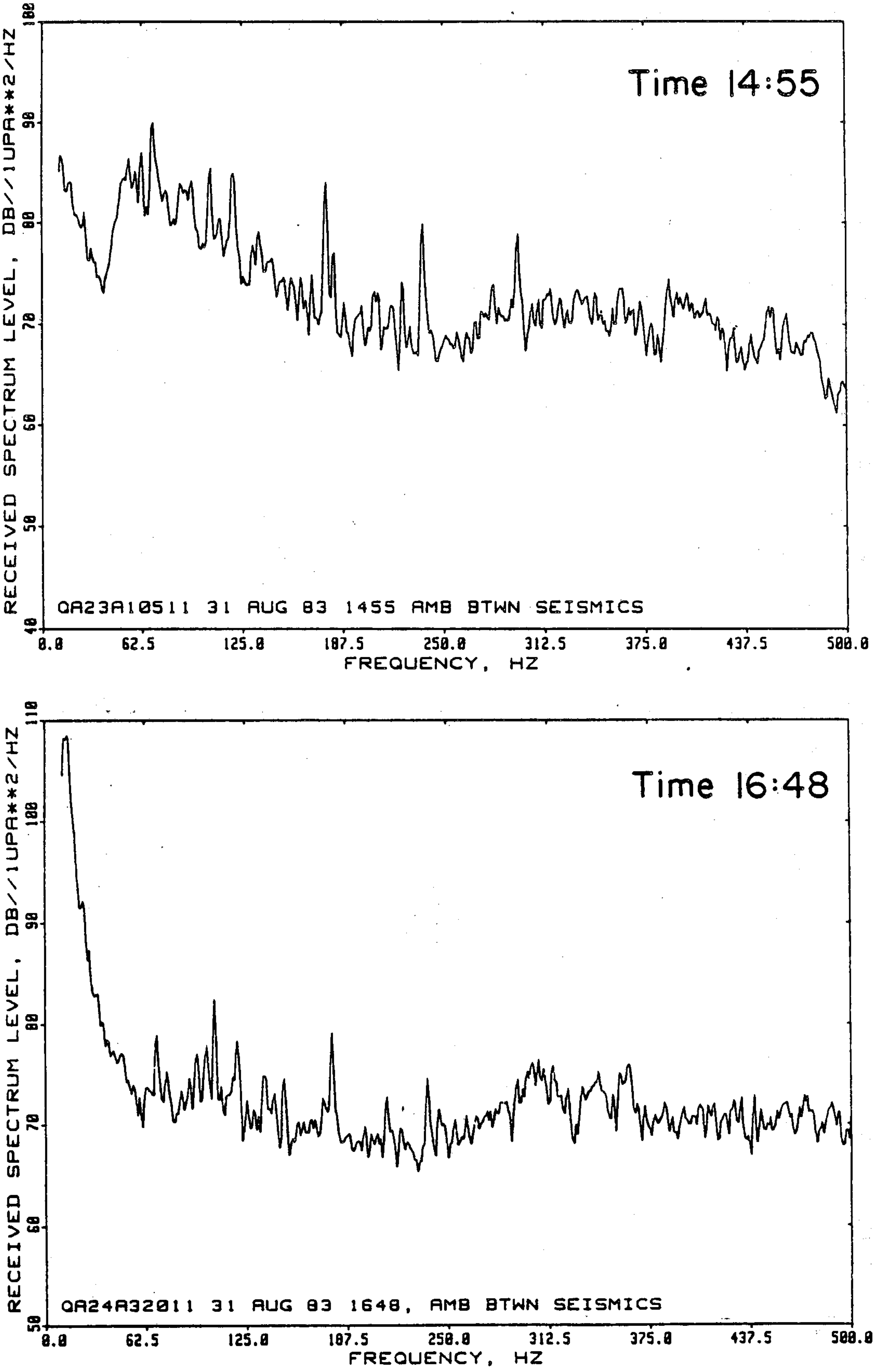


FIGURE 9. Ambient noise spectra at a sonobuoy, 31 August 1983, in water 19 m deep.

the norm. For the 20-1000 Hz band, the levels ranged from 78 to 111 dB, with levels of 95-100 being the norm. The 10-20 Hz band often had disproportionately high levels, probably the result of surface waves. The lowest levels were observed from a sonobuoy in water only 12 m deep; in this case the hydrophone was resting on the bottom. We did not record underwater sounds during periods of bad weather when the background noise would be expected to be higher.

The frequency distribution of energy in the ambient noise spectra generally followed the shape of underwater noise spectra found throughout the world, viz, sloping downward with increasing frequency.

Simultaneous recordings at different depths in the water column showed that ambient noise levels at frequencies up to 20 Hz usually were significantly higher at 3 m depth than at 9 and 18 m depths. Otherwise, there appeared to be no obvious relationship between ambient noise levels and hydrophone depth.

Aircraft Noise

Measurement of helicopter noise was assigned a high priority in the 1983 field season, but our opportunities were severely limited, not only by the weather but by the economics of flight operations. The Dome Petroleum air operations department was willing to divert their helicopters slightly in order to fly directly over 'Sequel'. However, poor weather limited the number of opportunities, and poor visibility limited the results (the pilots of a Sikorsky 61 were unable to spot 'Sequel' soon enough to assure a pass directly overhead). Other aircraft sounds recorded in 1983 came from the Twin Otter used initially for the bowhead behavior monitoring operations and from the Britten-Norman Islander used for the majority of the bowhead observations.

Sikorsky 61 Helicopter, 6 August 1983. -- 'Sequel' was anchored at 70°10.3'N, 134°09'W, water depth 37 m, wind estimated to be between 10 and 20 km/h. Weak seismic signals were present. The aircraft first flew over at altitude 1067 m (3500 ft) but it was not heard. The helicopter made a second pass at 152 m (500 ft), but was unable to fly directly over the boat. The helicopter was at an elevation angle of about 70° at its closest point (90° = vertical). The received signal spectra for hydrophones at depths 3, 9 and 18 m are presented in Figure 10. These spectra were computed with a resolution of 3.4 Hz and resulted from averaging over a signal length of 4 s. The peak at 102 Hz was undoubtedly from the helicopter, as it was strongest at the 3 m hydrophone (95 dB//1 µPa), prominent for less than 2 s (Fig. 11), and absent 2 min later (Fig. 2). Band levels for this overflight, 20-1000 Hz, were 102 dB//1 µPa at 3 m, 111 dB at 9 m and 105 dB at 18 m. The background level in this band just after the helicopter overflight was 101 dB at depth 3 m and 100 dB at 9 m depth.

Figure 11 contains a waterfall spectrum display* for the signal from the Sikorsky 61 flying over at 152 m. The hydrophone was 3 m deep. A transient of unknown origin produced spectral peaks near 200 Hz at the beginning of the waterfall. The dominant spectral component from the helicopter occurred at 102 Hz, corresponding to the 95 dB//1 µPa tone in Figure 10. The lower frequency peak was at 32 Hz.

Britten-Norman Islander, 18 August 1983. -- The Islander was the main aircraft used to monitor bowhead behavior during the 1983 field season, and the only aircraft used in 1980-82. During most observation sessions, it circled using reduced power at an altitude of 457 m (1500 ft) or 610 m (2000 ft) and at a speed of about 140 km/h.

To determine the characteristics of aircraft sounds in the shallow water where most of our 1983 work was done, the Islander passed over 'Sequel' at various altitudes and power settings on 18 August. 'Sequel' was anchored northeast of Kay Point (Yukon Coast) at 69°26.6'N, 138°31.5'W, water depth 15 m. (This was the location of a drillship playback experiment on this date--Fig. 1.) Background noise levels on this occasion were very low. The

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* For this display, the signals were sampled at a rate of 1024 samples/s. Each line in the display represents the amplitude spectrum computed from 128 samples, or 0.125 s of signal. We used an overlap factor of 0.875 in selecting the following 128 samples to transform, meaning that only 16 new samples were used along with the last 112 samples from the previous transform. Thus, time is incremented by only 1/64th s between adjacent spectra. A total of 160 such spectra are displayed, spanning 2.6 s. The amplitudes are all scaled to the highest spectrum level in the 160 spectra.

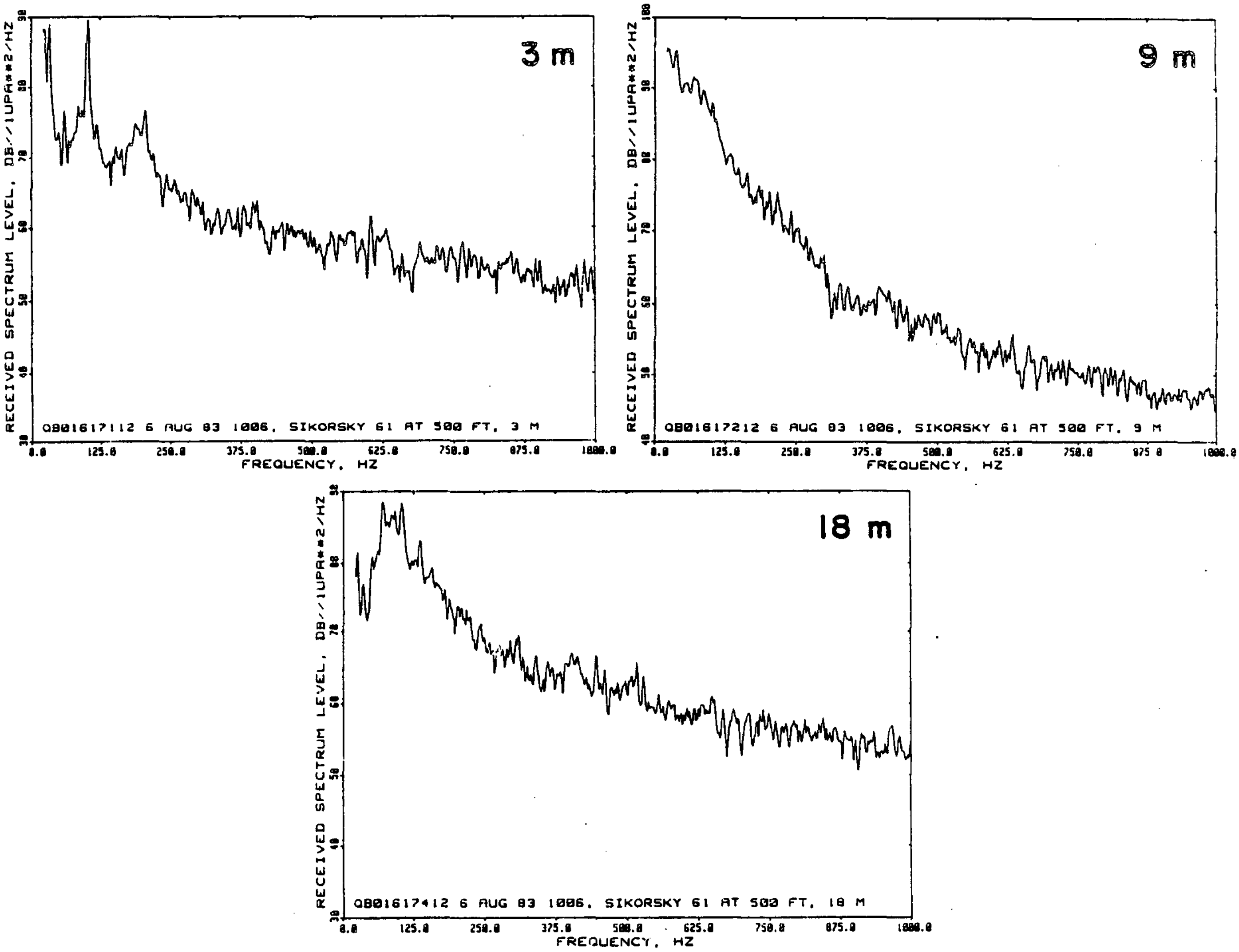


FIGURE 10. Spectra at depths 3, 9 and 18 m for a Sikorsky 61 helicopter at altitude 152 m, 6 August 1983. The water depth was 37 m. The strong tone on the graph for depth 3 m was at 102 Hz.

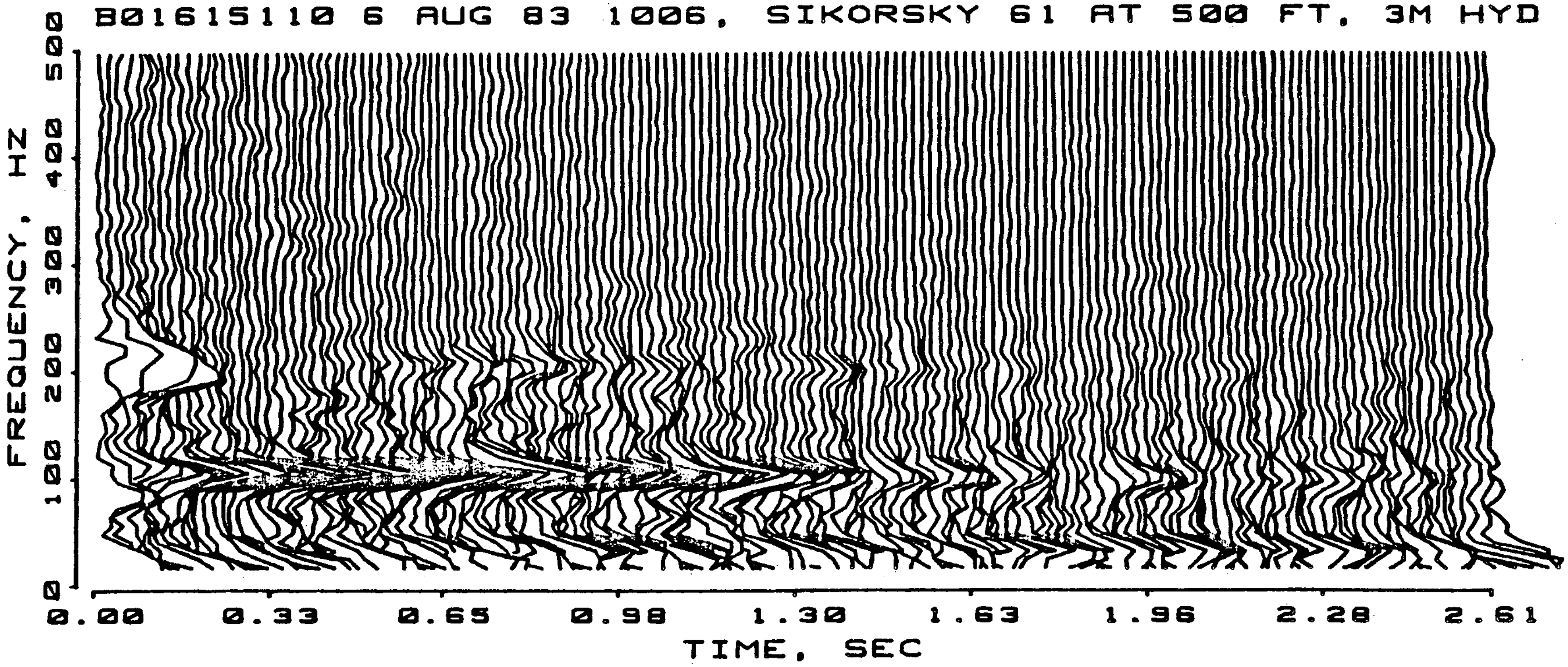


FIGURE 11. Waterfall spectral display for the flyby of the Sikorsky 61 helicopter at altitude 152 m. The hydrophone depth was 3 m.

ambient noise measured from the sonobuoy following the drillship playback experiment was the lowest observed in 1983 (Fig. 6B). Because of the shallow water, we were unable to deploy our 18 m hydrophone from 'Sequel'. However, levels at depths 3 and 9 m were only 83 and 85 dB//1 μPa in the 40-1000 Hz band.

Table 3 presents the durations of audibility of the Islander during the overflights. The investigator simply listened to the recording, under optimum conditions, and noted when he could and could not hear sounds from the Islander. As predicted by theory, the shallow (3 m) hydrophone always received the signal for a longer period of time than did the deeper (9 m) hydrophone.

Table 3. Duration of audibility of Britten-Norman Islander aircraft flying over 'Sequel' on 18 August.

		Duration at Depth	
Type of Pass	Aircraft Altitude	3 m	9 m
Circling, 140 km/h	610 m	110 s	78 s
	610	84	66
	610	89	66
	610	99	72
Straight pass, 200 km/h	610	84	52
	610	59	39
Straight pass, 200 km/h	457	58	42
	457	44	34
Circling, 140 km/h	457	continuous	58
	457	continuous	75
Straight pass, 200 km/h	305	76	75
	305	53	49
Straight pass, 200 km/h	152	72	60
	152	87	52

In 1981, with a hydrophone 9 m deep, we found that overflights by a Bell 212 helicopter and a Twin Otter were audible for 16-37 s (Greene 1982, p. 313). Sea states were Beaufort 0 and Beaufort 1 for those measurements and the water depths were 22.5 and 25 m. For the 1981 Twin Otter measurements, the ambient noise level was 95 dB in the 20-1000 Hz frequency band. In the

FIGURE 12. Spectra at depths 3 and 9 m for the Britten-Norman Islander circling at altitude 610 m, 18 August 1983. The water depth was 15 m.

1983 overflights by the Islander, the sea state was 1 but the water depth was

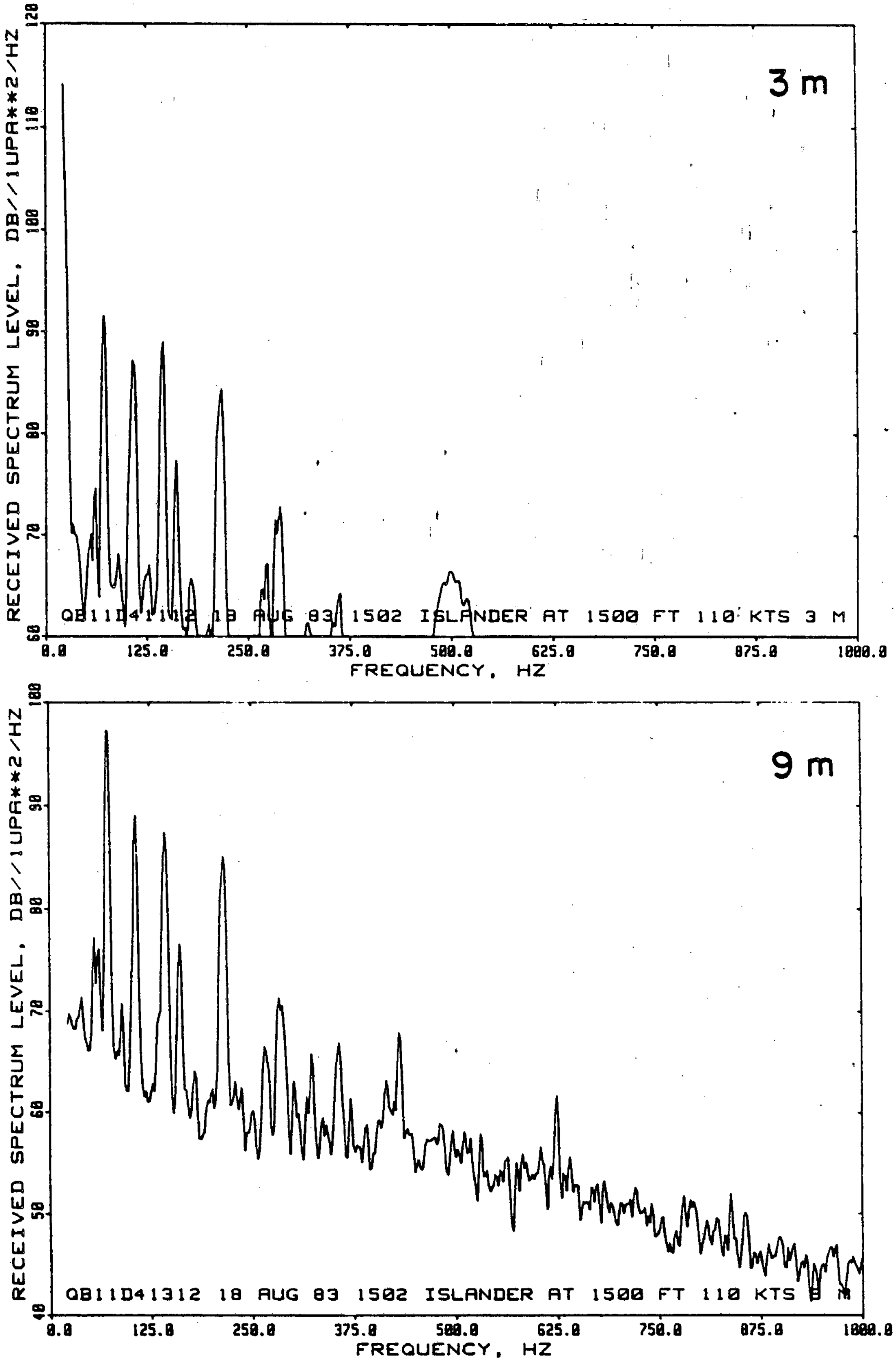


FIGURE 13. Spectra at depths 3 and 9 m for the Britten-Norman Islander in a straight pass at altitude 457 m over 'Sequel', 18 August 1983. The high levels at the 3 m depth, 10-20 Hz, probably arise from surface waves.

blade rate, and 70 Hz corresponds to 2100 rpm. At 9 m the tone level was 103 dB.

Figure 14 contains spectra for the Islander at altitude 305 m in a straight line pass at 200 km/h. At 3 m depth, the blade rate tone was 105 dB at 70 Hz; at 9 m its level was 103 dB. Finally, Figure 15 presents spectra for a 200 km/h straight line pass at altitude 152 m. The 70 Hz level was 109 dB at 3 m and 106 dB at 9 m.

Table 4 lists all available data concerning (1) levels of the blade rate tone and (2) band levels for 40-1000 Hz. The data show that the received levels at the 3 m depth are generally higher than the levels at the 9 m depth. As a rule, the levels for the lower altitudes are stronger than the levels for the higher altitudes.

Table 4. 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 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 3 m and 85 dB at 9 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						

* This value came from a 'circling' pass at 140 km/h. Other values came from straight-line passes at 200 km/h.

Although the Islander could be heard at depth 3 m for at least 72 s when it flew over at 152 m altitude (Table 3), the sound was intense for only a few seconds (Fig. 16A). As expected, the strong spectral components persisted longer during the pass at higher altitude (Fig. 16B).

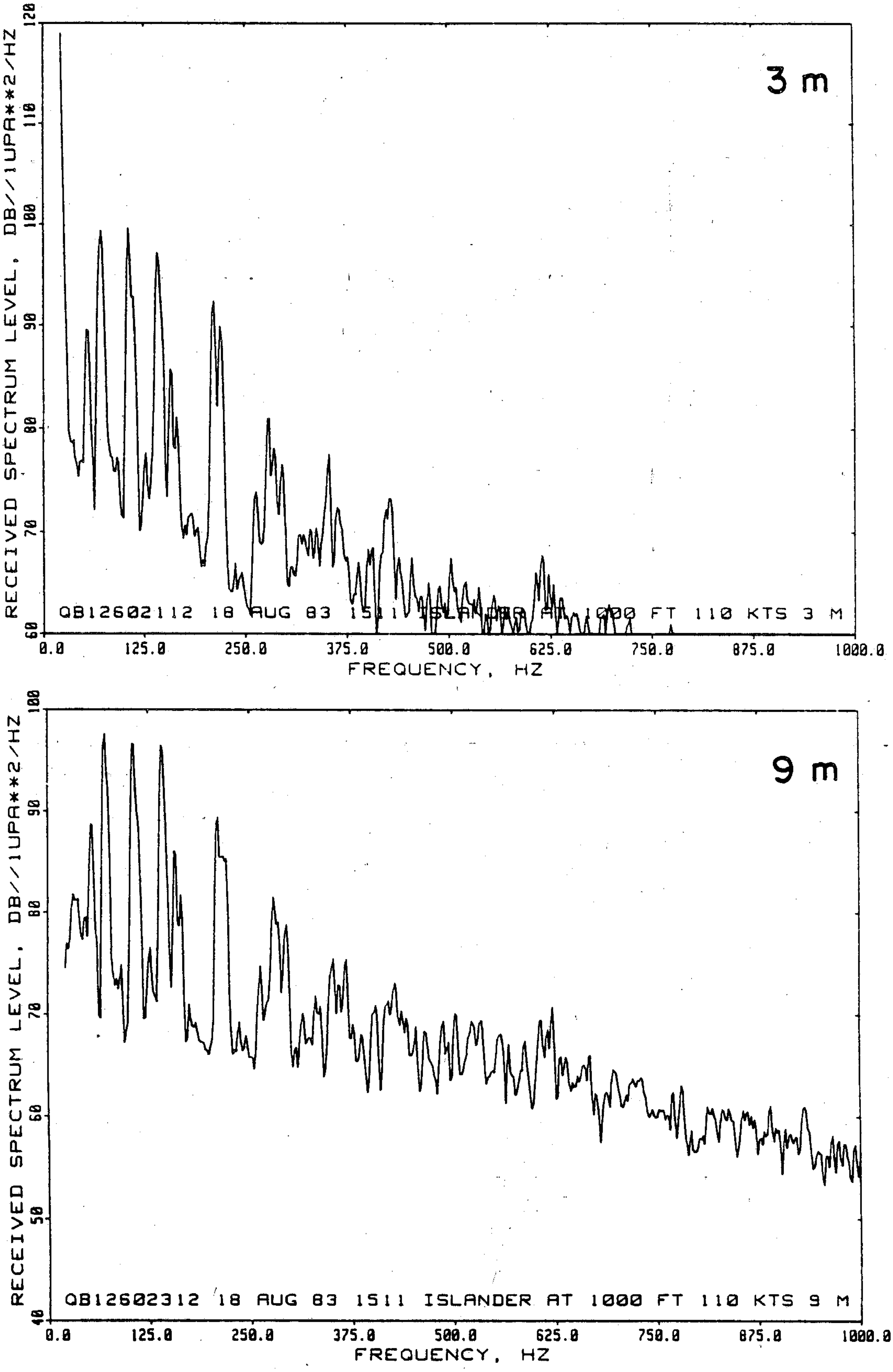


FIGURE 14. Spectra at depths 3 and 9 m for the Britten-Norman Islander in a straight pass at altitude 305 m over 'Sequel', 18 August 1983. Surface waves probably cause the high levels below 20 Hz at 3 m depth.

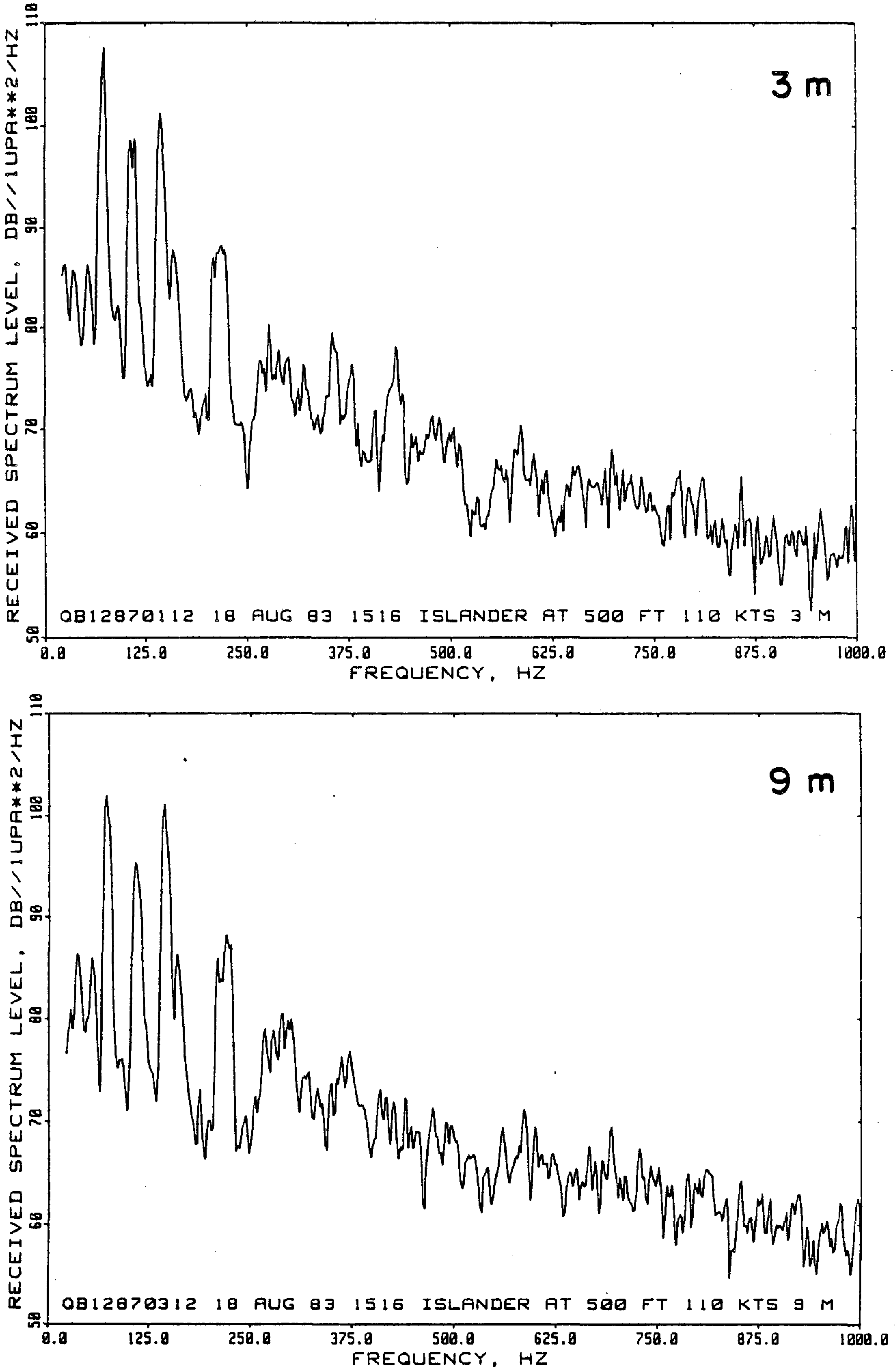
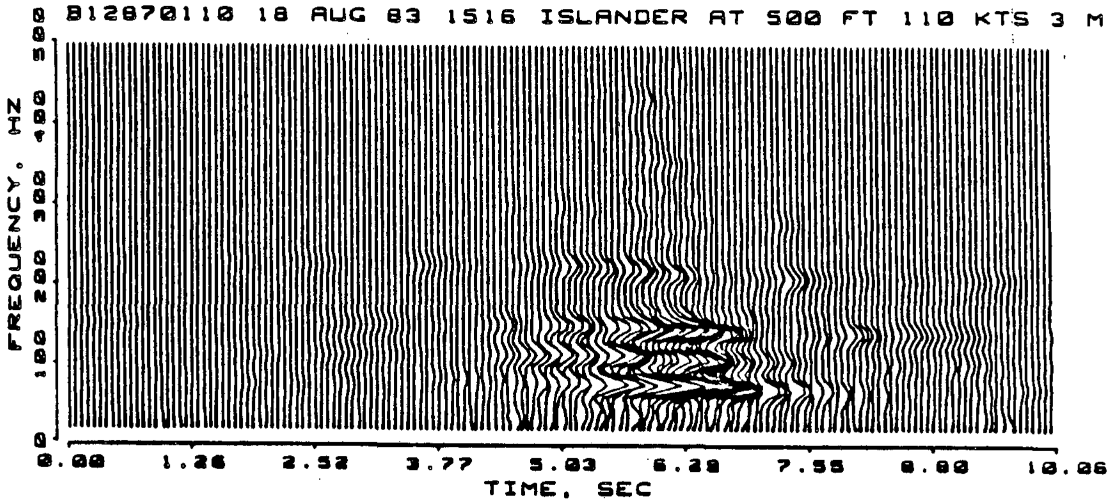


FIGURE 15. Spectra of noise from the Britten-Norman Islander received at depths 3 and 9 m during a straight pass at altitude 152 m over 'Sequel', 18 August 1983.

A. Altitude 152 m



B. Altitude 610m

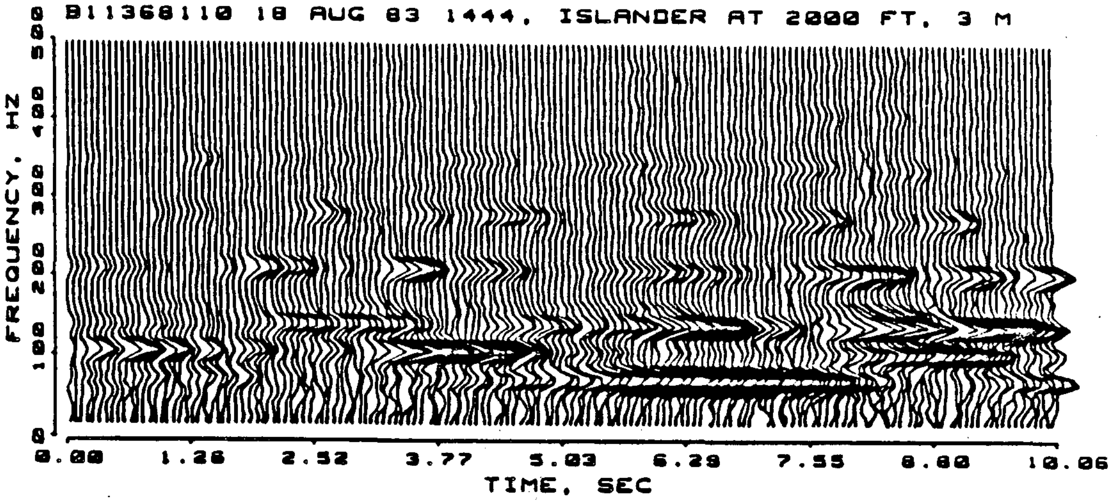


FIGURE 16. Waterfall spectral displays for overflights of the Britten-Norman Islander at altitudes (A) 152 m and (B) 610 m. The signals were recorded on a hydrophone at depth 3 m.

In 1980, the Islander flew over a sonobuoy whose hydrophone was resting on the bottom in 14.5 m of water. The altitudes were the same four used in 1983. Although the passes were all straight-line rather than circling, in 1980 the passes were made at the lower power used for circling. For both years, all analyses considered the 4 s period of maximum amplitude, and the comparisons are for the propeller blade rate tone near 70 Hz. Received levels were lower in 1980 than in 1983 (Table 5). Two possible explanations for the differences are (1) the reduced power settings of the 1980 passes, and (2) a reduction in the received level with a hydrophone resting on the bottom, as compared to a mid-water hydrophone at 9 m depth.

Table 5. Comparison of Islander blade rate tone levels (dB//1 µPa) measured in 1980 and 1983. The 1980 levels are from a hydrophone on the bottom at depth 14.5 m; the 1983 levels are from a hydrophone at depth 9 m in water 15 m deep.

Altitude (m):	610	457	305	152
1980 levels:	96, 97	93	95, 96	100, 102
1983 levels:	103, 97	101, 103	103, 106	107, 108

<u>DeHavilland Twin Otter, 9 August 1983</u>. -- The Twin Otter at altitude 457 m flew at reduced ('circling') speed over a sonobuoy in water 210 m deep. Figure 17A presents the spectrum. The resolution was 3.4 Hz and data from 4 s were used in averaging. The 20-1000 Hz band level was 103 dB and the three dominant tones were 82 Hz at 100 dB, 168 Hz at 94 dB; and 250 Hz at 88 dB. Figure 17B presents a waterfall display of spectra for the same Twin Otter overflight. An interfering noise prohibited starting the waterfall before the period of strong levels had begun.

In 1981, a Twin Otter twice flew at an altitude of 457 m over a hydrophone 9 m deep in water 22.5 m deep. The received levels of the blade rate tone at 82 Hz were 99 and 102 dB in 1981, and 100 dB in 1983. Thus, the results were virtually identical despite the use of a cruise power setting in 1981 and a lower, circling power setting in 1983.

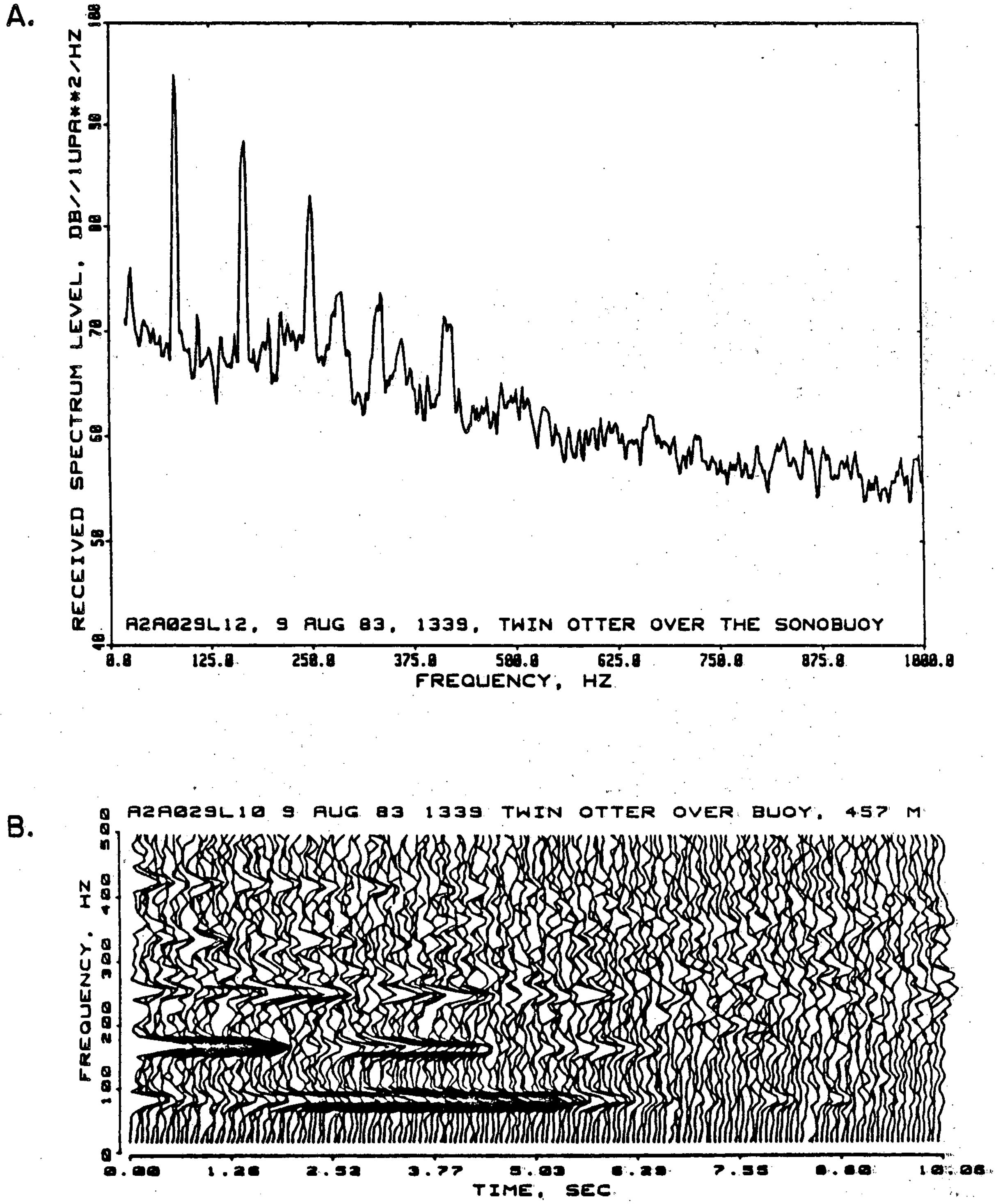


FIGURE 17. Spectra for a Twin Otter flying at altitude 457 m over a sonobuoy in water 210 m deep. **(A)** is the power spectrum averaged over 4 s with 3.4 Hz resolution. **(B)** is a waterfall display of amplitude spectra spanning close to 10 s; the resolution is 13.6 Hz.

Summary of Aircraft Noise. -- The Sikorsky 61 helicopter noise was characterized by a tone near 102 Hz. Even at an altitude as low as 152 m, this helicopter was relatively quiet. The Britten-Norman Islander noise was dominated by tones with a fundamental frequency of 68-74 Hz, corresponding to the propeller blade rate. In shallow water and at higher altitudes (above 450 m) this airplane can be expected to be heard underwater at ranges exceeding 1.5 km under conditions with a low to moderate background level. However, its underwater sound will be strong only within a few hundred metres. Twin Otter noises are characterized by a family of tones whose fundamental frequency is near 82 Hz (depending upon operating settings).

For all altitudes, the level and duration of audibility of aircraft sounds were higher at the shallow (3 m) hydrophone than at the deeper (9 m) hydrophone. This is predicted by theory (Young 1973).

