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Abstract:

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Blue and fin whales observed on a seafloor array in the Northeast Pacific

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INTRODUCTION

Many baleen whales produce loud low-frequency underwater sounds a significant percentage of the time, providing a practical tool with which to study whale distribution and movements (Watkins and Wartzok, 1985; Nishimura and Conlon, 1994; Clark, 1994). Studies of whales have used arrays of acoustic sensors to determine swimming speed and direction as well as to monitor call interaction between whales (Patterson and Hamilton, 1964; Cummings *et al.*, 1968; Watkins and Schevill, 1977; Cummings and Holliday, 1985). Temporal patterns in acoustic call sequences provide a measure of respiration times (Cummings *et al.*, 1986) while call characteristics may separate stocks or groups within the species (Winn *et al.*, 1981; Ford and Fisher, 1983). Further study of whale calls may allow them to be used to monitor behavioral changes associated with man-made noise sources.

The data used for this study were recorded with a seafloor seismometer array having an aperture of about 10 km, allowing measurement of directionality, apparent acoustic velocity, relative amplitude and absolute amplitude of signals. Whale calls were detected during approximately 10% of the eleven day recording period (a seismology experiment provided these whale recordings incidentally). Whale calls were most easily identified when observed in repetitive sequences, typically lasting for hours. With the 128-Hz sampling rate used in our seafloor recording system, only low-frequency sounds, such as those produced by blue and fin whales, were recorded. Whale calls were detectable at ranges up to 30 km during this study, although only calls within about 15 km of the array were analyzed because of the higher signal-to-noise ratio.

I. METHODS

A. Recording instruments

The study site is about 500 km offshore from Astoria, Oregon (Fig. 1), in 2400 m of water on the southern Juan de Fuca Ridge, about 60 km north of the Blanco Fault Zone. During August of 1990, eight seafloor seismometer recording packages were deployed with 4 to 6 km between adjacent instruments. Data were recorded internally on optical disks and examined after instrument retrieval. There were two instrument deployments during the study, each for about 5.5 days. The location of the instruments on the seafloor was known to within a few tens of meters and instrument clock drifts were known to within about 10 ms, as discussed in McDonald *et al.* (1994). Imprecision in the instrument timing and navigation is negligible relative to the errors in call locations resulting from picking errors in the arrival times of the whale calls. The call arrival time picking errors limit call position accuracy to several hundred meters theoretically and to some lesser accuracy, on the order of 1 km, as practiced in these analyses. The number of instruments used in plotting the call tracks varied, but was never less than four.

The primary sensor used for recording the signals under discussion was the vertical component of a 3-axis seismometer (Mark Products L-4, 1-Hz natural period). The response for this sensor is nearly flat to particle velocity from 1 to over 100 Hz. The electronics system response was low pass filtered at 60 Hz because of the 128-Hz sampling rate used. Background ambient ocean noise levels are higher at low frequency, so the system gain was 20 dB lower at 1 Hz relative to 10 Hz. The spectrograms and amplitude plots shown in this paper are not corrected for system roll-off below 10 Hz and above 60 Hz. Signal amplitudes were converted to dB *re*: 1 μPa using correlations between the seismic sensor package and calibrated hydrophones (Benthos AQ-1), as performed during previous seafloor experiments in similar water depths where the hydrophones were attached to the seafloor recording package. No hydrophones were deployed during this study. Experiments using both vertical seismometers and hydrophones have shown a higher signal-to-noise ratio for whale calls on seismometers than on hydrophones. We suggest this is partially due to the direction-

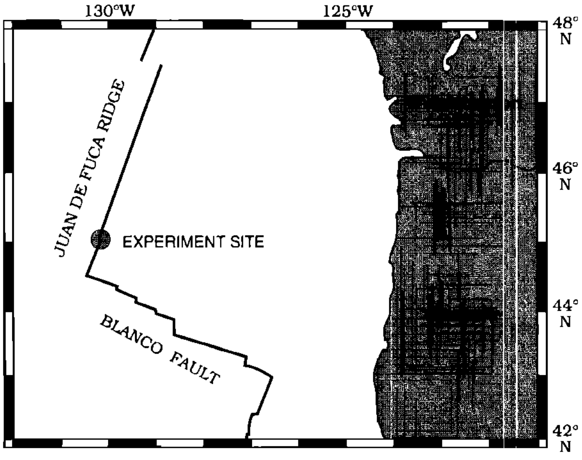

FIG. 1. The observation site was located on the Juan de Fuca Ridge about 500 km offshore Oregon in 2400 m of water.

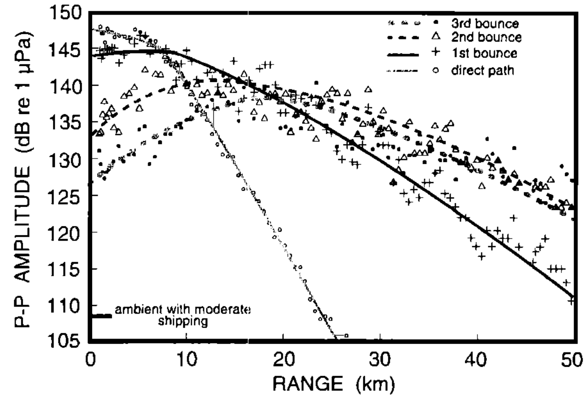

FIG. 3. The amplitude of an airgun source versus range for the direct water path and bounce paths as received on a seafloor recorder during this study.

ality of the vertical component seismometer and the high incidence angles associated with the whale signals.

