ACTIVITIES AND UNDERWATER SOUNDS OF FIN WHALES*

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ABSTRACT

Routine activities observed in fin whales (*Balaenoptera physalus*) were correlated with their underwater sounds. The acoustic and behavioral observations throughout 23 years were from a variety of geographical areas, but were more frequent in waters of the western North Atlantic around Cape Cod, Massachusetts, USA. Shipboard and aerial observations using arrays of hydrophones with low-frequency capability and radio tracking of tagged whales provided confirmation of both acoustics and behaviors. Routine activities were described including blowing, short dives (apparently a search behavior), long dives (often feeding), near-surface slow swimming (resting), rapid travel, and surface feeding. Underwater sounds included higher frequency sounds (under about 100 Hz), 20-Hz pulses (both single pulses and patterned sequences), ragged broadband low frequency pulses and low-frequency rumbles, as well as non-vocal sharp implusive sounds. Occurrence of the sounds, typical levels, responses, seasonality, and relationship to behavior suggested that the sounds were used in specific ways: the higher frequency sounds appeared to be for communication with nearby finbacks, the 20-Hz single pulses seemed to be used for both local and longer distance communication, the patterned seasonal 20-Hz pulses appeared to be courtship displays, the low-frequency rumble seemed to have surprise or agonistic significance, and the non-vocal impulsive sounds apparently were adventitious and related to surface feeding. Other sounds and behaviors were not as well defined or repeated enough for such analysis. Mechanisms of sound production, the effect of the environment on the low frequency sounds, the propagation of these sounds, and the relationship of the sounds from similar whale species is discussed.

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INTRODUCTION

Finback whales, *Balaenoptera physalus* (Linné, 1758), are seen world wide and their behaviors at the surface of the sea are often observed, but very little is known of their activity underwater. In this paper an attempt is made to correlate our observations to provide an interpretation of some behaviors and to relate these to the underwater sounds of finback whales. Emphasized is the population that we have studied most—the whales of the western North Atlantic, and particularly those that come close to the shores of Cape Cod, Massachusetts.

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Impressions of finback activity usually are based on the behaviors that are seen at the surface of the sea. This includes only a small portion of the whales' behavior because they are at the surface for very short periods. Behavioral interpretations, therefore, have had to be based mainly on this visible surface activity even though it may not be related directly to the whales' underwater behavior. Blows, for example, probably have little relationship to underwater feeding, resting, and social activity.

In order to reach below the surface and try to assess the behaviors of submerged whales, we utilized underwater sound. The underwater sounds produced by finbacks have been studied (since 1958) during different behaviors and in different geographical areas and seasons. Multiple hydrophones were used to separate sound arrival times in order to locate and track the sound sources and to distinguish the whale sounds from other sounds in the sea. Special techniques and equipment were required to record and study the very low frequencies (as low as 18 Hz) and the very wide dynamic ranges in the finback sounds.

New techniques often had to be developed for specific studies including the design and fabrication of special hydrophones, amplifiers, recorders and analytic equipment, quiet boat propulsion, and tagging and tracking gear. Methods were devised for study of these animals at sea—for surface and aerial photography, for broadband (including very low frequency) acoustic recording and signal analysis, for acoustic tracking underwater, and for radio tagging and tracking. The sounds from finback whales (Schevill, Watkins, and Backus, 1964) provided the stimulus for much of the early progress in design of equipment and techniques for the acoustic observations at sea.

Although the behavioral and acoustic observations in this report are largely unpublished findings, emphasis is not on detailed descriptions of events or sounds. Instead, correlations of behavior with underwater sound are made to try to outline finback acoustic behavior. The limitations of our data are recognized—the small sample sizes, the sometimes incomplete observations, the lack of supporting secondary information—but perhaps the extrapolations and the correlations that are made will provide impetus for further work and greater understanding of finback activity.

METHODS

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Observation techniques

Observations and recordings of finbacks were made in a wide variety of geographical locations, worldwide, and recordings made on bottom-mounted hydrophone systems by other researchers have been studied (including recent recordings by Peggy Edds, 1980). Our own sampling of finback acoustic behavior since 1958 has included approximately 4,000 hours of hydrophone listening and observations at sea, including the deep ocean at several locations in both the Atlantic and the Pacific as well as shallow water observations off the eastern and western coasts of the USA, in the Gulf of St. Lawrence, and off Greenland and Alaska. The Cape Cod, Massachusetts area with finbacks available year round has provided consistent opportunities for repetitive study and has allowed comparisons with these other observations. Replications of the observations of behavior with comparable underwater acoustic recordings have allowed confidence in the analyses.

A wide variety of observation platforms were utilized for study of finback activity including vessels of 15 to 75 meters (m) for pelagic work. The quieter boats consistently have been the most successful, so that we have several times used sailing ships for work with finbacks.

Aerial observations were used extensively to watch the near-surface behavior of finbacks, particularly in coastal waters around Cape Cod (cf. Watkins and Schevill, 1979). Depending on the transparency of the water and sometimes the color of the bottom in shallow water, whales have been followed visually to depths of about 30 m. The quieter, slow flying aircraft have been the most useful, flying at an altitude of 300 m for spotting and then dropping to 50 or 100 m for photography and closer inspection. Keeping the aircraft off to the side and down-wind of the animals has reduced disturbance from engine noise. Flying so that the shadow of the aircraft remained a short distance from the whales has avoided their reaction to it; the shadow often was used to measure the whales.

In protected areas near shore, small boats were particularly useful for close approaches to finback whales. Small boats with motor, sail, and oars have been used, including small 2.5-m dinghys, for taking hydrophones very near a whale. Finbacks often seemed to make closer approaches to the smaller quieter vessels than they did to larger ones.

Shore-based observations were useful for monitoring near-shore whales, and bottom-mounted hydrophones even at some distance from shore provided good information about the patterns of sound from whales in those areas. The separation of deep hydrophones from surface wave-noise, and the more advantageous sound-paths provided by deeper hydrophones often have permitted hearing sounds from greater distances. Moored hydrophones (both deep and near the surface) also recorded good sounds apparently without disturbing the whales. Although such systems did not allow direct observation, they have been useful for monitoring the occurrence of particular sounds or patterns. For example, we were able to examine in detail the continuous recording (since 1958) of low frequencies from offshore bottom-mounted hydrophones at the Bermuda Sofar station to trace the seasonal occurrence of finback sounds (cf. Patterson and Hamilton, 1964).

Comparisons of our acoustic observations of finbacks were made with those of other species in the same waters and under the same conditions. This has provided means of checking the characteristics of the sounds in relation to the effects of the environment (relative levels, sound path variations, noise backgrounds) and it has allowed assessments of the reactions of different species in a variety of behaviors. Our experience with the underwater sounds of more than 60 species of marine mammals has provided a good base for comparison. Ten or more species of cetaceans are available in local Cape Cod waters. Most often seen are *Balaenoptera physalus*, *B. acutorostrata*, *Megaptera novaeangliae*, *Eubalaena glacialis*, *Lagenorhynchus albirostris*, *Lagenorhynchus acutus*, *Phocoena phocoena*, and less often *Balaenoptera borealis*, *Globicephala melaena* and *Orcinus orca*. The effects of different seasons and environments have been noted, and when possible, we have tried to trace the movement of populations and individuals.

Near-surface activity of the whales was documented by photography whenever possible. From ships, a close scrutiny of behaviors often was possible, but because of low angle reflection off the surface, usually only the portions of the animals above water were visible or able to be photographed (Fig. 1). Correlation of acoustic data with the visible surface activity was attempted from the ship observations. Aerial observation usually allowed a better (higher angle) view of the whales underwater, and polarizing filters on the camera lenses often were used to reduce the effect of surface reflections. We tried to combine surface and aerial glimpses (sometimes from simultaneous observations) to provide a coherent picture of finback whale behavior.

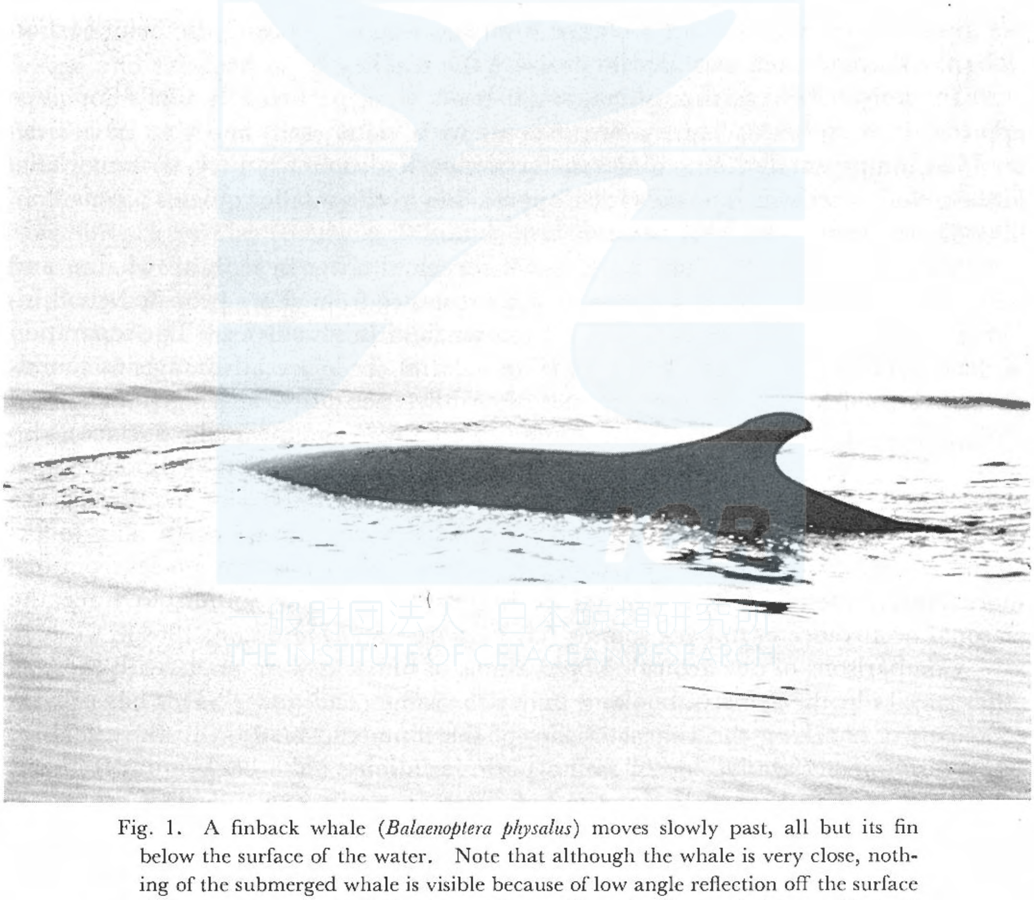

Fig. 1. A finback whale (*Balaenoptera physalus*) moves slowly past, all but its fin below the surface of the water. Note that although the whale is very close, nothing of the submerged whale is visible because of low angle reflection off the surface of the water—typical of ship observations. Photo by Karen E. Moore, 26 April 1977. Cape Cod Bay.

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Sound systems

Because of the potential of reaching below the surface with sound to learn more about the animals, we have emphasized acoustics and developed sound systems especially for work with finbacks.

