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Male sperm whale behaviour during exposures to distant seismic survey pulses

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Abstract

The behaviour of adult, male sperm whales in polar waters (69°20′N, 15°40′E) during exposure to pulses from a remote (>20 km) seismic survey vessel and artificial codas is described and discussed. Five hours of recordings with a large aperture array contained both air gun pulses and sperm whale clicks. The seismic survey pulses received were smeared-out in time and high-pass filtered due to multipath propagation in shallow water. The pulses received had a −10 dB spectrum content in the frequency range of 210–260 Hz and a maximum −10 dB duration of 1400 ms. Estimated maximum sound pressure received at the whales were 146 dB re 1 μPa (p-p) (124 dB re 1 μPa^{2}s in energy terms). The exposure to the seismic survey pulses did not elicit observable avoidance and the whales stayed in the area for at least 13 days of exposure. Nor did the whales fall silent or change their normal vocal patterns during feeding dives. It appears that foraging male sperm whales in this habitat and at these received levels are not more susceptible to air gun pulses than are cetaceans in general.

During emissions of artificial codas, sound levels at the whales being unknown, the sperm whales did not cease clicking as reported from previous investigations, but two whales seemed to direct their high power, narrow-beam sonar towards the coda transmitter.

Key words: Sperm whale, seismic survey, air gun, coda, noise, *Physeter*

Introduction

Because sound, unlike other stimuli, propagates efficiently in water, fully aquatic mammals have developed sensory systems suited for detection and processing of sounds used in orientation and communication. The crucial role of sound reception in marine mammals makes them potentially vulnerable to noise that masks or interferes with signals of interest. Marine mammals are exposed to sound from natural sources such as vociferous animals, wave-action and natural seismic activity.

During the last century increased human activity offshore has elevated background noise levels in the oceans. Due to the possible deleterious effects of noise on marine organisms, a number of investigations have tested the effects of anthropogenic sound sources on marine mammals (Richardson *et al.*, 1995). Motorized shipping is a prominent and constant source of noise in the sea with possible masking effects on baleen whale communication as a possible consequence (Payne & Webb, 1971). Nevertheless, most effort has been put into understanding the effects of ATOC (Acoustic Thermography of Ocean Climate) (Au *et al.*, 1997; Popper *et al.*, 2000), LFA (Low Frequency Active Sonar), (Frantzis, 1998; Miller *et al.*, 2000), and seismic surveys on the behaviour and physiology of marine mammals.

In a seminal review, Richardson *et al.* (1995) outlined four zones of influence of human-made noise on marine mammals: (1) zone of audibility, (2) zone of responsiveness, (3) zone of masking, and (4) zone of discomfort and injury. Various natural and anthropogenic sound sources may cause effects pertaining to one or more of the zones of influence, depending on source parameters and transmission effects.

Pulse-generators used in seismic surveys are the most powerful, routinely used, civilian sound sources with nominal source levels[1] (SL) up to 265 dB re 1 μPa (p-p) (Richardson *et al.*, 1995). Such high SL's are back-calculated from far-field properties of the sound pulse, where the array can be considered a point source. The actual SL in the near-field (<75 m or so) of an air gun array is some 15–20 dB lower due to multiple sources (Caldwell & Dragoset, 2000).

Seismic survey pulses are normally generated by rapid emission of a large volume of gas into the

[1]Referenced to 1 m.

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water (Greene & Richardson, 1988). The output pulse are of short duration (<100 ms) and have a centre frequency of 50–100 Hz. Using an array of guns, achieves a largely downward-projected, directional beam of the pulse (Barger & Hamblen, 1980). Owing to the high sound pressure levels and widespread use of this technique, the possible effects on marine animals have been investigated (for a review, see McCauley *et al*., 2000). The possible deleterious effects of seismic surveys on marine mammals may be relevant at all four zones of influence, including discomfort and injury, if the animal is in close proximity beneath the source.

The effects of seismic surveys on baleen whales include studies on bowhead whales off Alaska (Ljungblad *et al*., 1988; Richardson *et al*., 1986; Richardson *et al*., 1999), humpback whales (McCauley *et al*., 1998) and gray whales (Malme & Miles, 1985). The general observation is that baleen whales change their behaviour by avoidance or increased ventilation rates when the levels received exceed 130–150 dB re1 μPa, with some inter- and conspecific variation (Reeves *et al*., 1984; Richardson *et al*., 1995).