B. Signal localization methods

Different methods are used to locate short transient sound sources (fin whale calls), long transient sources (blue whale calls) and earthquakes. The short (one second) transient sounds were most easily located, because multipath arrivals are separated in time from the direct arrival and from each other. Figure 2(a) shows an example of the received signal from a one second transient sound (fin whale call) on

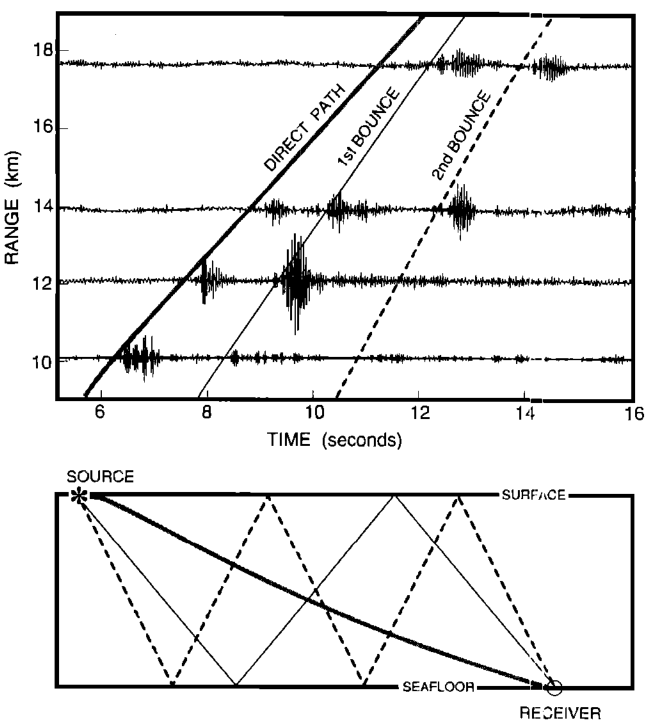

FIG. 2. (a) The amplitude display of a 1-s duration fin whale pulse received on each of four seafloor recorders at different ranges. The earliest arrivals are the direct water path and the later arrivals are bounce paths between the seafloor and sea surface. (b) A cross-section diagram illustrating the direct and bounce paths seen in (a).

four array elements. Figure 2(b) shows the corresponding raypaths for each arrival. Since most whale calls occurred outside of the array, the relative travel time information allows computation of the azimuth to the source. Relative amplitudes of the several multipath arrivals allow range estimation from each instrument. The amplitude of the direct arrival in Fig. 2(a) decreases steadily with range, while the first bounce path amplitude reaches a maximum at about 12 km and the second bounce path provides a relatively higher amplitude signal at longer ranges.

Direct and multipath amplitude ratios are plotted versus range from airgun pulses during this study in Fig. 3. The airgun pulses are sufficiently similar to the whale calls under discussion to expect similar reflection coefficients and similar multipath amplitude variations as a function of range. Most of the energy in these airgun pulses is in a frequency band between 10 and 35 Hz and has a duration of several hundred milliseconds. The observed amplitude variation as a function of range can be explained in terms of the downward refraction of the direct path due to the water sound-speed profile and by the change in seafloor reflection coefficient as a function of incidence angle. We compared these airgun data to whale data to estimate the range of the whale from each instrument. Range information has been combined with relative arrival time information to determine best estimates for call locations. Each location is overdetermined by using range data from several instruments, resulting in better location estimates. Because the reflection coefficients are site dependent and the sound-speed profile is both site dependent and time variant it was important that the airgun amplitude data were gathered at the same site and at nearly the same time as the fin whale calls.

Transient signals having durations greater than several seconds (blue whale calls) have overlapping multipath arrivals making it more difficult to use multipath relative amplitudes for range estimation. When the source is within 10 km of the array or inside the array, relative arrival times locate the source adequately. At ranges beyond 10 km from the array, the bearing determination is quite accurate but the range determination, using only arrival time data, becomes poor. By calculating the average source level of well-located calls of a given type, the amplitude versus range relationship derived from the airgun data was used to estimate range. Earthquake ranges are readily determined using relative arrival times of the compressional and shear wave energy traveling in the rock (e.g., Mallick and Fraser, 1990) while their bearing is determined by relative arrival times on multiple instruments.

II. RESULTS

A. Recorded sounds

The observed signals can be described in three categories; seismic, biologic, and man-made. The most common signals are those in the seismic category, including those from seafloor hydrothermal flow (Sohn *et al.*, 1992), earthquake T-phases (Walker and Bernard, 1993) and earthquake body waves. In the biologic category are whale calls and the so called "fishbumps" (Buskirk *et al.*, 1981), which can sometimes be identified as biologic because they occur more frequently at certain times of day and certain water depths. Man-made signals observed were primarily those associated with ships. Less common signals in this type of data include tidal current flow noise (Duennebier *et al.*, 1981; Ambos *et al.*, 1985) and volcanic tremor (Talandier and Okal, 1984; Talandier and Okal, 1987).

We analyzed two sequences of repetitive, two part, approximately 20 Hz, whale calls from the eleven days of recordings. These two part calls consist of: A 19-s signal (type A) followed by a 24-s interval, a different 19-s signal (type B), followed by a 60-s interval before the first signal (type A) of the next pair occurs. These signals lasted for 10.5 h (August 18, 0030 to 1100 Local) and 5.2 h (August 19, 0640 to 1150 Local), consisting of about 375 and 180 calls, respectively. The 10.5-h sequence was in progress when data recording began and continued until the whale was beyond the detection range of the array. There were also other faint 19-s signals which were not analyzed because of low signal-to-noise ratio, but which have the same characteristics.

There were two sequences of 1-s duration whale calls near 20 Hz, repeating at an average interval of 19 s, except for pauses which typically last 150 s. These sequences lasted 2.2 h (August 21, 0410 to 0620 Local) and 8.0 h (August 28, 2010 Local to August 29, 0410 Local), consisting of about 1000 and 4000 calls, respectively. Only the 8.0-h sequence was analyzed because of the poor signal-to-noise ratio on the 2.2-h sequence. We also recorded signals from 65 regional and local earthquakes, several of which occurred during a whale call sequence.