Boat Noise

In 1983 we recorded noise from the vessels 'Canmar Teal', 'Cornelius Zanen', 'Imperial Sarpik', 'Arctic Sounder' at anchor (generators only), and 'Sequel' passing a sonobuoy. Noise from several other vessels operating in the Canadian Beaufort Sea was recorded in 1980-82 (Greene 1982, 1983).

'Canmar Teal', 11 August 1983. -- 'Canmar Teal' is a small ship that, in 1982 and 1983, was outfitted with an array of 3 airguns for high resolution seismic work. We recorded sounds from 'Teal' at a range of 4.6 km while 'Sequel' was anchored at 70°09.5'N, 134°05.7'W, water depth 34 m. 'Teal' was not operating her airgun array at the time of this measurement; she was underway at an unknown speed. The spectra at three hydrophone depths are presented in Figure 18. There was a strong tone at 52 Hz and a pair of strong tones at 291 and 301 Hz. The 20-1000 Hz band levels were 98, 103, and 105 db//1 µPa at the 3, 9 and 18 m depths, respectively. The levels of the 52 Hz tone were 85, 96 and 99 dB at those same depths, respectively. The higher received level at 9 and 18 m depths than at 3 m was characteristic of sounds from low frequency in-water sources (see below), and different from the pattern for aircraft noise. The levels of the 291 Hz tone at the three depths were 88, 87, and 82 dB, respectively. The corresponding levels of the

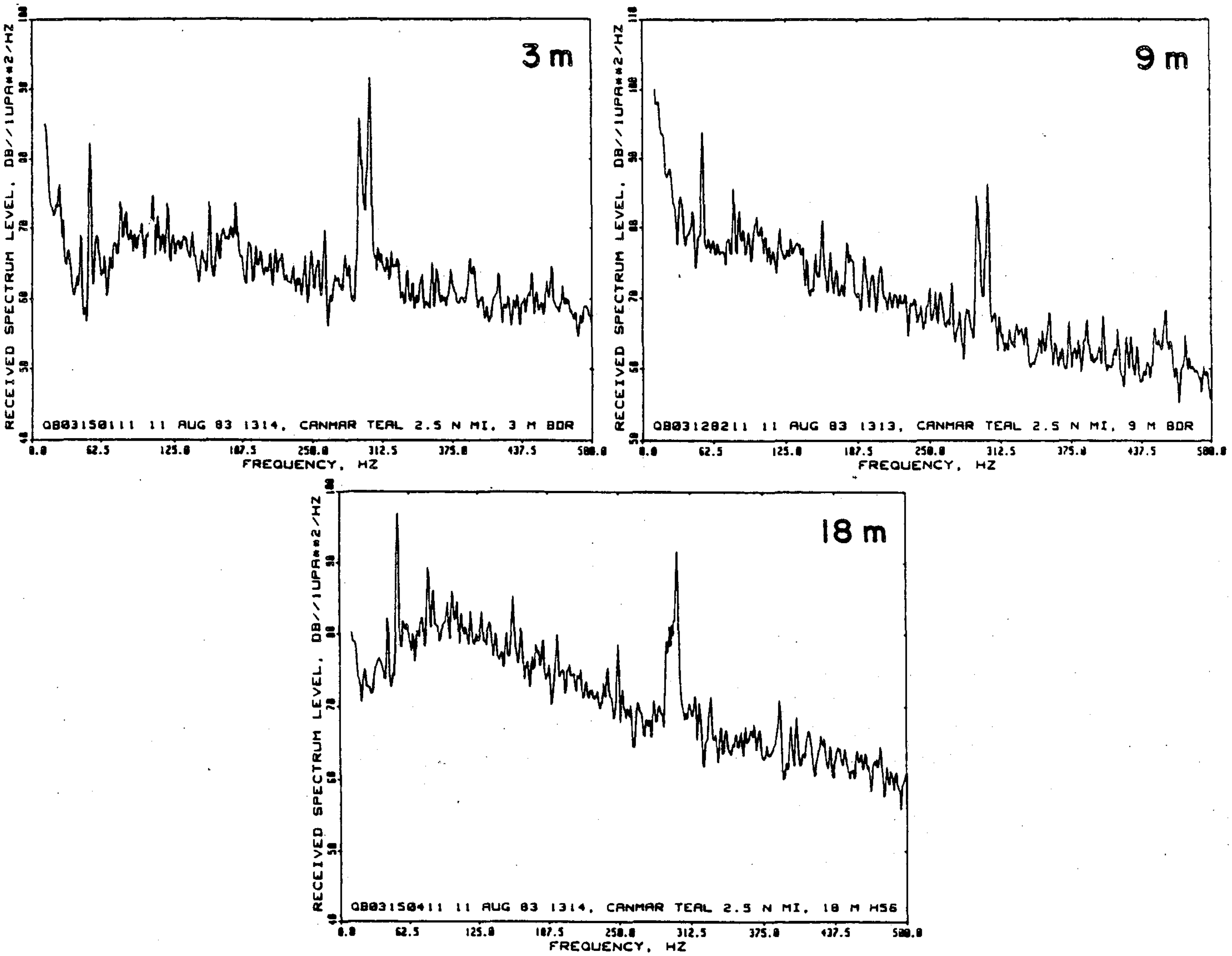


FIGURE 18. Spectra of noise from 'Canmar Teal' received at depths 3, 9 and 18 m and range 4.6 km in water 34 m deep, 11 August 1983.

301 Hz tone were 94, 89, and 94 dB. As expected, the depth effect is not manifest at these higher frequencies.

'Cornelius Zanen', 7 and 13 August 1983. -- 'Zanen' is a suction hopper dredge powered by 11.1 MW (15,000 hp) and is capable of making 28.7 km/h. Her load capacity is 8000 m^3. In a later section we describe sounds from 'Zanen' while she was dredging. Here we describe her noises while she was underway. On 7 August, 'Sequel' was anchored at the Ukalerk dredging site (Fig. 1) and recorded 'Zanen' departing after she had picked up a load. The wind was about 20 km/h and the sea state was 2. Signals received at the hydrophone 9 m deep were analyzed for three ranges. Noise levels in the 20-500 Hz band were 127 dB//1 µPa at 2.4 km, 124 dB at 3.2 km, and 116 dB at 5.0 km. The power density spectrum revealed closely spaced peaks at low frequencies (Fig. 19). The separation of 5 Hz between peaks suggested a source with fundamental frequency 5 Hz--possibly associated with the propeller blades. Closely spaced spectral peaks were also seen when 'Zanen' was dredging (Fig. 36) but only at frequencies above 250 Hz.

On 13 August 'Sequel' was anchored 7.4 km from the dredge 'Beaver Mackenzie', which was working at Amerk (Fig. 1). When 'Zanen' passed at a range of 7.4 km, her noise dominated the background sound field. The level at depth 9 m was 100 dB in the 20-1000 Hz band. The water depth at 'Sequel' was 29 m.

'Imperial Sarpik', 16 August 1983. -- 'Sequel' was anchored at Nipterk (69°48.1'N, 135°20.8'W, Fig. 1) in water 11 m deep, when 'Sarpik' motored past at high speed. 'Sarpik' is a 21-m diesel-powered high speed personnel transport vessel operated by Esso Resources Canada, Ltd. Spectra for ranges 2.8 km (the closest point of approach) and 4.6 km, measured with the 9 m hydrophone, are presented in Figure 20. The 20-1000 Hz band levels were 110 and 105 dB for the 2.8 and 4.6 km ranges, respectively. The strongest tone at 2.8 km was at 195 Hz, 100 dB; at 4.6 km the strongest tone was at 202 Hz, 94 dB. For Doppler shift to account for this 7 Hz change in frequency, vessel speed would have to exceed 186 km/h (100 knots). Thus, it appears that 'Sarpik' changed engine settings between the two measurements, as the frequencies of all the major tones were higher at range 4.6 km (time 18:11)

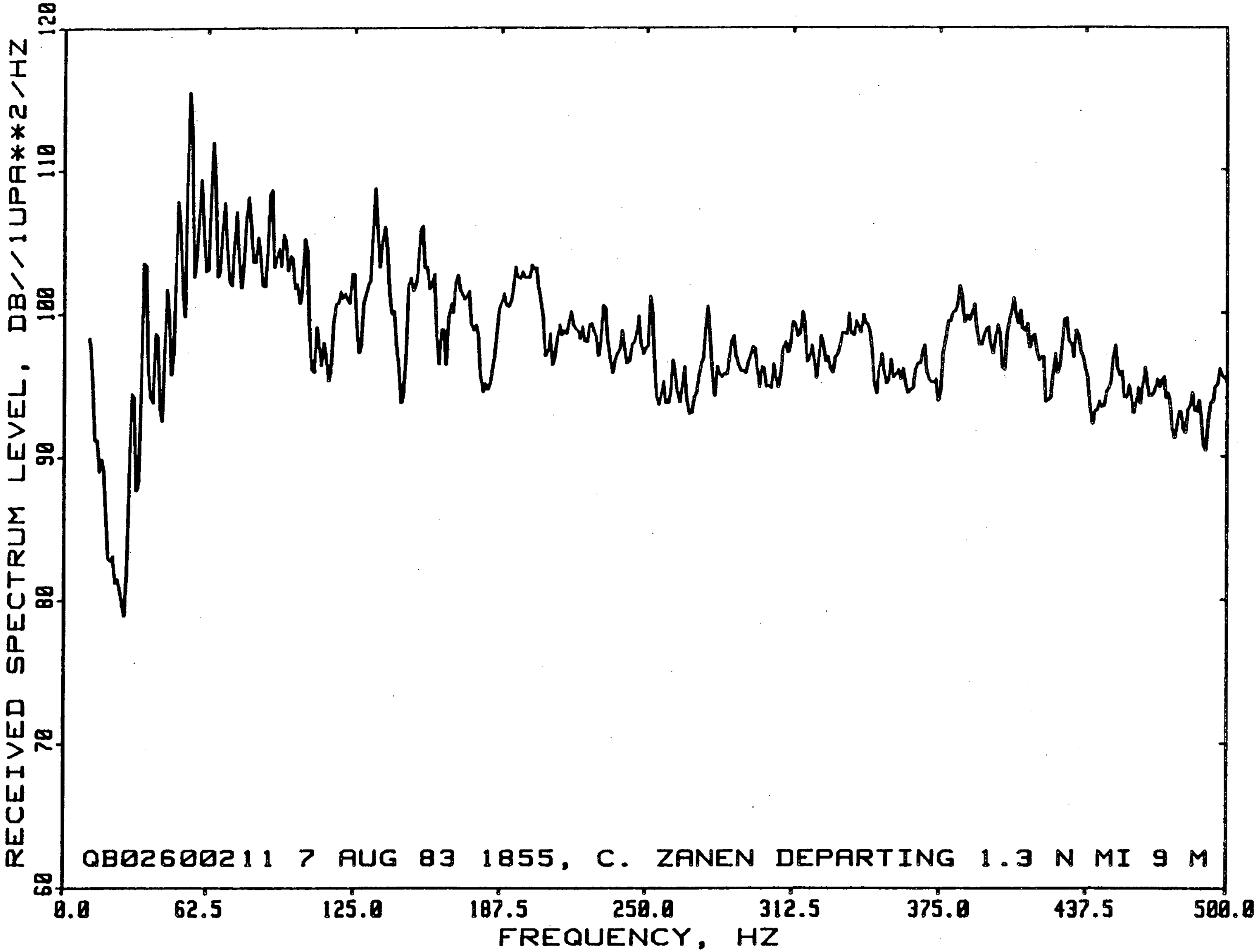


FIGURE 19. Spectrum for dredge 'Cornelius Zanen' underway with a full load, range 2.4 km from 'Sequel'. The receiving hydrophone was 9 m deep.

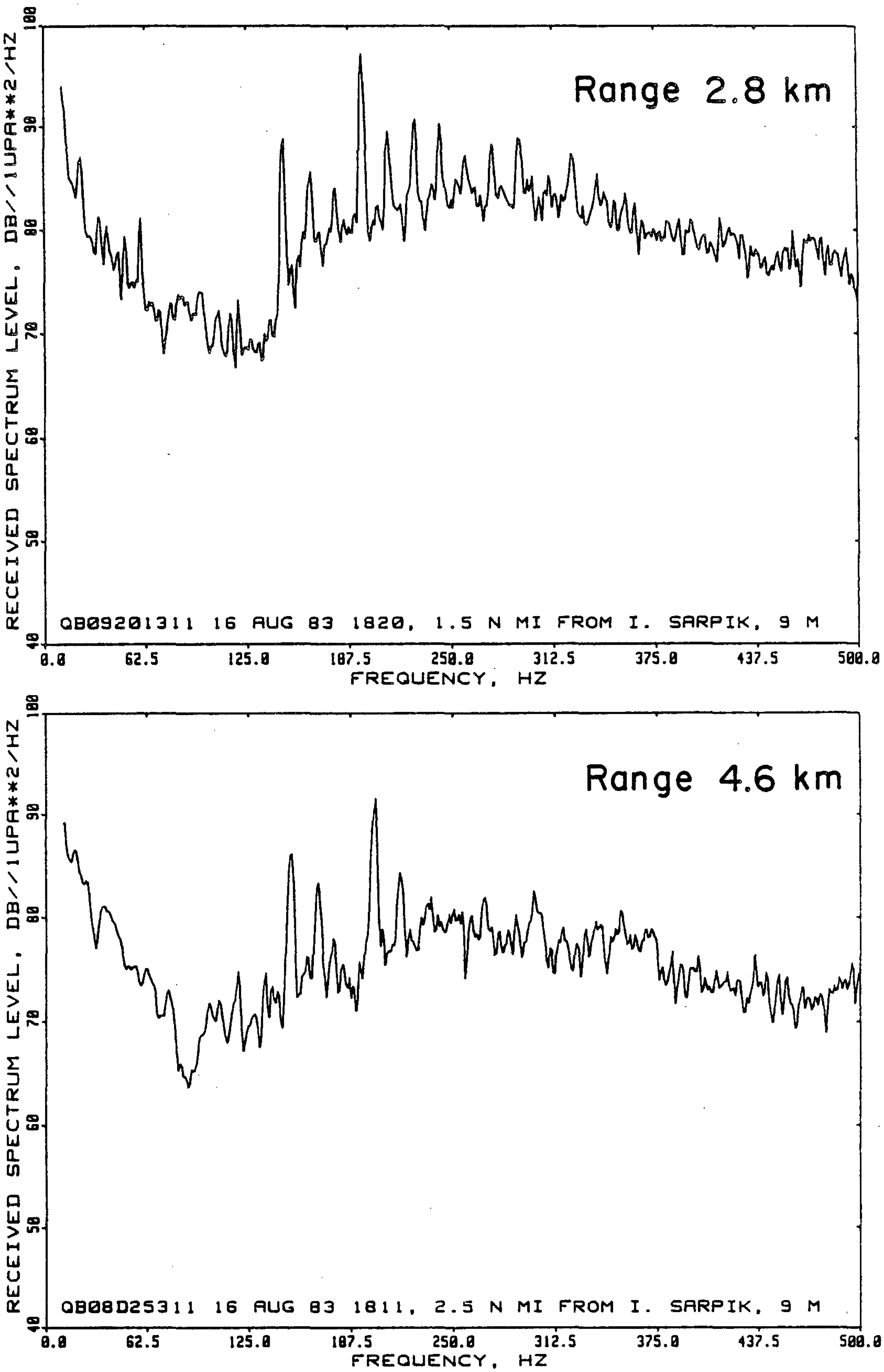


FIGURE 20. Spectra of noise from 'Imperial Sarpik' received at depth 9 m and ranges 2.8 and 4.6 km in water 11 m deep, 16 August 1983, at Nipterk.

than at range 2.8 km (time 18:20). Received levels at about 50-150 Hz were lower than those at lower or higher frequencies (Fig. 20), probably because of a high rate of attenuation in the shallow water.

In 1980, measurements of noise from a 16.1 m crew boat, 'Imperial Adgo', moving past a sonobuoy at an estimated range of 200 m (Greene 1982, p. 284-5), revealed a strong tone at 90 Hz, 113 dB. The 195 Hz, 100 dB, tone from 'Sarpik' at 2.8 km indicates that her noises are comparable. In 1981,'Sequel' had a strong tone at 33 Hz, 102 dB, at an estimated range of 100 m. We would not expect 'Sequel' to be as noisy as either 'Sarpik' or 'Adgo'.

'Arctic Sounder' at Anchor, 16 August 1983. -- 'Arctic Sounder' was the survey vessel at the Nipterk island construction site; she was riding at anchor waiting for a dredge to deliver another load of fill. The water depth was 11 m, and hydrophone depth was 9 m. 'Sequel' anchored first at range 0.5 km and then at 0.9 km from 'Sounder' to record the sounds of the generator on 'Sounder' (Fig. 21). The strongest tone received at 0.5 km range, 59 Hz at 97 dB//1 µPa, was undoubtedly from the generator. Both the second and third harmonics, at 118 and 177 Hz, were strong, as was a tone at 354 Hz. Other tones occurred at 75, 79, 89, 98, 138, 217, 268 and 315 Hz. The 20-1000 Hz band level was 103 dB. Most of these tones were also evident at 0.9 km range, but the 59 Hz tone was much less prominent. The 20-1000 Hz band level at 0.9 km range was 97 dB.

'Sequel', 28 August 1983. -- In advance of the airgun disturbance test, 'Sequel' passed near a sonobuoy at idle speed, about 6 km/h. The 20-1000 Hz band level was 93 dB//1 µPa. The first four strong tones were at 44, 70, 88 and 104 Hz. The spectrum in Figure 22 exhibits many more tones than have been seen for 'Sequel' in the past (Greene 1982, p. 285; Greene 1983, p. 258). The spacing of these tones, allowing for some that are suppressed, is about 11 Hz. Translated into a rotation rate, 11 Hz corresponds to 660 rpm, which is reasonable for a propeller shaft rate. It is possible that a single propeller blade was damaged, or even that the shaft was slightly bent--either occurrence would account for the appearance of a family of tones traceable to the drive shaft speed.

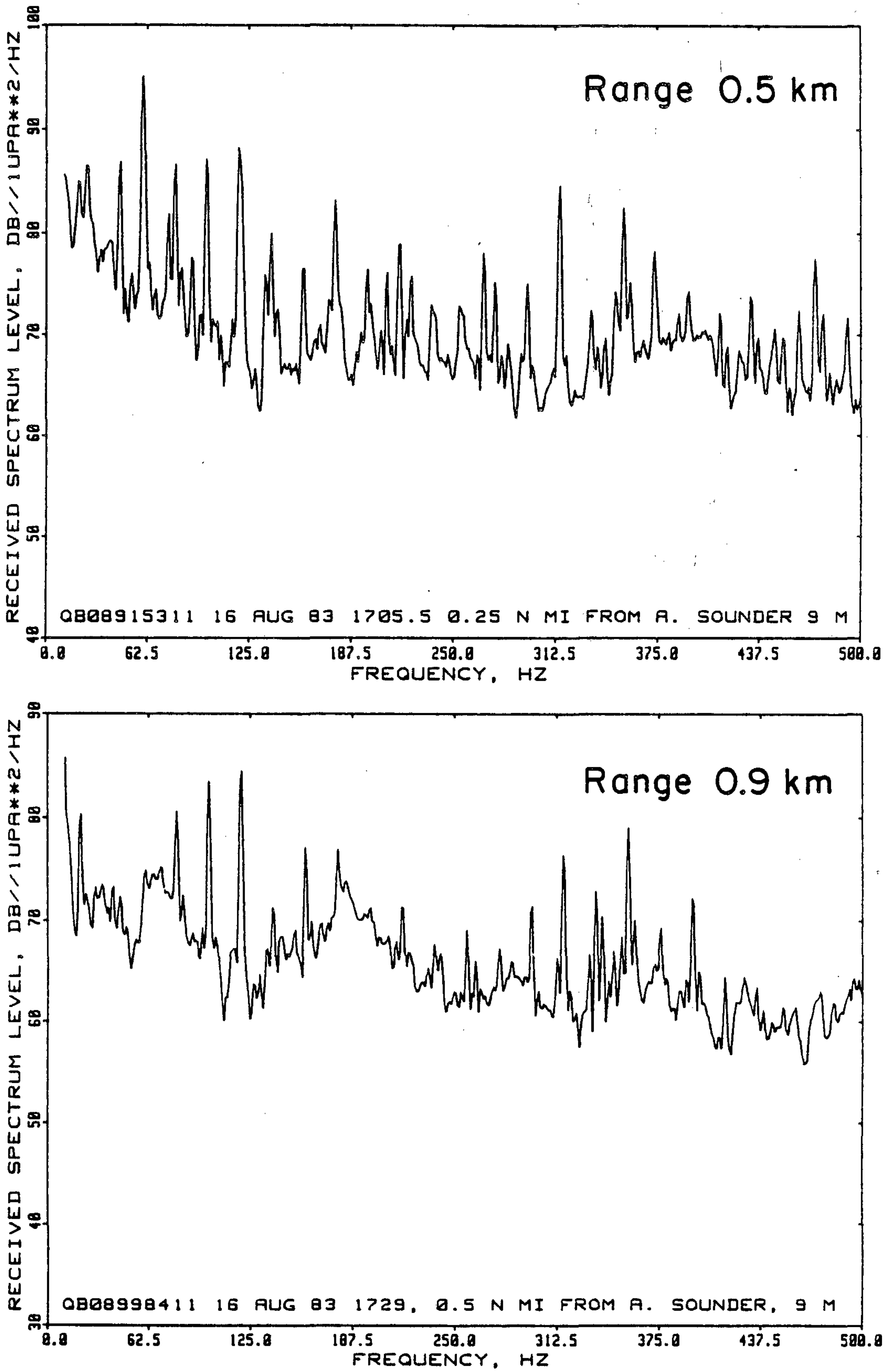


FIGURE 21. Spectra of noise from 'Arctic Sounder' received at depth 9 m and ranges 0.5 and 0.9 km, in water 11 m deep, 16 August 1983. 'Arctic Sounder' was anchored with only generators running.

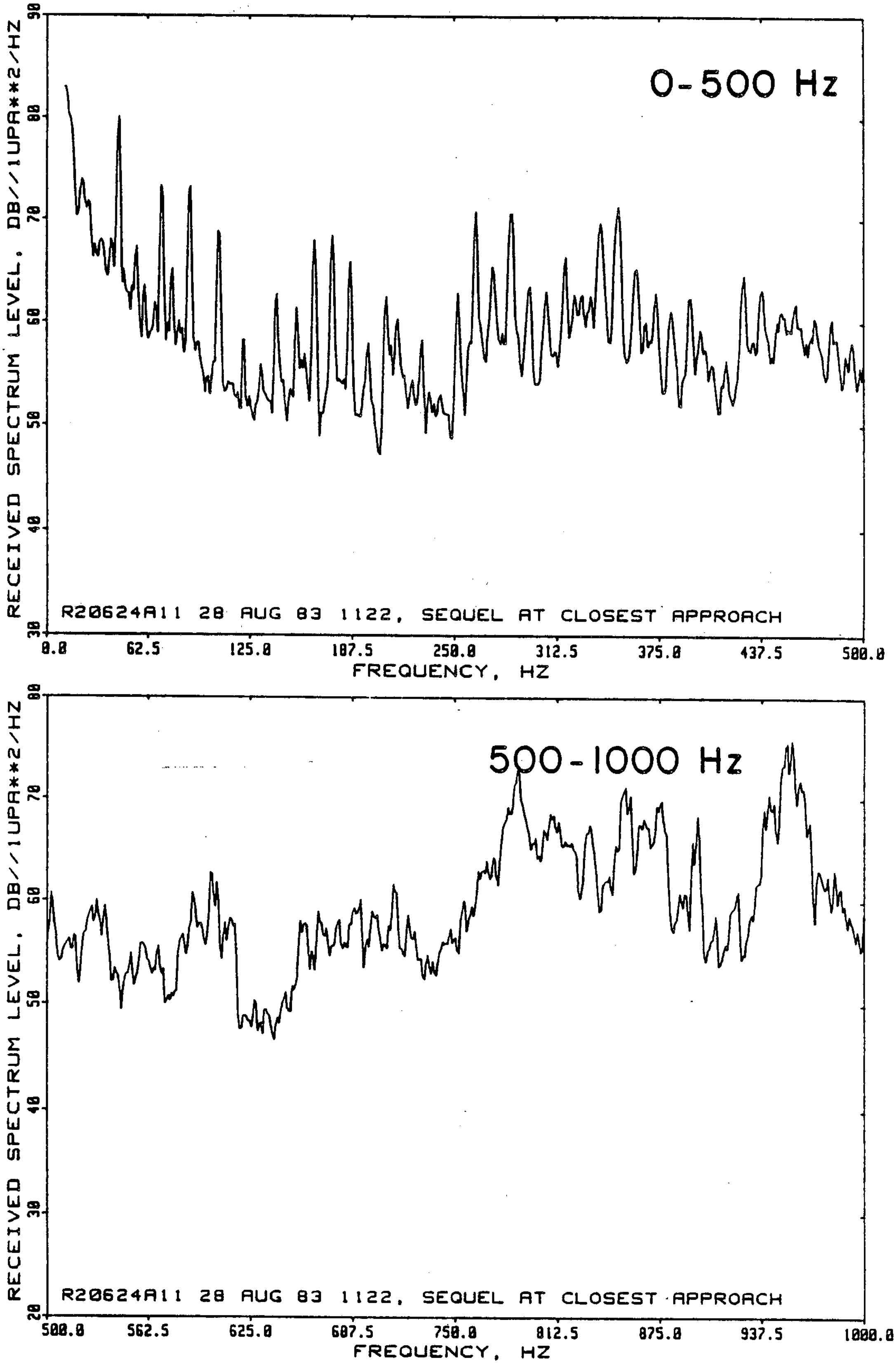


FIGURE 22. Spectrum of noise from 'Sequel' passing a sonobuoy, in water 18 m deep, 28 August 1983.

Summary of Boat Noise. -- Strong tones at 52, 291 and 301 Hz characterized the noise from 'Canmar Teal'. The pair of tones at frequencies as high as 291 and 301 Hz were unusual. The radiated noise from dredge 'Cornelius Zanen' underway was distinguished by a family of tones spaced 5 Hz apart. 'Imperial Sarpik', consistent with its high operating speed, had a strong tone near 200 Hz. 'Arctic Sounder' at anchor, with only her generators operating, exhibited a sound field rich in tones whose frequencies were presumably related to power generation. 'Sequel' had a radiated noise spectrum dominated by tones, including four strong tones near 100 Hz and below. 'Arctic Sounder' at anchor would not be detected at very great ranges, given the rather low levels received at 0.5 and 0.9 km, but the other three boats could be, depending on acoustic transmission conditions.

Seismic Signals

In 1983, seismic signals were received via sonobuoys on four dates, and via Sequel's hydrophones on several occasions. As in 1980-82, we determined an effective level (in dB//1 µPa) of the received seismic signal by measuring the maximum amplitude (see METHODS). We used the same technique to describe the received level of the airgun signals during the airgun disturbance test.

It is important to keep in mind, in viewing waveforms of signals from sonobuoys, that the sonobuoy does not have a constant response with frequency. Low frequencies are attenuated and high frequencies are emphasized. Thus a signal may appear to have a relatively high level of energy at higher frequencies than it actually does. This bias is accounted for when we compute spectra from sonobuoy signals, and when we convert an amplitude on a voltage vs. time plot to an effective level in dB//1 µPa.

It is also important to note that received levels derived from sonobuoy recordings may be underestimates if there was signal overload in the sonobuoy, receiver, or tape recorder. This potential problem cannot be corrected during data analysis. Seismic signals recorded via the hydrophones deployed from 'Sequel' were not subject to this limitation. In 1983, seismic signals from 'Canmar Teal' were recorded via the latter system. All other seismic and airgun signals discussed below were recorded via sonobuoys, and therefore their levels may be underestimated.

<u>'GSI Mariner', 7-9 August 1983</u>. -- On 7 August, the sonobuoy was at 70°32'N, 138°10'W, where water depth is 950 m (Fig. 1). 'GSI Mariner' was travelling west 79-81 km south of the sonobuoy; water depths at Mariner's location were 150-190 m. This ship uses an array of airguns with total volume about 23 L, and source level about 246 dB//1 µPa at 1 m (G. Bartlett, GSI, pers. comm.). The array is discharged at intervals of about 13-16 s. The received signals sounded distorted, probably because of the poor antenna available on the Twin Otter. The nominal frequency of the received signals at the time of maximum amplitude was about 150 Hz (Fig. 23). The durations of the pulses were rather long, at least 0.5 s (Fig. 23). Five seismic pulses were analyzed for times between 17:17 and 18:43 MDT. The effective received levels, in dB//1 µPa, were as follows:

Time:	17:17	17:21	17:34	17:53	18:43
Level:	127	131	128	115	119

As noted above, these are minimum values. Until 17:34, the Twin Otter aircraft that was receiving the sonobuoy signals was close to the sonobuoy. However at 17:53 and 18:43, the aircraft was about 18 km away. The seemingly lower received levels of the seismic pulses at the latter two times may have been an artefact attributable to the suboptimal antenna on the Twin Otter (see Methods); the range and aspect from 'GSI Mariner' to the sonobuoy were very similar throughout the recording period.

On 9 August the sonobuoy was at 70°00'N, 138°56'W, where water depth is 210 m (Fig. 1). Seismic signals began to be received at 13:48 and continued, with brief interruptions near the start, until 18:43 when the aircraft departed. 'GSI Mariner' was 57 km to the southwest, in water only 20 m deep, at the start of this period. (We have no information about her subsequent movements.) The dominant frequency in the received pulses was unusually high, above 350 Hz, and the pulses were comparatively short in duration (Fig. 24). Effective received levels, in dB//1 µPa, were as follows:

Time:	13:48	13:58	14:03	14:10.5	14:11	14:23
Received Level:	114	114	110	123	117	114
Record Level:	6	6	6	2	4	6

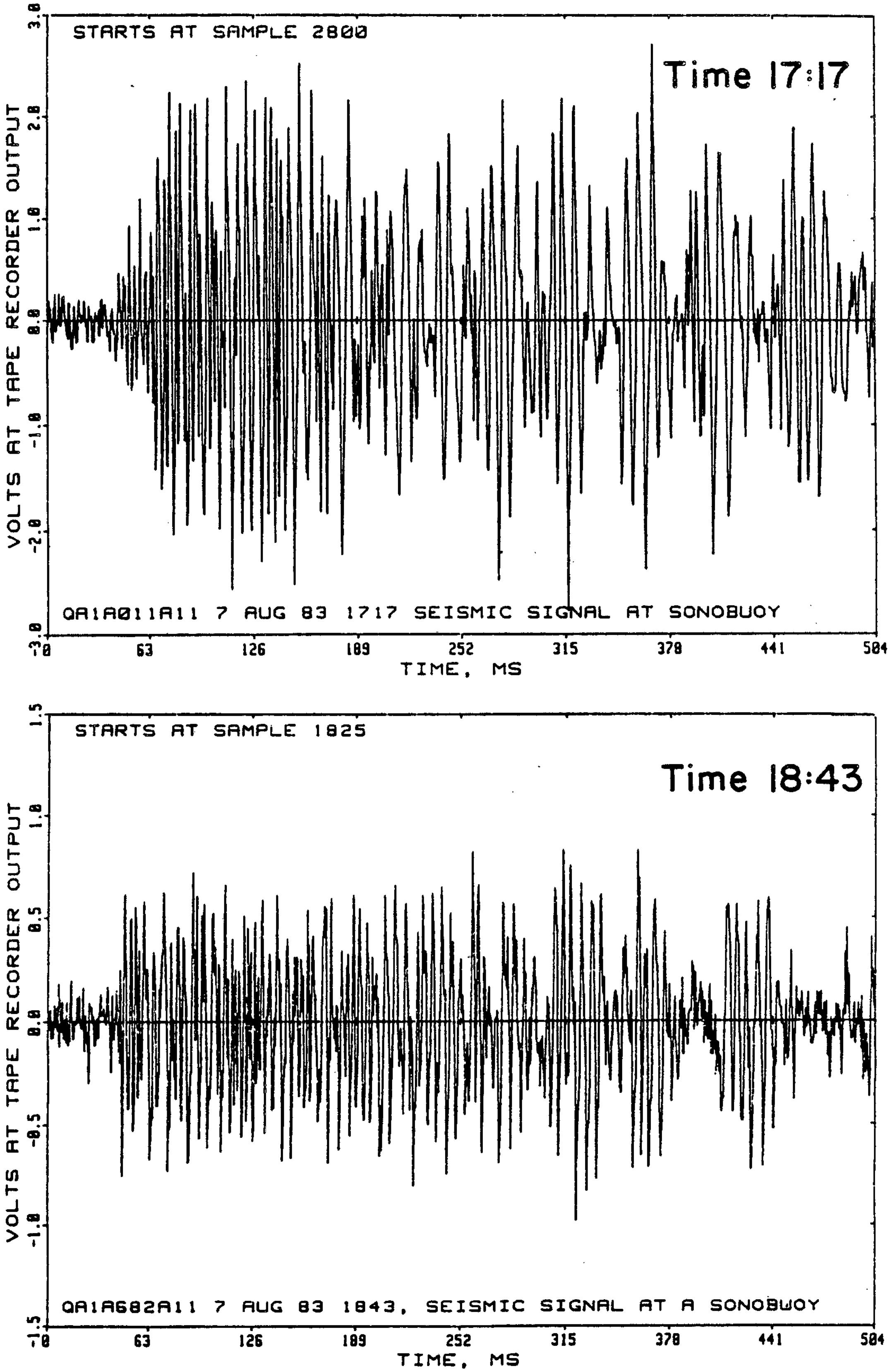


FIGURE 23. Waveforms of seismic signals from 'GSI Mariner' received at a sonobuoy 80 km away in water 950 m deep, 7 August 1983.

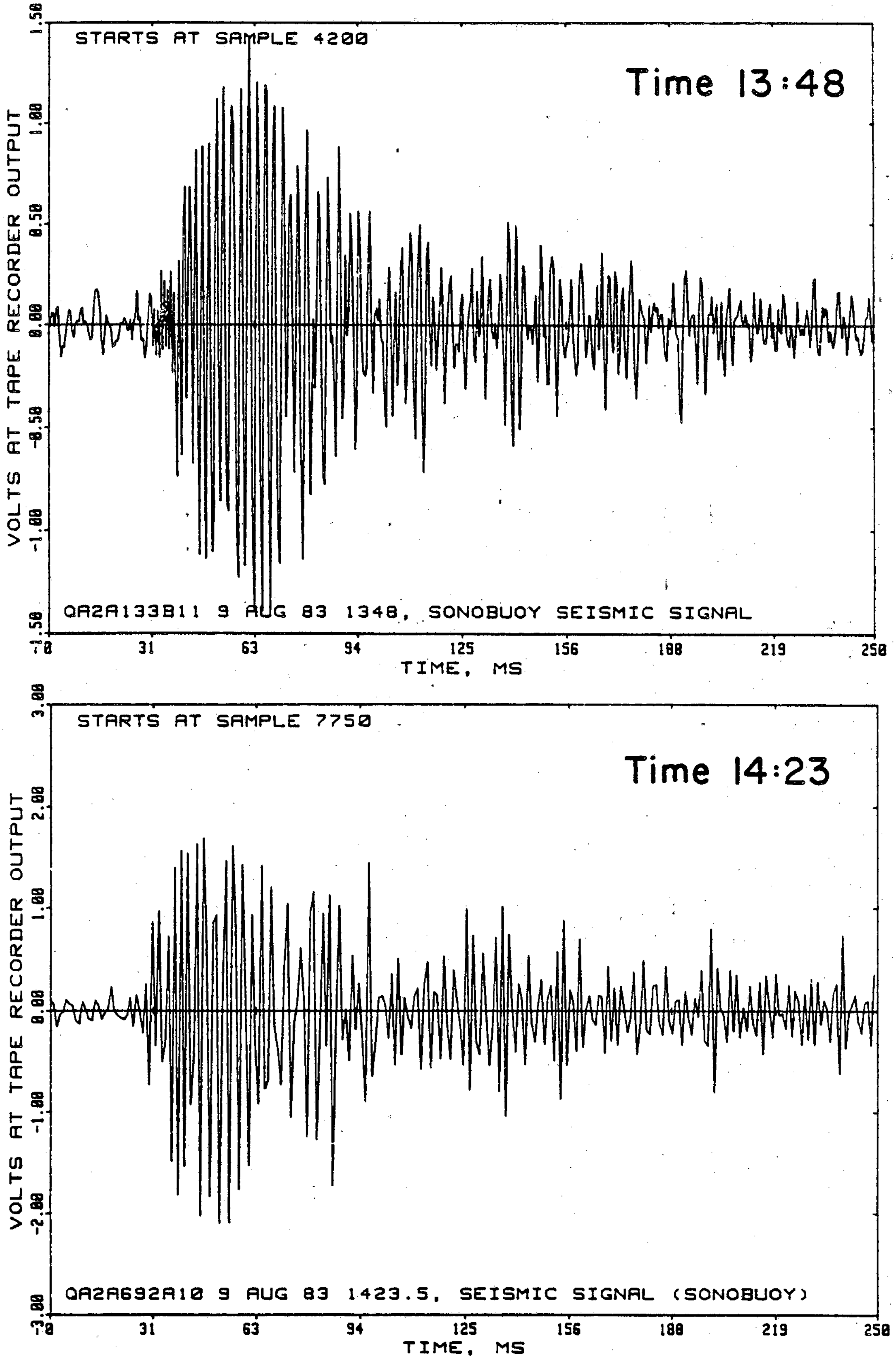


FIGURE 24. Waveforms of seismic signals from 'GSI Mariner' received at a sonobuoy about 57 km away in water 210 m deep, 9 August 1983.

The higher received level for record level 2, plus the fact that the record level had to be reduced from 6 to 2 to avoid excessive peak levels on the recorder's VU meter, suggests that the signals were too strong to be recorded with fidelity at record levels 4 and 6. Despite this, there is no indication of overloading in the waveforms (e.g. Fig. 24). Thus, the appearance of the recorded waveform is apparently not a reliable indicator of the fidelity of a recording of seismic pulses.

'Arctic Surveyor', 31 August 1983. — Greene (1983) obtained detailed data on the seismic sounds produced by this vessel in 1982. The 'Arctic Surveyor' employed the same seismic gear in 1983—open-bottom gas guns. Seismic signals were received from the 'Arctic Surveyor' while a sonobuoy was deployed at 69°51'N, 136°31'W, water depth about 19 m, from 14:45 through 17:10 MDT (Fig. 1). 'Arctic Surveyor' was operating in shallow water about 52 km to the east. A signal at 16:24 was weaker than one at 14:55 (Fig. 25). Effective signal levels decreased toward the end of the recording session, and were barely detectable in the background noise at 16:48:

Time (MDT):	14:55	15:29	15:37	16:00	16:24	16:48
Dom. freq. (Hz):	138	117	115	107	109	-
Eff. level (dB):	124	125	122	128	119	<107

It is not obvious why the received level decreased at 16:24. The range from 'Arctic Surveyor' to the sonobuoy remained nearly constant throughout the period of recording (53-52 km). Note that the dominant frequency also decreased with time.