Odontocetes have shown mixed reactions to seismic survey noise. Rankin & Evans (1998) could not demonstrate that seismic surveys had a negative impact on large-scale distribution of delphinids in the Gulf of Mexico. Goold (1996) indicated avoidance reactions by common dolphins to operating air guns. Mate *et al*. (1994) found a negative correlation between seismic surveys and the presence of sperm whales in the Gulf of Mexico. Bowles *et al*. (1994) reported that sperm whales in the Indian Ocean ceased clicking, possibly as a response to seismic survey pulses, with received levels some 15 dB above background noise levels. In contrast, Stone (1998, 2000) reported that sperm whales sighting rates did not differ significantly with seismic surveys.

Sperm whales seem to respond to various sound sources (for a summary see: Madsen & Møhl, 2000). In particular, coda-like patterns of transients with modest received levels have been shown to evoke reactions among exposed sperm whales (Watkins & Schevill, 1975; Andre *et al*., 1997).

Recordings in July 2000 of sperm whale sounds off Andenes, northern Norway, coincided with the activity of a seismic survey vessel. The recordings provided information on sperm whale clicking behaviour before, during, and after exposures to pulses from the seismic survey vessel. Sperm whales were also exposed to artificial codas to test the responsiveness of the whales.

Materials and Methods

Recordings were carried-out from 12 to 21 July 2000 in Bleik Canyon, off Andenes, northern Norway (69°20′N, 15°40′E). Variable numbers of adult, male sperm whales inhabit the canyon all the year round, presumably engaged in feeding (Ciano & Huerle, 2001). Andenes Whale Safari has two vessels for whale watching in the canyon area. On every trip, time and position of the whales observed are noted in the ship's log. Observations from 6 to 25 of July were made available to the present study (courtesy of G. Maan).

A seismic survey vessel was exploring the continental shelf between 20 and 140 km SW of the canyon between the 12 and 25 July 2000 at water depths varying between 30 and 1100 m (Fig. 1). The survey vessel towed a tuned HGS sleeve air gun array with four sub-arrays of 10 guns. The array was towed at a depth of 7 m and the guns were firing simultaneously.

Total volume of the array was 3800 cubic inches (62 L) with a nominal working pressure of 2000 psi and a 10 s repetition period. The far-field signal was a one-cycle transient with 30 ms duration and most energy in the frequency range of 10–80 Hz. The SL (with the amendments of a point source, see introduction) of the downward propagating part of the signal was 109 bar-m (p-p) (filter bandwidth unknown), corresponding to 261 dB re 1 μPa (p-p) (Kjell Aubert, pers. comm.). The SL of the horizontally propagating part of the signal was lower due to the downward directing properties of the array (Richardson *et al*., 1995).

A custom-built piezo-ceramic pinger, omnidirectional in the horizontal plane, was used for generation of artificial codas. The signal applied to the piezo-ceramic element was a 20 ms downward sweep from 30 kHz to 10 kHz. The operator manually controlled the repetition pattern. The pinger was lowered to a depth of 5 m during transmissions. The SL was 164 dB re 1 μPa (p-p).

Acoustic recordings during sleeve air gun investigations were performed on 15, 18 and 20, July with a large aperture array of non-linked recording platforms spaced in the order of one kilometer. Each platform was equipped with a calibrated hydrophone (B&K 8101, HS-150 or Reson TC-4032), which via an anti-alias filter (−12 dB/oct, f_0=11 kHz) relayed the signals to one of the channels of a DAT stereo-recorder (Sony TCD-D3,7 and 8), sampling at 48 kHz. Hydrophones were lowered to depths between 5 and 30 m. Calibration signals from a B&K 4223 pistonphone-calibrator were sent through the entire recording chain and stored on each tape. Filters were compensated for during analysis, given a flat (within 2 dB) frequency response from 0.01 to 22 kHz of the recording systems. A 40-dB attenuator could be inserted in the recording chain to avoid overload.