III. CALLS ASSOCIATED WITH BLUE WHALES (*B. musculus*)

A. Spectra

The 19-s duration signals are recognized as blue whales because of a similarity to signals recorded in the presence of blue whales (Cummings and Thompson, 1971; Edds, 1982; Thompson *et al.*, 1987; Alling *et al.*, 1991; Alling and Payne, unpublished manuscript), and because of considerable unpublished navy research on these signals (Cummings and Thompson, 1994). Similar recordings are reported that lack

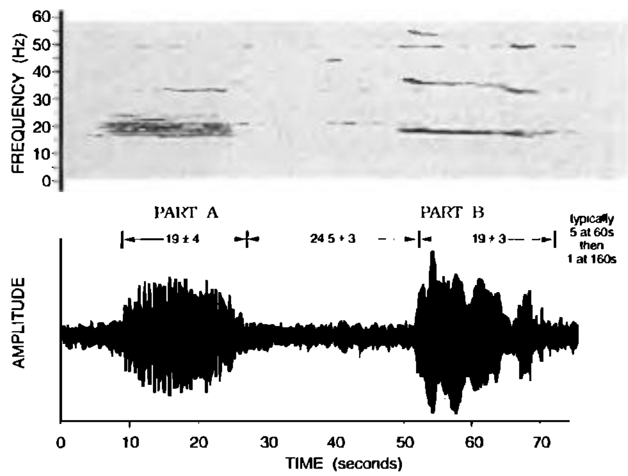

FIG. 4. The spectrogram and corresponding time series record of a typical blue whale call pair. The spectrogram was made using a filter bandwidth of 1.55 Hz and a time window of four seconds. The average duration and standard deviation for each portion of the call pair sequence is shown from one sequence of 132 call pairs. The call is divided into two portions, parts A and B.

visual corroboration (Weston and Black, 1965; Kibblewhite *et al.*, 1967; Northrup *et al.*, 1968; Northrup *et al.*, 1971; Thompson, 1965; Thompson *et al.*, 1979; Thompson and Friedl, 1982) and we understand that other recordings with visual corroboration remain unpublished as this correlation is well accepted in the whale acoustics field.

A typical two part blue whale call waveform and corresponding spectrogram are shown in Fig. 4. The first 19-s call segment (part A) shows a series of six spectral lines about 1.5 Hz apart with the lowest at 17.5 Hz. Spectral lines like this can be generated by a pulsed tone and have been referred to as pulsive (Watkins, 1964). A pulselike amplitude modulation is evident in the waveform display. Spectrograms computed for more than 100 call pairs from the August 18 sequence reveal remarkably little variability in character.

The second segment (part B) in the blue whale call pair is probably not amplitude modulated. The amplitude variability seen in the records appears to be the result of constructive and destructive interference of several reflected paths and the direct travel path as evidenced by differences in the time-versus-amplitude character of the same signal observed at different ranges. The fundamental tone in this call begins at 19 Hz and sweeps down in frequency to 18 Hz in the first 3 to 4 s (Fig. 4). The 18-Hz tone is then carried until the last 5 s where the dominant tone sweeps down to 17 Hz. Since the sampling rate was 128 Hz there may be segments or components of the call sequence above 60 Hz which were not recorded. Higher frequency segments and components have been reported by Cummings and Thompson (1971), Thompson *et al.* (1979), and Alling *et al.* (1991), although the whales recorded by Alling *et al.*, may be pygmy blue whales (*B. musculus brevicauda*).

B. Temporal pattern in calls

Only the August 18 blue whale call series was suitable for analysis in terms of the gaps between calls, since airgun shot noise made it difficult to pick the beginning and end of

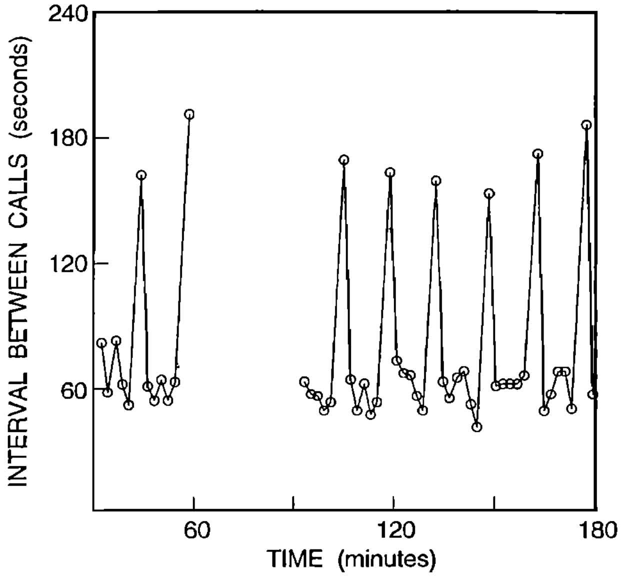

FIG. 5. The time interval between successive blue whale call pairs is typically 60 s but after about five calls there is a longer (160 s) interval, interpreted to be a breathing pause.

each call from the August 19 series. Spectrograms were computed and call start and stop times were picked for 134 consecutive pairs having a high signal-to-noise ratio. All but one of the 134 call pairs followed a stereotype pattern consisting of a 19-s pulsive signal followed by a 24.5-s gap and a 19-s monotonic signal. One unusual call was missing part B and the next call pair began 45 s later.

A plot of interval time between call pairs (Fig. 5) shows a longer time after every five or six calls, which may represent a respiration pattern. This would correspond to a typical dive time of 660 s and a breathing time of 160 s. Similar patterns in call intervals were reported by Thompson *et al.* (1987) where call pairs occurred in series of two to six with a median repetition interval (breathing time) of 131 s. Edds (1982), however, reports exceptions to the pattern of calling during dives and not calling during breathing and reports surface slicks during the call sequences demonstrating the whale to be at shallow depth during some calls.