'Western Aleutian', 1 September 1983. -- A sonobuoy was deployed by the Islander crew at 69°50'N, 136°30'W, where water depth is 19 m (Fig. 1). Seismic signals from 'Western Aleutian' were received throughout the recording period, which extended from 15:33 to 18:26 MDT (Fig. 26). The ship travelled ESE from a point 31 km NNW of the sonobuoy to a point 30 km NE during the observation period. The closest point of approach was at range 26 km. 'Western Aleutian' uses an array of airguns with source level 250 dB//1 μPa (Reeves et al. 1983). The nominal frequency of the signal at the time of maximum amplitude was between 160 and 200 Hz, and the received

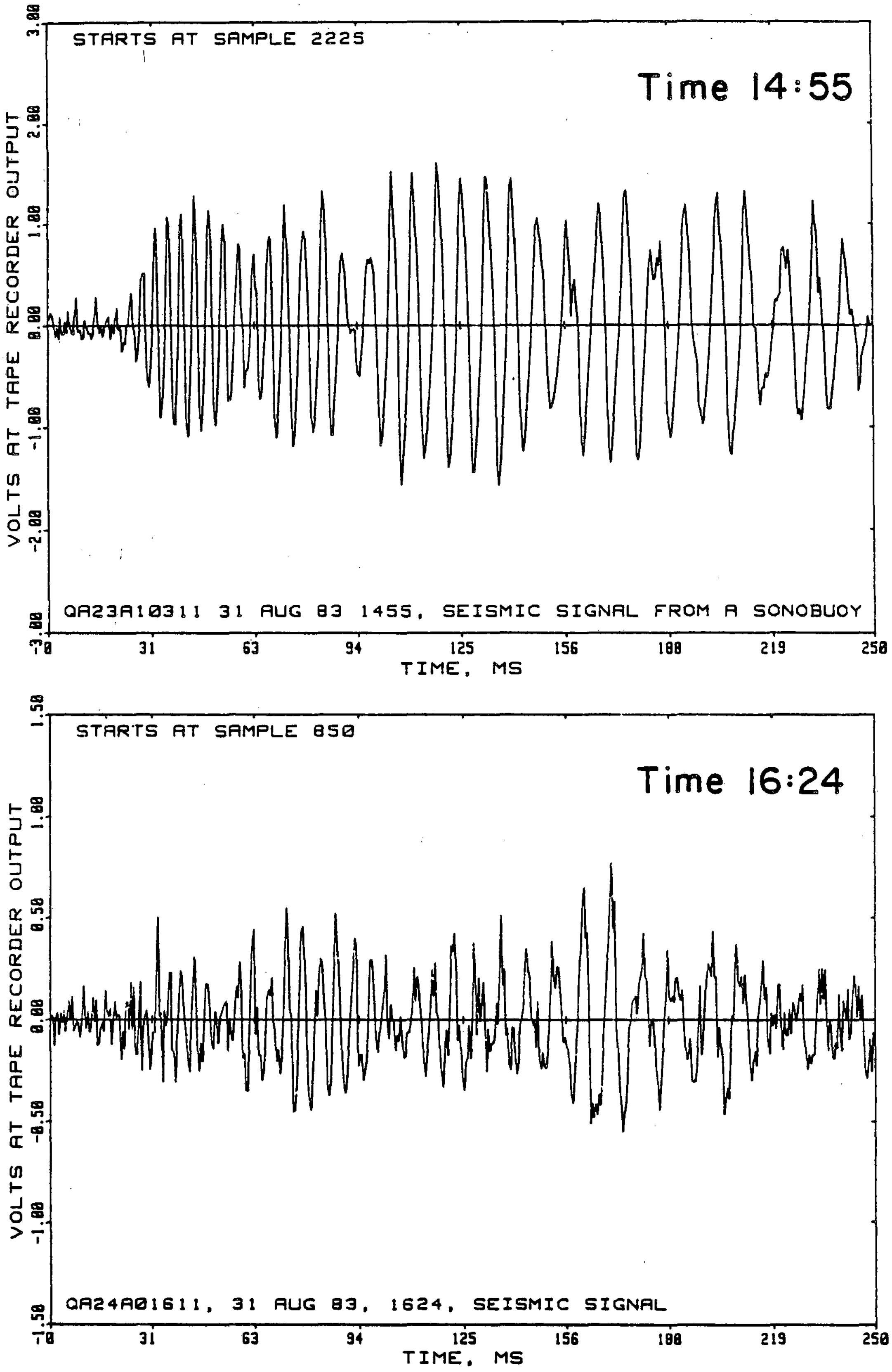
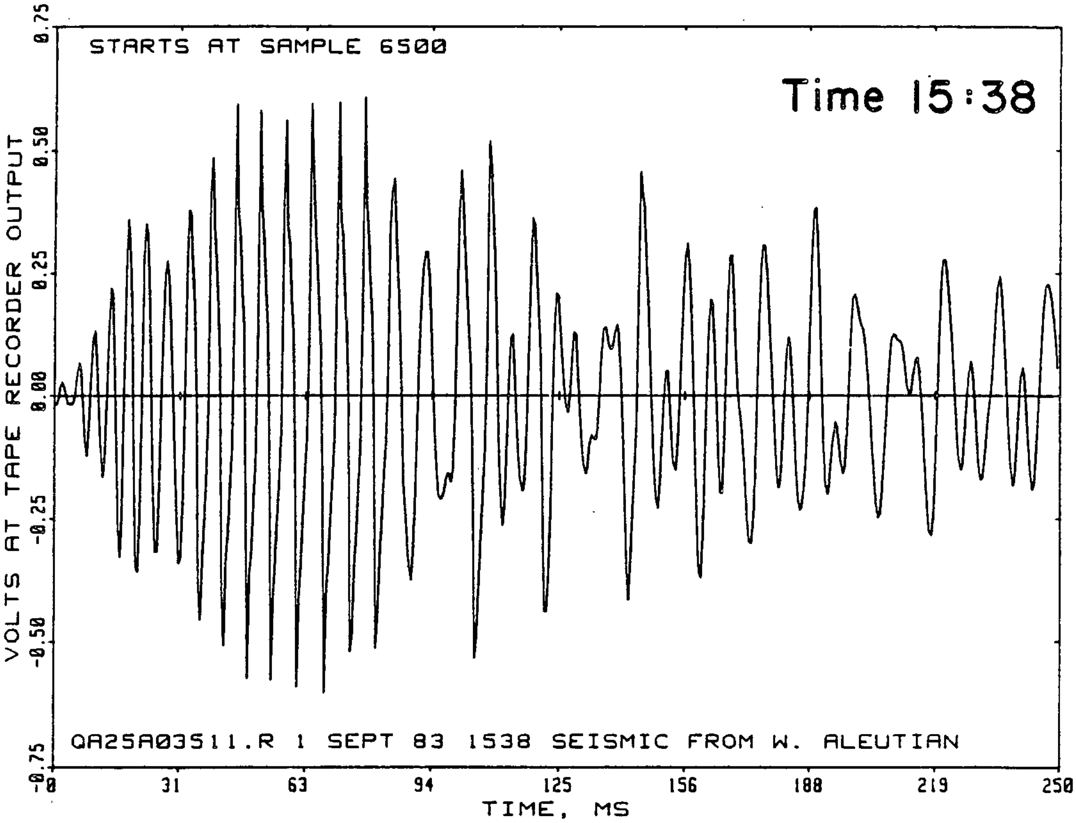


FIGURE 25. Waveforms of signals from open-bottom gas guns deployed by 'Arctic Surveyor' as received at a sonobuoy about 52 km away in water 19 m deep, 31 August 1983.



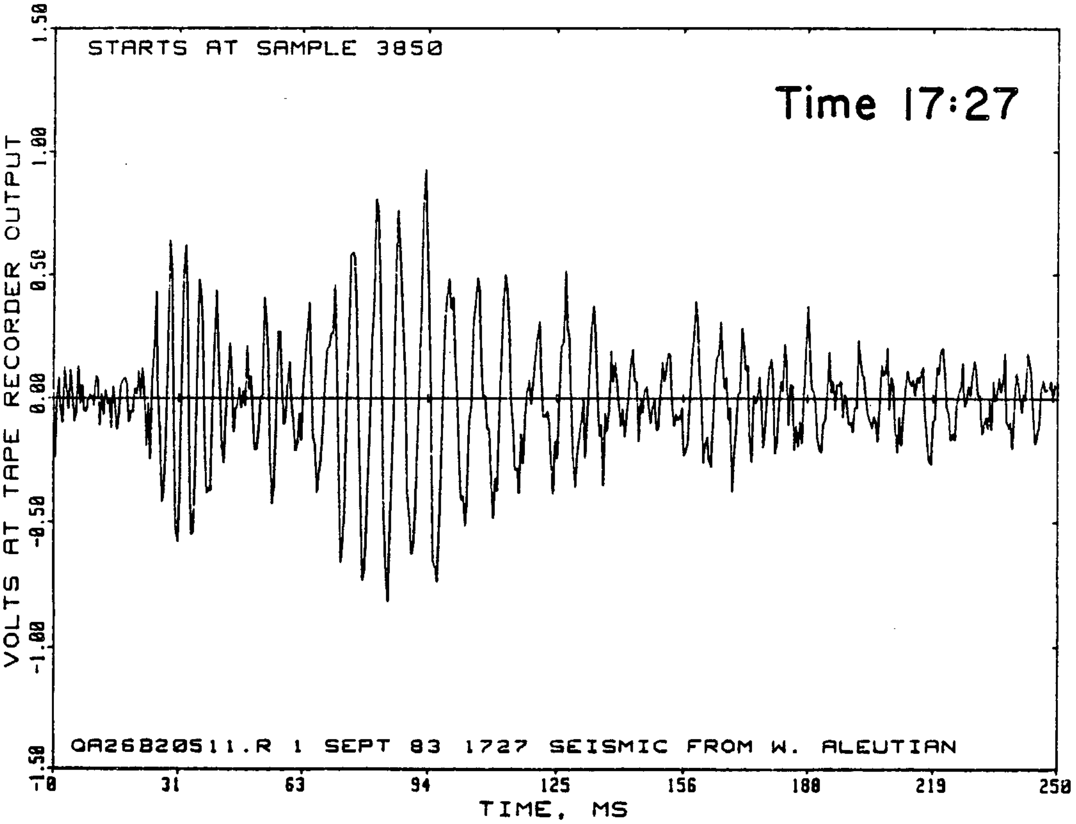


FIGURE 26. Waveforms of seismic signals from 'Western Aleutian' received at a sonobuoy about 30 km away in water 19 m deep, 1 September 1983.

levels ranged from at least 136 dB//1 µPa at 15:38 to 120 dB at 17:11 and 121 dB at 17:27.

Figure 27A,B displays waterfall spectra for airgun signals from 'Western Aleutian' received at the sonobuoy. The distance to the source was about 30 km for both signals, but the received signals changed considerably during the 2.7 h that elapsed between the two signals. (A) has stronger spectral components, as its background is almost totally suppressed by the normalization relative to the strongest peak in the waterfall (see METHODS). There is evidence of multiple modes of propagation for the signal shown in (A), while (B) appears to consist of one arrival.

'Canmar Teal', 11 August 1983. — 'Sequel' was anchored at 70°09'N, 134°09'W, water depth 34 m, low wind and sea, but with visibility less than 2 km in fog. 'Canmar Teal' was performing various survey operations in our vicinity, although we never saw her except on radar. She was equipped with a 200 kHz echo sounder, 100 kHz side scan sonar, 3.5 kHz sub-bottom profiler, a 300-joule boomer (400-2000 Hz) firing 4 times per second, and a 3-element airgun array with total volume 5.2 L operating at 2000 psi (138 bars) 5 m deep, firing once each 6 seconds. The airgun signals were conspicuous at 'Sequel', although they were not present continuously. Figures 28 and 29 display signals received at three depths when the range was 3.0 km and 10.4 km. A waterfall display for an airgun pulse from range 13 km shows the usual decrease in peak frequency with increasing time (Fig. 30). The steady tone just below 300 Hz is from an unknown source.

For low frequency sounds originating in the water, we expected the received level to be lowest at the shallow hydrophone (Richardson et al. 1983). Table 6 presents the effective levels for the six instances we analyzed. In 5 of 6 cases, the received level was indeed lowest at the 3 m hydrophone and highest at 18 m; the difference between 3 and 9 m was usually greater than that between 9 and 18 m. On average, levels at 3 m were 7 dB less than those at 9 m. There was one exceptional case, at 08:23 MDT, when the 18 m figure was unexpectedly low relative to the others (Table 6). The nominal signal frequencies were above 100 Hz, and approached 200 Hz at the shorter ranges.

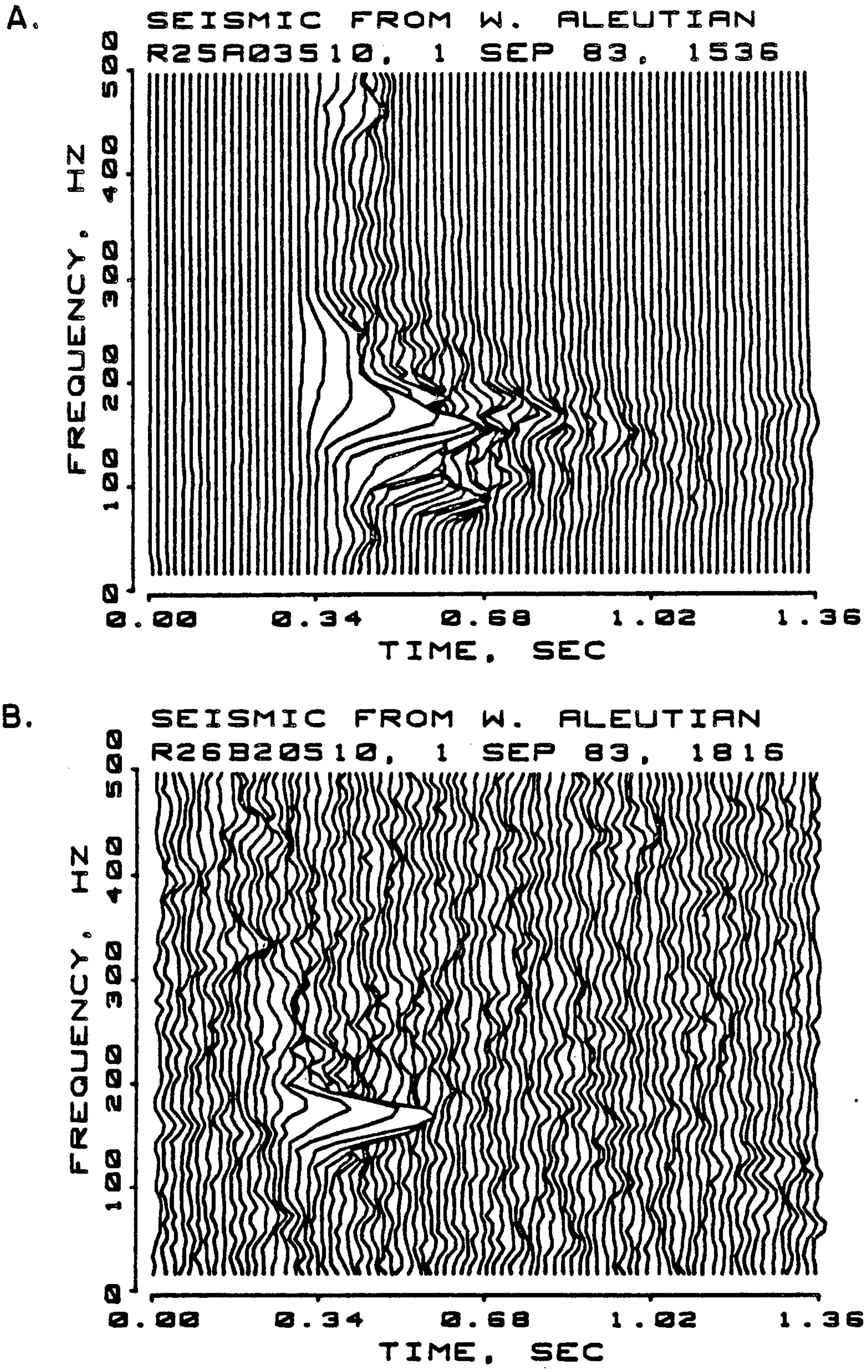


FIGURE 27. Waterfall spectral displays for the airgun signals from 'Western Aleutian'. (A) is for a signal received via sonobuoy at 15:36 MDT, range 31 km. (B) is for a signal received at 18:16 MDT, range 30 km.

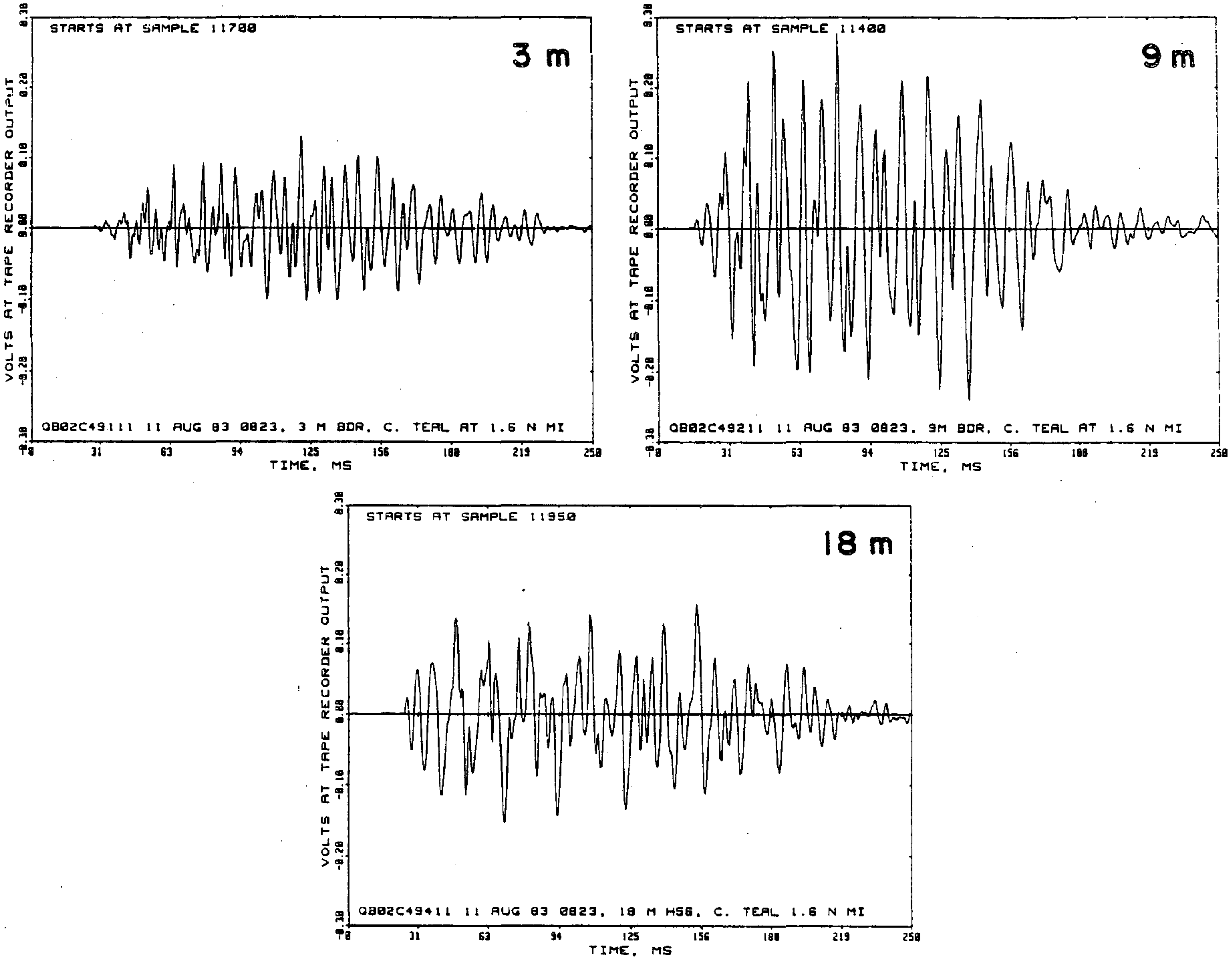


FIGURE 28. Waveforms of an airgun signal from 'Canmar Teal' received simultaneously at depths 3, 9 and 18 m in water 34 m deep, 11 August 1983. The range was 3.0 km, and the hydrophones were deployed from 'Sequel'.

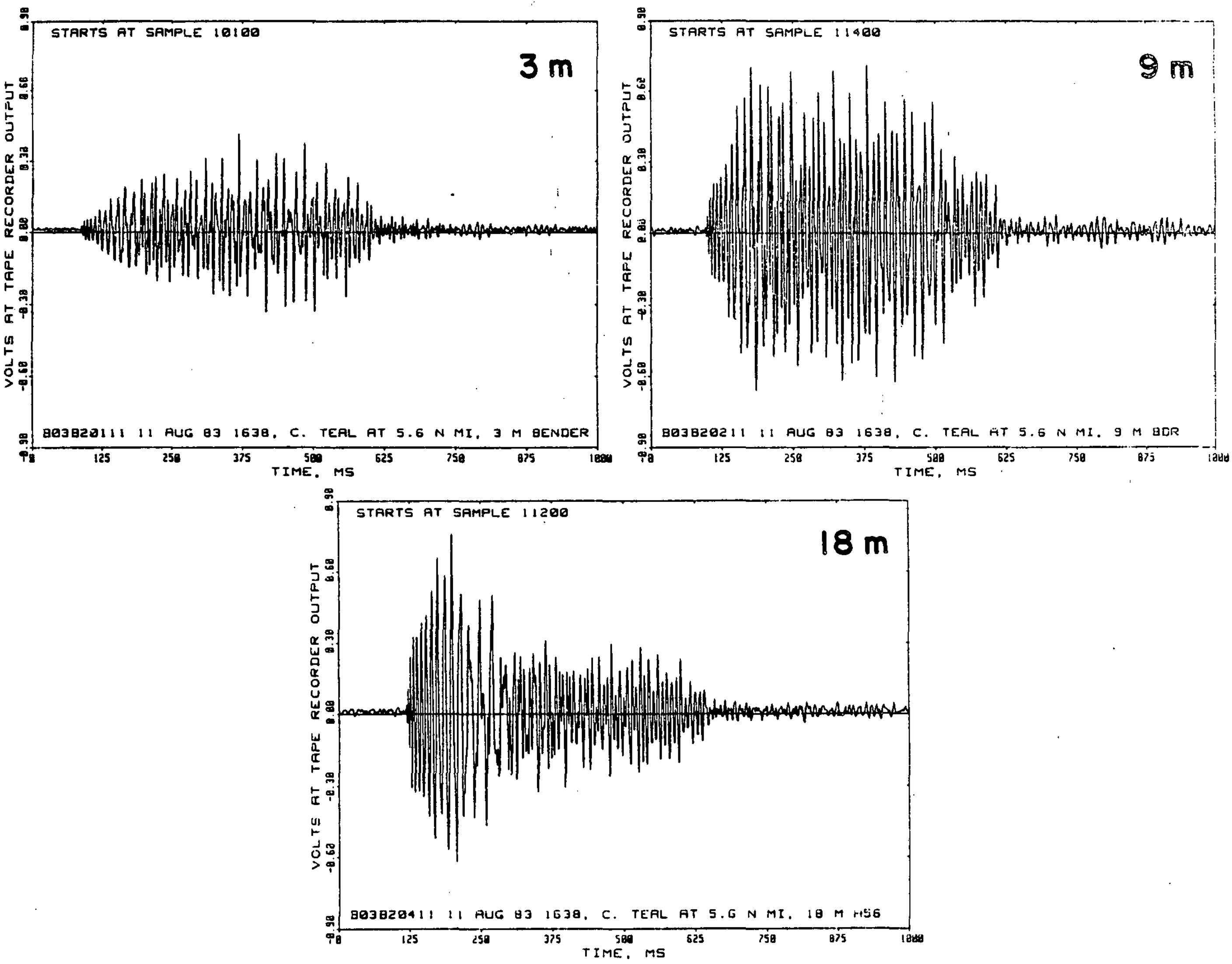


FIGURE 29. Waveforms of an airgun signal from 'Canmar Teal' received simultaneously at depths 3, 9 and 18 m in water 34 m deep, 11 August 1983. The range was 10.4 km, and the hydrophones were deployed from 'Sequel'.

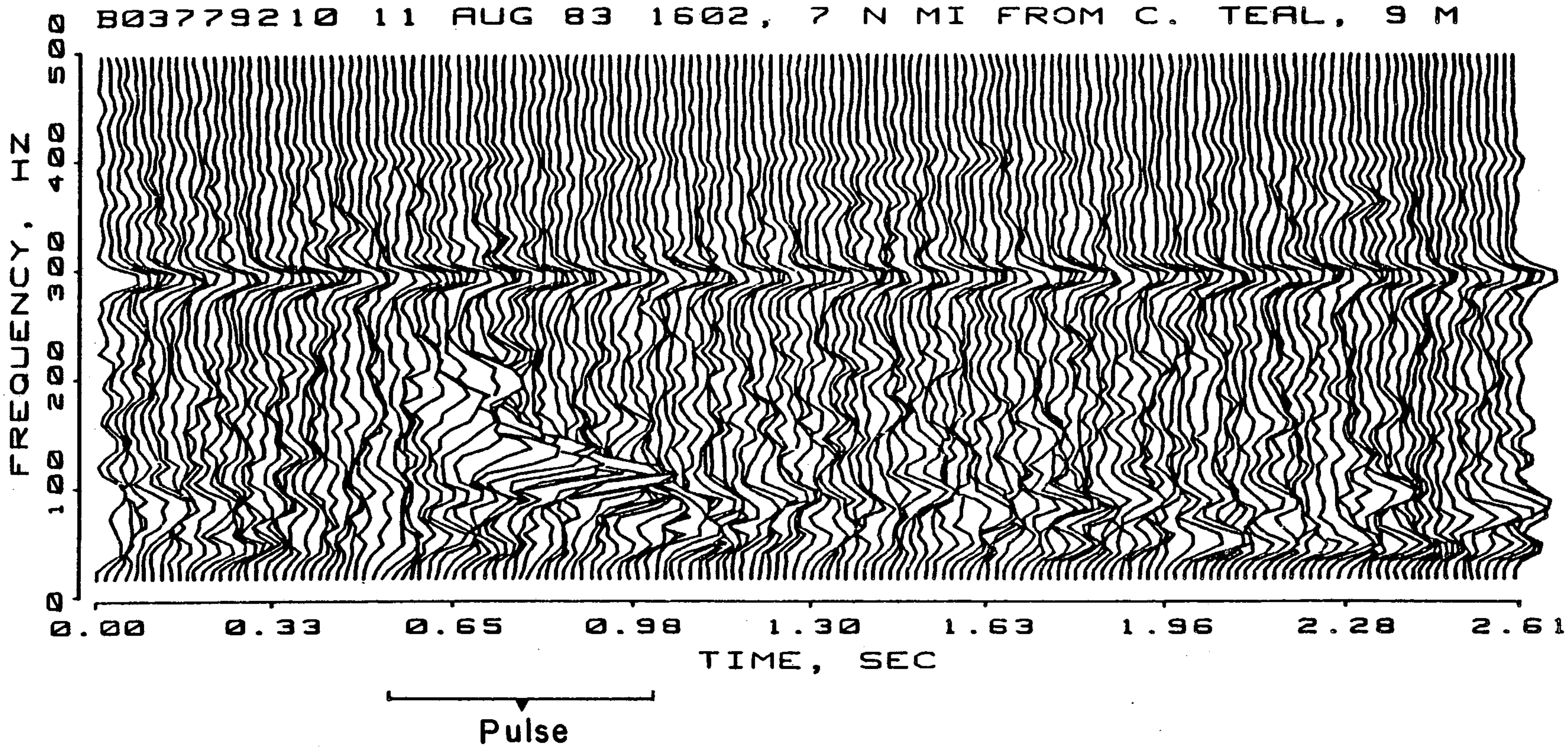


FIGURE 30. Waterfall spectral display for an airgun signal received from 'Canmar Teal' at range 13 km. The steady tone just below 300 Hz is from an unknown source. The hydrophone was deployed from 'Sequel' and was at depth 9 m.

Table 6. Effective levels (dB//1 µPa) vs. range and hydrophone depth for airgun signals from 'Canmar Teal', 11 August 1983.

Time (MDT):	07:31	08:23	14:33	15:02	16:35	16:38
Range (km):	5.9	3.0	ukn.	8.2	9.3	10.4
3 m level:	141	161	143	135	137	141
9 m level:	151	167	150	145	143	145
18 m level:	152	158	151	147	146	149

Airgun Disturbance Test, 28 August 1983. -- The Islander crew dropped two sonobuoys to monitor sounds near bowheads during a disturbance experiment with the 0.66 L (40 in^3) airgun deployed from 'Sequel'. The 'near' buoy was about 2 km from the airgun, and the 'far' buoy was about 5 km away. The water depth was about 12 and 18 m at the near and far buoys, respectively. Fifteen minutes before the experiment began, 'Sequel' was at 69°05.5'N, 137°41.2'W (Fig. 1). The airgun was fired every 15 s for 25 min, during which period the air pressure dropped from an initial 152 bars (2200 psi) to less than 35 bars (500 psi).

Table 7 presents the effective received levels at the near and far sonobuoys during four of the airgun pulses. Levels received during portions of the pulse with low and higher dominant frequency are shown separately; the higher frequency energy tended to arrive first (Fig. 31,32). Levels decreased by several decibels as the operating pressure decreased.

Table 7. Effective levels (dB//1 µPa) of signals from a 0.66 L airgun as received at near (2 km) and far (5 km) sonobuoys during a disturbance trial, 28 August 1983.

Time Within Airgun Firing Period	(a) 200 Hz*		(b) 70-80 Hz*	
	Near	Far	Near	Far
Start	131	129	138	128
Start	132	130	137	128
Middle	126	122	130	122
End	127	120	132	118

* Received level (dB//1 µPa) during portion of pulse when predominant frequency was (a) about 200 Hz, and (b) about 70 Hz.

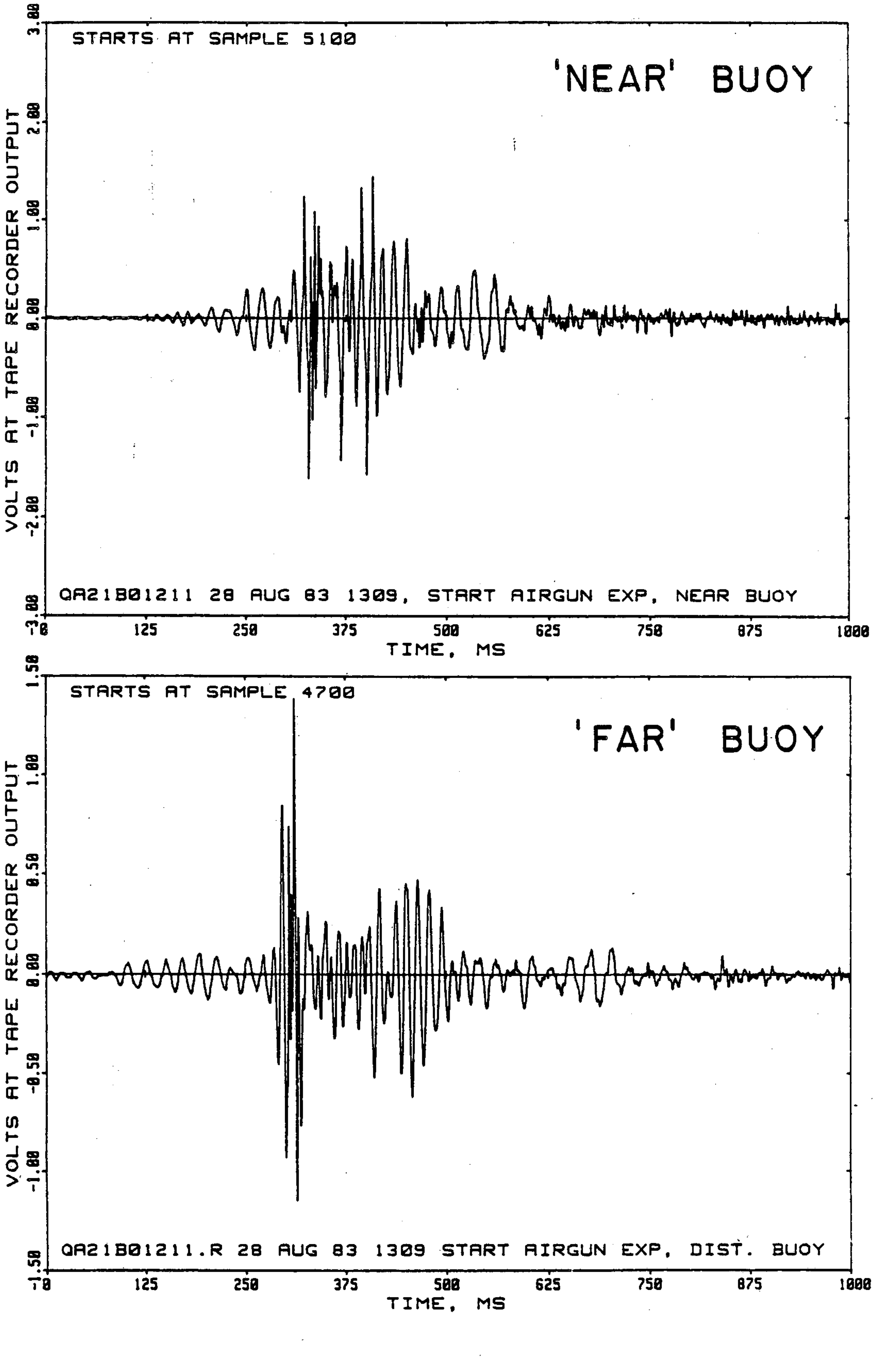


FIGURE 31. Waveforms of signals from a 0.66 L airgun as received at sonobuoys about 2 and 5 km from the source in shallow water, 28 August 1983. These waveforms are from the start of the test, when the airgun was operating at about 152 bars.

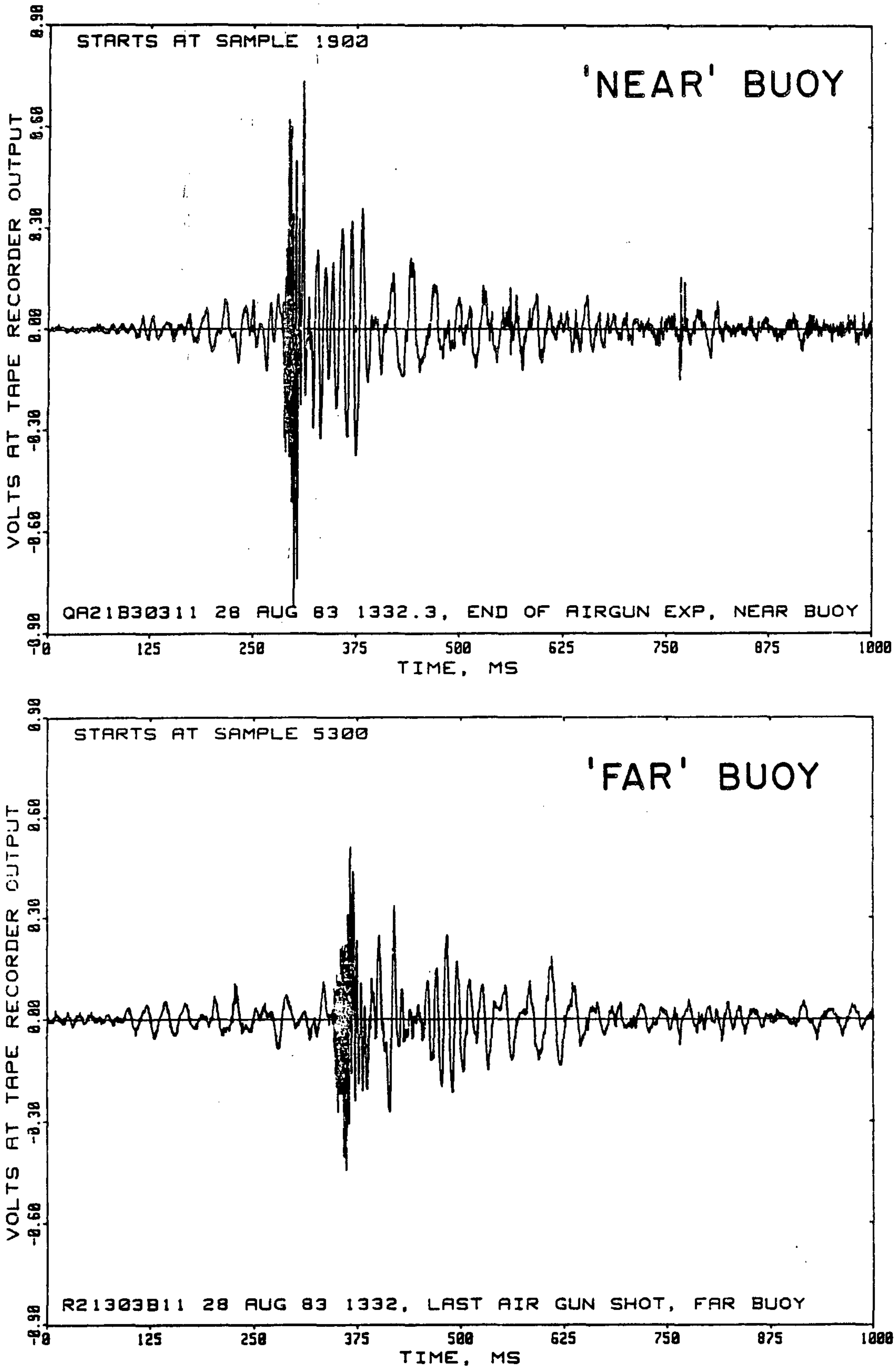


FIGURE 32. Waveforms of signals from a 0.66 L airgun as received at sonobuoys about 2 and 5 km from the source in shallow water, 28 August 1983. These waveforms are from the end of the test--airgun pressure <35 bars.

The signals received at the near sonobuoy (range 2 km) sounded slightly distorted compared to the signals at the far buoy (5 km). Also, the difference between the received levels at the two buoys was less at the start of the airgun firing period, when the signals were strongest, than at the end (Table 7). The results suggest that the signals received at the near sonobuoy at the start of the airgun firing period were too strong to be recorded with fidelity, and that their actual received level was a few decibels greater than shown in Table 7.

Figure 33 displays waterfall spectra for signals received at the near and far sonobuoys at the start of the experiment. At least three propagation modes can be seen in the waterfall for the far buoy. The first arrival is at a low frequency and has probably travelled through layers in the ocean bottom--it continues after the waterborne waves have died out. The first waterborne wave is the second arrival. It includes frequency components up to almost 400 Hz, with a low frequency peak that drops to lower frequencies with time. The third arrival is concentrated at one low frequency, but that frequency diminishes with time.

The levels received from the one airgun a few kilometres away were comparable to those from a full-scale seismic vessel a few tens of kilometres away. The frequency and temporal characteristics of the received airgun pulses were also similar to those from a distant seismic vessel.

Summary Observations, Seismic Signals in 1983. -- The most important observation in 1983 was the consistently lower received level of seismic signals at 3 m beneath the surface as compared to the level of the same signal at depth 9 or 18 m. Theory predicts that, above a certain depth, the received levels of signals originating in the water will diminish as the receiver approaches the surface. The 'certain depth' depends on the signal wavelength and is deeper for longer wavelengths (lower frequencies). Our observations in 1983 confirm that a whale at or very near the surface is exposed to lower levels of seismic noise than are present at deeper depths.

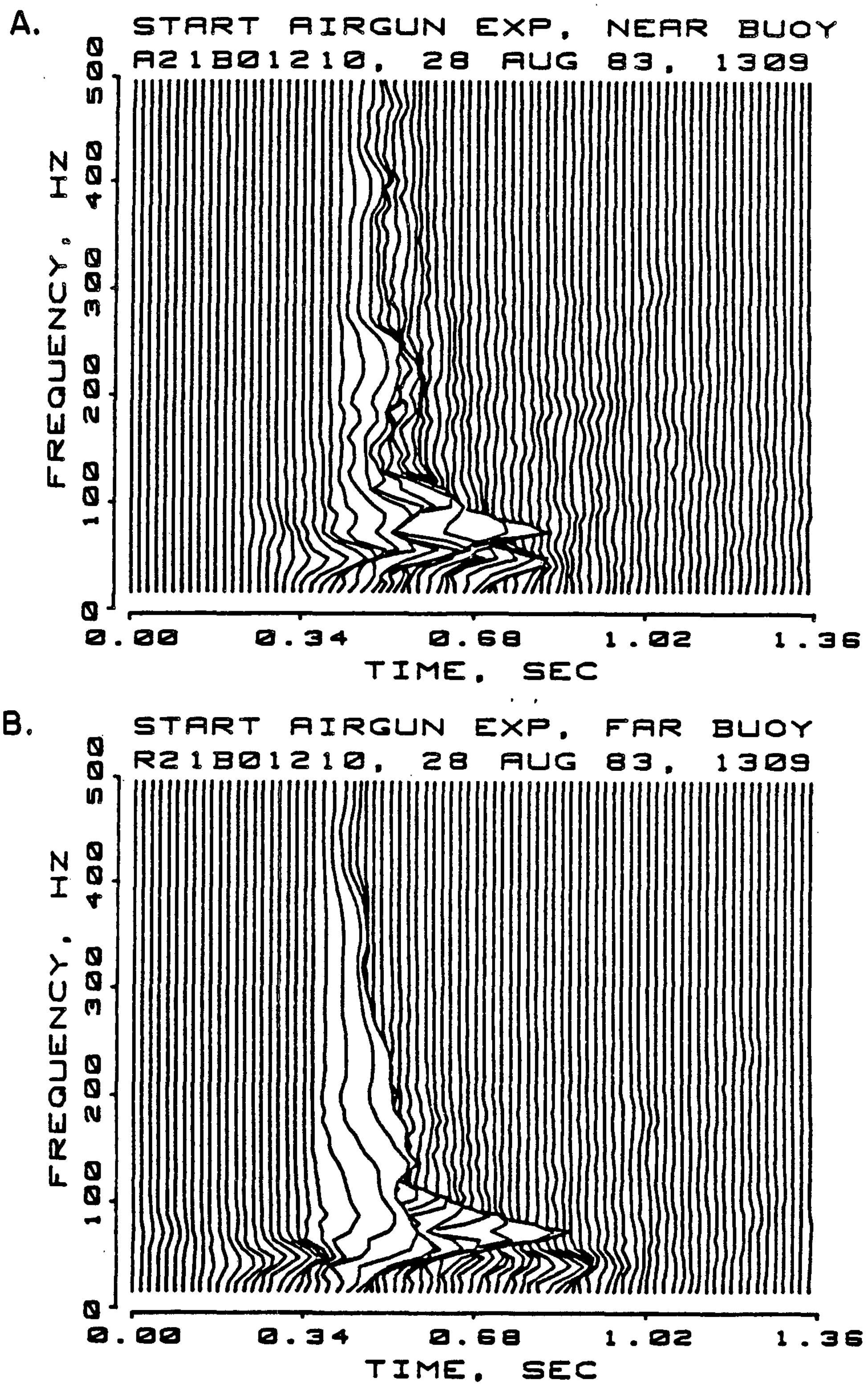


FIGURE 33. Waterfall spectral displays for airgun signals near the start of the airgun disturbance trial. **(A)** is for the near sonobuoy (range 2 km) and **(B)** is for the far sonobuoy (range 5 km).

