CHARACTERISTICS OF
WATERBORNE INDUSTRIAL NOISE, 1980-84*

By

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TABLE OF CONTENTS

ABSTRACT

This section documents underwater sounds to which bowhead whales were exposed during disturbance experiments and other behavioral observations in the Canadian Beaufort Sea, 1980-84. Data were collected with calibrated low noise hydrophones suspended 3-18 m beneath a sparbuoy, and with sonobuoys dropped and monitored from the aircraft used to study bowhead behavior. Results are for hydrophone depth 9-18 m unless otherwise stated. Laboratory analysis included power spectrum analyses of continuous sounds, and waveform and peak signal analyses for seismic survey pulses. Overall levels are given for the 20-1000 Hz band, which includes most components of the industrial and bowhead sounds.

Ambient noise ranged from below the typical values for sea state zero to high levels characteristic of storms at sea. The median level for the 20-1000 Hz band in August 1980-84 was 99 dB, equivalent to sea state three.

Fixed-wing aircraft sounds beneath the aircraft averaged a few decibels greater at 3 m depth than at 9 m. Noise levels were highest when the passing aircraft was low, but peak levels persisted for only a few seconds, especially at low aircraft altitudes. During straight line passes, aircraft were audible for longer in shallow than in deeper water. Sounds from an Islander and Twin Otter included numerous tones at frequencies related to propeller and engine rotation rates.

Helicopter sounds included tones associated with the main and tail rotor rotation rates. The overall levels below a Bell 212 were 3 dB higher for passes at 305 m altitude than for 610 m. For oblique passes, the shallow (3 m) hydrophone detected the lowest levels.

Boat and ship sounds for the 20-1000 Hz band included the following:

-Crew boats underway	118 dB at 0.2 km	105 dB at 4.6 km
-Supply & survey boats underway	129 dB at 0.2 km	103 dB at 4.6 km
-'Geopotes X' dredge underway	150 dB at 0.5 km	131 dB at 7.4 km
-Anchored supertanker	120 dB at 0.2 km	95 dB at 9.3 km

'Geopotes X' was the strongest source of continuous noise studied during this project. Received levels of boat noise were usually several dB less at depth 3 m than at 9-18 m, as expected for an in-water source.

Seismic signals from sleeve exploders, open-bottom gas guns, airgun arrays, and a single airgun were similar. Propagation in shallow water elongated the initially-sharp pulse into a longer pulse with quasi-sinusoidal waveform gradually decreasing in frequency. At ranges of a few kilometres, waterborne pulses are typically 0.25-0.5 s long. The predominant frequency at the leading edge of the pulse is often 200-400 Hz, diminishing to 100-200 Hz at the end of the pulse a fraction of a second later. Energy at frequencies <100 Hz is rapidly attenuated in shallow water, but can travel long distances in some sediments and may reenter the water far from the source. The strongest seismic signal recorded was 177 dB//1 μPa from an array of open bottom gas guns at range 0.9 km. Signals from airgun arrays ranged from 160 dB at 12 km to ≤110 dB at 75 km. Received levels were several dB less at depth 3 m than at 9 or 18 m.

Drillship sounds, including adjacent support vessels, were as follows:

-'Explorer I', logging	122 dB at 0.17 km	100 dB at 10.3 km
-'Explorer II', drilling	134 dB at 0.2 km	111 dB at 7.4 km
-'Kulluk' CDU, drilling	143 dB at 0.9 km	117 dB at 14.8 km

Dredging sounds recorded near suction and hopper dredges were as strong as 145 dB 0.6 km from a hopper dredge that was loading, and 118 dB from a dredge at range 14.8 km. Hopper dredge sounds tended to vary over time. Caisson-retained islands where there was construction, well testing, or drilling produced sound levels of 130 dB at ranges 0.22 to 1.1 km, and 111-118 dB near 3.8 km. Some of this noise came from attending support vessels.

In general, many industrial sources increased the level of continuous noise (20-1000 Hz band) by about 25 dB at 1 km radius and 10 dB at 10 km radius, relative to the median ambient level. The noisiest ships produced higher levels. Noise pulses from seismic surveys were far stronger and often detectable ≥50 km away.

INTRODUCTION

Marine mammals (including bowheads) use sound to communicate and to receive information about their environment. Sound travels very efficiently in water, day or night, winter or summer, and regardless of the water's clarity. At least in deep water, the intense, low-frequency sounds produced by baleen whales, including bowheads, are believed to be transmitted especially well and with little attenuation (Payne and Webb 1971). The very advantages of underwater sound so useful to marine mammals give rise to potential problems related to underwater industrial sounds (Acoustical Society of America 1981). Many industrial sounds are also intense and of low frequency, and consequently are transmitted efficiently over relatively long distances. Thus, the acoustic effects of industrial operations may be manifested far from their source, and this greatly expands the area potentially affected. Possible ways in which underwater industrial sounds could affect whales include direct disturbance and the masking of important communication, echolocation and/or environmental sounds (Møhl 1981; Richardson et al. 1985).

From 1980 to 84, the Bureau of Land Management and Minerals Management Service, U.S. Department of the Interior, have supported a study of the behavior of bowhead whales and how they may be influenced by oil industry activities offshore in the Beaufort Sea. Motivation for the research came from the potential for oil exploration and development north of Alaska, and questions about its effects on bowheads. However, the field work was conducted during August of 1980-84 in the Canadian part of the Beaufort Sea, east of Alaska (Fig. 1.). Bowheads feed there at that time, and offshore oil exploration is considerably more advanced in the Canadian than in the Alaskan part of the Beaufort Sea. Thus, the Canadian Beaufort Sea provided a study area with both animals and potential sources of disturbance.

Approach

Our general approach to the research centered on boat- and airplane-based observations of whale behavior and measurements of underwater sounds. It was important to know what sounds the whales were exposed to while being studied from the air, and the air crew deployed sonobuoys and recorded the signals on the airplane. The boat crew, which included the acoustician, recorded signals from hydrophones deployed from a sparbuoy drifting near the boat. The boat motored to various industrial sites to record the sounds of dredges, drillships, boats, and artificial islands; it anchored in open areas to record the sounds of passing ships and aircraft. In 1980-81 we attempted shore-based studies of sounds and whale behavior from camps at Herschel Island and King Point, Yukon Territory (Fig. 1), but bowheads were not close enough. In 1983-84 the whales were in those areas and we studied them from the airplane and boat.

An underwater projector was used from the boat to perform controlled 'playback' experiments. Previously recorded underwater industrial sounds were played back near whales being observed from the airplane. We also used a single 40 in^3 (0.66 L) airgun deployed from the boat to conduct controlled tests of bowhead reactions to seismic survey impulses. It was necessary to measure the sound levels to which bowheads were exposed during playback and airgun tests.

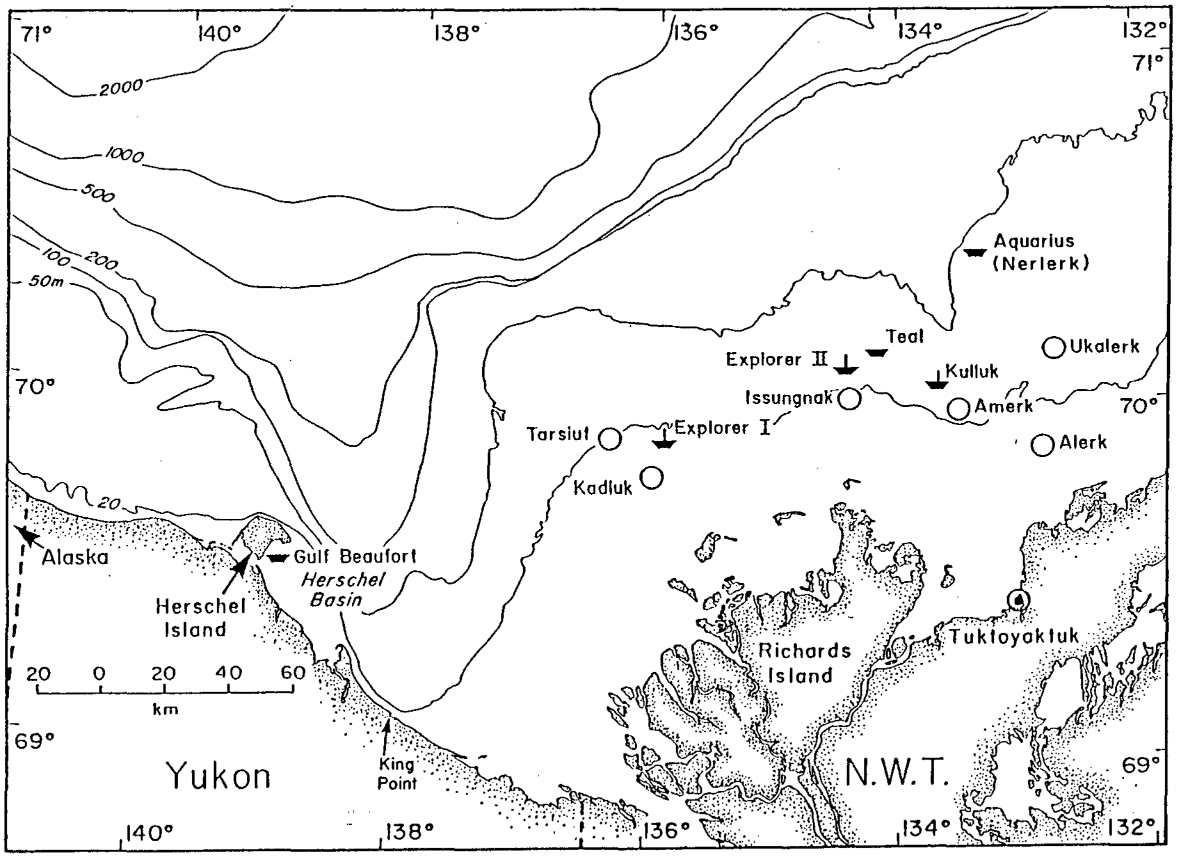

FIGURE 1. Map of the study area, east-central Beaufort Sea, showing major industrial sites mentioned in the text.

The report describes our experimental methods and equipment, the measurement results, and their significance. The results section is organized by type of sound source (e.g., aircraft, boats and ships, seismic survey signals, drillships, dredges), paralleling the preceding 'Disturbance Responses of Bowheads' section. For each type of industrial sound source, the report contains a review of what was known before, our own results, and a discussion.

Acoustic Terminology

This section is provided to acquaint readers who are not acousticians with the acoustical terminology used in this report. A good discussion of these terms appears in Ross (1976, p. 4-8). In the following discussion I have used the term 'signal' to mean the waveform of the sound pressure at the hydrophone. I am not distinguishing among the sources of that waveform as being signals or noises but include them all.

A simple form of a 'sonar equation' is

$$\text{Received level (dB//1 }\mu\text{Pa)} = \text{Source level (dB//1 }\mu\text{Pa at 1 m)} - \text{transmission loss (dB)}.$$

The terminology used in this equation is defined below. In general, the equation defines the transmission loss in terms of the difference in dB between the source level and the received level. Note that all terms in the equation may vary with frequency and with direction from the source. The equation could relate spectrum levels at source and receiver by changing the reference unit from 1 μPa to 1 $\mu Pa^2/Hz$.

dB, decibel: A unit on a logarithmic scale for sound levels. Sound pressure level in dB is defined by 20 log (P2/P1) where P2 is a pressure of interest, P1 is a reference pressure such as 1 microPascal, and the logarithm is to the base 10.

Source level: An idealized description of the intensity or power of a sound source in terms of a root mean square pressure at some short reference distance (e.g. 1 m) from the source. Idealization is essential because most sources of interest (e.g. drillship or dredge) are not point sources and an actual measurement at 1 m would not yield the effective source level. There is a strong possibility of inaccurately computing source level (at 1 m) from measurements at practical distances (say 200 m) when transmission loss from 1 m to the practical distance is assumed rather than measured. The uncertainty is especially high in shallow water.

Received Level: The sound level from a particular source of interest, as received at some location of interest. Conceptually, received level is the source level reduced by the transmission loss for the distance between source and receiver.

Tone: A signal component whose energy is at one specific frequency--i.e., whose bandwidth is infinitesimal or at least small compared to the resolution bandwidth of a spectrum analyzer. It is difficult to present tones and broadband components on the same graph correctly because the ordinates differ: dB//1 μPa for tones and dB//1 $\mu Pa^2/Hz$ for broadband components.

Spectrum Level: This is a measure of sound intensity per unit frequency. It is usually expressed in dB referred to 1 microPascal squared per Hz (1 $\mu Pa^2/$ Hz), or to 1 μPa per square root Hz. 'Spectrum density' and 'power spectrum density' or 'power spectrum' are other terms used to describe the levels of broadband signals and noises. Generally, a sound is analyzed with some non-zero bandwidth filter and the result is 'reduced to a 1 Hz band' assuming implicitly that the spectrum is constant across the analysis band.

Broadband Level: The total mean square pressure level of a signal in a wide frequency band. 'Wide' generally means large compared to 1 Hz. The broadband level is obtained by integrating spectrum levels over the band. Narrowband components (tones) falling within the band should be included.

Spherical Spreading: The attenuation of intensity or power proportional to the square of the distance travelled. It is described in dB by 20 log (R2/R1) where R1 is the reference range. Often, R1 is 1 m and the relationship reduces to "spreading loss = 20 log (range in metres)". Ideally, spherical spreading is ascribed to sound propagation where the surface and bottom are far removed from the source and receiver, and the ray paths are not refracted significantly. With spherical spreading the attenuation rate is 6 dB per distance doubled.

Cylindrical Spreading: The attenuation of intensity or power proportional to the distance travelled. It is described in dB by 10 log (R2/R1) where R1 is the reference range. Ideally, cylindrical spreading is ascribed to sound propagation where the source and receiver are far apart compared to the water depth. The surface and bottom reflections or special channeling processes serve to retain the energy within the water. With cylindrical spreading the attenuation rate is 3 dB per distance doubled.

Units of Pressure: 1 Pascal = 1 newton/m^2
1 μbar = 1 dyne/cm^2
1 Pascal = 10 μbars
100,000 μPa = 1 μbar

Thus, sound level (dB//1 μPa) = sound level (dB//1 μbar) + 100.

METHODS

Two main data collection systems were used: the system used on the airplane to record sonobuoy signals, and the system used on the sound boat. This section also describes the analysis techniques.

Airplane System

The airplane sound recording system was based on sonobuoys. During flights to observe whales, at least three sonobuoys were carried. On most occasions when whales were found and observations of their behavior were to be made, at least one sonobuoy was deployed. Occasionally a second sonobuoy was deployed nearby, sometimes with a second group of whales, sometimes with the first group after it had moved away from the first sonobuoy, and sometimes at a different distance from a nearby source of actual or simulated industrial noise. Sonobuoy hydrophones were set to deploy to 18 m depth, with the exception of a few sonobuoys modified for 9 m deployment in 1981. Two calibrated receivers for sonobuoy FM radio signals were carried. The signals were recorded on the two channels of a calibrated Sony Model TC-D5M cassette tape recorder with servo-controlled capstan for precise speed control. The operator maintained a log of activities, sounds recorded, and tape recorder settings, and he made voice announcements at the beginning of each tape and otherwise as necessary. Positions were determined from the aircraft's VLF/Omega navigation system, and an airborne radar provided measurements of distances from industrial sites.

We used two types of sonobuoys: AN/SSQ-57A and AN/SSQ-41B. The 57A's are delivered with calibration data and the 41B's are not, but otherwise both models perform to the same specification. In 1980-81 we used the middle of the allowable response envelope as the calibration response for the 41B's. In 1982-84 we used the average of the 57A calibrations as the calibration for the 41B's. The two 41B calibrations were essentially the same. Comparison of results from the sonobuoy system and from simultaneous recordings with the calibrated hydrophones on the boat (see below) confirmed that the sonobuoy system provided accurate data on sound levels and characteristics.

To permit wider signal dynamic range without distortion, the sonobuoy acoustic response attenuates low frequencies relative to high frequencies. Sounds at 10 Hz are deemphasized by about 35 dB relative to those at 10 kHz (see Greene 1982, Fig. 2, p. 269, or Military Specification, sonobuoy AN/SSQ-41B, MIL-S-22793E (AS). U.S. Navy, 24 p., 1979). The rising slope of the sonobuoy response with increasing frequencies is roughly opposite to the falling slope of average sea noise (low frequency ambient sounds tend to have higher spectrum levels than do high frequencies). This procedure provides, on average, an overall flat ambient sound spectrum through the sonobuoy/receiver system. We corrected all received signal spectra to remove the effect of the sloped sonobuoy system response and to provide sound spectra based on a unit acoustic pressure of 1 µPa (microPascal), root mean square.

Boat System

The boat-based sound recording system used hydrophones suspended beneath a 4-6 m long sparbuoy made from 76 mm (3 in) i.d. PVC pipe. The sparbuoy drifted vertically near the sound boat and served to decouple the hydrophones from wave and boat motion. The boat was the 14-m wooden-hulled ketch 'Ungaluk' in 1980 and the 12.5-m fishing boat 'Sequel' in 1981-84. The hydrophones were of two types: (1) U.S. Navy model H56 wide band, low noise hydrophones, and (2) low frequency, low noise bender hydrophones made by Polar Research Laboratory. Both types had preamplifiers with the sensing element. The nominal sensitivity of the H56's was -172 dB//1v/µPa (dB referred to 1 volt per microPascal); the nominal sensitivity of the benders was -152 dB//1v/µPa.

In 1980 we attempted to make the recordings with hydrophone depth 18 m, for compatibility with the sonobuoys, but shallower water forced compromises. In 1981-82 we adopted 9 m as the standard hydrophone depth. In 1983-84 we used a vertical string of hydrophones at depths 3, 6, 9, and 18 m. (Not all these depths could be recorded all the time.)

We always used a Sony Model TC-D5M cassette tape recorder (low noise, servo-controlled capstan drive for constant tape speed) on the boat, as on the airplane. On the boat in 1983-84 we also had a Fostex model 250 4-channel cassette recorder, permitting simultaneous recording of hydrophones at multiple depths. All equipment was battery-powered.

To test the reactions of bowhead whales to playbacks of recorded industrial sounds, we used a U.S. Navy model J11 underwater sound projector driven by a 250 watt Bogen power amplifier. We operated the projector at depth 9 m. A monitor hydrophone was mounted (1982) or suspended (1983-84) a measured distance (1.9 m in 1982; nominally 1 m in 1983-84) in front of the projector face to measure the projected sound level. The sample of industrial sound being played back was recorded on a two-minute tape loop.

Other essential equipment on the boat included radar for distance measurements to industrial sources, coastlines, etc., a satellite navigation set to determine geographical positions accurately, and marine VHF and HF radios for communications. There was also a portable aviation VHF radio for communication with the project airplane. All recording and playback equipment was battery-powered; no generator or other engines were running on the boat during acoustical work, although a small refrigerator compressor motor sometimes ran.

Data Analysis

The recorded signals were analyzed using an analog-to-digital converter and a general purpose digital computer to process the digitized samples. For data collected in 1980-82, the analysis was done with Polar Research Lab's Data General Nova 3. In 1983 the work was done partly at Polar Research and partly at Greeneridge on a Hewlett-Packard 9816 technical desktop computer. Some analyses were done on both systems to assure identical results. In 1984 all the work was done on the Greeneridge system.

Spectral Analyses

Sounds that continued more or less without change (continuous signals) were analyzed for their frequency content using Fourier analysis to compute average power spectra. The results were displayed in a graph of spectrum level (dB//1 $\mu Pa^2/Hz$) vs. frequency (Hz or kHz). The process began with lowpass filtering ('anti-aliasing') at a frequency just below half the sample frequency, then sampling and conversion to 12-bit numbers, and storage of the digitized data on disk. The sample size was typically 17,408 values. At a sample rate of 2048 samples/s, one of the standard rates, 8.5 s of data were stored.

Power spectrum analysis was done on weighted, overlapped blocks of data (Carter and Nuttall 1980). A block of samples, typically 2048 or 1024 samples in length, was multiplied by a 'window' function (Blackman-Harris minimum 3-term window, Harris 1978) to minimize 'leakage' of the power in one frequency cell from appearing in adjacent cells. The result was then analyzed with a fast Fourier transform routine to compute the power spectrum for that block. Then another block of samples was selected, half of which had been in the previous block; it was analyzed the same way as the previous block and the results were added to those from the previous block. This process was continued until the entire set of samples was analyzed and the averaged power spectrum determined. The parameters of power spectrum analysis and the relationship of sample frequency and analysis block size to spectrum cell spacing and resolution are presented in Table 1.

Table 1. Parameters of spectrum analysis. The number of cells in the resulting spectrum was always 1 more than half the number of samples in the block.

Sample Rate (samp./s)	Block Size (samples)	Data Averaged (s)	Cell Spacing (Hz)	Cell Resol. (Hz)	Analysis Range (Hz)
1024	1024	16.5	1	1.7	0-512
2048	1024	8.25	2	3.4	0-1024
2048	2048	8.5	1	1.7	0-1024
4096	2048	4.25	2	3.4	0-2048
4096	1024	4.125	4	6.8	0-2048
8192	1024	2.06	8	13.7	0-4096
16384	1024	1.03	16	27.4	0-8192

Our calibrations did not generally extend below 10 Hz and we did not compute results below that frequency. High and extremely variable levels of water and wave noise often dominated the very low frequencies, and 20 Hz was often the lower practical limit for consistent results. For an upper limit we selected 500, 1000, 2000, 4000, or 8000 Hz as appropriate for the sampling rate.

From the spectrum analysis results we derived two other types of results. One was the level of each tonal component in the sound. These sinusoidal components, which may themselves be harmonics of complicated periodic components, theoretically have an infinite power density because there is actually non-zero power at the exact frequency of the tone. We computed the level of each tonal component by removing the correction for the analysis cell bandwidth. The result was a sound level expressed in dB//1 µPa.

The other result derived from spectrum analysis was the sound level within a band of frequencies--the band level, expressed in dB//1 µPa. For specified band limits, we integrated the spectrum to compute the band level within those limits. We generally used the band from 20-1000 Hz, because most industrial (and bowhead) sounds contained very little power at higher frequencies. Because most industrial sounds were mainly at <500 Hz, band levels for 20-1000 Hz, 20-8000 Hz, etc., were usually <1 dB greater than those for 20-500 Hz.

Waveform Analyses

For transient signals, those with definite starts and finishes like seismic survey signals and bowhead tail slaps, we plotted the signal waveform and measured the peak amplitude. Transient signals generally took on an oscillatory form after travelling a few kilometres in the shallow water of the Beaufort Sea, and we converted the peak amplitude into an 'effective level' by (1) assuming a sinusoid of the measured peak amplitude, (2) determining the corresponding rms level, and (3) converting the result to a level in decibels referred to 1 µPa.

Waterfall Diagrams

It is often valuable to see how the frequency content of an acoustic signal varies with time. For example, during the fraction of a second while a waterborne seismic signal is received, its peak frequency decreases with increasing time when the receiver is more than 3 or 4 km from the source in shallow water. Whale calls often change in frequency across the duration of the call. Sounds from an aircraft wax and wane as it passes overhead. To display spectral amplitudes vs. frequency and time, we used a 'waterfall' spectrogram. The same discrete Fourier transform process used to compute average power spectral densities was used to compute the waterfalls except that (1) the overlap was 75-90% rather than 50%, and (2) the results of analyzing each block were not averaged but were presented in a tight progression of spectra plotted against time. The spectral magnitudes were plotted, not powers or log spectra, and all magnitudes were scaled relative to the largest magnitude in each waterfall display.

RESULTS AND DISCUSSION

Sound Propagation Conditions

Figure 2 presents some examples of sound ray paths computed from measured temperature-salinity-depth profiles in our study area. Urick (1983, p. 111-128) presents a useful discussion of sound velocity and ray paths. The upper 10 m of the depth dimension in Figures 2B and C demonstrate how an increasing sound speed with increasing depth causes sound rays to bend upward, reflecting from the surface but also being scattered by waves or ice. Figure 2A demonstrates how a decreasing sound speed with increasing depth causes sound rays to bend downward, reflecting from the bottom but also being absorbed and scattered. In fact, for the generally shallow waters studied, sound waves would be continually reflected from the surface and the bottom, continually losing energy to scattering and absorption.

Ambient Noise

Background

In discussions of underwater sound, the standard ambient noise fiducials have been the average noise spectra of Knudsen et al. (1948) for various sea states. His data were generally for deep water and did not extend below 500 Hz; his noise spectra were for 1 kHz and above. His curves show the ambient noise spectrum level to vary with sea state or wind force and to decrease at 5 dB per octave with increasing frequency. Knudsen's curves are often extended to lower frequencies by extrapolation at slope -5 dB/octave, although Wenz (1962) showed that noise at lower frequencies (10-200 Hz) depends strongly on shipping traffic density rather than wind force. Urick (1983, p. 202-236) presents a comprehensive discussion of ambient noise in the sea. Other reviews of ambient noise in cold water regions appear in Greene (1981) and Richardson et al. (1983). Shallow water noises can extend over a wide range of levels and should be measured on a site-specific basis.

In this report we use the sound level in the 20-1000 Hz frequency band as an overall summary value for industrial sounds. For comparison, the integrated 20-1000 Hz level for Knudsen's Sea State Zero spectrum extended to low frequencies is 87 dB//1 μPa. For Beaufort Wind Force Five (approx. 31-39 km/h; Sea State Four), the corresponding level is 107 dB.

Measurements

We did not make comprehensive measurements of underwater ambient noise, but numerous recordings were analyzed to determine background levels during bowhead observations and to compare with the strength of industrial sounds. The data summarized here were from recordings made specifically to document background noise. Weak industrial or aircraft sounds were sometimes present, but man-made sounds were not dominant. Such background sounds are a part of the ambient noise near the industrial part of the Beaufort Sea. When several ambient noise measurements were made at nearly the same time and place, we averaged them to obtain a single independent measurement. However, data from different hydrophone depths were not averaged. There were 81 independent measurements over the five years of study, although only 15 came from 1980-82. The data are the 20-1000 Hz band levels, in dB referred to 1 microPascal:

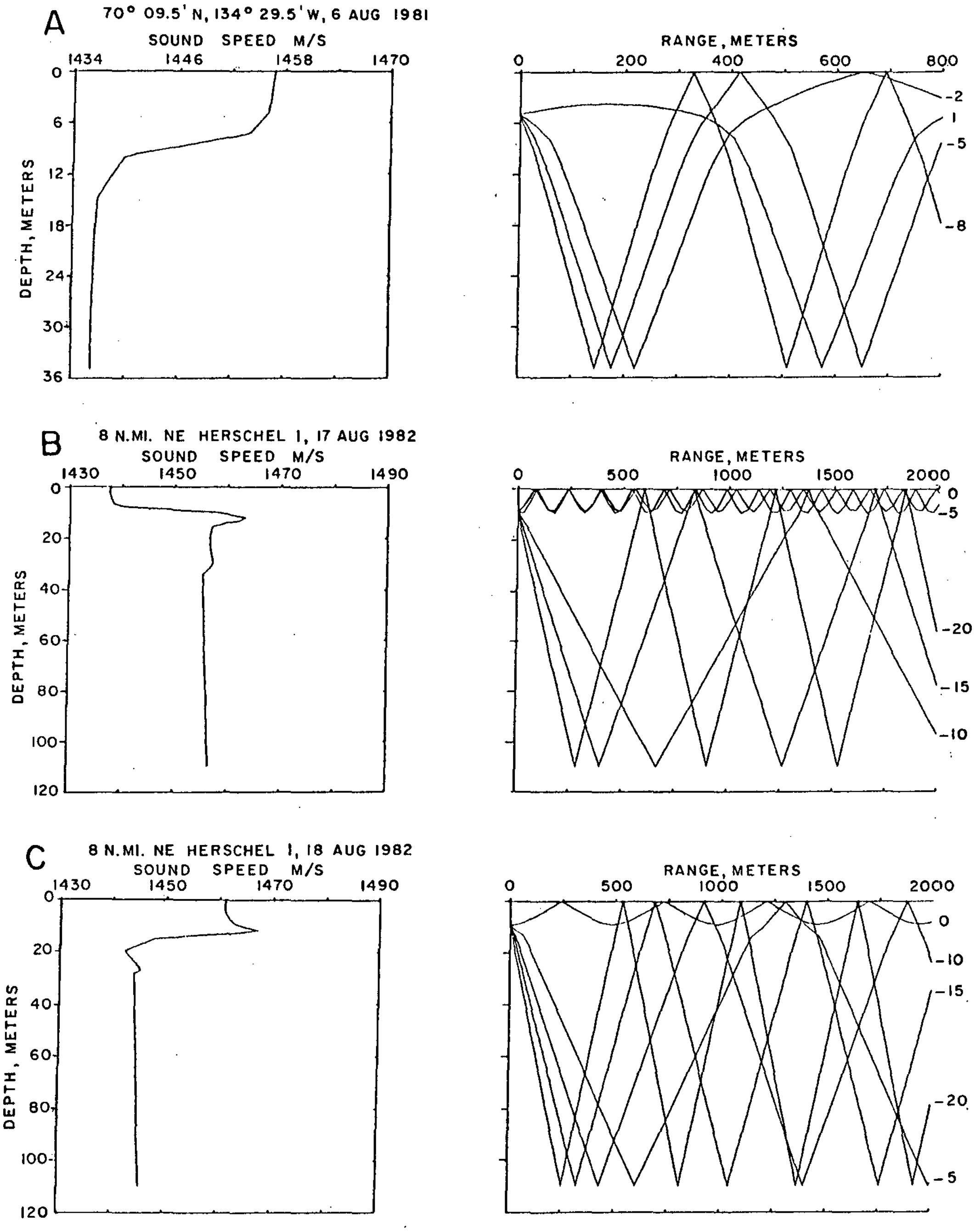

FIGURE 2. Sound speed profiles and examples of associated sound ray paths. **(A)** is from the industrially active area north of Tuktoyaktuk, 6 August 1981. The source depth for the ray paths was 5 m and the initial ray angles are specified at the right end of each ray. **(B)** is for the deeper (110 m) area northeast of Herschel Island from within an area dominated by ice. The cold surface water and the warmer layer beneath account for a shallow surface duct. **(C)** is the same area as **(B)** but one day later and without ice.

Measurement Source	Depth (m)	No. of Obs.	Percentiles 10%	50%	90%
Sonobuoys	18	29	86 dB	99 dB	111 dB
Boat	18	22	81	99	117
Boat	9	15	77	94	112
Boat	3	15	71	99	121

For comparison, the expected levels for sea states 0, 1, 2, 4 and 6 are 87, 95, 100, 107 and 112 dB, based on Knudsen's curves extended to low frequencies.

Median levels for the sonobuoy and boat measurements at hydrophone depth 18 m were the same, 99 dB. This is 1 dB less than the fiducial level (extended to low frequencies) of 100 dB for Sea State Two (wind 13-18 km/h). It is important to recognize that most measurements from both the boat and aircraft were made in low wind conditions (Sea State 0-3). Thus, our analysis excludes data from times expected to have high noise.

Analysis of the 1984 data alone revealed that the median level for hydrophone depth 3 m was 8 dB lower than the median level for depth 18 m. Adding the 1983 measurements resulted in a median level for depth 3 m equal to the median level at depth 18 m. In both 1983 and 1984, the range of the measured noise levels was greater at depth 3 m than at depths 9 and 18 m. Levels at 3 m were sometimes much higher than at 9 and 18 m depths, probably because of surface wave action that affected low frequencies (<40 Hz). This surface effect was not observed at depth 9 m.

Figure 3 presents five representative spectra for ambient noise observed during the project. In 1982 we worked with bowheads near an area of ice floes northeast of Herschel Island. Figure 3A is the background noise spectrum, frequency resolution 1.7 Hz over the 10-500 Hz band, detected with a sonobuoy near ice. The water depth was 80 m, the sea state was zero, and the ice coverage was 10%. Three strong tones appear from the Britten-Norman Islander airplane. The 10-500 Hz and 20-1000 Hz band levels for this sample were 97 and 98 dB, respectively. Excluding the three strong airplane tones, the band level was 96 dB. Figure 3B is the 160-8000 Hz spectrum, frequency resolution 27.4 Hz, for the same time. The 160-8000 Hz band level was 98 dB, exemplifying the observation that the energy in the noise was concentrated at lower frequencies. The high levels, relative to the expected values for sea state zero, were probably attributable to the ice. The dip in the spectrum near 3000 Hz is unexplained.

Figures 3C and 3D are presented to provide a comparison of the ambient noise spectra at hydrophone depths 3 and 18 m, respectively. At the time of the recording, 'Sequel' was in Mackenzie Bay, water depth 26 m, low sea state. The 20-1000 Hz band levels were 73 dB//1 µPa for depth 3 m and 85 dB for depth 18 m, exemplifying the common tendency for lower levels at shallow receiver depths. The relatively low level spikes at frequencies <60 Hz

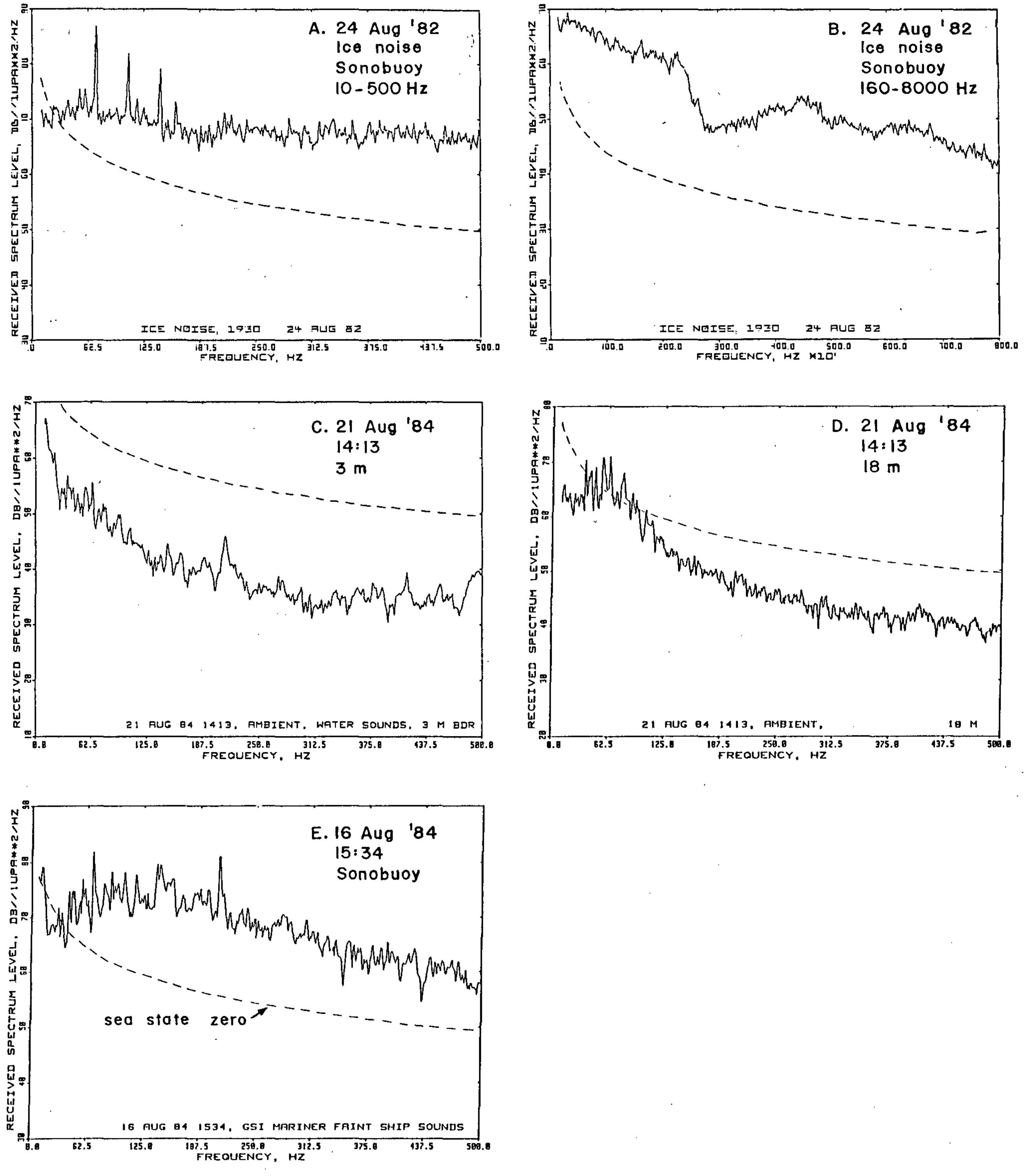

FIGURE 3. Examples of ambient noise sound pressure spectra. The extended sea state zero spectrum has been added for reference. Note the variable vertical scales.

suggest the presence of weak machinery sounds, probably from a distant source. This was a time of very low background noise.

Figure 3E shows the background noise spectrum in Mackenzie Bay just before the start of a disturbance experiment with a full-scale airgun array, 16 August 1984. The water depth was 18 m, as was the sonobuoy hydrophone depth, and the sea state was one. The 20-1000 Hz band level was 98 dB. Faint ship sounds could be heard, and the spectrum shows the presence of tones; these probably came from the vessel 'GSI Mariner', which was about 7.5 km from the sonobuoy.

Discussion

Our data show instances of sound spectrum levels well below Knudsen's fiducial curve for Sea State Zero extended, which is not surprising considering the shallow water, relatively calm weather, and the absence of shipping noises in some of the areas where we worked. At other times, we recorded high levels of ambient noise, similar to levels expected in stormy seas. We sometimes found that sound levels at depth 3 m were lower than at depth 18 m, as theory predicts for sound pressure near the air/water boundary (Urick 1983, p. 131-4). However, levels at 3 m depth in open water appeared to be strongly affected by wave action, and sometimes exceeded those at deeper depths. Greene and Buck (1964) reported measurements of ambient noise below ice in deep water (Beaufort Sea) and noted that the level was nearly constant below a depth corresponding roughly to one-half the wavelength. Above that depth the level decreased. In shallow water the effect would be modified by the influence of the bottom, depending on frequency, depth, and bottom material characteristics.

Aircraft Sounds

Background

The theory of sound propagation from a source in air to a receiver underwater has been well documented, but there are relatively few published measurements of aircraft noise in water (Medwin and Hagy 1972; Urick 1972; Waters 1972; Young 1973). Although sound power or energy is poorly transmitted from air into water, it is also true that sound pressure is rather well transmitted from air into water under the right circumstances. Snell's law predicts a critical angle of 13° from the vertical for the transmission of sound pressure from air into water. For greater angles the sound is totally reflected.

For vertical incidence, the sound pressure at the water surface is twice what the sound pressure would be at that distance from the source if the water were not present. Within the water, the levels decrease as the receiver depth increases. For receivers not directly beneath the source, the pressure pattern is complex. For intermediate lateral distances, on the order of the aircraft height and somewhat greater, the sound pressure is less near the surface than at greater depths, contrary to the situation directly below the aircraft (Urick 1972). In rough water we expect the sound to enter the water over a larger area than in smooth water because the slope of the waves extends the range at which sound rays impact the surface within 13° of normal to the wave face. In shallow water we expect bottom and surface reflections to carry the sound farther horizontally than would be the case in deep water.

Measurements

Sounds from five types of aircraft were measured during the project, two types of fixed-wing airplanes (deHavilland DHC-6 Twin Otters and a Britten-Norman BN-2A-21 Islander) and three helicopters (Bell 212, Bell 214ST, and Sikorsky 61). Table 2 presents the 20-1000 Hz band levels for these measurements. The power settings were not all comparable for these aircraft, as the Islander was at circling power for some of its passes. The level in the 20-40 Hz band was highly variable in the data for the Islander overflights, especially at depth 3 m. Hence, we also present Islander measurements for the 40-1000 Hz band, along with the levels of the dominant blade rate tone in the Islander's noise spectrum (Table 3). This tone was at 68-74 Hz, depending upon operating power levels.

Table 2. Measured 20-1000 Hz band levels, in dB//1 μPa, for five types of aircraft vs. aircraft altitude (152-610 m) and hydrophone depth (3-18 m). All measurements are for the 4 s during which peak sound level was received (i.e. while the aircraft was directly overhead or almost so).

Type	Water Depth (m)	Alt. 610 m		Alt. 457 m		Alt. 305 m		Altitude 152 m		
		3 m	9 m	3 m	9 m	3 m	9 m	3 m	9 m	18 m
Twin Otter	22		106		101		113			
	22		104		106					
B-N Islander	15	108	107	116	105	121	110	117	114	
	15	106^{a}	103^{a}		105^{a}	122	112	123	113	
	15	104^{a}	105^{a}	119^{a}	106^{a}					
	15	109	108							
Bell 212	25		108				111			
Bell 214ST^{b}	22							104		amb.
Sikorsky 61^{c}	37							102	111	105

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[a] Islander was circling at reduced power.

[b] The Bell 214ST did not pass directly overhead and was barely audible at depth 18 m; the ambient level was 110 dB in the 20-1000 Hz band. The Bell 214ST passed about 150 m astern of the sound boat. The peak sound levels were received when the helicopter was approaching at range about 200 m.

[c] The Sikorsky 61 was not audible underwater during a pass at altitude 1070 m. Its pass at altitude 152 m was not overhead, but about 50 m to the side (i.e. at an estimated elevation angle of 70°).

Table 3. Level of the 68-74 Hz blade rate tone and the 40-1000 Hz band level, in dB//1 μPa, for the Britten-Norman Islander overflights at 152-610 m altitude on 18 August 1983. Levels were measured over the 4 s period of maximum amplitude. The background level in the 40-1000 Hz band was 83 dB at hydrophone depth 3 m and 85 dB at 9 m. Water depth 15 m.