C. Call tracking

Call locations were calculated [Fig. 6(a)] at regular time intervals for a portion of the August 18 series by fitting smoothed curves through the amplitude and relative arrival time data from four seafloor instruments. Changes in both bearing and received call amplitude [Fig. 6(b)] occur smoothly, suggesting relatively continuous movement of the whale during the call series. Each track could have been generated by either a single whale or a group of whales traveling together if separations were less than one km. This series contains no overlapping calls which would be indicative of a second whale at the same location. Other recordings (Thompson, 1965, in Urick, 1983, p. 219) have shown overlapping calls.

The speed of the whale(s) was 6 km/h averaged over the first track and 10 km/h averaged over the second, while the average speed per $\frac{1}{2}$-h interval ranged from 4.5 to 13 km/h. All speeds were computed between the points marked with times on the track plot of Fig. 6(a). The whale(s) may be swimming an irregular course between the computed points implying a higher speed. Reported observed speeds for blue whales are 2 to 6.5 km/h while feeding, 5 to 33 km/h while cruising or migrating and a maximum speed of 20 to 48 km/h when being chased or harassed (Yochem and Leatherwood, 1985).

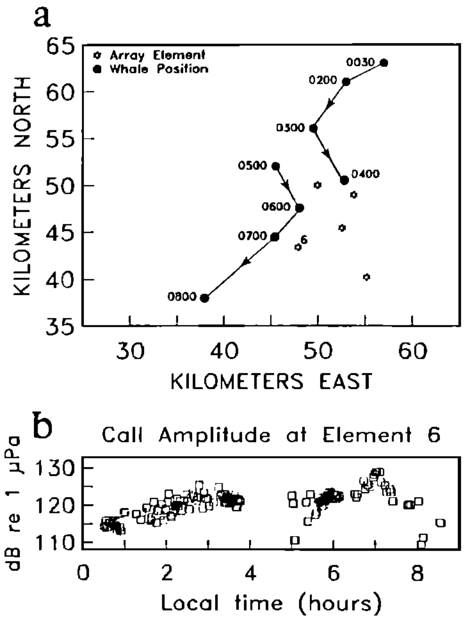

FIG. 6. (a) The track of a blue whale with local time shown adjacent to each of the points for which position was calculated. (b) The blue whale call amplitude changes with time. Each point plotted represents one blue whale call pair, so the gaps indicate breaks in the call sequence.

IV. CALLS ASSOCIATED WITH FIN WHALES (*B. physalus*)

A. Correlation of 1-s signal with fin whales

The 1-s, frequency-downswept, pulses recorded during this study (Fig. 7) are known to be typical fin whale calls

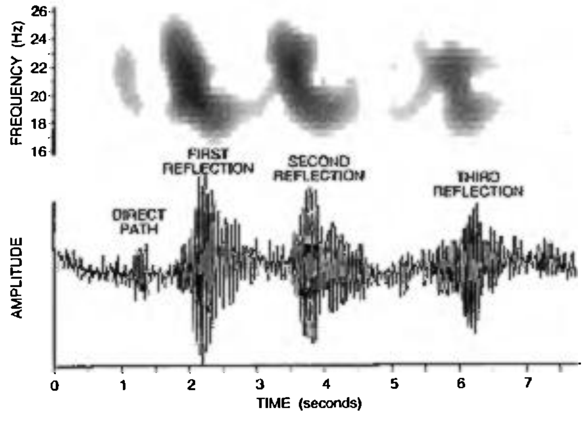

FIG. 7. Spectrogram and time series for a typical fin whale call, the first sound at 1.3 s is the direct water arrival and subsequent sounds are the multipath arrivals of the same signal. The spectrogram was made using a filter bandwidth of 6.19 Hz and a time window of 2 s.

(Schevill *et al.*, 1964; Thompson *et al.*, 1979; Watkins *et al.*, 1987; Richardson *et al.*, 1991; Thompson *et al.*, 1992). Identification of acoustic signals from the fin whale is primarily from combined visual observations and recordings off the east coast of the U.S. where there is a seasonal pattern of signals common off Bermuda only in winter and common in the St. Lawrence estuary and off the New England coast only in summer (Edds, 1988; Watkins, 1981).

B. Temporal pattern in calls

We describe call series durations and rest intervals, associated with the respiration cycle of fin whales (Cummings *et al.*, 1986), using the terms: Pulse interval, rest, and gap, as defined by Watkins *et al.* (1987). The average pulse interval of the fin whales, excluding rests, is 19 s averaged over 467 calls from one continuous series, having no gaps (exceptionally long rests), during the 28–29 August series. This 19-s pulse interval is similar to prior observations (Watkins *et al.*, 1987). The rest durations, corresponding to breathing times and the pulse series durations corresponding to dive times, suggest typical dive times of 600 s and breathing times of 150 s, from this study. Pulse interval times of 900 and 720 s with corresponding breathing times of 150 and 120 s have been reported respectively by Patterson and Hamilton (1964) and by Watkins *et al.* (1987). These acoustically interpreted durations are longer than the 201 and 90 s average dive times and the 90 and 55 s average breathing times from visual observations, reported by Stone *et al.* (1992) and by Edds and MacFarlane (1987), although, other factors such as the activity of the whale and the water depth, make these comparisons difficult to interpret.