Drillship Playback Noise

On three occasions in 1983 the sound crew on 'Sequel' was able to coordinate a drillship playback experiment with the bowhead observers aloft in the Islander aircraft. The sounds played back over the J-11 projector had been recorded in 1981 at Canmar's drillship 'Explorer II'. The drillship noise recording used in 1983 was the same one used for similar experiments in 1982. During two of the three experiments in 1983, sounds reaching the whales were monitored by sonobuoys dropped amidst the whales.

Drillship Playback Test, 18 August 1983. — 'Sequel' was anchored at 69°26.6'N, 138°31.4'W, water depth 15 m, in good weather with sea state 1 (Fig. 1). The projector, at a depth of 9 m, was turned on at 13:02 MDT at a very low level, which we gradually increased to its maximum level of 164 dB//1 µPa at 13:12. At 13:32 we began to diminish the projected level until all drillship sound was off at 13:42. The sonobuoy was about 1.2 km from 'Sequel', and the bowheads were about 0.4 km to 1.7 km from 'Sequel'.

Table 8 presents the band levels and the level of the dominant drillship tone, 275 Hz, received at the sonobuoy amongst the bowheads. During the period of peak playback level, the received level at the sonobuoy was 108-112 dB in the 10-1000 and 20-1000 Hz bands, and 104-109 dB for the strongest tone, which was at 275 Hz. These levels are similar to or slightly greater than those projected to sonobuoys 1.5-2 km from 'Sequel' during the drillship noise playback experiments in 1982 (cf. Greene 1983).

Table 8. Received levels (dB//1 µPa) at a sonobuoy during the drillship playback test on 18 August 1983.

Time	Test condition	20-1000 Hz Band Level	275 Hz Tone Level
13:07.5	5.5 min after test start	97	83
13:13	1 min after max start	108	104
13:30.7	1.3 min before max end	112	109
13:37.2	4.8 min before test end	98	94
13:44.7	Ambient after test	78	-

Figure 34 presents spectra for the signal received at the sonobuoy near the end of the period of maximum playback level and 4.8 min before the end of the test. The low levels around 100 Hz are probably due to the very shallow water; the spectrum of the signal projected from 'Sequel' did not include the 'dips' at 50-140 Hz or at about 400 Hz (cf. Greene 1982, p. 322).

Drillship Playback Test, 22 August 1983. — 'Sequel' was anchored at 69°15.2'N, 138°01.5'W, water depth 36 m, in fair weather with sea state 3 (Fig. 1). With the J-11 projector at 9 m, the test began at 14:21 MDT. The sound level was gradually increased to its maximum level of 164 db//1 µPa at 14:31. At 14:51 we began decreasing the level until the drillship sound was gone at 15:01. The sonobuoy was again about 1.2 km from 'Sequel', and the bowheads were about 0.8 to 1.8 km from 'Sequel'.

Table 9 presents the 20-1000 Hz band level and the level of the major tone at 275 Hz, as received at the sonobuoy. During the peak playback period, the received level at the sonobuoy was 112-113 dB in the 10-1000 and 20-1000 Hz bands, and 107-110 dB at 275 Hz. These values are slightly higher than were received at similar range on 18 August, perhaps because of the deeper water (36 vs. 15 m).

Table 9. Received levels (dB//1 µPa) at a sonobuoy during the drillship playback test on 22 August 1983.

Time	Test condition	20-1000 Hz Band Level	275 Hz Tone Level
11:06	Ambient (different sonobuoy)	97	-
14:29.3	0.7 min before max start	105	101
14:31.7	0.7 min after max start	113	110
14:40.1	middle of max level	112	107
14:52	1 min after max end	108	101
14:56.5	4.5 min before test end	98	93
15:03	Ambient after test	93	-

Figure 35 displays the received signal spectra just after the period of maximum transmission level began, and 4.5 min before the end of the test. In contrast to the results from shallower water on 18 August, no broad 'dips' near 100 Hz or 400 Hz were present in the spectra for the 22 August test.

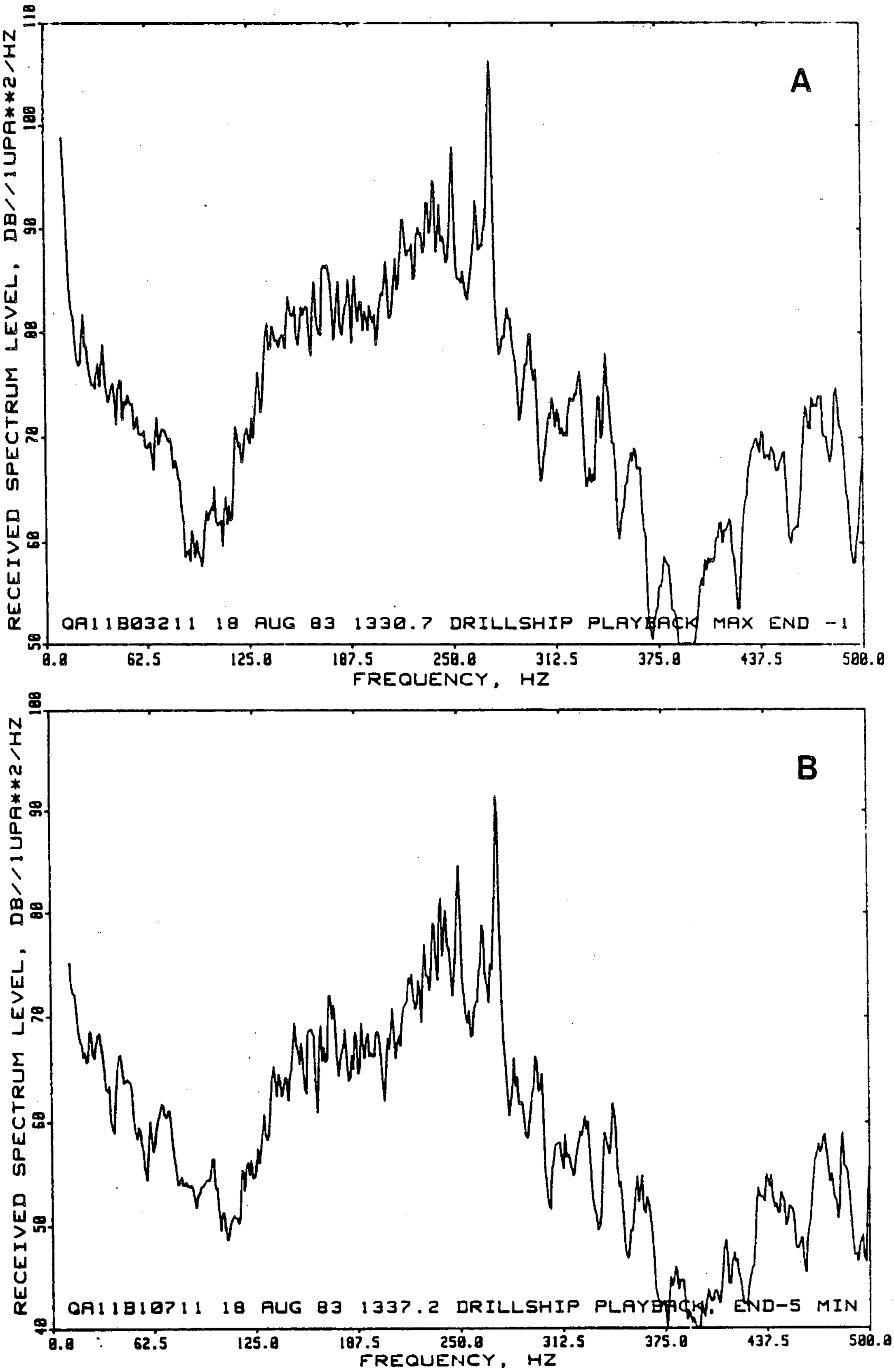


FIGURE 34. Spectra of the drillship playback signal received at a sonobuoy near bowheads, 18 August 1983. **(A)** is for a time 1 min before the end of the 'maximum level' period; **(B)** is for a time 5 min before the end of the test.

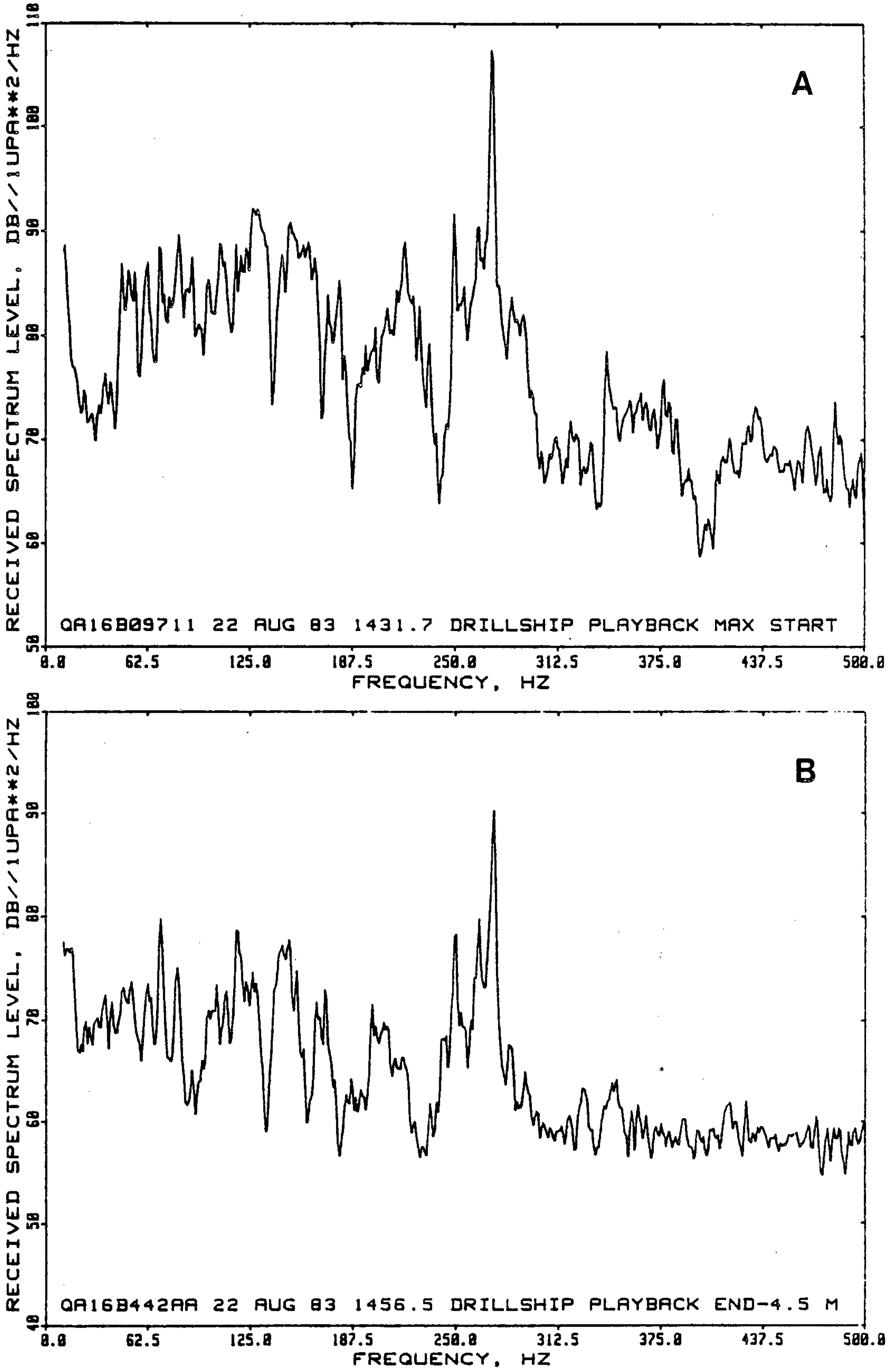


FIGURE 35. Spectra of the drillship playback signal received at a sonobuoy near bowheads, 22 August 1983. (A) is for a time just after the 'maximum level' period began; (B) is for a time 4.5 min before the end of the test.

Dredge Noise

Signals from three working dredges were recorded on 'Sequel' during August 1983: 'Cornelius Zanen', 'Aquarius', and 'Beaver Mackenzie'.

'Cornelius Zanen' at Ukalerk, 7 August 1983. — Ukalerk is a dredging site at 69°59'N, 133°10'W (Fig. 1). It is used by many hopper dredges when loading fill material to transport to various artificial island and berm construction sites. The water depth is 20 m. 'Sequel' was anchored at Ukalerk on 7 August and recorded the sounds from the suction hopper dredge 'Cornelius Zanen' picking up a load. The wind was about 20 km/h; the sea state was 2. The dredge has a load capacity of 8000 m^3, draws 8 m, transits at 15.5 knots (28.7 km/h), and has engines of 15,000 hp (11.1 MW). We were not able to establish radio contact with 'Zanen'.

We analyzed sounds recorded at ranges from 0.63 to 1.19 km while the dredge maneuvered slowly to load. The 20-500 Hz band levels for those ranges extended from 140 dB//1 μPa to 145 dB, with one exceptional level of 136 dB at a range of 0.70 km. As one might expect, the character of the sounds varied considerably during the period of loading, and at the time of the relatively low 136 dB level the sounds had faded to such an extent we thought the dredge was 'idling'. The corresponding spectrum from depth 9 m is interesting because of the family of tones spaced every 5 Hz from about 250 Hz to over 1000 Hz (Fig. 36). Such a pattern would be expected from impulsive events occurring five times per second. A plot of pressure vs. time revealed weak pulses, although in the portion of the signal we studied the rate varied around 10 pulses per second. We do not know what activity on the vessel may account for such a signal. Sounds recorded when 'Cornelius Zanen' departed Ukalerk, no longer dredging, are reported above in the section 'Boat Noise'.

'Aquarius' at Nerlerk, 12 August 1983. — 'Aquarius' is a suction hopper dredge about 90 m long and 12 m wide. At Nerlerk (70°25.8'N, 133°21.6'W, Fig. 1), the dredge operated as a transfer vehicle in a moored position, pumping bottom material through pipes to the desired berm location. Numerous vessels were nearby. When 'Sequel' was anchored 0.20 km from 'Aquarius',

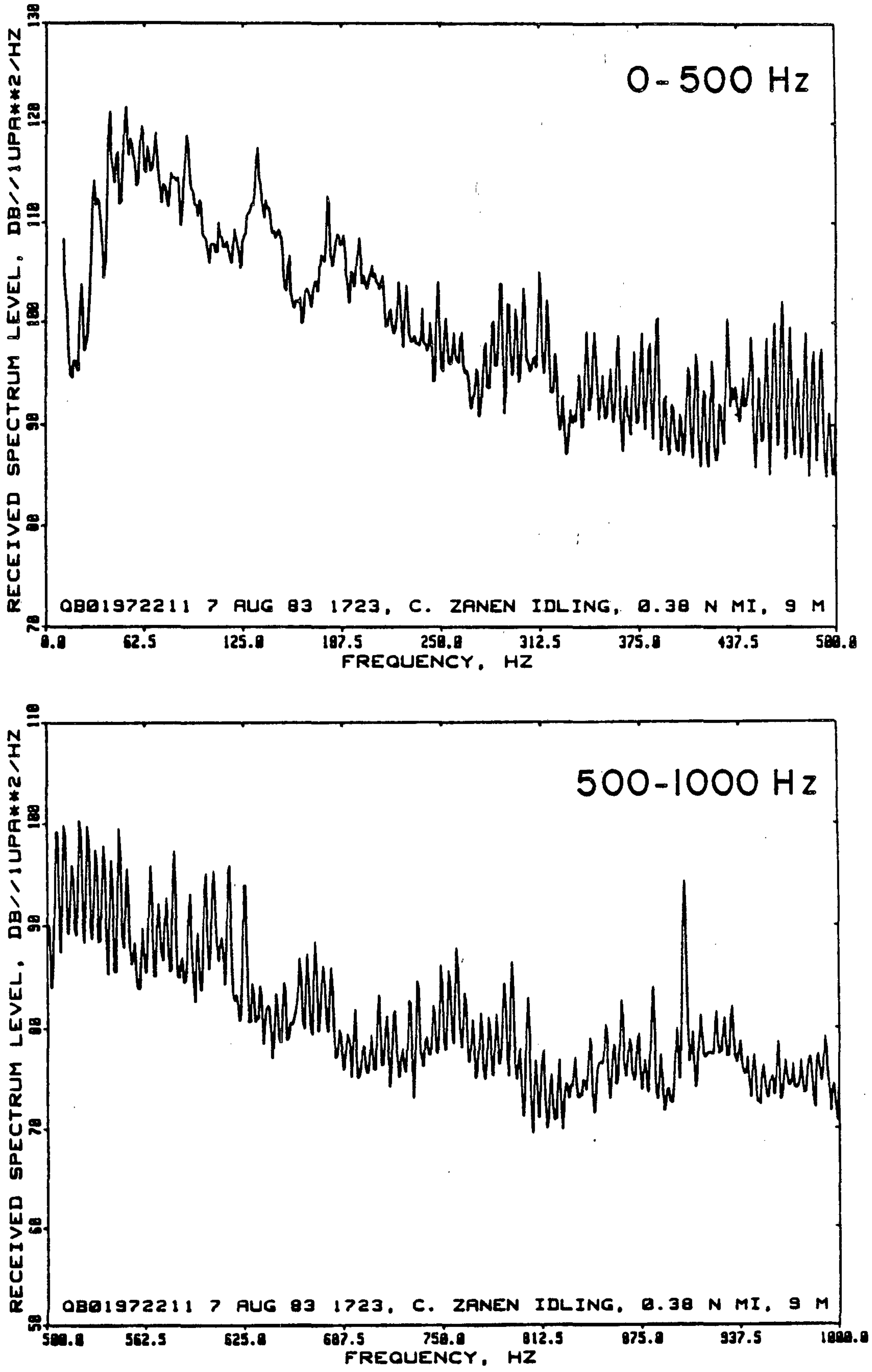


FIGURE 36. Spectra for dredge 'Cornelius Zanen' while dredging at range 0.7 km from 'Sequel'. The hydrophone depth was 9 m.

'Canmar Constructor' (a crane and camp barge) was at range 0.7 km, 'Tugger 2' was at range 0.8 km, 'Tugger 1' was at range 1.5 km, and 'Canmar Widgeon' was somewhat farther away. During the measurements, the wind was about 20-28 km/h (11-15 knots) and the sea state was 3. Water depth was 46 m near the dredge and increased to 60 m at range 14.8 km. We recorded signals from the dredge using hydrophones at depths of 3, 9, and 18 m at ranges of 0.20, 0.46, 0.93, 1.87, 3.84, 7.41, and 14.8 km.

The pattern of tones in the spectra for ranges 0.2 and 14.8 km differ (Fig. 37). This indicates that the dredge operating load or conditions probably changed during the period of measurements, which extended from about noon until 16:00. Personnel on the dredge did not report any change of operation other than to say at one time that rocks were going through the pipes and that as a consequence we might hear a rumbling sound. Machinery speeds probably changed with differing loads, resulting in changes in the tonal patterns in the signal spectra.

Sound levels for the frequency band from 20 to 500 Hz were computed from the 10-1000 Hz spectra for each range and hydrophone depth. The measured received band levels, in dB//1 µPa, were as follows:

	Depth		
Range, km	3 m	9 m	18 m
0.20	139	143	140
0.46	133	139	135
0.93	133	138	134
1.87	128	133	130
3.84	124	129	126
7.41	112	123	121
14.82	110	119	118

Consistent with theory for sound pressure interference and cancellation near the water surface (Urick 1975), the shallow hydrophone received the lowest

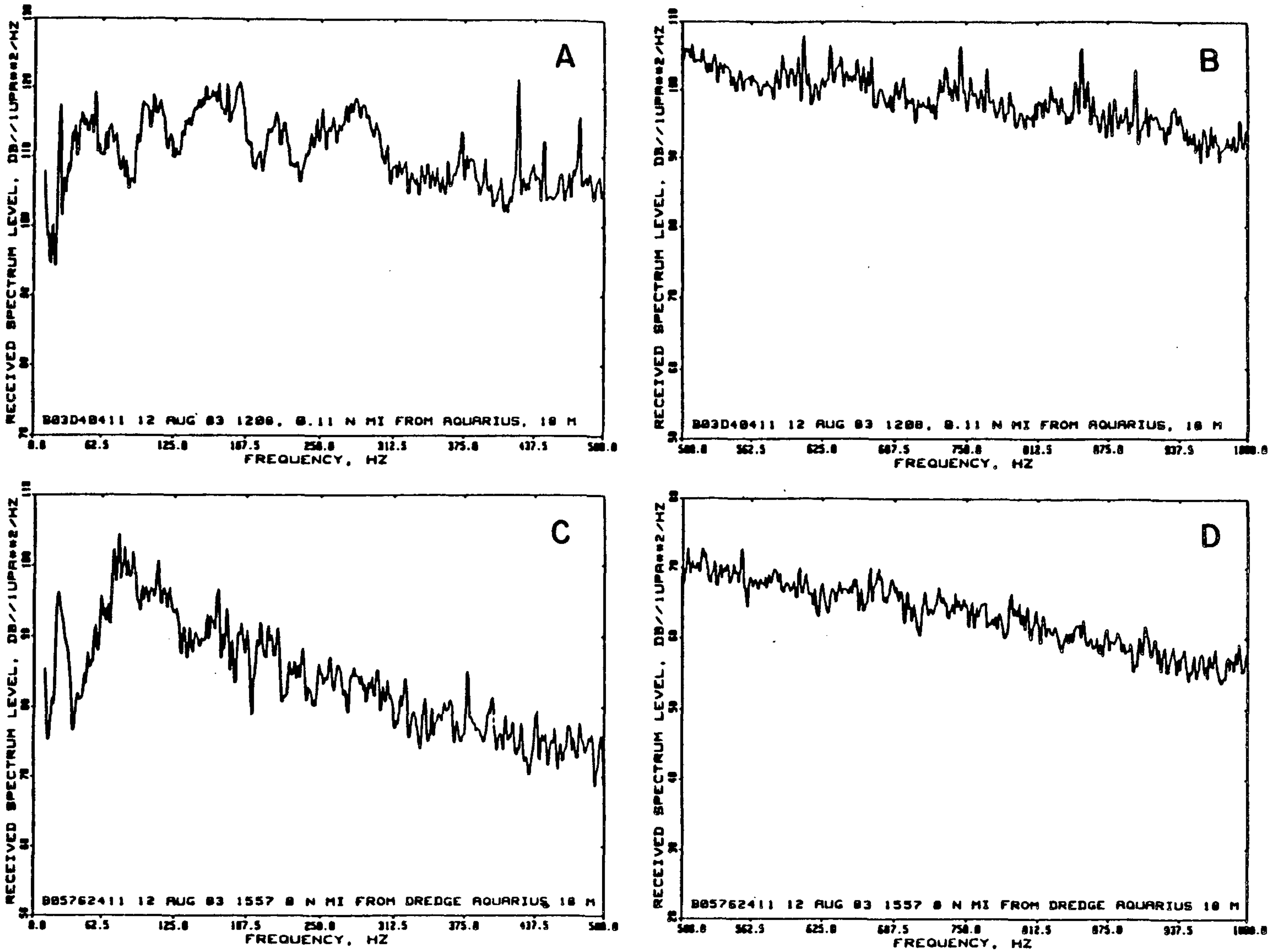


FIGURE 37. Spectra for signals from dredge 'Aquarius' working at Nerlerk. (A) and (B) are for range 0.2 km; (C) and (D) are for range 14.8 km. The hydrophone was deployed from 'Sequel'; hydrophone depth was 18 m at both ranges.

levels. It also had an unexpectedly large drop in received level between 3.84 and 7.41 km.

Regression analyses were performed with these data to derive equations for received level vs. range at each depth. The results are presented below, where RL is received level, R is range in km, r^2 is the coefficient of determination, and se is the standard error in dB. Seven data points were used for each equation:

Depth (m)	Equation	r^2	se (dB)	
3	$RL = 131.3 - 0.61*R - 11.96\log(R)$	0.96	2.9	(1)
9	$RL = 136.3 - 0.42*R - 10.14\log(R)$	0.99	1.1	(2)
18	$RL = 132.7 - 0.23*R - 10.32\log(R)$	0.99	1.2	(3)

The R term accounts for the losses due to scattering at the surface and bottom, and absorption at the bottom. The coefficients in these equations are consistent and physically reasonable. All equations include negative coefficients for the R term (received levels should decrease with increasing range), and coefficients near 10 for the $\log(r)$ terms (10 is the ideal cylindrical spreading term expected in shallow water).

Cylindrical spreading ($10\log(R)$) is expected in shallow water where the sound rays are continually reflected between the surface and the bottom. It seemed reasonable to force a $10\log(R)$ term into each regression. The results were as follows:

Depth (m)	Equation	se (dB)	
3	$RL = 131.6 - 0.82*R - 10\log(R)$	2.6	(4)
9	$RL = 136.3 - 0.43*R - 10\log(R)$	1.0	(5)
18	$RL = 132.8 - 0.27*R - 10\log(R)$	1.0	(6)

Again, RL is the received level in dB//1 μPa for the 20-500 Hz band of frequencies, R is the range in km, and se is the standard error in dB//1 μPa. The values of the coefficient of determination are not included because they are not meaningful for regression with a predetermined coefficient. The measured data and the fitted equations (4, 5, and 6) are presented in Figure 38.

The received levels from 'Aquarius' were measured with two independent variables, depth and range. There were seven ranges and three depths for a total of 21 data points. We experimented with multiple regression using various functions of range and depth as variables. The best result, in terms of having the smallest standard error, was the equation

$$RL = 122.7 - 1.07*R - 1.30*D - 10.81\log(R) + 26.57\log(D) + 0.73*R*\log(D) \quad (7)$$
$$(r^2 = 0.97;\ se = 1.7\ dB//1\ \mu Pa).$$

RL is the received level in dB//1 μPa for the 20-500 Hz frequency band, R is the range in km, D is the hydrophone depth in m, r^2 is the coefficient of determination, and se is the standard error. The net effect of the three terms involving depth is to predict a maximum received level near 10 m depth, a rapidly diminishing received level closer to the surface, and a more slowly decreasing level at depths beyond 10 m. A simpler equation with only a slightly larger standard error is as follows:

$$RL = 119.9 - 0.42*R - 1.31*D - 10.81\log(R) + 29.63\log(D) \quad (8)$$
$$(r^2 = 0.96;\ se = 2.1\ dB)$$

Such an equation should be useful in predicting sound levels vs. range and depth, at least for 'Aquarius' and associated vessels operating in waters about 50 m deep. However, for more generalized use a more sophisticated model is needed because the depth effect is expected to be a function of signal frequency. If a hydrophone is moved from the surface to increasing depths, the received level will initially increase but will later become relatively constant. The depth below which the level will become relatively constant depends on frequency, water depth and, if shallow, properties of the bottom. This 'rule of thumb' is better for deep water.

Murphy et al. (1976) report measurements of signals from ranges to 35 km in water 110 m deep using hydrophones at depths of 2 and 50 m. At

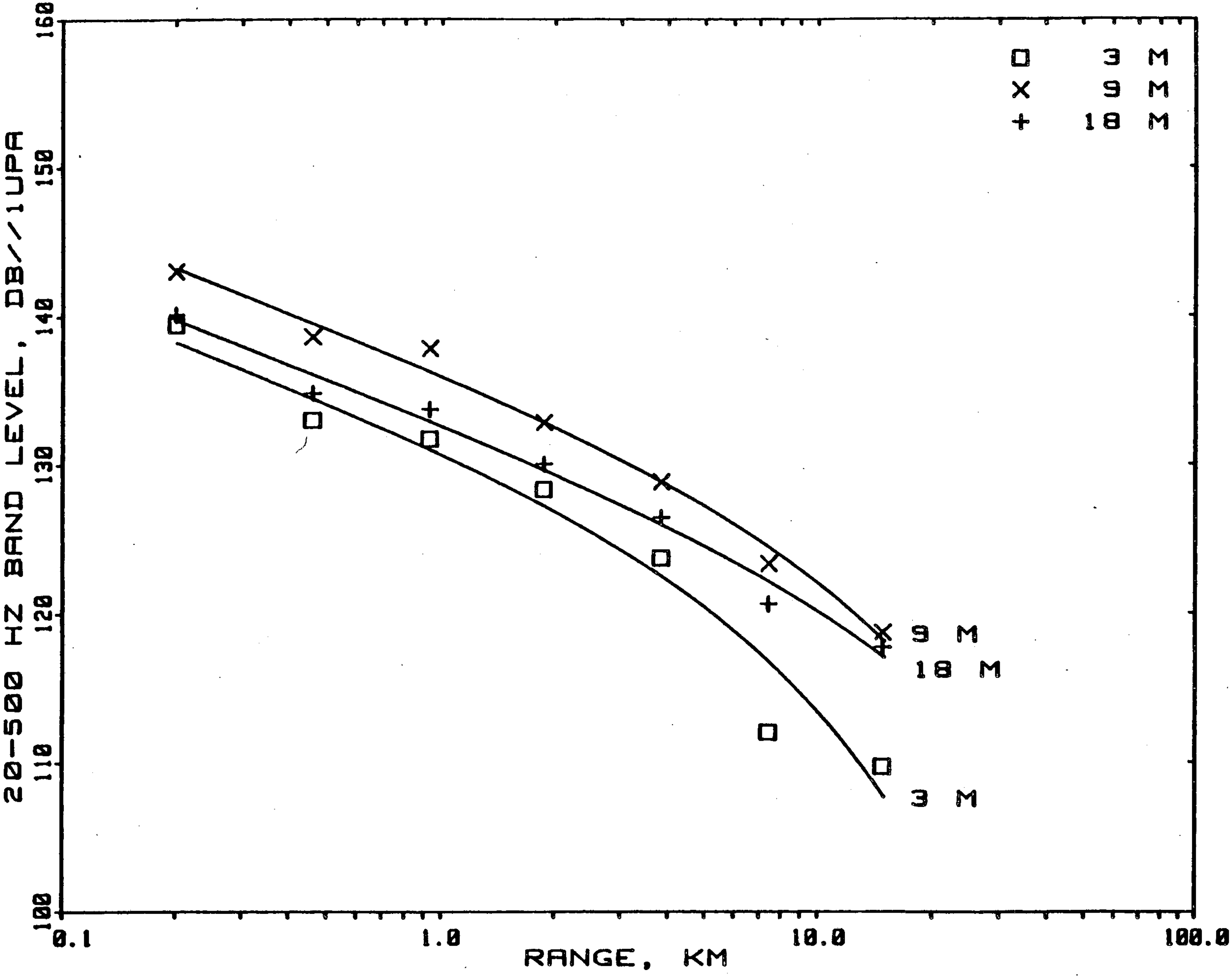


FIGURE 38. Measured received levels for the frequency band 20-500 Hz vs. range from dredge 'Aquarius' for hydrophone depths 3, 9 and 18 m. Also plotted are the fitted regression equations that assume cylindrical spreading (Eqs. 4, 5 and 6, see text).

frequencies near 100 Hz, the levels at depth 2 m were 10–20 dB less than the levels at depth 50 m for all ranges. They attributed the effects near the surface to the influence of the bottom and used mode theory to predict their measured results.

'Beaver Mackenzie' at Amerk, 13 August 1983. -- We recorded this dredge again in 1983; we had previously recorded her sounds at Issungnak Island in 1980 and at Alerk in 1981 (Greene 1982). On 13 August 1983, we recorded dredge signals on board 'Sequel' at ranges of 14.8, 3.7 and 1.9 km from 'Beaver Mackenzie'. There were often other vessels around, and measurements from range 7.4 km were not possible because of interference from other dredges.

The closest station was 1.9 km north of 'Beaver Mackenzie'. At that location, our position was 69°59.8'N, 133°31.2'W and the water depth was 29 m. The sounds were not like those of the previous recordings. More tones were recorded in 1983. The spectra in Figure 39, measured at 16:12 and 16:28 MDT, were also different (cf. Greene 1982, p. 326-336). The 20-1000 Hz band level at 16:12, 9 m hydrophone, was 112 dB//1 μPa; at 16:28 it was 111 dB. The major tone at 340 Hz at 16:12 was 93 dB; at 16:28 its frequency had shifted to 344 Hz and the level was 90 dB. Two support vessels, 'Arctic Breaker' and 'Arctic Pelly', were anchored near the dredge and reported they were operating only their generators. Other workboats idled near the dredge.

In 1981, at Alerk, this same dredge radiated tonal components at 100 Hz and at 374 Hz. The higher of these tones varied to as high as 384 Hz, indicating a changing operating condition. From the regression equation for received level of this tone vs. range, derived in 1981 for water 13-15 m deep, we expected a level of 105 dB at 1.9 km. No such tone or level was present in 1983.

The levels measured in 1983 were not a consistent function of range, either because the dredge changed operating conditions between measurements or because of interference from other vessels. At the 1.9 km range, seismic signals occurring at 6 s intervals prevented us from analyzing segments of data longer than 4 s; hence, we used a sample rate of 4096 s/s. There was

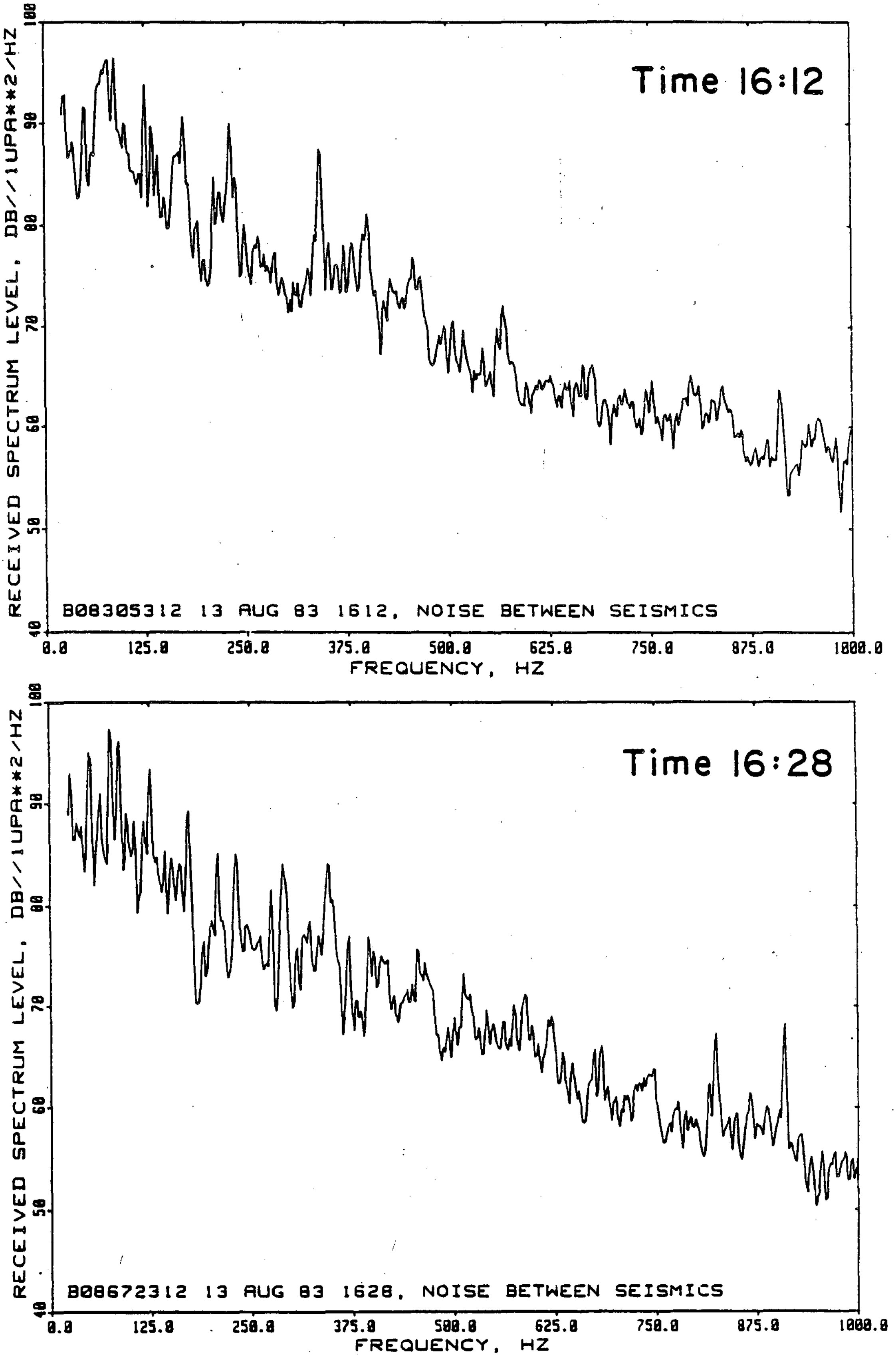


FIGURE 39. Spectra at 9 m for sounds 1.9 km from the dredge 'Beaver Mackenzie' operating at Amerk on 13 August 1983. The water depth at 'Sequel' was 26 m.

considerable noise in the 20-40 Hz band in some recordings, especially at the 3 m depth. Thus, we considered the 40-1000 Hz band. At range 1.9 km, the levels at depth 9 m were 110-113 dB//1 µPa. At range 3.7 km, the level at depth 9 m was 104 dB. At range 14.8 km, the level at depth 9 m varied from 98 to 112 dB. The levels at depth 3 m were always 4 to 10 dB below the levels at the 9 and 18 m depths.

Construction at Caisson Retained Island

Late in the evening on 16 August, 'Sequel' moved to a site 3.8 km east of Kadluk and anchored for the night. Kadluk is at 69°46.6'N, 136°00.6'W (Fig. 1). A consortium led by Esso Resources was installing its caisson retained island (CRI) at Kadluk. The CRI is a large octagonal structure that is floated into position and then ballasted down to rest on a berm previously built up by hopper dredges. The center of the caisson is then filled with dredged sand to form the drill rig platform. Kadluk was the first site where the CRI had been installed. However, it is expected to be refloated and moved to other sites in later years. The CRI had arrived at Kadluk a few days before 16 August, and by 16 August it was resting on the berm and was being filled with sand.

The water depth at the 3.8 km range was 12 m, and sounds were recorded at 23:15. The large crane barge 'Arctic Immerk Kamotik', the CRI, and the dredge 'Cornelius Zanen' were all at range 3.8 km. Another vessel, probably the barge 'Arctic Breaker', was 4.2 km distant. The smaller workboats around the construction site were not distinguishable on our radar display.

The following morning 'Sequel' moved to a range of 1.8 km from the CRI for a second sound recording. At this point the dredge 'Cornelius Zanen' was 5.4 km distant, the crane barge was 1.9 km distant, and five workboats were at ranges 1.6, 1.9, 2.6, 2.8 and 2.8 km. The water depth was 13 m.

Finally, 'Sequel' moved to 0.93 km from the CRI for the last recording at Kadluk. The water depth was again 13 m. Vessels were scattered about us; a workboat moved past us at close range, and a floating boom about 200 m from our hydrophones made an intermittent, strong, resonant banging sound. We avoided times with banging sounds and when the boat was close in analyzing data for 0.93 km range from the CRI.

The results of the measurements at these three ranges were as follows:

Range	Sound pressure level, dB//1 μPa, 40-1000 Hz band, for hydrophone depth 3 m	9 m
0.93 km	115 dB	117 dB
1.8	114	118
3.8	114	116

The apparent lack of variability with distance is an indication of the variability of the noise levels with time plus the distributed noise sources. The measured levels were not particularly high. They were similar to the levels of underwater sound from dredge 'Aquarius' at range 15 km, from dredge 'Cornelius Zanen' underway at range 5 km, and from the Britten-Norman Islander airplane during an overflight at 152 m altitude.