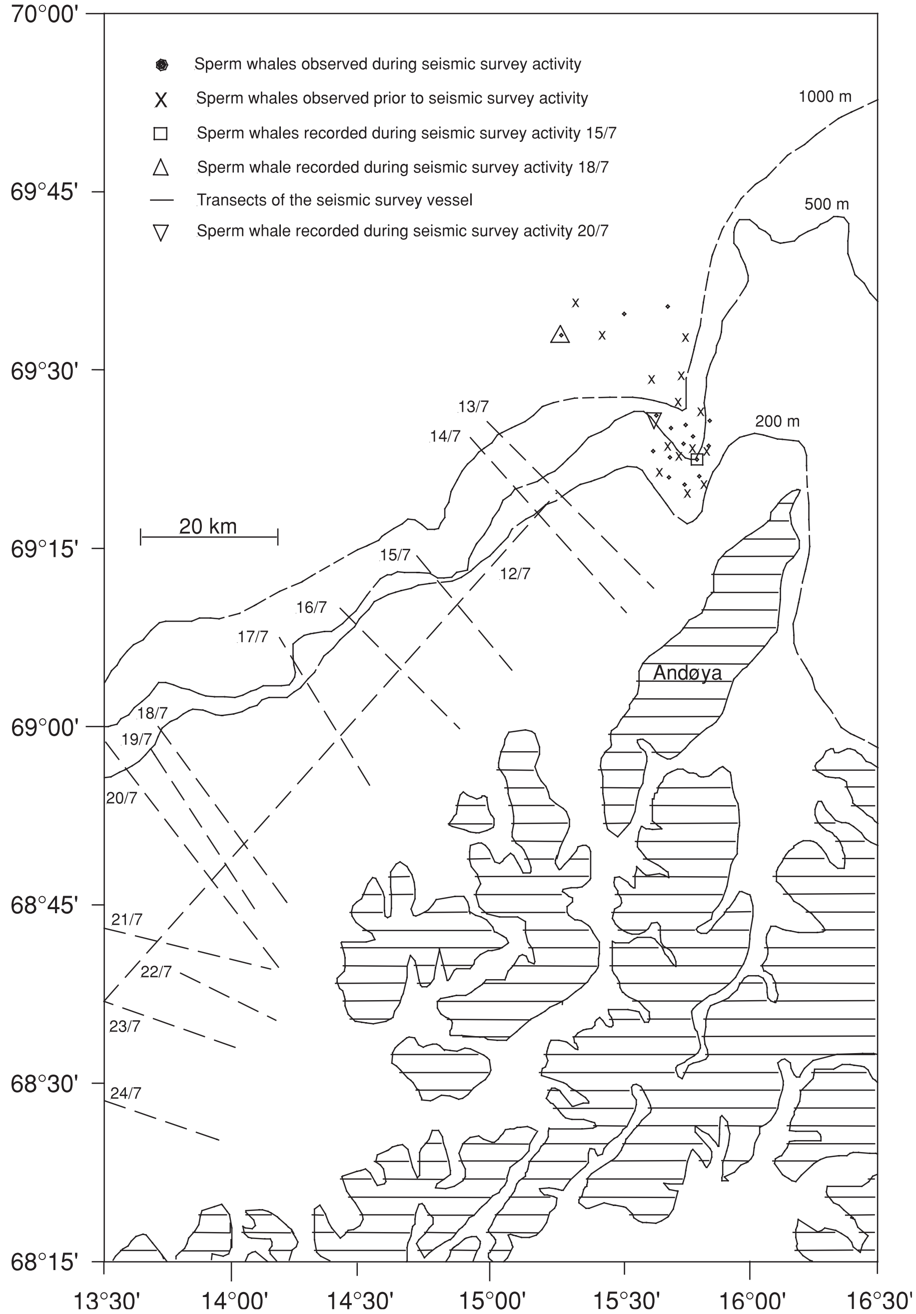

Figure 1. Map of sperm whale observations and transect lines of the seismic survey vessel. Abscissa—numbers denote eastern longitude and ordinate -numbers denote northern latitude. Numbers associated with transect lines denote date. Whale Safari boats and/or research vessels were looking for whales during the entire period (6 to 25 July) and whales were observed on all dates except on the 17 July. The five sperm whale observations in the outermost part of the canyon were all concomitant with observations of pilot whales or killer whales in the inner part of the canyon.

Table 1. Properties of received seismic pulses. Energy integration time 200 ms, rms SL calculated from − 3 dB interval of the envelope function. S/N calculated from energy integration of the signal and a segment of background noise of equal length.