(a) Hydrophones were developed for receiving the very low-frequency sounds associated with these whales. Broadband systems (to 200 kHz) also were designed to make sure that we were able to record the entire spectrum of their underwater sounds. Wide dynamic ranges were required to avoid overload distortion from the relatively loud sounds, as well as to receive low-level vocalizations. Many different systems were successfully utilized including large rochelle-salt crystal units, magnetostrictive hydrophones, variable-reluctance plate and moving coil detectors, and small ceramic sensors (barium titanate, lead zirconate titanate, lithium sulphate monohydrate).

(b) Cables of different lengths allowed the hydrophones to be floated away from the ship to separate the sensors from the noise of waves against the vessel, and to be suspended deep enough to reduce noise from the sea surface above the hydrophones (Watkins, 1966). To keep wave noise low and to allow for drift compensation, long cables often were paid out to keep the hydrophones stationary in the water as the ship drifted. Cables as long as 1 kilometer (km) or more sometimes were used. Impedances of the cables, therefore, had to be sufficient to allow for the variety of lengths so that both good low frequency and good high frequency response could be maintained. Motion of the cables and hydrophones was damped by a variety of methods, such as by using floats to support the cables in self-damping catenaries.

(c) Amplifiers for boosting signals to proper recording levels were chosen according to the requirements of the hydrophone system (bandwidth, gain, and dynamic range). Low-noise and low-distortion systems were emphasized. Impedance-matching and cable-driving amplifiers were located as close to the hydrophone sensors as possible.

(d) Recorders were designed to register the important sounds that were received, and they were made portable so that work from small boats was always possible. High quality recording equipment was used in calibrated systems to be sure of consistent, repeatable sound recordings. Bandwidth and distortion adjustments were made to achieve the best recorded spectrum for the sounds (often a different adjustment for the low-frequency finback vocalizations than for broadband sounds). Mechanical stability and constant tape speed were maintained in the recording systems for faithful reproduction of low-frequency sounds. Practical power-supply systems used rechargeable battery packs, not dependent on ship's power.

(e) Monitors that provided good quality sound reproduction were used to check on recording excellence. These were power amplifiers with speakers or headphones that allowed good response to broadband signals and visual monitors that provided accurate indications of relative signal levels over the recording spectrum. Signals out of the range of our (human) audible spectrum, as were many of the finback sounds, were monitored with special systems (oscilloscope, pen recorder, heterodyne converter). Signals were assessed immediately after recording (separate recordings and playback systems) so that the recorded sounds could be compared realistically with sounds as heard before they passed through the recorder.

A practical arrangement of this sea-going listening system worked well with finback sounds from a ship (Watkins, 1966; Watkins and Schevill, 1971). The hydrophone, connected to a long cable, was suspended from a visible buoy at the surface. The cable was supported by floats at intervals adjusted to allow maximum distance from the ship and reduction of wave motion on the hydrophone. The depth of the hydrophones was kept shallow enough (7 to 30 m, often 15 m) to try to restrict the listening range to only local animals. This was possible because in warm weather the surface waters of the open sea during daylight often had downward refraction of sound.

A typical sequence of events at sea during observations of finback whales and the recording of their underwater sounds usually included the following: (a) Whales were located. (b) Their surface behavior was observed. (c) The ship was maneuvered, with as little underwater noise as possible, to be near the whales, to drift past them or to be in their path. (d) The ship was silenced—all machinery stopped. (e) Hydrophones and cables were put out quietly. (f) Observations were correlated by time and running commentary on tape. (g) Patterns of underwater sounds and surface behavior were followed as long as possible. (h) As the whales moved out of acoustic and visual range, the hydrophones were pulled in and the ship moved as unobtrusively as possible to a more favorable position to resume the observations. Sequences of four hours or more have been possible.

Array of hydrophones

Arrays of hydrophones were used successfully to locate and track whales producing sounds underwater. A three-dimensional track of successive sounds was provided by means of a floating 4-hydrophone arrangement (Watkins and Schevill, 1972). Each hydrophone was recorded on a separate tape channel, and relative hydrophone positions were calculated from pinger sounds in the water. Sound arrival-time differences at each hydrophone were used to calculate the locations of the hydrophones as well as for the underwater sound sources. When the sound sources were nearby, accurate three-dimensional underwater positions were possible, but at a distance only direction and depth vectors were available from the array analysis.

Linear towed arrays of hydrophones also were used effectively to locate finbacks with only two hydrophones separated by 100 m or more. By maneuvering the ship, thereby changing the orientation of the array, relative direction to the sound source could be determined. Two or more hydrophones also were useful in distinguishing these low-frequency finback signals from noise. Local wave noises usually registered on each hydrophone separately, while whale sounds were heard on all hydrophones, delayed according to relative direction and sound-path differences.

All of our recordings were made broadband at sea, with as wide a recording spectrum as possible. Then, in the laboratory, the sounds were analyzed for their component parts. Filters to reduce wave-noise interference during field recording were not used because of the potential modification of higher-frequency signal components by the lower-frequency filtering. To study relative time patterns and amplitude relationships of finback sounds, oscillographic and continuous spectrographic analyses, and computer time-series analyses were used. Frequency patterns and spectra of sounds were assessed by sound spectrographs, computer Fourier transform and power spectra analyses, and frequency analyzers.

During our acoustic observations of finbacks, the whales generally have not appeared to react negatively to our presence as long as we utilized relatively silent, unobtrusive arrangements. We have therefore carefully tried to keep our ship quiet during listening sequences with as little splashing as possible and no engine or machinery noise. We have also tried to reduce the visual effect of our underwater equipment with blackened housings and dark lines to avoid light reflections. During close approaches by finbacks to our ship or cables, the animals have reacted when they suddenly appeared to notice the objects and turned away sharply or suddenly stopped their activity and left the area. The degree of their avoidances has seemed to depend on the whales' previous behavior. When the whales were active socially or feeding, they seemed to take little notice of our presence. When not obviously preoccupied, they generally could not be approached closely and would move cautiously away from even a silent drifting ship.

Radio tracking

Radio tagging and tracking of whales (Watkins and Schevill, 1977b; Watkins, Wartzok, Martin, and Maiefski, 1980) has given good confirmation of behaviors noted in other ways, as well as providing much new information about finbacks. Tagging has been particularly needed for finback whales since it is difficult to distinguish individuals of this species. The radio tags provided positive individual identification that was not dependent on visibility or weather. The tags were remotely implanted in the blubber so that they remained in place for several weeks. The whales did not react negatively to the tag implantation, but they sometimes reacted to the sounds of the tagging boat (Watkins, in press). Tagged finbacks returned to " normal " behavior within a short time after tagging, and they appeared not to notice the tags or the tracking boats as long as the boats did not come close. Finbacks were tagged and tracked in protected waters of the St. Lawrence River, Canada (Ray, Mitchell, Wartzok, Kozicki, and Maiefski, 1978) and in Prince William Sound, Alaska (Watkins, Johnson, and Wartzok, 1978; Watkins, Moore, Wartzok, and Johnson, 1981), and in the open sea between Iceland and Greenland (Watkins, 1981). The longest sequence of radio tracking one finback whale was 28 days, in Alaska (Fig. 2). The greatest distance covered in one track was 2.095 km during 10 days in the Atlantic (Fig. 3). Throughout these tracks, behavioral changes seemed to depend on the whale's activity, participation with

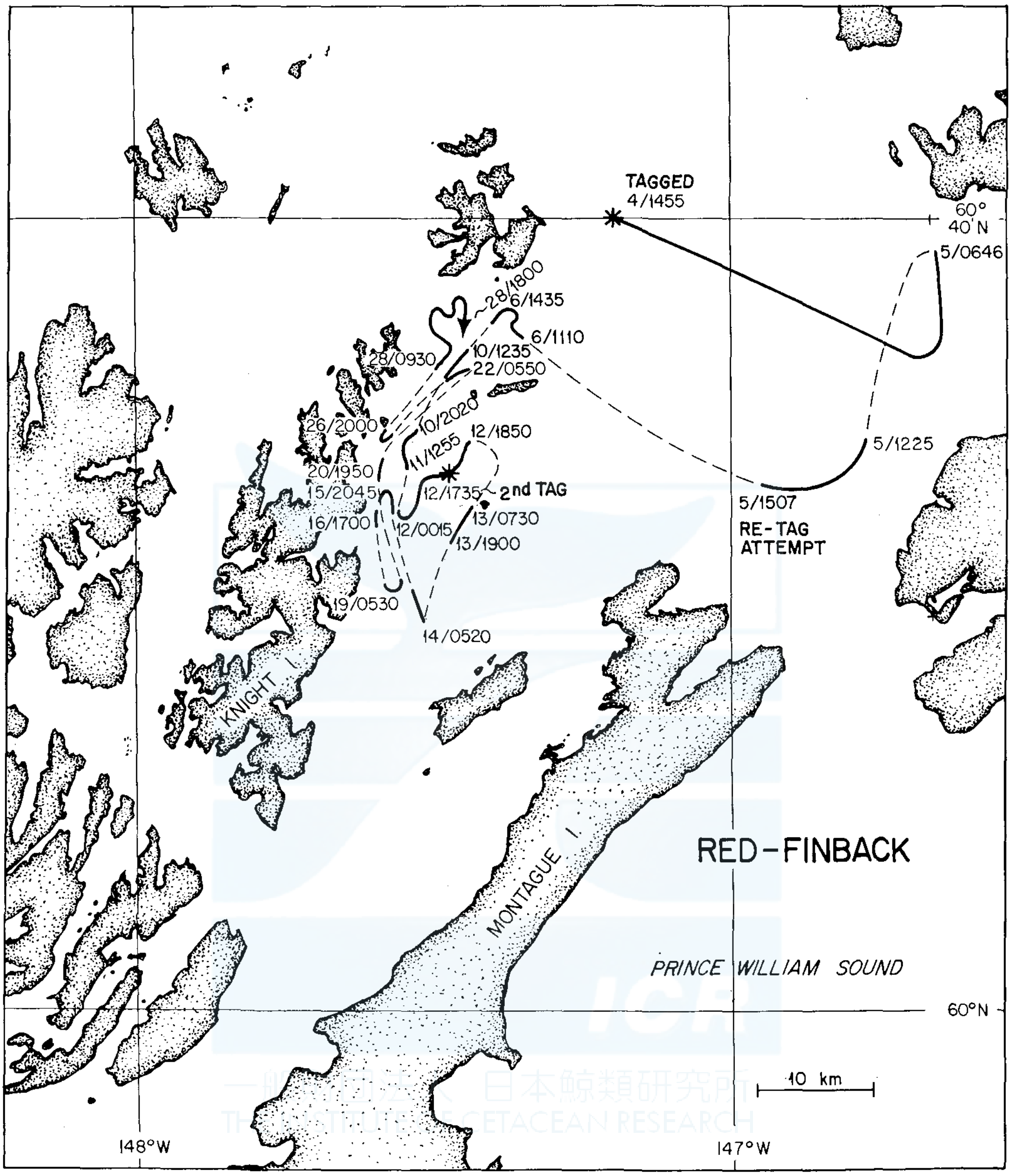

Fig. 2. The track of a radio-tagged finback whale in Prince William Sound, Alaska, June 1978, demonstrated this whale's preference for one particular part of the Sound for 28 days. This whale was not tracked continuously, but the radio signals indicated long dive routines (11 to 12 min) during much of the day and a change at dark to near-surface behavior (Fig. 2 in Watkins, Moore, Wartzok, and Johnson, 1981, courtesy of Deep-Sea Research). Solid lines indicate periods of continuous tracking. " Red " refers to the color of the streamer on the tag.