At the 9 m depth, the levels in the 20-1000 Hz band were essentially the same as the levels in the 40-1000 Hz band. At depth 3 m, the 20-40 Hz band levels typically were far higher and more variable than the levels for the 40-1000 Hz band. For instance, at the 0.93 km, 1.8 km and 3.8 km ranges, the 20-40 Hz band levels were 137 dB, 110 dB, and 129 dB, respectively. We attribute the high levels and the variability to the effects of surface waves, as such higher levels were often observed for the 3 m hydrophone in recordings made throughout the field trip.

Bowhead Breaches and Tailslaps

Sounds from whale activities at the water surface were recorded from a sonobuoy on 22 August 1983. The buoy was at 69°07'N, 137°40'W, water depth 19 m, sea state 1. The active whale was estimated to be 30 whale-lengths (about 450 m) from the sonobuoy. Würsig et al. (1984) described the breaching and tailslapping behavior on this occasion. Table 10 presents the effective levels, measured in the same manner we measured the levels of seismic signals, for five breaches and five tailslaps. Received levels from breaches and tailslaps were very similar.

Table 10. Effective levels of sounds of bowhead breaches and tailslaps as received at a sonobuoy about 450 m away, 22 August 1983.

Time	Type of Sound	Level, dB//1 μPa
10:26	breach	115
10:26	breach	115
10:28	tailslap	111
10:28	tailslap	114
10:28	tailslap	118
10:29	tailslap	118
10:29	tailslap	107
10:31	breach	118
11:00	breach	115
11:01	breach	116

The breach sounds were always at a low nominal frequency, between 40 and 100 Hz (e.g. Fig. 40A). The tailslap sounds were at higher frequencies (Fig. 40B), always over 100 Hz and twice over 300 Hz. This difference in frequency is also evident on waterfall spectral displays (Fig. 41). The frequency scales in Figures 41A and 41B are different, but the differences in energy distribution with frequency are manifest. The breach sound is concentrated at frequencies below 100 Hz, while the tailslap sound extends above 600 Hz.

DISCUSSION

The 1983 measurements of waterborne sound augmented our knowledge in several areas, most importantly those having to do with the received levels of seismic survey signals from a variety of source vessels and with the sounds from the Islander overhead at various altitudes and power settings. The new information about relative levels of many types of signals as received at depths of 3, 9 and 18 m is also significant.

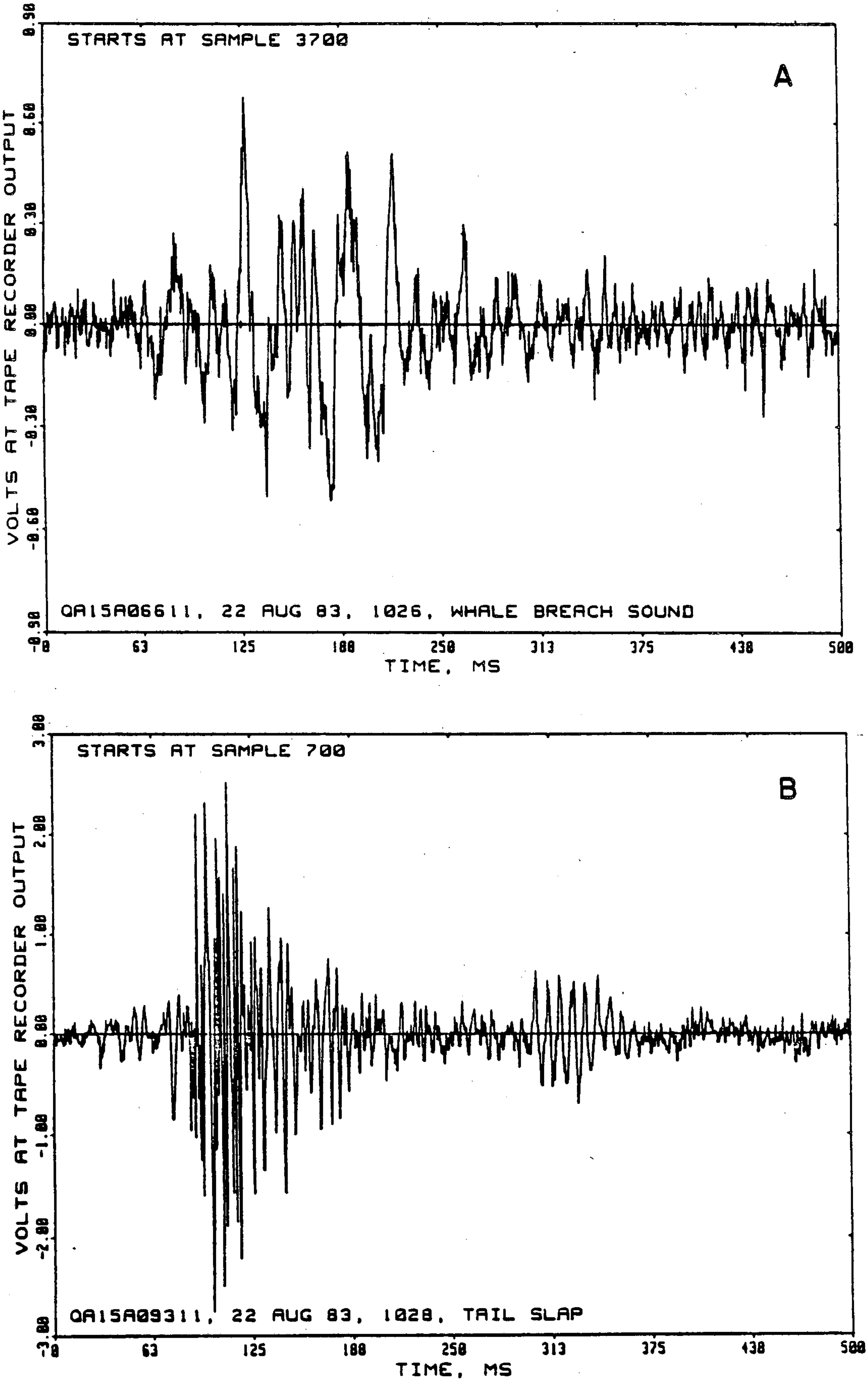


FIGURE 40. Waveforms of the sounds of (A) a bowhead breaching, and (B) a tail slap received at a sonobuoy in water 19 m deep, 22 August 1983.

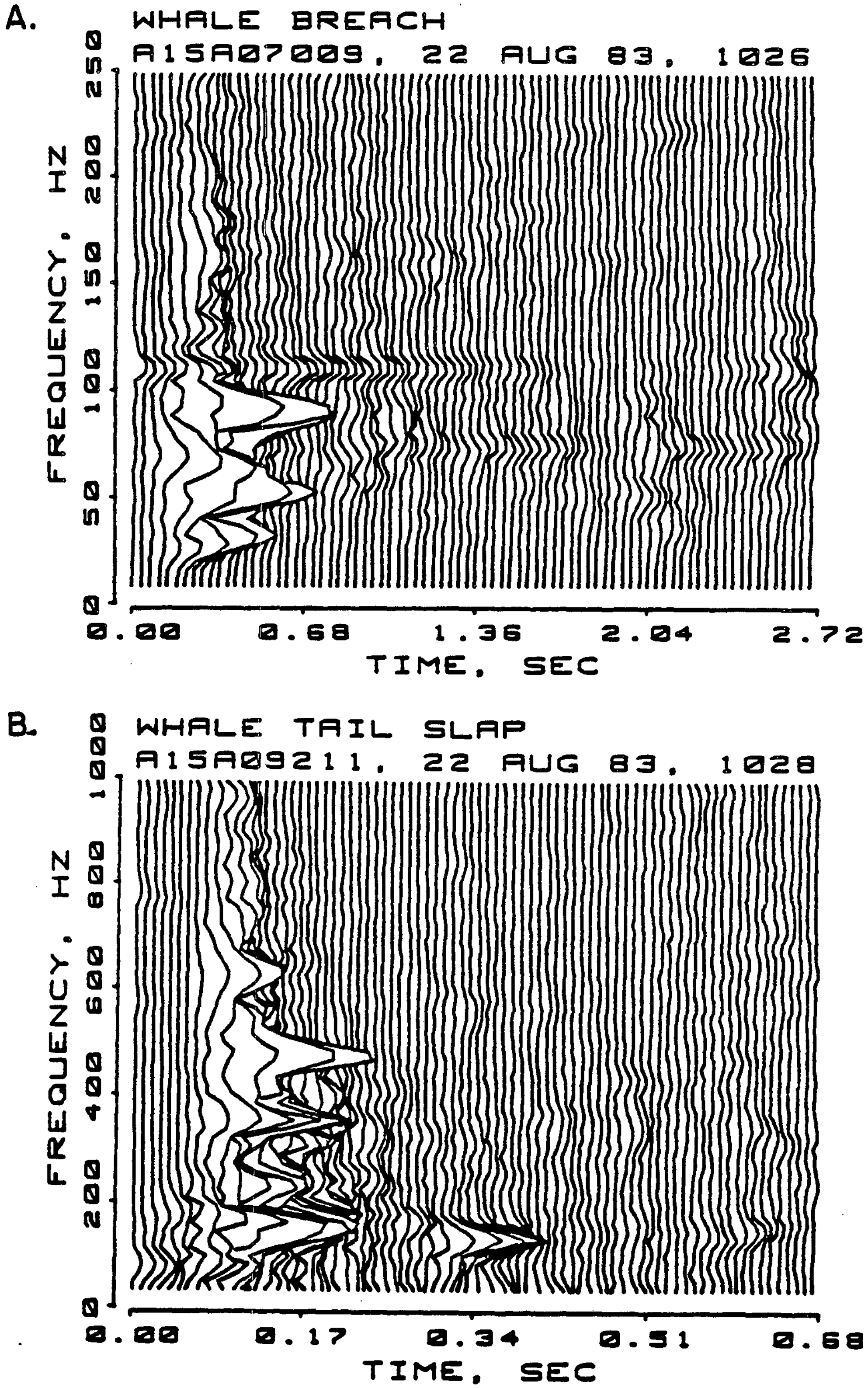


FIGURE 41. Waterfall spectral displays for sounds from (A) a whale breach, and (B) a whale tail slap. The tones at about 70 and 110 Hz in the breach waterfall probably came from the Islander.

Ambient noise has not been studied systematically in any year of this project, but we have analyzed some recordings from each field season to assess the background and to provide points of comparison with industrial noises. In 1980, a sonobuoy recording proved to have sound spectrum levels 10 to 15 dB below the widely accepted fiducial of 'Knudsen sea state 0' extended to low frequencies (Knudsen et al. 1948). This recording was purposefully selected from a quiet time. In 1981, ambient levels were determined from eight hydrophone recordings obtained in the general area of industrial activities. Even though the nearest known noise sources were as much as 15 km away, and the sea states were low, the levels were always above 'sea state zero' and tones were present. In 1982, the four reported ambient analyses, from both sonobuoys and 'Sequel' hydrophones, all provided levels above 'sea state zero'. In this report, for 1983, eight diagrams present pairs of ambient noise spectra. In five cases spectrum levels are above the fiducial, one is close, and two are below. The lowest (Fig. 6), from a sonobuoy recording on 18 August 1983 and on the order of 0 to 10 dB below 'sea state zero', was in water 12 m deep with the hydrophone on the bottom. Recordings of noises were not feasible during storms, when the background levels are expected to be extraordinarily high. Ambient noise levels higher than any that we recorded certainly do occur in the Beaufort Sea. In summary, the Beaufort Sea during the open water season can exhibit a wide range of background noise levels comparable to those seen in any of the world's open oceans.

Depth dependence of the ambient noise was measured in 1983. At frequencies below 20 Hz, spectrum levels at depth 3 m were often higher than those recorded simultaneously at 9 and 18 m. We attribute this effect to the action of surface waves. At other frequencies the ambient noise appeared to be independent of hydrophone depth.

Previous measurements of aircraft noise during this project included data from a Bell 212 helicopter, the Britten-Norman Islander used in the bowhead behavior studies, and a Twin Otter (Greene 1982). In this report we have added data from a Sikorsky 61 helicopter, another Twin Otter, and the same Islander but in a more comprehensive series of overflights at different altitudes and power settings over water 15 m deep. The Sikorsky 61 at altitude 1067 m was not detected, either audibly or in a spectrum analysis. During a pass at altitude 152 m, the Sikorsky 61 did not fly directly over 'Sequel', but we received a tonal component at 102 Hz that was not present in the ambient noise. Its level, 95 dB//1 µPa, was low for such a low altitude. The noise from the Bell 212 helicopter was considerably stronger; its dominant tone was at 20 Hz, level 109 dB during a pass at 152 m altitude. This difference may or may not be real, depending on how much stronger the noise from the Sikorsky 61 would be if it passed directly overhead. We suspect that underwater noise from the Sikorsky 61 would be less than that from the Bell 212 under comparable conditions, despite the fact that the Sikorsky 61 is a larger helicopter.

The 1983 Twin Otter measurement came from a sonobuoy when the aircraft flew overhead at altitude 457 m while circling whales (a condition of reduced power setting, relative to a cruise condition). In 1981 the Twin Otter blade rate tone level was measured twice when the aircraft flew over at cruise power and altitude 457 m. Received levels of the blade rate tone at 82 Hz were 99-102 dB in each case, based on 4 s averaging.

The Islander noise measurements in 1980 came from flights over a sonobuoy in water 14.5 m deep with the hydrophone on the bottom. The measurements in 1983 were over essentially the same water depth but the hydrophones were at 3 and 9 m depths. The observed levels for the dominant blade rate tone near 70 Hz were higher in 1983--101 and 103 dB for aircraft altitude 457 m, as compared to 93 dB in 1980. The lower levels in 1980 perhaps occurred because the hydrophone was on the bottom, or because of a lower power setting in 1980, or both. The Islander results from 1983 were also noteworthy in confirming that received levels of aircraft noise are higher just below the surface (3 m depth) than at deeper depths. In contrast, sounds from various in-water sources (seismic ships, dredges, etc.) were more intense at 9 and 18 m than at 3 m.

Sounds from two ships and three boats were recorded in 1983; four of these had not been recorded previously. Noise from the geophysical survey vessel 'Canmar Teal' was moderate compared to the noise from the larger vessel 'Cornelius Zanen'. The generator noise from 'Arctic Sounder', a small survey vessel at anchor in 11 m of water, was relatively weak. Noise from 'Imperial Sarpik', a crewboat operating at high speed, was relatively strong, comparable to the noise observed from the crewboat 'Imperial Adgo' in 1980. Noise from 'Sequel' appears to have changed from that in 1981-82. A family of strong tones, related to the propeller shaft rate, has appeared in Sequel's radiated noise spectrum. These tones were not present in 1981 or 1982.

With one exception, the seismic signals analyzed for 1983 were recorded as received by sonobuoys. We have pointed out in previous reports that overload and distortion sometimes occurred when strong seismic pulses were received with sonobuoys. Reeves et al. (1983) have reported that sonobuoys overload and distort signals whose pressures exceed levels on the order of 124 to 140 dB, depending on frequency and type of sonobuoy. Many of the received levels computed for seismic signals in 1983 fall within the suspect range.

Noise from the large airgun array on 'GSI Mariner' was stronger when received at range 80 km on 7 August than at 57 km on 9 August; the best estimates of the levels are 131 dB from 80 km and 123 dB from 57 km. The water depths at both the sonobuoy and the 'Mariner' were greater on 7 August (210 m and 150-190 m, respectively) than they were on 9 August (210 m and 20 m). Evidently the shallow water accounts for the lower sound pressure even though the range was significantly shorter. Seismic signals received from 'Arctic Surveyor' on 31 August, range about 52 km and shallow depths, spanned a great range of levels from less than 107 dB (noise limited) to 128 dB. Levels of signals received from 'Western Aleutian' on 1 September were 120 to 136 dB, even though the range varied only between 31 and 26 km. These values may be underestimated because of the limitations of the sonobuoy system. However, rapid attenuation of the signals would be expected because the water depths near 'Western Aleutian' and the sonobuoy were shallow, less than 40 m. All of these results support the observation that the levels of seismic signals received from long ranges are influenced not only by range, but also by other factors.

The levels from the single 0.66 L airgun deployed from 'Sequel' during a disturbance trial were stronger by about 10 dB at 2 km than at 5 km.

Furthermore, the signal level received from the same size airgun at 5 km range in a 1981 experiment (Greene 1982) was in the middle of the range of received levels for 5 km in 1983. However, the test at 3 km range in 1981 showed a received level of only 118 dB, which is 12 dB below the lowest level observed at 2 km and just equal to the lowest level at 5 km in 1983. This anomalous result may be at least partly attributable to signal overload in the 1981 measurements.

Measurements of noise levels received from the small airgun array on 'Canmar Teal' also depended on more than just the range. These measurements were made with data recorded from hydrophones on 'Sequel' and were not distorted. The highest levels (167 dB) were seen at the closest range (3.0 km) but the levels at 10.4 km were stronger than those from 9.3 km. The seismic signals from 'Canmar Teal' were recorded on hydrophones at depths 3, 9 and 18 m. Received levels at 3 m depth were 4 to 10 dB less than at 9 m. The levels at the 9 and 18 m hydrophones were not so different. At the closest range, 3.0 km, the signal at 18 m depth was weakest and the signal at 9 m depth was stronger by 9 dB. This was anomalous.

We recorded noise from the dredge 'Beaver Mackenzie' for the third time in 1983. The results from 1980 and 1981 appeared to be comparable, but in 1983 the signals appeared to be weaker and the characteristic tones of 1980-81 were missing.

The suction hopper dredge 'Cornelius Zanen' was new to the Beaufort Sea in 1983 and we were able to record its sounds during dredging at Ukalerk. At ranges from 0.63 to 1.19 km the sound level in the 20-500 Hz band was usually between 140 and 145 dB. These levels compare with a level of 141 dB, 10-500 Hz, from dredge 'Geopotes X' at range 0.43 km, measured in 1982 at Ukalerk.

Our most detailed measurements of dredge sounds in 1983 involved the suction hopper dredge 'Aquarius' operating in a transfer mode (moored in place, transferring sand from the bottom near the ship to a berm construction site) at Nerlerk. We had not studied the sounds from this dredge previously. Over ranges from 0.2 to 14.8 km, we measured sound levels between 143 and 118 dB in the 20-500 Hz band at hydrophone depths of 9 and

18 m. Regression analysis revealed that the relationship between received level and range could be closely approximated by assuming cylindrical spreading loss (i.e., a 10log(R) term) plus a linear loss term of 0.43 dB/km at 9 m depth and 0.27 dB/km at 18 m depth. The equation fits the data well, with a standard error of 1 dB. At hydrophone depth 3 m, the received levels were 139 to 110 dB at ranges 0.2-14.8 km. These values were a few decibels lower than the levels at 9 and 18 m, as predicted by theory. Regression analysis for depth 3 m revealed cylindrical spreading plus a linear loss of 0.82 dB/km, standard error 2.6 dB. In previous years we have also found that propagation loss in the shallow waters of the eastern Beaufort Sea involves a cylindrical spreading term plus a linear term (Greene 1982, 1983).

The 'Aquarius' data allowed us, for the first time during this project, to derive a relationship for received level in terms of both depth and range. The range-dependent terms included -10.81*log(R) (almost cylindrical spreading) and -0.42 dB/km. The depth-dependent terms included +29.63*log(D) and -1.31 dB/m. The net effect of the depth terms is to predict a reduced received level just below the surface relative to that farther down in the water. Based on our measurements of received sounds from 'Aquarius', 'Beaver Mackenzie' and 'Canmar Teal', this reduction in received level near the surface appears to be a general phenomenon when the noise source is in the water and the noise frequency is low. This effect was expected for physical reasons (Urick 1975), but it had not been demonstrated previously in our study area.

ACKNOWLEDGMENTS

During the field experiments several people helped with the underwater sound work. Mr. W. Koski of LGL operated the sonobuoy receivers and tape recorder on the aircraft. Peter Thomas, Gary Miller and Dr. Roger Payne, biologists on 'Sequel', helped with the deployment of sound equipment. Len Pearson, skipper of 'Sequel', was outstanding in his operation of the vessel and his support of our technical work. The radio operators at Dome Petroleum's 'Tuk Base' were patient and gracious in handling radio traffic from 'Sequel', as were the operators on Dome's drillships and Gulf Canada's marine base at Herschel Island. Field personnel with Dome, Gulf Canada, and

Esso Resources were all helpful in apprising us of their activities and cooperating with our efforts to measure industrial sounds.

Fred Jodrey at Bedford Institute of Oceanography provided the 0.66 L airgun for use in the airgun disturbance test and Geophysical Service Inc. in Inuvik generously repaired it for us.

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Dr. W. John Richardson of LGL, responsible for the overall conduct of the project, was most helpful and effective in the field season planning and coordinating the operations of 'Sequel' and the Islander. His editing of this report has enhanced it significantly. I am grateful for his support. I also thank D. Richardson and H. Hogarth for typing, B. DeLong for drafting the map, and R. Evans and C. Holdsworth for helping with the figures; all are with LGL Toronto. Helpful comments on the draft manuscript were provided by Drs. C.W. Clark and R.A. Davis, and by Minerals Management Service.

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DISTRIBUTION OF BOWHEADS AND INDUSTRIAL ACTIVITY, 1983*

By

W. John Richardson[1], Pamela Norton[2] and C. Robert Evans[1]

[1]LGL Ltd., environmental research associates
44 Eglinton Ave. W.
Toronto, Ont. M4R 1A1, Canada

[2]LGL Ltd., environmental research associates
2453 Beacon Ave.
Sidney, B.C. V8L 1X7, Canada

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ABSTRACT

A preceding section on 'Disturbance Responses of Bowheads' examined short-term behavioral responses of summering bowheads to activities associated with offshore oil exploration. However, the behavioral approach cannot determine whether these activities result in long-term displacement. This section summarizes the distribution of bowheads summering in the Canadian Beaufort Sea in 1983. It then discusses whether, over the past few years, there have been any distributional changes attributable to oil exploration. This report is an update of a corresponding analysis of data from 1980-82 (Richardson et al. 1983a).

Methods. -- Sightings of bowheads during this and other studies conducted in the Canadian Beaufort Sea from 1 August to 10 September 1983 are compiled here onto a series of maps by 10-d periods. Survey routes are also shown on these maps. For each 10-d period, we include a map showing the sites of offshore drilling, dredging, etc., along with the approximate number of boat trips along each route. Additional maps show locations of seismic lines and low-energy sounding, helicopter traffic, and ice conditions.

We use the phrase 'main industrial area' to refer to the region off the Mackenzie Delta where there is island construction, drilling, dredging, and intensive boat and helicopter traffic. Seismic exploration occurs over a wider area, and noise from distant seismic exploration is detectable over a still wider area.

Results in 1983. -- In 1983, as in 1982, most bowheads remained outside the main industrial area. In early August, bowheads were found far offshore just east of the Alaska-Yukon border and far north of Herschel Island. These whales were far outside the main industrial area, but were exposed to noise from distant seismic exploration. There were only a few sightings in more easterly parts of the Beaufort Sea.

In mid and late August, there was a dense concentration of several hundred bowheads, most if not all subadults, in shallow water along the Yukon coast southeast of Herschel Island. These whales were not exposed to much industrial activity. In mid and late August there were also some bowheads in

shallow water in the main industrial area, plus a few far offshore near the Alaska-Yukon border. In addition, during late August bowheads were widely dispersed off Cape Bathurst and the Tuktoyaktuk Peninsula, mainly outside the industrial area.

In early September, there were many widely dispersed whales off the Tuktoyaktuk Peninsula, outside the main industrial area but probably exposed to distant seismic noise. Whales had left the Yukon coast by 6 September, and few were present in the main industrial area.

Discussion. -- Qualitatively, bowhead numbers in the main industrial area in 1980-83 were 'many, some, very few and few', respectively. We consider the difference between 1982 (very few) and 1983 (few) to be insignificant. Thus, the trend for reduced utilization of the main industrial area identified from the 1980-82 data continued in 1983.

Intense offshore industrial activity began in the central part of the main industrial area in 1976. In that area, limited data on bowheads were obtained in 1976-79. Bowheads were numerous there in the summers of 1976 and 1977, not numerous in 1978 or 1979, very numerous in 1980, less so in 1981, and not numerous in 1982 or 1983. The reappearance of many whales in 1980, after being scarce for two years, makes it questionable whether the trend toward reduced utilization of the main industrial area was attributable to industrial activity. However, the intensity of offshore industrial activities has increased gradually since 1976, and industry may have begun to affect bowhead distribution since 1980.

In 1980-83, seismic exploration occurred over much of the Canadian Beaufort Sea--both within and beyond the main industrial area. Numerous bowheads were in areas with seismic exploration in 1980-82. Fewer bowheads were in such areas in 1983, but many whales were apparently exposed to noise from distant seismic vessels. There was a possible trend for reduced numbers of bowheads in areas where they were exposed to intense seismic noise in previous years, but there were important exceptions to this trend.

Bowhead distribution in summer may or may not be influenced by industrial activities, but some whales still do enter the main industrial area and other areas with seismic exploration. Aside from possible industrial effects, bowhead movements probably depend strongly on the distribution and abundance of zooplankton. Until zooplankton dynamics and resultant effects on bowheads are better understood, it will be difficult to assess whether changes in bowhead distribution are partly in response to industrial activities.

INTRODUCTION

The main focus of the study reported in this volume has been the short-term behavioral reactions of bowheads to actual and simulated industrial activities. Behavioral responses are studied primarily because a positive response provides an immediate indication that the whales may be sensitive to the industrial activity. We have studied the behavior of bowheads in the presence of aircraft, boats, seismic exploration, drillships and dredging (Fraker et al. 1982; Richardson et al. 1983c, 1984).

The long term reactions of the bowhead population to offshore industrial activity are ultimately of greater concern than are short term behavioral responses. 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. All of these medium to long term effects are difficult to detect. Even if detected, it would be difficult to determine whether they were attributable to industrial activity rather than to some form of natural variation.

The one type of long term effect on bowheads that might be detectable from data now being collected is displacement from parts of the traditional range. Aerial surveys provide the type of comprehensive information about bowhead distribution that can be used in detecting changes in distribution. This technique has been used extensively to detect seasonal changes in distribution during spring and autumn migration around Alaska and during the summer in the Canadian Beaufort Sea. If continued over a period of years, aerial surveys could show whether long term changes in distribution had occurred.

By 1980, when detailed studies of Western Arctic bowheads in their Canadian summering areas began, full-scale offshore oil exploration had been underway there for some years. Drilling from artificial islands in very shallow nearshore waters off the Mackenzie Delta began in the early 1970's. Drillships began to work farther offshore in 1976, and an artificial island was constructed in water 13 m deep in that year. The intensity of offshore industrial activity has generally increased since 1976. By the end of the 1983 open water season, there were five drillships, two active drilling caissons and one inactive caisson, six suction and hopper dredges, ten helicopters, four industry-owned icebreakers, and many other support vessels operating offshore in the southeastern Beaufort Sea.

Systematic aerial surveys of the Canadian summer range of Western Arctic bowheads began in 1980. Previous non-systematic sightings suggested that most bowheads spend the early summer in Amundsen Gulf and the extreme eastern part of the Canadian Beaufort Sea--east of the area of offshore oil exploration (Fig. 1)--and then move westward off the Tuktoyaktuk Peninsula, Mackenzie Delta and Yukon coast in August and September, often in shallow water (Fig. 2; Fraker and Bockstoce 1980). The aerial surveys in 1980-82 showed that many bowheads occur in the areas of most intense industrial activity at certain times in certain years. At other times, bowheads are very scarce in the industrial area. Furthermore, the systematic surveys in 1980-82 showed major year to year differences in summer distribution (Renaud and Davis 1981; Davis et al. 1982; Harwood and Ford 1983).

Richardson et al. (1983a) summarized the available information about distribution of summering bowheads in relation to industrial activities. For each 10-day period in the late summers of 1980-1982, they mapped the aerial survey routes and the sightings of bowheads. They included not only the above-cited systematic surveys, but also the survey routes and sightings during various other studies of bowheads, including the 1980-82 phases of this behavioral study. Richardson et al. (1983a) also compiled maps, for the same 10-d periods in 1980-82, of vessel and helicopter traffic, active offshore sites, seismic exploration, and ice conditions. The very limited available data on bowhead distribution in the summers of 1976-79 were also summarized. Richardson et al. then assessed whether there were any consistent trends in the summer distribution of bowheads during the 1980-82 period, and whether the trends could be related to industrial activities.

From 1980 through 1982, bowheads became progressively less common in the 'main industrial area', i.e. the area of island construction, drilling, and intense boat and helicopter traffic. This suggested the possibility that

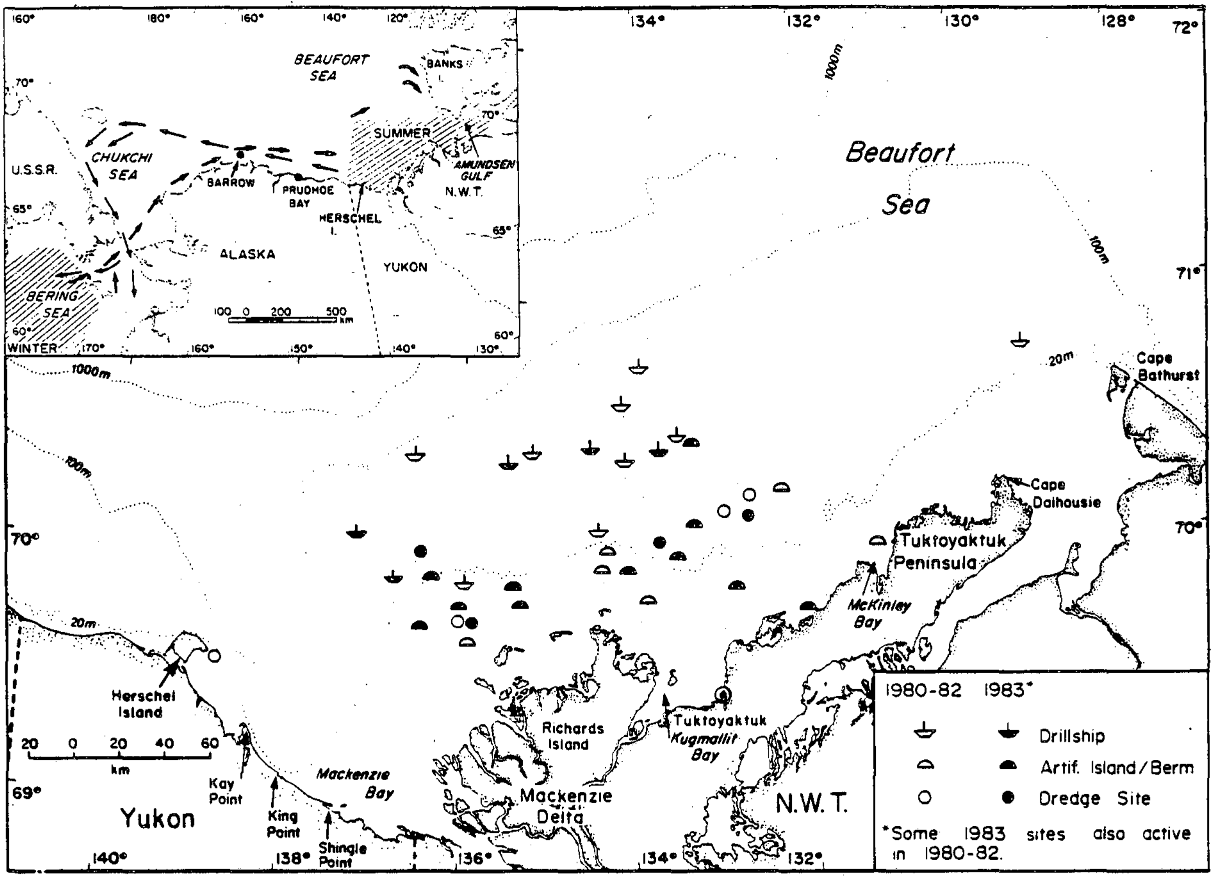

FIGURE 1. The eastern Beaufort Sea--study area for this project--showing the main sites of offshore industrial activity in August and early September 1983 (solid symbols) and 1980-82 (open symbols). **Inset:** Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

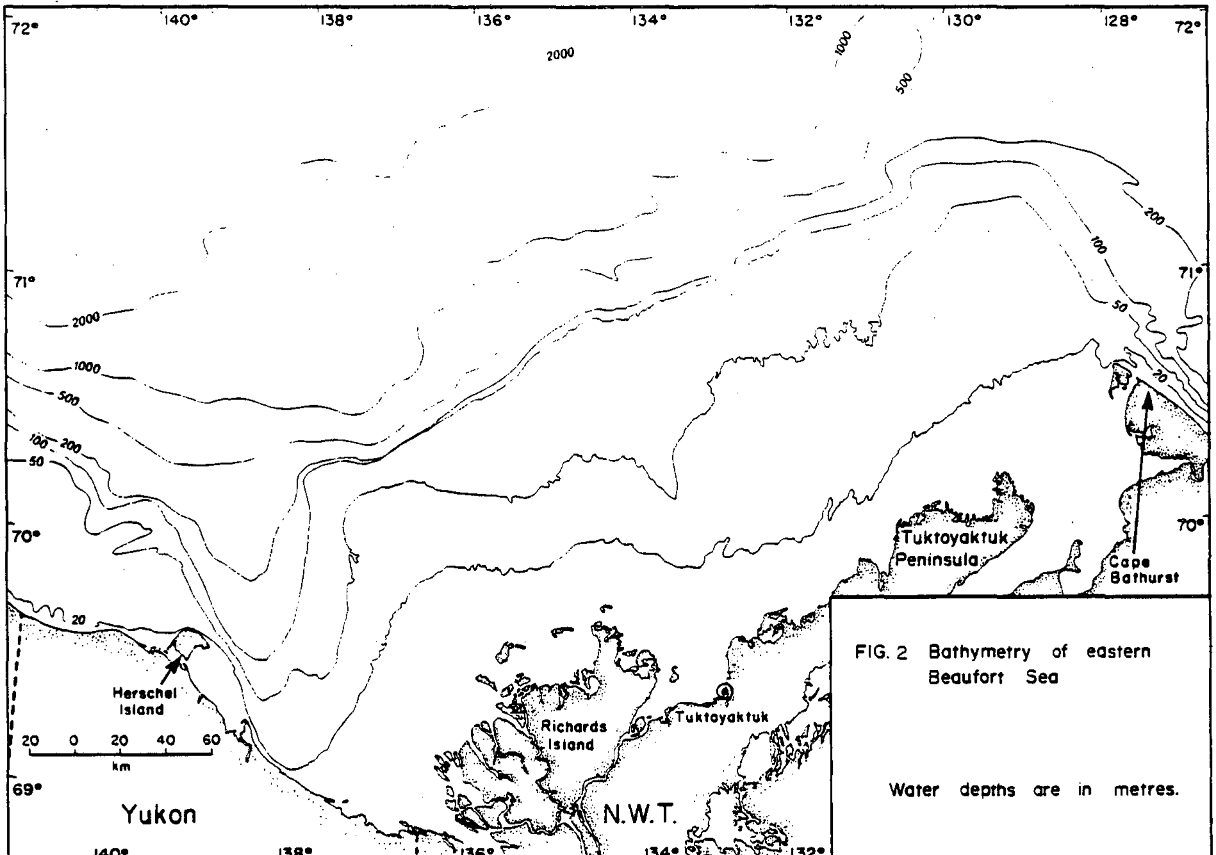

FIG. 2 Bathymetry of eastern Beaufort Sea

Water depths are in metres.

bowheads were being progressively excluded by the ongoing and intensifying level of offshore industrial activity. However, this possibility could not be proven from the available data. The limited data from 1976-79 suggested that there had been considerable variability in distribution in that period as well, and that large numbers of whales had entered the main industrial area in 1980 after a 2-yr period (1978-79) of scarcity in that area. Thus, the decline in numbers in the industrial area in 1980-82 might be a result of natural variability in bowhead distribution, unconnected with industrial activity.

The lack of information about natural factors that may affect the distribution of summering bowheads, or their zooplankton prey, was recognized as a serious problem in attempting to interpret the data on bowhead distribution (Richardson et al. 1983a). Variables that could be important in affecting bowhead distribution, directly or through effects on zooplankton, might include the variable volume and movement of fresh water from the Mackenzie River, the variable distribution of ice, and variable hydrographic phenomena at the shelf break and ice edge.

In the absence of an understanding of natural factors affecting bowhead distribution, one approach for determining whether industrial activities might be at least partly responsible for year to year variation in bowhead distribution is to continue monitoring distribution over a period of years. If many bowheads return to the main industrial area in future years, then it is likely that industrial activity was not the main factor responsible for the decreasing number of whales in that area over the 1980-82 period. However, if bowheads remain scarce in the main industrial area in subsequent years, it will become increasingly likely that industrial activity is at least partly responsible for displacing bowheads from a major part of their summer range.

The present report compiles the available data on the distributions of bowheads and industrial activities in the eastern Beaufort Sea in the late summer of 1983. The scope, procedures and format are the same as in our previous compilation of data for 1980-82. The objectives are (1) to compile these data into a useful format while they are still readily accessible, and

(2) to use the results, in conjunction with data from previous years, to reassess the possibility that bowheads are avoiding the area of offshore oil exploration in the eastern Beaufort Sea. This analysis of possible medium-term effects complements our study of short-term behavioral reactions to industrial activities (Richardson et al. 1984), 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.

METHODS AND DATA SOURCES

Information about bowhead distribution in the eastern Beaufort Sea is available from early August to early September 1983. Hence, we include maps for four 1/3 month periods in 1983: 1-10, 11-21 and 22 to 31 August, and 1-10 September. These correspond to periods used in our similar compilation of data from 1980-82 (Richardson et al. 1983a). We did not attempt to compile information about industrial activities before 1 August or after 10 September, when there was little or no information about bowheads. Bowheads are infrequent in the area of intense industrial activity off the Mackenzie Delta before late July and after early September (Fraker and Bockstoce 1980; Richardson et al. 1983a).

Bowhead Sightings

For each 10 or 11 day period (hereafter referred to as 10-d period), we present one or two maps showing all aerial survey routes and bowhead sightings known to us. One map shows sightings during non-systematic searches for bowheads. For two periods when systematic aerial surveys were done, a second map shows the results of those surveys.

Non-systematic surveys of bowheads summering in Canadian waters in 1983 were conducted during three projects: our behavior study for MMS; a bowhead photography study by Cascadia Research Collective; and the Naval Ocean System Center's work in Alaska, some of which extended into Canadian waters.

During the behavior study, we searched for bowheads in areas from the shore northward beyond the continental shelf, and from the Alaskan border (141°W longitude) east beyond Cape Bathurst (128°W). Figure 1 shows the study area and locations mentioned in this text. Offshore flight time totalled 113.6 h and spanned the period 1 August to 1 September. During the first half of August we searched widely within the study area, but thereafter almost all effort was in and near Mackenzie Bay, i.e. between the Mackenzie Delta and Herschel Island. General procedures are given elsewhere in this volume (Würsig et al. 1984; Richardson et al. 1984); flight routes and sighting locations are mapped here.

On behalf of the U.S. National Marine Fisheries Service, Cascadia Research Collective covered much of the same area during August and early September 1983 while searching for whales to be measured and identified by photogrammetry. In early August their only flight over Canadian waters was far offshore from the Yukon coast. From mid August to early September their survey effort expanded into offshore waters from Herschel Island east beyond Cape Bathurst. Their coverage extended farther north and east than any other survey coverage in 1983 (Cubbage et al. 1984). Information from their report has been augmented with unpublished data about survey dates and numbers of bowheads seen (J.C. Cubbage, pers. comm.) and re-mapped into our standard format.

The Naval Ocean Systems Center (NOSC), on behalf of the U.S. Minerals Management Service, conducted large scale aerial surveys for bowheads in the Alaskan Beaufort Sea in the summer and autumn of 1983. In August, several NOSC flights extended east of 141°W, although rarely beyond Herschel Island. In early September, some flights extended as far east as Richards Island and as far north as 72°N latitude. Our maps include the flight lines and bowhead sightings obtained in Canadian waters during all but two of NOSC's flights (unpubl. data courtesy of D.K. Ljungblad, NOSC). These NOSC data were obtained from two Grumman 'Super Goose' twin-engine amphibian aircraft and a deHavilland Twin Otter aircraft. Flight lines were not available for surveys conducted in Canadian waters by the Twin Otter aircraft on 8 and 9 September.

