An Update on Feeding by Bowhead Whales near an Offshore Seismic Survey in the Central Beaufort Sea

KOSKI, W.R.[+], FUNK, D.W.[*], IRELAND, D. S.[*], LYONS, C.[*], CHRISTIE, K.[*], MACRANDER, A.M.[#] AND BLACKWELL, S.B.[++]

[+] *LGL Limited, environmental research associates, PO Box 280, 22 Fisher Street, King City, Ontario L7B 1A6, Canada.*
[*] *LGL Alaska Research Associates Inc., 1101 East 76th Avenue, Suite B, Anchorage , Alaska 99518, USA.*
[#] *Shell Exploration & Production, 3601 C Street, Suite 1334, Anchorage, Alaska 99503, USA.*
[++] *Greeneridge Sciences, Inc., 1411 Firestone Road, Goleta, California 93117, USA.*

Contact e-mail: bkoski@lgl.coml

ABSTRACT

Aerial surveys were conducted in the Central Beaufort Sea during late summer and early autumn of 2006-8 to monitor bowhead whale distribution during periods with and without seismic exploration. During some of the 2007-8 surveys large numbers of feeding bowhead whales were seen in an area where feeding has been recorded in the past, but has not been common. Feeding bowheads appeared to remain in the same general area in the West sub-area of our Camden Bay survey grid for 16d in 2007 and for 6d in 2008 while seismic surveys were conducted 10-50km east of them. During feeding and travelling periods, averages of ~2,500 and ~350 bowhead whales were present in our survey area. The mean distance from the centre of the seismic survey area was not significantly different between periods with (51.4km) and without (49.6km) seismic during feeding periods, but the mean distance was significantly greater with seismic during travelling periods (51.5 vs 27.3km, respectively). During feeding periods, the highest sighting rates were recorded in the West sub-area in areas where seismic sounds were estimated to have been ≥120dB re 1 µPa (rms). During the travelling period, sighting rates in the sub-area that included the seismic operation declined as seismic exposure increased suggesting localized avoidance of seismic operations, but sighting rates were not significantly different among the East, Central and West sub-areas. Based on aerial sightings and observations from vessels, feeding bowheads appeared to tolerate seismic sounds until levels approached ~160dB but some feeding whales appear to have tolerated higher levels. One group of three whales tolerated received levels of seismic sounds ~180dB re 1 µPa (rms) and eight groups (12 individuals) tolerated levels >170dB. The latter levels are much higher than the 120-30dB threshold for avoidance by migrating bowhead whales observed during seismic operations near the same location in 1996-98. Detections of bowhead calls via acoustic recorders during the same period had similar distribution patterns during seismic and non-seismic periods, suggesting that bowheads did not divert 50-75km around seismic operations. The latter distances correspond to the ~120dB distances from the two seismic survey areas. Thus, it appears that bowhead whales will tolerate higher levels of seismic sounds when feeding than when travelling. Similar tolerance to seismic has been seen in the summer feeding areas in Canadian waters.

KEY WORDS: ACOUSTICS; ARCTIC; BEAUFORT SEA; BOWHEAD WHALE; FEEDING; NOISE; SURVEY-AERIAL; SURVEY-VESSEL

INTRODUCTION

Bowhead whales have been observed to change their distribution and behaviour in reaction to offshore seismic programs at widely varying distances, depending on the season, geographic location and activities of whales (reviewed in Richardson *et al.*, 1995; Gordon *et al.*, 2004). Richardson *et al.* (1986) observed bowhead whales near seismic operations on 21 occasions during summer in the Canadian (i.e., Eastern) Beaufort Sea. No changes in distribution or avoidance by whales of seismic operations were observed when whales were 6-99km from the seismic source where received sound levels were estimated to be 107 to 158+dB re 1 µPa (rms). They did, however, find subtle changes in surfacing, respiration and dive behaviours that appeared to be related to the nearby seismic operations. Similar results were obtained by Ljungblad *et al*. (1988) in the Central Beaufort Sea, who saw subtle changes in behaviour at 3.5 and 8.2km from the source vessel when received sound levels were 157 and 142dB re 1 µPa, respectively, and total avoidance when the source vessel approached to 1.3-7.2km where received levels were 152-178dB. Miller *et al.* (2005) made similar observations and noted that some feeding whales in the Canadian Beaufort Sea tolerated approach of active seismic vessels to distances where received levels would have been >180dB.