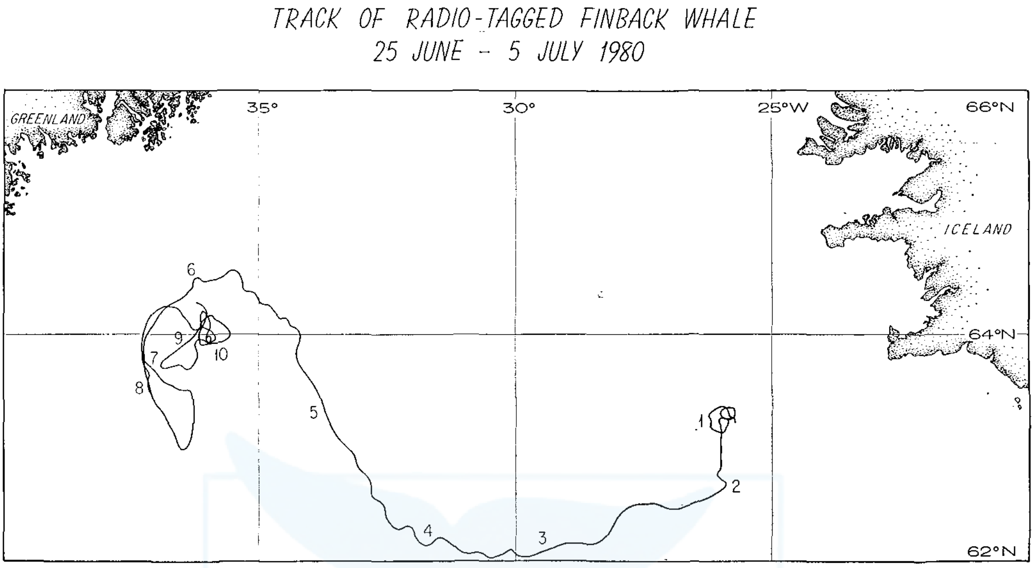

Fig. 3. A finback whale that was radio-tagged off Iceland was tracked continuously for ten days, June-July 1980. The whale travelled 2095 km during this period, and as much as 292 km in one day, 1 July. The tagged whale was with one to seven other finbacks for most of the time, and behavior varied throughout the track. The whales fed on krill off Iceland, then left that area and fed on schooled small fish off Greenland during the last four days of the track off Greenland (Fig. 6 in Watkins, 1981).

other whales, and the activity of their prey. During some behaviors the finbacks were easily identifiable at the sea surface, but during others not enough of the whales' bodies was visble (for hours) to permit recognition (the presence of any whales) without confirmation from the radio-tag signal.

Our observations of finback whales have not been systematic in any locality, but they have been more frequent in waters around Cape Cod. Generally, these whales were noted and observed as they were encountered during cruises that often were designed for other work. However, we have consistently prepared acoustic equipment that could record finback sounds well on all cruises. Most observations have been in waters of less than 200-m depth within 25 km of shore. Although some authors have considered that finbacks are mostly an offshore species (Nishiwaki, 1972, p. 22) their occurrence nearshore often has been noted (c.f. Allen, 1916). Our observations from aircraft have mostly been during the spring, and generally in relatively good weather. Our few opportunities to observe these whales in bad weather have indicated that the whales take little notice of the sea conditions so that their behaviors have remained about the same as in calmer water. The locations for the observations of finback behavior noted below are in the Cape Cod Bay and Massachusetts Bay area (roughly bounded by 41°40′ to 42°40′ N, and 69°30′ to 70°40′ W); otherwise specific positions are given.

Correlation of observations

The descriptions of behavior and sounds below are generalized to focus on the apparent correlations, both negative and positive. In each activity, there was a wide spectrum of variation—the broader our opportunity for observation, the larger the apparent variability. By noting the norms, we hope that the basic patterns of underwater sound and activity will be seen.

To put the observations in perspective, some of the general conditions of sound production by finbacks are given, then routine behaviors and associated sounds are identified, and the sounds are related to behavior. As more is understood of the underwater activity of finbacks, more behavioral and acoustic patterns can probably be recognized.

RESULTS

General observations

The obvious activities of these whales fell into a few routine behaviors and there were some specific underwater vocalizations. Definite associations of the underwater sounds (both positive and negative correlations) could be made with specific activities.

Finback activity is categorized below in a few of the most obvious behaviors: (1) Blowing at the surface was the most visible behavior. (2) Short (2–6 min) dive routines generally were the most common activity. (3) Long (6–14 min) dive routines were apparently related to feeding underwater. (4) Near-surface slow swimming seemed to be a " resting behavior ". (5) Rapid travel near the surface was characteristic of whales in transit. (6) Surface feeding on schooled fish was easily visible. Other behaviors were less frequent or less identifiable. There was a continuous gradient between types of behavior, of course, but the categories listed here appear to be representative, and they occupied the whales for long enough to be apparently distinct.

Underwater sounds from finback whales also are categorized for reference: (1) " Higher frequency sounds " included a variety of vocalizations from approximately 100 Hz to 30 Hz, most sweeping downward in frequency. (2) The " 20-Hz pulses " produced both as single pulses and patterns of repeated pulses also mostly had downward sweeping frequency, near 20 Hz and often quite stereotyped. (3) " Ragged low-frequency pules " were short, broadband pulses often with low frequency emphases. (4) " Low-frequency rumbles " were longer duration, broadband sounds below about 30 Hz. (5) Sharp impulsive sounds did not appear to be vocalizations but were characteristic of certain behaviors.

When finback whales were found completely alone, separated apparently by 20 km or more from any other finback, no vocalizations were heard. On the other hand, when underwater sounds were heard from a finback, other finbacks have always been found within a few km. Even in company with other finbacks, however, these whales were silent much of the time. The underwater vocalizations of finbacks appeared to be produced voluntarily, and sometimes could be correlated with specific behaviors. These sounds seemed to be noticed by other finback whales.

Finback whale activity

Blowing at the surface during respiration was the most visible activity of finbacks. A general description of the surface behavior of finbacks was given by Andrews (1909) and Mackintosh and Wheeler (1929), including blow series. The whales seldom appeared at the surface without blowing 1 to 20 or more times. During respiration, the whales generally lifted the blowhole well out of water. Sometimes, however, only a small portion of the whale was visible during respiration, with only the prominence around the blowhole out of water, as seen in the radio tracking experiment off Iceland, (Watkins, 1981). During some activities the radio

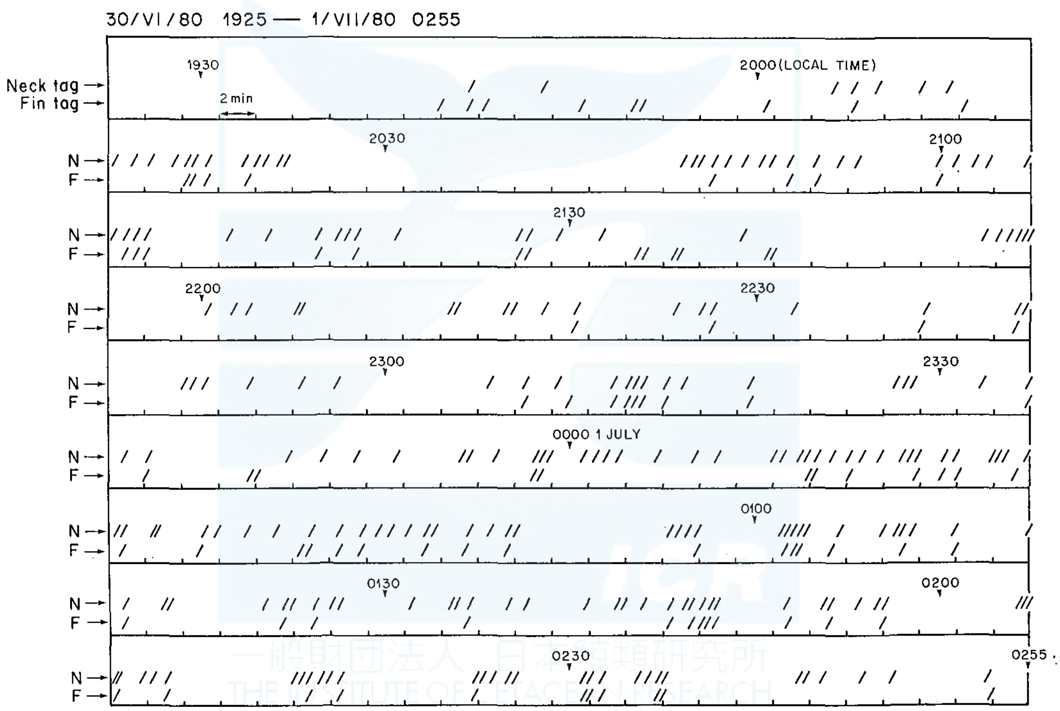

Fig. 4. Signals from the two radio tags on a finback whale are plotted from 1930, 30 June to 0255, 1 July 1980 during the continuous track from Iceland to Greenland (Fig. 3). Signals from the tag at the base of the fin (F) are shown as the bottom line of each row and those from the tag on the whale's neck (N) are shown above. Each slanted line represents a set of signals during one surfacing, 0.5 to 2 sec or longer. The back (neck) tag was exposed much more often than the fin tag, and these signals correlated somewhat with breathing. During this period, the whale averaged one exposure of the back tag in 1.85 min (233 signals/430 min). Sometimes the whale blew without exposing the tag, and occasionally signals were received although the whale did not breathe (Fig. 7 in Watkins, 1981).

tagged whale and its one to seven companions exhaled underwater and then only inhaled when they surfaced, producing no visible blows.

The time between blows in a series was variable, with intervals of 5 sec to 2 min or longer, apparently depending on the whale's exertion and interest in other behaviors. Often the first few and sometimes the last few blows of a series were separated by the least time.

Over periods of a few hours, finbacks generally have averaged about one blow for 1 to 2 min of dive-cycle (total dive time plus surface time). Radio tagging experiments have provided long enough observations of identified whales to be able to follow their respiration patterns (Fig. 4; Ray, Mitchell, Wartzok, Kozicki, and Maiefski, 1979; Watkins, 1981; Watkins, Moore, Wartzok, and Johnson, 1981). Blow sequences for individual whales sometimes were consistent, apparently varying with the level of exertion. Individual whales often had slightly different respiration rates and differences in blow characteristics though participating together in the same activities. The apparent effort connected with finback blows also varied. The first blow of a series, especially after a longer dive, often was more intense than the following blows, louder in air, with a more " explosive " beginning and a higher visible plume. Later blows in a series seemed to be much more relaxed.

Finback whales usually swam forward while blowing, and generally the back was lifted well out of water during each blow. In still water, sometimes only the raised area around the blowhole was brought above the surface so that the forward motion of the whale directed the water flow around and away from the open blowholes. When combined with other near-surface activities, the whale's surfacing, the attendant forward motion, and the blow-all often weve accomplished very rapidly. In finbacks, the exhalation generally has lasted about one sec, slightly longer than the subsequent inhalation, and the blowholes were opened less widely during exhalation, producing more sound in air (turbulence). Inhalation with very widely opened blowholes has consistently been almost inaudible. Just before a dive, particularly before longer or more hurried dives, the finbacks usually have " rounded-out ", and raised their backs high as they began a dive.