Systematic Surveys. — On behalf of the 'Environmental Studies Revolving Fund', McLaren and Davis (1984) conducted two extensive, systematic surveys of the eastern Beaufort Sea on 19-24 August and 6-11 September 1983. They flew north-south lines spaced 20 km apart from the Alaska-Yukon border to the eastern end of the Tuktoyaktuk Peninsula (total of 23 lines during the first survey and 24 lines during the second). Most lines extended from near shore north to 25 km or more beyond the 100 m depth contour. Thus, McLaren and Davis surveyed the main industrial area plus additional areas to the west, north and east. The surveys were conducted using a deHavilland Twin Otter aircraft equipped with bubble windows and flying at altitude 152 m. We have re-mapped their results into our standard format. For clarity, we present their results on maps separate from those showing results of the non-systematic surveys.

Procedures for Compiling Data. — The 1983 data have been compiled using the same conventions as were used for the 1980-82 data (Richardson et al. 1983a). All aircraft used for the surveys had accurate Very Low Frequency (VLF) navigation systems. With very few exceptions, the flight routes and sighting locations were precisely known. Because many flights were not systematic surveys with defined transect widths, we have mapped all sightings, whether or not they were classified as on- or off-transect in the original reports. The exact number of whales seen at each location could not be shown in compact format. Instead, 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 within a 10-d period were so close together that their symbols overlapped broadly, they are shown as a single symbol.

On the main map for each 10-d period, we have used a format that differentiates sightings and routes during the first 5 days from those during the next 5 or 6 days. Triangular symbols and dashed lines are used for days 1-5; circles and solid lines are used for days 6-10 or 6-11. This level of detail is rarely needed for the broad-scale interpretations in this report. However, it may be useful for other purposes.

In some 10-d periods, there was so much aerial survey activity near the Yukon coast 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.

The maps based on non-systematic surveys provide only a qualitative indication of the relative abundance of bowheads in different areas, and therefore must be interpreted with caution. Survey procedures differed between 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 were undoubtedly counted more than once in a 10-d period, especially in areas where there was much survey coverage.

Offshore Industrial Sites and Vessel Movements

The second type of map presented for each 10-d period shows the offshore locations where industrial activities were concentrated, and the number of vessel movements along each route. The main activities at specific offshore sites were dredging, island construction or maintenance, drilling from drillships, and island clean-up. (There was no drilling from islands during our 1983 study period.) Most of these activities are shown by separate symbol types. However, underwater berms have not been differentiated from islands on these maps; the same symbol type is used for berms and islands. The activity is mapped even if it occurred on only 1 day within the 10-d period.

Vessel traffic, excluding seismic and sounding operations, is shown on the same maps. The approximate number of vessel trips along each route is shown by the thickness of the line. Procedures used in tabulating and mapping vessel movements were the same as in 1980-82 (Richardson et al. 1983a, p. 284). The maps do not record every vessel movement, and the mapped routes are approximations. However, the maps are indicative of the relative amounts of traffic in various offshore areas and periods. Characteristics of underwater noise from several of the vessels were described by Greene (1982, 1983, 1984).

Seismic Exploration and Sounding

The third type of map for each 10-d period in the late summer of 1983 shows locations where seismic and sounding vessels operated. Procedures used in compiling information about seismic exploration were the same as those used for 1980-82 (Richardson et al. 1983a). Solid lines depict geophysical surveys shot by three vessels using large arrays of airguns--the 'GSI Mariner', 'GSI Explorer', and 'Western Aleutian'. Dashed lines depict surveys by the 'Arctic Surveyor', a vessel with an array of 12 open-bottom gas guns. Additional symbols show lines shot by 'Canmar Teal', a vessel using a small array of airguns. The characteristics of these vessels and of the sounds they produce are summarized by Greene (1983, 1984) and by Richardson et al. (1983c, 1984). Locations of low-energy sounding operations are also shown on our maps.

The exact locations of the seismic lines and (for most lines) the dates on which they were shot were kindly provided by Geophysical Service Inc., Western Geophysical Inc., Gulf Canada Resources Inc., and Esso Resources Canada Ltd. (No seismic lines were shot specifically for Dome Petroleum Ltd. during the period of interest in 1983.) Supplementary information was obtained from our records of the locations and dates in 1983 when seismic vessels were seen at sea during the behavior study.

In recent years there has been much seismic exploration in the eastern part of the Alaskan Beaufort Sea during late summer. In 1983, seismic exploration began there in mid August. Many of these seismic lines extended east to 141°W longitude, the nominal western edge of our study area, and some extended a few kilometres farther east. These 'Alaskan' seismic lines are close to the western edge of our maps. We did not attempt to include them in either our 1980-82 analysis or in this report. Seismic lines that crossed 141°W but also extended far to the east are included on our maps.

Helicopter Movements

A fourth type of map presented for each 10-d period shows the offshore industrial sites and the number of helicopter trips along each offshore route. The information was obtained from Dome, Esso and Gulf records, and mapped using the same procedures as in 1981-82. 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. Offshore flights by fixed-wing aircraft are also excluded.

Ice Conditions and Bathymetry

Ice conditions in each 10-d period are shown on the helicopter traffic maps. These maps distinguish areas of open water, 1-30% ice cover, 31-79% cover, and 80+% cover. We prepared these maps from the Weekly Composite Charts compiled by Ice Forecasting Central, Atmospheric Environment Service, 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.

The 100-m depth contour is shown on all vessel traffic maps. Figure 2 is a more detailed bathymetric map, based on the International Map of the World--Firth River sheet, and Dome Petroleum Ltd. map E-BFT-100-03. In most parts of the study area, water depths increase very gradually out to the 100 m contour, and then increase rapidly. The 100 m contour is 110-140 km offshore from the Mackenzie Delta and Tuktoyaktuk Peninsula, but only 25-70 km offshore from most points along the Yukon coast. The 100 m contour is within 10 km from the shoreline at two locations within the study area--off the east sides of Herschel Island and Cape Bathurst.

RESULTS

The results appear in Figures 3 to 21. Abbreviated names of offshore locations mentioned in the text are given on Figure 4 or, if not present there, on the first vessel traffic map where that site appears.

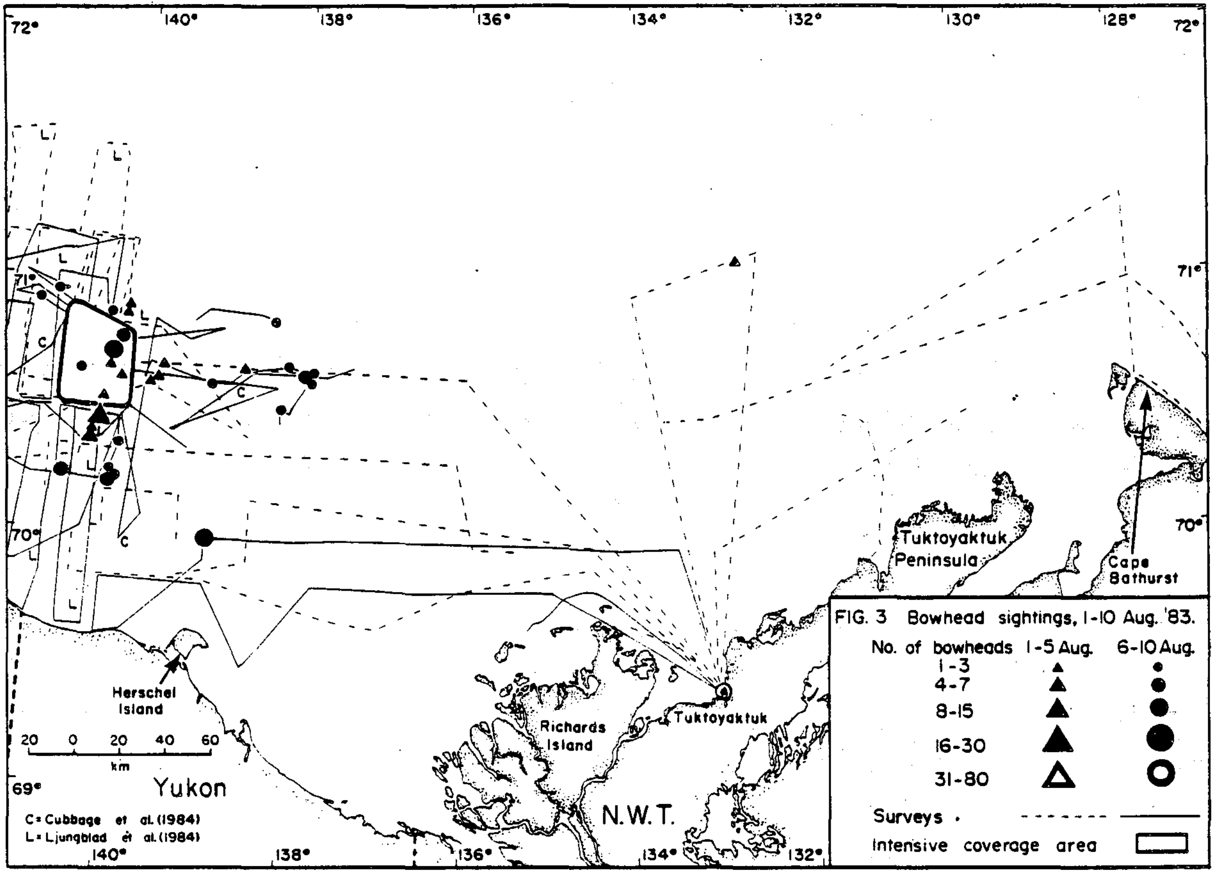

FIG. 3 Bowhead sightings, 1-10 Aug. '83.

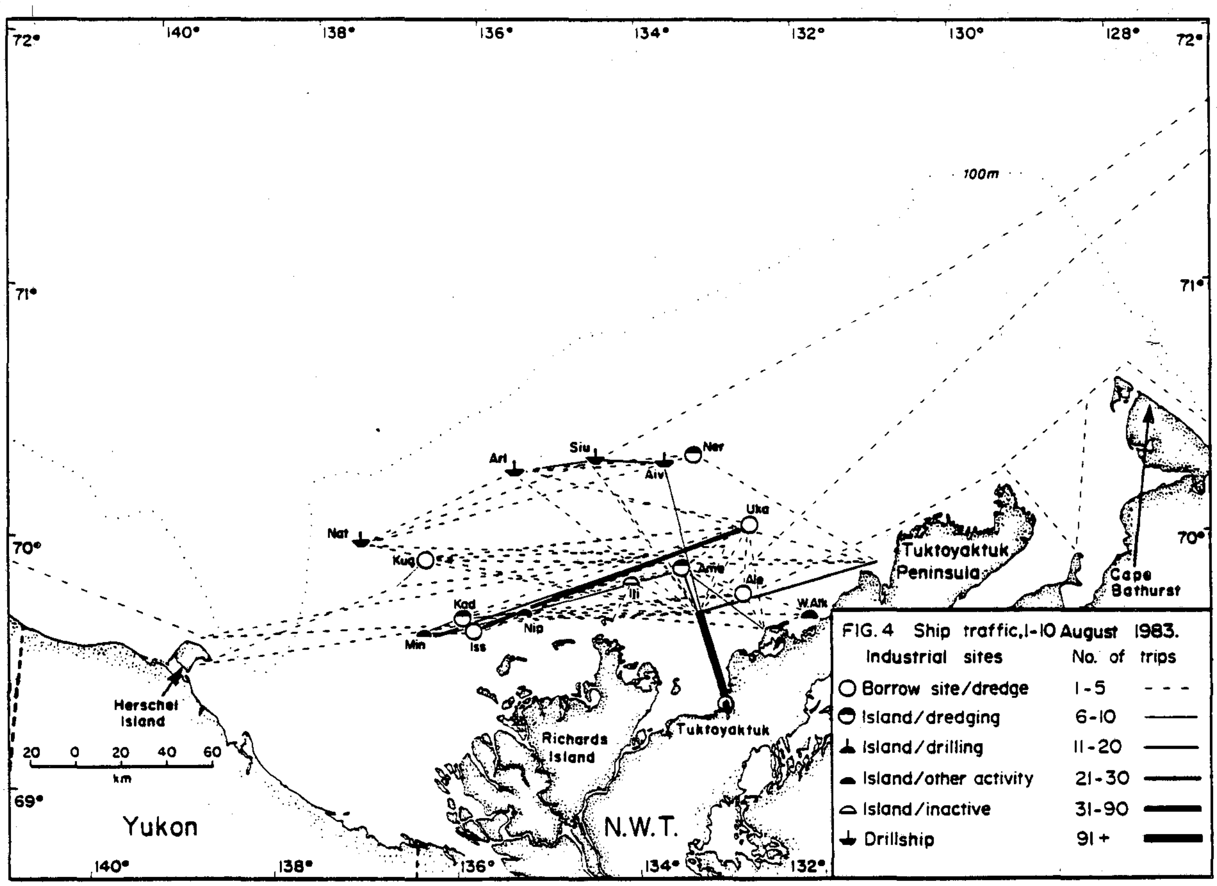

FIG. 4 Ship traffic, 1-10 August 1983.

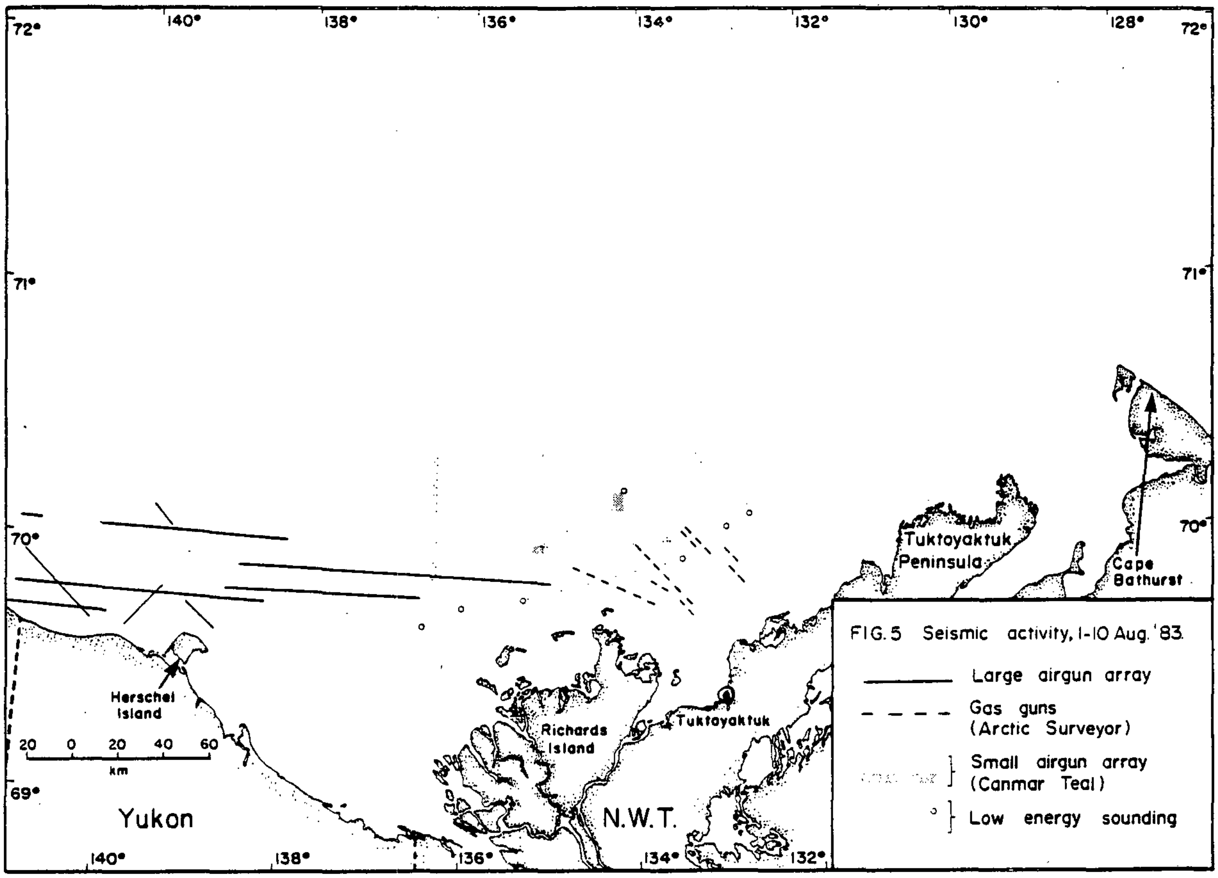

FIG. 5 Seismic activity, 1-10 Aug. '83.

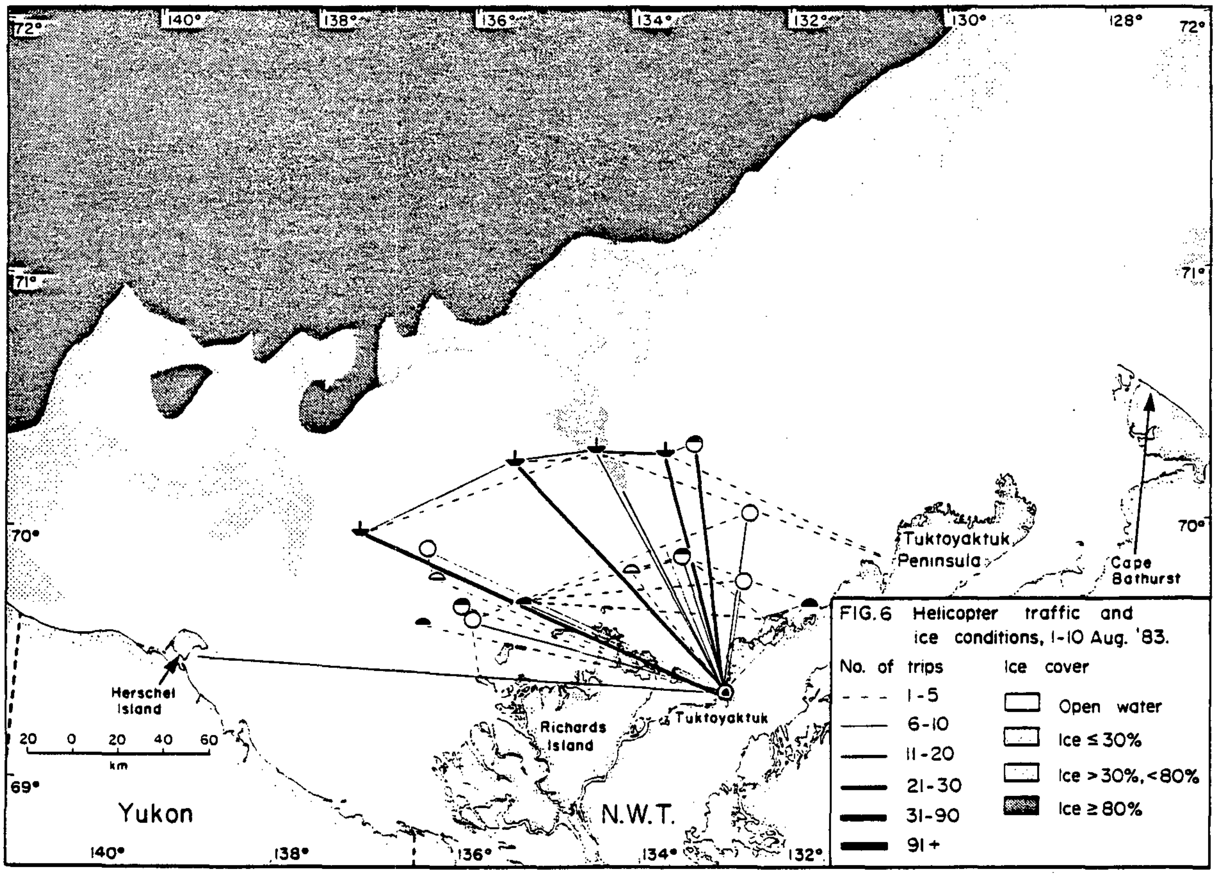

FIG. 6 Helicopter traffic and ice conditions, 1-10 Aug. '83.

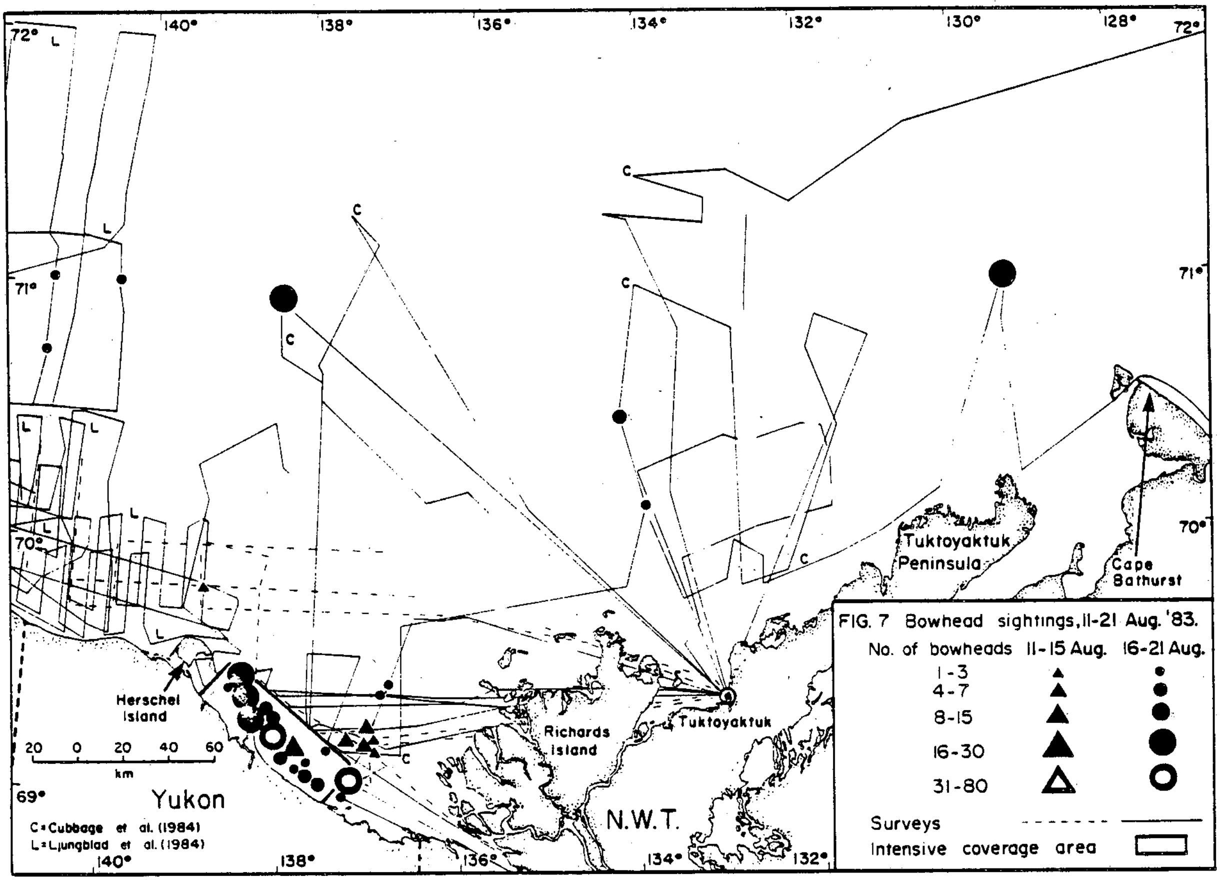
FIG. 7 Bowhead sightings, 11-21 Aug. '83.

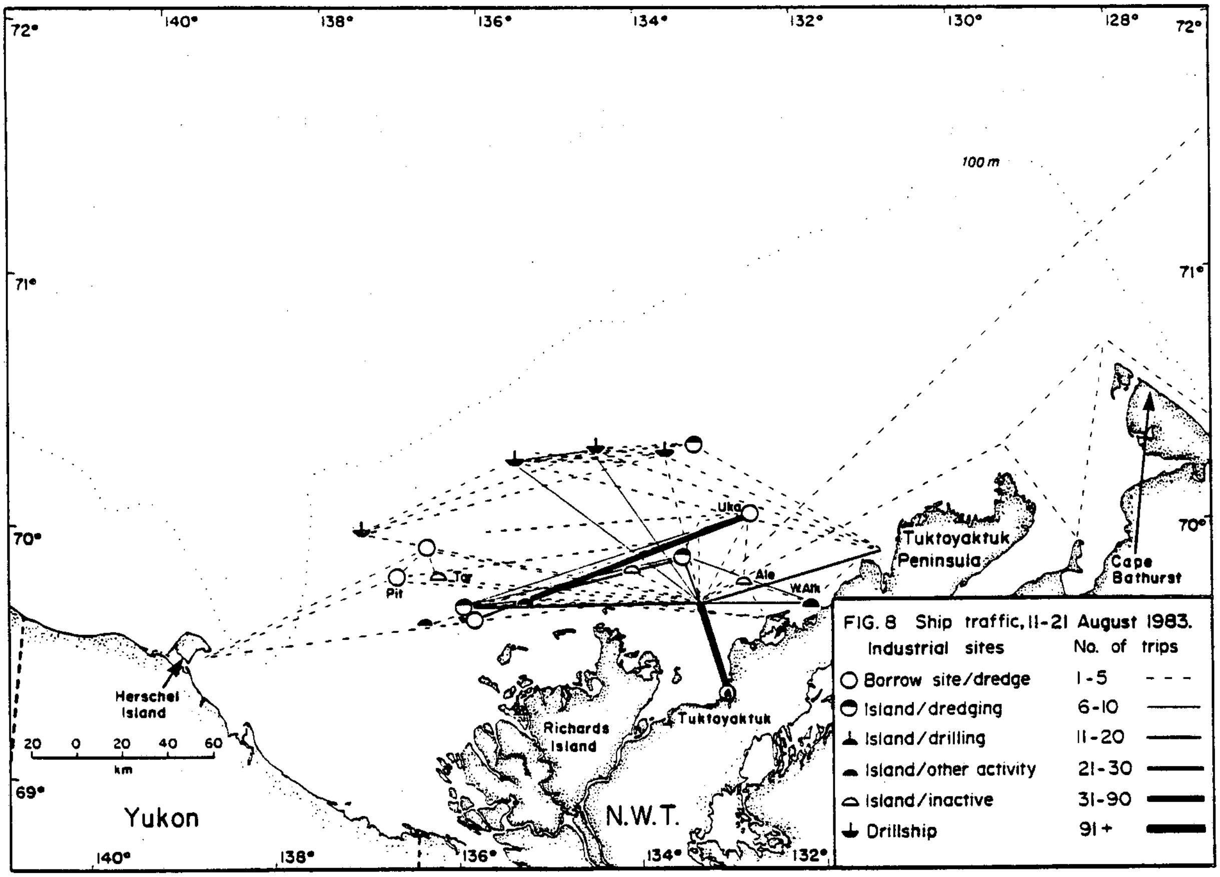
FIG. 8 Ship traffic, 11-21 August 1983.

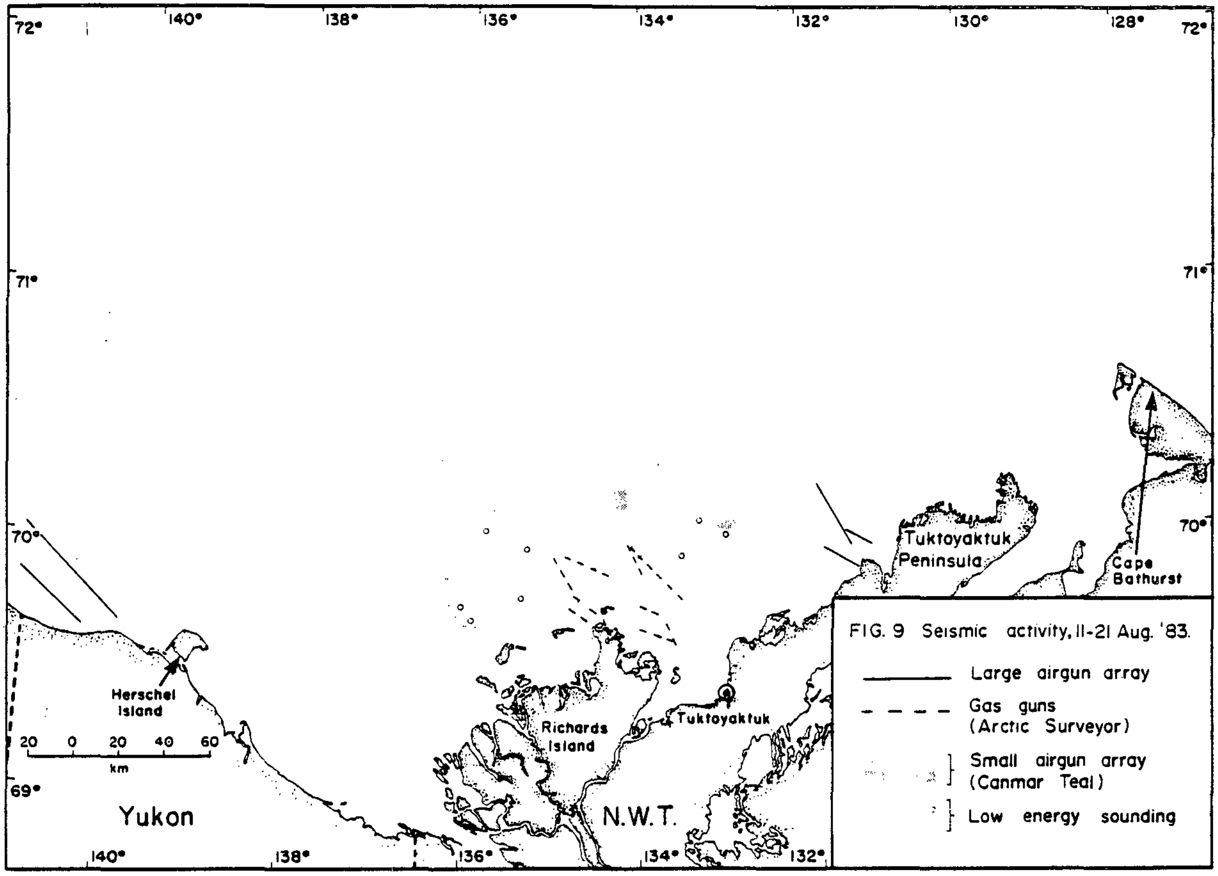

FIG. 9 Seismic activity, 11-21 Aug. '83.

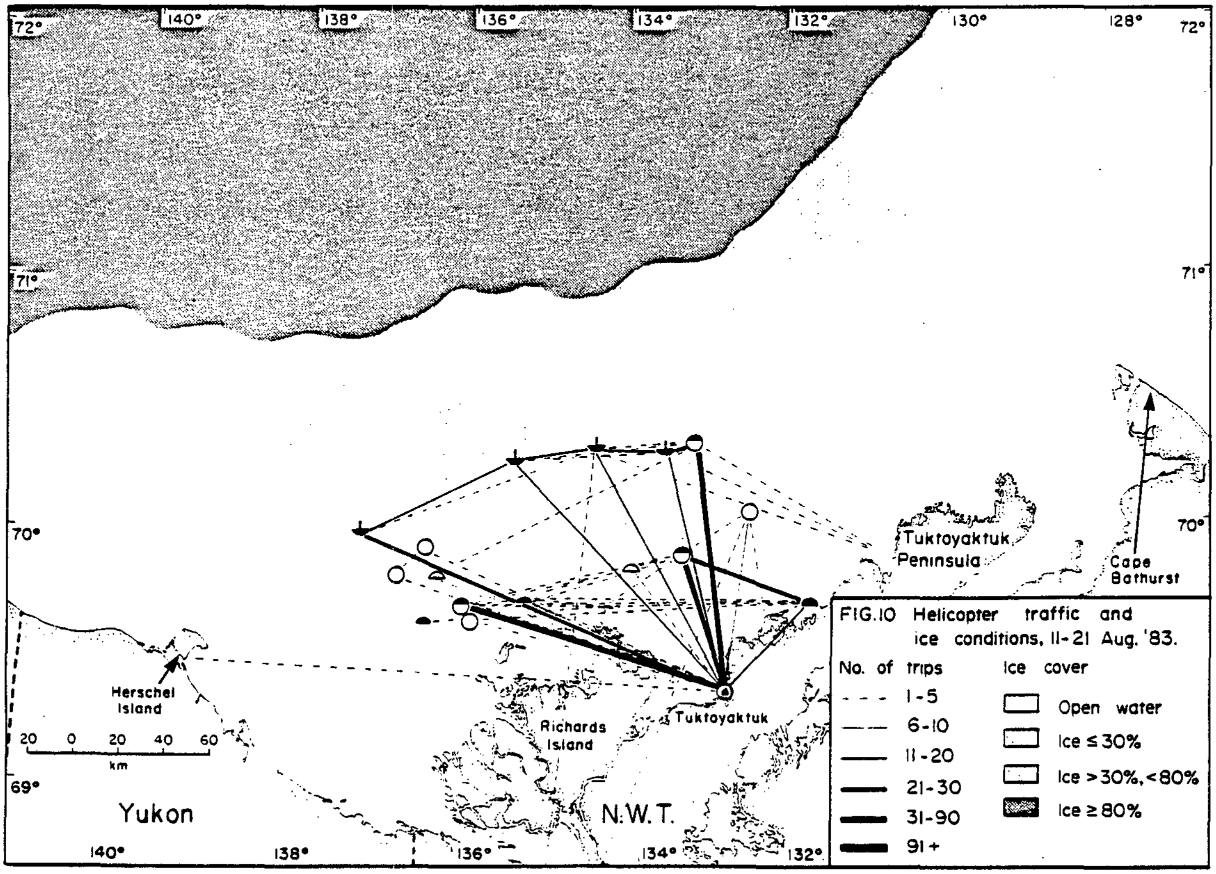

FIG. 10 Helicopter traffic and ice conditions, 11-21 Aug. '83.

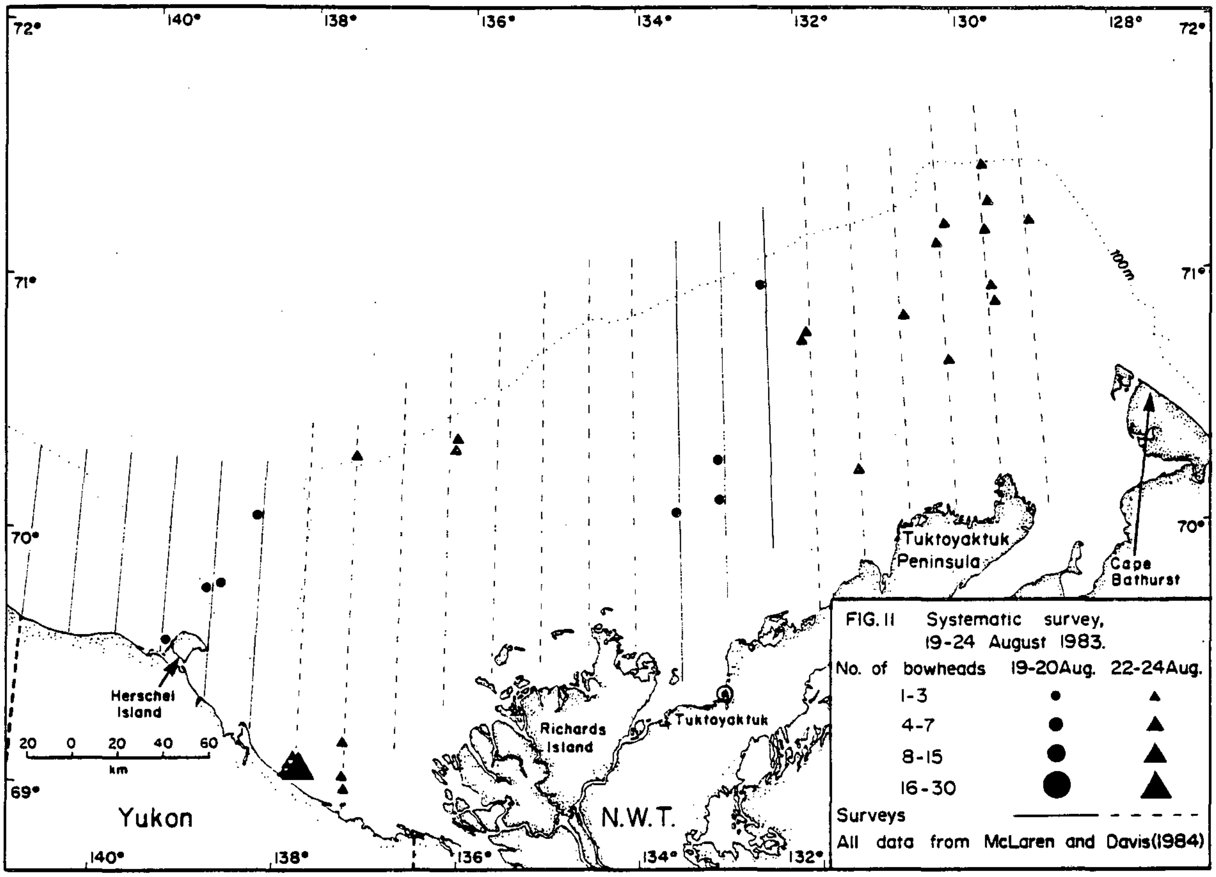

FIG. 11 Systematic survey, 19-24 August 1983.

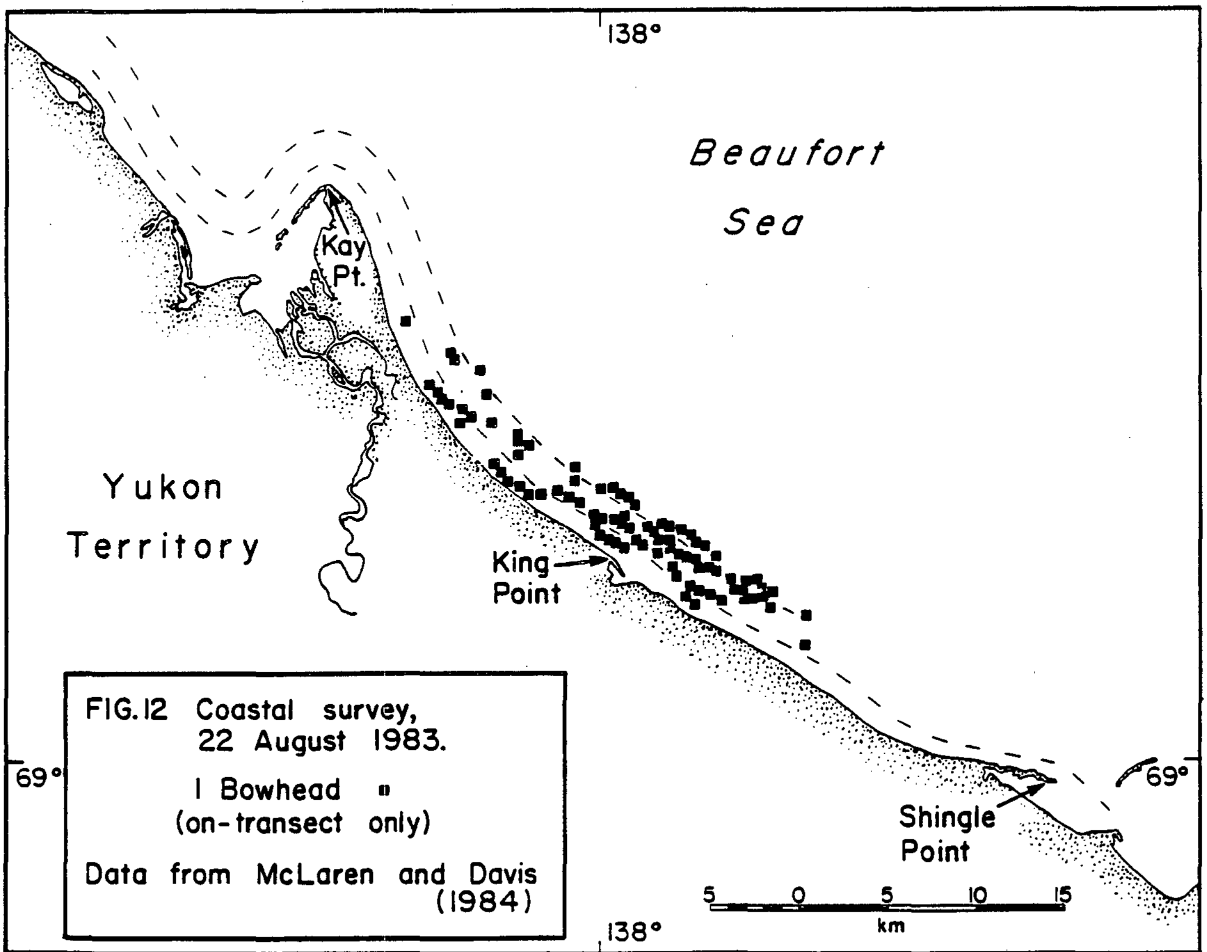

FIG. 12 Coastal survey, 22 August 1983.