At the other extreme, Miller *et al.* (1999) found that most migrating bowheads in the Central Beaufort Sea avoided the area within about 20km of seismic operations in open water conditions and some avoided them when 20-30km away. At 20-30km, received levels of seismic pulses were estimated to be ~120-30dB re 1 µPa (rms) (Miller *et al.*, 1999; Richardson *et al.*, 1999), which is much lower than sound levels tolerated by whales during the summer studies. The reason for this wide range of reactions to the same sound levels is speculative, but the reactions appear to be influenced by the activities of the whales, and possibly their geographic location. Feeding and socialising bowheads in the Eastern Beaufort Sea seem to be more tolerant of potential sources of disturbance than are bowheads migrating through open water in the Central Beaufort Sea. The results of Ljungblad *et al*. (1988) suggest that responsiveness may also be relative low at certain times in the Central

Beaufort Sea. If so, that could suggest that the variation in responsiveness is more a function of whale activity than of geographic location.

During the late summers and autumns of 2006-8, aerial surveys, vessel-based observations and acoustic monitoring were conducted in the Central Beaufort Sea by Shell Offshore, Inc. (Figs 1-3). These projects were part of a mitigation and monitoring program associated with seismic and other exploration and development activities. During the aerial, vessel and acoustic surveys, bowhead whales were seen near the seismic operation. The results of the surveys are reported here to contribute to the understanding of the reasons for the wide variation in the reactions by bowhead whales to seismic operations.

METHODS

Information on bowhead whale distribution and numbers was available from three components of the monitoring program. (1) Aerial surveys provided information on the distributions and numbers of bowhead whales present before and during the seismic survey period. (2) Observations from the source and support vessels provided information on the closest approaches of whales to the seismic operation. (3) Data from an array of acoustic recorders provided information on the distribution and frequency of occurrence of whale calls during seismic and non-seismic periods both near and far from seismic operations.

Aerial surveys

Aerial surveys were conducted in the Central Beaufort Sea from 26 August through 24 September 2006, 22 August through 8 October 2007 and 6 July through 11 October 2008 (Figs 1-3). They were flown at 305 or 457m above sea level in a twin engine, high-wing deHavilland Twin Otter aircraft. Three or more observers were present during all surveys; one primary observer on each side of the aircraft recorded marine mammal observations and a third observer operated a laptop computer to record data. The aircraft position and altitude were automatically recorded onto the laptop from a GPS. For each marine mammal sighting, the number, species, and inclinometer angle when the sighting was perpendicular to the aircraft track were entered into the computer by the third observer. Each observer dictated those and additional details of sightings into a digital recorder for validation of real time entries and to record information that was not entered in real time. The additional details included whale activities or behaviours, relative speed, heading, size class, sea conditions using the Beaufort wind force scale, percent ice cover, percent of viewing area obscured by glare and a subjective evaluation of overall sighting conditions.

Survey grids

The survey grids varied among years and among periods within each year, depending on the sizes of airgun arrays that were used, or planned to be used, during seismic operations. Surveys were conducted on all days when weather was suitable and the aircraft was available (Table 1). One survey grid was flown in 2006 and all surveys were conducted before a brief seismic survey was conducted using a single airgun. Surveys started on 26 August and the last survey was attempted on 24 September. Transects ranged in length from 51 to 74km and were equally spaced within the 5,658km^2 survey area (Table 1; Fig. 1).

Three survey grids were flown in 2007; one grid was designed to monitor marine mammal distribution near operations offshore of Harrison Bay at the Phoenix prospect (Fig. 2). Surveys began on 22 August and ended on 8 October. Transects ranged in length from 60 to 76km and were equally spaced within the 9,477km^2 survey area. Two additional survey grids were designed to monitor marine mammal distributions during operations at the Sivulliq prospect in Camden Bay. The first Sivulliq grid (Fig. 2) was designed to monitor operations before the seismic survey started. Transects ranged from 47-64km long within the 15,565km^2 survey area. The second Sivulliq grid was designed to monitor marine mammal distribution around a deep-penetration seismic program and was implemented on 18 September (Fig. 2). Transects ranged from 87-146km long within the 23,962km^2 survey area.