During " normal " blowing, there generally was little water disturbance or splashing as finback whales surfaced to blow and then submerged. The whale's surfacing and submergence usually has been slow and smooth, even in rough water. The tip of the whale's rostrum usually remained below the water and their flukes seldom appeared at the surface.

It was not surprising, therefore, that very little underwater sound was ever heard during respiration. Neither the movement of the whale's body at the surface nor the whale's blows produced much sound underwater. The slight splashing sounds of the whale's body moving at the surface usually were less than the sounds of local wavelets. Occasionally a whale produced a cough-like sound in air from the blowhole or restricted the lips of the blowhole to form more prolonged air turbulence during exhalation. This was more audible both in air and underwater than the sounds of normal blowing. In finbacks, these sounds have not appeared to be produced purposefully, in contrast to other species, such as humpbacks (*Megaptera novaeangliae*) that produced apparently purposeful blowhole sounds used for underwater signalling (Andrews, 1909; Watkins, 1967).

Dive routines (whale submerged between blow series) were of two types distinguishable as separate, somewhat stereotyped behaviors-short dive of 2 to about 5 or 6 min and longer dive of 6 or 7 to about 14 min. The separation of these routines at 6 min is artificial but at about 5 to 7 min the behaviors usually changed character as the whale shifted from one dive routine to the other. Generally, several whales in an area participated in the same dive routines for prolonged periods (hours) at a time. Some of the intermediate length dives (5 to 7 min) and short dives of less than 2 min were not characteristic of the short or long dive routines, but often appeared to be indicative of transitional behaviors.

Short dive routines of approximately 2 to 6 min were the most common activity noted in finback whales. During short dive routines the whales blew only a few (2 to 8) times between dives and often these blows appeared to be quite unhurried. Between blows of a series, the whales generally moved slowly near the surface. During short dive routines the whales appeared to travel underwater for only short distances, usually only 100 to 500 m during each dive. There was little observable pattern to locations of successive surfacings, although surfacings sometimes were along a line of bathymetric features. Generally, even though all the finback whales visible in an area participated in the same short dive routines, their surfacings normally were not synchronized. Whales were separated by 200 m or more as they moved slowly across an area, often all making some progress in the same direction, but on seemingly random courses. Thus, over several hours, during short dive routines a group of two or more finbacks would progressively cover a wide area.

Both the higher frequency sounds and a few 20-Hz pulses (described below) were heard occasionally from finbacks during short dive routines, but there was no particular sound sequence that characterized this behavior. The calls heard during these times were no different from sounds heard during most other behaviors. The higher frequency calls were the most common, usually without obvious response from another finback. They occurred irregularly, averaging about one sound per half-hour recording. In addition, occasional 20-Hz single pulses and ragged 20-Hz pulses sometimes were heard. Few vocalizations (often none) were heard during short dive routines.

Whales participating in short dive routines in an area appeared to be in contact with each other since changes in behavior were observed as shifts in the activities of all the whales. A group of finbacks usually remained within 1 to 3 km of each other, although moving about apparently quite independently.

Long dive routines were dives of 6 to 14 min or longer. Because the dives were longer, they appeared to require more exertion than the shorter ones, evidenced by the greater intensity of the blows that followed long dives (c.f. Andrews, 1909). During long dive routines finback whales usually blew 6 to 14 or more times in a series with the first blows relatively intense (see above) and separated by short intervals. Sometimes at the whale's surfacing, their mouths were seen to be slightly open with water flowing out through the sides of baleen (nomenclature after Williamson, 1973). Occasionally after a long dive, their throats were enlarged with ventral grooves expanded indicating that the whales had been feeding (Watkins and Schevill, 1979). After the last blow of a series, the whales rounded-out quite high and dove steeply to begin another long dive. This was usually accompanied by prominent fluke disturbances on the surface of the water (" foot-prints " made by the upward thrust of the flukes) as if the whale were in a hurry to get back down (cf. Gunther, 1949). From aerial observations, this could be seen clearly. Although several whales were diving in the same area, they usually surfaced seprately after long dives.

Underwater vocalizations of both the higher frequency calls and occasional 20 Hz pulses were heard from finbacks more often during long dive routines than during the short dives. As in the shorter dive routines, there were no particular sound sequences that characterized this behavior. Although both types of calls were heard, the higher frequency sounds were the more common. Compared to the blows following short dive routines, the vigorous intense blow after long dive routines produced slightly more sound underwater and the water splashes also were more audible as the whale moved more rapidly at the surface.

When several whales dove together in long dive routines near each other, there were likely to be underwater vocalizations, particularly those of higher frequency, sometimes in sequences of 5 to 10 sounds, and produced by more than one whale (different sweep rates). Consistently, when two or more whales were in a long dive routine near each other, the occurrence of underwater sounds was likely.

Near-surface slow swimming behavior of finback whales (less than 1 km/hr), was often within only 10 to 20 m of the surface and was especially visible from the air. In this activity, finbacks blew at irregular intervals of one to four min often with only one or two blows per surfacing, usually with very little of the body visible above water. The whales swam slowly and travelled along a meandering track. Sometimes two or more whales were seen to move slowly in this near-surface behavior, often 100 m or more apart but sometimes within 15 m of each other. There was no obvious interaction with their companions, and they seemed to ignore passing boat traffic that probably would have disrupted many other behaviors. This slow swimming activity continued for periods of 10 to 30 min or longer, and did not occur at regular intervals. Underwater vocalizations were not heard from finbacks during this near-surface slow swimming behavior.

Rapid travel near the surface was typical of finbacks in transit. Often they moved along relatively straight courses and at relatively constant speeds (10 to 16 km/hr) for prolonged periods. The radio tracked whale between Iceland and Greenland (1980) continued this behavior for most of four days. Sustained speeds of 20 km/hr or more have been observed for at least 20 minutes (from the air three whales were followed for 7 km, 1 May 1975). Blows during rapid travel were sometimes at quite regular intervals, especially in calm seas, of 30 sec to 4 min or longer. In rough seas, the whales seemed to blow as they had opportunity in deeper troughs between seas. Finbacks travelling rapidly often rose relatively high out of water when blowing, sometimes cutting the surface of the water with the forward part of the jaw (chin) and rising high enough so that ventral grooves were visible. Once from an aircraft we saw a large finback travelling very rapidly whose body arched completely out of water in a " porpoising " leap as it blew (Cape Cod Bay, 26 April 1974).

Up to six finback whales have been seen swimming rapidly together, spaced at least 15 m apart and blowing within a short time of each other. One such group was observed (1 May 1975, 35 km N. Cape Cod) swimming 12 to 15 km/hr. They were continuously visible from the air as they swam at 5 to 10-m depths heading toward a large group of feeding finbacks 10 km away (Watkins and Schevill, 1979).

Underwater sounds of rapid swimming were noticeable only during calm sea conditions and consisted mainly of splashing sounds at the surface. Low-frequency rumble vocalizations (see below) also were heard occasionally when travelling whales passed very close to our ship (Fig. 5). The rumble was a vocalization and not a hydrodynamic sound.

Near-surface feeding behavior on schooled fish (Nemoto, 1970, Tomilin, 1957; Watkins and Schevill, 1979) had distinctive components that varied with the finback whale's prey, but the behaviors included the common elements noted below.

Fig. 5. A finback whale approaches to dive and pass beneath our boat while producing a low-frequency rumble sound (as in Fig. 11). Photograph by Karen E. Moore, 12 June 1980, Cape Cod Bay.

Near-surface feeding sometimes followed a period of short diving but did not appear to be related to long dives or to near-surface slow swimming activities. The schooled fish were chased in the surface waters by the whale. Often it was possible to watch this behavior for long periods from an aircraft. Typically, after reaching its prey, the whale moved through the schooled fish, mouth opening and closing to engulf prey and water. The whale opened its mouth as it reached the fish school and reduced its swimming speed as it closed its mouth. The ventral grooves of the finback were expanded with the large mouthful (Fig. 6) (Ingebrigtsen, 1929; Gaskin, 1976; Watkins and Schevill, 1979). When at the surface, water could be seen to flow through the sides of baleen as the throat region shrank in size. Most passes by feeding finbacks through fish schools were with the body parallel to the surface so that little of this behavior was visible from ships. Usually only a portion of the whale's back and fin and sometimes part of the head were visible above the surface. Occasionally, as the whale turned sharply onto its side in pursuing the fish school, a fluke and flipper were visible above water as well (Gunther, 1949, p. 124).

All of the whale's orientations during feeding—on the side, upside down, or

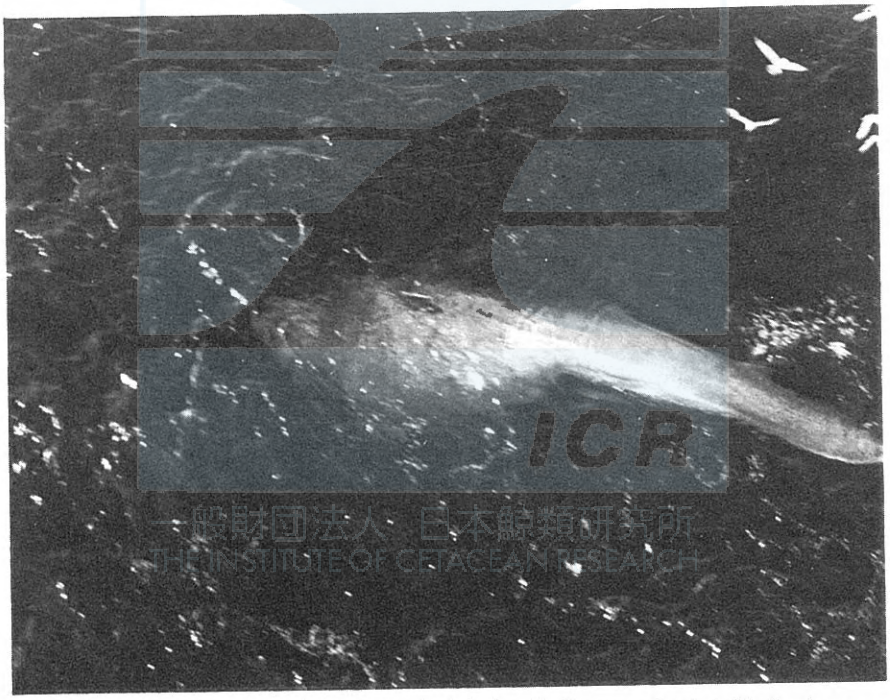

Fig. 6. A finback whale is photographed during feeding on schooled fish (perhaps *Clupea harengus*). Although feeding usually is with the back uppermost, the whales sometimes turn on either side in order to chase active prey. The whale seems to be able to change direction more rapidly by turning onto its side. Note the expanded ventral grooves allowing the whale to swell to about twice its diameter (Fig. 1 in Watkins and Schevill, 1979, Courtesy of Journal of Mammalogy) Photo by Watkins, 29 April 1976, 10 km north of Cape Cod.

even vertical—were related to the mobility of the prey. From long-term aerial observations, it was obvious that the whales chased schooled fish and followed the school in all directions. Side swimming seemed to allow the whale to turn rapidly in either direction by strong horizontal fluke movements. The whales often turned on their sides at the end of a feeding pass as they rapidly changed course. Whales were seen swimming on either their left or right sides, and sometimes they followed a fish school down and back up so that the whales were inverted with ventral grooves uppermost as they opened their mouths. Side swimming during feeding sometimes was visible at depths greater than 20 m and obviously was not related to feeding near the surface. Against a light colored bottom, we have watched from the air as finbacks dove and twisted and turned, apparently chasing schooled fish near the bottom in water depths to 30 m. Feeding activity that included side swimming at the surface often was conspicuous from the ship observations because of the splashing of flukes and flippers (noted by many authors, cf. Andrews, 1909; Tomilin, 1957), while the usual feeding passes with the whale's rostrum parallel to the surface generally was not identifiable except by aerial observations (Watkins and Schevill, 1979).