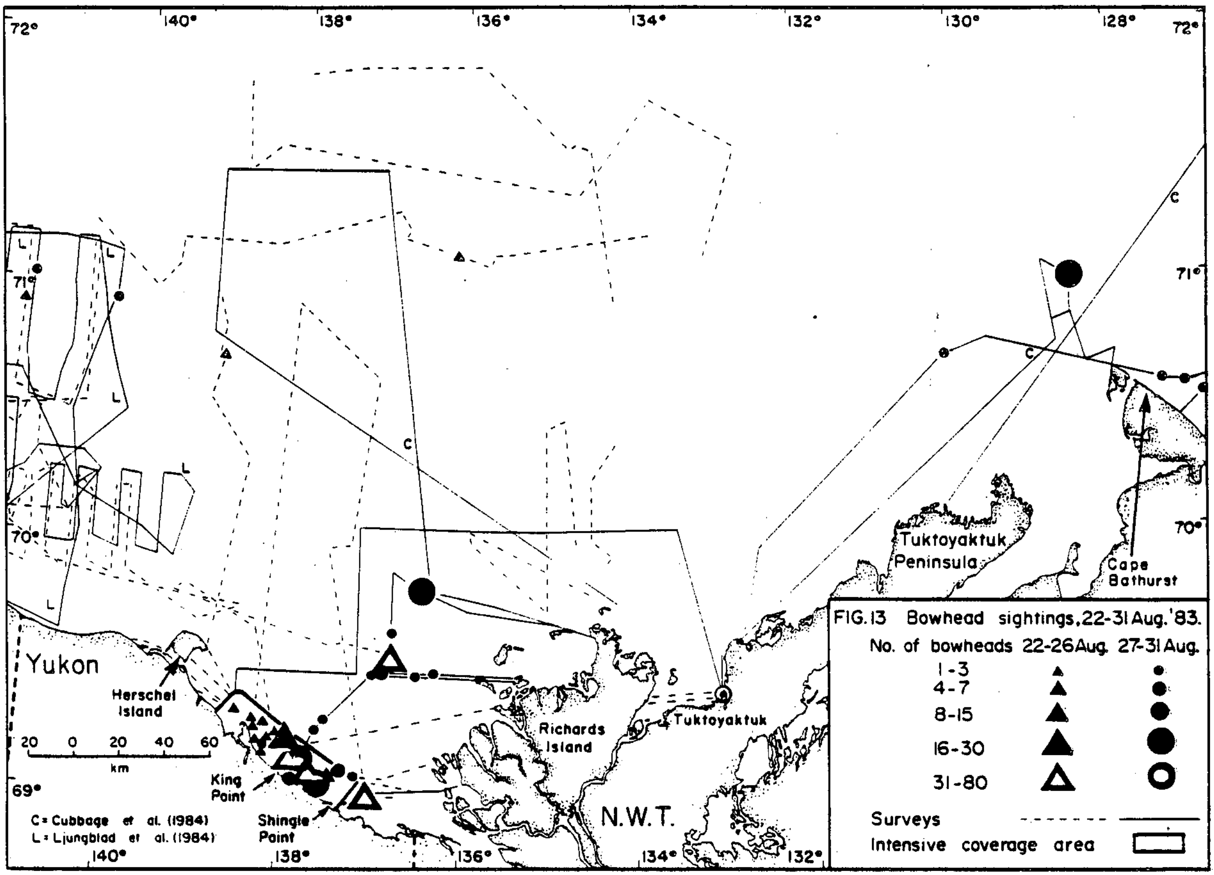

FIG. 13 Bowhead sightings, 22-31 Aug.'83.

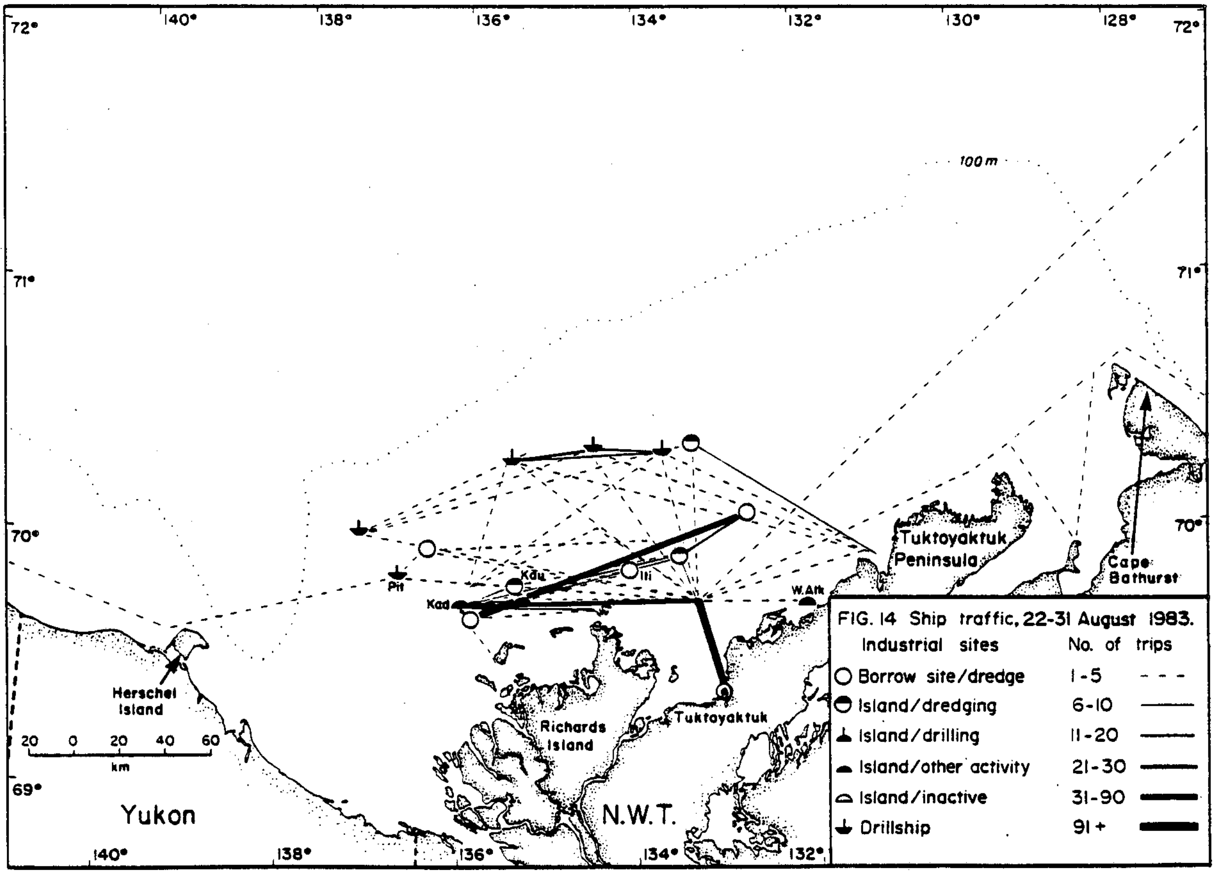

FIG. 14 Ship traffic, 22-31 August 1983.

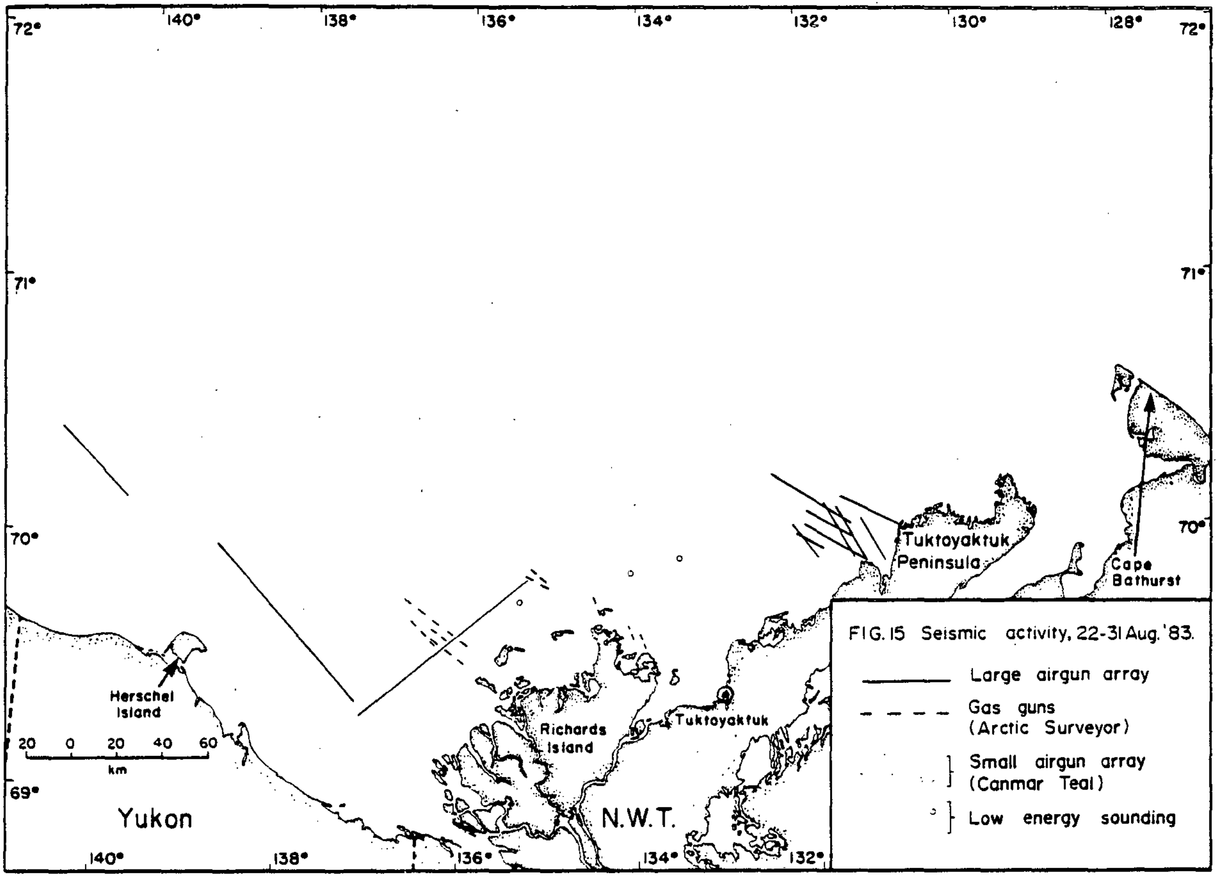

FIG. 15 Seismic activity, 22-31 Aug. '83.

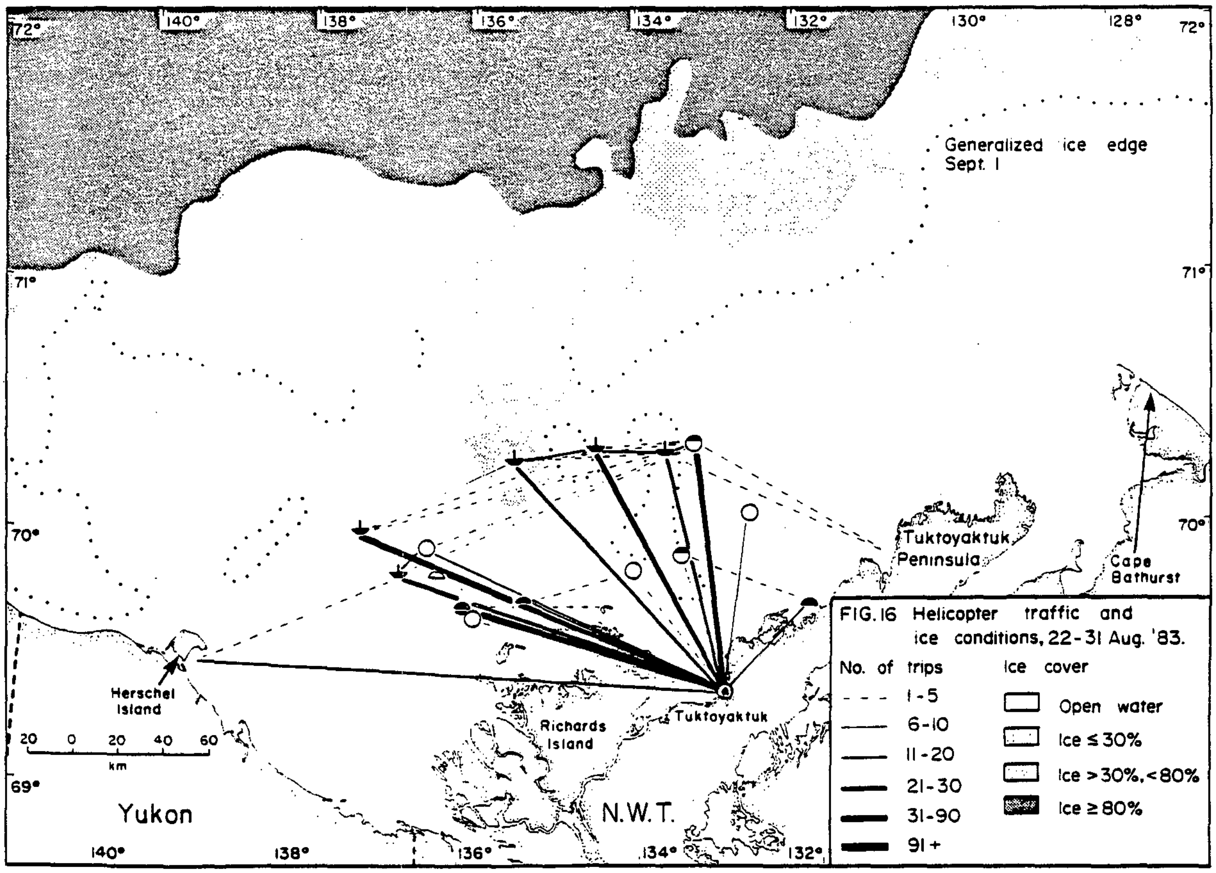

FIG. 16 Helicopter traffic and ice conditions, 22-31 Aug. '83.

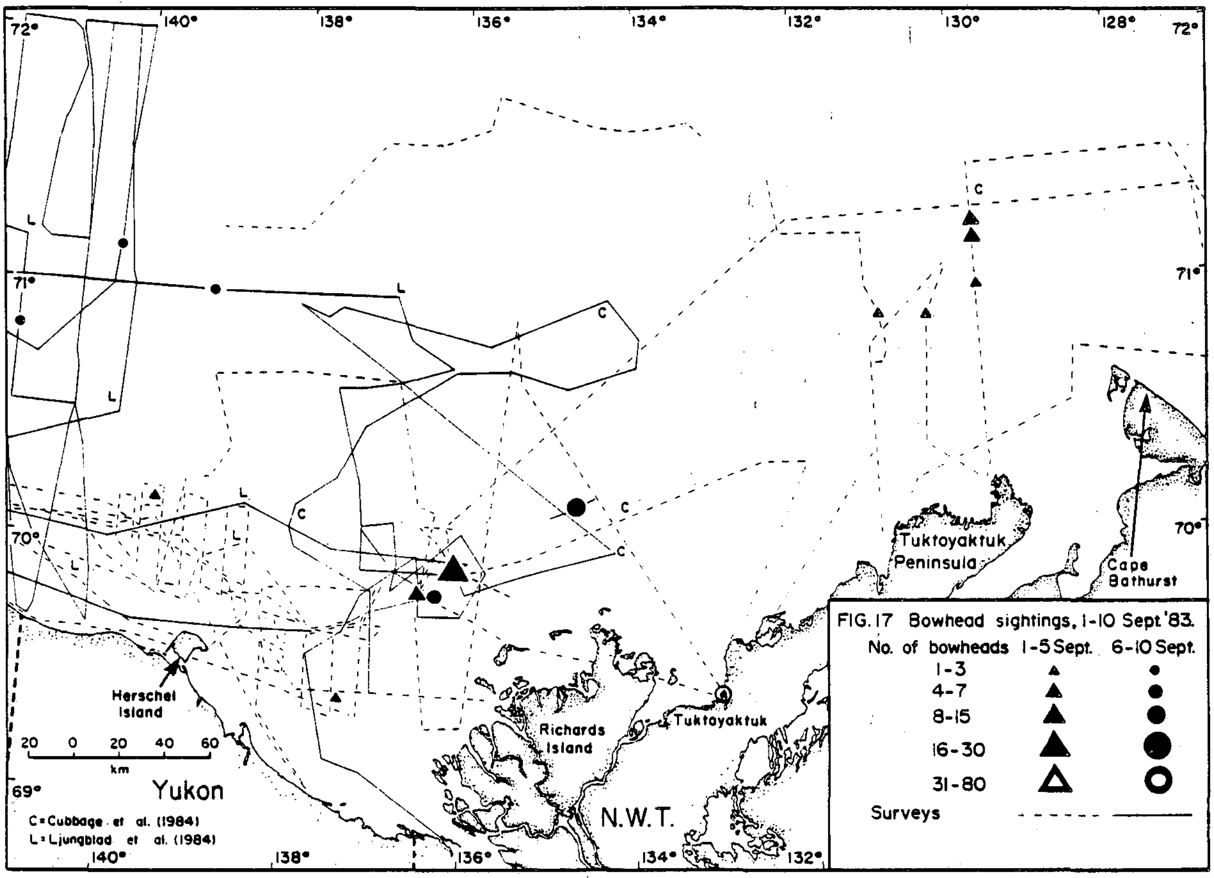

FIG. 17 Bowhead sightings, 1-10 Sept.'83.

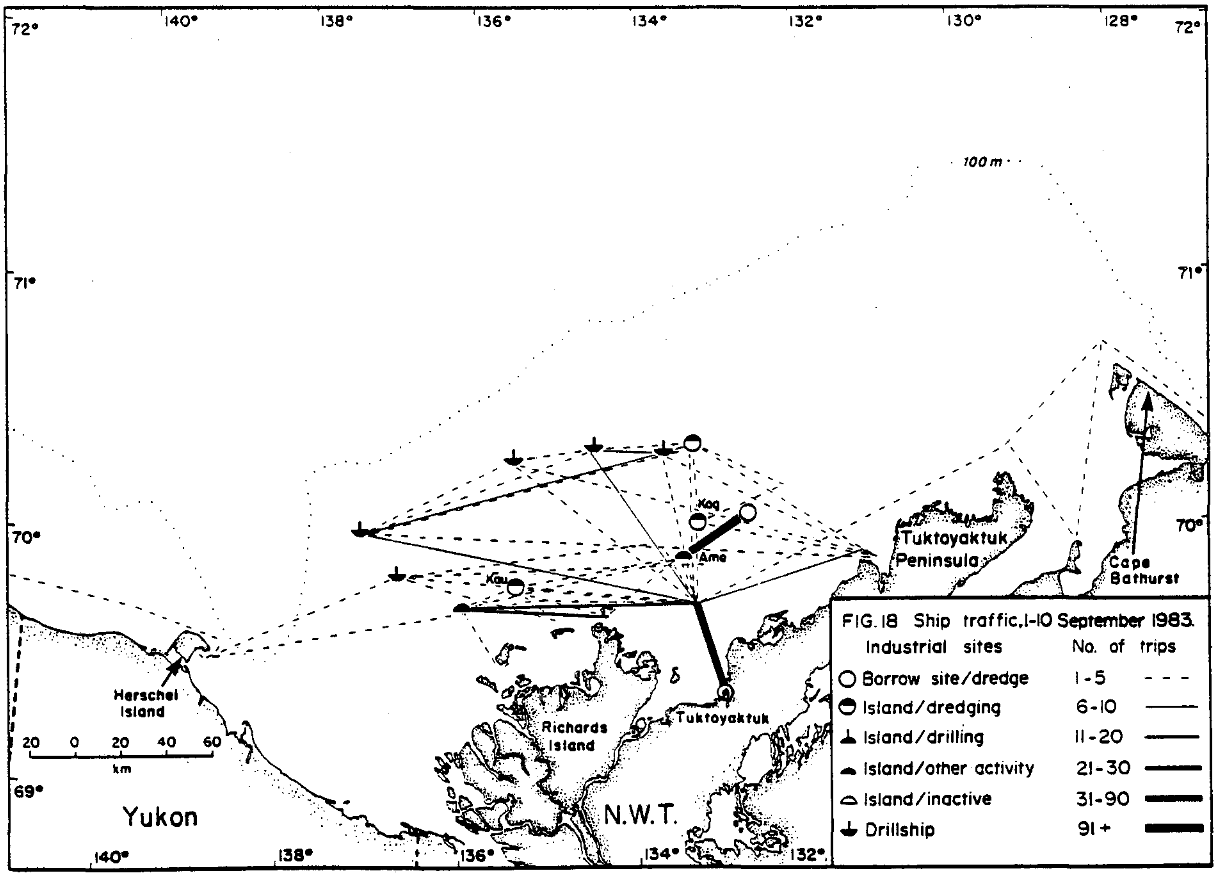

FIG. 18 Ship traffic, 1-10 September 1983.

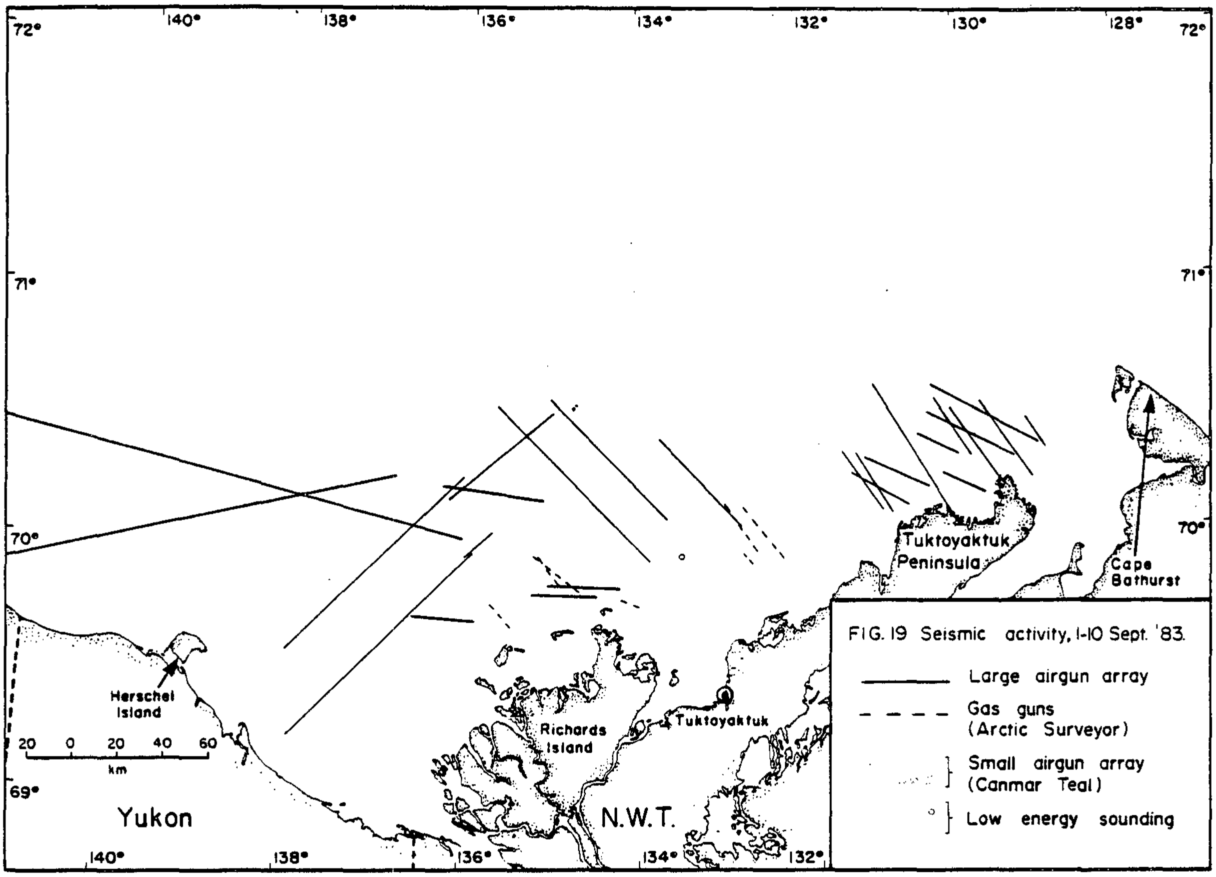

FIG. 19 Seismic activity, 1-10 Sept. '83.

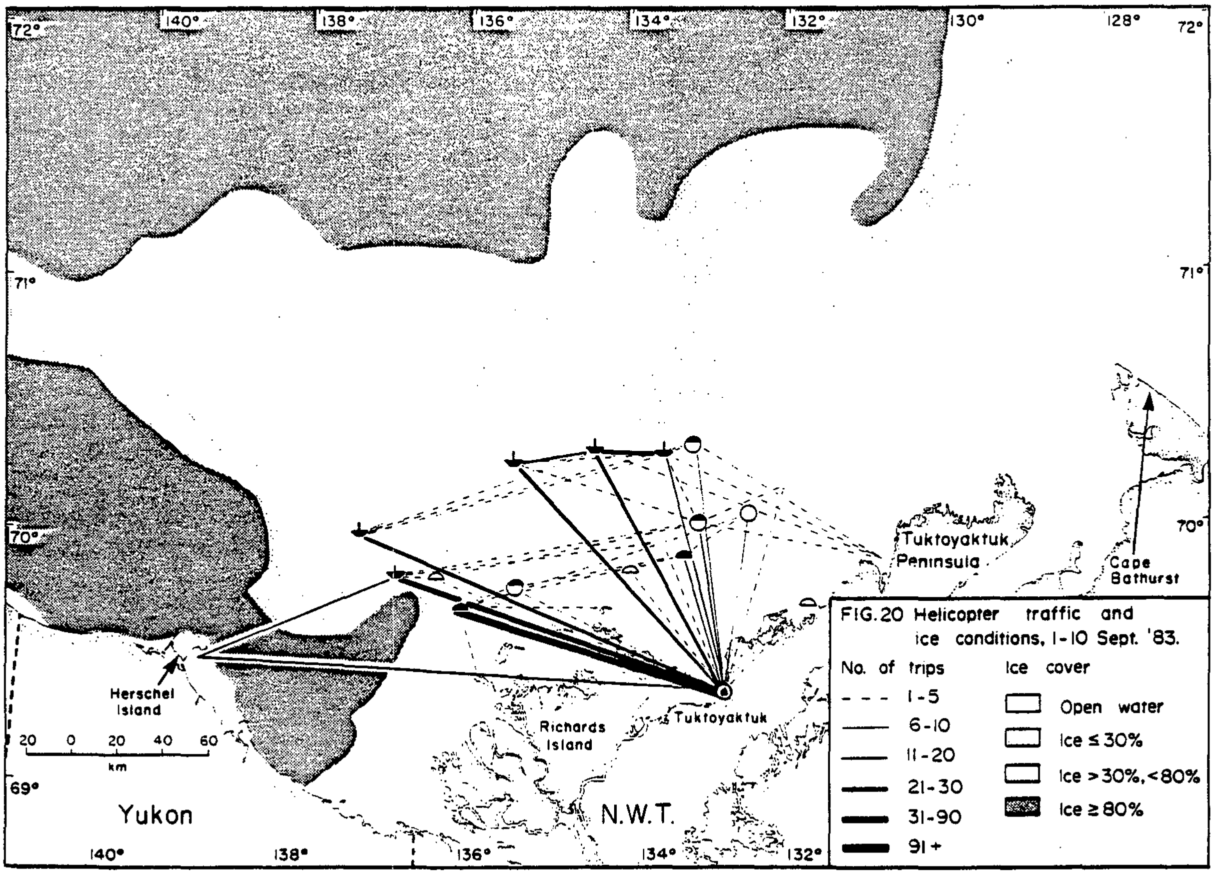

FIG. 20 Helicopter traffic and ice conditions, 1-10 Sept. '83.

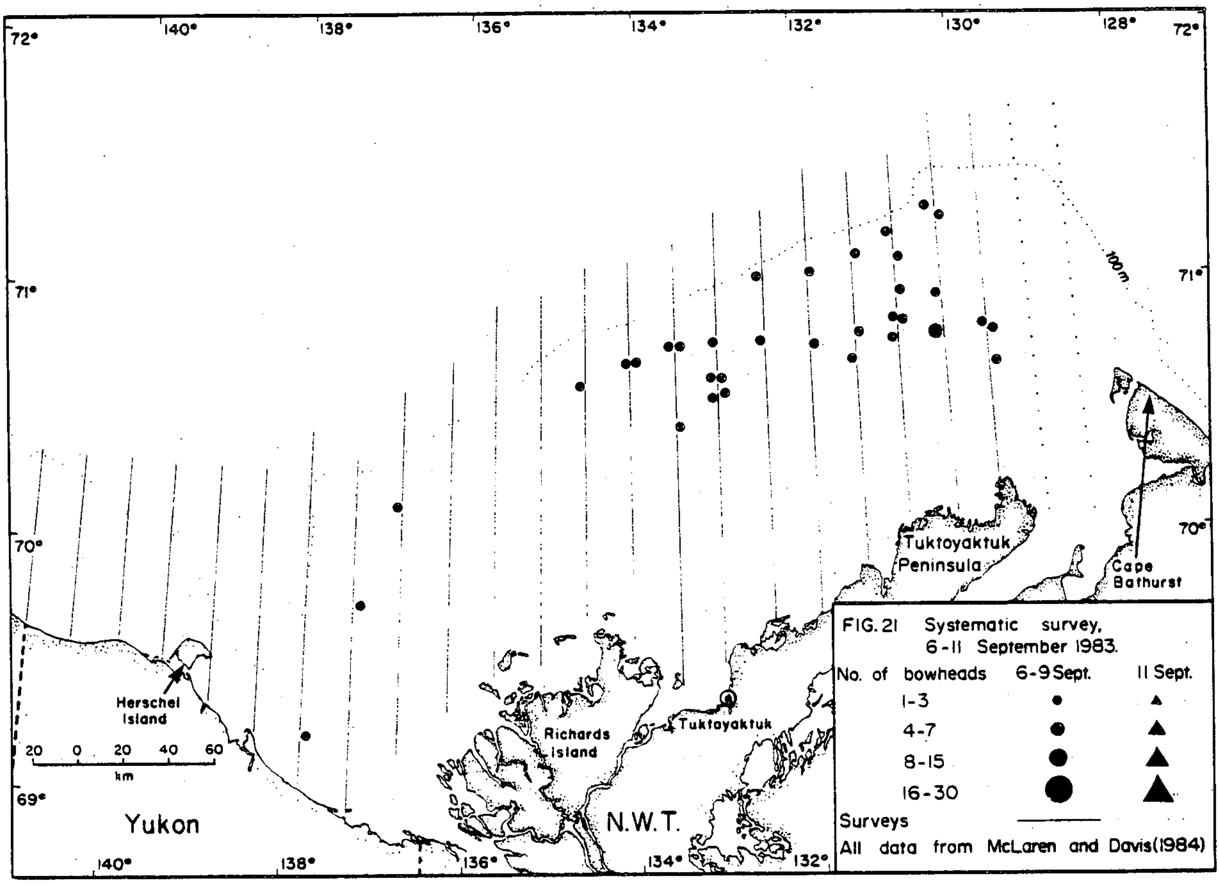

FIG. 21 Systematic survey, 6-11 September 1983.

All data from McLaren and Davis(1984)

Industrial Activities, 1983

The overall level of offshore industrial activity in the Canadian Beaufort Sea in 1983 was somewhat greater than in any previous year. Operations by Dome Petroleum in 1983 were somewhat less than those in 1982 (four drillships, usually two dredges as opposed to three in 1982, numerous support vessels). However, Esso Resources Canada and especially Gulf Canada Resources expanded their offshore operations in 1983. Esso, in addition to continuing the types of operations conducted in previous years, brought another suction hopper dredge ('Cornelius Zanen') and another seismic vessel ('GSI Explorer') into the Beaufort Sea. Esso also finished constructing its first caisson retained island (Kadluk) in the summer of 1983. BeauDril, a Gulf subsidiary, brought a new, unconventional circular drillship ('Kulluk') into the Beaufort Sea in August 1983, along with two new supply ships, two new icebreakers, an oil tanker (for fuel storage), and other support vessels.

Dome's drillships, 'Canmar Explorers I-IV', began operations in mid July. These ships operated at the same four drillsites throughout the 1 August-10 September period; from west to east, these were Natiak, Arluk, Siulik and Aiverk (Fig. 4). Water depths at these sites ranged from about 40 m at Natiak to 58 m at Arluk. Before and after but not during our study period, there was a drillship at Havik, a site off the Tuktoyaktuk Peninsula (70°20'N, 132°13'W). Gulf's new circular drillship, 'Kulluk', began operations about 22 August at Pitsiulak (Fig. 14). There was no drilling from artificial islands or caissons during the 1983 open water season.

Two suction dredges and four suction hopper dredges were working in the Canadian Beaufort Sea during the late summer of 1983. This is the same number of dredges as in 1982, but more than in any previous year. Besides these six dredges, two or three barges with clamshells were also present and in intermittent use.

The suction dredge 'Beaver Mackenzie' was constructing an underwater berm at Amerk, north of Tuktoyaktuk in water about 23 m deep (Fig. 4), until 28 August. This dredge then moved to Kaubvik (Fig. 14). The other suction dredge, 'Aquarius', was constructing an underwater berm at Nerlerk, north of Tuktoyaktuk in water about 45 m deep (Fig. 4), throughout most of the study period. After 6 September 'Aquarius' was in McKinley Bay.

The four hopper dredges were more mobile. During much of August, 'Geopotes X' worked at Nerlerk. 'Geopotes IX' dredged at Nerlerk and at Kugdjuk for 5 d and 8 d, respectively, in August (Fig. 4). Both of these dredges were at Kogyuk from 7 September on (Fig. 18). During August, the other two suction hopper dredges, 'W.D. Gateway' and 'Cornelius Zanen', hauled dredged material over various routes, mainly from the Ukalerk and Issigak borrow sites to Nipterk, Minuk and Kadluk (Fig. 4). From 31 August to 10 September these two dredges made 344 trips between the Ukalerk borrow site and the underwater berm under construction at Amerk (Fig. 18).

Vessel traffic in 1983, as in other recent years, consisted mainly of movements by hopper dredges and vessels supporting the drilling, dredging and island construction operations (Figs. 4, 8, 14, 18). Support vessels included supply boats, icebreakers, tugs with barges, crew boats, and various other types of vessels. Several additional vessels arrived in the Canadian Beaufort Sea in 1983, mostly in association with Gulf's expanded offshore operations. There was some vessel traffic west to Herschel Island, where Gulf's barge camp was anchored. A few vessel movements during August were in support of island clean-up operations at West Atkinson (Fig. 4). Vessels operated by Northern Transportation Company Ltd. (NTCL) made several trips to communities and DEW radar sites to the east.

Seismic exploration occurred from the Alaska-Yukon border eastward to Cape Dalhousie (Figs. 5, 9, 15, 19). 'Arctic Surveyor' worked in shallow water north of the Mackenzie Delta and Kugmallit Bay throughout the study period; this ship used open bottom gas guns in 1983, as in 1982. Three ships using large arrays of airguns worked in the Canadian Beaufort Sea during our study period:

- 'GSI Explorer' worked in shallow water north of the Tuktoyaktuk Peninsula from mid August onward.
- 'GSI Mariner' worked in the central and western part of the Canadian Beaufort Sea at various times during the study period, but from 9 to 29 August was in Alaskan waters most of the time.

- 'Western Aleutian' was mainly in Alaskan waters, but worked in Canadian waters north of the Yukon and Mackenzie Delta on 1-2 September.

In addition, from the start of our study period until 17 August, 'Canmar Teal' used a small (320 in^3) array of airguns at various locations north of the Mackenzie Delta and Kugmallit Bay.

Low-energy sounding was done from four vessels operating at 16 locations, most <1 km^2 in area. These sites were off the Mackenzie Delta and Kugmallit Bay. Sounding occurred at some sites during more than one of the 10-d periods.

Helicopter traffic was concentrated in the same area as vessel traffic (Fig. 6, 10, 16, 20). A high proportion of the helicopter movements were along straight lines between Tuktoyaktuk and the various offshore industrial sites. However, there was also traffic between offshore sites operated by the same company, e.g. between Dome's four drillships. Although helicopter traffic was concentrated in the central part of the Canadian Beaufort Sea, there was some helicopter traffic west as far as Gulf's barge camp at Herschel Island, and east as far as Dome's base at McKinley Bay.

The general pattern of helicopter operations was similar to that in other recent years. However, the number of helicopters in use offshore in 1983--ten, all of twin turbine engine design--was more than in any previous year (cf. Richardson et al. 1983a, p. 296). Helicopters used offshore in 1983 consisted of two relatively small machines (1 Aerospatiale TwinStar, 1 MBB BO-105), five medium sized machines (1 Bell 212, 2 Bell 412, 2 Sikorsky S76), and three larger helicopters (1 Bell 214ST, 1 Aerospatiale Super Puma, 1 Sikorsky S61).

Ice Conditions, 1983

Ice conditions in 1983 differed somewhat from those in 1980-82. There was, as usual, a broad band of open water north of the Mackenzie Delta and Tuktoyaktuk Peninsula in August 1983 (Figs. 6, 10, 16). However, this open water area was somewhat narrower than in August 1980, and much narrower than in August of 1981 or 1982 (cf. Richardson et al. 1983a). The zone of open water north of the Mackenzie Delta was sufficiently narrow that drillships operating there in August occasionally ceased drilling and moved off their drillsites to avoid encounters with ice.

There was little ice near the Yukon coast in August 1983. This was similar to the situation in August 1980 but different from August of 1981 and 1982, when there was much ice near the Yukon shore for much of August. Ice conditions in the Alaskan Beaufort Sea in 1983 were relatively severe, and ice moved into the area off the Yukon coast in early September (Fig. 20).

Bowhead Distribution, 1983

In early August 1983, we and Cubbage et al. (1984) found bowheads, including calves, in deep water north of Herschel Island (Fig. 3). In the same period, Cubbage et al. and Ljungblad et al. (in prep.) found bowheads NNW of Herschel Island, between 140° and 141°W longitude (Fig. 3). Almost all of these sightings were in water 200 - 2000 m deep. Most were in or near the southern edge of pack ice (Fig. 6). Survey coverage in the eastern part of the Canadian Beaufort Sea was limited; our only sighting there was of one bowhead along the shelf break at the southern edge of the ice 190 km north of Tuktoyaktuk (Fig. 3).

None of the bowheads seen during aerial surveys in early August were in the 'main industrial area', i.e. the area of drilling, dredging and island construction (compare Figures 3 and 4). We received only two reports of 1 or 2 bowheads seen by industry personnel in early August. Both sightings were near the east edge of the industrial area. The bowheads seen north and northwest of Herschel Island were, however, in or north of an area of seismic exploration (Fig. 5). During two of the three flights when we found bowheads north of Herschel Island (7 and 9 August), sonobuoys revealed that the whales were exposed to strong seismic noise (Greene 1984; Richardson et al. 1984).

In mid August 1983, we discovered a very large concentration of bowheads off the Yukon coast east of Herschel Island (Fig. 7). During our first flight into this area, on 14 August, we found whales in the middle of Mackenzie Bay, but did not search near the coast. On 15 August we found whales in water as shallow as 8 m and as little as 12 km from the Yukon coast. On 17 August we found bowheads <1 km from shore. We saw as many as 60 whales during a single flight near the Yukon coast southeast of Herschel Island in the mid-August period, with no allowance for unseen whales below the surface or beyond our range of vision. In contrast, almost no bowheads were seen in nearshore waters west of Herschel Island, despite intensive survey coverage during the 16-21 August period (Figs. 7, 11). Whether bowheads were present near the Yukon coast east of Herschel Island before 14 August is unknown; there were no earlier surveys in that area. However, pilots did not begin to report bowheads in this area until mid August, suggesting (but not proving) that there was no large concentration of whales there in early August.

Survey coverage elsewhere in the eastern Beaufort Sea during mid August was extensive but of uneven intensity (Fig. 7). A few whales were seen near the ice edge far offshore from the Yukon (Figs. 7, 11). There were also a few sightings generally north of Tuktoyaktuk, within the main industrial area (Figs. 7, 11). Industry personnel and our boat crew saw a few bowheads near and west of the dredge at Amerk, north of Tuktoyaktuk and Richards Island, on several dates from 11 to 19 August. There were also three industry sightings near drillships at the north edge of the main industrial area on 17-20 August. Survey coverage off the Tuktoyaktuk Peninsula in mid August was limited, but Cubbage et al. (1984) sighted a large group of bowheads far off Cape Dalhousie, outside the industrial area (Fig. 7). [McLaren and Davis (1984) did not survey the area off the Tuk Peninsula until 23-24 August, when widely distributed bowheads were found (Fig. 11).]