610 m		457 m		305 m		152 m	
3 m	9 m	3 m	9 m	3 m	9 m	3 m	9 m
Level of blade rate tone at 68-74 Hz							
102*	94*	105	101	105	103	113	107
93*		97	103	109	106	114	108
90*	89*	98*	102*				
105	103	102*	102*				
101	**97**						
40-1000 Hz band level							
106*	103*	109	107	112	110	117	114
106*		102	105	113	112	117	113
103*	105*	106*	105*				
109	108	108*	106*				
108	107						

* These values came from 'circling' passes at 140 km/h. Other values came from straight-line passes at 200 km/h.

Tables 2 and 3 indicate that, for flights overhead, the sound levels decreased with increasing aircraft altitude. This is especially clear from Table 3, where wave and water noise have been reduced by restricting the frequency band to 40-1000 Hz. Also, the shallowest hydrophone usually received the highest sound level. Noise levels from the Twin Otter and Islander, at least in the 20-1000 Hz band, were similar to one another.

The limited sound level data for the Bell 212 helicopter were similar to those for the fixed-wing aircraft in the 20-1000 Hz band (Table 2). However, levels at <20 Hz were higher for the Bell 212 because of its strong blade rate tone near 11 Hz (see below). A comparison of the sound levels from the three helicopters would be misleading, as there are no data for the Bell 212 at altitude 152 m, and neither the Sikorsky 61 nor the Bell 214ST flew directly overhead. In general, for helicopters it may be important to include lower frequencies, at least down to 10 Hz, to assure that the fundamental frequency resulting from the main rotor blade rate is included. Whether bowhead whales can hear sounds at these low frequencies is unknown.

The Islander airplane was audible for longer periods at depth 3 m than at 9 m (Table 4). The shallower water and the significantly lower background levels account for the longer durations of audibility of the Islander than of other aircraft. Sound physics predicts this shallow water effect because, theoretically, airborne sound is reflected from the water surface except within a cone delimited by 13° from vertical. The shallow water permits the

Table 4. Duration of audibility of various aircraft.

Aircraft Type	Aircraft Altitude	Water Depth	Sea State	20-1000 Hz Ambient Noise at 9 m	Duration (s) at Depth	
					3 m	9 m
B-N Islander (circling)	457 m	15 m	1	86 dB	continuous	58-75
"	610	15	1	86	84-110	66-78
B-N Islander (Cruise Power)	152	15	1	86	72-87	52-60
"	305	15	1	86	53-76	49-75
"	457	15	1	86	44-58	34-42
"	610	15	1	86	59-84	39-52
Bell 212	152	25	1	100		16-21
"	305	25	1	100		18-27
"	457	25	1	100		
"	610	25	1	100		26
Twin Otter	152	22.5	0	95		33-36
"	305	22.5	0	95		29
"	457	22.5	0	95		37
"						
Bell 214ST (oblique pass)	152	22	3	100[a]	38	11[a]

[a] Hydrophone depth was 18 m, not 9 m, in this case.

sound entering the water within the cone to be reflected from the bottom to the surface and back, spreading out to more distant ranges than would be possible in deeper water. In theory, an aircraft flying over calm deep water at an altitude of 610 m and a speed of 200 km/h would be heard for only about 5 s with a shallow hydrophone.

In general, the sounds from approaching aircraft were detectable much earlier in the air than in the water. For example, prior to the arrival of the Bell 214ST, it was audible for over 4 min in the air but for only about 20 s in the water (depth 3 m).

Tones were present in the sound spectra from all these aircraft (Fig. 4). In the five power spectra displayed (Fig. 4A-E), the frequency range is 20-1000 Hz, the analysis cell spacing is 2 Hz, the effective cell bandwidth is 3.4 Hz, and the averaging time is 4 s. For comparison, the dashed spectra show the background noise at the times of the measurements.

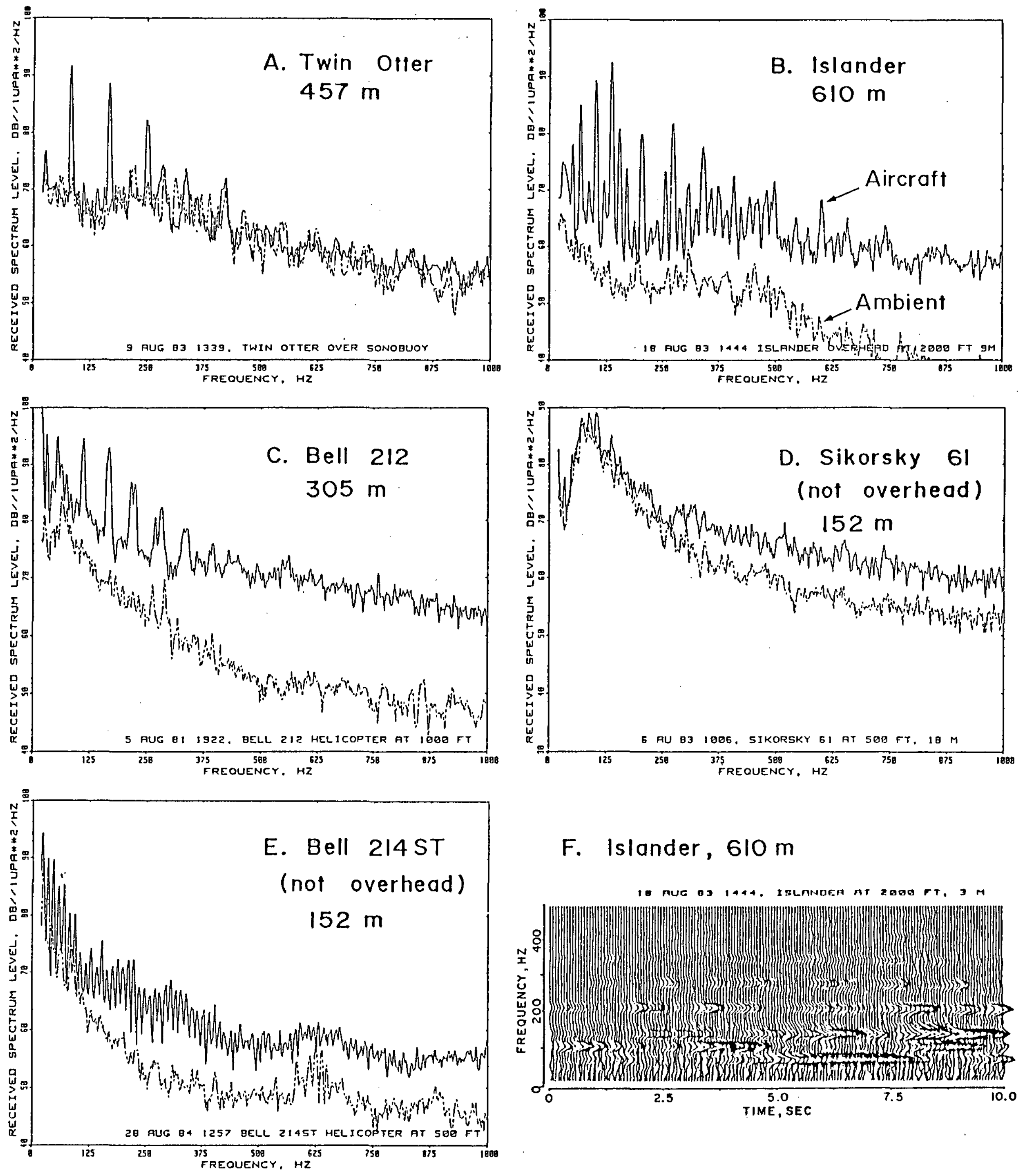

FIGURE 4. Aircraft spectra compared with ambient noise: **(A)** deHavilland Twin Otter overhead at altitude 457 m; **(B)** Britten-Norman Islander overhead at altitude 610 m; **(C)** Bell 212 helicopter overhead at altitude 305 m; **(D)** Sikorsky 61 helicopter about 20° from overhead, altitude 152 m; **(E)** Bell 214ST helicopter about 55° from overhead, altitude 152 m; **(F)** waterfall spectrogram of the Islander overhead at 610 m. Spectra in (A)-(E) were averaged over 4 s.

For a DHC-6-300 Twin Otter circling at altitude 457 m over a sonobuoy (hydrophone depth 18 m) in water 210 m deep (Fig. 4A), the fundamental frequency of the harmonic family is 83 Hz, corresponding to the propeller blade rate on a shaft turning 1670 rpm (3-bladed propellers). The 20-1000 Hz band level was 102 dB//1 µPa. Only the tonal components in the Twin Otter spectrum extended above the ambient noise spectrum, whose 20-1000 Hz band level was 95 dB.

For the Islander circling over 'Sequel' at altitude 610 m, hydrophone depth 9 m, water depth 15 m (Fig. 4B), the propeller blade rate tone is at 68 Hz, the fundamental frequency of a harmonic family corresponding to an engine shaft speed of 2040 rpm (2-bladed propellers). The cylinder firing rate is 102 Hz, the fundamental frequency of another harmonic family whose second and higher harmonics coincide with harmonics from the blade rate. The 20-1000 Hz band level was 103 dB; for the background noise it was 83 dB.

For a Bell 212 helicopter flying straight over 'Sequel' at 185 km/h, altitude 305 m, hydrophone depth 9 m, water depth 25 m (Fig. 4C), strong tones occur for harmonic families with fundamentals at 10.67 and 55 Hz. The 10.67 Hz tone corresponds to a (2-bladed) main rotor rate of 320 rpm, compared to 324 rpm reported by a factory representative as normal. The fundamental frequency is not displayed in Figure 4C, as data are displayed only for the frequency range 20-1000 Hz. The 55 Hz fundamental frequency is for the tail rotor blade rate and corresponds to a rotation rate of 1650 rpm (2-bladed tail rotor). This agrees with the normal speed reported to us by the Bell factory representative. The 20-1000 Hz band level for this overflight by the Bell 212 was 111 dB//1 µPa. The corresponding level for the background noise was 99 dB.

For a Sikorsky 61 helicopter at altitude 152 m flying past 'Sequel' at an elevation angle of approximately 70°, hydrophone depth 18 m, water depth 37 m (Fig. 4D), the 20-1000 Hz band level was 105 dB. The two strongest tones occurred at 68 and 102 Hz, but their levels were not much greater than the background spectrum levels. The 20-1000 Hz level for the background noise was 104 dB.

For a Bell 214ST helicopter flying past 'Sequel' at an altitude of 152 m, about 150 m aft of the boat, the strongest sounds underwater occurred before the closest point of approach, when the range was about 210 m and the elevation angle was about 35° (Fig. 4E). The water depth was 22 m, the hydrophone depth was 3 m, and the 20-1000 Hz band level was 104 dB//1 µPa (vs. 97 dB for background noise). This level cannot be compared with those for other aircraft that flew directly overhead. The spectrum for depth 3 m displays a harmonic family whose fundamental frequency is close to 11.8 Hz, corresponding to a main rotor rate of 354 rpm (2-bladed rotor). For tones at 36 and 154 Hz, levels at depth 18 m were 2 and 13 dB greater, respectively, than levels at 3 m depths. The theory of sound travelling from air to water predicts higher levels at greater depths for horizontal ranges greater than the altitude (Urick 1972), which was the case here.

Figure 4F is a waterfall spectrogram of the same Islander overflight whose average spectrum for depth 9 m is presented in Figure 4B. However, the waterfall is for depth 3 m. Perhaps because of aspect changes as the airplane flew over, or perhaps because of changes in reflection interference (water depth only 15 m) as the airplane flew over, the waterfall shows the different tonal frequency components fading in and out over the 10 s period.

Discussion

Our measurements demonstrated that aircraft sounds are received at significant levels underwater. It is not clear from the band level data that any particular aircraft is louder than the others. However, the Bell 214ST and the Sikorsky 61 did not pass over the hydrophone and are presumably louder than the measurements indicate. In air, the Bell 214ST seems particularly noisy to the human ear. The Islander overflights were over shallower water than those of the Bell 212 or Twin Otter (15 m vs. 22-25 m), which probably accounts for the longer periods of audibility for the Islander.

Moore et al. ([1984] p. 40-42) report a sound power spectrum for a Twin Otter at altitude 450 ft (137 m), presumed to be nearly directly over a sonobuoy. They found a strong family of tones with fundamental frequency 83.75 Hz; the shape of their spectrum was similar to ours (Fig. 4A).

Summarizing the main conclusions regarding underwater noise from aircraft: (1) the levels are high for only a few seconds; (2) the duration of audibility depends on the hydrophone and water depths; (3) immediately below the aircraft, the levels are highest just below the surface; (4) to the side, in shallow water, the levels appear to be higher at greater depths; and (5) there are many tones in aircraft signatures, and most of the energy occurs at frequencies below 500 Hz.

Boat and Ship Sounds

Background

Ship-radiated noise has always been of interest to navies because such noise, depending on its source, either permits or interferes with detection and tracking of submarines. Much information on ship-radiated noise is not available to the public. However, Ross (1976) provided an overview of noise generation, and Buck and Chalfant (1972) and Cybulski (1977) provided specific measurements of the sounds from large vessels. Recent summaries include Ross (1981) and Richardson et al. (1983, p. 41-46).

On a ship or boat, the propulsion machinery accounts for a major portion of the radiated sound. This includes the main engines, motors (if diesel-electric drive), gear reduction transmissions, and propellers. Other sources of sound include pumps, ship's service electric generators, ventilators, compressors and the like. Flow noise from the water dragging along the hull is also a source of noise, as are the bubbles breaking in the wake.

The sounds may be of two types: (1) broad band 'hissing' sounds not concentrated at any particular frequencies but spread continuously over a band of frequencies, and (2) narrowband tonal sounds concentrated at particular frequencies associated with rates of events in machinery operation. Examples of tonal sources are engine cylinder firing rates, shaft rotation rates, and blade rotation rates in propeller and turbine operation. Typically, tonal components from propulsion machinery are at low frequencies, rarely exceeding 100 Hz. Auxiliary machinery tones may occur at frequencies up to a few kiloHertz. These types of machinery often give rise to harmonic families of tonal components. Examples of broadband noises include the rushing sounds of fluids in pipes, and the sounds of propeller cavitation. Cavitation is a major source of sound, and it may be modulated by low frequencies associated with the shaft and blade rates.

Although sound levels emitted by a ship can be strongly affected by its design and speed, there is a rough correlation between sound levels and the size of the vessel. Large size implies high power. Even if only a small fraction of this power is radiated as acoustic power, it may create a strong sound. Large vessels also tend to have large drafts, creating large hull areas for efficient coupling to the water. Small vessels typically radiate higher proportions of their sound at higher frequencies. Their propellers are relatively small and turn relatively fast, operating under ideal conditions for noisy cavitation.

Depending on the background noise, low frequency sound from ships (below 100 Hz) sometimes can be detected at great distances, on the order of hundreds of kilometres, in deep oceans. Higher frequency sounds do not travel as far because of their generally lower source levels and higher rates of absorption.

Measurements

During the project we measured the sounds from three small diesel-powered boats (personnel transports, our sound boat), four supply and survey vessels, three dredges underway, and a large tanker at anchor. The results of band level analyses are summarized in Table 5, which presents the received sound levels for different measurement distances and different hydrophone depths. Data for the 18 m hydrophone depth, and the 9 m depth when 18 m was not available, are also summarized in Figure 5 to show how the various boat and ship sounds compare with one another.

The highest levels were from hopper dredge 'Geopotes X' underway at 24 km/h, reportedly with a damaged propeller. Somewhat lower levels were received from the bow thrusters on 'Canmar Supplier III', 'Canmar Supplier VIII' underway, and hopper dredges 'Gateway' and 'Cornelis Zanen' underway. Then, at somewhat lower values, are the levels from the anchored supertanker 'Gulf Beaufort', the crew boats 'Imperial Adgo' and 'Imperial Sarpik', the fishing boat 'Sequel', and survey vessel 'Canmar Teal'. The lowest levels, predictably, came from the anchored, small survey vessel 'Arctic Sounder' running only a generator for ship's service.

Figure 5 also provides an indication of the rate of attenuation of a signal with increasing range. A reasonable model for received level vs. range includes a log term for spreading loss and a linear term for the combination of absorption, scattering, and reflection losses. The log term plots as a straight line on a graph scaled like Figure 5, and the linear term causes the line to droop with increasing range. This effect can be seen in the plotted points for hopper dredge 'Cornelis Zanen' and for the three longer ranges for hopper dredge 'Geopotes X'. The amount of droop, i.e., the magnitude of the linear coefficient of range, will be greater for higher frequency and/or shallower water (Greene 1982).

Table 5. Boat and ship sound levels, in dB//1 μPa, in the 20-1000 Hz band. Vessels were underway unless noted as "anchored" or "bowthrusters".

	Water Depth (m)	Range (km)	Level at Depth		
			3 m	9 m	18 m
Small Diesel Boats	18.5	0.2			118
Imperial Adgo	18.5	0.4			117
(16 m crew boat)	18.5	3.7			107
Imperial Sarpik	11	2.8	107	110	
(21 m crew boat)	11	4.6		105	
Sequel	18	2.6			104
(12.5 m fishing boat)					
Survey & Supply Boats					
Arctic Sounder, anchored	11	0.5		103	
	11	0.9		97	
Canmar Supplier III, bowthrusters	27	0.19		137	
Canmar Supplier VIII	46	0.2			129
Canmar Teal	34	4.6	98	103	105
Dredges Underway					
Geopotes X	25	0.46		150	
(17,981 tons)	25	7.4		131	
Gateway	12	1.1		123	
(14,000 hp; cap. 6000 m^3)	12	1.1		130	
	12	1.3		131	
	12	1.5		128	
	12	1.5		131	
Cornelis Zanen	20	2.4		128	
(15,000 hp; cap. 8000 m^3)	20	3.2		124	
	20	5.0		116	
	29	7.4		108	
Tanker Anchored					
Gulf Beaufort	20	0.19	114	120	120
(153,000 dwt)	20	0.37	113	118	118
	20	0.93	115	120	120
	20	0.93	116	121	122
	20	1.85	103	110	111
	20	3.7	88	101	103
	20	9.3	89	95	95

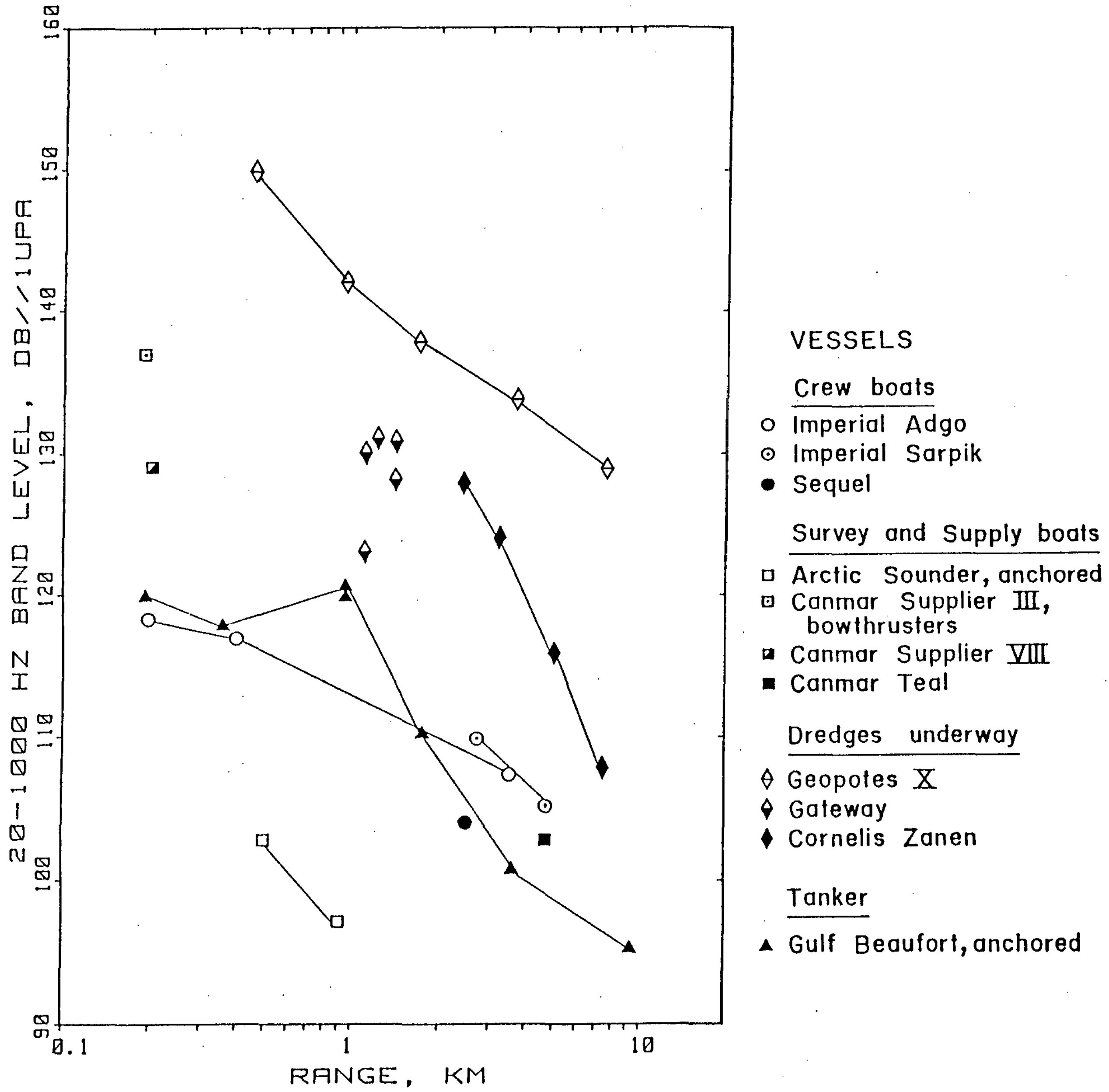

FIGURE 5. Boat and ship sound levels in the 20-1000 Hz band, in dB//1 μPa, vs. range. All values are from hydrophones at depths 18 or 9 m. These data are also presented in Table 5. Vessels were underway unless noted as "anchored" or "bowthrusters".

The peak in the data for 'Gulf Beaufort' at 0.93 km (Fig. 5) shows clearly that the source level of the sounds increased between the recordings at 0.37 and 0.93 km. The final point, at range 9.3 km, may have included a substantial level of background noise; unfortunately, we could not measure the background without the tanker sounds.

Representative boat and ship spectra are presented in Figure 6, along with corresponding background noise spectra. All spectra span the frequency range from 10-500 Hz with analysis cell spacing of 1 Hz, effective bandwidth of 1.7 Hz, and 8.5 s averaging. Figure 6A shows the tones in the signature of crew boat 'Imperial Sarpik' underway at high speed at range 2.8 km, water depth 11 m. The strongest tone was at 195 Hz, and other tones were separated by 15-17 Hz. However, there was no clearly defined harmonic family. The tones can be accounted for by a modulation model in which the 195 Hz tone is modulated by a signal rich in the harmonics of frequency 16 Hz, which may be the blade rate. The 20-1000 Hz band level was 110 dB. The background spectrum included tones presumed to be from 'Arctic Sounder' anchored 0.93 km away and operating only housekeeping generators. The 20-1000 Hz background noise level was 99 dB. 'Arctic Sounder' was 2.2 km away when 'Sarpik' sounds were recorded.

Figure 6B shows a harmonic family from operation of the bow thrusters on 'Canmar Supplier III' as it pulled away from drillship 'Explorer II', range 0.2 km. The fundamental frequency was at 118 Hz, corresponding to a rate of 7080 events/s, probably the blade rate of a multibladed wheel. Although not all are shown in this graph, the first nine harmonics were prominent, to 1064 Hz. The 20-1000 Hz band level of this signal was 138 dB. The corresponding background noise level was 130 dB, the result of drillship 'Explorer II' being only 0.2 km away.

For 'Canmar Supplier VIII' underway at range 0.2 km (Fig. 6C), the 20-1000 Hz band level was 129 dB. The strongest tone was at 57 Hz, 119 dB//1 µPa. The background noise, recorded 1 min later, included sounds from vessels 3.7 km away; the 20-1000 Hz level was 126 dB.

Figure 6D is the spectrum for hopper dredge 'Geopotes X' underway at 24 km/h at range almost 500 m, water depth 25 m, hydrophone depth 9 m. We were informed that the ship had a damaged propeller that season, which probably is at least partly responsible for the broad spectral hump whose maximum is at 80 Hz. A family of tones can be seen along the left, rising slope of the hump. These peaks were 4-7 Hz apart. The 20-1000 Hz band level was 150 dB at range 0.5 km. 'Geopotes X' produced the strongest continuous noise recorded during this project. The 20-1000 Hz background noise level was 99 dB, but only a few components appear on Figure 6D because of the scale needed to show the strong ship sounds.

The relatively low received levels at frequencies below 50 Hz are probably a result of the high rate of attenuation of these long-wavelength sounds in shallow water. Although we have no data at ranges less than 0.5 km, it is very probable that much energy was produced at frequencies below 50 Hz as well as near 80 Hz. This same effect is evident in Figures 6E and 6F, and in some similar diagrams later in the report.

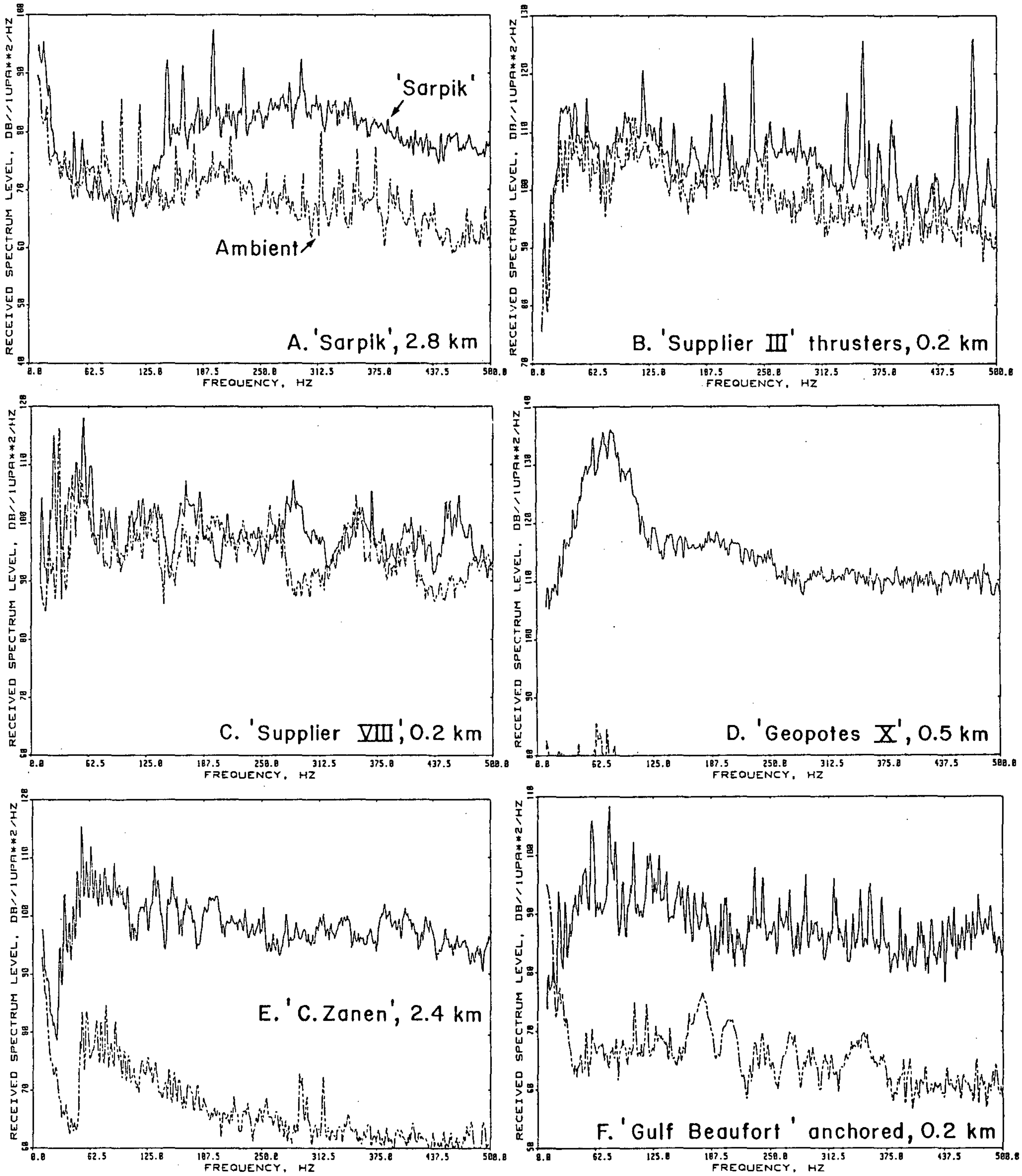

FIGURE 6. Representative boat and ship sound spectra (continuous lines), superimposed onto ambient noise spectra (dashed lines). **(A)** crewboat 'Imperial Sarpik' at range 2.8 km. **(B)** bow thrusters on 'Canmar Supplier III' at range 0.2 km. **(C)** 'Canmar Supplier VIII' at range 0.2 km. **(D)** hopper dredge 'Geopotes X' underway at range 0.5 km. **(E)** hopper dredge 'Cornelis Zanen' underway at range 2.4 km. **(F)** anchored tanker 'Gulf Beaufort' at range 0.2 km. Hydrophone depth was 9 or 18 m in each case.

For another hopper dredge underway, 'Cornelis Zanen' at range 2.4 km (Fig. 6E), the 20-1000 Hz band level was 128 dB. The spacing between tones was 5 Hz, but again these appear to be modulation components, perhaps around the peak tone at 54 Hz. The 20-1000 Hz background noise level was 98 dB, including some weak ship sounds.

An anchored supertanker in Herschel Basin, 'Gulf Beaufort', was running only generators and housekeeping auxiliaries, perhaps including pumps. The spectrum at range 0.2 km includes many spikes from tones (Fig. 6F). The 20-1000 Hz band level was 120 dB at both the 9 and 18 m hydrophone depths. The 'background' noise, for comparison, was measured 9.3 km from 'Gulf Beaufort'; the 20-1000 Hz level was 95 dB.

Figure 7 presents spectra of the two diesel-powered boats used in boat disturbance tests during the project, the crewboat 'Imperial Adgo' and the sound boat 'Sequel'. The 20-1000 Hz band levels were 119 dB for 'Adgo', range approximately 0.2 km, underway at 41 km/h, and 102 dB for 'Sequel', range 2.6 km, underway at 13 km/h. The spectrum for 'Adgo' shows several tones below 400 Hz. Both boats produced considerable broadband noise at frequencies of several hundred Hertz. The 20-1000 Hz background noise levels for the 'Adgo' and 'Sequel' measurements were 102 dB and 94 dB, respectively.

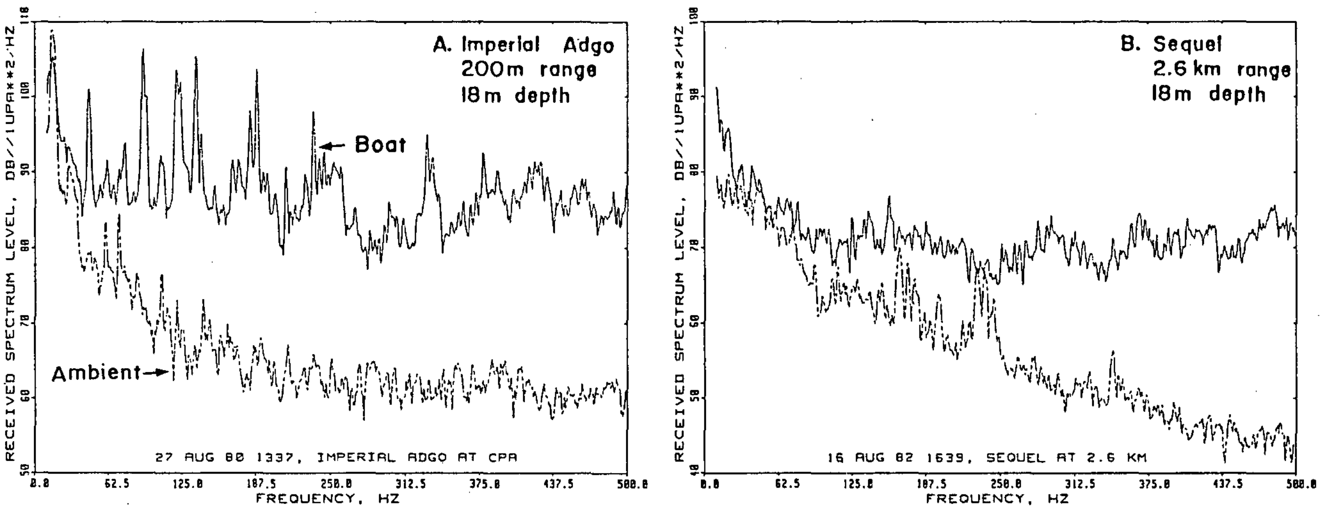

FIGURE 7. Sound pressure spectra for two diesel-powered small boats used in bowhead disturbance tests, the crewboat 'Imperial Adgo' and the sound boat 'Sequel'.

'Adgo and 'Sequel' produced waterborne noise with levels generally comparable to levels from crewboat 'Imperial Sarpik', survey vessel 'Canmar Teal', and the anchored tanker 'Gulf Beaufort' (Fig. 5). Only the anchored survey boat 'Arctic Sounder' was significantly quieter. The large dredges and supply boats produced levels 25-30 dB higher than those of 'Sequel' and 'Imperial Adgo' at corresponding ranges (Fig. 5).

Discussion

Few detailed reports of noise from small vessels and ships exist in the open literature (for review, see Richardson et al. 1983). However, the levels and the spectral characteristics measured during this project are consistent with those reported by others (Buck and Chalfant 1972; Ross 1976; Cybulski 1977); viz, high levels at low frequencies, broadband humps in the spectra (from propeller cavitation), and tones.

Seismic Signals

Background

Marine geophysical surveys are conducted to search beneath the sea for strata and locations that may contain producible quantities of hydrocarbons. Seismic survey signals were formerly produced by underwater detonations of explosives, but that technique now is rarely used in open waters, mainly because explosives can damage marine life. During the open water season in the Beaufort Sea, most seismic exploration is with arrays of airguns, but arrays of sleeve exploders or open-bottom gas guns are also used. Although these techniques are not based on chemical high explosives, a sharp, impulsive shock wave is generated at each source in the array, and the accumulation of the individual impulses provides a strong impulse beneath the sea floor. Useful summaries of the technology may be found in Kramer et al. (1968), Barger and Hamblen (1980), Fricke et al. (1981) and Johnston and Cain (1981).

Bowhead whales may be disturbed by seismic survey signal sources. To determine the sound levels that might cause a disturbance, it was important to measure the noise levels near whales that were being studied by Richardson et al. (1985). Also, measurements of received level vs. range were desirable to permit prediction of levels at different ranges. With such data, a 'range of disturbance' for bowheads around survey vessels might then be determined for areas with similar transmission loss.

Until recently, little was published about the waterborne sounds created by airgun arrays and other seismic sources. In 1979, Ljungblad et al. (1980) found that bowhead whales were sometimes exposed to noise pulses from seismic vessels operating many kilometres away. Richardson et al. (1983) summarized the early results from the present project and other data available up to 1981. Additional data on characteristics of waterborne impulses from seismic ships appear in Malme et al. (1983) and Moore et al. (n.d.).

Measurements

We recorded seismic signals from six survey vessels plus a single 40 in^3 airgun that we operated from the sound boat 'Sequel'. Many of the measurements were of sets of signals from the same source vessel at different ranges. We used multiple linear regression to determine coefficients of equations to model the received signal level vs. range.

Sleeve Exploder Signals.--Signals from the seismic survey vessel 'Arctic Surveyor' were received at 'Sequel' numerous times during 1981 while we were recording background and industrial noises. The signal source consisted of four sets of sleeve exploders, three sleeves per set, suspended over the side of 'Surveyor'. The geometry was a rectangle approximately 12 m long and 25 m wide (athwartship). The cylindrical sleeves were each about 1.2 x 0.3 m, and were deployed 6 m below the surface, water depth permitting. A mixture of propane and oxygen was exploded simultaneously in all the sleeves to produce a strong signal focused vertically. The signal echoes from bottom inhomogeneities were received at hydrophones in a long linear array deployed behind the ship. At each station, echoes from six 'pops' (= explosions) were recorded before the ship moved 40 m to the next station along the survey track. Six to ten seconds elapsed between pops while the exhaust gas was purged and the sleeves were recharged; 1/2-2 min elapsed between series of 6 shots as the ship moved to the next station.

For our measurements, the source (sleeve exploder array) depth was 6 m, the hydrophone depth was 9 m, and the water depths at the recording sites were about 15-30 m. Several signals were analyzed from each of three ranges: 8 km, 13 km, and 25.3-28.7 km. The received level of the pulses was 148-153 dB//1 μPa at 8 km and 115-117 dB at 28-29 km. After starting as an impulse at the source, the signal length was about 250 ms when received at 8 km and over 400 ms at 28.7 km; the reverberation extended much longer. At our working ranges, the impulse was received as a 'chirp' signal in which high frequencies were received first, followed by a downward transition to lower frequencies (Fig. 8B,D,F). This frequency change is represented in Figure 8A,C,E by the closer spacing of the oscillations at the left than at the right side of each pulse. These properties of impulsive signal propagation are characteristic of geometrical dispersion, which occurs when signals undergo multiple reflections between the surface and bottom.

Open Bottom Gas Guns.--In 1982 we again recorded seismic survey signals from 'Arctic Surveyor', but the sleeve exploders had been replaced by open bottom gas guns. Our recordings were made in water 9-11 m deep, hydrophone depth 8 m, ranges 0.9 to 14.8 km. Received levels ranged from 177 dB//1 μPa at 0.9 km to 123 dB at 14.8 km.

At the shortest range studied (0.9 km), frequencies below 100 Hz predominated (Fig. 9). At an intermediate range (3.7 km), low frequencies below 100 Hz arrived first, presumably via a bottom path, followed by frequencies above 200 Hz, presumably via a water path. At range 14.8 km, only frequencies above 200 Hz were received. Information on bottom stratigraphy might help explain the propagation of the low frequency components. At 14.8 km, it is noteworthy that high frequencies tended to arrive slightly before lower frequencies (Fig. 9F), consistent with the sleeve exploder results.

In 1983 seismic signals were received from the gas guns on 'Arctic Surveyor' at ranges of 52-53 km. The received signal levels ranged from 122-128 dB//1 μPa over 65 min. Then, 24 min later, the level was 119 dB, and another 24 min later the level was below the ambient level of 107 dB. We concluded that there had been enough movement of the ship that some propagation anomaly within the 52 km range intruded to blank out the signal. Water depth at the receiving location was 19 m.

Airgun Arrays.--Seismic signals were received from 'GSI Mariner' on numerous occasions. Airguns were discharged every 12-16 s as the ship steamed continuously at about 7 km/h along preselected lines. In 1982-83 the airgun array volume was 23 L and its source level was reported to be about

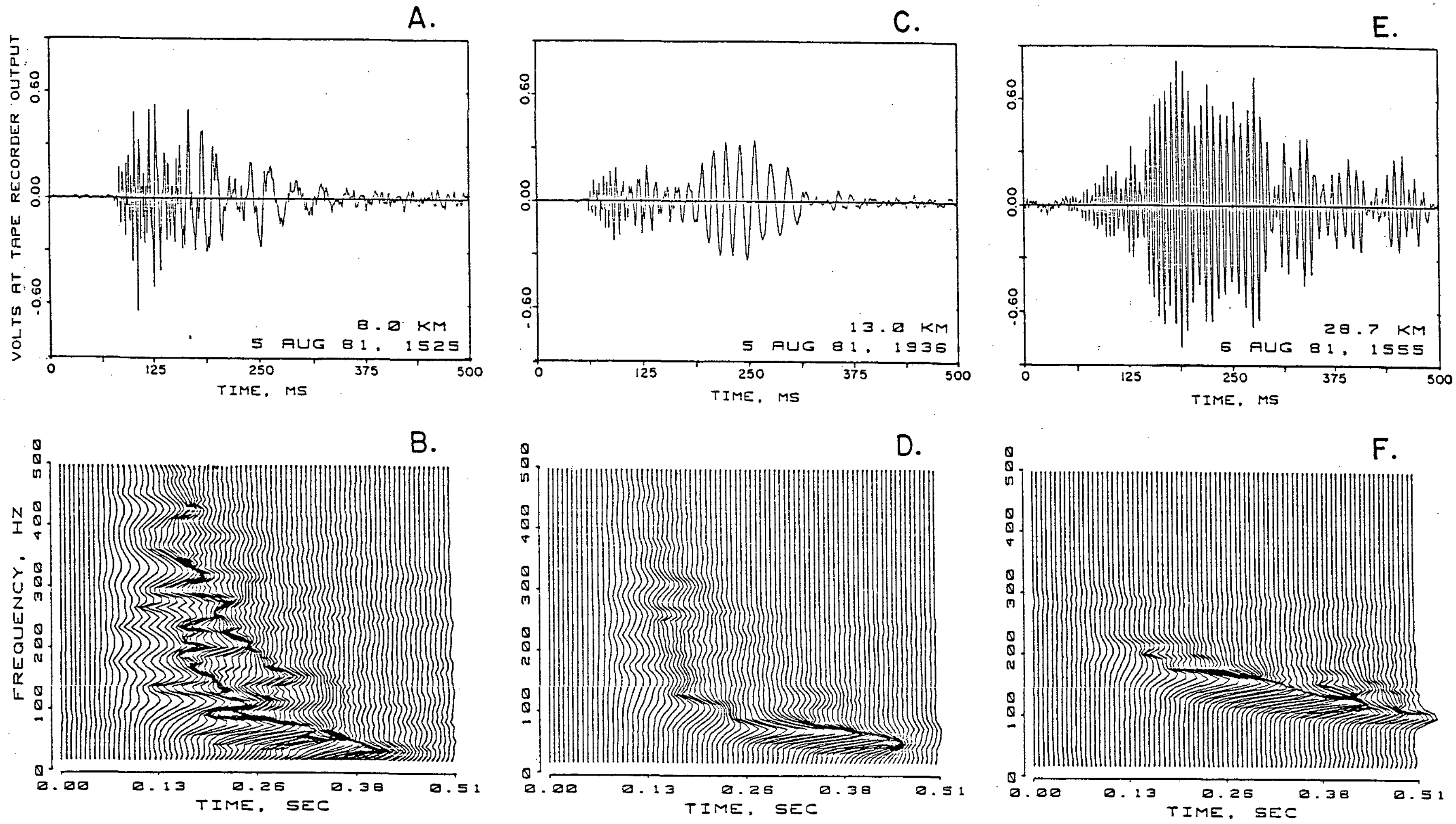

FIGURE 8. Waveforms and waterfall spectrograms for sleeve exploder signals received from 'Arctic Surveyor' in August 1981 at (A,B), 8 km range, (C,D) 13 km, and (E,F) 28.7 km. The signal in (E) was amplified by 40 times, compared to (A) and (C).