Date	Receiver depth [m]	Transmission range [km]	Duration − 3dB/ − 10dB [msec]	Received sound pressure [dB//1μPa, rms]	Received sound pressure [dB//1μPa, p-p]	Received energy [dB//μPa^{2}s]	S/N energy [dB]
15 July 2000	5	40	124/1480	123	138	116	11
18 July 2000	5	86	40/1420	130	141	120	15
18 July 2000	30	86	200/1400	130	146	124	24

All platforms were equipped with a dGPS-receiver, writing UTC (Universal Time Code) and absolute position every second to the other channel of the DAT recorder. For further information on this system, see Møhl *et al.* (2001). Data were tranferred from DAT-tapes to PC with a Zefiro card. Analysis was performed with commercially available software (Cool Edit, Syntrillium). The whales were localized from time of arrival differences of the same click at the dGPS positioned receiver platforms, using custom software (A. Heerford & M. Wahlberg) and algorithms as outlined in Wahlberg *et al.* (2001). Energy and duration calculations were made with Matlab 5.3 (MathWorks). The spectral content of the sleeve air gun pulses was described by the end points of the − 10 dB bandwidth. The duration of a received sleeve air gun pulse was defined as the interval restricted by the − 3 or − 10 dB points relative to the peak of envelope function. Energy was derived by integrating the square of the pressure over 200 ms (see discussion) around the maximum value of the envelope function.

Results

Positions of sperm whales, observed from Whale Safari boats and research vessels during the period from 8 to 25 July, are plotted in Figure 1, along with the transect-lines of the seismic survey initiated on 12 July. Sperm whales were observed from the Whale Safari boats in the canyon area both prior to (x) and during (o) the exposure (Fig. 1). The whales were observed in the area during 13 exposure days. Positions of sperm whales, observed from the Whale Safari boats from 25 July and onwards, were not available, but whales were seen throughout August (G. Maan, pers. comm.) and thereby more than a month after the last exposure.

On 15 July, the survey vessel was operating on a transect 22 nmi (40 km) SW of the canyon area (Fig. 1). The pulses received in the study area had been propagating some 30 km in rather shallow water before entering the canyon. The maximum values for the pulses received in the study area are listed in Table 1. Due to lack of reporting standard in the literature, sound pressure is given in both rms (− 3 dB interval as integration time) and peak-peak measures. The energy content of the seismic pulses was derived, beacuse it is a more robust measure of the sound level than p-p sound pressure for reverberant pulses.

The received levels across pulses varied in time within 10 dB for pressure units and 6 dB for energy units. The duration was also highly variable (Table 1). These durations are conservative numbers as the reverberation of the pulses were detectable above ambient noise for more than two seconds (Fig. 2a). The received pulses were frequency-modulated, sweeping from 100–500 Hz to 100–300 Hz. The spectral content (− 10 dB) ranged from 110 to 260 Hz (Fig. 2b).

Due to bad weather, the recording session on 15 July was terminated after 55 min. Both sperm whale clicks and air gun pulses were detectable throughout the recording. The sea conditions precluded visual observations of surface behaviour. During the recording session, three different sperm whales (distinguished via time of arrival differences at the various hydrophones of the array) were phonating within 2 km of the hydrophone array. The acoustic behaviour of the sperm whales consisted of patterns of usual clicks and creaks during the exposure (Fig. 3).

The next recording session, lasting 2.5 h, commenced on 18 July at 19.21 UTC in the outermost part of the canyon in the presence of a single sperm whale. No other sperm whales were observed in the canyon area on that day either by the research vessels or by the two Whale Safari boats. However, in the innermost part of the canyon, a pod of long-finned pilot whales was observed. The seismic survey ship started a transect at UTC 19.54, 47 nmi (86 km) SW of the study area. The recordings on this day were performed with hydrophones lowered to depths of 5 and 30 m. The levels recorded on the 5 m hydrophone were about 5 dB lower for energy and peak-peak sound pressure, than for the same