With some highly mobile prey, finbacks dashed at the surface of the water to catch a fish school. During this behavior the finbacks burst through the surface of the water at low 20 to 30-degree angles, often with considerable splashing. Sometimes the mouth was opened so that the sides of baleen cut the water as the whale moved forward at the surface. Sometimes also, during hard chases, a small (30 to 50 cm) disturbance like a gas bubble appeared behind the whale as it surfaced.

No vocalizations that could be related to hunting, chasing, or feeding were heard from finback whales. Frequencies to 500 kHz have been monitored and no vocalizations have been found during feeding. Nothing resembling echolocation signals was ever heard. During feeding at the surface on schooled fish, however, the sequence of splash sounds were characteristic of that behavior. In addition, there often was a sharp impulsive sound that coincided with the opening of the whale's mouth just at the surface of the water. Prior to the arrival of the whale at the surface, occasionally there also was a loud impulsive sound that preceeded the appearance of the bubble at the surface. Although these sounds apparently were not vocal, the combination of sounds connected with such surface feeding provided distinguishing acoustic indications of the whale's behavior.

Other finback behaviors also were partially visible at or near the surface. Such activity included social behavior, possible courtship routines, cow-calf behavior, and relatively short diving activity. These were variable, transient behaviors that were sometimes mixed with the more stereotyped activities, particularly the shallow dive routine. Although these were mostly activities involving interaction between individuals, very few sounds were heard from these whales. So far, we have not been able to relate any of the finback vocalizations to these behaviors.

Finback Vocalizations

The higher frequency sounds produced by finback whales (Fig. 7) generally were down-

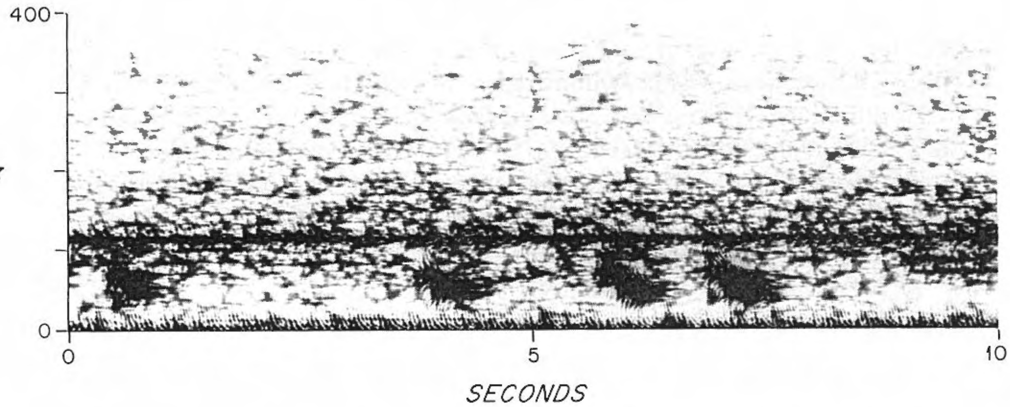

Fig. 7. A sound spectrogram of " higher frequency " finback sounds shows 75 to 40-Hz downward sweeping frequency in these sounds, generally without harmonics. The line at 120 Hz is the ship's generator. The sounds are from at least three whales and were recorded 12 September 1961, about 25 km east of Cape Cod. The filter bandwidth of the analysis was 13 Hz (Schevill and Watkins, 1962, Fig. 35).

ward sweeping pulses, many with frequencies from about 75 Hz to 40 Hz (Schevill and Watkins, 1962). To distinguish these sounds from the lower frequency " 20-Hz " pulses also from finbacks (see below), we originally called them " 40-Hz " sounds because the two could be separated by octave filters. The two sounds were not harmonically related. The " 40-Hz ", higher frequency sounds often were composed of about 20 cycles of the sweeping frequency with durations of about 0.3 sec. The level of the higher fequency sounds varied but was maximum at 55 to 60 dB (re 1 dyne/cm^2). The waveform of the sweeping frequency usually was sine-wave when recorded from nearby whales in deep water; there were no prominent harmonics. Successive pulses from individual whales had variable source levels though the sweeping frequency spectra of the sounds remained relatively constant. The received sounds were variable in duration, amplitude, and beginning and ending frequencies which were all potentially affected by multipath differences. Therefore, our descriptions are based on analyses of sounds from nearby whales in deep water.

The higher frequency sounds were the calls most often heard from finbacks during the summer season and they were heard occasionally from all sizes of adult whales (13–20 m long). These sounds were heard both as single relatively isolated calls and as repeated calls, repeated two to five or more times apparently by the same whale. When two or more whales were vocalizing, the sounds of individuals were separable by slight differences in the characteristic frequency sweep of those sounds as well as by directional differences to the sound sources. The higher frequency sounds were never repeated, unlike the 20-Hz pulse patterns (below).

Higher frequency finback sounds have been recorded during most our summer listening sessions. Our most recent recordings were in June 1980.

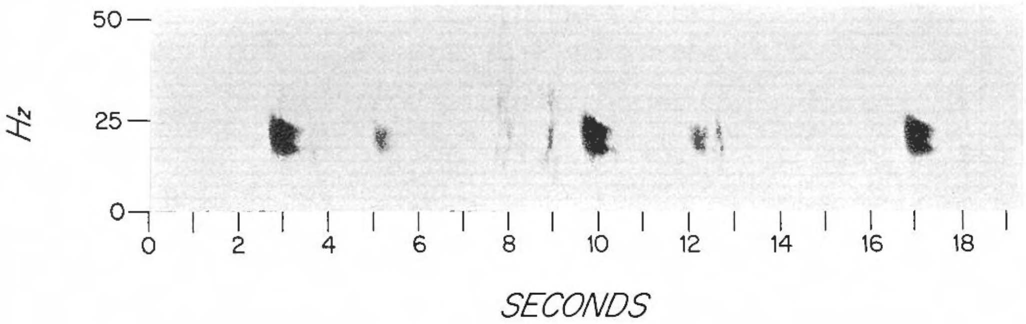

Fig. 8. A spectrogram of 20-Hz pulses from a finback shows the characteristic downward sweep in frequency, approximately 23 to 18 Hz. These sounds were in a patterned sequence of repeated pulses from one whale (at 3, 10, and 17 sec) with a 7-sec repetition rate. A second whale that was more distant also was pulsing at the same rate, and its sounds may be seen in the spectrogram (at 5 and 12 sec). The sounds were recorded 10 km north of Provincetown, Cape Cod, on 11 October 1978. The filter bandwidth of the analysis was 6.5 Hz.

The *20-Hz pulses* (Fig. 8) heard from finbacks (Schevill, Watkins, and Backus, 1964) were similar in composition to their higher frequency (" 40 Hz ") sounds, described above. The 20-Hz pulses swept downward in frequency usually from about 23 Hz to 18 Hz, and they were composed of approximately 20 cycles of the sweeping frequency with a duration of about 1 sec. The 20-Hz pulses generally were louder (than the higher frequency sounds) with maximum source levels of 75 to 80 dB, occasionally higher. The waveform of the pulses was sine-wave when recorded from nearby animals in deep water (without interference from reflections or other sound paths), and they usually had no prominent harmonics or higher frequency components. The pulses usually increased smoothly in amplitude over the first third of the sound, remained relatively constant in level during the middle third, then decreased in amplitude over the final third of the pulse. Successive pulses in a series had variable source levels although the location and orientation of the whales producing the sounds were not changing (demonstrated particularly by multiple hydrophone recordings, 11 October 1978).

Unlike the higher frequency sounds, the 20-Hz pulses were heard throughout the year but particularly in the summer as single pulses and in short series of two to five pulses. In the winter season (late October to early May) the 20-Hz pulses (Fig. 9) were heard in repeated stereotyped patterns with relatively fixed intervals between pulses. Pulse intervals in the repetitive patterns varied from 6 to at least 37 seconds (6, 7/11, 8, 9, 12, 15, 10/18 were common regular pulse intervals). Sometimes the patterns were in doublet form (such as the 7 sec/11 sec and 10 sec/18 sec sequences). The stereotyped patterns of 20-Hz pulses, apparently from the same individual, could be heard for hours, with silent periods of two to four min between pulse series lasting two to 20 min. Two or more pulse patterns have been observed to be produced alternately by the same whale.

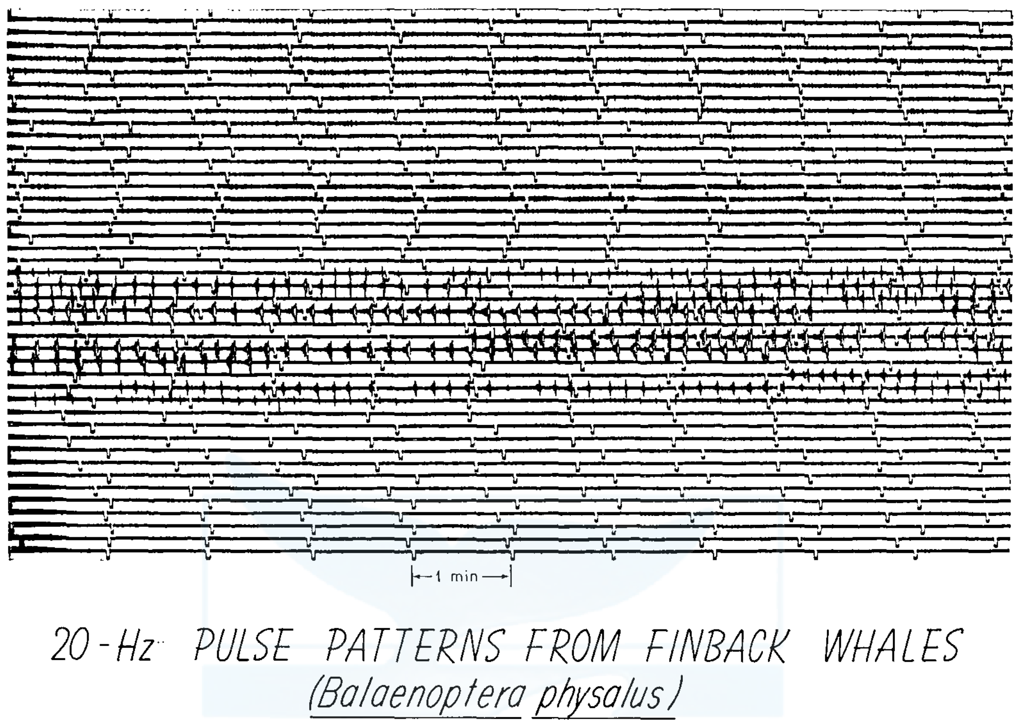

Fig. 9. A portion of a continuous drum oscillograph record shows patterned 20-Hz finback sounds recorded near Berrmuda. The sounds were from a bottom-mounted hydrophone, 12 December 1979 (courtesy of the Sofar Station, St. Davids, Bermuda). The signal was filtered 40 Hz, low pass. Markers on the record are at one min intervals. The record was continuous, three lines to one hour, so this sequence lasted approximately two and three-quarter hours. Note the periodic short break in the pattern of about two min, typical of the patterned 20-Hz pulse series. The breaks in the pattern do not necessarily coincide with breathing.