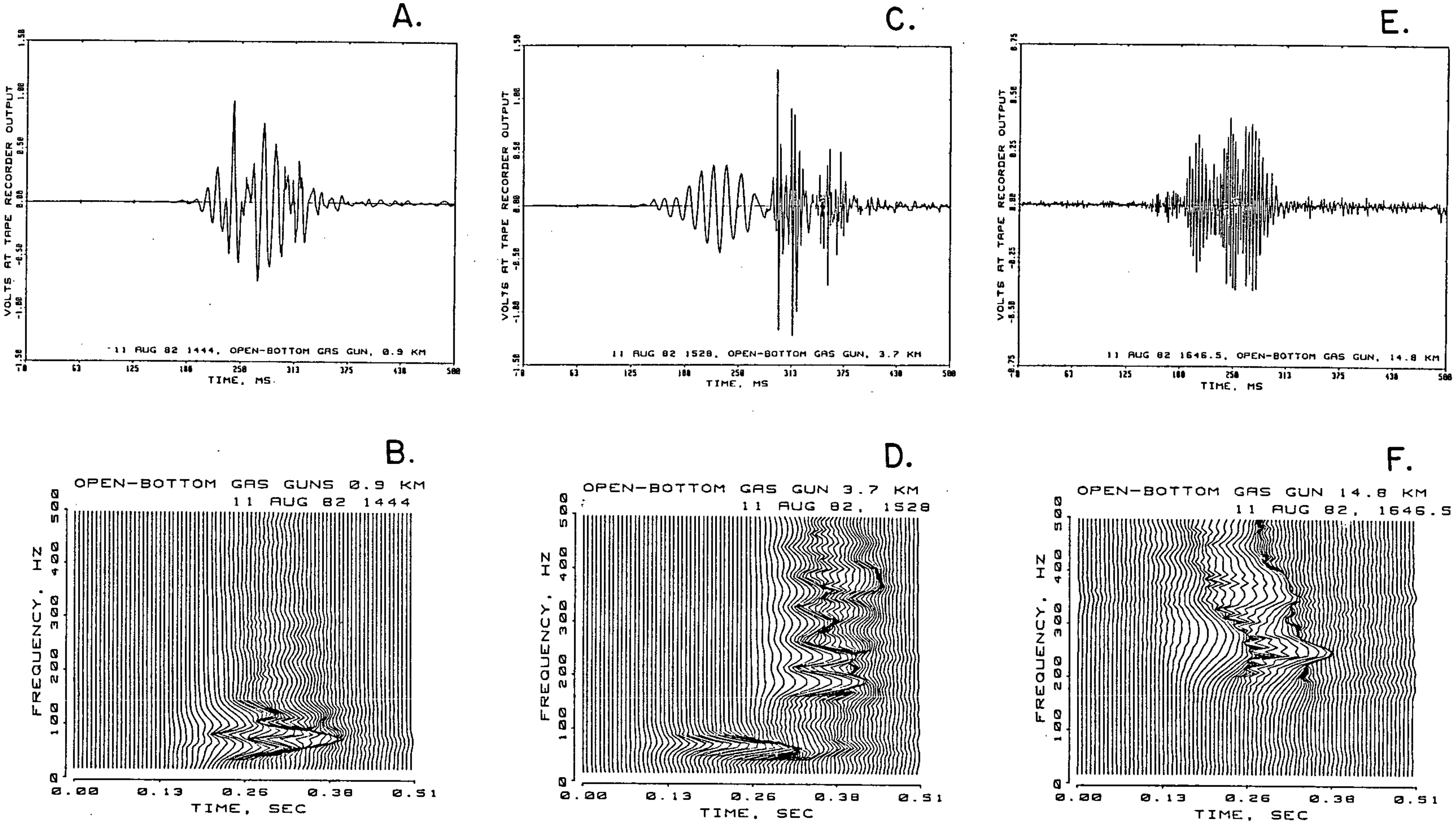

FIGURE 9. Waveforms and waterfall spectrograms of signals from open-bottom gas guns at ranges 0.9, 3.7, and 14.8 km. Water depth was 9-11 m; hydrophone depth was 8 m.

246 dB//1 µPa-m. In 1982, received levels included 119 dB//1 µPa at range 52 km, 128 dB at range 54 km (different time and transmission path), 126 dB at range 66 km, and 110 dB at range 75 km. In 1983, with the same airgun array, received levels were 127-131 dB for ranges 79-81 km on 7 August and 123 dB for range 57 km on 9 August. These signals were received at sonobuoys, which distort high amplitude signals; consequently, the foregoing levels should be taken as minimum estimates. The water depth for these signals was greater than the depth for the 'Arctic Surveyor' signals, assuring longer range transmission.

In August 1984 seismic signals were recorded from 'GSI Mariner' on several dates. The array volume had been increased to 47 L. Measurements from the sound boat on 14 August revealed levels between 143 and 160 dB for ranges 12-17 km (water depth 20-24 m, hydrophone depth 18 m). Several hours earlier, on a different track, 'Mariner' signals had been 154-158 dB for ranges 16-16.7 km, water depth 20 m. In general, there was considerable variability in received levels at specific ranges. Water depth, bottom characteristics, and horizontal aspect of the array were probably responsible. (Aspect is the orientation of the airgun array relative to the bearing to the receiver; see Malme et al. 1983.) At the 12 km range, the array was oriented broadside; thus, maximum received levels were expected on that occasion.

On 16 August 1984, 'GSI Mariner' participated in a bowhead disturbance experiment (see Richardson et al. 1985, in this volume). Although the ranges were no greater than 7.5 km, the airgun signal reverberation was longer than the 15 s period between firings. Such long reverberation times had not been seen previously, regardless of range. Because of the reverberations the received level between pulses did not decrease below 118 dB//1 µPa, which was 19 dB above the ambient level before the airguns began firing and after they stopped. Figures 10A-B contain the recorded waveform and waterfall spectrogram of a signal from range 7.5 km, water depth 25 m at ship and 18 m at sonobuoy. The received signal sounded distorted because of its high amplitude relative to the limited dynamic range of the sonobuoy. This signal was from the start of the full scale airgun array disturbance test on 16 August 1984. The long reverberation was characteristic of all the signals received at the sonobuoy during the test. It is possible that this long 'reverberation' was an overload response of the sonobuoy or the receiver, although this was not seen with other less severe overload signals.

Figures 10C-F were recorded with a hydrophone in an area somewhat west of the disturbance test area, water depth 44 m, 'Sequel' at anchor. Figures 10C-D were for range 8.7 km from 'GSI Mariner', just slightly longer than the range of Figures 10A-B, but with "Sequel's" hydrophones and without the severe reverberation. Figures 10E-F were for range 20.3 km. The waveforms in Figures 10C and 10E exemplify airgun signal propagation in shallow water over increasingly higher velocity strata beneath the water. The signals first received have travelled down through the bottom, bending upward back to the hydrophone. The solid black areas of the signal correspond to the sound carried solely by the water path. This is a short burst of high frequency sound, evident in Figures 10D,F at about 200 and 400 Hz, respectively. The waterborne signal is followed by additional bottom-travelling energy. Multiple propagation modes are evident, but the basic property to be observed is that the waveform in Figure 10E, range 20.3 km, is much longer than the

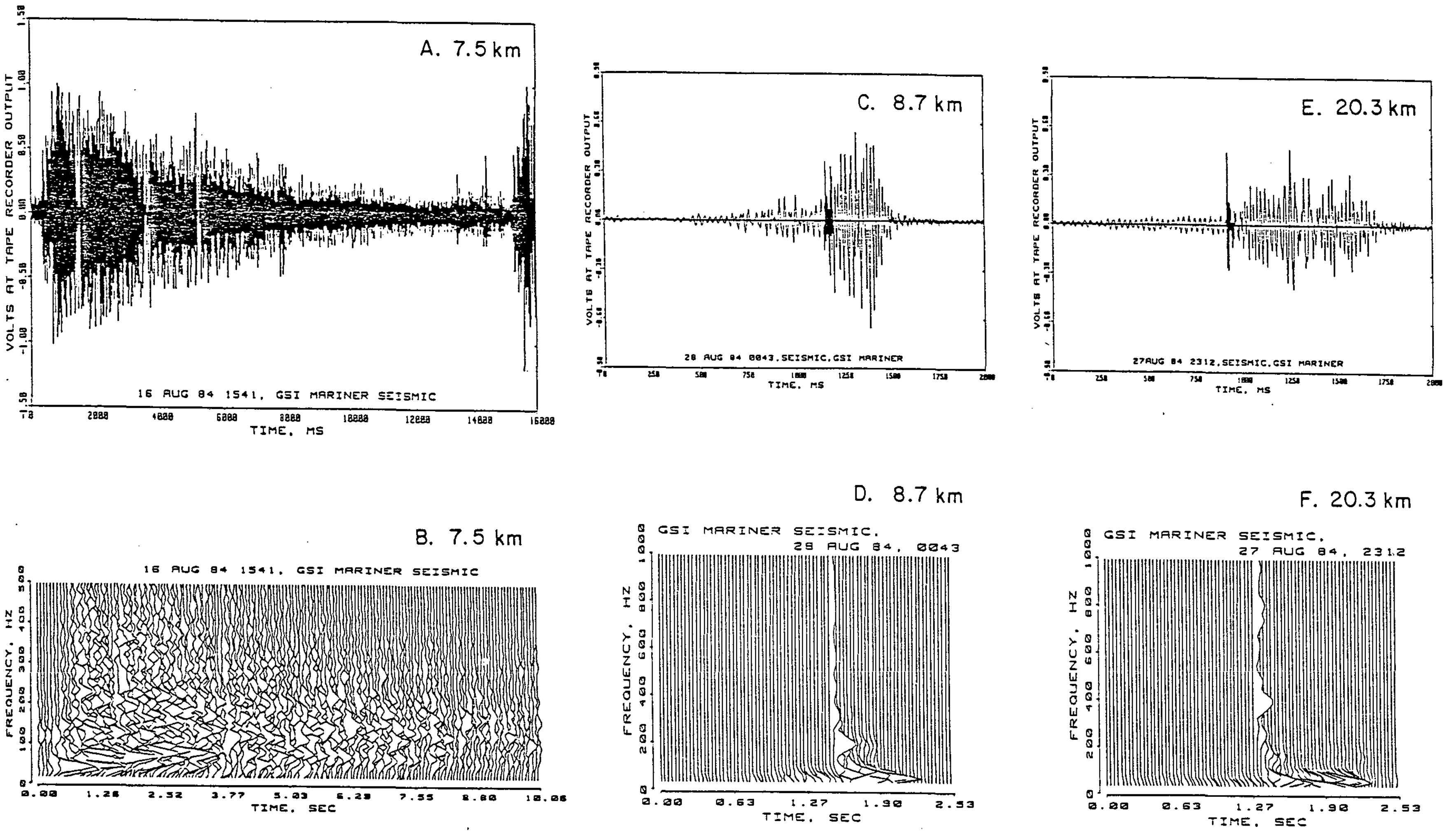

FIGURE 10. 'GSI Mariner' airgun array waveforms and corresponding waterfall spectrograms. (A) and (B) are from a sonobuoy and are undoubtedly distorted; (C-F) are from a hydrophone at 18 m depth.

waveform in Figure 10C, range 8.7 km. This demonstrates that the received signal lengthens as range increases.

The amplitudes of the signals in Figure 10C and 10E were as follows:

Figure	Range	Effective Pressure dB//1 µPa	Receiving System
10 C-D	8.7	157	Hydrophone
10 E-F	20.3	147	Hydrophone

Because of the limitations of sonobuoys, the received levels of seismic pulses could not be measured reliably during the experiment on 16 August 1984. Given the received levels of about 160 dB at ranges 9-12 km nearby on 14 and 28 August 1984, received levels were presumably far above 160 dB when 'GSI Mariner' reached its closest point of approach 1.5 km from the bowheads on 16 August. In both the 12 km and the 1.5 km cases, the long axis of the airgun array was oriented broadside to the receiver--the condition in which peak received levels are expected (Barger and Hamblen 1980; Malme et al. 1983).

On six occasions, pulses from 'GSI Mariner' operating 9-17 km away were received simultaneously at hydrophone depths of 9 and 18 m. The received level at 9 m was always 1-4 dB less than that at 18 m.

Received seismic survey signals rarely included much energy at frequencies above 500 Hz. However, on 1 August 1984 we received pulses of 500-1300 Hz energy from 'GSI Mariner'. The signals were received by a sonobuoy hydrophone on the bottom in 10 m of water, range 17-23 km, depth at boat 70 m, received level at least 119-117 dB. Within these pulses, there was the usual downsweep of frequencies. Although the pulses were consistently at 500-1300 Hz on this occasion, this was a unique and apparently anomalous situation.

Seismic signals from two other large arrays of airguns were recorded via sonobuoys. Airgun signals 50 km from 'Edward O. Vetter' were received at hydrophone depth 9 m with level 117 dB. Airgun array signals 26-31 km from 'Western Aleutian' were received at hydrophone depth 18 m, water depth 19 m, levels 120-135 dB. These levels may be underestimates because of sonobuoy limitations.

In 1983, signals from a small 3-gun 5.4 L array on 'Canmar Teal' were received simultaneously at 3, 9 and 18 m depth (water depth 34 m) for each of several ranges (Table 6). These data came from the hydrophones on the sound boat, and do not suffer from the limitations of sonobuoys. On average, levels at 3 m depth were 7 dB less than those at 9 m. Nominal signal frequencies were above 100 Hz, and approached 200 Hz at the shorter ranges. Within pulses, there was the usual decrease in peak frequency with increasing time.

Single Airgun.--The crew on 'Sequel' deployed a 40 in^3 (0.66 L) single airgun for controlled seismic disturbance tests when the aircrew could observe bowheads before, during, and after a period of firing. We began most tests with an air tank at pressure 1900-2200 psi and ran it down to about 500 psi. Except for being a single unit and therefore weaker in output pulse level, the waveform and frequency properties of our airgun were similar to

Table 6. Effective levels (dB//1 µPa) vs. range and hydrophone depth for airgun signals from 'Canmar Teal', 11 August 1983.

Range (km):	3.0	5.9	8.2	9.3	10.4	ukn.
Time (MDT):	08:23	07:31	15:02	16:35	16:38	14:33
3 m level:	161	141	135	137	141	143
9 m level:	167	151	145	143	145	150
18 m level:	158	152	147	146	149	151

those of a full-sized array of airguns. The firing period was 19-20 min with 10 s between firings (1981) or 25-30 min with 15 s between firings (1983-84). We operated the airgun at depth 6 m, attempting to simulate the operating conditions of a full-sized airgun array. Figure 11 contains the waveform and waterfall spectrogram of an airgun signal from 'Sequel' recorded during a disturbance test on 28 August 1983 at range 5 km. The water depth was 15 m. The received sound level of this and the other signals during the test ranged from 125 to at least 133 dB. The circumstances and sound levels of all airgun tests are summarized in Richardson et al. (1985: in this volume).

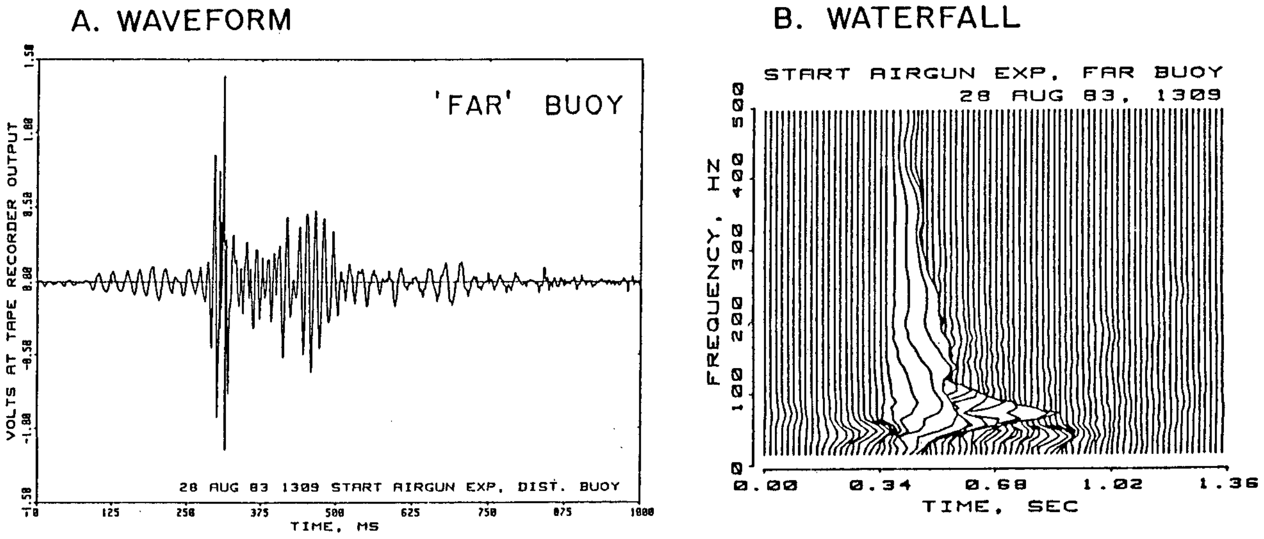

FIGURE 11. Waveform and waterfall of a signal from the single 40 in^3 airgun fired from 'Sequel' during a controlled seismic disturbance test on 28 August 1983. The range was about 5 km, water depth 15 m.

Sound Transmission Loss

Transmission loss information can be extracted from the measurements of received levels at various ranges. Figure 12 shows the data and the associated fitted curves for four seismic sources. The hydrophone was always an H56 deployed at depth 18 m except when the water depth was less. Sonobuoy data were not used.

The sleeve exploder measurements spanned the range 8-29 km; water depths were 15-30 m. When we fitted a simple logarithmic spreading loss model, we obtained the term -61.6*log(range). This was far from the expected -10*log (range) term for cylindrical spreading or even -20*log(range) for spherical spreading. When we added a term linear in range, appropriate for absorption and scattering losses, the fitted spreading loss term became -10.12*log (range)--very close to the expected -10*log(range) for cylindrical spreading. When we forced the spreading loss term to be cylindrical, the resulting regression equation was

$$\text{Received level (dB//1 }\mu\text{Pa)} = 170.1 - 1.39*R - 10*\log(R),$$

where R is range in km. The standard error (se) was 2.2 dB, the coefficient of determination (r^2) was 0.972, and the number of measurements (n) was 12. The equation is plotted in Figure 12. The result was reasonable because cylindrical spreading is expected in shallow water and because the losses from scattered reflections and absorption by the bottom are accounted for at the rate of about 1.4 dB/km. Strictly speaking, this equation is valid only for the ranges studied (8-29 km), for water depths of 15-30 m, and for the specific area where the data were collected. In particular, the equation is probably not valid at ranges less than 5 km because of the nature of impulsive sound propagation in shallow water.

The general regression equation for the open-bottom gas guns in water 9-11 m deep was RL = 177 - 1.55*R - 26.6*log(R), se = 1.5 dB, r^2 = 0.997, n = 6. The higher spreading loss coefficient of 26.6 dB per range decade is a result of including the much shorter ranges, and probably also the shallow water depth. When only the data from the three longest ranges (3.7, 7.4, 14.8 km) were used, and cylindrical spreading was forced, the best-fit equation for received level was

$$RL = 169.2 - 2.33*R - 10*\log(R),$$

se = 0.26, r^2 = 1.000, n = 3. This result was for ranges comparable to the ranges studied in 1981 with the sleeve exploder. The higher linear loss (2.33 vs. 1.39 dB/km) was probably attributable to the shallower water.

The 'GSI Mariner' airgun array data plotted in Figure 12 were not measured at the same time or place, and the source level of the array was slightly greater for the 1984 data than for 1982. The four points spanning ranges 9-20 km were measured from 'Sequel' while anchored on 27 and 28 August 1984, water depth 44 m. Six other measurements were also made of 'Mariner' seismic signals at that time and within that range span. The two points plotted for ranges 52 and 75 km were measured from 'Sequel' on 16 and 18 August 1982, water depth 110-130 m. Because of the heterogeneous data, the fitted equations may be only rough approximations of the results that would be obtained in any one situation. All 12 measurements were used to fit the

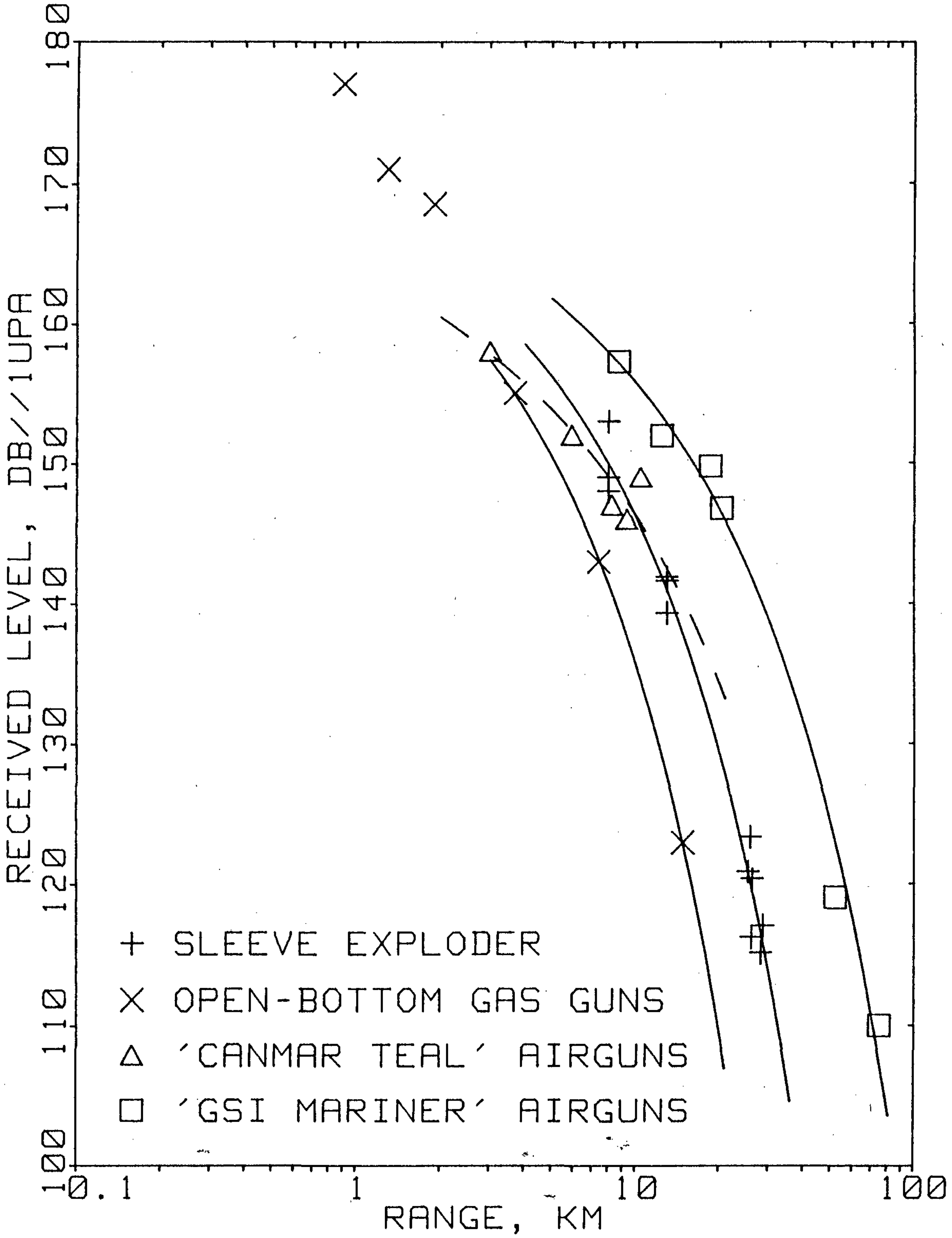

FIGURE 12. Received levels of seismic signals vs. range. Data and equations derived by regression are shown for four seismic signal sources: the sleeve exploder array on 'Arctic Surveyor' in August 1981; the open-bottom gas gun array on 'Arctic Surveyor' in August 1982; the 3-airgun array on 'Canmar Teal' in August 1983; and the large arrays of airguns on 'GSI Mariner' in 1982 and 1984. All data included in this figure were recorded on the boat; no sonobuoys were involved.

general equation RL = 177.2 - 0.53*R - 15.67*log(R), se = 2.1, r^2 = 0.984, n = 12. When cylindrical spreading was forced in the model, the result was

$$RL = 171.8 - 0.61*R - 10*\log(R),$$

se = 2.0 dB, r^2 = 0.975, n = 12. The absorption/scattering loss coefficient of 0.61 dB/km is smaller than the 1.39 and 2.33 dB/km terms derived for the shallower water measurements of the sleeve exploders and open-bottom gas guns. This was expected; we expect lower rates of scattering loss and bottom absorption loss in the deeper water where these data were collected.

Five measurements from the 3-airgun array on 'Canmar Teal' are plotted on Figure 12. The water depth for these measurements was 34 m. An 'outlier' received level of 149 dB at range 10.4 km caused a poor regression result. When we averaged the measurements at the three longest ranges, 8.2-10.4 km, to obtain one 'long-range' datum, we obtained the following fitted equation with the -10*log(R) term forced:

$$RL = 165.3 - 0.90*R - 10*\log(R),$$

se = 0.36 dB, r^2 = 0.992, n = 3. The equation is plotted as the dashed line on Figure 12.

The four equations for received level provide an indication of the behavior of seismic signals in the shallow Beaufort Sea. The reliability and utility of the equations could be enhanced with data from a wider span of ranges (especially longer ranges). However, more attention should be paid to the dependence of transmission loss on frequency, water depth, sea state, and bottom characteristics, and to the effects of aspect of the source array.

Discussion

When received at distances of at least a few kilometres, pulses from sleeve exploders, open-bottom gas guns and airgun arrays were very similar. Their characteristics can be summarized as follows:

Seismic survey signals were by far the strongest sounds encountered, but they were almost always of short duration, with 8-15 s between pulses. The amplitudes at ranges 9-20 km were 12-30 dB greater than the 20-1000 Hz band level of 'Geopotes X' at range 7.4 km. 'Geopotes X' produced the strongest non-seismic sounds detected in this study. The levels of seismic pulses attenuated with increasing range in the same way that other sounds attenuated. However, because of the very high source levels of seismic impulses, they were received above the typical background level to distances approaching 100 km, even in relatively shallow water.

For concentrated measurements of seismic signals from one vessel operating in one area at modest ranges (to about 15 km), we observed consistent relationships between range and amplitude. As the range decreased, the received levels increased. However, when we compared results from different survey tracks, the level vs. range relationships were not always consistent. Contrary to expectation, the signal level was sometimes stronger at longer ranges. Consistent with theory, the water depth and bottom materials appear to have an important influence on the levels of the received seismic signals.

As with other sounds originating underwater, the received levels of seismic signals were less at shallower depths, increasing at least until the hydrophone depth was 18 m. This is consistent with theory, which predicts zero pressure at a pressure release boundary like the sea surface (Urick 1983, p. 131-4).

Pulse lengths tend to increase with increasing distances because of the effects of different sound speeds for different modes of propagation. Within each mode, different frequencies are received at different times. For shallow water propagation, high frequencies are received first, followed by low frequencies. This leads to the 'chirp' signal characteristic of many seismic impulses as received at long ranges. The opposite occurs for propagation via bottom sedimentary layers. At ranges beyond a few kilometres, the waterborne sound is mainly at frequencies of 200-400 Hz, even though most energy at the source is <100 Hz (Barger and Hamblen 1980). Lower frequencies (<100 Hz) are sometimes received via bottom pathways, but the low frequency energy apparently is attenuated more quickly than the slightly higher frequencies in the shallow waters where most of our data were obtained.

Drillships

Background

Drillship sounds had not been reported before this project began, although there were reports of sound measurements near offshore drilling platforms and semi-submersibles (Buerkle 1975; Gales 1982). Results from those studies are difficult to interpret because of low frequency resolution (Buerkle 1975) or restrictions to near-field measurements (Gales 1982). Sounds from the 'SEDCO 708' semi-submersible were measured recently during drilling operations in the Aleutians (Greene, in press). Several tones from 'SEDCO 708' operating in water 114 m deep could be detected at range 18.5 km, although they were weak. Broadband components were generally down to background levels for ranges >1.9 km. The background levels were 102-112 dB//1 μPa for the 10-4000 Hz frequency band.

One might predict that drillships would be noisier underwater than semi-submersibles or drilling platforms, given the broad hull area in contact with the water. The hull would be expected to serve as a relatively efficient radiator of low frequency sounds into the water.

Measurements

Sound levels and spectra were measured at various ranges from three drilling vessels: drillship 'Explorer I' while logging, drillship 'Explorer II' while drilling, and the Conical Drilling Unit (CDU) 'Kulluk' while drilling (Fig. 13). 'Kulluk' is a circular platform 81 m across and sloping inward below the water line to deflect ice. It must be moved by support vessels and tugs, but it can operate longer in the fall because of its ice deflection design. 'Explorer I' and 'Explorer II' are conventional drillships; four of these vessels operated in the Canadian Beaufort Sea during each year of our study. Logging operations were not as noisy as drilling,

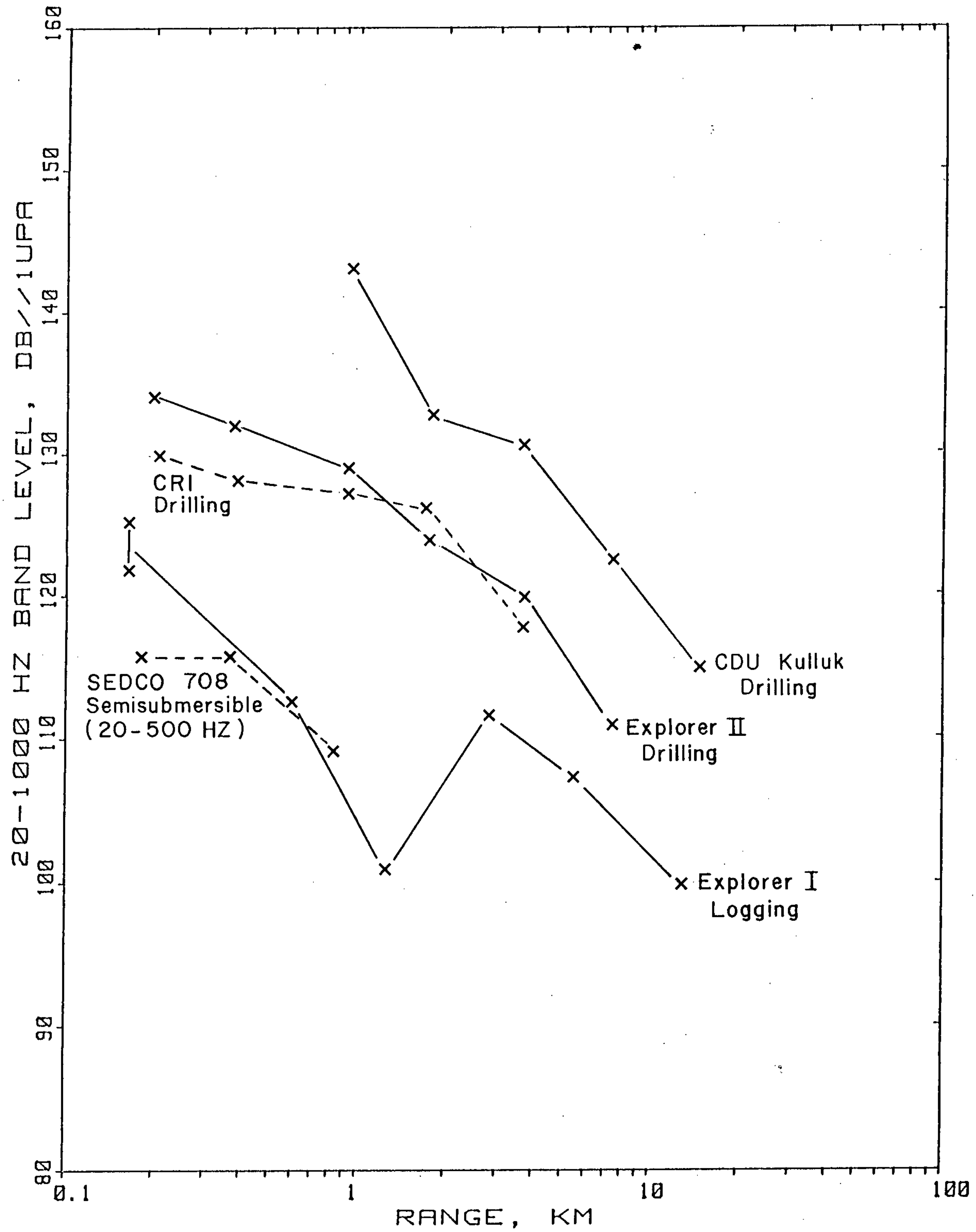

FIGURE 13. Drillship sound levels in the 20-1000 Hz frequency band vs. range for three drilling vessels. Levels near drilling operations on a caisson-retained island (CRI) in the Canadian Beaufort Sea and a semisubmersible near the Aleutians (Greene, in press) are also shown for comparison. The hydrophone depth was 9-18 m in each case.

and the CDU drilling was clearly the noisiest of the three operations (Fig. 13). Stand-by vessels were near each of the three drillships during our recording sessions, and their variable activities were probably responsible for some of the apparent differences in sound levels near the three operations.

'Explorer I' was northwest of the Mackenzie Delta (Fig. 1) in 1982 when we recorded its sounds while it was conducting logging operations. The water depth was 17 m; hydrophone depth was 9 m. The variability in the received levels vs. range shown in Figure 13 probably was partly due to the changing nature of machinery operations during the time of our measurements. The relatively low level at range 1.3 km is conspicuous in this regard. The support vessels in the vicinity did not appear to be active.

'Explorer II' was drilling north of the Mackenzie Delta (Fig. 1) at depth 2030 m, water depth 27 m, when we measured its noise in 1981. The hydrophone depth was 9 m. 'Supplier III' was drifting nearby.

Gulf Canada's CDU 'Kulluk' was drilling at East Amauligak in 1984 when we recorded the sounds. Our sound boat was not permitted within the mooring lines, restricting our closest range to about 1 km. A tug was grappling for lost mooring anchors nearby, and there were other work boats around. It is certain that our measurements of 'Kulluk' sounds also contain sounds from these other active vessels. The vessel sounds overlap 'Kulluk' sounds in both time and frequency, and the sounds of 'Kulluk' and other vessels cannot be separated.

Figure 14A,B shows examples of spectra computed for 'Explorer II' drilling at ranges 0.2 and 7.4 km. The strong tone at 278 Hz was characteristic and easy to identify when heard on sonobuoys or the 'Sequel' hydrophones. This tone varied in frequency during the drilling operations but was always accompanied by a weaker tone at a slightly lower frequency. The 20-1000 Hz band level for range 0.2 km was 134 dB//1 µPa; for range 7.4 km it was 111 dB.

Figure 14C-F shows spectra for 'Kulluk' drilling at ranges 1.0 and 14.8 km, including spectra for hydrophone depths 3 m and 12 or 18 m (at 14.8 km range, water depth was only 15 m, denying us the use of a hydrophone at depth 18 m). The 'Kulluk' spectra are not especially distinctive, although tones at 51 and 89 Hz were persistent. The strong tone at 333 Hz in Figure 14F was not detected at ranges less than 7.4 km, presumably because of some change in the industrial activities between the recording times. Broadband levels were unusually flat up to 750 Hz; the typical decrease in level with increasing frequency was not evident in this frequency range (Fig. 14C-F). Received levels at 18 m depth were 20 dB higher than those at 3 m for frequencies 30-100 Hz, and about 9 dB higher for frequencies 250-500 Hz (Fig. 14E vs. C; Fig. 14F vs. D). This difference was consistent in direction with results for other in-water sources, but greater in magnitude than some others.

In some of the spectra shown in Figure 14, received levels for frequencies below about 50 Hz were lower than those for some higher frequencies. This was probably attributable to the high rate of attenuation of low frequency sounds in shallow water.

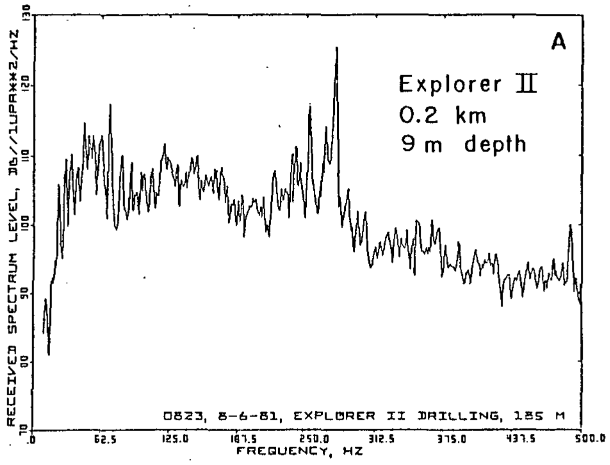

FIGURE 14. Sound pressure spectra for drillships 'Explorer II' and Conical Drilling Unit 'Kulluk' from recordings made while drilling. Note the varying vertical scales.

Discussion

The sound level for the 'SEDCO 708' drilling at range 0.19 km, hydrophone depth 10 m, 20-500 Hz band, was 116 dB//1 μPa (Fig. 13; Greene, in press). The sound level in the 400-1600 Hz band was 110.8 dB, making the level in the 20-1600 Hz band 117 dB at 0.19 km range. In contrast, the quietest drillship we measured during this project was the 'Explorer I' conducting logging operations; its sound level in the 20-1000 Hz band was 122-125 dB at range 0.17 km. Clearly, noise from the quietest drillship operation was stronger than the semi-submersible during drilling. Drillship levels were similar to levels near an actively drilling caisson-retained island (CRI) (Fig. 13).

The Conical Drilling Unit 'Kulluk' was the noisiest of the drilling vessels studied during this project. Its large size and large hull area in contact with the water probably contributed to the high noise levels. The nearby tug grappling for anchors probably accounted for some of the noise measured near 'Kulluk'.

Dredging

Background

Ford (1977) measured the sounds from cutter suction dredge 'Beaver Mackenzie' during construction of the Arnak artificial island in the southeastern Beaufort Sea, July 1976. He found that most energy in the sounds was at frequencies between 250 and 2000 Hz. We are unaware of other reports concerning dredge sounds.

There are two main types of dredge operation in the Beaufort Sea. In one, a dredge like 'Beaver Mackenzie' is moored in place and extends suction pipes to the bottom and discharge pipes to a barge or construction site. In the other, a hopper dredge moves over the dredging site picking up material to fill its hoppers, and then steams to the construction site to dump the load either through gates in the bottom of the ship or by pump-out methods.

Measurements

We measured sounds both from dredges moored in place and from moving hopper dredges during this project. We discussed the sounds of hopper dredges underway in 'Boat and Ship Sounds' earlier in this report; here we confine our presentation to the sounds of dredging.