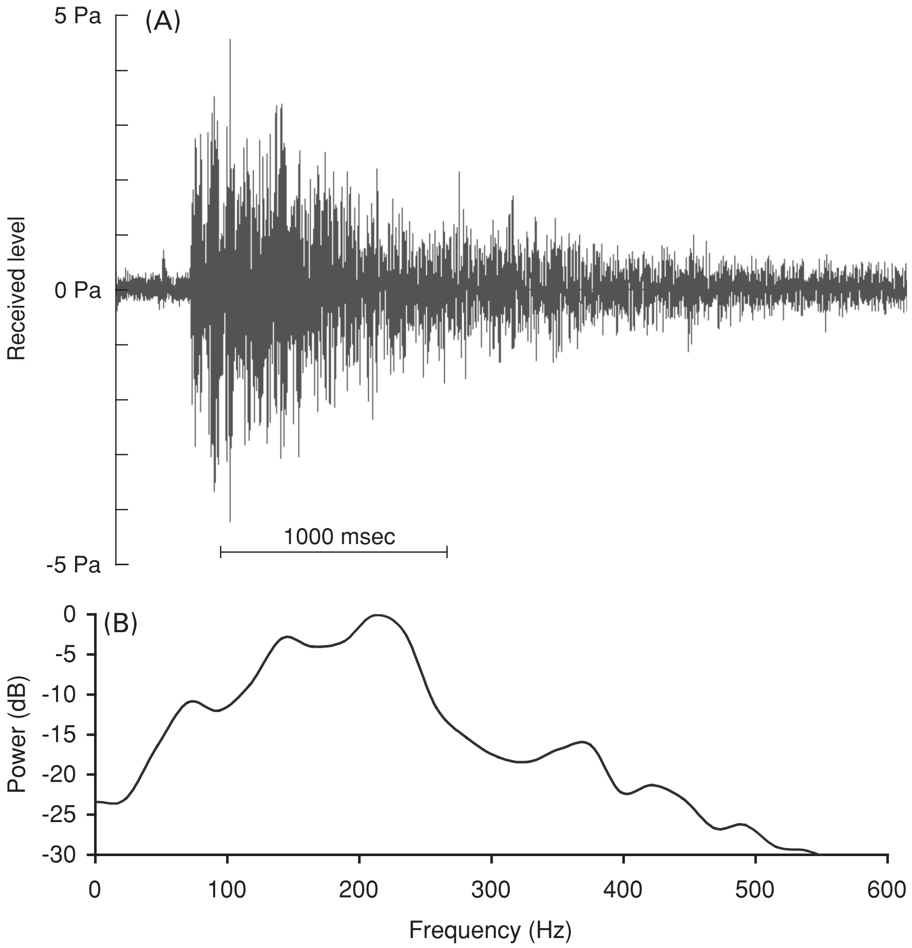

Figure 2. (A) Waveform of a sleeve air gun pulse. (B) Power-spectrum of the pulse from Figure 2A. FFT-size=2048.

pulse recorded on a 30 m hydrophone (Table 1). During the start-up of the sleeve air gun, the whale continued clicking. In addition, the mean click rate 10 s before and after the first air gun pulse was not significantly different (*t*-test, $P=0.53$). The sounds from this specimen also consisted of patterns of usual clicks and creaks. The final recording session, lasting 2 h, was carried-out on 20 July at 20.10 UTC in the presence of three phonating sperm whales. The recording setup was similar to the one deployed on 18 July and the distance between the recording area and the survey ship was 51 nmi (94 km). The seismic pulses received showed generally the same properties as derived from recordings on 18 July and they are accordingly not tabulated. All three whales performed a normal acoustic behaviour of usual clicks and creaks.

On 22 July, a single hydrophone and a pinger were deployed in the presence of soniferous sperm whales at unknown range. Artificial codas (3+1) were generated every 5 to 10 s during a 15 min period in an attempt to mimic coda signatures (Watkins & Schevill, 1977). After two min of artificial coda emissions, the hydrophone, placed within 5 m of the pinger, was illuminated for 10 s by the sound beam (Møhl *et al.*, 2000) of one of the sperm whales with received click levels of at least 170 dB re 1 μPa (p-p). Five min later, another specimen illuminated the hydrophone-pinger assembly for 5 s with received click levels of at least 180 dB re 1 μPa (p-p).

Discussion

Seismic pulses

Data presented in this study are opportunistic in the sense that the array was deployed to gain information on properties of sperm whale clicks and diving