The 20-Hz single pulses and 20-Hz pulse patterns have been recorded at sea from ships since 1958, and arrays of hydrophones were used to locate the pulsing whales (our latest opportunity was 11 October 1978, in Cape Cod Bay). In addition, aerial observations were correlated with bottom hydrophone recordings to relate sound sequences with the occurrence of finback whales (as in tests off Halifiax, Nova Scotia 1961; Schevill, Watkins and Backus, 1964). Analyses of long-term records from bottom-mounted hydrophones such as the Bermuda Sofar recordings (1958–1980) have confirmed pattern variations. Comparison of recordings from other bottom systems at a variety of locations have shown the seasonality and geographic distributions of the pulse patterns from finbacks (including our own work off Maine and California; that of Walker, 1963, off Massachusetts; the southern Norwegian Sea by Weston and Black, 1965; New Zealand by Kibblewhite, Denham, and Barnes, 1967; the central Pacific by Northrop, Cummings, and Thompson, 1968; and Northrop, Cummings and Morrison, 1971).

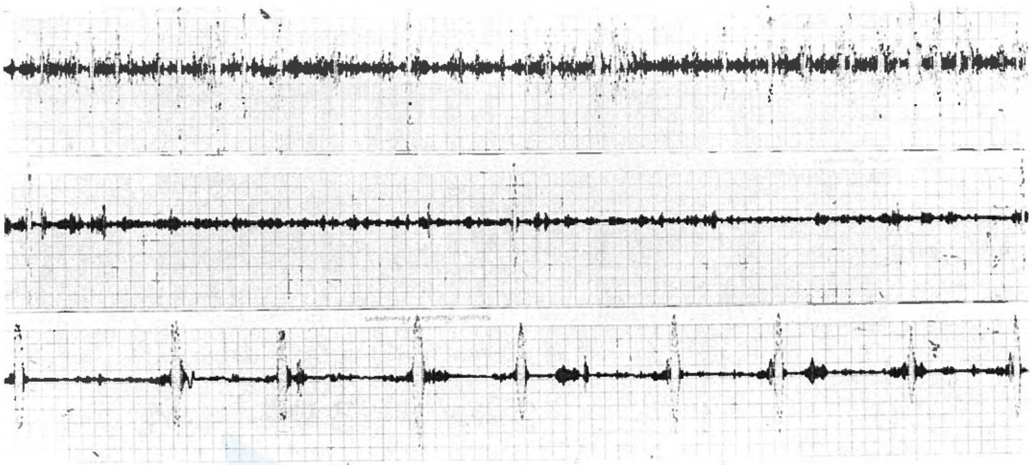

Fig. 10. Three types of 20-Hz pulses are compared in the oscillographs; pulse pattern (top), single pulse (middle), and ragged pulses (bottom). All three were recorded within one hour from the same group of whales on 14 September 1961, north of Race Point, Cape Cod. The regular pattern (top) is at an 8-sec rate within a pair (doublet) of pulses and 10 to 12 sec between pairs. The three " single " pulses (middle) are 39 sec and 37 sec apart. There apparently were several whales producing the ragged pulses (bottom), while the patterned and single pulse series were each from one whale.

Ragged low-frequency pulses also were heard from finbacks. These sounds had a relatively broadband spectrum below 30 Hz, somewhat similar to the low-frequency rumble (below), and they also had narrowband components at particular frequencies, often with 20-Hz emphasis. The pulse durations were variable from short bursts of less than 0.1 sec to defined pulses of about 1 sec. The ragged pulse envelopes were highly variable, with maximum level of the sounds about 40 dB (re 1 dyne/cm^2). Because of similarities in spectra, ragged pulses may be short segments of the " low-frequency rumble ". The ragged pulses appeared to be easily masked by wave noise. These finback pulses are compared in Fig. 10.

The ragged low-frequency pulses were recorded during many encounters with finbacks, but were particularly noticeable in the winter season, often before or after a patterned series of 20 Hz pulses. The ragged pulses were recorded from within 1 m of a finback trapped by low water near Brewster Mass., 27 May 1963 (Schevill, Watkins, and Backus, 1964).

The *low-frequency rumble* is hard to describe because it often was partly masked by local wave noise. The sound was a broadband noise sequence with energies concentrated below 30 Hz, much like the ragged pulses mentioned above. Amplitude peaks in the sound were distributed somewhat randomly throughout the sound (Fig. 11), which lasted from 2 to 8 sec, sometimes longer. The 20-Hz components of the sound sometimes were prominent.

Low frequency rumble sounds have been recorded during many close approaches by finback whales to our ship or our hydrophone cables. The sound was

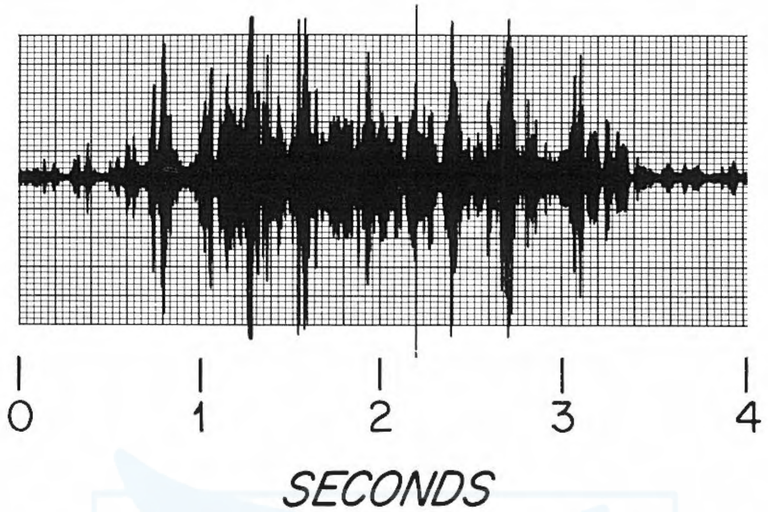

Fig. 11. The low-frequency rumble sound is heard during close approaches by finback whales. The frequency spectrum is mostly below 30 Hz with a very ragged amplitude envelope. The sequence in this oscillograph is about 3.5 sec long, and was made by one whale passing under our boat (as in Fig. 5). This sound was recorded 11 August 1961 and was one of the first rumble sounds that we noticed from finbacks, recorded at 40°27′N, 70°57′W, South of Cape Cod.

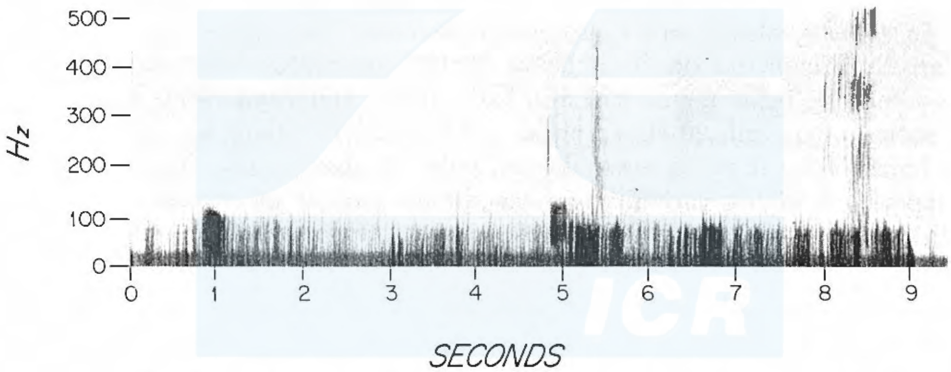

Fig. 12. Non-vocal, broadband, impulsive sounds associated with surface feeding by two finback whales are shown in the middle and to the right of this spectrogram. A "higher frequency" vocalization is seen at the left. The whales were feeding on *Ammodytes americanus* schooled near the surface, and they were recorded 23 May 1980 in Cape Cod Bay. The filter bandwidth of the analysis was 65 Hz.

first noticed during recordings at 40°30′N, 71°W on 11 August 1961, and our most recent recording of a rumble was from a finback that passed 3 m under our boat 12 June 1980 (6 km N. Race Point, Cape Cod).

The sharp *impulsive sounds* heard particularly in connection with some surface feeding behaviors did not appear to have been purposeful vocalizations. The sounds were composed of short broadband pulses with sharp rise-times, energy to at least 10 kHz and exponential decay over the 0.1 sec or less duration of individual pulses. Pulse levels were estimated sometimes as high as 80 dB or above (re 1 dyne/cm^2), but most were less. These and other impulsive sounds from finbacks have been recorded for years, but only recently have we been able to relate the sound sequences (Fig. 12) specifically to surface feeding activities (lastest recordings were June 1980, off Provincetown, Cape Cod).

None of the finback vocalizations was directional; the propagation pattern of all of these underwater sounds appeared to be omnidirectional. In addition, they did not appear to be affected by the depth of the whale producing the sounds or by the size of the whale—the same range of sounds was made by large and small whales. The sounds were not heard at the same time as a blow.

Association of Underwater Sounds with Behavior

The higher frequency sounds apparently were used as signalling between finback whales, and were heard most often during group activity. The sounds from one group were sometimes answered by similar sounds from other finbacks, sometimes at distances estimated up to 5 km. The sounds were produced by whales both at the surface and by whales diving to at least 200 m (from hydrophone array data) with no obvious differences that could be related to depth of the vocalizing whales. The higher frequency sounds were recorded in both daylight and darkness, though our night-time observations have been too limited for good comparisons. The higher frequency sounds were more prevalent in the summer, and were heard particularly when several whales were near each other and participating in long dive routines or surface feeding activities. Individuals were often silent for long periods even during group activity. Few of these higher sounds were heard during other activities, including occasional near-surface social or apparent courtship behavior.

The higher frequency sounds were not heard from whales that were apparently alone, that is, no other finbacks found within a 15 to 20 km radius. None of these sounds were heard from whales feeding by themselves near the surface, or in long dives by themselves. As noted earlier, lone finbacks usually were silent.

Similar correlations also could be made for the single 20-Hz pulses, indicating that they too were used in signalling between whales. Single pulses and short series of 20-Hz pulses apparently were utilized in many of the same situations as were the higher frequency sounds. When we were able to remain with the same group of whales for long periods it was evident that 20-Hz pulses occurred less often than the higher sounds. Like the higher sounds, the 20-Hz pulses sometimes were heard in response to similar pulses from both nearby and distant whales. We noted also that pulses from finbacks could be stimulated occasionally by the sudden introduction of a loud low frequency sound in the water, such as the starting of a ship's engine.