Figure 15 displays measured 20-1000 Hz band levels vs. range for several operating dredges. The strongest sounds came from hopper dredge 'Cornelis Zanen' picking up a load at Ukalerk on 7 August 1983. 'Zanen' is powered by 11.1 MW, can make 28.7 km/h, and carries a load of 8000 m^3. The water depth was 20 m, the hydrophone depth was 9 m, and the ranges varied from 0.63 to 2.45 km. The levels were on the same order as levels measured for 'Geopotes X' picking up a load at comparable ranges at the same site on 29 August 1982, for 'Gateway' dumping a load at Kadluk on 11 August 1982, and for 'Cornelis Zanen' pumping out material on 31 August 1984. All three are hopper dredges. These dredging data for 'Cornelis Zanen' were taken at shorter ranges than the underway data for the same ship (see Fig. 5) but the two sets

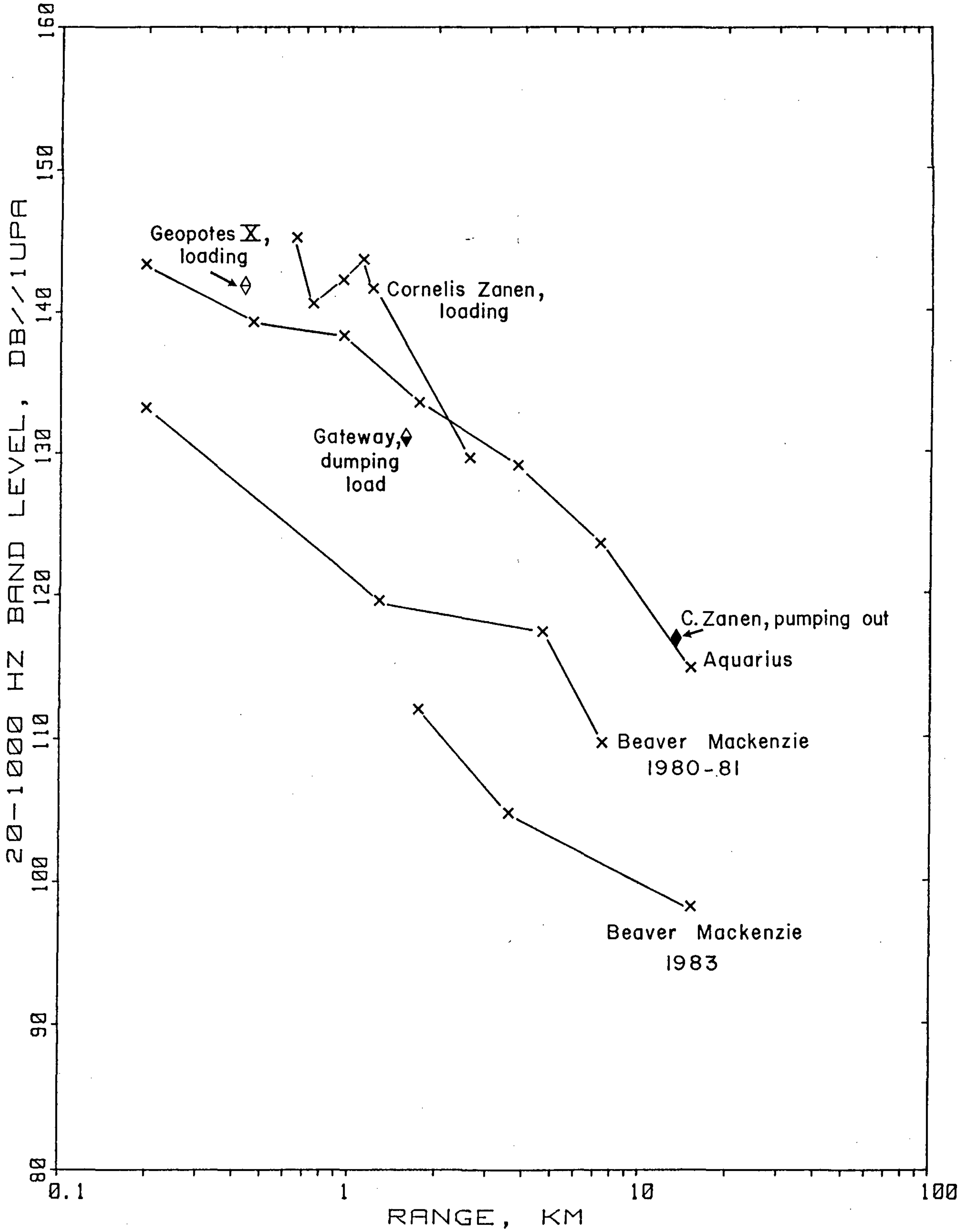

FIGURE 15. Dredge sound levels in the 20-1000 Hz frequency band vs. range for dredges that were actively dredging; hydrophone depths 9-18 m.

of levels line up, suggesting that the sound levels while dredging may not be much different than the levels while underway.

'Aquarius' is a suction dredge about 90 m long and 12 m wide; it was moored at Nerlerk on 12 August 1983 transferring material from the bottom to a berm construction site. It can transfer up to 100,000 m^3/day. The sounds were notably stronger (by 10-15 dB) than those recorded for dredge 'Beaver Mackenzie', which also operated as a transfer dredge capable of moving 70,000 m^3/day. We recorded 'Beaver Mackenzie' sounds on 7 August 1980 at the Issungnak artificial island construction site, and on 6 August 1981 at the Alerk artificial island site. Interestingly, noise levels from 'Beaver Mackenzie' at Amerk on 13 August 1983 were 7-12 dB quieter than they had been in 1980-81. The dredge sounded different to the human ear, and the spectrum revealed more tones in 1983 than in 1980-81. Water depths were 46 m at Nerlerk, 18 m at Issungnak, 13 m at Alerk, and 29 m at Amerk (see Fig. 1 for locations).

Figure 16 presents sound level spectra for three dredges. Figures 16A and B are from two analyses of the same sound from 'Beaver Mackenzie' at Issungnak. This recorded sound was used in the dredge playback experiments on 16 and 24 August 1984 (Richardson et al. 1985); the tone at 1775 Hz was unusually strong for a tone at a frequency above 500 Hz. Figure 16C is for the same dredge at Amerk in 1983, when there was no strong tone between 1 and 2 kHz. Figure 16D is for 'Cornelis Zanen' picking up a load at Ukalerk, and Figures 16E and F are for the dredge 'Aquarius' at Nerlerk, 0.2 and 14.8 km ranges. All these spectra are for dredges whose band levels are plotted against range in Figure 15. In some spectra, received levels were rather low for the lowest frequencies. As discussed earlier for boat and drillship sounds, low frequency sounds often attenuate at a high rate in shallow water.

Discussion

Based on our measurements, suction hopper dredges and some transfer dredges are the strongest sources of continuous industrial noise of any activities associated with offshore oil exploration in the Beaufort Sea. The higher levels from hopper dredges than from 'Beaver Mackenzie' are probably explained by the absence of sounds from propulsion machinery in the cases of moored dredges. Although the measurements did not overlap in range, data for 'Cornelis Zanen' indicated that sound levels from hopper dredges may be similar while dredging and underway. Sound levels for hopper dredges dumping a load and pumping out a load were also similar to the levels for picking up a load.

Spectrum analysis did not reveal any unusual frequency characteristics in dredging sounds other than the tone at 1775 Hz from 'Beaver Mackenzie' in 1980-81. There was no similar tone in 1983.

Operations at Islands

Background

Once an artificial island or berm has been constructed, equipment and facilities for exploration drilling are moved onto it. Malme and Mlawski (1979) reported on the sounds of drilling from islands during winter. They reported, 'the broadband component decayed rapidly within 0.5 to 1.0 miles

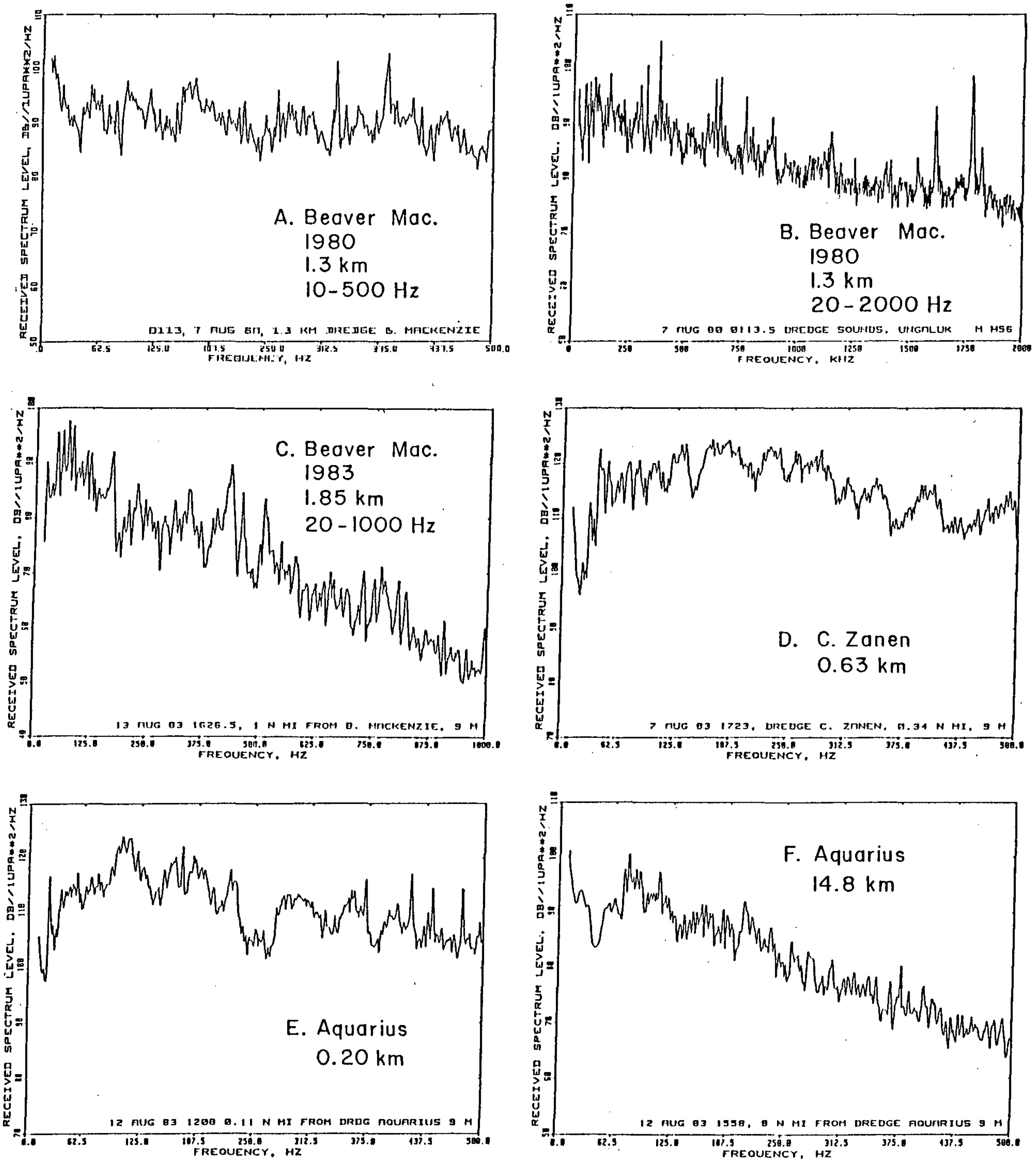

FIGURE 16. Sound pressure spectra from working dredges.

from the rig leaving low frequency tonal components...observed out to 4-6 miles under low ambient noise conditions'.

Measurements

During the project we measured sounds at three operating island sites: (1) at the Tarsiut caisson retained island (CRI); (2) at Kadluk while a different caisson was being installed on a berm, and (3) at the Amerk CRI during drilling.

When the sound boat 'Sequel' reached Tarsiut on 6 August 1982, drilling had already been completed and 'wiper tripping' was in progress. Anchored at range 1.1 km, water depth 21 m, hydrophone depth 9 m, we recorded sounds from the area for over 12 h. The movement of support craft (especially tugs and workboats; a crane barge remained in place alongside the caisson) undoubtedly contributed to the sounds recorded. The 20-1000 Hz band levels varied from 121 to 130 dB. Further data were obtained on 15 August 1982, when activities reportedly included pile driving on one corner of the island; 20-1000 Hz band levels diminished from 119-125 dB at 0.46 km to 100 dB at 18.5 km. We did not distinguish any sounds that we could associate with pile driving.

On the evening of 16 August 1983, 'Sequel' anchored 3.8 km east of the caisson being installed on a berm at Kadluk. This particular caisson was an octagonal structure that had been floated over a berm and ballasted down. On 16 August 1983 it was being filled with sand to form the caisson-retained island. However, at the time of our measurements, filling was not in progress. Kadluk was the first site where this particular caisson had been installed. We recorded sounds at ranges of 3.8, 1.8, and 0.93 km, where water depths were 12, 13, and 13 m. Numerous support boats, a crane barge, and dredge 'Cornelis Zanen' were all in the vicinity. The 20-1000 Hz band levels were 116, 119, and 117 dB, respectively, for ranges 3.8, 1.8, and 0.93 km, hydrophone depth 9 m. We attribute the lack of dependence on range to the varying presence and activities of the operating vessels around the Kadluk area. Measurements at ranges that were large compared to the separations of the working vessels would be expected to show the usual sound attenuation with increasing distances.

On 29 August 1984 we maneuvered 'Sequel' to a range of 0.2 km from the same caisson, now installed at Amerk (Fig. 1). A crane barge and workboat were moored at the caisson, and a second workboat was underway slowly nearby. After confirming by radio that drilling was underway, we recorded the sounds at ranges 0.22, 0.39, 1.85, 3.7, 7.8 and 13.2 km. The corresponding sound levels in the 20-1000 Hz band were 130, 128, 128, 126, 118, 113 and 112 dB. However, it appears likely that the levels for ranges 7.8 and 13.2 km were predominantly background noise. The other five levels have been plotted on Figure 12 for comparison with the drillship sound level measurements vs. range. The CRI drilling sounds were comparable in level to those from drillship 'Explorer II'.

Figure 17 contains six spectra associated with operations at caisson retained island operations. Figure 17A is from Tarsiut at range 0.46 km on 15 August 1982, and Figure 17B is from Tarsiut at range 1.1 km on 7 August 1982 (hydrophone depth 9 m). The former shows a strong tone at 120 Hz; such a tone is usually associated with electric power generation. Figure 17C is a spectrum for a hydrophone at depth 9 m at range 0.93 km from the caisson

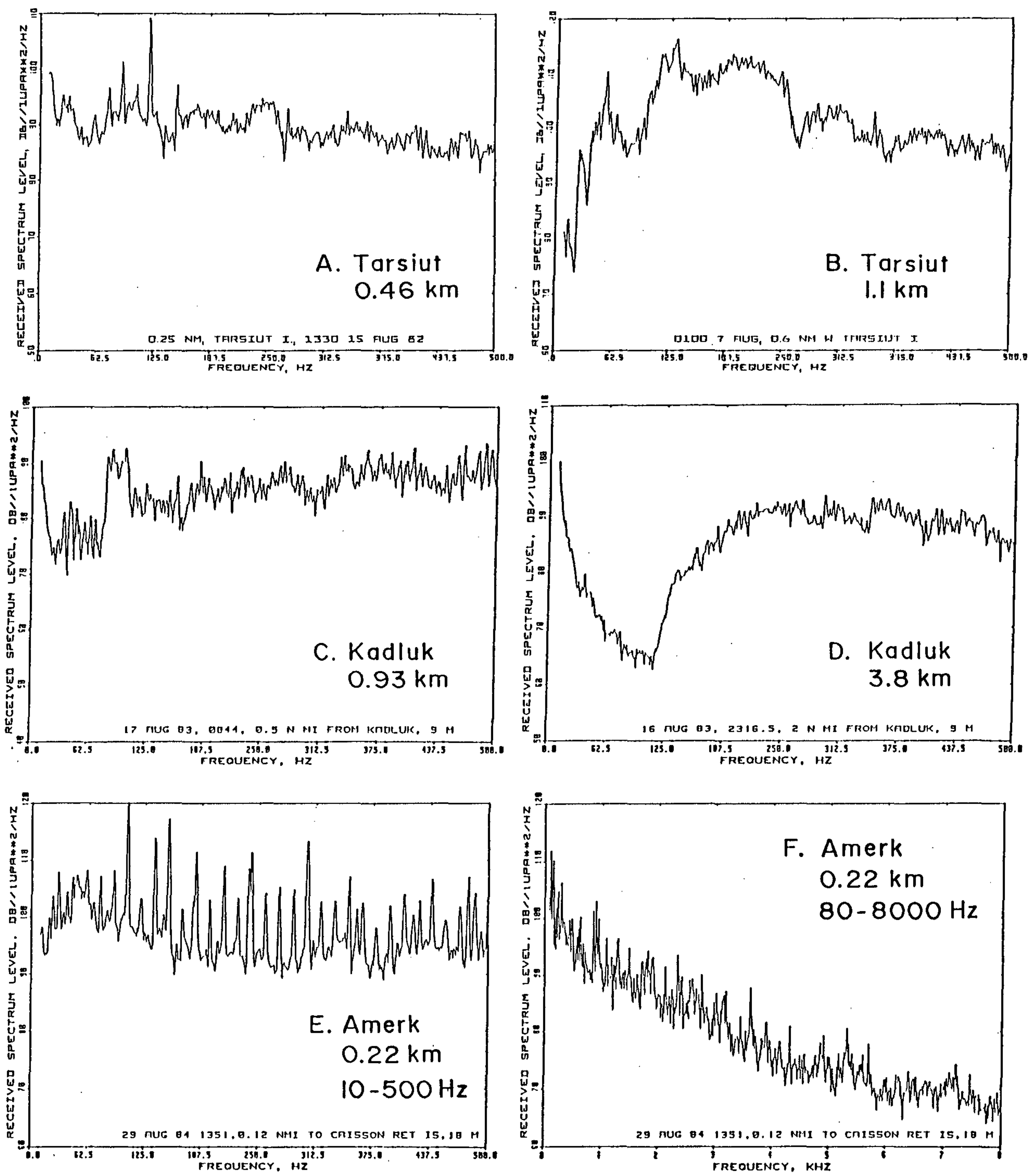

FIGURE 17. Sound pressure spectra from operations at caisson islands.

being installed at Kadluk (water depth 12 m). This case is unusual in that levels increased with increasing frequency, up to 350 Hz. Figure 17D is a spectrum for a hydrophone at depth 9 m at range 3.8 km from the same operation. It shows a dip in received level at frequencies up to 100 Hz; we often noted such a dip in shallow water sound measurements, presumably because low frequency, long wavelength sound energy is rapidly attenuated in shallow water. Figure 17E is a spectrum to 500 Hz for the CRI during drilling at Amerk, range 0.22 km, water depth 26 m, hydrophone depth 18 m. Figure 17F is the same sound analyzed to 8 kHz; the tonal spikes can be seen easily up to 5.7 kHz. The frequency resolution is only 27.4 Hz in Figure 17F, compared to 1.7 Hz in Figure 17E, so the tones are not displayed as prominently in Figure 17F.

Discussion

The activities at the three caisson retained island sites were widely diverse. The levels of sounds during drilling at Amerk were comparable to the levels during drilling by the drillship 'Explorer II'. Comparing the 20-1000 Hz band levels of the three caisson island activities at range 1.8 km, the drilling operation at Amerk produced a sound level of 126 dB, the caisson installation at Kadluk produced 119 dB, and the general activities at Tarsiut produced 113 dB. However, at range 0.93 km the corresponding levels were 128, 117, and 124 dB, making Tarsiut noisier than Kadluk. At all three sites, the radiated sound levels could vary considerably because of the varying activities of the surrounding support vessels. However, such vessel support is standard practice at offshore exploration sites and it must be expected to contribute to the overall industrial noise for such sites.

GENERAL DISCUSSION

As an aid in comparing the measured sound levels with one another and with ambient levels, Figure 18 summarizes 20-1000 Hz band levels vs. receiver range. Only representative sound sources have been included (see also Figs. 5, 13, 15). However, we will discuss other sounds in relation to those plotted.

The strongest levels on the graph are airgun array signals from 'GSI Mariner' at ranges 12-17 km. These signals are transitory, usually lasting less than a second and occurring once each 12-15 s. Other 'GSI Mariner' airgun array signal levels are plotted for ranges 62-73 km on 18 August 1982. We noted considerable variability in airgun signals from longer ranges, as shown by these examples, and attribute it to the important influences of water depth and bottom sediment properties on sound propagation. Aspect with respect to the long axis of the airgun array was probably also a factor (Barger and Hamblen 1980; Malme et al. 1983).

Sounds from the sleeve exploders on 'Arctic Surveyor' were received at nominal ranges of 8, 13, and 28 km in water 15-30 m deep, hydrophone depth 9 m. Figure 18 includes the curve derived from multiple regression analysis of the measured levels relative to range. The curve shows that the sound levels diminished with increasing range in two ways: by cylindrical spreading (10*log(range)) and by a combination of absorption and scattering losses amounting to 1.4 dB per kilometre. The latter linear term is very important for longer range sound transmission. Data not shown here (see Greene 1982, p. 338) revealed that the linear term was generally larger for shallow depths

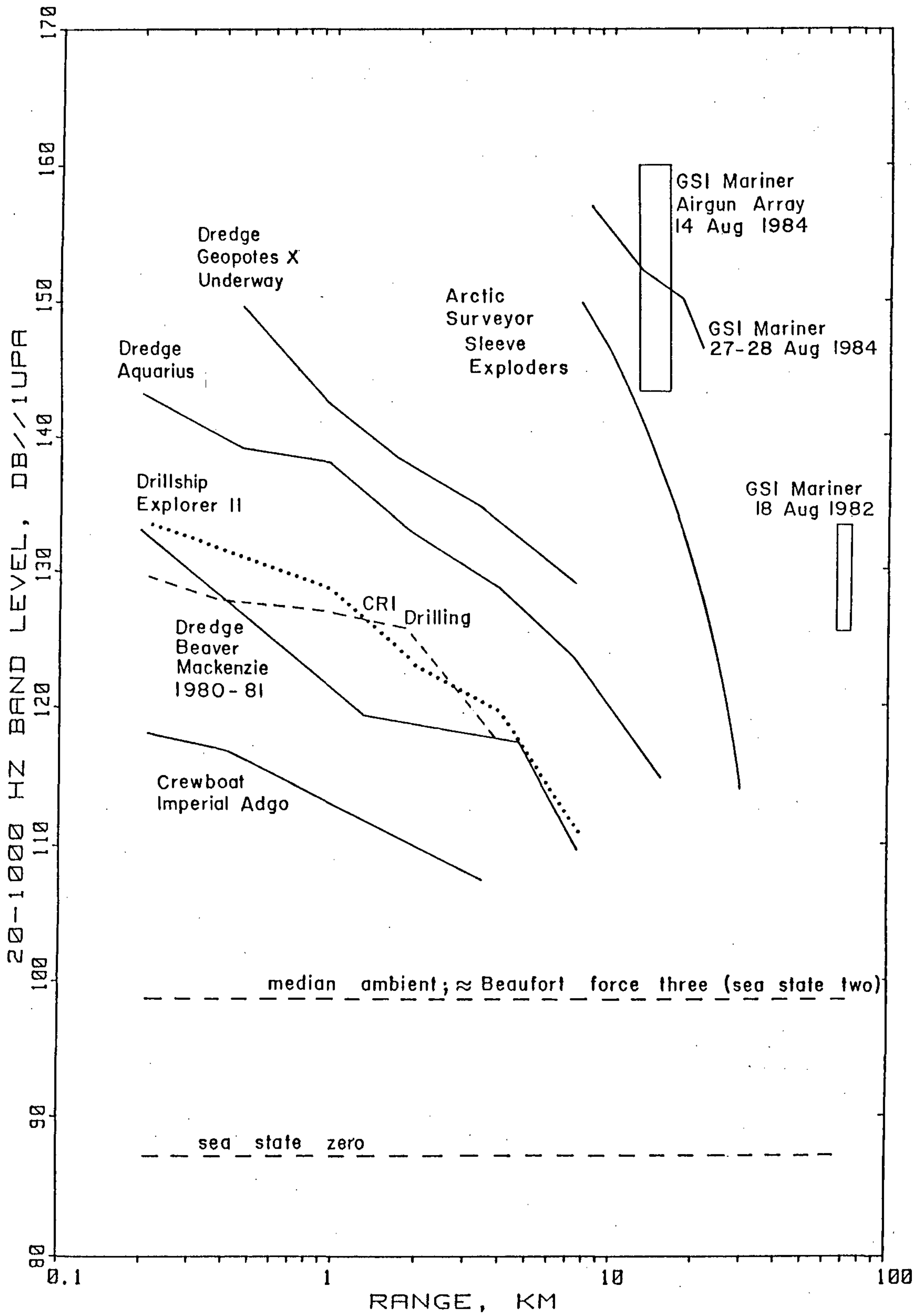

FIGURE 18. Summary of levels vs. range for various industrial sounds. The boxes circumscribe the ranges and levels received from 'GSI Mariner' during various short spans of time.

and/or higher frequencies. For example, for a 1000 Hz tone for 'Geopotes X' in water 25 m deep, the absorption/scattering loss term was 2.53 dB per kilometre.

The strongest continuous type of signal received during the project came from hopper dredge 'Geopotes X' underway. The ship was apparently operating that season with a damaged propeller, which probably accounts for the high levels. Also shown on Figure 18 is the curve connecting the measured levels of sound from crewboat 'Imperial Adgo' operating over shallow water (18.5 m). Sound levels from crewboat 'Imperial Sarpik' and the sound boat 'Sequel' were similar. These were among the quietest industrial noises recorded. Only 'Arctic Sounder', anchored and running only its electric generator, was quieter. Other boat and ship sound levels, including those from supply boats and other dredges underway, fell between the levels for 'Geopotes X' and 'Imperial Adgo'.

The sound levels near drillship 'Explorer II' while drilling are also presented in Figure 18. The sounds near conical drilling unit 'Kulluk' while drilling were stronger by 10-15 dB, but sounds from 'Explorer I' while logging were 5-10 dB weaker. Sounds from Amerk caisson retained island while drilling were on the same order as sounds from 'Explorer II'. In all these cases, some of the sounds probably came from ancillary vessels nearby, and some of the differences may have been attributable to the variable types and activities of those vessels.

The received levels for sounds from transfer dredges 'Aquarius' and 'Beaver Mackenzie' are graphed on Figure 18. Sounds from hopper dredges like 'Cornelis Zanen' picking up a load were received at somewhat higher levels (by about 5 dB) than the sounds from 'Aquarius' at comparable ranges. We attributed the higher levels from hopper dredges to the contributions from the propulsion machinery. 'Beaver Mackenzie' in 1983 was significantly quieter than it had been in 1980-81.

Below the industrial sound levels in Figure 18 we have plotted the median of the ambient noise levels measured during the 1984 season (excluding measurements near industrial sites) and the expected 20-1000 Hz band level for sea state zero. The 1980-84 median level (99 dB) was 1 dB less than the expected level for Beaufort Wind Force 3 (Sea State Two). These ambient levels are not range dependent and are, therefore, plotted as straight lines independent of range.

The sound levels received from overflying aircraft are not plotted because they were not analyzed for range dependence. However, the received levels can be compared with the plotted levels for other sources. For example, the maximum noise level below the Islander at altitude 152 m was 117-123 dB at a hydrophone 3 m deep; those levels are comparable to 'Imperial Adgo' at range 0.2 km and to drillship sounds at ranges near 4 km. Levels of aircraft noise decreased with increasing aircraft altitude and increasing hydrophone depth. At depth 9 m, Twin Otter and Islander sounds from altitude 457 m were 101-106 dB, or just above the 1984 median ambient noise level. These levels are averages for the 4 s when the aircraft sound was strongest. The maximum level was received for only a few seconds.

Sound levels from caisson retained islands at Kadluk and Tarsiut are not plotted on Figure 18, but Tarsiut levels were generally similar to levels from drillship 'Explorer II', CRI drilling, and dredge 'Beaver Mackenzie' in 1980-81. Kadluk sound levels were also about the same.

The following are the fitted equations for received level in the 20-1000 Hz band (dB//1 μPa) vs. range (km) for three industrial sound sources in the shallow Beaufort Sea. Cylindrical spreading (10*log R) was forced.

Drillship 'Explorer II' drilling:

$$RL = 128.4 - 0.985*R - 10*\log(R) \qquad se = 1.06\ dB,\ r^2 = 0.892,\ n = 6.$$

Hopper dredge 'Geopotes X' underway:

$$RL = 143.9 - 0.916*R - 10*\log(R) \qquad se = 2.27\ dB,\ r^2 = 0.634,\ n = 5.$$

Dredge 'Beaver Mackenzie' dredging (at Alerk):

$$RL = 127.1 - 1.197*R - 10*\log(R) \qquad se = 1.57\ dB,\ r^2 = 0.847,\ n = 6.$$

For dredge 'Aquarius' dredging at Nerlerk (depth 46-60 m), we derived an equation for received level in the 20-500 Hz band (dB//1 μPa) as a function of both range in km and hydrophone depth in m (from Greene 1984, p. 293):

$$RL = 119.9 - 0.42*R - 1.31*D - 10.8*\log(R) + 29.6*\log(D)$$
$$se = 2.1\ dB,\ r^2 = 0.96,\ n = 21.$$

We can make several summary statements about industrial sounds in the Beaufort Sea:

1. Sounds from an aircraft overhead diminish in strength with increasing receiver depth. Sounds from an aircraft not directly overhead increase in strength with increasing receiver depth. Low flying aircraft induce stronger peak levels of sound underwater than do high flying aircraft. The peak levels of aircraft sound are short-lived, especially when the aircraft is low. Sounds from passing aircraft are audible longer in shallow water than in deep water.

2. Sounds from underwater sources are weaker near the surface. For the low frequencies (<100-200 Hz) dominating the industrial sound sources that we studied, this shallow depth effect is most noticeable within 9 m below the surface.

3. The impulsive sounds from distant seismic surveys can travel via both water and bottom paths. In shallow water, the waterborne sound reaching ranges of several kilometres or more is limited to frequencies above about 100 Hz, and sometimes to even higher frequencies. Generally, the summation of multiple reflections over a long path leads to the appearance of higher frequencies first, followed by decreasing frequencies, in the waterborne sound. Longer distances mean more multipaths and, hence, a longer-lasting signal. Sound may also travel via bottom paths, bending upward and reflecting at the surface many times on its way to the receiver.

Low frequencies travel via these bottom paths and generally the lowest frequencies arrive first, followed by increasing frequencies.

4. Sounds from offshore sites generally include sounds from numerous support vessels--supply boats, tugs, crane barges, and camp barges. Drilling vessels are also sometimes protected by icebreakers. The sounds from these vessels are an integral part of the noise fields around the offshore sites, but these sounds can be highly variable, depending on activities.

5. Ambient noise levels in the Beaufort Sea vary from below the levels expected for sea state zero (deep water) to above levels expected for Beaufort Wind Force 8. The median level for the 20-1000 Hz band, excluding measurements near industrial sites, was 99 dB. This is equivalent to the expected level for Beaufort Wind Force 3. It should be noted that measurements were generally not made during bad weather, either from the sound boat or the airplane, and the true median level would be higher.

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The staff at the LGL office in King City devoted extra effort to the production of this report. C. Holdsworth and R. Evans looked after details, B. DeLong did the graphic art, and B. Griffen and R. Stark typed the text and tables.

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OCS STUDY

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

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DISTRIBUTION OF BOWHEADS AND INDUSTRIAL ACTIVITY, 1980-84*

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TABLE OF CONTENTS

ABSTRACT

This section summarizes seasonal and year-to-year trends in the summer distribution of bowheads during 1980-84. It identifies locations where bowheads tended to concentrate, documents the locations of offshore industrial operations within the summering area, and discusses whether any year-to-year changes in distribution are attributable to oil exploration. Sightings of bowheads during all studies in the Canadian Beaufort Sea in mid-late summer of 1980-1984 are mapped by 10-d period. Other maps show sites of offshore drilling, dredging, boat and helicopter traffic, seismic lines, and ice conditions. The 'main industrial area' is off the Mackenzie Delta, and includes island construction, drilling, dredging, and intensive boat and helicopter traffic. Seismic exploration occurs over a wider area.

In 1980, bowheads were more numerous close to shore than in the subsequent four years. Some were <5 km from an island construction operation off the central Mackenzie Delta. By late August, very large numbers (probably well over half the population) were widely distributed off the Tuktoyaktuk Peninsula, many in water <20 m deep. Numbers off the Delta were somewhat reduced by late August, but still high. In 1981, most bowheads

remained farther offshore. In early August many moved south onto the outer continental shelf off the Mackenzie Delta, with lesser numbers off the Tuk Peninsula. None were seen where whales were abundant in early August 1980. In mid August the whales were widely distributed in waters >50 m deep, but there was a concentration off the central Delta, with some whales <10 km from industrial sites.

In 1982, most bowheads were far enough offshore or west to be outside the main industrial area. In mid-late August, there were concentrations near Herschel Isl and near the shelf break. In 1983, most bowheads again remained outside the main industrial area. In early August, bowheads were found far off the western Yukon, sometimes exposed to noise from distant seismic exploration. In mid and late August, several hundred subadult bowheads were along the Yukon coast, distant from industrial activity. Some bowheads were near the edges of the industrial area in late Aug-early Sept. In 1984, bowheads were somewhat more common in the main industrial area than in 1982 and 1983, although less so than in 1980 and 1981. Most of those in the industrial area were around its periphery, not in the central part where bowheads were abundant in 1980 and, to a lesser extent, 1981. From mid Aug to early Sept, many were along the Yukon coast and along the edge of the turbid Mackenzie River water in Mackenzie Bay.

Discussion.--From 1980 to 1982, bowhead distribution overlapped progressively less with the main industrial area. Peak numbers there in 1983 were slightly greater than in 1982, and there was some further increase in 1984. Most of those in the industrial area in 1983-84 were near its edges, unlike the situation in 1980. Intense offshore industrial activity began north of the Mackenzie Delta in 1976. Very limited data from 1976-79 indicate that bowheads were numerous in the central part of the main industrial area in August of 1976 and 1977 but not 1978 or 1979, i.e. in 3 of 5 years from 1976-80, and in 0 of 4 years from 1981-84. The reappearance of many whales in 1980 makes it questionable whether the apparent trend toward reduced utilization of the main industrial area was attributable to industrial activity. However, offshore industrial activities have increased gradually since 1976; industry may have begun to affect bowheads after 1980.

In 1980-84, seismic exploration occurred both within and beyond the main industrial area. Bowheads were often seen in areas with seismic noise, and in areas where whales had been exposed to seismic noise the preceding year. Thus, we found no evidence that bowheads avoided areas of previous exposure to seismic noise.

Bowhead distribution varied markedly from summer to summer in the feeding grounds of the Canadian Beaufort Sea. This variation occurred outside as well as within the main industrial area. At present, it is not possible to determine whether the scarcity of bowheads in the central part of the main industrial area in 1982-84 was related to industrial activities. Assumed variation in food availability (zooplankton concentrations) may also have been involved. Zooplankton is probably controlled by oceanographic and meteorological factors that vary seasonally and annually. Until the influences of these natural factors on zooplankton and bowhead distribution are understood, it may be impossible to determine whether any of the variation in bowhead distribution is a result of industrial activities.

INTRODUCTION

The main focus of this volume is a study of short-term behavioral reactions of bowhead whales to offshore industrial activities. An observable behavioral response provides an immediate indication that whales are sensitive to the industrial activity. However, it is difficult to determine whether brief behavioral reactions have any long-term negative consequences. Long term reactions might, in theory, include such interrelated factors as increased stress, reduced overall food intake during the summer feeding season, reduced reproductive success or survival rate, and displacement from parts of the traditional range. Of these, the potential effect that might be detected most easily is displacement.

The literature contains little quantitative information about prolonged displacement of other species of baleen whales by human activities. Gray whales apparently were displaced from a wintering lagoon when ship traffic and other human activities intensified, and returned several years later when ship traffic decreased (Gard 1974; Reeves 1977; Bryant et al. 1984). In other cases, suggested displacements have not been demonstrated convincingly (reviewed by Richardson et al. 1983b). These possible cases include other gray whale wintering areas and migration routes (Rice 1965; Rice and Wolman 1971; Wolfson 1977; Dohl and Guess 1979), humpback whale wintering and feeding areas (Norris and Reeves 1978; Jurasz and Jurasz 1979; MMC 1979/80), and whales in areas of heavy ship traffic off Japan (Nishiwaki and Sasao 1977). Most of these data are equivocal regarding whether whales are displaced by industrial activities. However, it is clear that whales often return each year to areas where they have been hunted or exposed to heavy vessel traffic.

By 1980, when detailed studies of Western Arctic bowheads in their Canadian summering areas began, full-scale offshore oil exploration had been underway for some years. Drilling from artificial islands in very shallow nearshore waters off the Mackenzie Delta began in 1972. In 1976, drillships began operating offshore, and island-construction also extended offshore into waters where bowheads occur. The intensity of offshore industrial activity has generally increased since 1976. By 1983 and 1984, five drillships, two active drilling caissons, 5-6 suction and hopper dredges, 9-10 helicopters, 3-4 seismic exploration boats, four industry-owned icebreakers, about 10 supply ships and many other support vessels were operating offshore in the southeastern Beaufort Sea (Fig. 1).

Before 1980, the only data about summer distribution of bowheads were from commercial whalers operating in the area around 1890-1914, and recent incidental sightings. Those records showed that bowheads migrate eastward into the Canadian Beaufort Sea in May and June, mainly along routes far offshore in the pack ice (Fraker 1979; Braham et al. 1980). Most sightings in early summer were in western Amundsen Gulf and the extreme eastern part of the Canadian Beaufort Sea -- east of the area of offshore oil exploration (Townsend 1935; Sergeant and Hoek 1974; Fraker et al. 1978; Fraker 1979; Fraker and Bockstoce 1980). Some bowheads occurred as far east as western Victoria Island (118°W) in May-August (Sergeant and Hoek 1974; Hazard and Cubbage 1982).

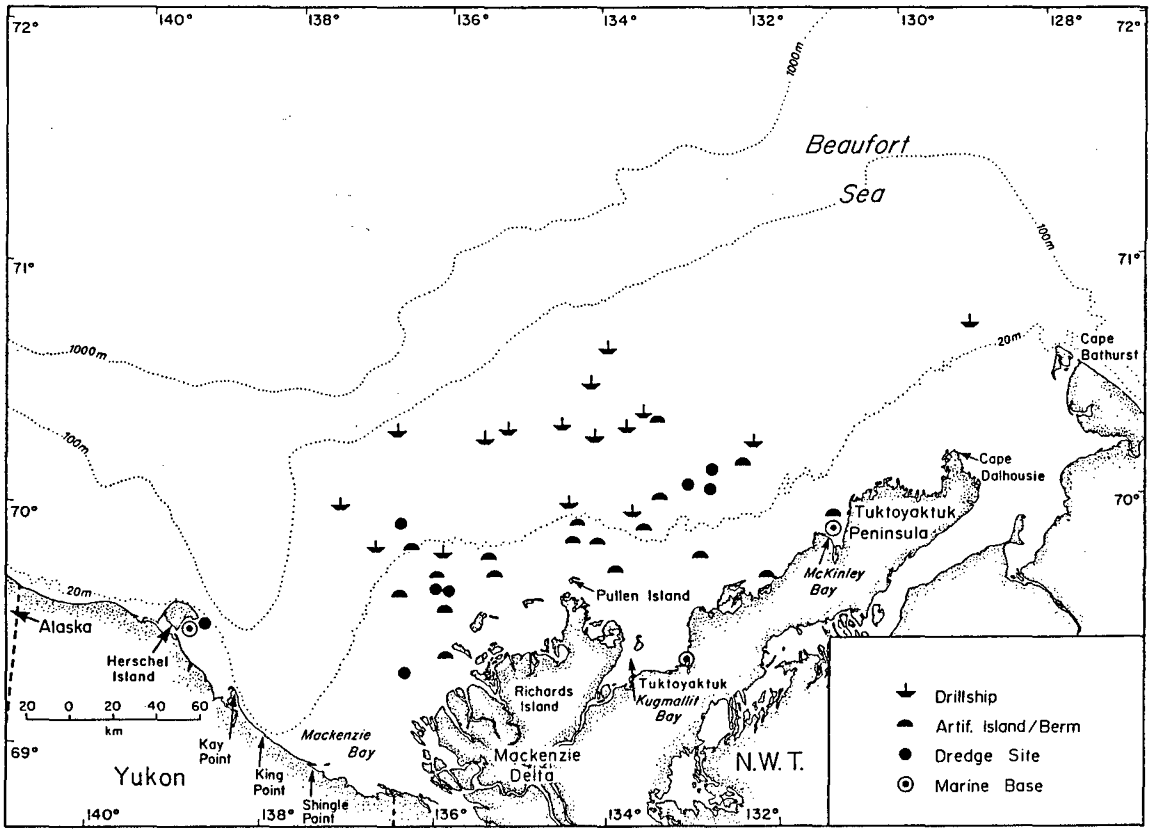

FIGURE 1. The eastern Beaufort Sea, study area for this project, showing the main sites of offshore industrial activity in August and early September, 1980-84. **Inset:** Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

During both the whaling era and the 1970's, the distribution of bowheads seemed to spread gradually westward off the Tuktoyaktuk Peninsula, Mackenzie Delta and Yukon coast in August (Townsend 1935; Sergeant and Hoek 1974; Fraker et al. 1978). The westward trend was considered real although (1) changing ice conditions were known to cause biases in detectability, and (2) most bowheads seen during August 1976-78 were oriented eastward (Fraker and Bockstoce 1980). In September, bowheads moved westward between Cape Bathurst (128°W) and the Alaska border (Sergeant and Hoek 1974), sometimes concentrating near the Yukon coast (Fraker and Bockstoce 1980). The last sightings in Canadian waters were in early October (Fraker and Bockstoce 1980).

Aerial surveys provide the type of comprehensive information about bowhead distribution that can be used to detect changes in distribution. Systematic surveys of parts of the Beaufort Sea were conducted in late summer of 1980-84. Coverage was incomplete and variable, but provided a far more detailed view of bowhead distribution and movements than was evident up to 1980. The surveys also showed major year to year differences in summer distribution, and in number of bowheads within the area of offshore oil exploration (Renaud and Davis 1981; Davis et al. 1982; Harwood and Ford 1983; Harwood and Borstad 1984; McLaren and Davis 1985).

Besides the systematic surveys, numerous other studies of bowheads have been conducted in the eastern Beaufort Sea since 1980. These included the behavioral study reported in this volume (1980-84), photogrammetric studies (1982-84), Alaskan aerial surveys that sometimes extended into Canadian waters (1980-84), and an attempt at radio-tagging (1980). All these studies included aerial surveys or reconnaissance; all bowhead sightings were recorded, although many of these distributional data were not included in resulting project reports. These non-systematic data included many locations and periods for which no systematic survey coverage was obtained.

The objectives of this report are twofold:

1. Draw together in a standardized way the available published and unpublished information about bowhead distribution in relation to industrial activities in the eastern Beaufort Sea during the summers of 1980 to 1984.