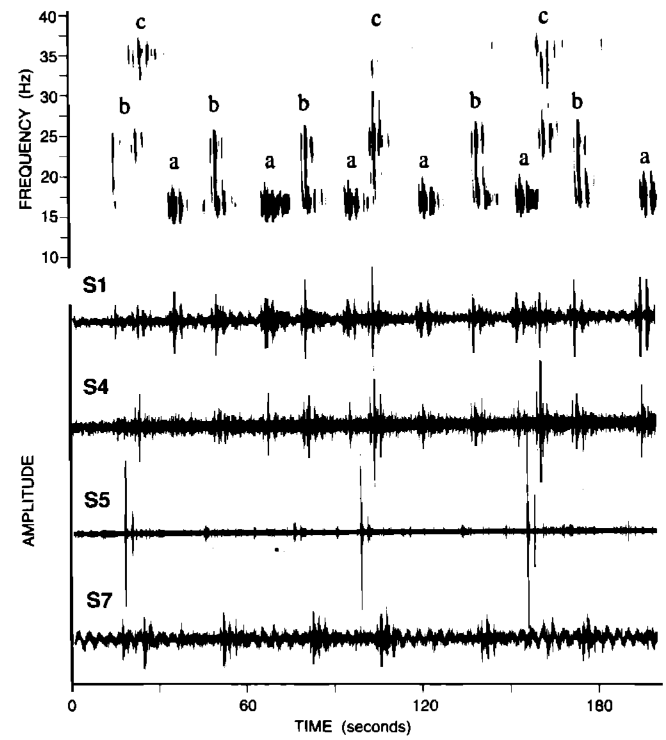

FIG. 8. Time series for elements S1, S4, S5, and S7, and spectrogram for element S1 from several minutes of a typical fin whale call series with multiple whales. The frequency and bandwidth differences make up the distinctive signatures associated with three whales labeled "a," "b," and "c." That the whales are interacting rather than just independently calling is suggested by the consistent alternate spacing between calls with nonoverlapping calls and a distinctive call signature for each whale. The time series records from the four seafloor instruments demonstrate the separation between the three whales with different instruments showing the highest amplitude for the nearest whale.

C. Call tracks and whale interaction

The 28–29 August series of fin whale calls indicates repeat interactions among three whales located several kilometers apart. Figure 8 shows the time series and corresponding spectrogram from several minutes of a typical fin whale call series with multiple whales. At this compressed time scale it is not possible to see the downsweep associated with each pulse, but the frequencies and bandwidth show the distinctive signature associated with each of three whales. Whale "a" in Fig. 8 has a signature consisting of a downsweep from 18 to 14 Hz, while whale "b" has a 25- to 16-Hz downsweep signature, and whale "c" a 37- to 22-Hz downsweep signature. These signatures were very consistent throughout the sequence of 467 calls which were examined in detail. That the whales are interacting, rather than just independently calling, is suggested by the consistent alternate spacing between calls with the calls never overlapping, the distinctive call signature of each whale and the apparent synchronization of respiration. The time series records from the four seafloor instruments demonstrate the separation between these whales, with different instruments showing the highest amplitude for the whale nearest that instrument.

For the sequence of 467 calls analyzed in detail, the whale labeled "a" in Fig. 8 produced 46% of the total calls, "b" produced 41% and "c" produced 13%. Within these 467 calls there are only six occasions when a whale called twice without an intervening countercall, including the rest gaps in this sequence. Of these occasions, whale "a" called consecutively only once, that after a particularly long rest gap, such that the two calls were some 5 min apart. Whale "b" twice called consecutively and whale "c" on three occasions. On the occasions when whale "c" repeated its call without a response, it called two, three, and five times consecutively. Cursory examination of other similar data sets from the same area suggest this to be a common pattern, where calls of the type produced by whale "c" are fewer in total number but are most often repeated consecutively.

Figure 9 shows the tracks of the three whales over the 1.5 h while they were nearest the array. The whales traveled side-by-side rather than single-file and no whale appeared to be leading. The whales tracked in Fig. 9 were swimming at speeds of 5 to 14 km/h as averaged over the $\frac{1}{2}$-h intervals shown. Swimming speeds for fin whales from visual data are reported as 10 to 16 km/h for long periods when in transit and 20 km/h or more for shorter periods (Watkins, 1981). The lowest frequency whale, "a," swam most quickly, called most often and never called twice in a row; while the highest frequency whale, "c," swam slowest, called least often and called consecutively most often.

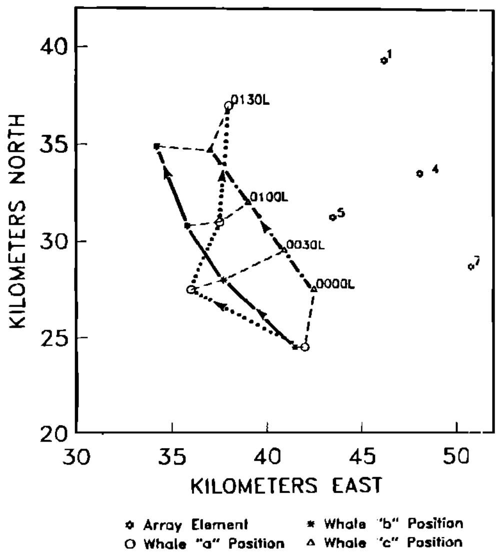

FIG. 9. Tracks of the three fin whales ("a," "b," and "c") from Fig. 8 travel together, showing their positions at equivalent times connected by dashed lines. The whales appear to travel side by side rather than in a single file. Whale "a" with the lowest frequency signature, travels the fastest (circles), whereas whale "c" with the highest frequency signature, travels the slowest (triangles).