In general, bowheads appeared to be scarce in most surveyed parts of the southeastern Beaufort Sea in mid August of 1983, with the exception of the major concentration near the Yukon coast. The bowheads near the Yukon coast were not exposed to significant human activity (cf. Figs. 8-10), aside from survey aircraft and our experimental work (Richardson et al. 1984). We dropped sonobuoys amongst this concentration of whales on three days in the mid August period (and on three days in late August); the only significant seismic noise that we detected was from our one airgun experiment, on 28 August. Some of the few sightings in other areas were within the main industrial area, but no large concentration of whales was found within that area. The largest groups of whales seen in mid August, aside from those along the Yukon coast, were far to the north of Herschel Island and Cape Dalhousie, far outside the industrial area.

In late August 1983, the large concentration of whales along the Yukon coast persisted until at least 28 August, the last day when the area was searched (Fig. 13). Numerous whales were sometimes found as far as 15 km from shore, and sometimes <1 km from shore; exact locations varied from day to day. McLaren and Davis (1984) saw 110 bowheads within about 4 km from shore on 22 August (86 on transect--Fig. 12), and we saw many bowheads a few kilometres farther offshore simultaneously. Behavioral observations showed that whales often dove out of sight even in the shallow nearshore water (Würsig et al. 1984), so actual numbers present were undoubtedly much greater than the number counted.

Direct observations indicated that the whales near the Yukon coast had few white markings, and no calves were seen. We applied the photogrammetric method of Davis et al. (1983) to a small sample of the whales within a few kilometres of the Yukon coast on 26 and 27 August; all 16 of those measured in this area were <13 m in length (W.R. Koski, LGL Ltd., unpubl. data). These characteristics are indicative of subadult animals.

Ljungblad et al. (in prep.) and Cubbage et al. (1984) searched for whales near the Alaska-Yukon border and in deep water north of the Yukon and Mackenzie Delta. They saw very few whales in these areas (Fig. 13). McLaren and Davis (1984) completed their first systematic survey on 22-24 August (dashed lines on Fig. 11). They found three whales near the 100 m contour far off the Mackenzie Delta, plus 15 widely scattered whales off the eastern Tuktoyaktuk Peninsula. There were additional sightings in the Cape Bathurst area (Cubbage et al. 1984; Fig. 13). There was also an industry sighting of several bowheads in the area where McLaren and Davis saw 15 whales, east of the main industrial area.

These results, along with the remainder of McLaren and Davis's coverage a few days earlier (solid lines on Fig. 11), show that bowheads were not concentrated anywhere in the southeastern Beaufort Sea other than along the Yukon coast, and possibly near Cape Bathurst, during the 19-24 August period. McLaren and Davis estimated that there were about 1057 bowheads dispersed in the area that they surveyed, excluding the concentration of whales (apparently several hundred) along the Yukon coast.

During the last few days in August, after McLaren and Davis had completed their first survey, we and Cubbage et al. (1984) found bowheads in shallow water (5-25 m) just northwest of the Mackenzie Delta (Fig. 13). Some of these whales were well within the main industrial area--about 10-12 km from the 'Kulluk' drillship, on the direct helicopter route between Tuktoyaktuk and 'Kulluk', in an area ensonified by seismic noise (Richardson et al. 1984). There were apparently few bowheads in other parts of the industrial area in the 22-31 August period (Figs. 11, 13).

In early September 1983, our non-systematic coverage was limited to a single flight off the Mackenzie Delta on 1 September. However, Ljungblad et al. (pers. comm.) and Cubbage et al. (1984) obtained non-systematic coverage of much of the study area (Fig. 17). There were a few sightings in the main industrial area in early September. Whales were still present off the Mackenzie Delta near 'Kulluk' on 1 September. Those whales were exposed to the same types of industrial activity as on 31 August (see above and Richardson et al. 1984). Bowheads were sighted here again on 6 September (Ljungblad et al. pers. comm.). Cubbage et al. (1984) also saw groups of bowheads within the main industrial area in early September (Fig. 17).

A few bowheads were seen far offshore near the Alaska border, and more were seen off the eastern end of the Tuk Peninsula (Fig. 17). A significant number of whales were still present as far east as Franklin Bay, east of our study area, in early September of 1983 (Cubbage et al. 1984). Bowheads were also present this far east in early September of 1981 (Davis et al. 1982).

McLaren and Davis (1984) conducted their second systematic survey on 6-11 September. They found only 3 bowheads in the western half of their study area, which contained much pack ice at this time (Figs. 20, 21). The concentration of whales along the Yukon coast had dispersed by 6 September, when that area was surveyed. However, McLaren and Davis found 47 whales widely distributed on the outer continental shelf north of the Tuktoyaktuk Peninsula and the eastern part of the Mackenzie Delta (Fig. 21). One adult-calf pair was seen, and there was evidence of prevailing southwestward orientation.

McLaren and Davis estimated that about 1700 bowheads were within the area that they surveyed on 6-11 September. Almost all of these were off the Tuktoyaktuk Peninsula and eastern Mackenzie Delta. This rough estimate is based on the ratio procedure and the correction factors of Davis et al. (1982), and allows for animals between survey lines, animals present at the surface but not seen, and animals below the surface when the survey aircraft passed overhead. None of the whales seen by McLaren and Davis were within the main industrial area. However, some were probably exposed to noise from the seismic vessels working near the Tuktoyaktuk Peninsula (Fig. 19). The non-systematic surveys (Fig. 17) showed that some bowheads were in the main industrial area during early September, but the systematic surveys showed that numbers there must have been low relative to numbers outside the industrial area.

The prevailing southwestward orientation found during the systematic survey suggested that autumn migration out of the Canadian Beaufort Sea was underway. However, some bowheads were still present as far east as central Franklin Bay (Cubbage et al. 1984). The animals in Franklin Bay and those far offshore near the Alaskan border (Fig. 17) were outside the area sampled by McLaren and Davis. Thus, the estimate of about 1700 bowheads in the Canadian Beaufort Sea in early September is conservative.

DISCUSSION

The distribution of bowheads in the eastern Beaufort Sea varies greatly both within and between summers. Nonetheless, some consistent patterns are evident. These patterns are summarized here before we consider the possible relationships of changes in distribution to industrial activity and other factors. This Discussion is, for the most part, an updating of the corresponding section of our report on distribution in 1980-82 (Richardson et al. 1983a, p. 339-352). Unless otherwise stated, data for 1976-82 are taken from that report.

Seasonal and Annual Trends in Distribution

Few bowheads occur in the shallow waters off the Mackenzie Delta and Tuktoyaktuk Peninsula before 1 August (Richardson et al. 1983a, p. 339). In August, many bowheads move into shallower waters in the southeastern Beaufort Sea, apparently from the north and east. However, the timing of this movement and the locations of concentrations vary from year to year. In 1980, many whales appeared in shallow waters (15-35 m) off the Mackenzie Delta around 2 August. This concentration did not occur in early August of 1981, 1982 or 1983. Fragmentary evidence from 1976-1979 indicates that numerous whales appeared in shallow waters off the Delta at about this time in 1976 and 1977, but not in 1978 or 1979.

Figures 22 and 23 summarize what is known about bowhead distribution in the eastern Beaufort Sea in early and late August of 1980, 1981, 1982 and 1983. We have categorized the region into areas with zero, low, moderate and high apparent densities of whales. The 1980-82 maps are from Richardson et al. (1983a). The 1983 maps are based on the detailed sighting maps in the Results section of this report, and were prepared using the same criteria as for 1980-82. Areas with widely separated sightings of 1-3 whales were designated as low density areas. Those with frequent sightings of 1-3 whales were treated as moderate density. Areas with sightings of large groups of whales were treated as high density.

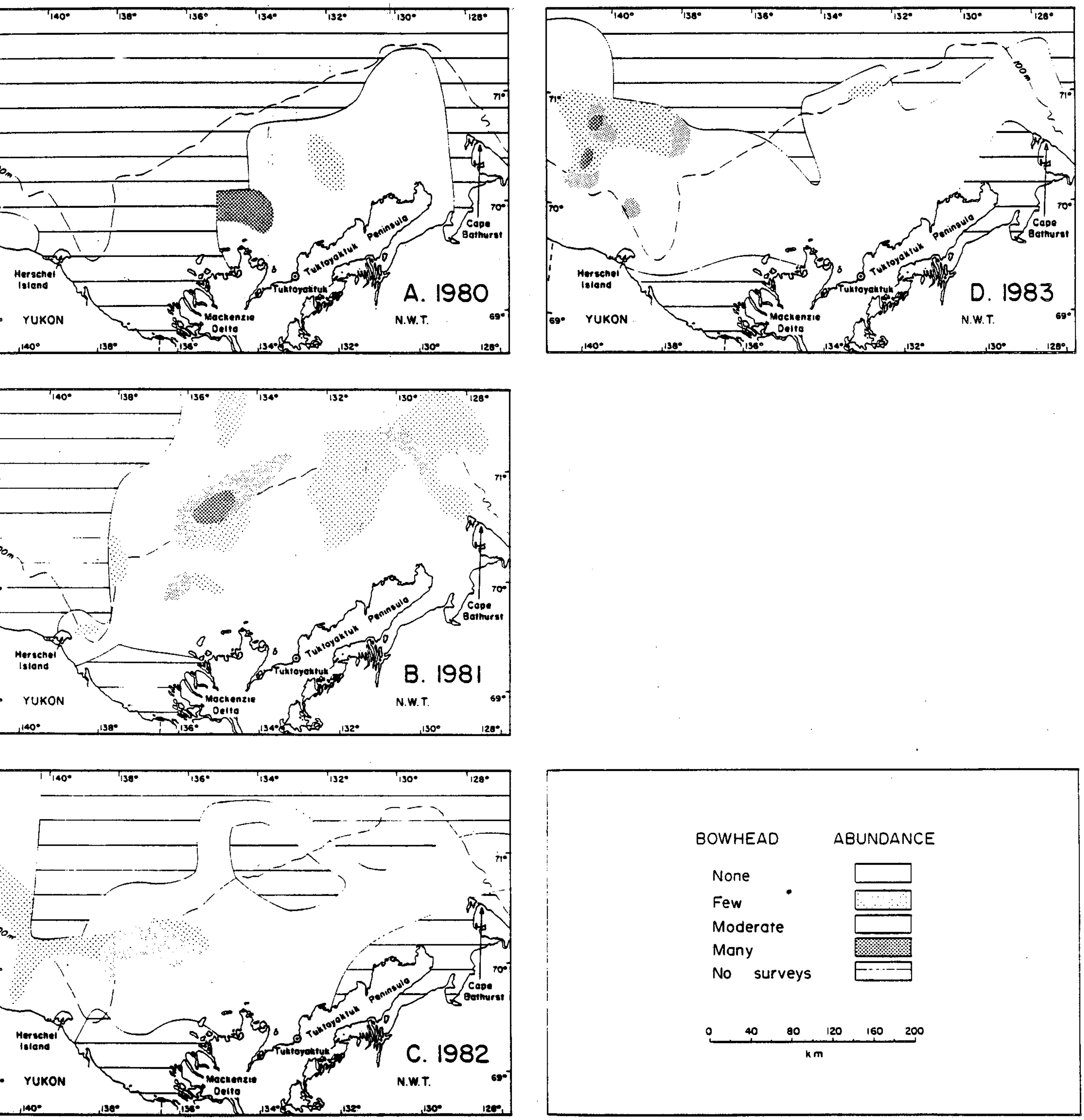

FIGURE 22. Distribution of bowheads in early August of 1980, 1981, 1982 and 1983.

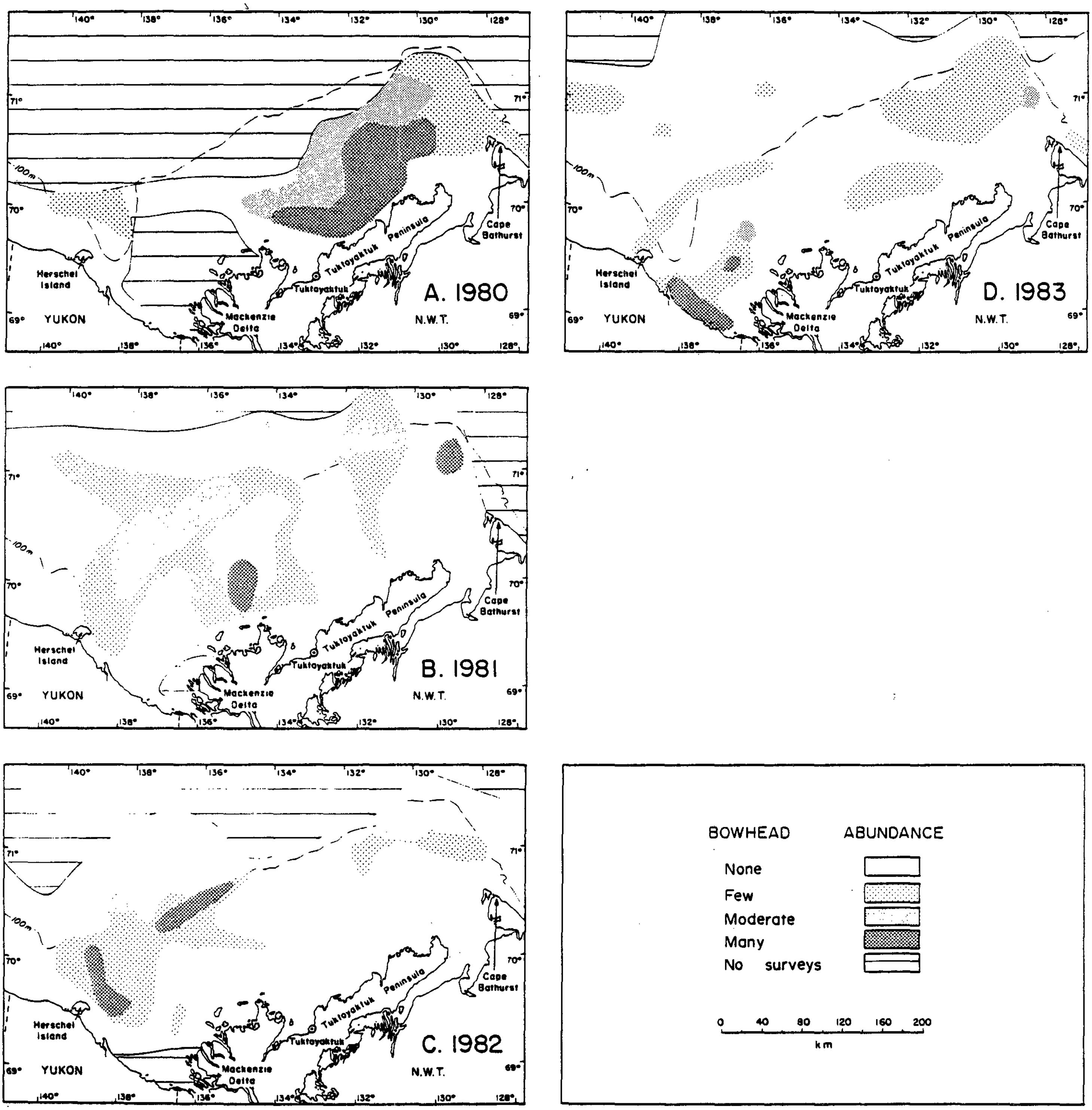

FIGURE 23. Distribution of bowheads in late August of 1980, 1981, 1982, and 1983.

Early August. -- Distribution in early August 1983 was very different than in 1980 and 1981, and somewhat similar to that in early August 1982 (Fig. 22). In 1980, many bowheads were in shallow water north of the Mackenzie Delta; there was almost no information about numbers north of the Yukon. In early August 1981, bowheads were widely distributed on the outer part of the continental shelf, mainly near the ice edge and the shelf break. The appearance of whales along most of the outer shelf off the Delta and Tuktoyaktuk Peninsula in mid August 1981 suggested that whales were moving more or less south on a broad front in early and mid August 1981. In early August 1982, whales were not as widely distributed; the only area with sightings was on the outer part of the shelf off the western Delta and the Yukon coast (Fig. 22C). Many of the whales off the Delta were moving west, and some whales were present on the outer shelf in the Alaskan Beaufort Sea (Ljungblad et al. 1983). Similarly, in early August 1983, virtually all of the bowheads seen in Canadian Beaufort Sea were on the outer shelf far north of the Yukon, in or near the ice (Figs. 3, 22D).

Mid August. -- In each of the four 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 the whales were already in shallow water in early August, but in 1981 and 1982 the shift was more dramatic. In mid August 1982, the only large concentration of bowheads within the eastern Beaufort Sea was near Herschel Island, off the Yukon coast. In mid August 1983, a concentration of several hundred bowheads, mainly subadults, was found very close to the Yukon shore southeast of Herschel Island. This was the largest nearshore concentration detected since detailed studies began in 1980. There were no surveys near this part of the Yukon coast in early August 1983, so it is possible that whales were there before mid August. However, the lack of reported sightings by pilots and industry personnel in early August suggests that there was no large concentration of whales close to shore before mid August 1983. Sightings by our boat crew and industry personnel showed that some whales were in shallow water (about 25 m) north of Tuktoyaktuk and Richards Island in mid August 1983.

Although movement toward shore occurred each year in mid August, the area of concentration was not the same in different years. In 1980, the major nearshore concentration was in shallow water off the eastern Delta and western Tuktoyaktuk Peninsula. In 1981 it was off the central Delta. In 1982 it was much farther west, in rather deep water just northeast of Herschel Island. In 1983, the major nearshore concentration was in very shallow water along the Yukon coast southeast of Herschel Island.

Late August. — Distributions in late August were related to those in early and mid August, and again were quite different in the four years. In 1980, there was a large area of concentration off the Tuktoyaktuk (Tuk) Peninsula and eastern Delta (Fig. 23A). The center of distribution had shifted eastward relative to that earlier in the month. Few whales were found farther west, although survey coverage there was meagre. In 1981, the areas of greatest abundance were in shallow waters off the central Delta and in deeper waters near the shelf break off the eastern Yukon, Delta and, to a greater extent than in mid August, the Tuk Peninsula (Fig. 23B). In late August 1982, whales were still concentrated near Herschel Island, but there were also concentrations near the steep shelf break off the Delta and, to a lesser extent, off the eastern Tuk Peninsula (Fig. 23C). In 1983, the major nearshore concentration of subadults persisted along the Yukon coast in late August. Whales were widely distributed at low densities on the outer shelf, especially off the Tuk Peninsula (Fig. 22D).

Early September. — Distributions differed less among years in early September than in August. Nonetheless, there were again considerable year to year differences. In 1980, numerous whales remained off the Tuk Peninsula, although farther offshore than in August (Renaud and Davis 1981; Hobbs and Goebel 1982; Richardson et al. 1983a). Also, whales appeared close to shore off Herschel Island. In 1981, whales moved closer to shore off the Tuk Peninsula in early September than they had been in August (Davis et al. 1982). 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 Island, but there were a few sightings off the Delta and Tuk Peninsula (Harwood and Ford 1983; Richardson et al. 1983a). In early September 1983, whales were widely distributed on the outer shelf off the Tuk Peninsula (very similar to the pattern in early Sept 1980), with a few off the Delta and Yukon (Fig. 17, 21).

One notable feature of bowhead distribution during early September of 1980-83 was the consistent occurrence of whales as far east as the Tuk Peninsula, and sometimes to or beyond Cape Bathurst. Although some bowheads occur in the Alaskan Beaufort Sea as early as August or early September (Ljungblad et al. 1982, 1983; Braham et al. 1984), many remain in Canadian waters in early and mid September. Davis et al. (1982) estimated that over 2500 bowheads were in the Canadian Beaufort Sea and Amundsen Gulf as late as 7-14 September in 1981. McLaren and Davis (1984) estimated that over 1700 bowheads were in the part of the Canadian Beaufort Sea that they surveyed on 6-11 September 1983, and additional bowheads were found by other investigators in areas not surveyed by McLaren and Davis (see Results). While some bowheads feed in Alaskan waters at this time, a major fraction of the population remains in Canadian waters until later in September. There have been sightings in Canadian waters as late as mid October (Ljungblad et al. 1983), but these are exceptional.

Bowheads were seen northeast of Herschel Island in early September of 1980-82, and were there in especially large numbers in mid and late August 1982. Bowheads also were found near Herschel Island in late summer and early autumn 70-90 years ago (Fraker and Bockstoce 1980). However, this pattern was broken in 1983, when very few bowheads were seen just north or northeast of Herschel Island at any time during late summer.

During the 1970's, bowheads were often seen along the Yukon coast southeast of Herschel Island in late summer (Fraker and Bockstoce 1980). The most impressive sighting was of 33 bowheads within a few kilometres of shore between Shingle and Kay Points on 13 September 1976 (W.R. Koski, LGL Ltd., cited in Fraker and Bockstoce). Aerial and shore-based surveys in 1980-82 showed that, in those years, there was no such coastal concentration; numbers were much lower than off Herschel Island. However, in 1983, several hundred bowheads were along the Yukon coast between Shingle and Kay Points from at least 14 to 28 August; they were no longer present on 6 September. In 1983, most if not all whales along this coast in August were subadults. The ages of those present here during September in the 1970's are unknown.

Distribution in Relation to Industrial Activities

Behavioral studies have shown that bowheads swim away from approaching boats and sometimes dive or move away as aircraft fly low overhead. However, bowhead behavior seems to return to normal after the boat moves away or the aircraft ceases flying directly overhead (Fraker et al. 1982; Richardson et al. 1983c, 1984). There is also limited evidence of avoidance of drillship and perhaps dredge noise when it first begins. On the other hand, we have seen bowheads on various occasions within a few kilometres of operating drillships and dredges, and in areas ensonified by strong seismic noise (levels up to ~150 dB//1 μPa). These whales were not swimming away from the drillships, dredges or seismic boats, and alterations in behavior were either absent or, at most, subtle and barely detectable.

Although short-term reactions to offshore oil exploration seem to be brief or absent, 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 the only straightforward way to address these questions.

In Figure 24, the primary areas of offshore industrial activity in early August of each year are superimposed on the maps summarizing bowhead distribution in early August. Similarly, in Figure 25, the areas of industrial activity in mid and late August of each year are superimposed on the maps of bowhead distribution in late August. The 1980-82 maps are based on the detailed maps in Richardson et al. (1983a). For 1983, the boundaries of the industrial areas are based on the industrial activity maps in the Results. Industrial activities have been separated into two types: (1) site specific activities such as dredging, island construction and drilling, along with vessel and helicopter traffic in support of those activities, and (2)

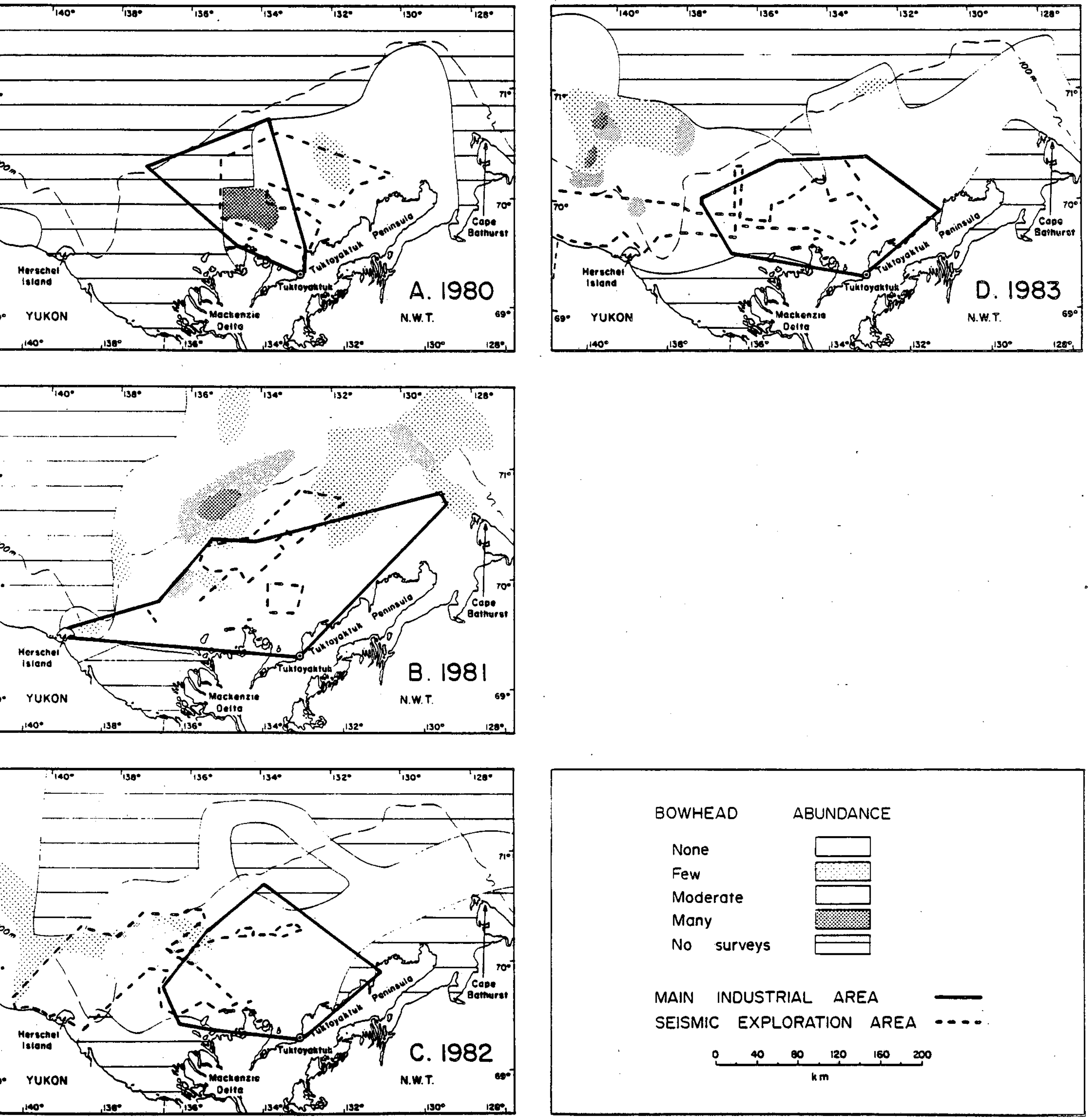

FIGURE 24. Distribution of bowheads in early August of 1980, 1981, 1982 and 1983 in relation to the area of industrial activity in early August.

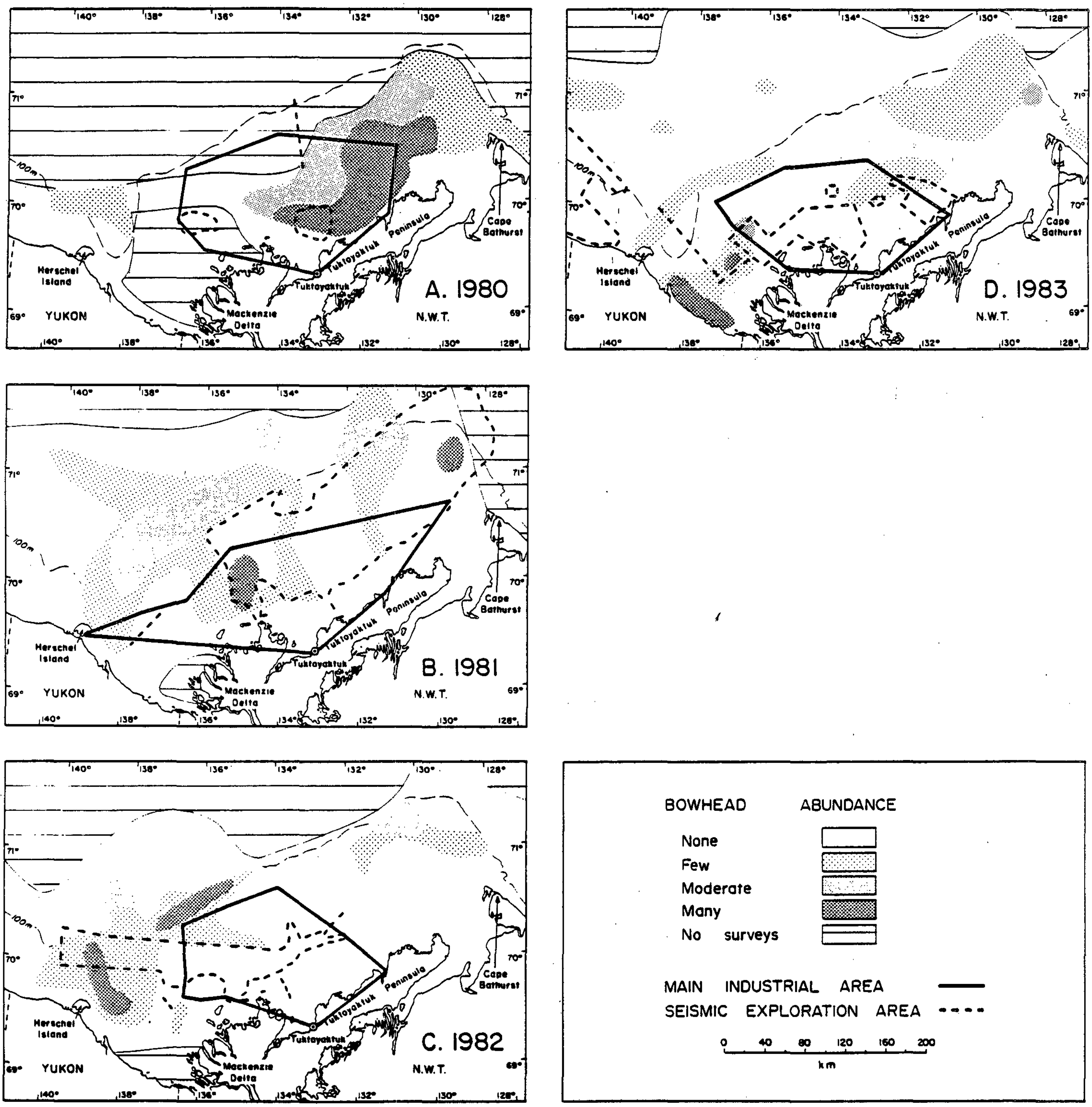

Figure 25. Distribution of bowheads in late August of 1980, 1981, 1982 and 1983 in relation to the areas of industrial activity in mid and late August.

offshore seismic exploration. The area with activities of type 1 is referred to here as the 'main industrial area'.

Bowheads and the Main Industrial Area

1980 to 1982. -- 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 August (Figs. 24A-C) and late August (Figs. 25A-C; see Richardson et al. 1983a for details). Bowheads were abundant within the main industrial area in 1980, much less abundant there in 1981, and virtually absent in 1982.

1983. -- In 1983, bowheads were again scarce in the main industrial area throughout August and early September. They were apparently virtually absent from that area in early August (Figs. 3, 24A). There were some sightings there in mid August, but no major concentration of bowheads was observed. The situation was similar in most of late August. However, during the last few days of the month there was one significant concentration of whales northwest of the Mackenzie Delta (Figs. 17, 25D). Parts of this concentration were only 10-20 km from the Pitsiulak drillsite and the Kadluk island construction site, and were along a main helicopter route. These whales were also exposed to seismic noise from at least two seismic vessels. Overall, however, only a small fraction of the Western Arctic bowhead 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 (Figs. 11-13; 25D) and far to the east near Cape Bathurst and in Franklin Bay (Cubbage et al. 1984; McLaren et al. 1984). The concentration northwest of the Delta persisted into early September (Fig. 17). However, a systematic survey on 6-11 September showed that most of the bowheads in the Canadian Beaufort Sea were outside the main industrial area (Fig. 21).

General Trend. -- In August and early September of 1983, few of the Western Arctic bowheads were in the main industrial area at any one time. There was also no evidence of any major movement through that area. Maximum numbers in the main industrial area in 1983 were apparently slightly greater than in 1982, but were less than in 1981 and much less than in 1980.

Quantitative data are lacking, but the number of bowheads in the main industrial area in the summers of 1980 through 1983 could be described qualitatively as many, some, very few, and few, respectively. We do not consider the difference between 1982 (very few) and 1983 (few) to be significant. Thus, there was no clear indication of a reversal, in 1983, of the 1980-82 trend for reducing numbers in the main industrial area.

In interpreting this trend, it is noteworthy that intensive offshore oil exploration had been underway in the same general area since 1976 (see Richardson et al. 1983a). Thus, the appearance of many whales within the main industrial area in 1980 occurred some four years after offshore operations in that area became intensive. Also, many whales were seen in shallow water off the eastern Delta and western Tuk Peninsula in early August of 1976 and 1977 but not in 1978 or 1979 (Richardson et al. 1983a, p. 334-338).

In summary, bowheads were numerous in the part of the industrial area off the eastern Mackenzie Delta in early August of 1976 and 1977, not numerous in 1978 or 1979, very numerous in 1980, less so in 1981, and not numerous in 1982 or 1983. Given the presence of many whales in 1980, there is no clear trend for decreasing numbers of whales after the onset of intense industrial activity in this one small area in 1976. However, the intensity of offshore industrial activities in the study area has increased gradually since 1976, so it is possible that industry has begun to affect bowhead distribution since 1980.

In last year's report we suggested that, if bowheads return in large numbers to the main industrial area in the summer of 1983 or 1984, then it will be much clearer that oil exploration is not the main factor responsible for summer to summer variations in bowhead distribution. This report shows that bowheads did not enter the main industrial area in very large numbers in 1983. If the situation in future years is similar, then the contrast with the abundance of whales in 1976, 1977 and especially 1980 will become more striking, and a connection with industrial activity will be more probable.

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 and dredging in 1980-83. 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 1984). The discontinuity in seismic noise has two components: (1) Noise from each seismic ship was pulsed; pulses were <1 s in duration and were spaced several seconds apart. (2) No more than four seismic vessels worked in the Canadian Beaufort Sea at any one time in 1980-83; some seismic vessels ranged widely and others worked within local areas, but at any given time strong seismic noise was present in only a fraction of the general area where the seismic vessels were working.

1980 to 1982. -- In these years, there was progressively less whale use of areas with dredging, island construction and drilling, but there was no similar trend for decreased use of areas with seismic exploration (Figs. 24A-C, 25A-C; see Richardson et al. 1983a for details). Seismic exploration occurred in the shallow areas off the eastern Mackenzie Delta every year from 1971 to 1982, including 1976, 1977 and 1980 when many bowheads were present. Concentrations of bowheads continued to overlap with areas of seismic exploration in 1981 and 1982, despite the fact that few whales entered the main industrial area in those years (Figs. 24B,C, 25B,C).

1983. -- In general, fewer whales were found inside areas of seismic exploration in 1983 than in 1980-82 (Figs. 24, 25). However, whales far north of the Yukon coast and Tuk Peninsula probably were often exposed to noise from distant seismic exploration, as were the few whales that entered the main industrial area.

In **early August 1983,** numerous bowheads were present in deep water far north of the Yukon (Figs. 3, 24A). At this time there was seismic exploration near the southern edge of the area containing whales (Fig. 5). On 7 and 9 August, we observed some of these bowheads when they were exposed to noise from a seismic vessel 80 and 57 km to the south and SW, respectively

(Richardson et al. 1984). The received levels were at least 131 and 123 dB//1 μPa (Greene 1984). Many of the other whales in the area must also have been exposed to such sounds during early August 1983.

Aerial surveys in **mid August 1983** did not locate many bowheads near seismic vessels. However, the few whales found far offshore near the Yukon-Alaska border may have been exposed to noise from distant seismic exploration closer to shore (Figs. 7, 9). Sound measurements by our boat crew showed that the few bowheads near the Amerk dredging site NNW of Tuktoyaktuk on 13 August were exposed to seismic as well as other industrial noise (Greene 1984; Richardson et al. 1984).

The large number of whales within 15 km of the Yukon coast SE of Herschel Island were not exposed to significant seismic noise on any of the six days in mid or late August when we dropped sonobuoys there. It is unlikely that they were ever exposed to strong seismic signals in mid August, given the lack of seismic exploration nearby (Fig. 9) and the rapid attenuation of seismic sounds in shallow water (Greene 1983). They may have been exposed to noise from distant seismic exploration on one or two occasions in late August (Fig. 15).

In **late August** and **early September 1983**, as in mid August, the few whales found far offshore near the Yukon-Alaska border probably were exposed to noise from seismic vessels operating closer to the Yukon (and Alaskan) shore. Similarly, whales off the Tuk Peninsula probably were exposed to noise from seismic vessels operating closer to shore in that region (Fig. 25D; see Figs. 11 and 13 vs. Fig. 15 for details in late August; see Figs. 17 and 21 vs. 19 for early September). Whales northwest of the Mackenzie Delta definitely were exposed to seismic noise on 31 August and 1 September; received levels were at least 128 and 136 dB, respectively (Greene 1984; Richardson et al. 1984).

Recurrence in Areas of Seismic Exploration. — Considerable numbers of bowheads were seen in areas with seismic exploration each summer from 1980 to 1983. However, areas where major concentrations of whales overlapped with seismic exploration in one year did not contain major concentrations of whales the following year (Figs. 24, 25). In the summer of 1983, no major concentration of bowheads overlapped with an area of seismic exploration, although many whales were exposed to noise from distant seismic vessels.

The 1980-83 results might suggest a gradual reduction in use of areas where seismic exploration occurs in summer, but consideration of earlier observations casts doubt on this interpretation. The occurrence of many whales in shallow water north of Tuktoyaktuk in 1976 and 1977 (Richardson et al. 1983a) and particularly 1980 (Figs. 24A, 25A) shows that an area of intense seismic exploration is not necessarily avoided in subsequent years. Seismic exploration has occurred in this area every summer since 1971.

This observation is corroborated by the recurrence of whales off Tuk Peninsula in late August and early September of 1981, 1982 and 1983 despite seismic exploration nearby at those times in 1980, 1981 and to a much lesser extent 1982 (Figs. 25A-D). Acoustic measurements near bowheads in this area in 1980 confirmed that, at least in that year, some bowheads definitely were exposed to strong seismic noise (Greene 1982). Also, bowheads occurred in deep water far north of the Yukon in early August of 1982 and 1983 (Figs. 24C,D) despite seismic exploration there in the late July-early August period in 1981 and 1982 (Figs. 19 and 41 in Richardson et al. 1983a). On one date in early August 1982 we confirmed that some bowheads definitely were exposed to seismic noise in this area (Greene 1983; Richardson et al. 1983c).

These observations suggest that seismic exploration has not caused large scale abandonment of parts of the summer range. However, nothing is known about the recurrence of specific individual whales at places where they were exposed to seismic noise in previous years. It is possible that the whales seen off Kugmallit Bay in 1980, off the Yukon in 1982 and 1983, and off the Tuk Peninsula in late summer of 1981-83 were not the same ones that were there in previous years. The recent development and use of techniques for recognizing individual bowheads (Davis et al. 1982, 1983; Cubbage et al. 1984) provides a method by which this question can be addressed.

Natural Factors Affecting Bowhead Distribution

The predominant activity of bowheads in summer is feeding. Analyses of food abundance in relation to energy demands suggest that bowheads must concentrate their feeding in areas of above-average plankton abundance (Brodie 1981; Griffiths and Buchanan 1982). The latter authors have demonstrated that copepod abundance in areas with bowheads tends to exceed that in other areas nearby. Copepods and euphausiids are apparently the main food items for bowheads in the Alaskan Beaufort Sea during early autumn (Lowry and Burns 1980; Lowry and Frost 1984), and presumably are also important to bowheads in summer. Thus, factors affecting the availability of these and other food organisms in the eastern Beaufort Sea probably have a strong influence on the distribution of bowheads. Variations in the distributions of some other species of baleen whales are related to variations in their food supplies (see Würsig et al. 1984 for review).

There has been little quantitative study of zooplankton in the Canadian Beaufort Sea, and no specific study of year-to-year variations in its abundance in different parts of the area. Thus, it is impossible to assess whether the observed year to year variations in bowhead distribution have any connection with variations in zooplankton abundance. However, relative abundance of zooplankton in different parts of the bowheads' summer range could be influenced by year to year variations in (1) the quantity and motion of fresh water from the Mackenzie River, (2) ice conditions, and (3) hydrographic phenomena at the shelf break and elsewhere (see Richardson et al. 1983a, p. 349-352, and LGL, ESL and ESSA 1984 for reviews).

At present, detailed data on bowhead distribution have been collected for only four years. This has been long enough to document pronounced year to year changes in bowhead distribution, but not long enough to allow a judgement about the role of offshore oil exploration in affecting that distribution. If continued studies show that bowheads return to the main industrial area as they did in 1980, then there will be 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. On the other hand, if a distribution similar to that seen in 1980 does not recur soon, then 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 river flow, wind, ice and upwelling 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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