2. Assess whether there are any consistent trends in the summer distribution of bowheads during this period, and whether any such trends can be related to industrial activities.

For each 10-day period in the late summers of 1980-84, we present a map of the aerial survey routes (systematic and non-systematic) and the sightings of bowheads. For each of the five years, we also include maps showing the active offshore industrial sites, vessel and helicopter traffic, seismic exploration, and ice conditions. The very limited available data on bowhead distribution in the summers of 1976-79 are also summarized. We then assess whether there were any consistent trends in the summer distribution of bowheads in recent years, and whether the trends are related to industrial activities. We use the term "main industrial area" to refer to the zone with drilling, island construction, and intensive support by vessels and helicopters. Some seismic exploration is in the main industrial area, but seismic vessels often operate outside that zone.

This analysis of possible medium- to long-term effects complements our study of short-term behavioral reactions to industrial activities (Richardson et al. 1985a,b), and should be helpful in assessing whether offshore oil exploration in the Alaskan waters is likely to displace bowheads from parts of their traditional Alaskan range. The present final report is self-contained and includes the data and interpretations pertaining to all years. However, earlier versions of this report (Richardson et al. 1983a, 1984a) include more details for 1980-82 and for 1983, respectively, particularly concerning industrial activities in those years.

The scarcity of information about natural factors affecting the distribution of summering bowheads, or their zooplankton prey, is recognized as a serious problem in attempting to interpret the data on bowhead distribution. Variables that could be important in affecting bowhead distribution, directly or through effects on zooplankton, might include the variable outflow from the Mackenzie River, the variable extent and location of the Mackenzie plume, the variable distribution of ice, and variable hydrographic phenomena at the shelf break, ice edge and elsewhere (Griffiths and Buchanan 1982; Borstad 1984; LGL, ESL and ESSA 1984). Ongoing and planned work to address these factors will, when completed, be important in understanding the distribution of bowheads as documented below.

METHODS AND DATA SOURCES

Bowhead Sightings

Information about bowhead distribution in the eastern Beaufort Sea is available from early August to early or mid September of 1980-84, plus parts of July in 1981 and 1984 (Table 1). We include maps of bowhead distribution for four 10- or 11-day periods: 1-10, 11-21 and 22-31 August, and 1-10 September. A map for late July 1981 is also included. Almost all bowheads seen in the area of intense industrial activity off the Mackenzie Delta were seen in these periods. Our study area was the Canadian Beaufort Sea from Cape Bathurst (127°W) to the Alaska border (141°W), and north to 72°N (Fig. 1). The map for each 10-d period shows all flight lines and bowhead sightings within the study area during the studies listed in Table 1.

Field procedures during the various surveys are described in the reports cited in Table 1. During almost all surveys, Very Low Frequency (VLF) navigation systems were used to determine flight routes and sighting locations. Many flights were not systematic surveys with defined transect widths. Hence, we mapped all sightings, whether or not they were classified as on- or off-transect in the original reports. Symbols of progressively increasing prominence are used to show sightings of 1-3, 4-7, 8-15, 16-30 or 31-80 bowheads. When two or more sightings were so close together that their symbols overlapped broadly, only the larger of the two symbols was shown. This procedure reflects the fact that some whales undoubtedly were seen more than once during single 10-d periods.

The map for each 10- or 11-d period differentiates sightings and routes during the first 5 days from those during the next 5 or 6 days. In some 10-d periods, there were so many aerial surveys in certain areas that it was impractical to show every flight line. These 'intensive coverage areas' are demarcated with a heavy line. Within these areas only the bowhead sightings, not the flight routes, are shown.

We emphasize that the non-systematic surveys provide only a qualitative indication of the relative abundance of bowheads in different areas, and must be interpreted with caution. Survey procedures differed among projects, and detectability of whales was better during some flights than others. Survey effort in different parts of the study area ranged from nil to intensive, and non-systematic surveys tended to be concentrated in areas with many bowheads. Some whales are undoubtedly mapped more than once in a 10-d period, especially in areas where there was much coverage.

Offshore Industrial Sites and Vessel Movements

For each year from 1980 to 1984, we mapped the offshore locations where industrial activities were concentrated in the 1 August to 10 September period. The main site-specific activities were dredging, island construction or maintenance, drilling from drillships or islands, and island clean-up. These activities are shown by various symbol types. Construction of underwater berms and of islands were not differentiated. Offshore sites were mapped even if active for only a few days.

Table 1. Systematic and non-systematic aerial surveys of bowhead whales in the Canadian Beaufort Sea, 15 July to 20 September of 1980 to 1984. Survey effort is summarized in terms of d, days of surveying; f, number of offshore flights; h, hours of surveying; km, kilometres of straight-line transects.

	1980	1981	1982	1983	1984
Systematic surveys	- **Renaud & Davis (1981)** - 6 Aug-4 Sept - 7 d/6258 km - 3 surveys off Tuk Pen (133° to 129°W)	- **Davis et al. (1982)** - 18 July-14 Sept - 28 d/37,745 km[g] - 4 surveys, AK border to Amund Gulf (138°-141° to 117°-126°)	- **Harwood & Ford (1983)** - 18 Aug-13 Sept - 9 d/7442 km - 2 surveys, AK border to C. Dalhousie (140°-141° to 129°-130°W)	- **McLaren & Davis (1985)** - 19 Aug-11 Sept - 9 d/7045 km - 2 surveys, AK border to C. Dalhousie (141° to 129°W)	- **Harwood & Borstad (1984)** - 18 Aug-18 Sept[a] - 10 d/11,170 km[a] - 2 surveys[a], AK border to Franklin Bay (141° to 126°W)
Behavior & disturbance	- **Richardson (1982)**[b] - 3-31 August - 16 f/101 h - Mostly N of Mack Delta & Tuk Pen	- **Richardson (1982)**[b] - 27 July-8 Sept - 27 d/32 f/117 h - Mostly N of Mack Delta & Yukon	- **Richardson (1983)**[b] - 1-31 August - 19 d/27 f/122 h - Widespread off Delta & Yukon	- **Richardson (1984)**[b] - 1 Aug-1 Sept - 18 d/28 f/114 h - Mostly N of Mack Delta & Yukon	- **Richardson (this vol.)**[b] - 1 Aug-3 Sept - 23 d/33 f/140 h - Widespread; much in Mack Bay
Alaskan surveys extending into Canada[d]	- **Ljungblad (1981)**[d] - 28 July-24 Oct - 8 f/8 d[e] - Mostly off Yukon; some off Tuk	- **Ljungblad et al. (1982)**[d] - 15 Aug-20 Sept - 10 f/10 d - Mostly off Yukon	- **Ljungblad et al. (1983)**[d] - 2 Aug-15 Oct - 16 f/16 d[e] - Mostly off W Yukon	- **Ljungblad et al. (1984a,b, unpubl.[c])**[d] - 2 Aug-5 Oct - 29 f/23 d[e] - Mostly off W Yukon	- **Ljungblad (unpubl.)**[c,d] - 17 July-11 Oct - 24 f/21 d[e] - Mostly off W Yukon
Photogrammetric & other studies	- **Hobbs & Goebel (1982)** - 21 July-12 Sept - 13 f/13 d[f] - Mostly off Tuk Pen & C. Bathurst	- part of Davis et al. (1982); see above	- **Davis et al. (1983)** - 12 Aug-5 Sept - 15 d/72+ h/>8781 km - AK border to C. Parry (141°-125°)	- **Cubbage et al. (1984)** - 7 Aug-6 Sept - 24 f - AK border to Amund Gulf (141°-122°)	- **Davis et al. (in prep.)** - 14 Aug-14 Sept - 23 d/90+ h - AK border to Franklin Bay (141°-126°)
	- **Norton Fraker & Fraker (1981)** - 24 July-9 Aug - 3 f/3 d - N of Delta near Issungnak				- **D. Rugh (U.S. Nat. Mar. Mamm. Lab.)**[c] - 13-17 Aug - 4 d/4 f - AK border to C. Bathurst (141°-128°)

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[a] Harwood and Borstad (1984) also summarize four July surveys (5 July-2 August 1984, 12 d, approx. 6400 km) of the Alaska border to Cape Bathurst area (longitudes 139°- 141° to 128°-131°W).

[b] Distributional data obtained during the behavioral study have not been presented in detail elsewhere.

[c] Unpublished distributional data are mapped here through the cooperation of the investigators cited above.

[d] Flights that extended east of 141°W are considered here.

[e] Flights after 20 September not counted.

[f] Excludes flights also mapped by Ljungblad (1981).

[g] Includes coverage in Amundsen Gulf as well as Beaufort Sea *per se*.

For 1 August to 10 September in each of 1980 to 1984, the approximate number of vessel trips along each route is shown by line thickness. We included supply and crew boats, tug/barge trains, dredges, icebreakers, and drillships moving between sites. Seismic, sounding and scientific research vessels were excluded. The information came from records kindly made available by the oil companies and other vessel operators (see Acknowledgments). All major offshore operators allowed us to use their records. The maps do not record every vessel movement, and the mapped routes are approximations. Data for 1982-84 were more complete than those for 1980-81. However, the maps are indicative of the relative amounts of traffic in various offshore areas and periods. The vessel maps in this report include the entire 1 Aug-10 Sept period. For vessel traffic by 10-d periods in 1980-83, see Richardson et al. (1983a, 1984a).

For 1976 to 1979, we mapped the offshore sites that were active in the 1 August to 10 September period. On those maps, we indicate the routes that we know or believe were used by vessels. However, we did not attempt to determine how many vessels travelled along each route in 1976-79.

Seismic Exploration and Sounding

A third type of map shows the lines along which seismic vessels operated in the 1 August to 10 September periods of 1980 to 1984. Noise impulses emitted by seismic vessels are the most intense sounds routinely introduced into the sea by the oil industry (Richardson et al. 1983b, 1985b; Greene 1985). Surveys by three types of vessels are distinguished: Solid lines depict geophysical surveys shot by vessels using large arrays of airguns. Dashed lines depict surveys by the 'Arctic Surveyor', a vessel with an array of 12 sleeve exploders (1980-81) or 12 open bottom gas guns (1982-84). Dotted lines show surveys by 'Canmar Teal', a vessel using a small array of airguns. Sounding and other activities involving single airguns and other low-energy sources are not mapped here. The characteristics of the noise sources and of the resulting sounds are summarized by Greene (1982-85) and Richardson et al. (1985b). For locations of the 1980-83 seismic surveys by 10-d periods, and for locations of low-energy sounding operations, see Richardson et al. (1983a, 1984a).

The locations of seismic lines were kindly provided by Geophysical Service Inc., Western Geophysical Inc., Dome Petroleum Ltd., Esso Resources Canada Ltd., and Gulf Canada Resources Inc. Supplementary information was obtained from our sightings of seismic vessels at sea (Richardson et al. 1985b). Some seismic lines in the Alaskan Beaufort Sea extended east to 141°W longitude, the nominal western edge of our study area, and some extended a few kilometres farther east. These seismic lines are close to the western edge of our maps, and we did not attempt to include them. Seismic lines that crossed 141°W but also extended far to the east are included.

Helicopter Movements

A fourth type of map presented for each of 1981 to 1984 shows the offshore industrial sites (as on the vessel traffic map) plus the number of helicopter trips along each offshore route. The information was obtained from Dome, Esso and Gulf records, and included data for helicopters chartered by those oil companies. No other operators fly helicopters over the eastern

Beaufort Sea on a routine basis. However, a few single-engine helicopters occasionally travel offshore; we have not attempted to map their movements.

No adequate records of helicopter traffic in 1980 were available, and no map was prepared for that year. In 1980, as in other years, helicopters undoubtedly travelled from Tuktoyaktuk to all of the mapped offshore sites, as well as between some pairs of offshore sites.

Offshore flights by fixed-wing aircraft are excluded from the helicopter traffic maps. Whale survey flights are mapped on the whale distribution maps. Most commercial and ice reconnaissance flights are at altitudes above 457 m (1500 ft), and thus are too high to affect whales significantly (*cf.* Richardson et al. 1985a,b).

Ice Conditions

Ice conditions in early August and early September of 1980-84 are mapped. These maps show the areas with over 1% cover and over 80% cover. The maps are based on Weekly Composite Charts compiled by Ice Forecasting Central, Environment Canada. Their maps are based on satellite photographs and ice reconnaissance flights. Locations of pack ice sometimes changed by many kilometres within a few hours. Thus, the generalized maps presented here provide only a rough indication of ice cover.

RESULTS

Bowhead Distribution and Industrial Activities in 1980 (Fig. 2-9)

Industrial Activities, 1980

The general level of industrial activity in 1980 was slightly greater than in 1976-79 but lower than in 1981-84. Esso Resources Canada Ltd. and Dome Petroleum Ltd. were the only two oil companies operating offshore in 1980.

All drilling during the 1980 study period was from the four Dome drillships, which were at four sites north of the Mackenzie Delta for most or all of the 1 Aug-10 Sept period (Fig. 6). The one suction dredge that operated offshore built or improved artificial islands at Issungnak (27 Jul - 24 Aug; depth 18 m) and later Alerk (25 Aug-Oct; depth 13 m; Fig. 6). Most vessel movements were in support of these drilling and island building activities in the central part of the study area. However, there were several supply trips to points farther east and west (Fig. 6).

At least five twin-engine turbine helicopters were used offshore in 1980 --fewer than in 1981-84 (Table 2). Details concerning routes and number of flights were not available. However, most flights were from Tuktoyaktuk to the offshore sites shown on Fig. 6, with lesser numbers of trips (a) between those sites and (b) between McKinley Bay (Fig. 1) and the drillships.

Seismic exploration occurred off the eastern part of the Mackenzie Delta and much of the Tuktoyaktuk Peninsula throughout the 1 Aug-10 Sept period. Seismic occurred northwest of the Delta in mid and late August, and far to

Table 2. Number of helicopters operating offshore from Tuktoyaktuk on behalf of the oil industry in the summers of 1980-84.

Type of Helicopter	1980	1981	1982	1983	1984
Light twin (AS-355, BO-105)	0	0	1	2	2
Medium twin (B212, B412, S76)	4+	6+	5+	5	4
Large twin (AS-332, B214ST, S61)	1	1	2-3	3	2-3
Total	5+	7+	8+	10	8-9

the east off Cape Bathurst in early Sept (Fig. 8). There was additional seismic exploration at unknown locations and times during the summer of 1980.

Bowhead Distribution, 1980

Many bowheads occurred close to shore off the eastern Mackenzie Delta and western Tuk Peninsula in August 1980 (Figs. 2-4)--more so than in 1981-84. Survey coverage of the more remote areas was not comprehensive in 1980. Hence, large scale movements of the whales in 1980 are not well documented. There was almost no ice in the areas surveyed during August, but ice moved closer to shore in early September (Fig. 9).

The whereabouts of the bowheads during late July 1980 is not known. None were seen during an intensive but restricted survey north of the Delta around Issungnak on 24 July (Norton Fraker and Fraker 1981). There were no definite sightings during the four flights elsewhere in the study area (Ljungblad 1981; Hobbs and Goebel 1982).

In early August 1980, many bowheads moved into shallow water north of the Delta (Fig. 2). From 2 August onward, aerial surveyors and industry personnel saw many bowheads within 5 km and a few within 1 km from the suction dredge and support vessels at Issungnak (Norton Fraker and Fraker 1981; Richardson et al. 1985a,b). The whales were socializing, diving, and feeding in this area. There were few bowheads off the Tuk Peninsula in early August (Renaud and Davis 1981; Fig. 2).

Many bowheads moved into the area of heaviest industrial activity in early August. Seismic exploration was occurring both north of Issungnak and off the Tuk Peninsula. Besides traffic in support of the construction operation at Issungnak, vessel and helicopter traffic to at least 3 of the 4 drillships passed through the area where bowheads were concentrated (Fig. 2 vs. 6).

In mid August 1980, bowheads were still numerous near Issungnak, but many appeared farther east off the Tuk Peninsula around 14 August (Fig. 3). During flights on 19, 20 and 21 August, Hobbs and Goebel (1982) saw 114, 157 and 245 bowheads, mostly in shallow waters off the Tuk Peninsula. Many whales were feeding in waters as shallow as 10 m (Würsig et al. 1982). Aerial

1980

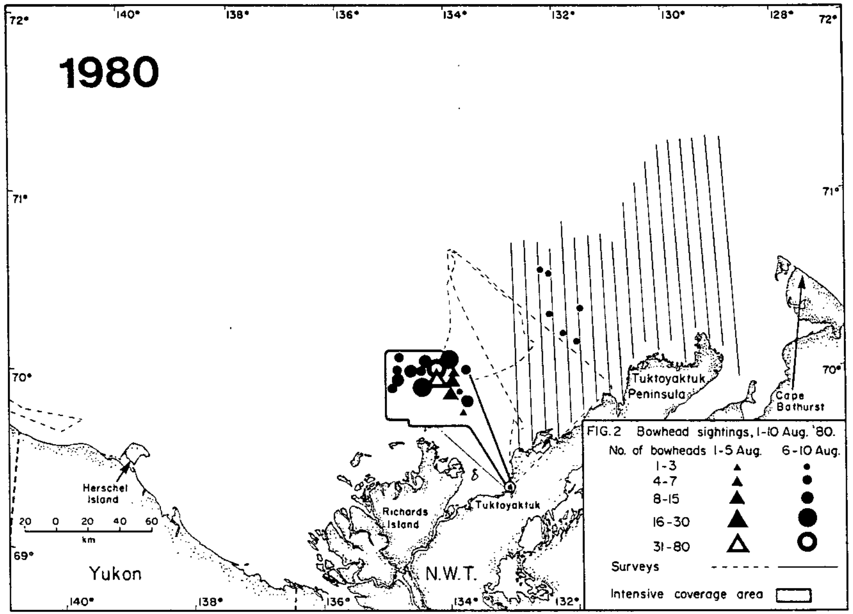

FIG. 2 Bowhead sightings, 1-10 Aug. '80.

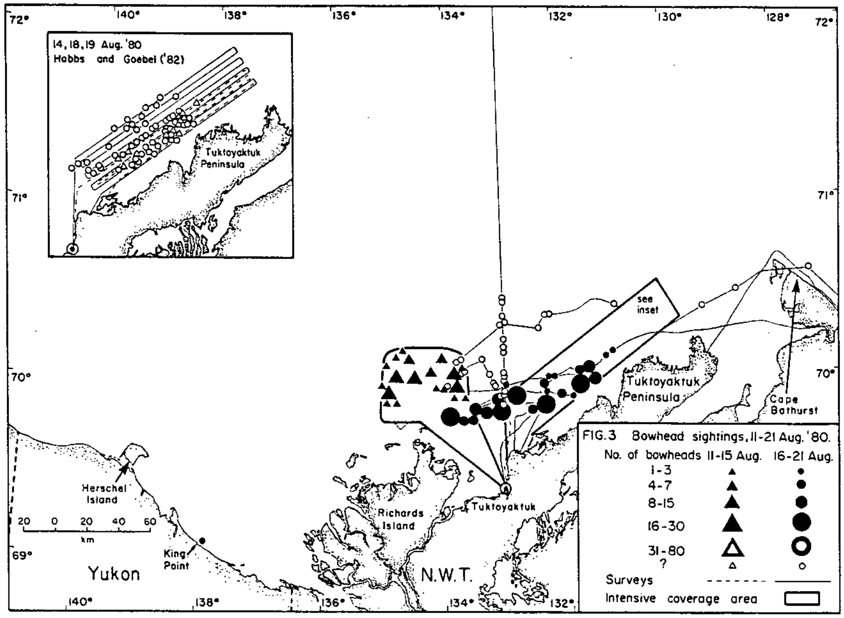

FIG. 3 Bowhead sightings, 11-21 Aug. '80.

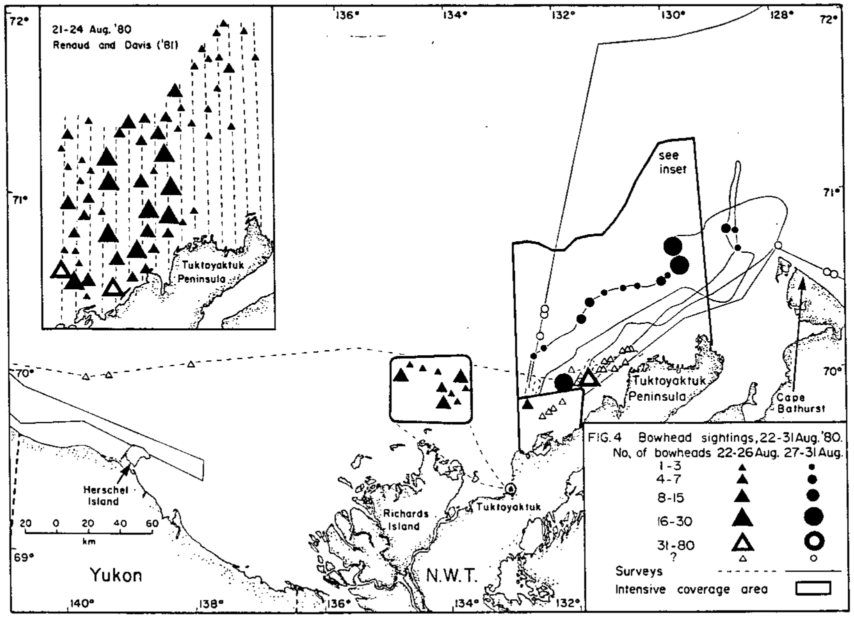

FIG. 4 Bowhead sightings, 22-31 Aug. '80.

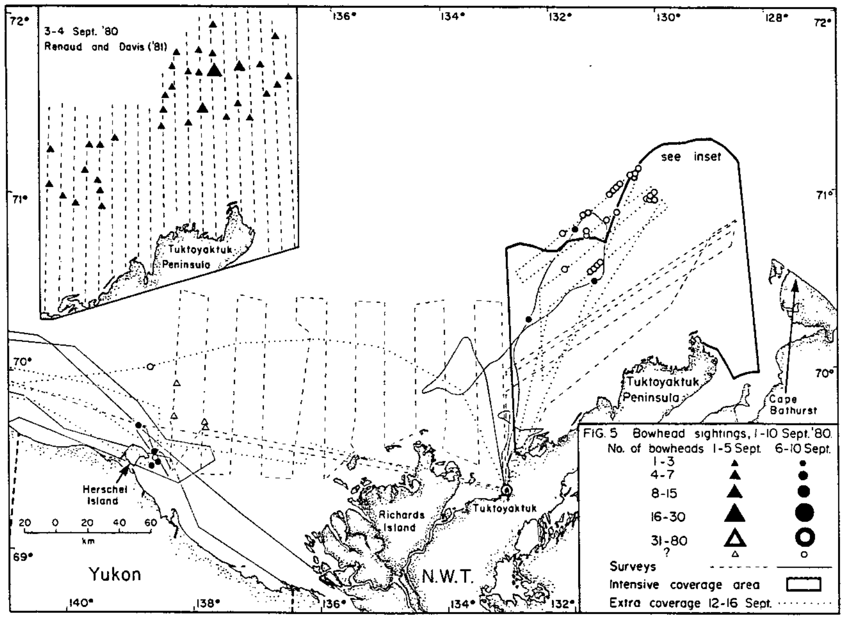

FIG. 5 Bowhead sightings, 1-10 Sept. '80.

1980

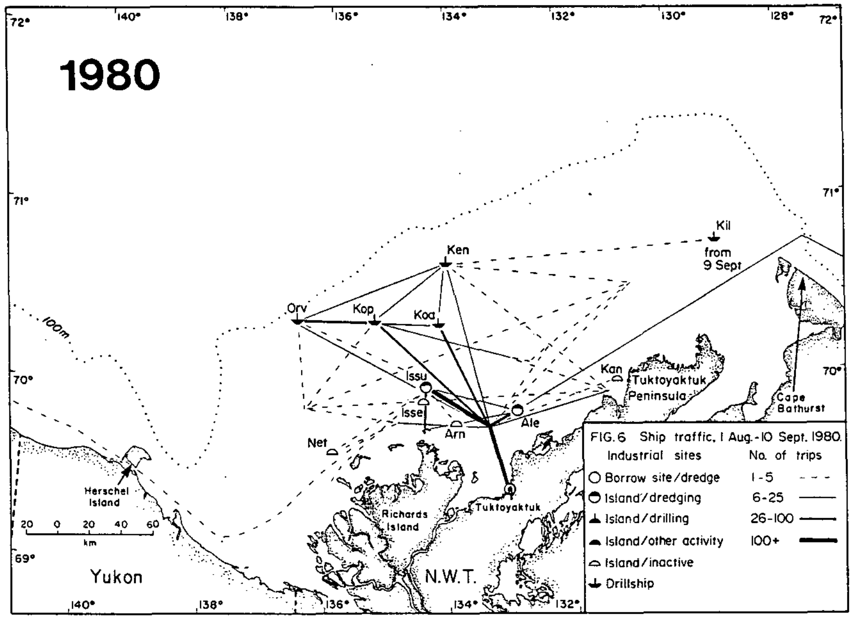

FIG. 6 Ship traffic, 1 Aug.-10 Sept. 1980.

Industrial sites	No. of trips	
○ Borrow site/dredge	1-5	- - -
Island/dredging	6-25	——
Island/drilling	26-100	——
Island/other activity	100+	▬▬
Island/inactive		
Drillship		

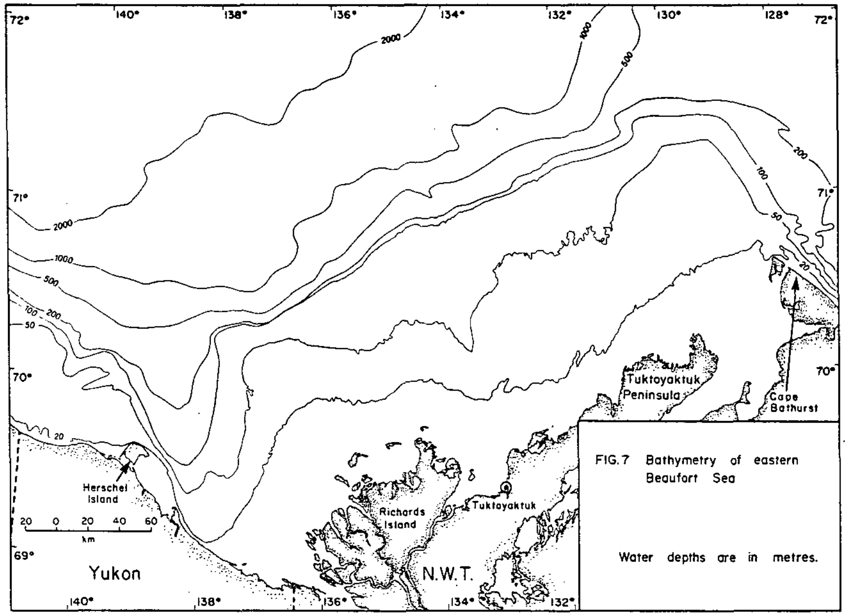

FIG. 7 Bathymetry of eastern Beaufort Sea

Water depths are in metres.

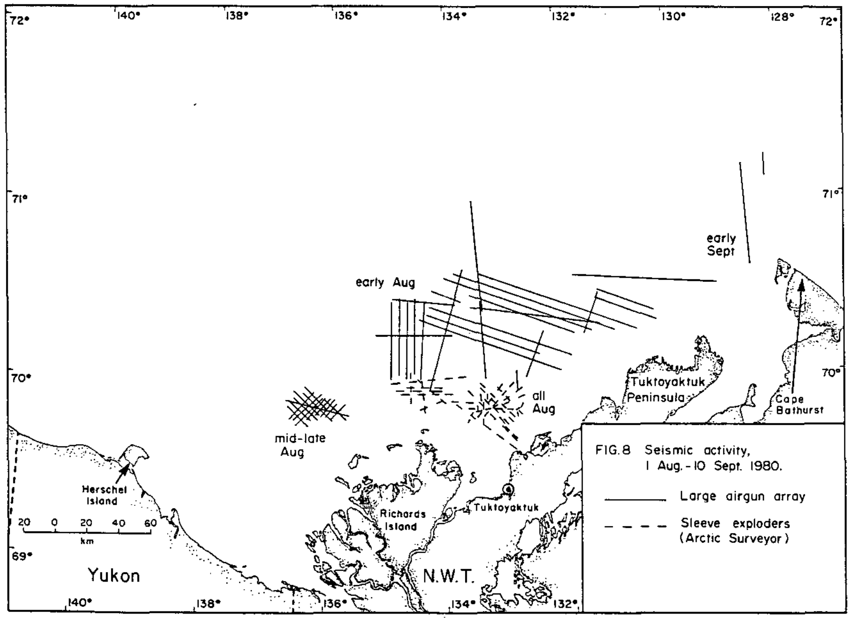

FIG. 8 Seismic activity, 1 Aug.-10 Sept. 1980.

——	Large airgun array
- - -	Sleeve exploders (Arctic Surveyor)

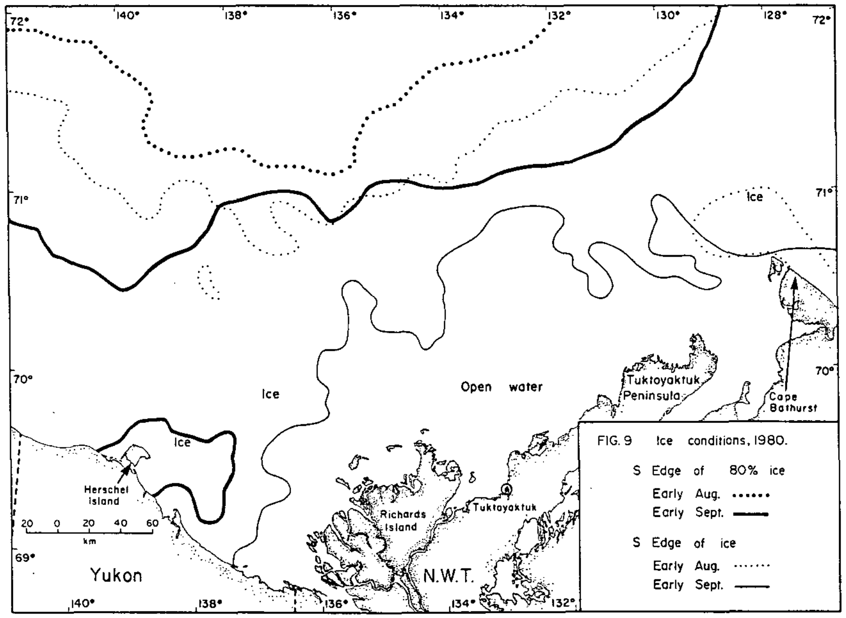

FIG. 9 Ice conditions, 1980.

S Edge of 80% ice

Early Aug.	••••••
Early Sept.	▬▬

S Edge of ice

Early Aug.	······
Early Sept.	——

coverage elsewhere in the study area was virtually nil, but observers who were at King Point, Yukon coast, from 16 Aug to 13 Sept saw only one bowhead throughout that period, on 18 Aug (Würsig et al. 1982).

During mid August, island construction and frequent vessel traffic continued around Issungnak; industrial activity was much less intense off the Tuk Peninsula (Fig. 6). One or two seismic boats worked north of Tuktoyaktuk (132°45'-133°40'). Some whales were exposed to strong noise pulses from a seismic vessel as close as 8-13 km away on 20-21 Aug (Richardson et al. 1985a,b).

During late August 1980, very large numbers of bowheads were off the Tuk Peninsula; densities near Issungnak were reduced from those in early August (Fig. 4). Renaud and Davis (1981) estimated that 755 bowheads were off the Tuk Peninsula within the 50 m contour on 21-24 Aug, with no allowance for missed whales. More whales appeared to be moving east than west, and numbers were significantly higher off the west than the east part of the Tuk Peninsula (Fig. 4, inset). Many bowheads were feeding at or near the surface off the Tuk Peninsula; others were socializing (Würsig et al. 1982). The size of this concentration was unique in the 5 years of study. Based on conservative correction factors for missed whales at and below the surface (Davis et al. 1982), >50% of the Western Arctic bowhead population apparently was in the shallow waters (≤50 m) off the Tuk Peninsula. Industrial activities were similar to those in mid August. Numerous whales were near Alerk, where there was dredging and seismic exploration, but the majority of those seen were farther north and east where there was less industrial activity.

Hobbs and Goebel (1982) found no bowheads far offshore during a flight northeast to Banks Island on 31 Aug, but 12 were seen in water about 50-250 m deep off the Yukon on 22 Aug (Fig. 4). It is not known whether bowheads were present off the Yukon coast earlier in August. No bowheads were seen in the Alaskan Beaufort Sea in July or August 1980 (Ljungblad 1981).

During early September 1980, bowhead numbers off the Tuk Peninsula were about 1/3 those in late August, and all were in water at least 25 m deep (Fig. 5 vs. 4, insets). Most were oriented southwest or west (Renaud and Davis 1981). Bowheads were still present far off the Tuk Peninsula on 12 Sept (Fig. 5; Hobbs and Goebel 1982). None were seen during surveys off the Mackenzie Delta in early Sept, and only one was reported by industry personnel at Issungnak. Bowheads were present farther west, near Herschel Island, in early Sept (Fig. 6). Observers on Herschel Isl saw bowheads about 5 km offshore on 3-11 Sept; none were seen 19 Aug-2 Sept (Würsig et al. 1982). The last September coverage was on 16 Sept, when Ljungblad (1981) saw three bowheads just east of Herschel Island.

Most bowheads seen in early September were distant from industrial activity. However, a few off the eastern Tuk Peninsula were near seismic lines (Fig. 5,8).

In the Alaskan Beaufort Sea, the first autumn sighting was on 4 Sept east of Barter Island (Ljungblad 1981). Bowheads became numerous there by 14 Sept, and the last sighting in the Alaskan Beaufort was a pilot's report on 17 Oct. On 21 and 24 Oct, Ljungblad found no bowheads near Herschel Island.

Bowhead Distribution and Industrial Activities in 1981 (Fig. 10-18)

Industrial Activities, 1981

The level of industrial activities, especially dredging, increased in 1981. Four dredges worked offshore, including the first two hopper dredges to operate in the study area. The hopper dredges loaded at Herschel Isl, South Tarsiut, Ukalerk and Banks Isl, and brought material to berm construction sites at Tarsiut (23 m deep) and Uviluk (31 m; Fig. 15). One suction dredge alternated between two island construction sites NW and north of Tuktoyaktuk, Itiyok and Alerk, from 20 July to 6 Sept (Fig. 15). Another dredged at South Tarsiut until 12 Aug; barges hauled the material to Tarsiut (Fig. 15).

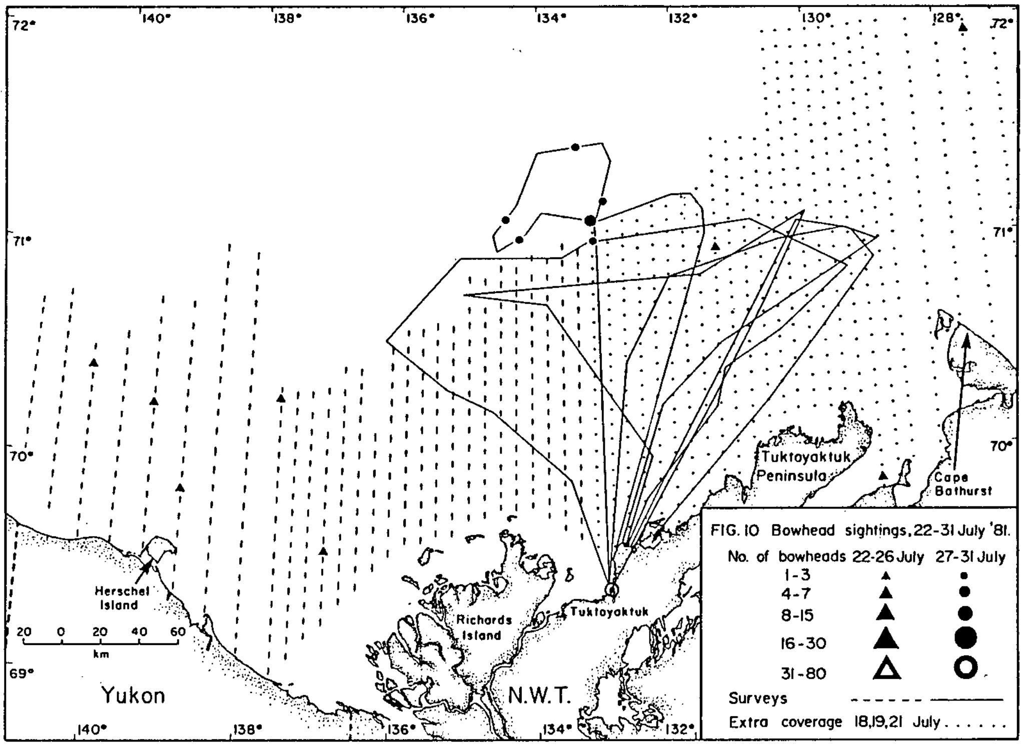

FIG. 10 Bowhead sightings, 22-31 July '81.

All drilling during the 1981 study period was from four drillships working at five drillsites. Drilling at Issungnak island ended before 1 Aug, but the island was still occupied and serviced by vessels and helicopters during August.

Most vessel traffic was in support of island building or drilling. The oil industry used over 30 supply boats, tugs and other vessels, including one icebreaker. Vessel traffic occurred over a wider area in 1981 than 1980, partly because hopper dredges operated west to Herschel Isl and northeast to Banks Isl, and partly to support the drillship operating far to the east at Kilanik (Fig. 15). There was additional traffic to the west because caissons for Tarsiut were assembled at Herschel Isl in late summer.

1981

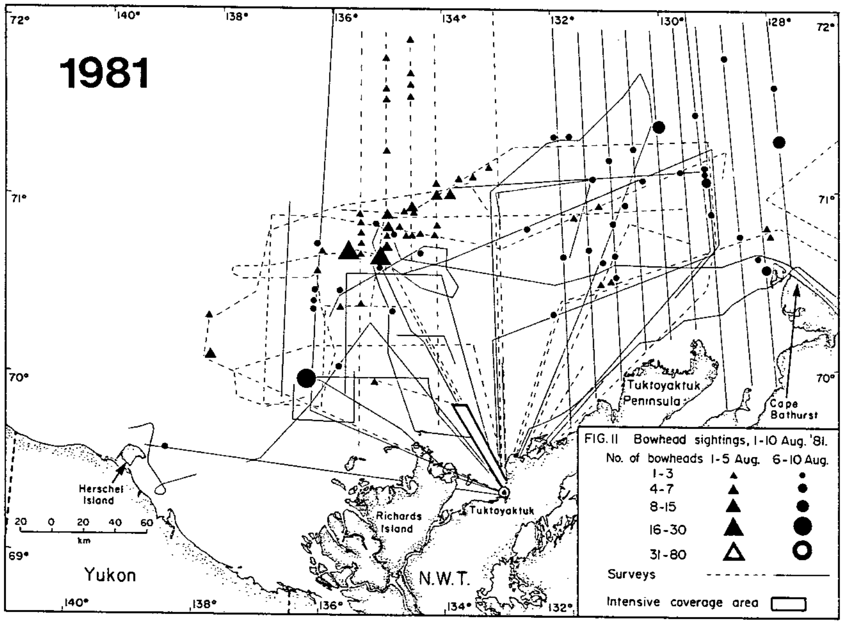
FIG. 11 Bowhead sightings, 1-10 Aug. '81.

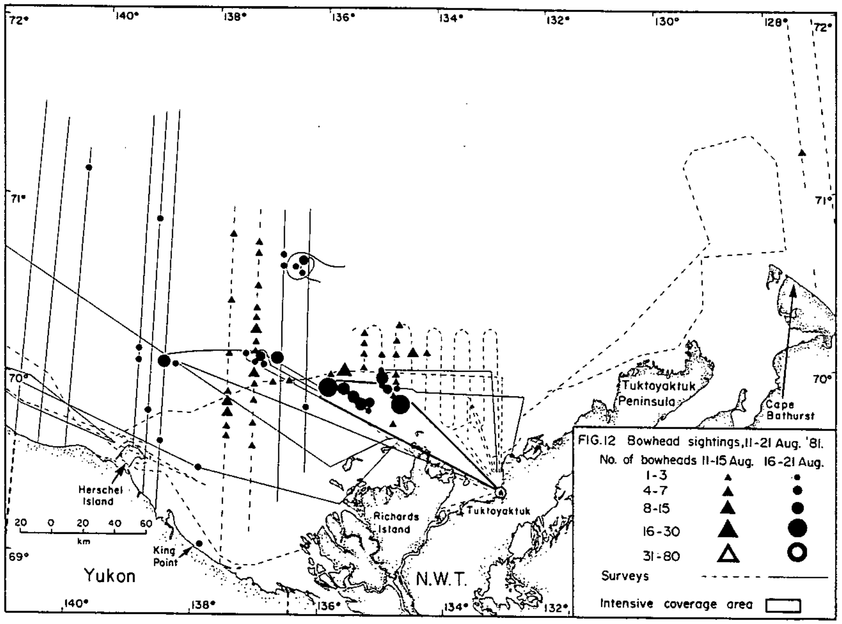
FIG. 12 Bowhead sightings, 11-21 Aug. '81.