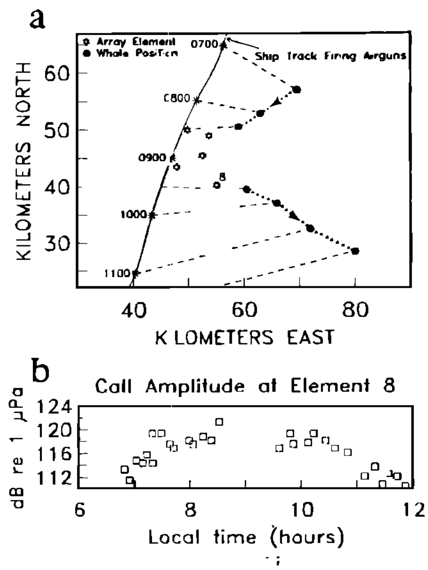

FIG. 10. (a) A blue whale track during airgun operations. The dashed lines connect the location of the airgun ship with the whale location at the corresponding time. The whale started its call sequence well within the tracking range of the array when the airgun ship was 15 km distant (0700 h local time). The whale followed a pursuit track until it stopped calling at a range of 10 km. After a gap in the call sequence, the whale track moved diagonally away from the ship. (b) The received whale call amplitude changed with time. Each point plotted represents one blue whale call pair, so the gaps indicate pauses in the call sequence.

V. WHALE RESPONSE TO MAN-MADE AND SEISMIC NOISE IN THE OCEAN

A. Significance

Concern for the welfare of marine mammals has focused attention on the effects man-made noise may have on the behavior, communication, or general welfare of whales. Under the Marine Mammal Protection Act, increasingly strict guidelines for the use of man-made noise in the oceans are being applied as a precaution against disruption of whale behavior (Hofman, 1989; Green *et al.*, 1994). Natural transient noises in the ocean are primarily associated with earthquakes and volcanic eruptions while man-made transients include shipping, geophysical surveying with airguns, underwater explosions and hydraulic sound sources such as are used with acoustical oceanography experiments.

B. Airgun noise

We conducted a seismic refraction survey with a four airgun array having a total capacity of 1600 cubic in., fired at 1800 psi. These airguns are individually larger than those typically used in oil exploration, resulting in lower maximum sound levels at lower frequency, near 15 Hz. The airgun array produced about 215 dB P-P *re*: 1 μPa at 1 m over a 10- to 60-Hz band (a suboptimal sound-pressure level because of depth and towing speed constraints) as estimated from seafloor measurements. The array was nearly symmetric in azimuth. The directionality of the airgun array was not measured, but this source level measurement is appropriate for estimating received level at the whales because the seafloor reflected paths will be the loudest received at the whales. Figure 10 shows a blue whale track during airgun operations. The dashed lines connect the airguns location with the whale location for the matching time. This whale, in Fig. 10, was moving slightly faster than the whale tracked in Fig. 6(a), with an average speed of 10 km/h, varying from 7 to 13 km/h. The whale started its call sequence well within the tracking range of the array when the airgun ship was 15 km distant (0700 h local time). The whale closed on the ship following a pursuit track until it stopped calling at a range of 10 km. At this point, the ship was moving about 10 km/h and was beginning to increase its distance from the whale; the sound level of the airguns then was 143 dB P-P *re*: 1 μPa over a 10- to 60-Hz band at the whale. After a gap in the call sequence, a new call series, presumably by the same whale, was again located 10 km from the ship, suggesting it had taken a track generally paralleling the ship. The series of positions after 0930 shows the whale moving diagonally away from the ship. Comparing this track with that of Fig. 6(a), it appears the whale may have been approaching the ship intentionally, or perhaps was unaffected by the airgun ship. More data of this type will be needed to draw conclusions about the affect of such noise on blue whale behavior. Studies of bowhead and gray whale behavior in the presence of airgun noise indicate avoidance at broadband levels of about 160 to 170 dB 0-P *re*: 1 μPa (Malme *et al.*, 1984; Richardson *et al.*, 1986; Richardson *et al.*, 1991; Tyack, 1993).

C. Ship-generated noise

Noise created by the research vessel did not significantly increase the background noise level between 10 and 60 Hz at the study site (except during airgun operations), but regular passages of larger merchant ships were observed to increase 10- to 60-Hz noise levels by as much as a factor of 20 in amplitude (26 dB) relative to times when no merchant ships

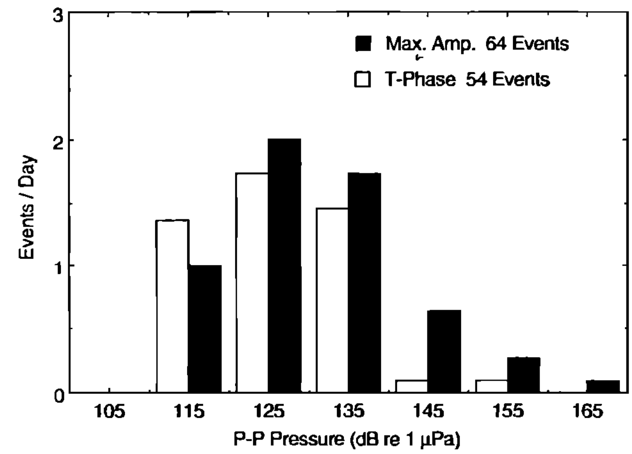

FIG. 11. The peak amplitudes of body-phase or t-phase pressure signals, whichever is greater, and the t-phase pressure signals from the 64 earthquakes observed in this study. At low amplitudes the smaller number of detected events is attributed to detection limitations related to the variability of background noise from local shipping.

were nearby. The blue whale track illustrated in Fig. 6 could not be located after 0800 h because an approaching merchant vessel increased the noise level so that it was difficult to pick the arrival times and amplitudes of the blue whale calls. This merchant vessel came from the north-northwest, passing about 5 km west of the nearest array element at 0940 h when the whale was approximately 5 km west of the vessel. Sound levels at the whale were about 106 dB rms *re*: 1 μPa over the 10- to 60-Hz band (115 dB P-P), yet the blue whale continued to call as before. In contrast, avoidance behaviors have been observed in beluga whales at ship noise levels of only 94 to 105 dB rms *re*: 1 μPa in the 20- to 1000-Hz band from ships 35 to 50 km distant (Finley *et al.*, 1990). Bowhead whale avoidance behaviors have been observed in half the animals when exposed to 115 dB rms *re*: 1 μPa broadband drillship noises (Richardson *et al.*, 1990), but behavioral reactions are considered to vary depending on the characteristics of the noise, whale activity and the physical situation (Richardson and Greene, 1993).