The patterns of repeated 20-Hz pulses were heard mostly in the winter season, and they were produced by only one finback whale in a group. With multiple hydrophones (Fig. 13) the vocalizing whale often could be located, and in every

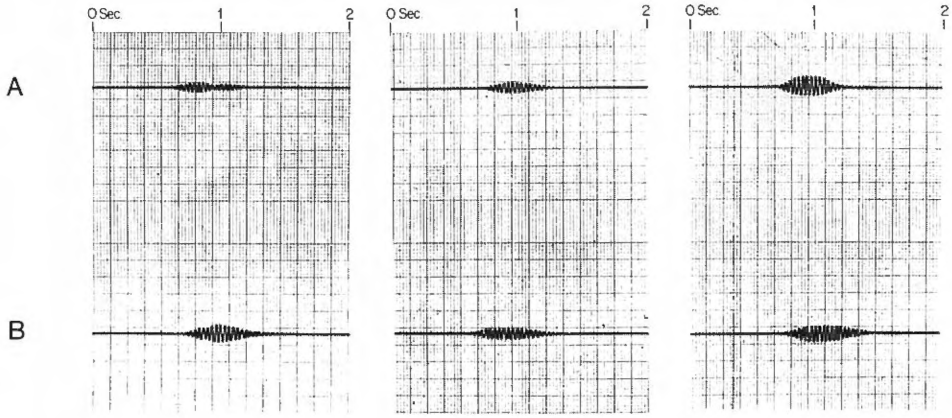

Fig. 13. A sequence of patterned 20-Hz finback whale sounds is shown in these oscillographs. The sounds were recorded on two hydrophones, A and B, separated by about 240 m. The relative position of the whale over a 20-min period is at first off the end of the array beyond hydrophone A (left), and then off the other end beyond hydrophone B (middle), and finally back nearer the first position (right). During analysis, levels were adjusted for approximately equal signal amplitudes from both hydrophones. The 20-Hz pulse pattern was continuous throughout this 20-min recording while the group of four whales appeared to be in a short dive routine. The recording was made 12 September 1961, about 50 km east of Cape Cod.

case, this was not one of the largest whales of the group. When more than one whale in an area was producing the stereotyped pulse patterns, the pulsing whales were always separated by at least 1 km. A pulsing finback was sometimes in a group of whales and sometimes was separated by a few km from other finbacks. Pulsing whales appeared to participate in shallow dive routines with other whales and the sounds continued sometimes throughout blow sequences—although a blow never actually coincided with a 20-Hz pulse. The 20-Hz pulse patterns (sequences of pulse-to-pulse intervals) from all pulsing whales within a local area sometimes were remarkably alike.

Ragged low frequency pulses often with 20-Hz emphasis also were heard from groups of whales, most often during the winter season. None of these pulses were heard from finbacks that were separated by more than a few km from other finbacks. During the winter season, the ragged sounds were heard only when there was no established pulse pattern. Although several whales in a group were heard producing these ragged pulses, the sounds usually stopped when a regular 20-Hz pulse pattern started, with little overlapping of sound types. Thus there appeared to be several sources in a group of whales for the ragged pulses and only one source in a group for the 20-Hz pulse pattern. The whales always appeared to be near the surface when the ragged pulses were heard.

We termed the low-frequency rumble a " proximity burst " on our field tapes because it usually was heard during very close approaches by a finback whale to our silent ship or a drifting hydrophone cable. The rumble appeared to be a response to the whales' unexpected encounter with these objects. The rumble also has been heard when whales passed close to each other. As with the ragged pulses, the whales were always near the surface when these rumble sounds were produced (see Figs 5 and 11).

The impulsive sounds were associated only with near-surface feeding, and when we were close enough, we sometimes saw the bubble-like disturbance break at the surface shortly after the sound occurred. This initial sound with accompanying " bubble " only occurred during very rapid, high exertion maneuvering in connection with feeding on fish schools such as herring (*Clupea harengus*) and occasionally sand lance (*Ammodytes americanus*).

Attribution of Low Frequency Pulsed Sounds to Finbacks

The association of these low frequency underwater sounds with finback whales was by means of a long series of studies. The sounds could not be positively identified with any whales until improved listening capability at low frequencies was developed. The sounds then could be tracked to finback sources, and the behaviors of the whales were monitored for correlation with these vocalizations.

Some of these low-frequency sequences were noted originally on deep hydrophone lowerings (depths to 1,000 m and more) made by Henry Johnson from Woods Hole Oceanographic Institution ships in 1950–51, during geophysical studies, but the sounds were not heard near the surface. We realized later that this was largely because of masking at the same frequencies by local wave noise. Specialized equipment was needed to work with the low frequencies (see Methods section), and experience was required to separate these signals from background noise, so that our data now constitute most of the ship recordings to date of finback sounds.

The 20-Hz sound work began with the attention given by military listening systems to the pulse patterns. The relative precision of pulse repetition, the sine-wave character of the sounds and the long repetitive patterns, all seemed to indicate man-made signals. A wide variety of other possible sources also were suggested (Walker, 1963, 1964; Patterson and Hamilton, 1964). Recordings were made in different localities, and we collected information from experimental bottom-mounted hydrophones operated by other workers. With more sampling, the signals were seen to be less precise and the variability typical of biological systems became more obvious. Efforts to record the sounds from ships at sea were expanded and we began to be successful in hearing the sounds at the surface. Aircraft surveillance of animals in the listening areas was used to identify animal species that were present. The 20-Hz sounds were associated increasingly with the presence of finback whales. The list of these early identifications had six entries, but all linked the sounds with finbacks (Schevill, Watkins, and Backus, 1964, p. 149). To test the correlation, a listening site off Halifax, Nova Scotia was occupied, with continuous aerial observation of the hydrophone area. When the 20-Hz pulses were heard underwater, finback whales were found near the hydrophones. Next, extensive acoustic surveys were made by ship, and the 20-Hz signals were associated only with finbacks, never with other species. Arrays of two and four hydrophones were used to track the 20-Hz pulses underwater, and in each case the tracks led to finback whales. Also, as indicated above, we recorded the ragged sounds having 20-Hz emphasis from a trapped finback barely covered with water (Brewster, Mass., 27 May 1963). In the years since, all of these sounds have continued to correlate only with finbacks.

Useful distances for finback sounds

Because the finback sounds travel well through water over relatively long distances, an understanding of the possible utility of the sounds to the whales required an assessment of the useful intensities and distances for hearing the sounds. Although maximum source levels of the 20-Hz sounds were 80 dB or higher (re 1 dyne cm^2), most of the sounds, including the 20-Hz sounds, were seldom that high, often not more than 40 to 60 dB. There was a wide variability in the level of the same type of calls from the same whale. Finback sounds, therefore, were seldom produced at their loudest. Nearby whales obviously were not " shouting ", and responses from other whales mostly were at relatively low levels. Sometimes successive pulses in a series had 20 to 30 dB level differences. Whales occasionally responded loudly to distant pulses. The levels of the sounds apparently were controlled by the whales.

Most finbacks were observed to be in small groups (2–5), but they occasionally moved about alone. This was true both in the summer and winter seasons. When underwater sounds were heard from finbacks, the whales producing the sounds generally were not far from another finback, usually less than 1 km and within at least 15 km. The need for loud calling, therefore, was not evident, and in fact, the whales seldom produced high level calls, especially in the summer season. In the winter season, the patterns of 20-Hz pulses sometimes were quite loud, although these signals, too, often were produced at relatively low source levels, less than 40 dB (re 1 dyne/cm^2). The proximity of other whales did not seem to relate to the level of the pulse patterns.

The distance at which sounds can be heard underwater is a function of the environment (see texts like Urick, 1967). At sea, within 500 m of the surface, the usual day-time arrangement of temperature layers produces downward bending sound paths. In shallow water, the sound paths are more complicated because of signal interaction with bottom and surface reflections, as well as temperature stratification and tidal currents. Thus, in our experience the distance at which a whale could be heard was as much a function of the environment as of the intensity of their calls. The low frequencies of finback calls generally allowed their reception at greater distance than for other whale sounds, but practical distances for receiving the sounds on hydrophones within 50 m of the surface usually was limited in shallow water to 8 to 10 km, sometimes to as much as 25 km. In deeper water the downward sound paths generally also were limiting, so we often found that our listening limit was 12 to 15 km (demonstrated by locating the vocalizing whale).

These sound-producing whales apparently did not go deeper than about 500 m, because the ranges could have been greater if the whales were deep.

The pulse patterns from finbacks often were heard continuously enough so that the vocalizing whales could be located by acoustic tracking. From more distant, deeper whales, the signals sometimes were not receivable when the whales rose to the surface to breathe, due to the downward bending sound paths. During very stable sea conditions, sound path estimates from bathythermographic measurements could be used to judge distances to vocalizing whales (confirmable by finding the pulsing whales). We were able to track the sources of the 20-Hz pulse patterns sometimes by intensity differences alone—moving our ship in the direction of increasing pulse amplitude. At other times, the levels of sequential pulses in a pattern varied too much for such tracking, but towed hydrophone arrays, usually with only two hydrophones 100 to 300 m apart, could be used to obtain relative bearings to the sound source (ship stopped during listening). Tracking of the winter season pulse patterns consistently led us to vocalizing finbacks.

Day and night differences

Finback activity apparently changed at night. Their diving behavior during daylight has often included dive sequences longer than three or four min (including the dive routines noted above), but the night-time observations have indicated shorter submergence times, few longer than four min. When we were able to get close to these animals at night, they were staying near the surface, and generally were in small groups. Our night-time acoustic observations have been limited since we usually did not know where the whales were during darkness, but there sometimes was an apparent increase in the rate of sound production, both of higher frequency and 20-Hz sounds. If these sounds had a social context, the nocturnal sound increase would be expected as the whales apparently remained in social groups at night. The radio tracking experiments with finbacks as well as with *Megaptera novaeangliae* (Watkins, Johnson and Wartzok, 1978; Watkins, Moore, Wartzok and Johnson, 1981) and on *Balaenoptera edeni* (Watkins, di Sciara, and Moore, 1979) demonstrated generally shorter submergence times during darkness in all of these species.

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DISCUSSION

Interpretation of behavior

Our observations of both behavior and underwater sounds present a consistent picture of finback activity. The large number of observations over more than 23 years from many geographic areas in different seasons have provided a general view of the whales' visible activities. The emphasis on long term observation of one local population (Cape Cod) has provided comparative data to balance out the unusual occurrences that could otherwise dominate scattered sampling. Increasing experience, better equipment, and improved techniques have allowed increasingly detailed observations.

Interpretation of the portions of behavior that were observed has required the use of all available observational methods. Certainty of identification of individual whales through radio tagging and tracking over long sequences allowed confidence in our observations. Mixing visual, acoustic, and tracking techniques (radio and hydrophone array) often confirmed interpretations of whale activity.

The differences observed in behaviors, such as the varying blow characteristics and spacing of blows may reflect individual differences and preferences of particular whales. The differences may also have been indicative of other activities, social pressures, levels of exertion, relative health, or previous experience that could not be assessed. The whales' activity at depth probably affected the observable surface behavior which usually centered around respiration.