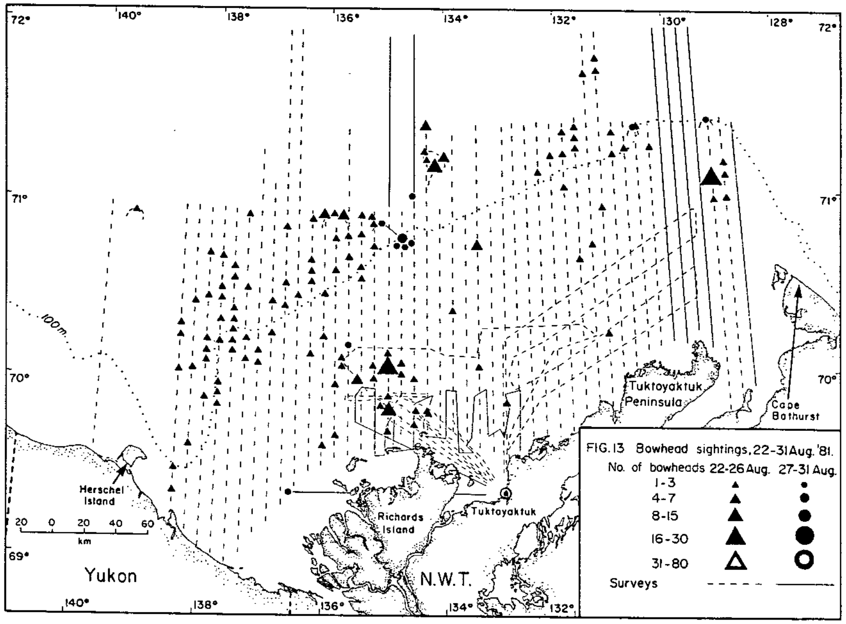
FIG. 13 Bowhead sightings, 22-31 Aug. '81.

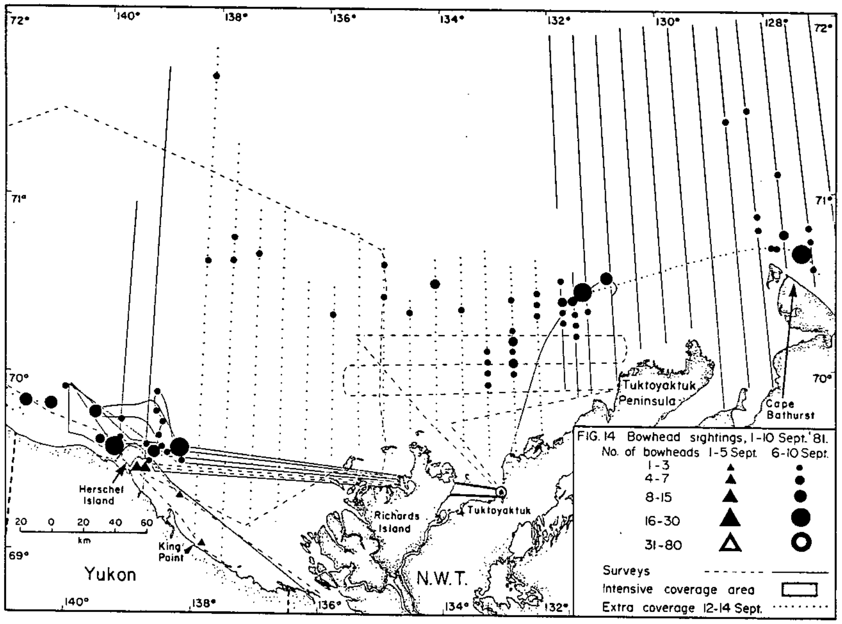
FIG. 14 Bowhead sightings, 1-10 Sept. '81.

1981

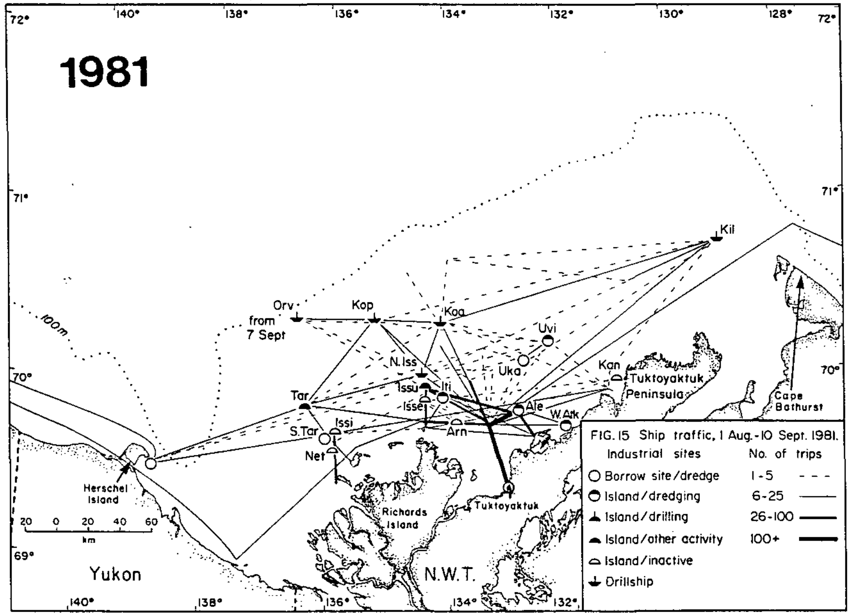

FIG. 15 Ship traffic, 1 Aug.-10 Sept. 1981.

Industrial sites	No. of trips	
○ Borrow site/dredge	1-5	- - -
Island/dredging	6-25	——
Island/drilling	26-100	——
Island/other activity	100+	——
Island/inactive		
Drillship		

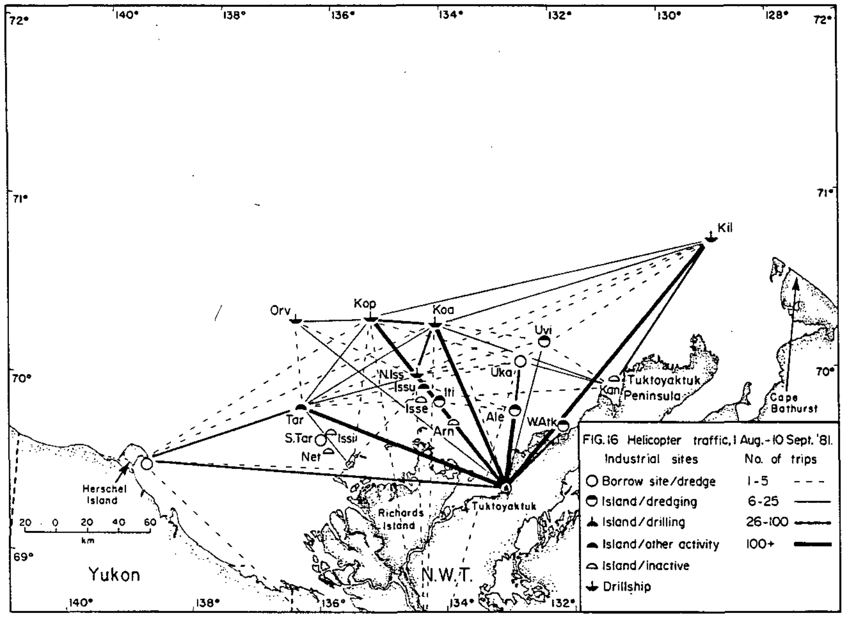

FIG. 16 Helicopter traffic, 1 Aug.-10 Sept. '81.

Industrial sites	No. of trips	
○ Borrow site/dredge	1-5	- - -
Island/dredging	6-25	——
Island/drilling	26-100	——
Island/other activity	100+	——
Island/inactive		
Drillship		

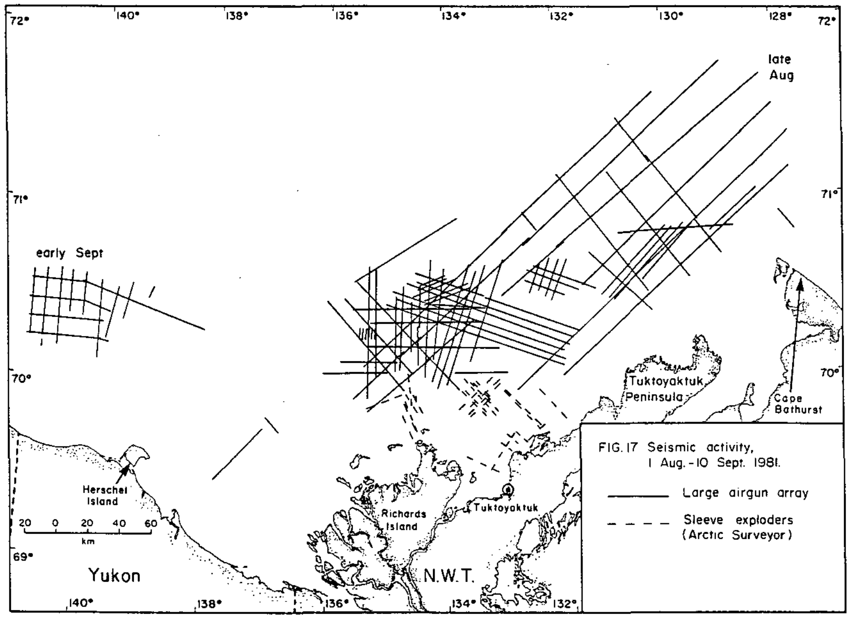

FIG. 17 Seismic activity, 1 Aug.-10 Sept. 1981.

—— Large airgun array

- - - Sleeve exploders (Arctic Surveyor)

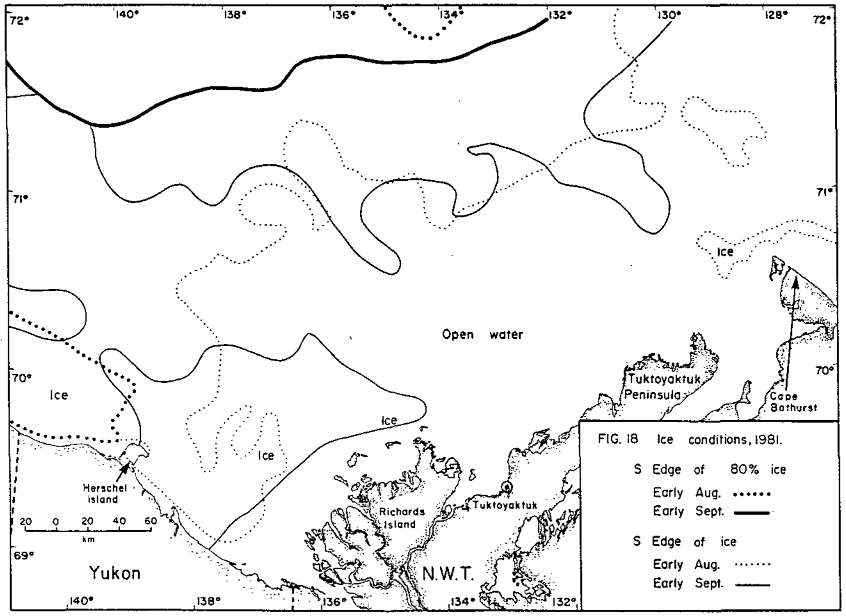

FIG. 18 Ice conditions, 1981.

S Edge of 80% ice

Early Aug. ••••••

Early Sept. ——

S Edge of ice

Early Aug. ······

Early Sept. ——

Helicopters travelled from Tuktoyaktuk to most offshore industrial sites, and between many sites (Fig. 16). Because industrial activity extended farther west and east than in 1980, helicopters ranged more widely in 1981.

Three high-energy seismic ships were present in 1981. They operated off the Mackenzie Delta and Yukon coast in late July; off the Mackenzie Delta in early August; from the Delta to Cape Bathurst in mid and late August; and off Tuktoyaktuk, the Delta, and the western Yukon in early September (Fig. 17; see Richardson et al. 1983a for data by 10-d period). Some additional seismic lines not on Fig. 17 apparently were also shot in August 1981. Furthermore, at least six vessels performed low-energy sounding off the Delta and Tuk Peninsula in 1981.

Bowhead Distribution, 1981

Large scale features of bowhead distribution are better documented for 1981 than for 1980. Four systematic surveys of most of the southeastern Beaufort Sea were done between late July and early September (Davis et al. 1982). The 1981 coverage began earlier than in 1980, and extended farther west and offshore, often beyond the edge of the continental shelf. In some periods, coverage also extended farther east. There were clear differences in distribution between the two years, although cautious interpretation is necessary because of the differences in survey effort.

Ice cover was extensive in western parts of the Canadian Beaufort Sea in Aug 1981 but not in Aug 1980 (Fig. 18 vs. 9). Surveys often extended well into the pack ice in 1981 but rarely did so in 1980. Bowheads were seen in the ice in August 1981; whether they were present there in August 1980 is unknown.

In late July 1981, few bowheads were on the continental shelf within the eastern Beaufort Sea. An intensive survey (19% coverage) of the entire shelf on 18-25 July detected only six bowheads (N-S grid on Fig. 10; Davis et al. 1982). Allowing for whales between grid lines, below the surface, etc., roughly 250 bowheads were in that area. More whales were in Amundsen Gulf, from 127°W to 120°W (Davis et al. 1982). However, the total estimate of 1250 whales in Amundsen Gulf and the surveyed areas of the eastern Beaufort Sea accounted for only 1/3 of the population, which is believed to be about 3871 whales (I.W.C. 1984). The majority were presumably in the Beaufort Sea north or west of the area surveyed by Davis et al. Limited non-systematic coverage of pack ice north of the 100 m contour confirmed that more bowheads were present far offshore (Fig. 10). There were no surveys of the Alaskan Beaufort Sea at this time. Only the very few bowheads off the Yukon coast were near industrial activities; noise from a seismic ship may have reached them.

During early August 1981, many bowheads moved into the southeastern Beaufort Sea. There was a concentration of whales about 125 km north of the Mackenzie Delta, near the southern edge of the pack ice and along the edge of the continental shelf (Fig. 11). One group of 30 plus many singles and smaller groups were found in open water on the shelf, with others in pack ice farther north. Numbers off the Yukon and Alaska were unknown. Based on a second systematic survey, an estimated 2860 bowheads (with broad confidence limits) were off the Delta, and 400 more were off the Tuk Peninsula (Davis et al. 1982). Numbers in Amundsen Gulf (128°-117°W) were very low on 5-17 Aug --

about 225 as opposed to 1000 in late July. Bowheads arriving in the SE Beaufort Sea during early August probably included animals travelling west from Amundsen Gulf and south from the offshore pack ice.

In early Aug 1981, unlike 1980, few whales were in the area of offshore drilling and island construction. However, some were not far north of the industrial area. Some whales far north from the Delta were exposed to seismic impulses on 5 Aug (Richardson et al. 1985a,b) and probably other dates.

In mid August 1981, the area of greatest known whale abundance was in shallow waters off the Delta, mainly between the 20 and 50 m depth contours, and off the eastern Yukon in slightly deeper water. Surveys did not extend far north of the Delta in mid August, but results from early and late August suggest that the whale concentration extended far offshore throughout August. Coverage off the Tuk Peninsula was minimal in mid August, but on both 6-10 and 22-26 Aug there were widely scattered whales far offshore (Fig. 11, 13).

In mid-August 1981, some groups of bowheads were <15 km from Issungnak island and North Issungnak drillship (Fig. 12, 15). However, most of those seen were north or west of the major industrial sites, contrary to results in mid-Aug 1980.

In late August 1981, some bowheads were in shallow water off the Mackenzie Delta, but most were widely distributed near and beyond the 100 m contour (Fig. 13). On 19-29 Aug, about 580, 1500 and 840 bowheads were estimated to be in the sampled parts of the Yukon, Delta and Tuk Peninsula zones, respectively (total 2918 ± s.e. 1015; Davis et al. 1982). There were apparently fewer whales off the Delta and more far off the Tuk Peninsula than during the 5-17 Aug survey, although confidence limits on all estimates were broad. The number and distribution of bowheads north of the Tuk Peninsula in late August 1981 were very different than in 1980 (Fig. 13 vs. 4). Excluding correction factors, estimated numbers were 755 in 1980 and 150 in 1981.

In late August, bowheads occurred at least as far west as Herschel Isl (Fig. 13). Observers on Herschel Isl from 23 Aug to 13 Sept first sighted bowheads on 29 Aug (Würsig et al. 1982).

In late August, most whales were near or beyond the shelf break, beyond most industrial operations. However, some whales far off the Tuk Peninsula were close to seismic lines (Fig. 13 vs. 17). On 24-26 August, the captain of 'GSI Mariner' saw groups of 2-4 bowheads an estimated 2-5 km from the ship while it was shooting here. Whales in shallow water off the Delta were near various industrial operations (Fig. 13). On 25 Aug, one group was only 6-8 km from a seismic ship; behavior was not noticeably unusual (Richardson et al. 1985a,b).

In early September 1981, most Western Arctic bowheads were apparently still in Canadian waters. Based on their incomplete fourth survey on 7-14 Sept, Davis et al. (1982) estimated that >2500 bowheads were still present. The whales were widely distributed from east of Cape Bathurst (126°W) to west of Herschel Island. Off the Tuk Peninsula, many whales were closer to shore than in late August (Fig. 13,14), contrary to the trend at this time in 1980 (Fig. 4,5). Bowheads seemed more numerous around Herschel Isl in early

September of 1981 than of 1980 (Fig. 14 vs. 5). Observers on the island saw whales until 10 Sept, and Ljungblad et al. (1982) saw bowheads just east of 141°W on 12-17 Sept.

Some whales off the western Tuk Peninsula and Delta in early Sept were probably exposed to seismic impulses, and some were in the general area of drilling and dredging. Whales just east of 141°W definitely were exposed to seismic impulses (Ljungblad et al. 1982).

The first autumn sighting off Alaska was on 7 Sept near the Alaska-Yukon border. Few whales moved west of Barter Island (143°W) until about 28 Sept (Ljungblad et al. 1982). Some bowheads were present east to Barter Island as late as 9 Oct.

Bowhead Distribution and Industrial Activities in 1982 (Fig. 19-26)

Industrial Activities, 1982

The level of industrial activities increased again in 1982. Two suction and four hopper dredges constructed artificial islands or subsea berms at five sites, including Nerlerk in water 45 m deep. Hopper dredges used several borrow sites from Herschel Isl to Banks Isl, but Ukalerk was used most heavily (Fig. 23). Drilling from Tarsiut caisson-retained island continued into early August. Testing extended into September, and several support vessels were usually present in August. Four drillships operated at five wellsites (Fig. 23).

The area of frequent vessel and helicopter movements extended less far to the east and west but somewhat farther north in 1982 than in 1981 (Fig. 23,24 vs. 15,16). There was no drillship northeast of the Tuk Peninsula in 1982, unlike 1981. There were again a few vessel trips west to Herschel Isl, but activity there was reduced from 1981. Vessels went north to Kenalooak, the northmost site yet drilled in the eastern Beaufort (also drilled in 1980). More helicopters (8+) were in use in 1982 than in earlier years (Table 2).

Seismic exploration by two high-energy vessels was primarily off the Mackenzie Delta and Yukon coast. Another vessel using a small array of airguns worked mainly off the Delta and north of Tuktoyaktuk (Fig. 25). Relative to 1981, seismic exploration was more extensive off the Yukon coast and much less so off the Tuk Peninsula. It was extensive off the Delta in both years. Low-energy sounding was done from seven vessels operating off the Delta and western Tuk Peninsula.

Bowhead Distribution, 1982

Bowhead distribution and movements in 1982 differed from both 1980 and 1981. There was much ice off the Yukon coast in 1982, especially after 16 Aug. However, north of the Delta and Tuk Peninsula, the ice edge was much farther offshore than in 1980 or 1981 (Fig. 26).

In early August 1982, bowheads were seen far offshore in open water NW of the Delta, and in pan ice far north and NW of Herschel Island (Fig. 19). Surveys off Alaska found bowheads west to Barter Isl (144°W) in deep water and heavy ice (Ljungblad et al. 1983). Intensive surveys within the main industrial area and limited coverage farther north and east found no bowheads (Fig. 19). Many whales off the Delta and off Alaska were travelling west. The sighting closest to any active offshore site was 21 km north of Tarsiut. However, there was seismic exploration in this area, and on one day seismic noise was measured near whales (Richardson et al. 1985a,b).

Distribution in early August was very different in 1982 than in 1980, when there were many whales in the shallow waters of the industrial area. Distributions in 1981 and 1982 were more similar, but in 1981 whales were more widespread on the outer shelf and shelf break, and most seemed to be travelling south, not west.

In mid August 1982, bowheads were concentrated off Herschel Isl, with many more distributed at lower densities farther offshore from the Yukon (Fig. 20). Most were close to or in pan ice; most either dove for long periods with little travelling, or remained quiescent at the surface (Würsig et al. 1983). Bowheads were common west to Barter Isl, Alaska (Ljungblad et al. 1983). The only sightings in the main industrial area were of two whales south of Tarsiut. Limited coverage north of the industrial area found few whales, and the only ones found to the east were near Cape Bathurst (Fig. 20). Whether there were bowheads near the shelf break north and northeast of the industrial area is unknown. Few whales were in water <50 m deep; those close to Herschel Isl and Cape Bathurst were in areas where deep water occurs near shore.

Although very few bowheads were in the main industrial area, those near Herschel Isl were exposed to seismic impulses. Noise pulses up to 133 dB//1 µPa (up to 40 dB above ambient) were recorded near whales on 16 and 18 Aug (Richardson et al. 1985a,b).

Distributions were very different in mid August 1980, 1981 and 1982. In 1980, whales were abundant in shallow water off the eastern Delta and western Tuk Peninsula. In 1981 they were not found there, but were widespread farther to the W, N and possibly NE. In 1982, they were most abundant off Herschel Isl.

In late August 1982, there were still bowheads off Herschel Isl, but others were distributed far offshore from west of Herschel Isl (140°W) to Cape Bathurst (128°W), particularly near the steep shelf break north of the Mackenzie Delta (Fig. 21). The few found off Alaska were far offshore at 145°W (Ljungblad et al. 1983). Few bowheads were within the main industrial area. Distribution in late August 1982 was more 'clumped' than in 1981, with more whales near Herschel Isl and fewer near the Delta (Fig. 21 vs. 13). Distribution in late August of 1980 was very different.

Based on a systematic survey on 18-24 Aug from 140° to 129°W and north at least to the 100 m isobath, Harwood and Ford (1983) estimated that there were ≥1224 whales off the Yukon, ≥256 off the Delta, and ≥459 off the Tuk Peninsula. These estimates were conservative because (1) non-systematic coverage found bowheads north of the surveyed area, and (2) correction for missed animals was only partial.

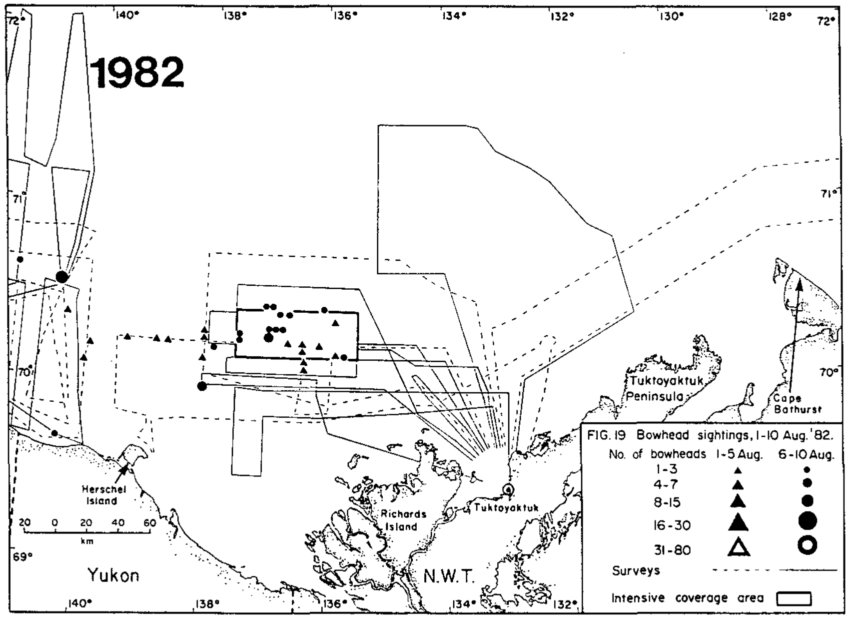

FIG. 19 Bowhead sightings, 1-10 Aug.'82.

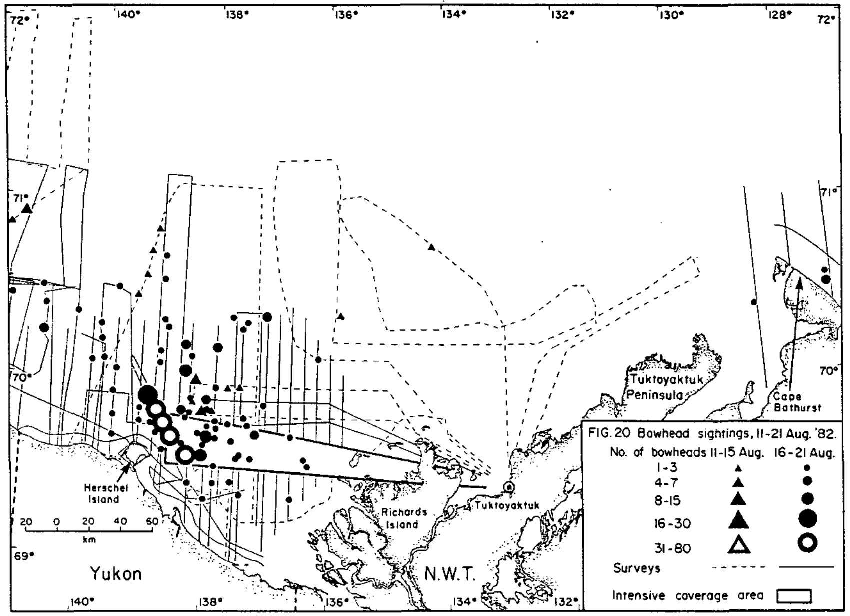

FIG. 20 Bowhead sightings, 11-21 Aug.'82.

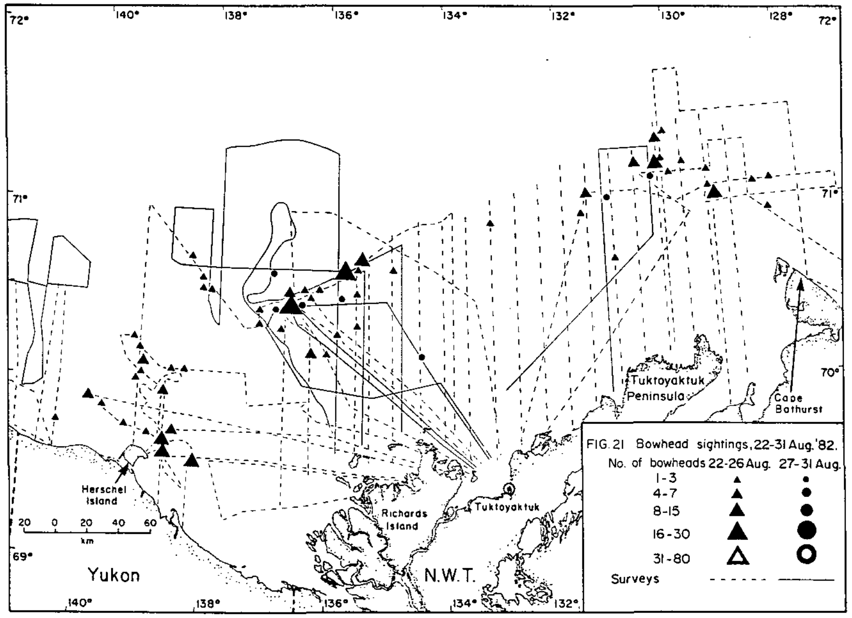

FIG. 21 Bowhead sightings, 22-31 Aug.'82.

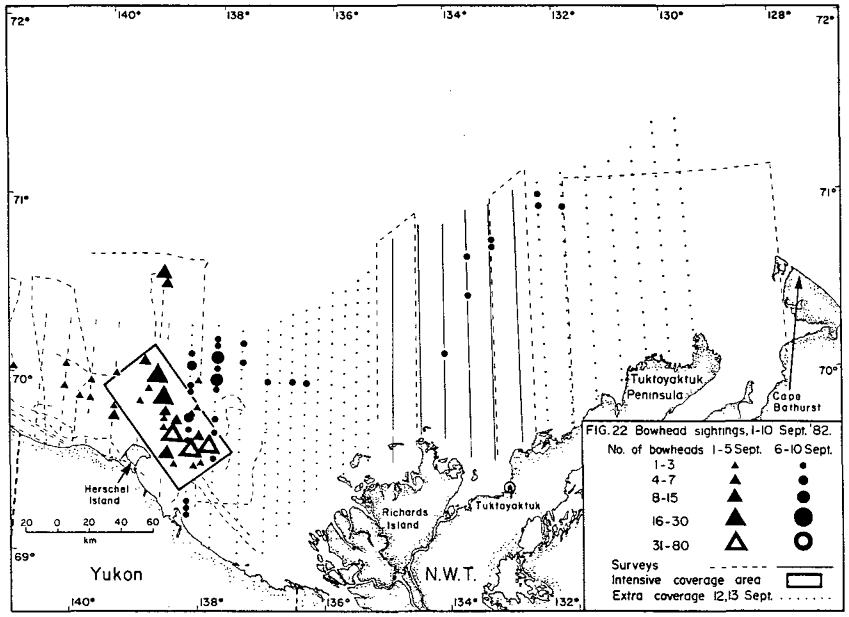

FIG. 22 Bowhead sightings, 1-10 Sept.'82.

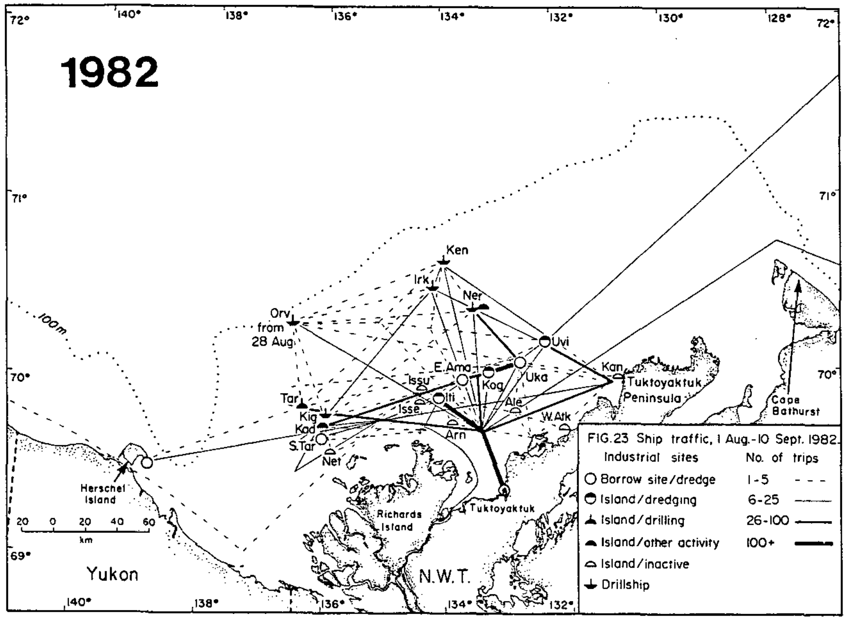
FIG.23 Ship traffic, 1 Aug.-10 Sept. 1982.

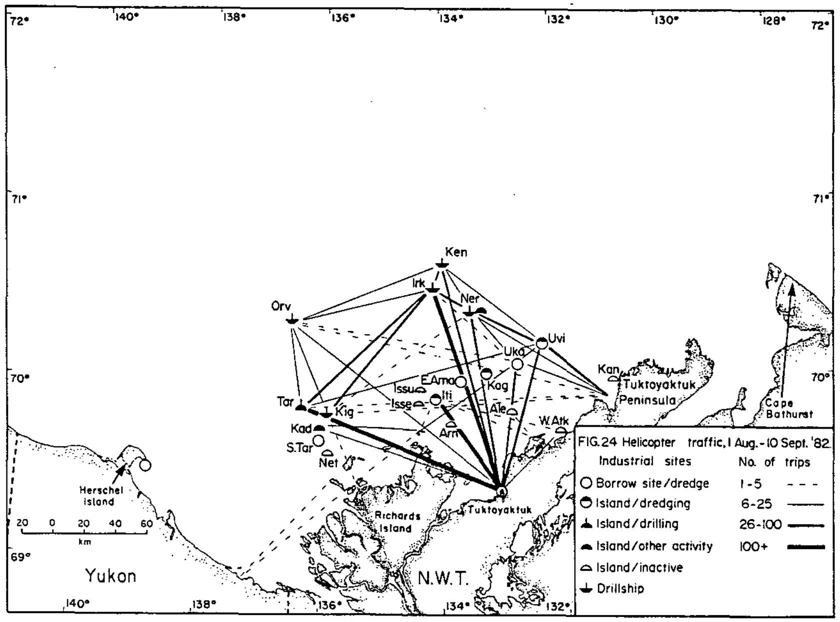
FIG.24 Helicopter traffic, 1 Aug.-10 Sept. '82

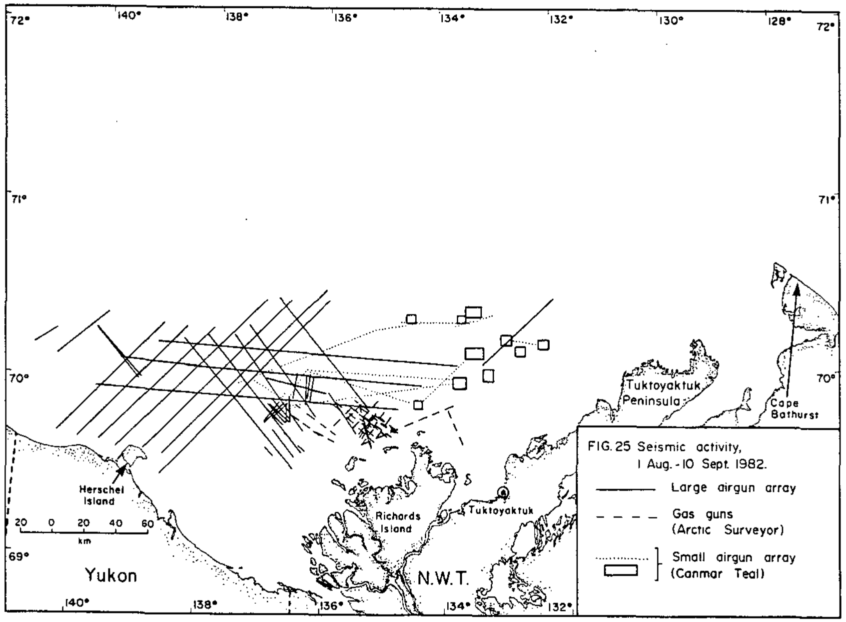
FIG. 25 Seismic activity, 1 Aug.-10 Sept. 1982.

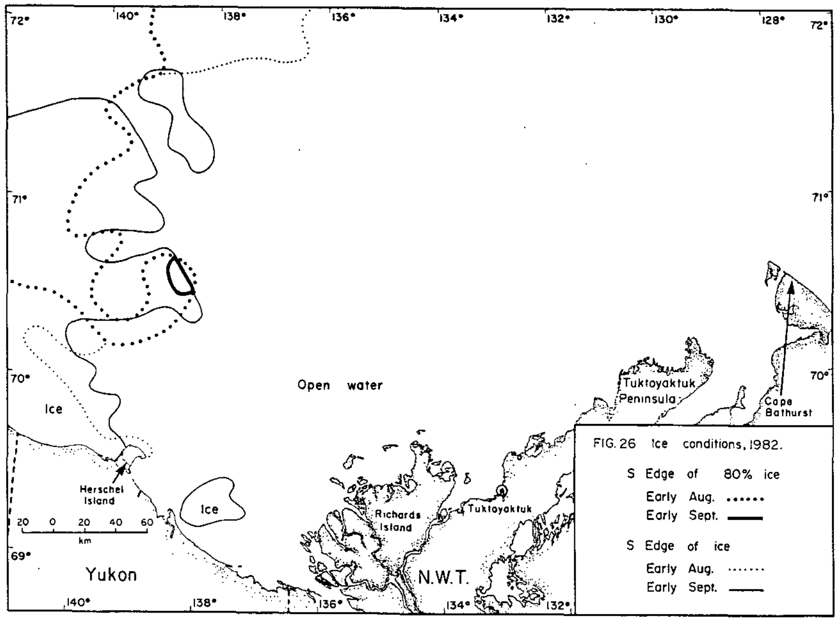
FIG. 26 Ice conditions, 1982.

In early September 1982, bowheads still were abundant off Herschel Isl, mainly over 50-200 m depths (Fig. 22). Few were found north of the Delta or Tuk Peninsula, but surveys did not extend off the shelf or east of 130°W. From systematic surveys on 5-13 Sept, Harwood and Ford (1983) conservatively estimated that ≥1112 whales were off the Yukon, ≥163 off the Delta, and ≥115 off the Tuk Peninsula. Very few were in the area of drilling and island construction. However, the many whales near Herschel Isl were probably exposed to seismic noise, as in mid August.

The one consistent feature of bowhead distribution in early Sept of 1980-82 was the occurrence of whales off Herschel Isl. Bowheads seemed especially numerous there in 1982. Fewer were found off the Delta and Tuk Peninsula at this time in 1982 than in 1980-81.

Aside from low numbers near 145°W, few bowheads moved into the Alaskan Beaufort until 15 Sept in 1982. The main movement through Alaskan nearshore waters began around 20 Sept (Johnson 1983; Ljungblad et al. 1983). A bowhead was seen at Herschel Isl in 7/10 ice on 15 Oct (Ljungblad et al. 1983).

Bowhead Distribution and Industrial Activities in 1983 (Fig. 27-34)

Industrial Activities, 1983

The level of offshore activities increased further in 1983. A new circular drillship began work at Pitsiulak in late August, supported by two new Class 4 icebreakers and two new icebreaking supply ships. Dome's four drillships worked at specific drillsites from 1 Aug to 10 Sept (Fig. 31). In 1983, as in 1982, two suction and four hopper dredges were used to construct seven islands and subsea berms; 2-3 barges with clamshells were also in intermittent use. The main borrow sites were Ukalerk, Issigak, and adjacent to some island and berm construction sites (Fig. 31).

Vessel traffic in 1983 consisted mainly of movements by the four hopper dredges and about 37 other vessels supporting the drilling, dredging and island construction (Fig. 31). Most helicopter traffic was from Tuktoyaktuk to the offshore sites, and between sites (Fig. 32). More helicopters (10) were used in 1983 than previously (Table 2). Considerable vessel and helicopter traffic extended west to Herschel Basin (Fig. 31,32), which became a major staging area in mid-August 1983.

Seismic exploration occurred from Alaska to Cape Dalhousie (129°W; Fig. 33). In Canadian waters, one ship used gas guns, 1-3 used large arrays of airguns, and one used a small array of airguns. Four more seismic ships operated near the Alaska border in late Aug-early Sept; Figure 33 shows their general locations by 'x' symbols, based on daily reports listed in Ljungblad et al. (1984b). Low-energy sounding was done from four vessels off the Mackenzie Delta and Tuktoyaktuk.

Bowhead Distribution, 1983

Bowhead distribution and movements in August-early September of 1983 were markedly different than in the three previous summers. Ice conditions also differed. The usual band of open water north of the Delta and Tuk Peninsula was somewhat narrower in August 1983 than in 1980-82. There was little ice near the Yukon coast in August 1983 (and 1980), unlike 1981-82.

Ice conditions in the Alaskan Beaufort Sea in 1983 were severe (Ljungblad et al. 1984a,b), and ice also moved onto the Yukon coast in early Sept (Fig. 34).

There were no surveys in July, but in early August 1983, bowheads occurred far off the western Yukon (Fig. 27). Most were in deep water (200-2000 m) in or near pack ice. The western edge of their distribution was just into Alaskan waters, near 142°W (Ljungblad et al. 1984a). Our limited surveys north and east of the Delta detected only one bowhead (Fig. 27).

Aerial surveys detected no bowheads in the main industrial area in early August. We received two reports of 1-2 bowheads seen by industry personnel in early August near the east edge of the industrial area. Seismic exploration occurred over a wider area, and sonobuoys showed that some whales off the Yukon were exposed to seismic noise on at least 4 dates in early August (Ljungblad et al. 1984a; Richardson et al. 1985b).

In mid August 1983, we found a concentration of bowheads along the Yukon coast east of Herschel Isl, often <1 km from shore (Fig. 28). We saw 60 whales near the Yukon coast on 17 August, with no allowance for unseen animals. Whether bowheads were near the coast east of Herschel Isl before the first survey there on 14 Aug is unknown.

Survey coverage elsewhere during mid August was extensive but of uneven intensity. Bowheads were almost absent from nearshore waters west of Herschel Isl. A few were seen near the ice far offshore from the Yukon (Fig. 28); none were seen west of 141°W (Ljungblad et al. 1984a). A few were seen in or near the main industrial area during aerial surveys. More were seen there by industry personnel but numbers are unknown, in part because of probable repeated sightings. Survey coverage off the Tuk Peninsula was limited, but Cubbage et al. (1984) sighted a large group of bowheads far off Cape Dalhousie (Fig. 28). In general, bowheads were scarce in most surveyed parts of the SE Beaufort Sea, except along the Yukon coast.

Bowheads near the Yukon coast were not exposed to much human activity, aside from survey aircraft and our disturbance experiments (Richardson et al. 1985b). No seismic boats operated in Mackenzie Bay in mid-August. The only other large groups seen were far north of Herschel Isl and Cape Dalhousie, far from seismic boats and the industrial area. Some bowheads were sighted in the industrial area, but no large concentration of whales was found there.

In late August 1983, the concentration along the Yukon coast persisted until at least 28 Aug (Fig. 29). Distances from shore were <1-15 km, varying from day to day. McLaren and Davis (1985) saw 110 bowheads <4 km from shore on 22 Aug. Whales often dove out of sight, and others were present farther offshore, so numbers present were much greater than 110. Photogrammetric data showed that whales along the coast were mainly immatures <13 m long (W.R. Koski, in Würsig et al. 1985b).