D. Earthquake-generated noise

Earthquakes are believed to have generated ocean noise at similar frequencies and magnitudes throughout the evolution of whales, and thus are a background noise to which the whales are presumably adapted. The frequency of occurrence of earthquakes producing transient sounds of given amplitude in the ocean can be predicted using observations such as were collected in this study together with the empirical relationship by which the frequency of earthquake occurrence rises by a factor of 10 (a close approximation) for each decrease in earthquake magnitude (Frohlich and Davis, 1993). The histogram shown in Fig. 11 provides a reference level upon which the empirical relationship is applied for this region of the north Pacific. Similar north Pacific data has been reported by Johnson and Jones (1978), Jones and Johnson (1978), Hyndman and Rogers (1981), and Fox *et al.* (1994) and there are at least 20 similar published data sets for other areas of the Pacific.

The data of Fig. 11 have been divided into two types, tertiary-phase (T-phase) energy which is transmitted in the water and body-phase energy transmitted in the rock, entering the water near the receiver. The earthquakes that generated the signals recorded during this study occurred at ranges as far as 170 km and as near as 1.1 km, with most at ranges near 65 km, the range from the study site to the Blanco Transform Fault Zone. Body-phase energy provides the highest amplitude sound in the water at near ranges, while at longer ranges the T-phases dominate showing energy above background levels from 3 to 35 Hz (Walker *et al.*, 1992) regardless of the earthquake range. Different regions in the ocean will be dominated by one or the other, depending on local seismicity levels.

Using this information, it is possible to estimate the earthquake sound level a whale will hear with a given frequency of occurrence. If we assume whale hearing has evolved to withstand the maximum level of earthquake generated sound, occurring once per lifetime, this level suggests how loud a man-made sound might be without causing permanent damage. For purposes of the calculation, we assume our study site receives earthquake noise typical of that received by the hypothetical whale. We believe the earthquake noise at our study site to be above average for the worlds oceans, but not extremely so. We also assume for the calculation that the pressure amplitude produced in the ocean is directly related, one to one on a logarithmic scale, with earthquake magnitude increase. Extrapolating from our sound level of 140 dB P-P *re*: 1 μPa in the 10- to 60-Hz band, from earthquakes once per day (Fig. 11), we calculate a sound level exposure of 204 dB P-P *re*: 1 μPa in the 10- to 60-Hz band for earthquakes occurring once per lifetime (50 years). In the less likely occurrence where the whale happened to be directly over the earthquake, the sound exposure level would be 231 dB P-P *re*: 1 μPa. We anticipate that SOSUS data (Gagnon *et al.*, 1993; Nishimura and Conlon, 1994; Fox *et al.*, 1994) will soon provide direct answers to the question of maximum earthquake sound pressure levels detected over a period of years, avoiding the assumptions implicit in our calculation. Very distant earthquakes, such as the very large and deep Bolivian event in 1994, have no bearing on this calculation, as that event produced no significant energy above 2 Hz in the region of this study. Possible effects of an intermediate range earthquake on gray whales is discussed by Malme *et al.*, 1989.

Figure 12 shows earthquake sound energies, both T-phase and body-phase during a fin whale call series. There is no disruption of the call interaction in this case when the sound level from the earthquake is 121 dB P-P *re*: 1 μPa over the 10- to 60-Hz band at the whale. When extrapolated back to the Blanco Transform Fault Zone, sound levels from this earthquake would be 27 dB higher (148 dB P-P *re*: 1 μPa) within a few kilometers of the epicenter. The range between the earthquake and the whales is practically the same as the earthquake to recording instrument range at the time scale of this plot.

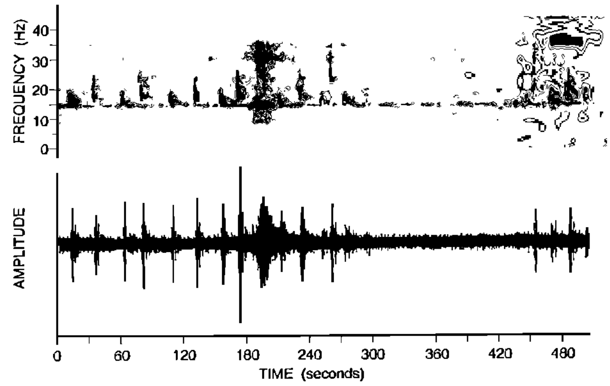

FIG. 12. Earthquake noise, including both t-phase and body phases during a fin whale call sequence. There appears to be no disruption of the call interaction in this case when the noise level from the earthquake is 121 dB P-P *re*: 1 μPa over the 10- to 60-Hz band, at the whale.

VI. DISCUSSION

A. Noise pollution of the deep ocean

Noise pollution, herein defined as anthropogenic noise, in the deep sound channel is basically of two types: Transient noises and background noise levels. Natural transients are primarily associated with earthquakes and volcanic eruptions, while manmade transients include geophysical surveying with airguns, underwater explosions and hydraulic sources such as those used for acoustical oceanography experiments. First we discuss the possible anthropogenic effects on background noise levels in the deep sound channel. It is important to keep in mind during this discussion that the sound channel has a profound effect: 20-Hz ambient noise levels in the sound channel are about 30 times louder in amplitude (30 dB) than noise levels at typical seafloor depths, such that while local wind noise (associated with breaking waves) may set the background noise level at the seafloor (McCreery *et al.*, 1993; Shooter *et al.*, 1990), the background level in the deep sound channel is associated with distant sources, including wind noise, shipping, seismicity and distant whale calls.