The shallow dive routines appeared to be a foraging or searching behavior. Whales spread out over several km and often worked back and forth to cover a large area. These whales would be able to alert each other to conditions approrate for feeding, either by vocalizations or by the sounds of their own feeding, especially when the prey was near the surface. It may be significant that the shallow dive routines seemed to be the most common behavior seen in finback whales, and that only a few sounds were heard during this activity, seldom with any response from other whales. This apparently was a search behavior with little vocal communication needed.

The longer dive routines often appeared to be associated with feeding at depth. During the long dives, several whales sometimes dove near each other, and feeding sometimes was indicated by water flowing from partly opened mouths as the whales surfaced, occasionally with throats still enlarged and full. Sea birds were seen sometimes hovering near the surfacing whales and picking up scraps from the water around the whales' mouths. Compared to other behaviors, whales in long dive routines often blew more rapidly and they appeared to be in a hurry to dive again, arching in a high " roundout " as they went down steeply. From an aircraft at such times, finbacks could be seen to stroke hard with their flukes as they dove. All of this seems to correlate the long dives with a deep (not visible from the air) feeding routine. That more vocalizations were heard during this routine may be indicative of several whales close together participating in the same activity. More sounds also were heard when several whales were feeding near each other at the surface. The fact that they were feeding may have been incidental to the occurrence of sounds and the presence of several whales close together may have been the significant ingredient for sound production.

The near-surface slow swimming appears to be a resting behavior, in which whales move slowly a few m below the surface for extended periods. During this behavior we have not heard vocalizations even though there may have been several finback whales together. Because very little of the whale is visible at the surface during this behavior, we may have missed seeing many resting whales. Shifts to such resting sequences from other activities might have been responsible for the occasions in which finback whales seemed suddenly to disappear (noted also in the radio tagged finbacks and humpbacks—Watkins, Moore, Wartzok, and Johnson, 1981).

The surface activity of finbacks does not include much splashing, so that the sounds associated with surface feeding may stand out prominantly. Other whale species often display aerial behaviors such as fluke waving, flipper slapping, lob-tailing, and breaching, but finbacks seldom do any of this. Actually, there is little noise produced underwater by the aerial activities of any species, except for lob-tailing and flipper slapping, which produce characteristic, recognizable sounds underwater. In our experience, breaching and fluking produce very little underwater sound even at extremely low frequencies. Local wave noise even in relatively calm sea conditions soon masks the loudest breaching sounds from a few hundred m distance.

Interpretation of the underwater sounds

The higher frequency calls seemed to serve as social communication with other finbacks and appeared to be used a little differently from the 20-Hz pulses The higher sounds were heard mostly during interaction of two or more whales, particularly when several whales fed together at the surface and during long dive routines. These sounds perhaps served to alert other whales of the group activity. The fact that the higher frequency finback sounds were never loud would seem to relegate them to communication with nearby whales In contrast, the 20-Hz pulses sometimes were very intense. Individual differences in the rate of the dropping frequency sweep of the calls (both in higher frequency and 20-Hz pulses) provided a means of separating the calls of individuals, which we assume that the whales could also utilize.

The low-frequency rumble often appeared to be a response to surprise, as when a finback passed close (within about a whale length) to a drifting silent ship or floating cable The sound was sometimes accompanied by a sharp turn or a dive to avoid the object. The rumble also has been heard when two finback whales approached each other, so that we have wondered it it could have an agonistic significance as well.

The non-vocal sounds associated with finbacks feeding at the surface were distinctive to that behavior. They did not appear to be produced purposefully, but they were adventitious to that mode of feeding. We have often been alerted by these sounds to the presence of such feeding finbacks, so we assume that the whales also might be alerted by this means.

The vocal sounds of finbacks include wide variations in spectrum and duration of the higher frequency sounds, the single 20-Hz pulses, and the low frequency rumble, but the pulses in the 20-Hz patterns were stereotyped in frequency and duration. All of the vocalizations of finbacks appeared to be controlled voluntarily by the whales, levels varying from " whispers " to " shouts ". This was demonstrated using acoustic location techniques with other cetaceans (Schevill and Watkins, 1966; Watkins and Schevill, 1974; Watkins, 1980) where sound levels varied without changes in the animal's orientation.

The high variability that we and others (Cummings and Thompson, 1977;

Thompson, Winn, and Perkins, 1979; Edds, 1980) have noted in the low frequency finback sounds often may be caused by environmental modification of the sounds. Low-frequency, long wavelength sounds are particularly susceptible to modification in shallow water, when depths are less than a few wavelengths and echo periods allow sound reflections to return within the duration of the sounds. This often is further complicated by multiple sound paths and refraction through distinct temperature layers as well as transmission through bottom material. Therefore, we have avoided detailed descriptions of sounds from shallow water and have based our analyses on deep water observations of nearby whales.

Fundamental frequencies and intervals between pulses were the components of the sounds that were most stable with distance, and therefore probably most important to the whales. Levels varied greatly so that the amplitude modulation, particularly the slighter differences in level, probably were meaningless (also apparently true for sperm whales which emphasized temporal coding, Watkins and Schevill, 1972). In finbacks, the rate of downward sweep in frequency may have been the most important component of the sounds. The sweep rate of one whale was relatively constant, at least for a few hours, and may have provided a means of individual identification. In deep water from nearby whales, the sweep rates often were very precise and repeated in both the higher frequency calls and 20-Hz sounds, as well as the 20-Hz pulse time-patterns.

Single 20-Hz pulses sometimes were used apparently for long distance signalling (up to 25 km). Usually, they were louder (sometimes by 40 dB) than the higher frequency sounds, and we occasionally noted responses from more distant whales. An example of this occurred (9 May 1975, Race Point, Cape Cod) when we were listening near a lone finback that was in a short dive routine near our boat. In the background, we heard five or six barely audible underwater 20-Hz pulses, then the nearby whale responded with two extremely loud 20-Hz pulses and immediately swam away at about 20 km/hr. The whale travelled fast near the surface going toward a group of finbacks identified previously by aircraft 20 to 25 km away. Our boat's speed was 12 km/hr, so we were soon left behind.

Patterned 20-Hz pulses perhaps were used as a reproductive acoustic display. The pulses were heard as established patterns only during the winter reproductive season. The patterns have not been heard from the largest finbacks, which probably are females. In a group of adult whales it was often a slightly smaller whale (therefore possibly a male; Ichihara, 1957; Ohsumi, 1960) that produces the pattern. The 20-Hz pattern may be recognizable at a distance because of the usual regularity of repetition rate of the low frequency signals. In some ways, the finback pulse patterns were similar to the humpback whale " song ", which also appears to serve as a reproductive acoustic display (Payne and McVay, 1971; Winn and Winn, 1978).

Although social and apparent courtship activity involved pairs or groups of whales, it was interesting that few sounds, not even the 20-Hz display patterns, were audible from these whales. In addition, we've not heard sounds that could be attributed to cows and their calves. This is different from our experience with some other whale species in which sounds from cows with calves (humpbacks) were audible and frequent, and groups of socializing whales were vocally active (right whales and humpbacks).

Long ranges unlikely for these sounds

Because of the low frequency and the intensity of at least some of the 20-Hz finback pulses, Payne and Webb (1971) speculated that these sounds could be used for extremely long distance communication, (to several thousands of km), particularly if the whales made use of the deep ocean sound channels (described in Urick, 1967). From our observations of finback behavior, this seems unlikely. The signal would be distorted and lengthened by the many transmission paths of the sound channel over long distances and the sounds would have to be " reconstructed " by the whale to allow recognition of the signal. To use the sound channel effectively, both the whale producing the sounds and the listener would need to be in the sound channel —usually deeper than 1,500 m in the open sea in lower latitudes. This is far deeper than data indicate as normal for finback dives. The utility of such long range communication in these whales does not seem to be evident. Although finbacks occasionally responded to sounds that appeared to be from other whales at distances up to 25 km, most of their responses were to signals from nearby whales. There were few lone finbacks; most were found in groups throughout the year, perhaps lessening the need for long range signalling.

Mechanisms and similarities in sound production

The mechanism of sound production in these whales is not understood. Any sound generating system would have to account for the observed characteristics of these underwater sounds: (1) low-frequency sine-waves, often intense, of one sec or longer duration; (2) sounds that do not change with (pressure) depth; (3) sounds of the same frequency and intensity ranges whether from small or large whales; (4) sounds in which the whale can control level, duration and repetition rate; (5) precise repetition in frequency and time over long periods and throughout a wide variety of activities. There has been a consistent negative correlation of finback vocalization with blowing at the surface, perhaps indicative of the sounds being made with air recycled internally and maybe involving the larynx (Schevill, 1964; Hosakawa, 1950). The similarities in the physical characteristics of the various sounds produced by finback whales suggest a common sound generator although there are two sound categories (narrow and broadband). The different sounds were not heard simultaneously from one finback.

The similarities of sounds from other related species also suggest similar sound generators. Minke whales (*Balaenoptera acutorostrata*) recorded in the waters of the Antarctic, Cape Cod, and the Gulf of St. Lawrence, all produced similar downward sweeping sounds but at higher frequencies, of generally shorter durations and with a wider frequency range (Schevill and Watkins, 1972, and unpublished recordings; Peggy Edds, pers. comm.). The sounds of Bryde's whales (*Balaenoptera edeni*) recorded by Cummings and Thompson (1977), and blue whale sounds (*Balaenoptera* *musculus*) reported by Cummings and Thompson (1971),—all are low-frequency (12 to 150 Hz), sine-waves with little harmonic energy, and often very loud. Our attribution of sounds to sei whales (*Balaenoptera borealis*) is still uncertain since our recordings in the presence of these whales have also included sounds from other *Balaenoptera* species. Patterned sounds similar to those of finbacks have not yet been found in these other species.

Finback whales that have produced sounds within range of our underwater listening systems consistently have produced the sine-wave and restricted bandwidth pulses at low frequencies. Although we have had long experience in listening to the various species of *Balaenoptera*, we have not heard the reported high frequency sounds (*B. physalus*, Perkins, 1966) or the broadband pulses and click-like sounds (*B. acutorostrata*, Beamish and Mitchell, 1973; Winn and Perkins, 1976; *B. musculus*, Beamish and Mitchell, 1971).

SUMMARY

Our observations to date have provided a fragmented though consistent picture of finback underwater acoustic behavior. These distinctive sounds appeared to be communicative. The higher frequency sounds seemed to be used primarily in signalling nearby whales—particularly during activities such as surface feeding and deep dive routines when several whales were together. Single 20-Hz pulses sometimes seemed to be used in longer distance (" shouting ") to whales that were farther away. The repetitive patterns of 20-Hz pulses were seasonal and perhaps were a courtship or reproductive acoustic display. The ragged low-frequency pulses have not been as clearly defined because of the difficulties in distinguishing these from background noise. The longer low-frequency rumble sounds were associated with surprise and perhaps agonistic responses. Surface feeding sounds were characteristic of that activity, although these sounds apparently were adventitious and not vocal.

The behaviors noted here were chosen because they had visible components and were repeated often enough to be identifiable. No specific underwater sounds were found to be characteristic of these behaviors, but instead, the vocalizations appeared to be related to interaction between whales during some of these activities, particularly during the long dive routines and surface feeding, and occasionally during short dive routines. The whales usually were silent during other behaviors: blowing, near-surface slow swimming, fast travel.

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