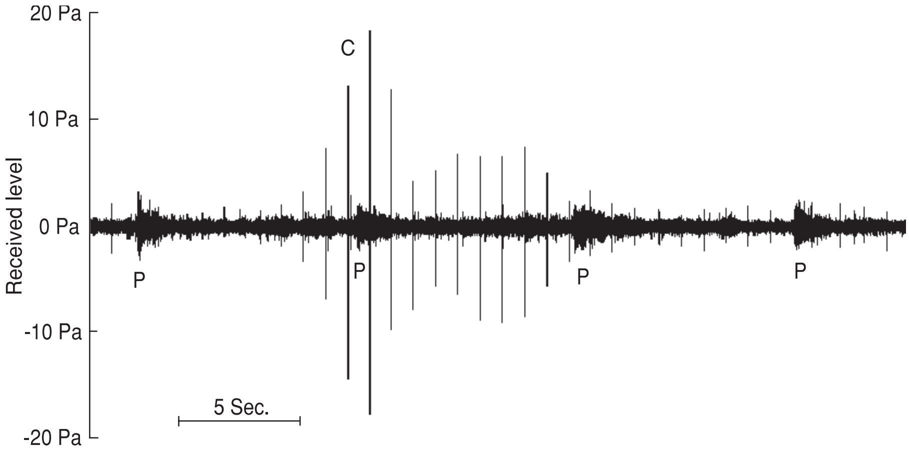

Figure 3 Waveform of sperm whale clicks and air gun pulses. P denotes seismic pulses. C denotes clicks.

behaviour. Only three of the recording sessions happened to coincide with the presence of the operating seismic survey vessel. The interpretation of the acoustic data should therefore be evaluated in the light of limited sampling.

The properties of the pulses received at the location of the whales are different from the output signal from the sleeve air guns. The duration has increased by a factor of 40, and the signal had a frequency emphasis at 200 Hz (Fig. 2b) compared to the 50 Hz peak of the signal at the source. These changes are the effects of multi-path propagation in shallow and subsequently deep water before the pulses reach the hydrophones and the whales in the canyon. When the signal is reflected from bottom and surface in shallow water, the received pulse will be the sum of several pulses with different transmission path lengths and therefore, different arrival times at the receiver, causing a smeared-out waveform with a -10 dB duration of up to 1400 ms (Table 1). This observation is consistent with the results from Greene & Richardson (1988) and Bowles *et al.* (1994). Multipath propagation leads to interference among pulses with different transmission paths, which could cause at least part of the rippled spectrum seen in Figure 2b.

The shift in spectral content (-10 dB) from 10–80 Hz in the output signal to 110–260 Hz in the received pulse (Fig. 2b) is characteristic of shallow water propagation by which the signal is high pass filtered (Richardson *et al.*, 1995). The 5-dB difference in received level (dB re 1 μPa (p-p)) between a hydrophone lowered to 5 m and a hydrophone at a depth of 30 m is consistent with observations by Greene & Richardson (1988), and can probably in part be explained by the Lloyd Mirror Effect (Urick, 1983). It is therefore expected that submerged whales are subjected to similar or higher sound pressures than what is recorded by the 30 m hydrophones.

Pressure units as dB re 1 μPa (peRMS, pp, p or rms) for characterizing the magnitude of an acoustic signal is merely a description of the instantaneous intensity. This is not a good measure for the level received by a mammalian ear, considering that this receiver is modeled as an energy detector, integrating intensity over time (Green, 1985). Since the integration time of the sperm whale ear is unknown, the value of a standard mammalian ear of 200 ms (Green, 1985) was used in sound energy derivations. This 200 ms integration time should not be confused with the integration time of 264 μs found in double-click experiments with *Tursiops* (Au, 1993). For a discussion of this topic, see Green (1985) and Tougaard (1998).

During all three recording sessions, the range between the source (the survey vessel) and the receivers (hydrophones and whales) was fairly constant. Nevertheless, within 1 h of recording, the received level varied some 10 and 5 dB, for sound pressure and energy, respectively. Transmission loss can ideally be estimated from a constant * log (range) (Urick, 1983), but variations observed in received levels during a recording session cannot be explained by range variations. Neither do the variations reflect variable outputs from the sleeve air gun array. The variations are presumably the result of minor changes in aspect and distance to the seismic survey vessel and changes in the submarine topography profile, bottom composition and sound velocity profile between the source and the receivers. This acts to change the interference patterns of the multi-paths, and thereby produce fluctuations in the amplitude of the received signals (Urick, 1983).

Accordingly, the measured levels at 30 m depth are the best available estimate of the level received at the whales. True received levels can only be provided by deployment of a calibrated sound recording tag on the target animal (Fletcher *et al.*, 1996; Burgess *et al.*, 1998; Malakoff, 2001). The influence of the submarine topography and water depth also is illustrated by the fact that the seismic pulses recorded on 15 July propagating some 40 km in shallow water, had a lower received level than the seismic pulses recorded on the 18 and 20 July, propagating mostly in deeper water for 86 km and 94 km, respectively (Fig. 1 and Table 1).