The analysis of Payne and Webb (1971) proposes that propeller driven shipping has changed the background noise levels of the entire worlds' oceans, negatively affecting the ability of the 20-Hz whale calls to be heard at long range. More recent work challenges that hypothesis, suggesting that sources other than shipping may cause the observed background levels at 20 Hz. Ambient noise levels in the deep ocean sound channel near the 20-Hz frequency range are bounded on the low side (below 5 Hz) by nonlinear wave–wave interaction, a phenomena which is relatively well measured and understood (Kibblewhite, 1985; Webb, 1992). Noise levels between 5 and 50 Hz have traditionally been attributed to shipping noise (Wenz, 1962), but may be alternatively and/or regionally sourced from high latitude winds (Bannister, 1986). Some authors have suggested other noise sources in this frequency range including atmospheric turbulence (Wilson, 1979; Copeland, 1993), lightning (Dubrovskiy and Kosterin, 1993), and glacial ice flow (Copeland, 1993), but we consider these sources improbable or insignificant.

Many observations of ambient noise levels have a peak at 20 Hz which is usually attributed to whale calls and assumed to be caused by whales relatively local to the observation site even though the whale calls may not be distinctive in the time series data (Kibblewhite *et al.*, 1976; Copeland, 1993). The important question is whether the source of background noise near this 20-Hz peak is shipping, a source the whales did not evolve with and may not be readily adapting to. Our calculations of earthquake T-phase noise levels in the sound channel, when extrapolated back to a frequency of occurrence of nearly continuous noise (the distinction between background and transient noise becomes blurred), suggest seismicity may be the dominant noise source at 20 Hz in some otherwise quiet regions of the ocean. This is significant because earthquakes would have been present throughout the period of whale evolution. A discussion of the assumptions used in these calculations would be too lengthy for this paper and recent SOSUS data may also provide better data upon which to base this type of calculation.

A good example of transient noise pollution is that from the seismic airgun array. Transient noises associated with geophysical surveying off the California coast have been readily recorded on land seismometer arrays 6100 km distant in Polynesia after traveling via the deep sound channel with little dispersion (Okal and Talandier, 1986). These noises, however, were probably not even heard by a whale near the surface in the mid-Pacific, because of the trapping of the sound in the deep sound channel. This type of noise will be heard only by the whales which dive below several hundred meters depth and to those in the polar regions where the sound channel shallows, assuming some land mass has not blocked the path. Prediction of airgun noise propagation is also complicated by the environment near the airguns, which in this instance may have been well suited for introduction of the airgun noise into the deep sound channel by downslope conversion where the sound is reflected off the seafloor, providing an efficient means of entering the deep sound channel (Jensen *et al.*, 1994).

B. Why blue and fin whales call

Speculations on why blue and fin whales call at 20 Hz have focused primarily on the question of communication with, or at least the broadcasting of relative location information to other whales of like species (Payne and Webb, 1971). The use of 20-Hz signals for depth finding sonar is somewhat discounted by the observation of calls when the whales are moving slowly and calling frequently, making the information content redundant. The whales would be expected to perceive the depth from the 20-Hz echos, but the signal is louder than would be necessary and a higher frequency signal would seem a more logical choice for this purpose. Relative location information is undoubtedly important to survival of the species if breeding pairs are to meet. Recent developments in long distance call tracking of blue whales using navy hydrophone arrays (Gagnon *et al.*, 1993) has raised speculation that the whales are horizontally echo-sounding the island of Bermuda from ranges up to 1000 miles (Clark, 1993).

The information contained in the multipath amplitude ratios, as used to track fin whales in this study, suggests that fin whales could measure oceanic sound speed profiles by countercalling among the pod. The direct path amplitude relative to the bounce path amplitudes would provide a measure of the magnitude of downward refraction associated with the shallow (upper 500 m) sound-speed profile. Sufficient information could be obtained by the whale receiving the signal if the source were at least several km distant from the calling whale. Countercalls could provide measurements of variability in the sound-speed profile which would not be possible simply by listening to the echo of their own call, because a horizontal travel path amplitude would be added for comparison with reflected path amplitudes. Extraction of water sound-speed and corresponding temperature profiles may be possible using the principles of matched field processing (Jensen *et al.*, 1994). Changes in the depth and sharpness of the thermocline may be estimated from these amplitude ratios and may help the whale locate food.

VII. CONCLUSIONS

The use of passive seafloor arrays to track and monitor the calls of passing whales has advantages over other methods, such as radio tracking or visual observations, not only in cost but also because seafloor recording arrays are unobtrusive, unlike methods, using ships or aircraft as observing platforms, which may interfere with whale behavior. The recordings from this study further show the use of signature calls among fin whales, as suggested by Watkins (1981). These recordings provide a minimum measure of how many whales were present in an area and provide information on the character and pattern of their calls, which may eventually lead to association with specific behaviors and/or the separation of population groups by characteristic calls. Tracking of the calls provides direction and speed of travel information which may prove complementary to future efforts towards an acoustic census of pelagic baleen whale populations.

As demonstrated during the eleven days of this study, acoustic recordings provide a measure of the low-frequency noise levels that whales are exposed to and observations of any response to such noise. The observed noise levels at the whale during this study were 143 dB P-P *re*: 1 μPa over the 10- to 60-Hz band for airgun noise, 106 dB rms *re*: 1 μPa over the 10- to 60-Hz band for ship noise and 121 dB P-P *re*: 1 μPa over the 10- to 60-Hz band for earthquake noise. These observations may help set the minimum level at which a response might be expected.

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