Bowheads were scarce or absent in most offshore areas in late August. The only concentrations were near the westernmost industrial sites, and far to the east (Fig. 29). Based on a systematic survey on 19-24 Aug from the

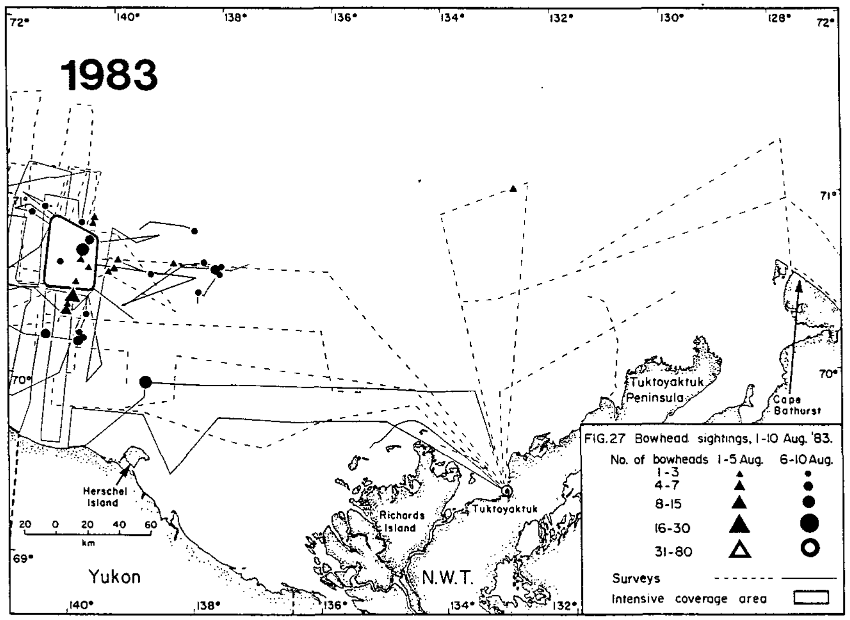

FIG. 27 Bowhead sightings, 1-10 Aug. '83.

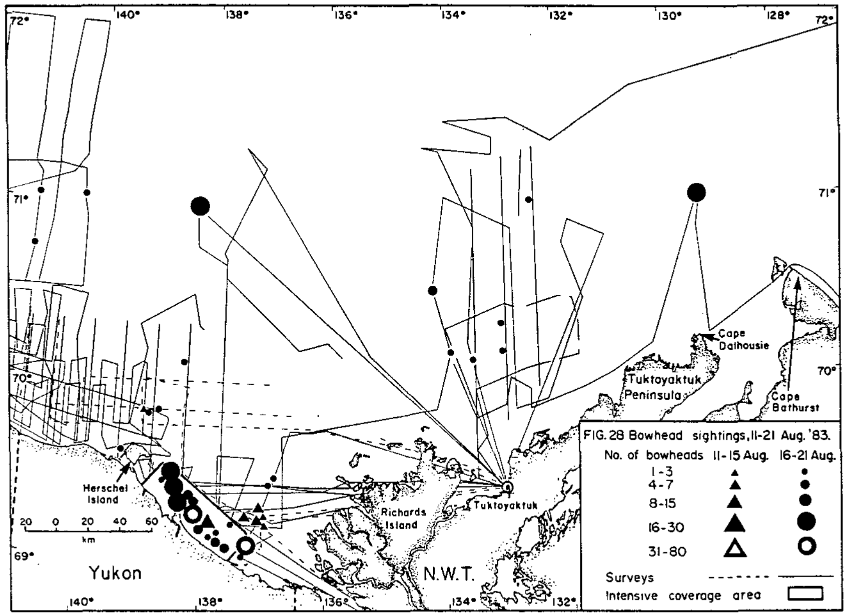

FIG. 28 Bowhead sightings, 11-21 Aug. '83.

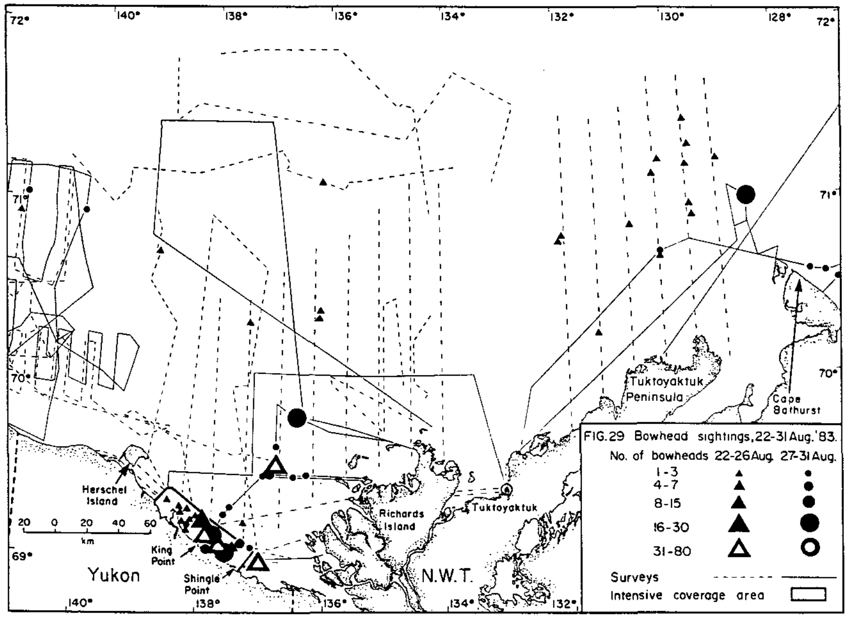

FIG. 29 Bowhead sightings, 22-31 Aug. '83.

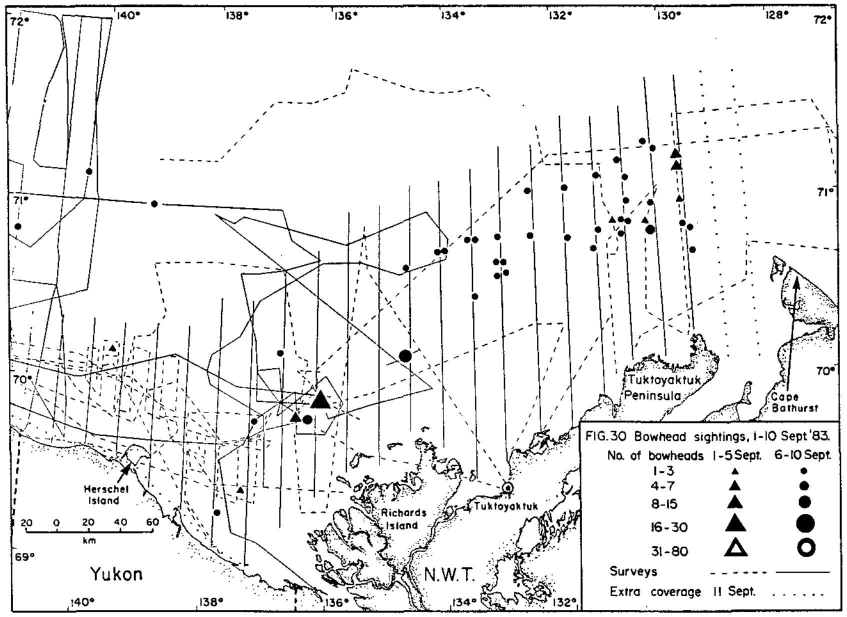

FIG. 30 Bowhead sightings, 1-10 Sept '83.

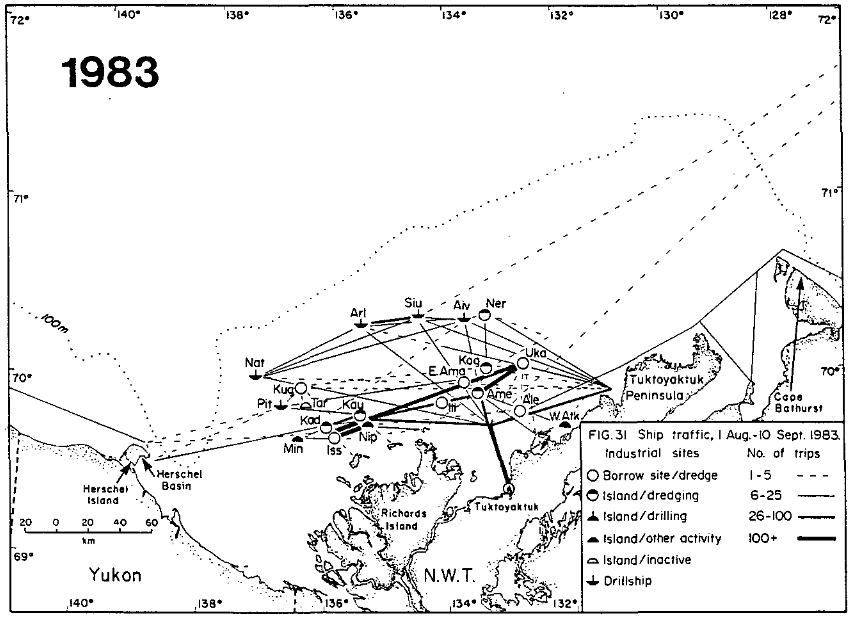

FIG. 31 Ship traffic, 1 Aug.-10 Sept. 1983.

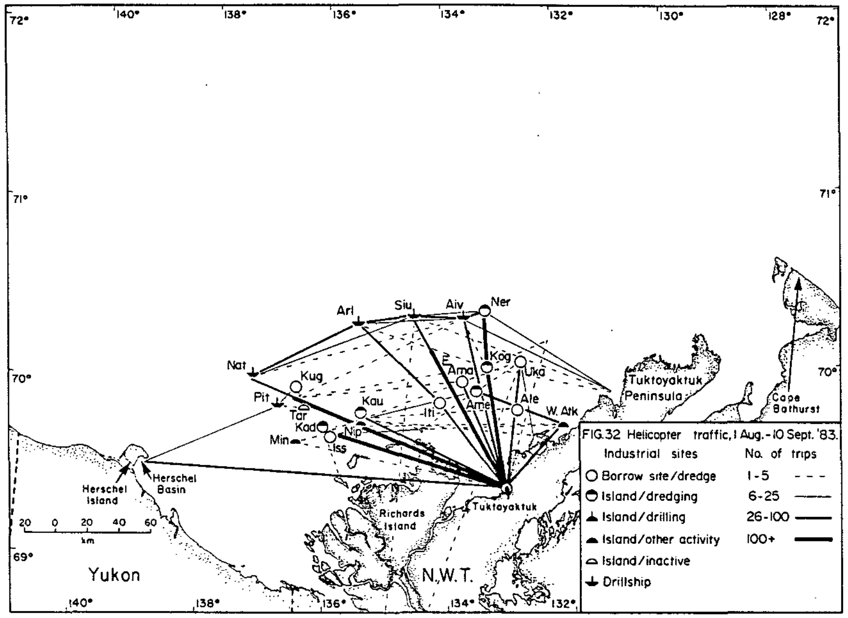

FIG. 32 Helicopter traffic, 1 Aug.-10 Sept. '83.

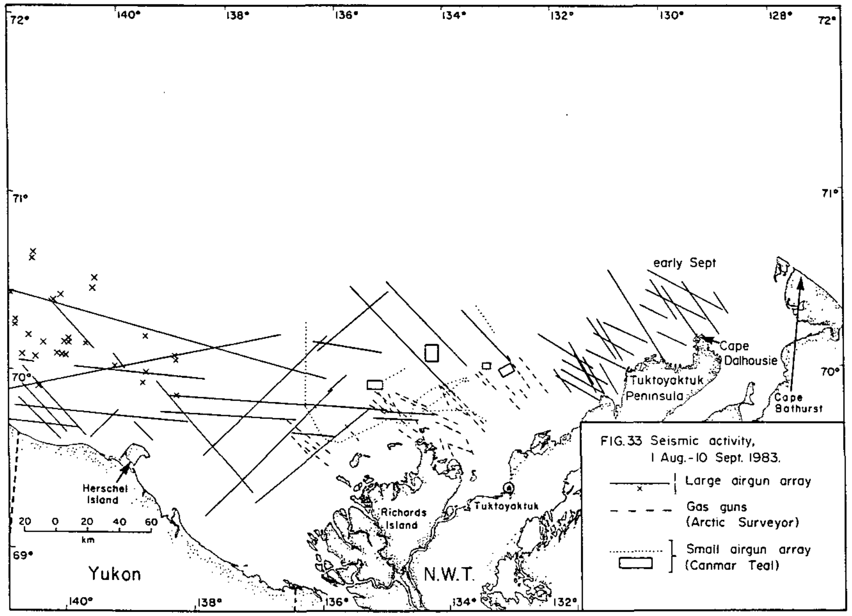

FIG. 33 Seismic activity, 1 Aug.-10 Sept. 1983.

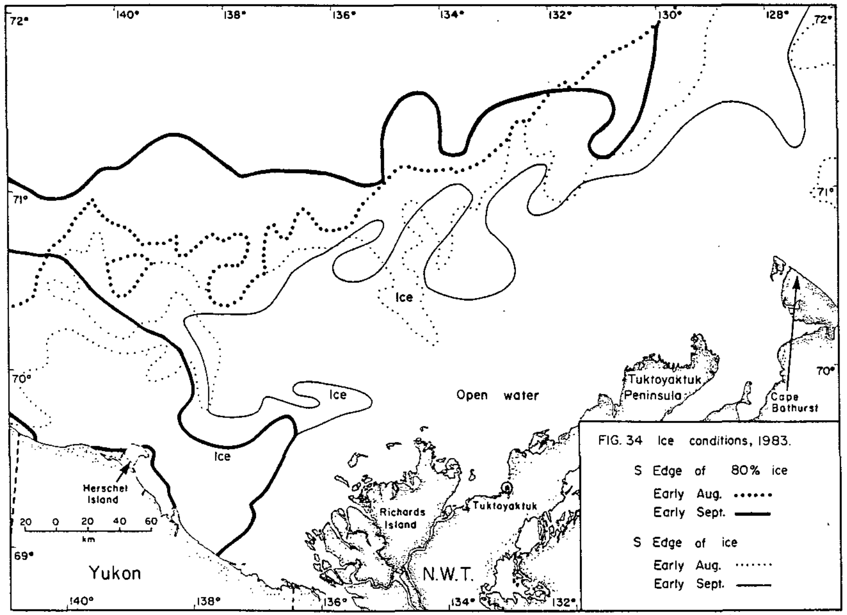

FIG. 34 Ice conditions, 1983.

Alaska border to Cape Dalhousie (141°-129°W) and north beyond the 200 m contour, McLaren and Davis (1984) estimated that about 1057 bowheads were in the surveyed area, excluding the concentration (apparently several hundred) along the Yukon coast. A few bowheads were seen in Alaskan waters west to 147°W in late August, but numbers there seemed very low (Ljungblad et al. 1984a,b). Larger numbers were found east of Cape Bathurst (Cubbage et al. 1984).

Bowheads apparently moved into the western edge of the industrial area in the last week of August. Some were 10-12 km from the conical drillship at Pitsiulak, and directly below the helicopter route to that site; they were also exposed to strong seismic noise, at least on 31 Aug-1 Sept (Richardson et al. 1984b). There were apparently few bowheads in other parts of the industrial area in late August.

In early September 1983, there were a few sightings in the main industrial area, especially just inside its western edge near Pitsiulak. These whales may have come from the Yukon coast, where no whales were found on 6 Sept. Few other bowheads were seen in the western half of our study area (Fig. 30). Reduced detectability because of ice (Fig. 34) may have been partly responsible. However, the majority of the population was apparently farther east. From a systematic survey on 6-11 Sept, McLaren and Davis (1985) estimated that about 1700 bowheads were north of the Delta and Tuk Peninsula, excluding waters beyond the 500 m (approx.) contour. More bowheads, not taken into account in the above estimate, were found farther east in Franklin Bay (126°W; Cubbage et al. 1984). Bowheads were also present this far east in early September of 1981 (Davis et al. 1982). Some bowheads off the Tuk Peninsula were probably exposed to noise from seismic vessels (Fig. 30,33).

Bowheads seen during the 6-11 Sept survey were oriented primarily southwest or west (McLaren and Davis 1985), and migration into Alaskan waters was underway by 3 Sept (Ljungblad et al. 1984a). Bowheads were last seen in Canadian waters on 2 Oct (140°; Ljungblad et al. 1984a).

Bowhead Distribution and Industrial Activities in 1984 (Fig. 35-42)

Industrial Activities, 1984

The region of offshore activities in late summer of 1984 was similar to that in 1983; the levels of various activities were similar or slightly reduced. Five drillships worked throughout the study period, drilling at six sites (Fig. 39). Drilling also began at Amerk caisson-retained island in late August. Four hopper dredges and several barges with clamshells were used to construct six islands or subsea berms. The main borrow sites included Ukalerk, Isserk, and Issigak, plus abandoned artificial islands at Tarsiut, Kadluk, Adgo and Sarpik (Fig. 39).

Patterns of vessel and helicopter traffic in 1984 were similar to those in 1983 (Fig. 39, 40). However, there was more traffic to Herschel Basin because support vessels, including the tanker 'Gulf Beaufort', were anchored there throughout the 1984 season.

Seismic exploration extended from the Alaska border to Cape Bathurst. However, at most times seismic vessels operated in rather confined areas (Fig. 41), partly because ice occurred relatively close to shore in 1984

(Fig. 42). Two or three vessels with large arrays of airguns plus one with gas guns were operating. In 1984, no Alaska-based vessels operated near the Alaska-Yukon border during our study period.

Bowhead Distribution, 1984

Surveys in early and mid July 1984 showed that few bowheads were over the shelf off the Yukon, Delta or Tuk Peninsula (Harwood and Borstad 1984). By late July, bowheads had begun to move into this area, especially off the eastern Yukon, Tuk Peninsula and Cape Bathurst. Most were in water 51-100 m deep and pack ice, not in nearshore ice-free waters (Harwood and Borstad 1984). Only one bowhead was seen in the main industrial area during four aerial surveys, but industry personnel reported 9 sightings totalling 16 bowheads there in July (Harwood and Borstad 1984). The whereabouts of the rest of the population in July is unknown. Bowheads were not seen in the Alaskan Beaufort (D. Ljungblad pers. comm.). There were no surveys in Amundsen Gulf or far offshore in the eastern Beaufort.

In early August 1984, there were still low numbers of bowheads off the eastern Yukon, but larger numbers in open water off the eastern Tuk Peninsula and Cape Bathurst (Fig. 35). None were seen west of Herschel Isl (Fig. 35, D. Ljungblad pers. comm.). We saw none in the main industrial area, but some were not far east of the easternmost drillship. The few whales east and north of Herschel Isl sometimes were exposed to seismic noise (Fig. 35 vs. 41; Richardson et al. 1985b).

In mid August 1984, large numbers of bowheads moved into shallow waters west of the Delta and along the Yukon coast (Fig. 36). Numbers along the shore SE of Herschel Isl were lower than in mid Aug 1983. However, whales also concentrated in some areas where they had not been in 1983--along the shore near and west of Herschel Isl, and in a narrow NNE-SSW band west of the Delta. The latter band was along a sharp discontinuity between turbid water of the Mackenzie River plume and less turbid marine water. Bowheads were still present at Cape Bathurst and low numbers were scattered elsewhere (Fig. 36). The westernmost sightings were just into Alaskan waters (141°25'W; D. Ljungblad pers. comm.).

Only a few bowheads were seen during surveys of the main industrial area north of the Delta. Some of the many whales along the plume edge west of the Delta were just beyond the westernmost artificial islands and along a major helicopter route (Fig. 40). They also were often exposed to strong seismic noise (Fig. 41; Richardson et al. 1985b). The concentrations along the Yukon coast were exposed to much less industrial activity.

In late August 1984, distribution was little changed. The largest concentrations were still along the Yukon coast and the plume edge west of the Delta (Fig. 37). Some whales in the latter area were exposed to helicopter overflights, seismic impulses, and noise from island construction at Minuk (Fig. 39-41; Richardson et al. 1985b). There also were several sightings near the east and NE edges of the main industrial area in late August. Whales were still present near Cape Bathurst, and probably were exposed to seismic noise there (Fig. 41). There were few or no sightings in other offshore parts of the study area (Fig. 37), and few bowheads were west of the Alaska border (westernmost sightings at 143°W; D. Ljungblad pers.

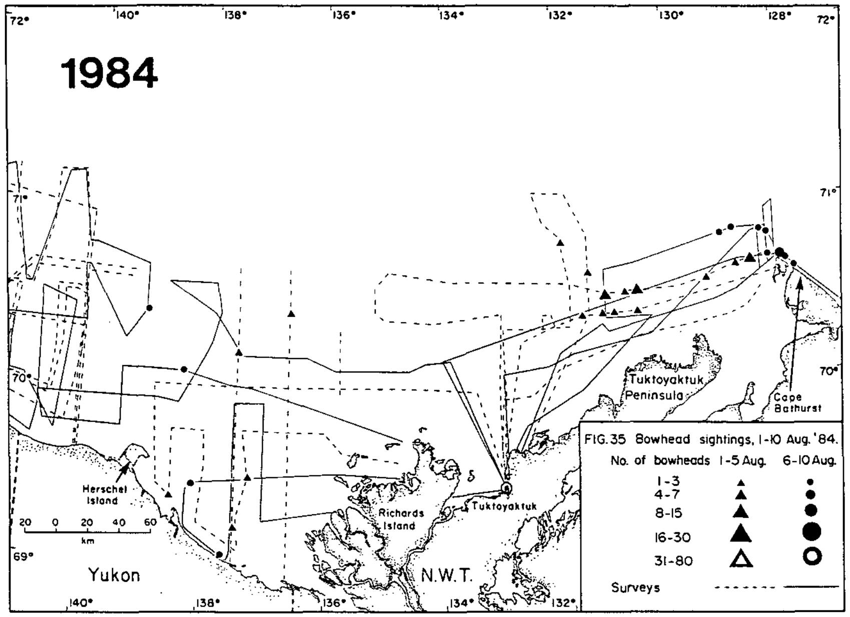

FIG. 35 Bowhead sightings, 1-10 Aug. '84.

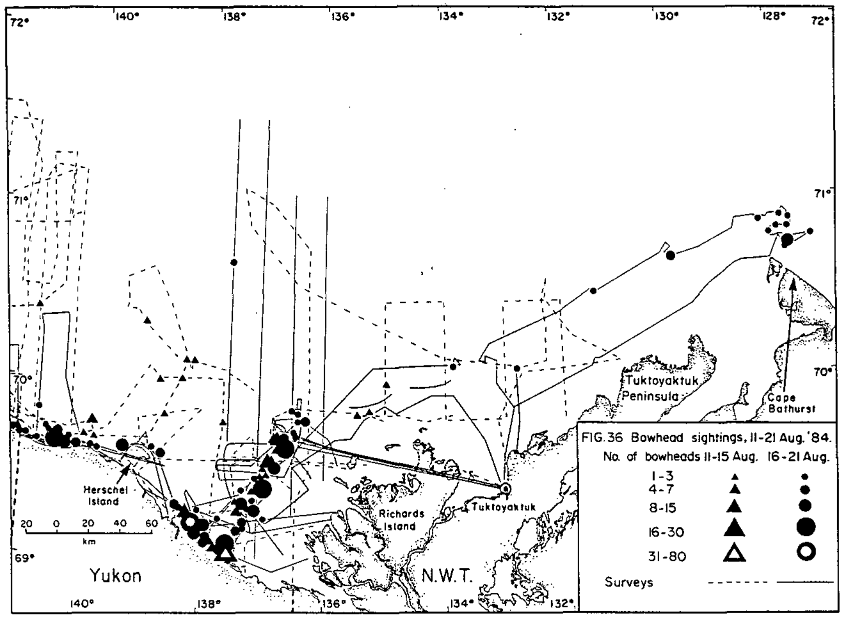

FIG. 36 Bowhead sightings, 11-21 Aug. '84.

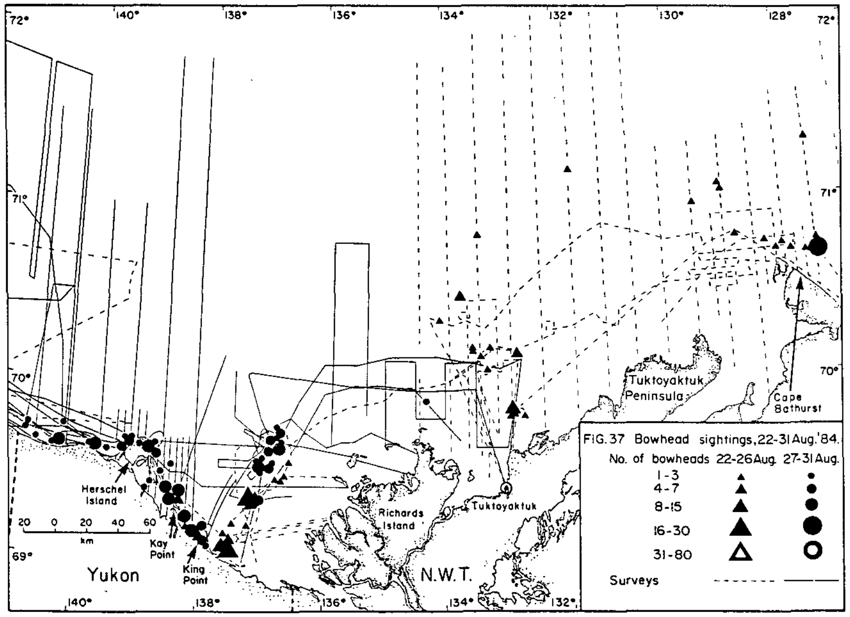

FIG. 37 Bowhead sightings, 22-31 Aug. '84.

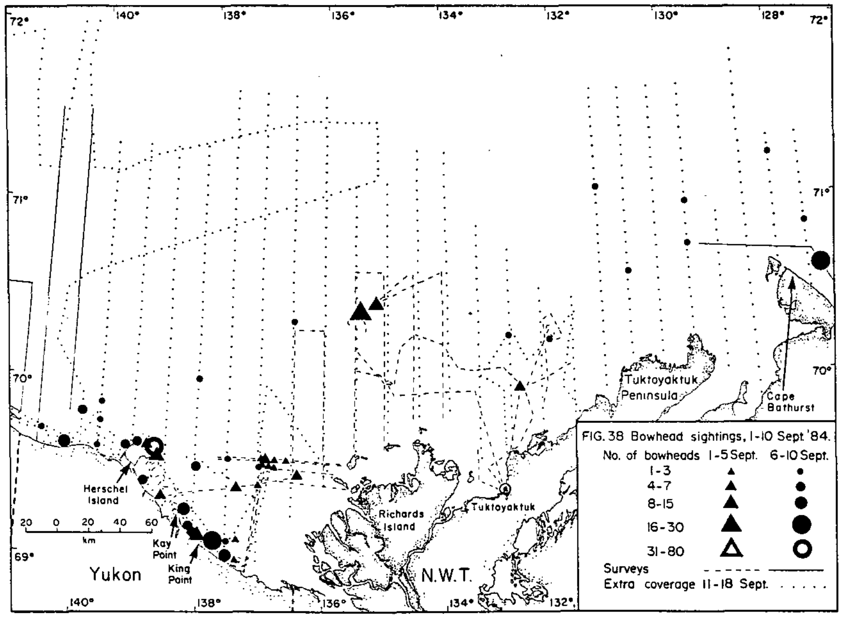

FIG. 38 Bowhead sightings, 1-10 Sept '84.

1984

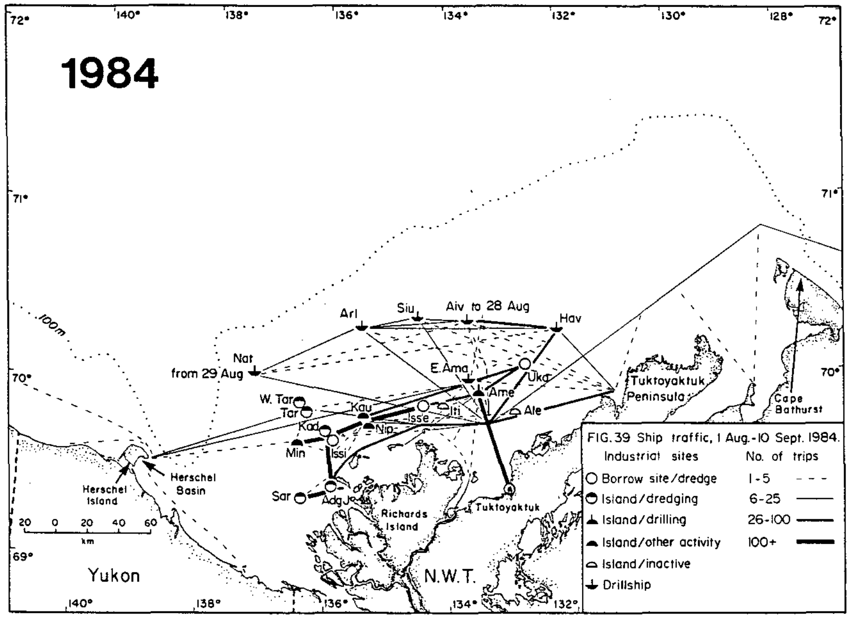
FIG. 39 Ship traffic, 1 Aug.-10 Sept. 1984.

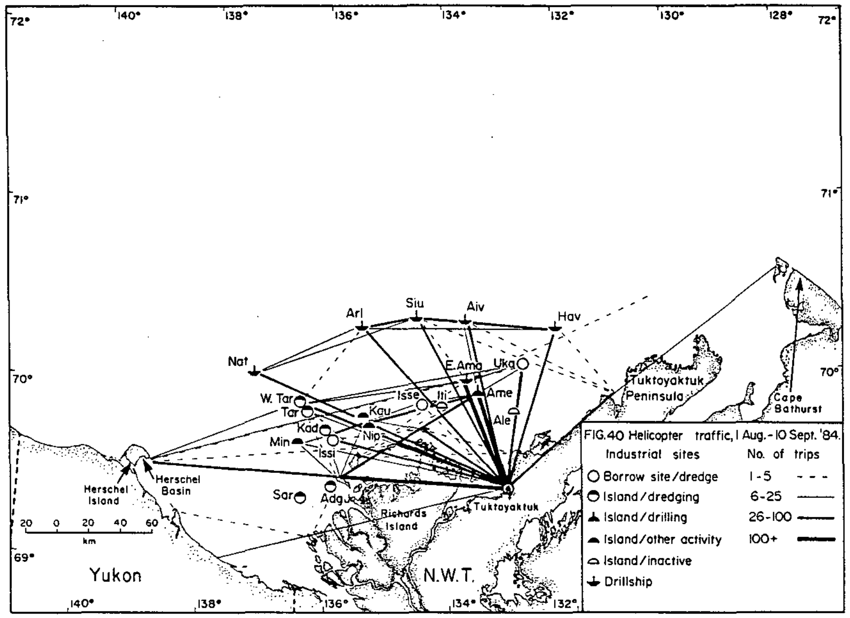
FIG. 40 Helicopter traffic, 1 Aug.-10 Sept. '84.

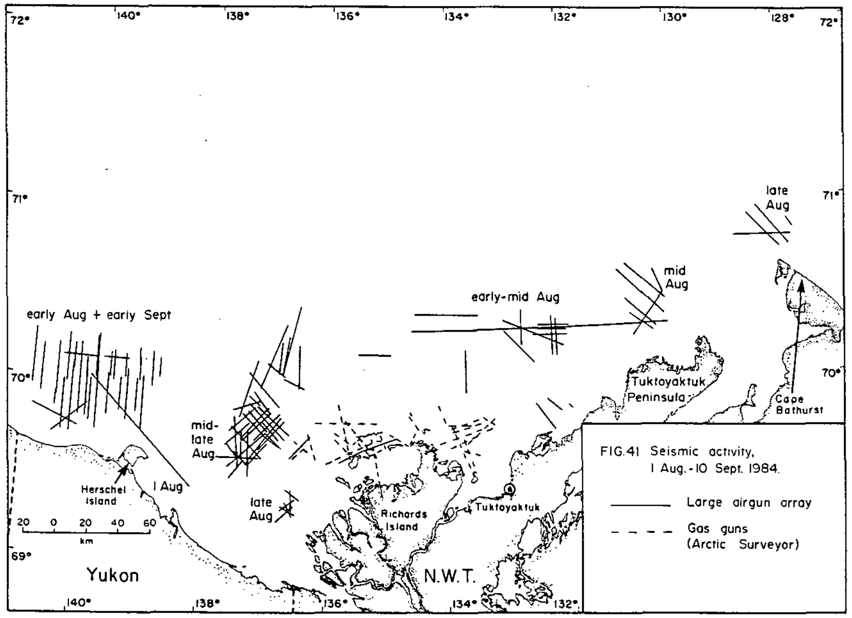
FIG. 41 Seismic activity, 1 Aug.-10 Sept. 1984.

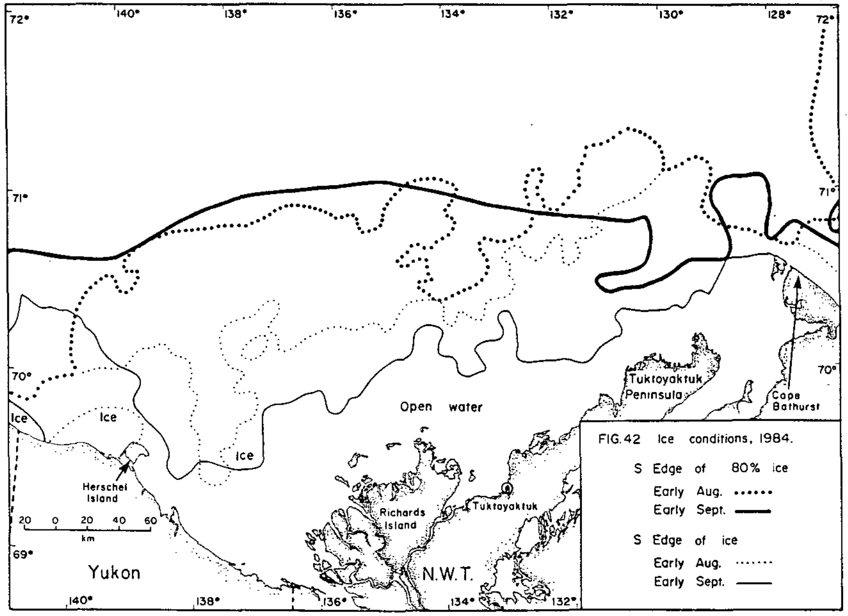
FIG. 42 Ice conditions, 1984.

comm.). However, there were numerous whales east of our study area in Franklin Bay (126°W) at this time (Harwood and Borstad 1984; Davis et al. in prep.).

In early September 1984, bowheads were still concentrated at some locations along the Yukon coast and west of the Delta (Fig. 38). Some of the latter whales were again exposed to helicopter traffic and noise from island construction. Aerial surveyors saw no bowheads within the industrial area north of the Delta, but industry personnel reported some sightings there in Sept (Harwood and Borstad 1984). There was a concentration just north of the industrial area, about 10 km north of the drillship at Arluk (Fig. 38,39). Bowheads were still numerous off Cape Bathurst and farther southeast in Franklin Bay (Davis et al. in prep.).

Offshore coverage in early Sept was meagre, but a systematic survey in mid Sept detected virtually no bowheads far off the Yukon or Delta, and few north of the Tuk Peninsula and Cape Bathurst (Fig. 38; Harwood and Borstad 1984). Bowheads were still concentrated along much of the Yukon coast in mid Sept (Davis et al. in prep.). In general, many bowheads were still in the SE Beaufort Sea, including Franklin Bay, in mid Sept, although others had moved west as far as Prudhoe Bay, AK (LGL unpubl. data). Bowheads were still present near shore SE of Kay Pt on 26 Sept and, in smaller numbers, 3 Oct (D. Ljungblad pers. comm.). On 5 Oct, a few bowheads were seen travelling west in offshore waters near the Alaska-Yukon border (LGL unpubl. data).

Bowhead Distribution and Industrial Activities, 1976-79

Before 1980, bowheads in the Canadian Beaufort Sea were little-studied. Very limited information came from (1) the commercial whaling era (1890-1914), (2) opportunistic observations during recent studies of other topics, and (3) reports by industry personnel (Fraker et al. 1978; Fraker and Fraker 1979; Fraker and Bockstoce 1980), along with (4) opportunistic vessel surveys in 1979 (Hazard and Cubbage 1982).

The area of shallow water off the eastern part of the Mackenzie Delta and western Tuktoyaktuk Peninsula is the one part of the Canadian Beaufort Sea where there was some study of bowheads each year since 1976 (Fig. 43). This area was within the main area of offshore oil exploration in 1976-79 (Fig. 44-47) as well as in 1980-84. Artificial islands had been built in very shallow waters just north of the Delta before 1976, but in 1976 island-building extended out to Isserk in 13 m of water. In both 1976 and 1977 there was much barge traffic between a dredging site at Tuft Point and Isserk. Also, the first three drillships arrived in the Beaufort Sea in 1976 and drilled at several sites (Fig. 44). In 1978 and 1979, dredging and island construction occurred at Issungnak, in water 18 m deep farther offshore than Isserk (Fig. 46, 47). There was much barge traffic between Tuft Point and Issungnak in 1978-79. A fourth drillship arrived in 1979.

In 1976, many bowheads were seen in water <15 m deep during the first half of August, with a few others later (Table 3; Fig. 43; Fraker 1977a). About 35-45 were seen on 10 August alone. Similarly in 1977, there were 26 sightings totalling almost 100 bowheads in water <15 m deep off the Delta and western Tuk Peninsula between 26 July and 17 Sept (Table 3; Fig. 43; Fraker 1977b). Many of these 1976-77 sightings were from vessels travelling farther

Table 3. Bowhead sightings off the eastern Mackenzie Delta and western Tuktoyaktuk Peninsula in the summers of 1976-80[a].

	Incidental Sightings[b]		Systematic Offshore Surveys, 1-15 Aug		Dates Observed	
Year	No. of Sightings	No. of Bowheads	No. of Bowheads	Density[c] (/1000 km^2)	First	Last
1976	15	46	-	-	3 Aug	16 Sept
1977	26	98	-	-	26 July	17 Sept
1978	5	58	1[d]	0.5	26 July	14 Sept
1979	1	6	1	0.5	8 Aug	9 Sept
1980	18	136	139	41.0	2 Aug	11 Sept

[a] Sources: Fraker (1977a,b, 1978), Fraker et al. (1978, 1982), Fraker and Fraker (1979), Fraker and Bockstoce (1980), and P. Norton (unpubl.).

[b] Sightings by industry personnel and biologists, excluding specific studies of bowheads.

[c] Uncorrected density; no allowance for submerged or missed whales.

[d] Plus sightings totalling 4 whales on 26 July 1978.

offshore than was common in previous years. Opportunities for observations thus were increased. Nonetheless, the sightings show that numerous whales occurred in the shallow waters of the Mackenzie estuary in 1976 and 1977.

In 1978, there were fewer incidental sightings in the shallow water off the Delta and western Tuk Peninsula--only 5 sightings of a total of 58 whales. All were seen from 7 to 14 Sept in water 11-18 m deep (Table 3; Fig. 43; Fraker 1978). Opportunities for incidental observations in August 1978 were similar to those in 1977, when many more whales were seen. Also, from 26 July to 8 August 1978, Fraker conducted four systematic aerial surveys north to about the 50-60 m isobath off the eastern Delta. Only 5 whales (uncorrected density 0.9/1000 km^2) were found, all near the 50 m isobath (Fig. 43). Only one was seen during the two August surveys (0.5/1000 km^2). Bowheads clearly did not move into shallow water off the eastern Delta as early in 1978 as in 1976 or 1977.

In 1979, only one bowhead was seen during three systematic surveys off the Delta on 21 July-8 Aug (Fig. 43; Fraker and Fraker 1979). The uncorrected density was 0.3/1000 km^2, or 0.5/1000 km^2 during two August surveys. Industry personnel at Issungnak and elsewhere reported only one sighting in 1979--6+ bowheads in 12 m of water on 9 Sept (Fig. 43; Fraker and Fraker 1979). Similarly, Hazard and Cubbage (1982) saw no bowheads west of 131°W, although they did find bowheads farther east in late July and August.

In summary, the abundance of bowheads in shallow waters off the eastern Mackenzie Delta varied markedly from 1976 to 1979. Bowheads were numerous there in August 1976 and 1977, infrequent until 7 Sept in 1978, and infrequent in 1979 (Fig. 43).