When trying to evaluate the potential impact of seismic pulses on sperm whales from the four zones of influence outlined by Richardson *et al.* (1995), it is worthwhile to consider the potential low frequency hearing capabilities of this species. Baleen whales are, based on their sounds (Au, 2000) and the anatomy of the ear (Fleischer, 1976), believed to be low frequency specialists with best hearing sensitivity below 3 kHz (Ketten, 2000). Smaller odontocetes are most sensitive in the 30 kHz -120 kHz range (Au, 1993) and rather insensitive to low frequency sounds (Au *et al.*, 1997). It is accordingly assumed that baleen whales, in general, are more susceptible to low frequency anthropogenic sounds than are odontocetes (Ketten, 2000). However, the sperm whale is not a normal odontocete in any respect, and its hearing abilities are unlikely to resemble those of smaller odontocetes. Ridgway & Carder (2001) provided the only existing information on sperm whale hearing. From ABR experiments on a neonate sperm whale, they found best hearing sensitivity between 5 kHz and 20 kHz with a better sensitivity at 40 kHz than at 2.5 kHz. This frequency range matches the spectral content (− 10 dB) of an on-axis click from an adult male sperm whale (Madsen & Møhl, 2000). Assuming that sperm whales possess the u-shaped hearing curve characteristic of all mammals investigated, it seems reasonable to believe that sperm whales have a lower best hearing range than most other odontocete species, but not as low as baleen whales.

Based on these assumptions, it is predicted that the sperm whales would have detected the seismic pulses with received levels between 136–146 dB re 1 μPa (p-p). Since the spectral content (− 10 dB) of the seismic pulses was in the frequency range of 110 Hz–260 Hz, it is unlikely that these pulses, being more than a decade lower in frequency, interfere strongly with the reception of echoes from sperm whale clicks in terms of masking. The pulses could interfere with low frequency sounds originating from prey-items and surroundings, potentially used by the sperm whales for passive sonar and navigation. However, the discontinuous nature of the seismic pulses presumably would have a strong ameliorative effect on any masking that might occur.

Sperm whales were sighted from the research vessels and Whale Safari boats every day (except on 17 July) throughout the entire exposure period of 13 days (Fig. 1), demonstrating that the received levels from the seismic survey vessel did not elicit general avoidance or displacement of the sperm whales in the canyon. On 18 July, only one sperm whale was found in the outermost part of the canyon. This apparent displacement was presumably not linked with the seismic pulses as it coincided with the presence of a large pod of long-finned pilot whales in the innermost part of the canyon. Pilot whales have been reported to harass sperm whales (Weller *et al.*, 1996), and their presence in the canyon area seems to be negatively correlated with the presence of sperm whales (Fig. 1, and G. Maan, pers. com). On 18 July, it is therefore possible that the sperm whales moved from the canyon to avoid the pilot whales.

The rather limited body of recordings from seven specimens shows that sperm whales in this habitat do not cease clicking, nor do they seem to alter their normal acoustic behaviour during feeding as a response to the seismic pulses (Fig. 3). During start-up of the seismic survey on 18 July, the first pulse did not evoke any abrupt changes in click rate as the mean click rate 10 s before and after the first pulse was not significantly different.

These observations are not consistent with two previous studies by Mate *et al.* (1994) in the Gulf of Mexico, where sperm whales reportedly moved more than 50 km away as a response to seismic survey pulses, and by Bowles *et al.* (1994) where male sperm whales reportedly ceased clicking as a response to weak seismic survey pulses (received level of 115 dB re 1 μPa). Mate *et al.* (1994) provided no estimates of the received levels at the whales and the difference from the results of the present study may simply be due to higher received levels in the Mate *et al.* study. Another plausible explanation for the discrepancy may relate to differences in sperm whale stock structure in the two habitats. Females and calves in social groups in tropical waters could be more susceptible to anthropogenic noise than solitary males engaged in feeding. This has been indicated to be the case for humpback whales, where males show less avoidance than females and calves when exposed to air gun pulses (McCauley *et al.*, 1998). The observation by Bowles *et al.* (1994) that male sperm whale may have ceased clicking as a response to low level (received level of 112–115 dB re 1 μPa) pulses from a seismic survey vessel more than 300 km away also differs from our results. Sperm whales stop clicking during ascents from feeding dives and during short and long periods of rest at the surface (pers. obs.). Even when they do produce clicks, the received levels may vary some 35 dB within seconds due the directional properties of the sound beam (Møhl *et al*., 2000). Moreover, sperm whales can alter the acoustic output by at least 20 dB (Madsen *et al*., 2002), which together with the directional effects can make it difficult to tell if a particular whale stopped clicking.

If the male sperm whales in the Bowles *et al*. study indeed stopped clicking as a response to seismic pulses with received levels of 115 dB re 1 μPa, it may be explained by differences in responsiveness of different groups of male sperm whales, depending on their prior exposures to anthropogenic noise.

The limited body of data in this study is consistent with reports by Stone (1998, 2000) and weighted to the view that foraging male sperm whales are not more susceptible to remote air gun pulses than other cetaceans investigated.

Artificial codas

The acoustic repertoire of sperm whales often includes stereotyped patterns of 3–20 clicks, termed codas, which are believed to serve a communicative purpose (Watkins & Schevill, 1977) in maintaining social cohesion (Weilgart & Whitehead, 1993). When coda-like signals are emitted near sperm whales, they often respond by click cessation and in some cases avoidance. The observed behavioural changes may reflect the response to a strange sound pattern rather than coda-recognition (André *et al*., 1997; Gordon, 1987; Watkins & Schevill, 1975; Watkins *et al*., 1985).

Since sperm whales generally react to coda-like signals, this signal type was used in the present study as a possible response reference to the potential effects of the seismic pulses. These pinger experiments were only performed on one occasion with only one hydrophone deployed, precluding derivation of the range to the whales. Accordingly, no estimates of levels received of the artificial codas at the whales can be given, but assuming the range between the pinger and the whales was more than 10 m, the levels at the whales would be equal to or lower than the maximum levels received of the seismic pulses. Two clicking sperm whales were exposed to artificial codas. None of them ceased clicking as the pinger was excited, but after two min of artificial coda emission, one of the sperm whales illuminated the hydrophone with its sonar beam and so did the other five min later. Recorded levels of sperm whale clicks are highly variable (Møhl *et al*., 2000). Normally, only a few powerful clicks are recorded as the beam sweeps by, as seen from Figure 3. However, during coda exposure, the sperm whale illuminated the hydrophone-pinger assembly twice with several powerful, usual clicks, indicating sonic investigation.

It cannot be excluded that the whales responded to a strange sound pattern, rather than to something perceived as codas. Given the two sperm whales in the present study were aroused by the artificial codas, the response is very different from the reactions reported from females and calves in the tropics. The whales did not stop clicking, but seemed to direct their sonar beam towards the coda source. This contrasting mode of response may be explained by the lack of apparent social cohesion among the solitary males off Andenes. During analysis of more than 100 h of recordings from the summers of 1997, 1998 and 2000 off Andenes, no click patterns resembling codas were identified.

That the sperm whales in the present study apparently reacted to coda-like signals and did not seem to respond to seismic pulses with levels received equal to or higher than the coda-like signals, advocate that assessment of potential impacts of anthropogenic noise cannot solely be based on received sound pressure levels. The characteristics of the possible deleterious sounds in terms of frequency content, duration and temporal pattern as well as habitat, sex, and size of the individuals exposed should also be evaluated.

In conclusion, the sleeve air gun pulses with received levels up to 146 dB re 1 μPa (p-p) did not elicit any apparent avoidance behaviour of the male, adult sperm whales off Andenes, nor did the pulses evoke changes in the acoustic behaviour during foraging. It is estimated that the pulses were well within the zone of audibility of the sperm whales, but that the pulses did not have masking effects in the frequency band of sperm whale clicks. The limited body of data in this study is consistent with reports by Stone (1998, 2000) and weighted to the view that foraging male sperm whales are not more sensitive to remote air gun pulses than are other cetaceans investigated. Present data should not be extrapolated to the possible effects of seismic pulses with higher received levels and different sperm whale stock compositions in different habitats.

At present, the small body of data on this issue is contradictory, and mitigations of seismic surveys in the presence of sperm whales must await data from controlled exposures and, optimally, deployment of sound recording tags on different animals in different habitats. Artificial codas did not make the whales cease clicking but may have caused two sperm whales to direct their high power, narrow-beam sonar towards the source.

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