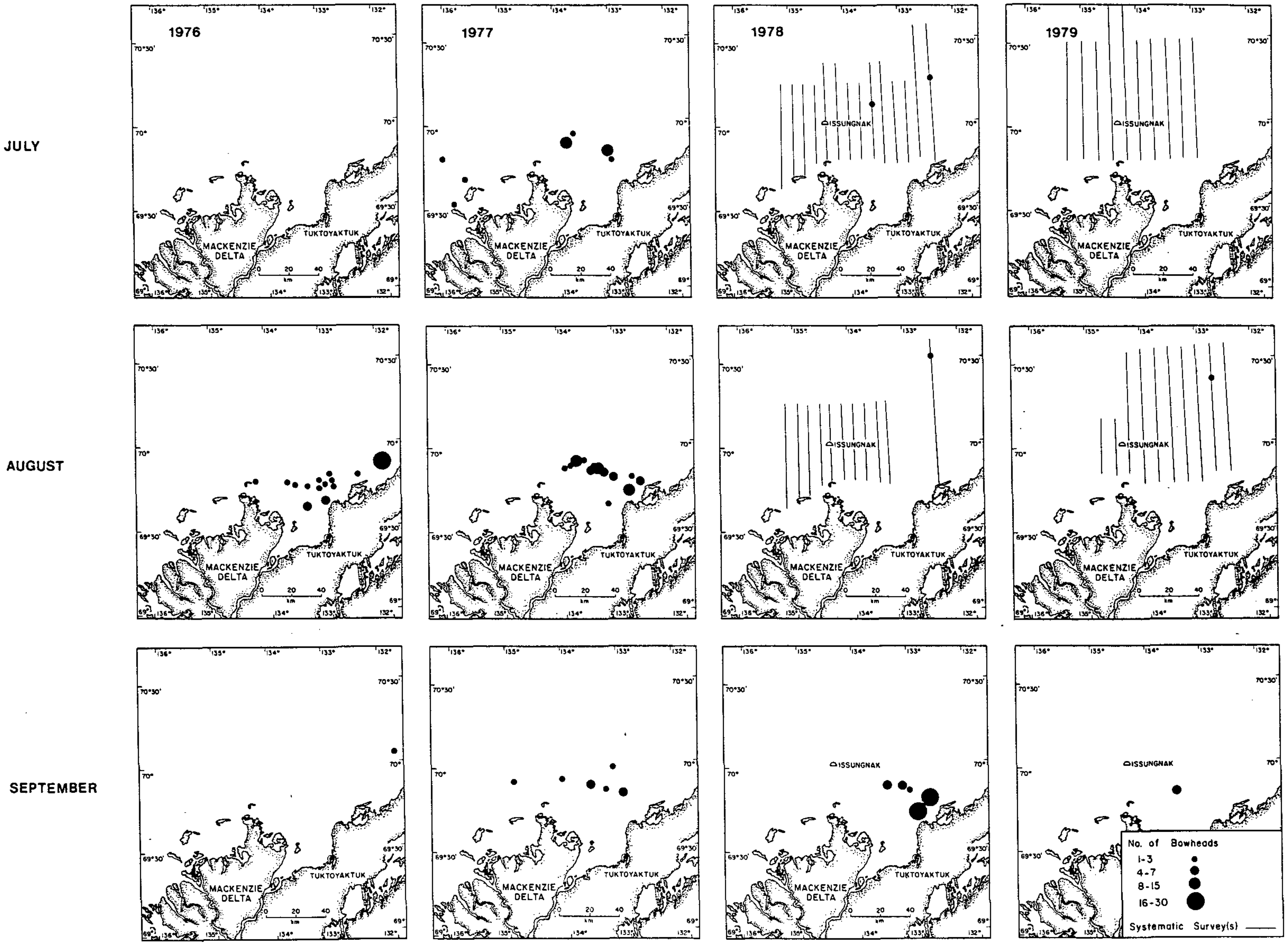

FIGURE 43. Bowhead sightings off the eastern Mackenzie Delta and western Tuktoyaktuk Peninsula in the summers of 1976-79. Sources as for Table 3. There were no systematic surveys in 1976-77. Each survey line shown on maps for 1978-79 was covered once or twice.

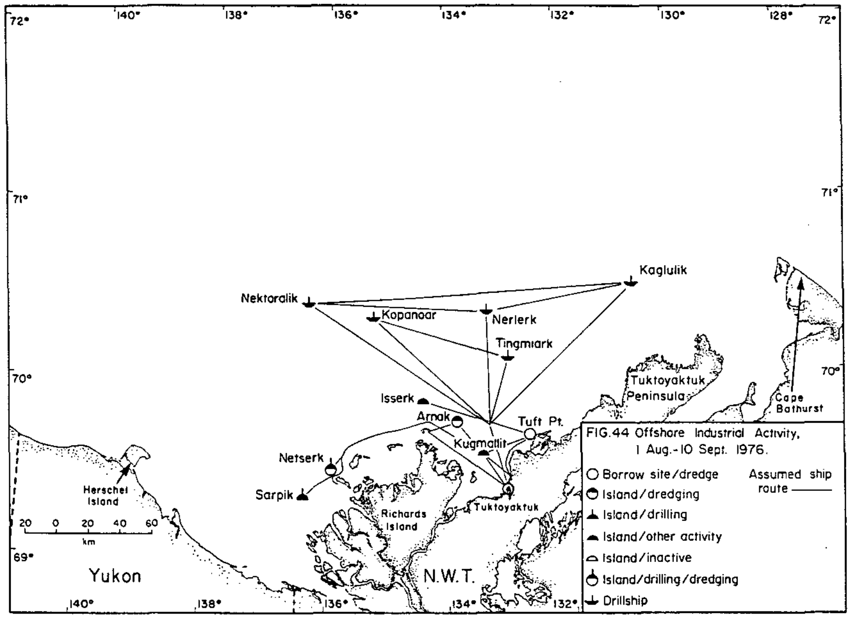

FIG.44 Offshore Industrial Activity, 1 Aug.-10 Sept. 1976.

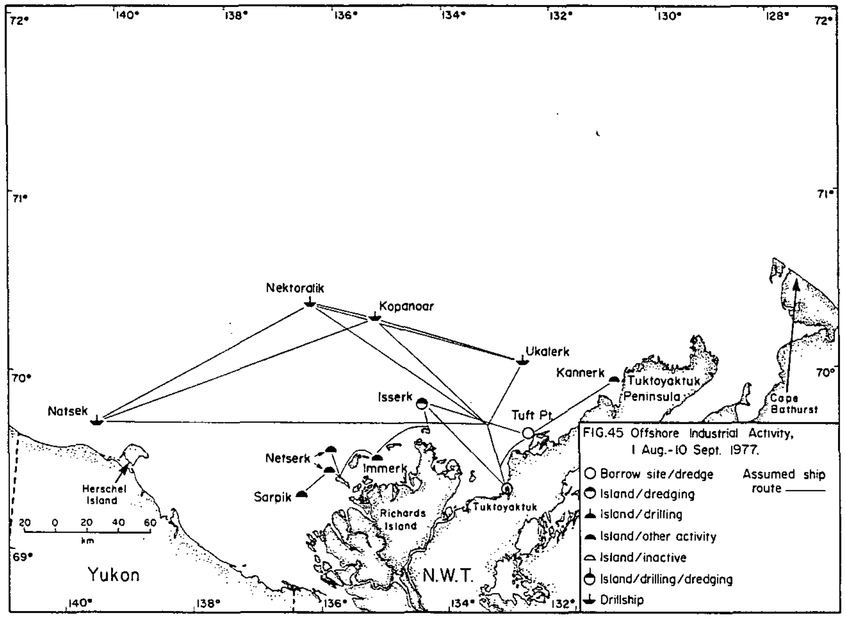

FIG.45 Offshore Industrial Activity, 1 Aug.-10 Sept. 1977.

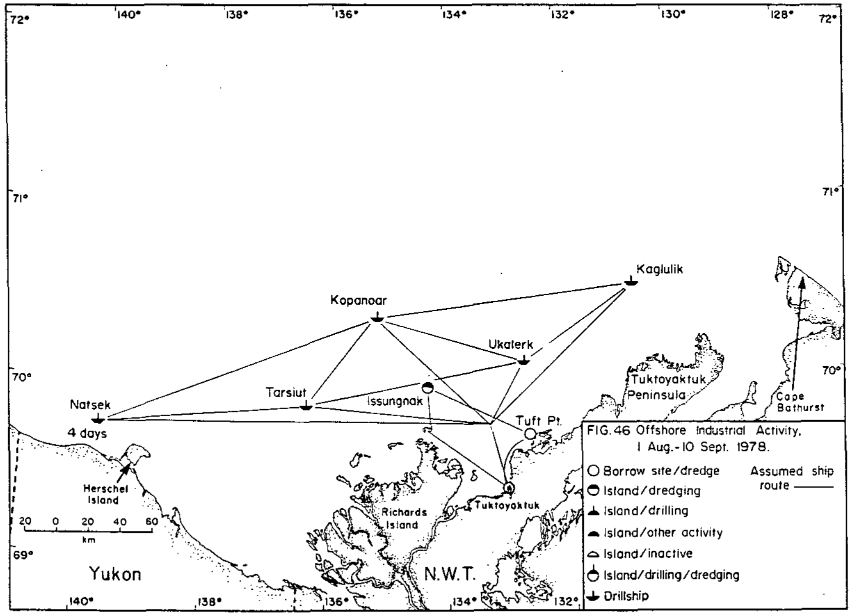

FIG.46 Offshore Industrial Activity, 1 Aug.-10 Sept. 1978.

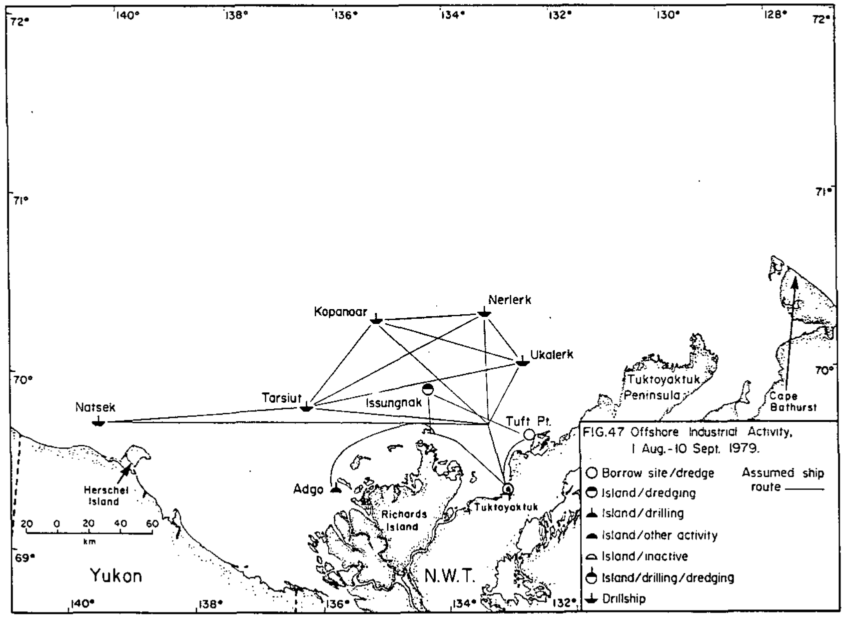

FIG.47 Offshore Industrial Activity, 1 Aug.-10 Sept. 1979.

DISCUSSION

Bowhead distribution in the eastern Beaufort Sea has varied greatly within and between summers. Nonetheless, some patterns are evident. These patterns are summarized before we consider whether there are any trends in distribution and, if so, whether these trends are related to industrial activities.

Seasonal and Annual Trends in Distribution

Few bowheads occurred in the shallow shelf waters off the Tuktoyaktuk Peninsula, Mackenzie Delta and Yukon before 1 August. In August, many bowheads moved into these shallower waters, apparently from the north and east. However, the timing of movement and locations of concentrations varied from year to year.

Summary Maps.--Figures 48 and 49 summarize distribution in early and late August of 1980-84. Areas with no survey coverage are identified. Areas designated as low, moderate and high density are those with, respectively, widely separated sightings of 1-3 whales, many sightings of 1-3 whales, and large groups of whales. The categorization is necessarily subjective. In borderline cases, we considered the amount of survey effort; the greater the amount of survey effort, the less emphasis we gave to any single sighting. The reader can compare Figures 48 and 49 with the detailed sighting and survey coverage maps given earlier to corroborate our categorizations.

Figures 48 and 49 must be interpreted with considerable caution. Survey coverage ranged from nil or sparse to extremely intense (see earlier maps), and survey procedures varied widely. Systematic surveys were not available from the entire study area in any period. In early August of 1982-84 there was considerable non-systematic but essentially no systematic coverage. Where and when available, systematic coverage was very helpful in comparing relative numbers of bowheads. When there was substantial coverage of both the systematic and non-systematic types, major concentrations detected by one approach were generally detected by the other as well. However, when coverage was sparse, moderate concentrations of whales were sometimes missed or, more commonly, greatly underrepresented by one type of coverage.

Both systematic and non-systematic surveys had major limitations. Because systematic surveyors usually did not circle whales, non-systematic coverage commonly detected groups where systematic coverage detected only 1 or 2 whales, or even no whales. On the other hand, the concentration of non-systematic coverage in areas where whales were expected caused considerable complications in estimating relative numbers in different areas. Ideally, this could be allowed for by converting to 'sightings per unit effort'. However, this was not practical here. Effort was not always quantifiable, and it was necessary to combine results from studies with widely varying field procedures.

In summary, caution is necessary in interpreting Figures 48 and 49 even for areas and times when systematic surveys were done. Apparent differences in bowhead abundance between areas and years should be considered proven only when the difference was large and there was considerable survey coverage.

Late July.--Only in 1981 and 1984 were there extensive surveys in late July. In 1981, very few bowheads were in the SE Beaufort Sea; more were in Amundsen Gulf. However, only a minority of the population was detected. Presumably most were far offshore in the pack ice, perhaps with some in unsurveyed Alaskan waters. In 1984, few bowheads were in the SE Beaufort in early-mid July (Harwood and Borstad 1984). Bowheads began to arrive in late July, earlier than in 1981. None were seen in Alaskan waters in July 1984 (D. Ljungblad pers. comm.).

Early August.--Distribution in early August differed greatly among years (Fig. 48). Within the 1980-84 period, only in 1980 did many bowheads move into shallow waters north of the Mackenzie Delta in early August. There was evidence of a similar concentration in early August of 1976 and 1977, but not 1978 or 1979 (Fig. 43). In early August 1981, bowheads were widely distributed on the outer continental shelf, mainly near the ice edge and the shelf break. Many seemed to be moving south on a broad front, although others apparently moved west out of Amundsen Gulf.

In early August of 1982 and 1983, bowhead concentrations were found well offshore in the western part of the study area (Fig. 48C, D). In 1982, many were in open water but moving west. Coincidentally or not, this was toward the ice edge, which was unusually far west. Other bowheads were in the ice, including some far offshore in the pack ice of the Alaskan Beaufort Sea (Ljungblad et al. 1983). In early August 1983, virtually all bowheads seen were in or near the ice beyond the shelf break off the western Yukon (Fig. 48D). In that year bowheads did not extend far into Alaskan waters. In early August 1984, as in late July, there were small numbers of bowheads off the Yukon, but more off the eastern Tuk Peninsula and Cape Bathurst, at or just south of the ice edge.

In general, recent data provide evidence of westward movement out of Amundsen Gulf in early August of some years, as hypothesized by Fraker and Bockstoce (1980). However, the majority of whales that enter the SE Beaufort Sea at this time probably come from the north, not the east. In 1980, many bowheads were in open water well south of the ice by early August, but in 1981-84 most were in or just south of the ice. In 1982, the one recent year when ice was absent east of Herschel Island, both ice and bowheads were concentrated to the west.

Mid August.--In each of the five years studied in detail, the area of peak whale concentration within the Canadian Beaufort Sea was closer to shore in mid August than in early August. In 1980 the shift was slight, since whales were already in shallow water in early August, but in 1981-84 the shift was more dramatic. In mid August 1982, the only large concentration of bowheads within the eastern Beaufort Sea was in an area where water >100 m deep occurs close to shore near Herschel Isl. Adults, immatures and calves were present (Davis et al. 1983). In mid August 1983, a concentration of several hundred bowheads, mainly subadults, was found very close to the Yukon shore SE of Herschel Isl. In mid August 1984, immature whales again concentrated not only there, but also west of Herschel Isl and offshore in Mackenzie Bay, along the edge of the turbid Mackenzie River plume. These coastal concentrations were definitely not present in 1980-82. In general, movement toward shore occurred each year in mid August, but the area of concentration varied among years.

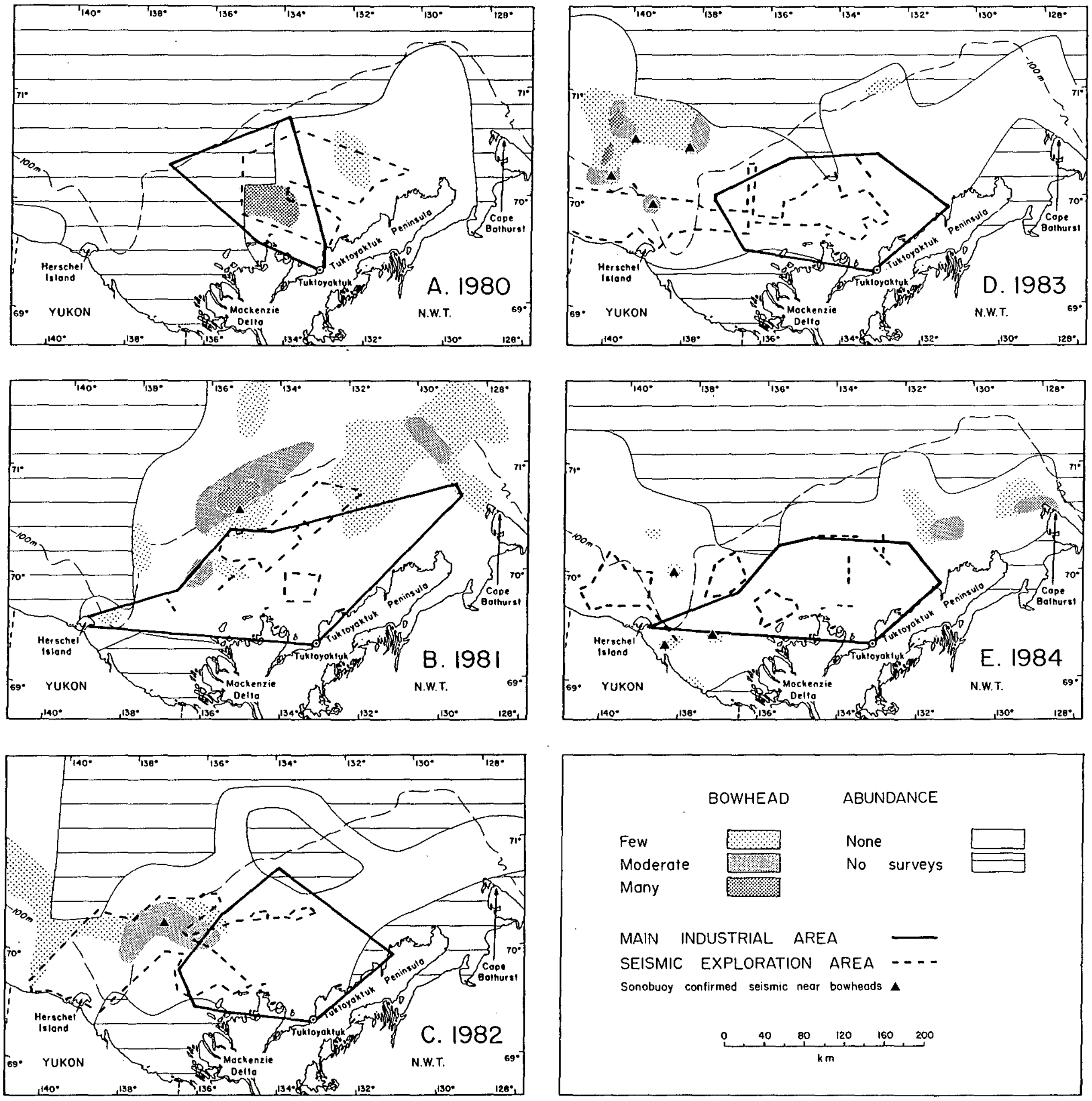

FIGURE 48. Distribution of bowheads on 1-10 August 1980-84 in relation to the area of industrial activity on 1-10 August. Triangles show locations where sonobuoys dropped near bowheads confirmed that bowheads were exposed to noise pulses from seismic vessels.

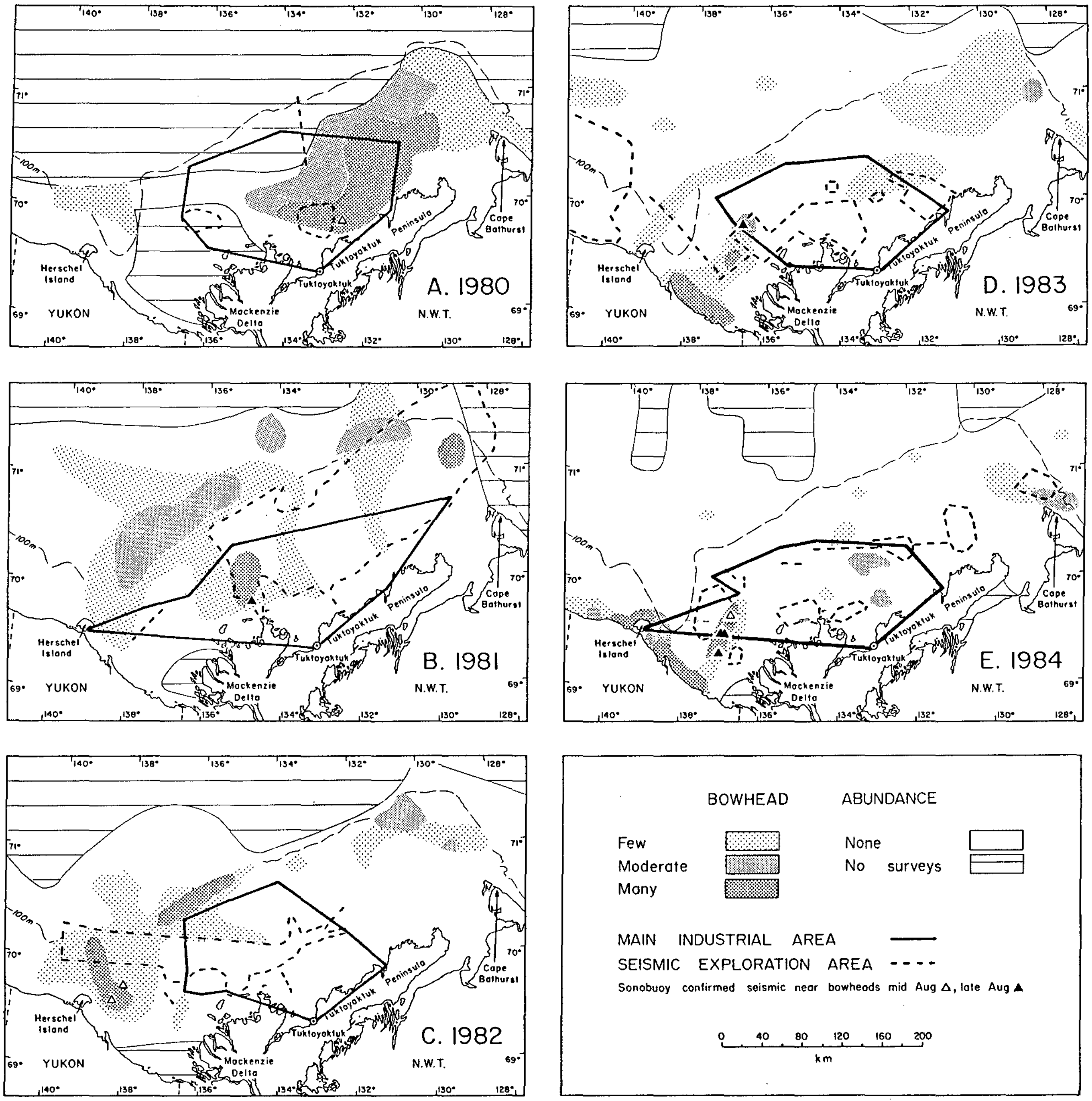

FIGURE 49. Distribution of bowheads on 18*-31 August 1980-84 in relation to the area of industrial activity on 11-31 August. Triangles show locations where sonobuoys dropped near bowheads confirmed that bowheads were exposed to noise pulses from seismic vessels.

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* Systematic surveys for the 'late August' periods of 1980-84 began on 18-21 Aug and ended on 24-29 Aug; all systematic coverage from 18 to 29 Aug was considered here, along with non-systematic coverage on 22-31 Aug.

Late August.--Distributions in late August were related to those in early and mid August, and differed among years. In 1980, there was a large area of concentration off the Tuktoyaktuk (Tuk) Peninsula and eastern Delta (Fig. 49A). This concentration was unique in the 1980-84 period, probably containing well over half the population. The center of abundance had shifted eastward relative to that earlier in August. In 1981, the areas of greatest abundance were in shallow waters off the central Delta and in deeper waters near the shelf break (Fig. 49B). In late August 1982, whales were still concentrated near Herschel Isl, but there were also concentrations near the shelf break, especially where it is steepest off the Delta (Fig. 49C). In late August of 1983 and 1984, the major nearshore concentrations of subadults persisted along the Yukon coast and, especially in 1984, along the turbidity front in Mackenzie Bay. In late August of 1981, 1983 and 1984, bowheads occurred near and beyond the eastern edge of our study area (Fig. 49D,E; Davis et al. 1982, in prep.; Cubbage et al. 1984; Harwood and Borstad 1984). No surveys were conducted east of the study area in 1980 or 1982.

Early September.--Distributions differed somewhat less among years in early September than in August. In 1980, numerous whales remained over the continental shelf off the Tuk Peninsula, although farther offshore than in August. Also, whales appeared close to shore off Herschel Isl. In 1981, whales moved closer to shore off the Tuk Peninsula in early September than they had been in August. There were many whales near Herschel Island, and low densities off the Delta and near Cape Bathurst. In 1982, the largest concentration was near and north of Herschel Isl, but there were a few sightings off the Delta and Tuk Peninsula. In 1983, whales were widely distributed on the outer shelf off the Tuk Peninsula (very similar to the pattern in early Sept 1980), with some off the Delta but virtually none near Herschel Isl. In 1984, unlike 1983, bowheads remained near the Yukon coast and Herschel Isl not only in early September (Fig. 38), but well beyond (D. Ljungblad pers. comm.).

Although some bowheads feed in the eastern Alaskan Beaufort Sea in early September (Ljungblad et al. 1984a), most are still in Canadian waters. Bowhead headings recorded during systematic surveys in early-mid Sept were predominantly westward in 1980, 1982 and 1983, but not in 1981 or 1984. Bowheads were present as far east as Franklin Bay (126°W) in early-mid September of all years with survey coverage (1981, 1983 and 1984). The main movement into Alaskan waters apparently is in mid-September of most years. There have been a few sightings in Canadian waters as late as early-mid October (Ljungblad et al. 1983, pers. comm.).

Geographic Areas Where Bowheads Often Concentrate

Amundsen Gulf and Franklin Bay.--Bowheads apparently concentrate in Amundsen Gulf in early-mid summer, presumably because break-up occurs early there (Sergeant and Hoek 1974; Fraker et al. 1978; Fraker 1979; Fraker and Bockstoce 1980). In 1981, there was evidence that some bowheads moved west out of Amundsen Gulf around 1 August. However, bowheads remain common in Amundsen Gulf and especially Franklin Bay in late summer (Davis et al. 1982, in prep.; Hazard and Cubbage 1982; Cubbage et al. 1984; Harwood and Borstad 1984).

Cape Bathurst.--Around 1900, bowheads were found near Cape Bathurst throughout the summer (Fraker and Bockstoce 1980). Bowheads also were seen there annually from 1979 to 1984, with substantial numbers in 1981 and 1984 (Hazard and Cubbage 1982; this report). Strong currents and sharp water mass boundaries occur there, and deep water occurs close to shore.

Off Tuktoyaktuk Peninsula.--Around 1900, whalers took many bowheads in shelf waters (<50 m) off the Tuk Peninsula in August and early September (Fraker and Bockstoce 1980). Bowheads still occur there at these times. The dates of occurrence, specific locations, and numbers of whales vary among years. Bowheads are often found over the outer shelf and shelf break north of Cape Dalhousie.

Shelf Break off Mackenzie Delta.--In August 1981-82, bowheads often concentrated about 125 km offshore NW or NNW of the Delta, at the edge of the continental shelf. The bottom slope is steeper here than anywhere else in the study area, dropping from 100 to 500 m in <10 km.

Yukon Coast.--During the 1970's, bowheads often were seen along the Yukon coast SE of Herschel Isl in late summer (Fraker and Bockstoce 1980). In 1980-82, there was no such coastal concentration, but in 1983 several hundred bowheads, probably mostly immatures, were there from at least 14 to 28 August. In 1984, bowheads (largely immatures) again concentrated there, and some remained until at least 3 October.

Herschel Island.--Bowheads were seen just N and NE of Herschel Isl in early September 1980-81, and starting in mid-August in 1982 and 1984. Bowheads also were found near Herschel Island in late summer and early autumn around 1900 (Fraker and Bockstoce 1980). This is the second of the two places in the study area where deep water occurs within a few kilometres of shore. Interestingly, very few bowheads were seen northeast of Herschel Isl during 1983.

Near Alaska-Yukon Border.--In mid to late September, bowheads often linger and feed in the 140°-142°W area (Ljungblad et al. 1980, 1982, 1983; Johnson 1983).

Distribution in Relation to Industrial Activities

Behavioral studies suggest that bowheads react only briefly to transient oil industry activities and to the onset of industrial noises, and that bowheads habituate to noise from ongoing drilling, dredging or seismic operations (Richardson et al. 1985a,b). However, the behavioral studies cannot determine whether fewer whales move into an area if industrial activity is present. They also cannot determine whether industrial operations result in a reduced tendency to return to the area in subsequent years. Large-scale survey results collected over a number of years provide a way to address these questions.

In Figures 48 and 49, areas of industrial activity in early and mid-late August 1980-84 are outlined on maps summarizing bowhead distribution in early and late August. Industrial activities are separated into (1) site specific activities such as dredging, island construction and drilling, along with vessel and helicopter traffic in support of those activities, and (2) offshore seismic exploration. The area with activities of type 1 is the 'main industrial area'.

Bowheads and the Main Industrial Area

In 1980, many bowheads were around the Issungnak island construction site north of the Mackenzie Delta in early and mid August (Fig. 48A). Vessel and helicopter traffic to drillships farther offshore also passed through or near that whale concentration. Behavioral and acoustic data confirmed that some whales were exposed to dredge and boat noise (Fraker et al. 1982; Greene 1982; Richardson et al. 1985a,b). By late August, most whales were somewhat east of the offshore construction and drilling sites; however, the western edge of the whale concentration was near Issungnak (Fig. 49A). In general, the only known concentration of bowheads was in the area of most intense industrial activities in early-mid August, and overlapped that area in late August.

In 1981, the main industrial area extended farther east and west but less far offshore. Most bowheads remained north or west of the area of intense industrial activity (Fig. 48B, 49B). The one concentration of whales near industrial sites was north of the Delta in mid and late August. They were, on most days, 10 km or more west of the artificial island and drillship in the Issungnak area. However, some of these whales were exposed to drillship, boat and probably helicopter noise (Richardson et al. 1985a,b).

In 1982, there was very little overlap between whale distribution and the area of intense offshore exploration (Fig. 48C, 49C). There were very few sightings within the main industrial area at any time during the summer.

In 1983, bowheads were virtually absent from the main industrial area in early August (Fig. 48D). There were some sightings there in mid August, but no major concentration. In late August a concentration of whales formed NW of the Delta (Fig. 49D). Some whales were only 10-20 km from the Pitsiulak drillsite and the Kadluk island construction site (Fig. 31), and were along a main helicopter route. These whales were also exposed to seismic noise (Fig. 49D). Overall, however, only a small fraction of the population was in the main industrial area in late August 1983. Much larger numbers were found outside the main industrial area, most notably along the Yukon coast and far to the east (Cubbage et al. 1984; McLaren and Davis 1985). The concentration NW of the Delta persisted into early September, but most bowheads remained outside the main industrial area (Fig. 30).

In 1984, bowheads were very scarce in the main industrial area in July (Harwood and Borstad 1984), and we saw none there in early August (Fig. 48E). From mid August to early September, many bowheads occurred west of the Delta in central Mackenzie Bay (Fig. 49E). Some of these were only 10-15 km west of the westernmost island construction site, and were exposed to occasional dredge noise from that site, seismic noise and helicopter overflights (Richardson et al. 1985b). Lesser numbers of bowheads occurred in eastern parts of the main industrial area (Fig. 49E).

General Trend.--Over the 1980-82 period, bowhead distribution overlapped progressively less with the area of offshore dredging, construction and drilling. This was true in both early and late August. Bowheads were abundant within the main industrial area in 1980, much less abundant there in 1981, and virtually absent in 1982. Maximum numbers in the main industrial area in 1983 were slightly greater than in 1982, and there was some further increase in 1984. Most bowheads in the industrial area in 1983 and 1984 were near its edges, unlike the situation in 1980. Thus, there was a pronounced decrease in utilization of the main industrial area from 1980 to 1982, and a much less pronounced increase from 1982 to 1983 and 1984. There has been no recurrence of the very large numbers seen in the main industrial area in 1980, or even of the lesser numbers seen there in 1981.

Offshore oil exploration north of the Mackenzie Delta became intensive in 1976 (Fig. 44-47). Thus, the appearance of many whales within the main industrial area in 1980 occurred four years after offshore operations in that area became intensive. The fragmentary data from 1976-79 indicate that many bowheads were seen in the middle of the main industrial area in early August of 1976 and 1977, but not in 1978 or 1979 (Fig. 43). Bowheads apparently entered the industrial area in early September of 1978, but in 1979 there were very few sightings at any time.

The presence of many whales in 1980, after a period of apparent scarcity in 1978-79, casts doubt on the suggestion that there is a trend for decreasing utilization of the main industrial area. However, bowheads were apparently abundant in the central part of the main industrial area in 3 of 5 years from 1976 to 1980, but in 0 of 4 subsequent years. The intensity of offshore industrial activities increased gradually from 1976 to 1983-84, and it is possible that industry began to affect bowhead distribution after 1980.

Overall, the data from 1980-84, and also those from 1976-84, provide some evidence of reduced utilization of the main industrial area, particularly the central portion north of the Mackenzie Delta, in recent years. However, some groups of bowheads occurred in the main industrial area in 1983-84, especially near its periphery. It may be of interest that most of the whales there in 1984, and possibly also 1983, were subadults (Davis et al. in prep.). Year-to-year fluctuations in bowhead abundance also occurred in most parts of the summer range outside the main industrial area. There is evidence that some of these variations in distribution may be attributable to variable food supply (see below). We conclude that it is presently uncertain

1. whether recent year-to-year variations in bowhead abundance are indicative of a long-term trend for reduced utilization of the main industrial area, and

2. whether these variations are connected with the gradually increasing level of industrial activity.

Bowheads and Areas of Seismic Exploration

We provide separate discussions of bowhead distribution relative to seismic exploration and the main industrial area. Seismic exploration occurred over a broader area than drilling, dredging and support traffic in 1980-84. Also, noise from seismic exploration was very intense but quite discontinuous, whereas drillsites, dredges and ships in the main industrial area produced continuous but less intense noise (Greene 1985). The discontinuity in seismic noise had two components: (1) seismic noise occurred as pulses spaced several seconds apart, and (2) at any given time seismic vessels operated in only a fraction of the entire zone of seismic exploration.

Seismic exploration occurred in shallow areas off the eastern Mackenzie Delta every year from 1971 to 1984, including 1976, 1977 and 1980 when many bowheads were present. In 1980, 'Arctic Surveyor' operated north of Tuktoyaktuk throughout August (Fig. 8). Bowheads were abundant nearby, and were seen only 8 and 13 km from the ship on two dates (Fig. 49A; Richardson et al. 1985a,b). In early August, when bowheads first moved into the area, another seismic vessel was operating just to the north and northeast (Fig. 8, 48A). In early September, whales far off the Tuk Peninsula were probably exposed to noise from seismic exploration just to the south (Fig. 8).

In August 1981, there was widespread seismic exploration north of the Mackenzie Delta and, from mid-month on, the Tuk Peninsula (Fig. 17). In early August, some whales far off the Delta were exposed to noise from a ship closer to shore; in late August, whales in shallow water off the Delta and in deeper water off the eastern Tuk Peninsula were exposed to strong seismic sounds on some days (Fig. 48B, 49B; Richardson et al. 1985a,b). In mid September, whales off the western Yukon were exposed (Ljungblad et al. 1982).

In 1982, bowheads NW of the Mackenzie Delta in early August were sometimes exposed to seismic noise, as was the concentration off Herschel Isl in mid August (Fig. 48C, 49C; Richardson et al. 1985a,b). There was probably continued exposure in the latter area in early September (Richardson et al. 1983a).

In 1983, fewer whales were found inside areas of seismic exploration than in 1980-82, but whales off the Yukon were often exposed to noise from distant seismic vessels (Fig. 48D, 49D; Ljungblad et al. 1984a,b; Richardson et al. 1984b, 1985b). The same was probably true for bowheads off the eastern Tuk Peninsula in late Aug-early Sept (Fig. 49D). In mid August, a few bowheads just north of Tuktoyaktuk were exposed to seismic and other industrial noise (Richardson et al. 1984b). Whales near the edge of the main industrial area northwest of the Delta definitely were exposed to seismic noise on 31 Aug-1 Sept (Fig. 49D; Richardson et al. 1985b).

In 1984, the concentration of bowheads west of the Delta in mid-late August was often exposed to strong noise pulses from a seismic vessel as close as 10 km away (Fig. 41, 49E; Richardson et al. 1985b). Bowheads scattered east and north of Herschel Isl in early August sometimes were exposed (Fig. 48E), and those near Cape Bathurst in late August probably were (Fig. 49E).

Recurrence in Areas of Seismic Exploration.--Many bowheads were in areas ensonified by seismic noise each summer from 1980 to 1984. Some concentrations were in areas where there was seismic exploration during the previous summer:

1. Many whales occurred in shallow water north of Tuktoyaktuk in 1980, and apparently also in 1976 and 1977. Seismic exploration has occurred there every summer since 1971.

2. Whales occurred off Tuk Peninsula in late Aug-early Sept of 1981-83 despite seismic exploration nearby at those times in 1980, 1981 and to a much lesser extent 1982 (Fig. 49).

3. Bowheads occurred far north of the Yukon in early August of 1982 and 1983 (Fig. 48C,D) despite seismic exploration there in the late July-early Aug of 1981 and 1982 (Fig. 19 and 41 in Richardson et al. 1983a).

4. Bowheads occurred west of the Delta in mid-Aug to early Sept 1984 despite the presence of seismic noise there in late Aug-early Sept 1983 (Fig. 49D,E).

Although these data suggest that seismic exploration has not caused large scale abandonment of parts of the summer range, little is known about recurrence of specific individual whales at places where they were exposed to seismic noise in previous years. Cases of apparent recurrence might involve different whales that were not exposed to seismic noise the previous year.

Natural Factors Affecting Bowhead Distribution

The predominant activity of bowheads in summer is feeding (Würsig et al. 1985a,b). To obtain sufficient energy, bowheads apparently must feed primarily in areas of above-average plankton abundance (Brodie 1981; Griffiths and Buchanan 1982). The latter authors found evidence that copepods are more abundant in areas with bowheads than in nearby areas without bowheads. Copepods and euphausiids are the main food items for bowheads in the Alaskan Beaufort Sea during early autumn (Lowry and Frost 1984), and presumably are also important to bowheads in the Canadian Beaufort Sea. Thus, factors affecting availability of zooplankton in the eastern Beaufort Sea probably have a strong influence on summer distribution of bowheads. Variations in the distributions of some other species of baleen whales are related to variations in their food supplies (for review, see Würsig et al. 1985b).

There has been no detailed study of factors affecting zooplankton abundance in different parts of the eastern Beaufort Sea. Thus, it is impossible to assess whether observed variations in bowhead distribution have any connection with variable zooplankton abundance. However, bowheads sometimes concentrate in areas where high zooplankton abundance would be expected. The early summer concentration in Amundsen Gulf might be related to the early bloom of phyto- and zooplankton that presumably results from the early ice breakup in that area. During late summer, concentrations of zooplankton (and bowheads) may occur because of the hypothesized higher productivity and/or concentrating effects associated with

- turbulence and eddies, e.g. near Cape Bathurst and Herschel Isl,
- hydrographic phenomena such as upwelling near the shelf break,
- occasional upwelling along the Yukon coast and ice edges, and
- hydrographic and nutrient conditions near the edge of the Mackenzie River plume.

(Herlinveaux and de Lange Boom 1975; Buckley et al. 1979; Owen 1981; Griffiths and Buchanan 1982; Borstad 1984; LGL, ESL and ESSA 1984).

Locations of zooplankton concentrations are expected to vary over time. For example, the occurrence of upwelling off the Yukon coast and the position of the estuarine front bordering the Mackenzie plume depend strongly on wind conditions on preceding days (Herlinveaux and de Lange Boom 1975; MacNeill and Garrett 1975). Thus, much of the within- and between-season variation in bowhead distribution may result from variation in areas of peak food availability. It should be noted, however, that this argument is largely speculation. There is very little empirical information about factors affecting zooplankton abundance in the eastern Beaufort Sea, or about the ways in which bowheads respond to variable food abundance and other environmental factors.

The detailed distributional data from 1980-84 and limited data from 1976-79 document pronounced year to year changes in summer distribution of bowheads. There is no evidence of avoidance of areas of seismic exploration. However, since 1980 fewer bowheads have tended to enter the main area of drilling, dredging and support activities, particularly its central zone. From present data it is not possible to determine whether activities in the main industrial area are affecting bowhead distribution. The trend is too imprecise, natural variability in bowhead distribution is too great, and our understanding of the roles of environmental factors, most notably food supply, is too rudimentary.

If many bowheads, particularly adults, return to the central part of the main industrial area in future, this will constitute strong evidence that oil exploration has not excluded bowheads from part of their range. The case will be especially strong if some recognizable individuals return to industrial areas where they were seen in previous years. Conversely, if a distribution similar to that seen in 1980 does not recur, there will be increasing reason for concern about possible long term effects of oil exploration on bowheads. In either case, a better understanding of the interrelated roles of oceanographic and meteorological phenomena in affecting plankton abundance and bowhead distribution may be necessary before firm conclusions about effects of industrial activity on bowhead distribution can be drawn.

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