Several aerial survey grids were flown in 2008. They covered the same general areas as 2006 and 2007 (Fig. 3). Surveys were started on 6 July and continued until 11 October. Initial surveys were flown in the Camden Bay area and transects ranged in length from 63-87km within a survey area of 5,658km^2 (Fig. 3). The second and third survey grids were flown in the Harrison Bay area to support Shell Offshore, Inc., PGS Onshore, Inc. and Eni U.S. Operating Co., Inc. activities and transect lengths and spacing varied during the season, depending on the activity that was taking place at the time of the survey. When seismic sources were small, transects were spaced closer together and did not extend as far north as when large seismic sources were operating in the area. The overall survey area was 18,299km^2. An expanded grid was flown in the Camden Bay area from 13 September to 11 October to encompass the larger sound radii associated with Shell's primary seismic vessel, the *Gilavar* (Fig. 3). Transect length was 67-129km within the 17,891km^2 survey area.

Transects in each of the Camden Bay and Harrison Bay areas were assigned to one of three sub-areas for analyses: East, Central and West. In each year, the Central sub-area contained the active seismic patch and

extended a few km east and west of it. The three sub-areas for each grid are shown on Figs 1-3. The West and East sub-areas were areas surveyed to the west and east, respectively, of the Central area.

Whale activities

The activities of whales frequently cannot be determined during the brief period that whales are in view during aerial surveys, but some behaviours are strong indications of specific activities. Würsig *et al.* (2002) describe the activities of bowhead whales during late summer and autumn in the Central Beaufort Sea and Thomas *et al.* (2002b) describe details of the surfacing, respiration and dive characteristics of bowheads engaged in these activities. The principal activities recorded by Würsig et al. (2002) were feeding (47%), travelling (31%), socialising (18%) and other activities (4%). Other activities included resting, milling, play and aerial.

Travelling whales leave a distinctive pattern of surface disturbance. They can be recognized by steady directional swimming at ~4.5km/h (Koski *et al.*, 2002; Rugh, 1990) with mean dive durations of ~14min and mean periods at the surface of ~1.5min. While they are at the surface, they blow ~6 times with ~16s between blows (Thomas *et al.*, 2002b). Whales surface briefly when they blow and leave a large ring at the surface. For travelling whales, these rings are about 20m apart and tend to be in a straight line behind the whale. When sea-state is low, they can be seen for several minutes after a whale dives.

Under some circumstances, feeding whales cannot be distinguished from travelling whales when they first surface. However, feeding whales typically slow down after arriving at the surface, sometime turn, are oriented in random directions and they sometimes dive steeply. Other whales are frequently seen nearby exhibiting similar behaviour. Signs of feeding include open mouth, mud streaming from the corner of the mouth, mud streaming off the body, defecation and a high fluke out dive (Würsig *et al*., 1985; 1989).

Socializing whales are readily recognized by white-water and vigorous activity, whales seen at the surface in groups, whales frequently chasing other whales and frequent lifting of flippers and flukes out of the water. Bowhead whales tend to spend longer periods of time at or near the surface when socialising than when engaged in other activities.

During this study, the data were classified as being from travelling periods or feeding periods based on the predominantly observed activity of whales during aerial surveys.

Data selection

Environmental factors such as sea conditions and glare can impact an observer's ability to see marine mammals during aerial surveys and hence bias results. Cetacean sightings were "useable" for quantitative analysis when the following criteria were met: Beaufort wind force of 4 (winds 20-30km h^{-1}) or less, glare covering 30% or less of the viewing field, overall sightability described as excellent to moderately impaired and whales were on transect. To be considered on-transect, sightings had to be of whales at the surface and within the truncation distance used for estimation of $f(0)$ in the DISTANCE program.

The effects of exposure to seismic sounds on whale distribution and behaviour are examined below. Sound exposure is categorized as "not exposed" when no known seismic sources were present and either "<120dB" re 1 μPa (rms) or "≥120dB"[1] whenever seismic sources were operating. Sound propagation equations derived empirically from sound source verification measurements in the seismic survey areas were used to estimate the received levels of seismic sounds at each bowhead whale sighting. Different equations were used for each combination of airgun array and seismic survey area to account for source and site-specific sound propagation characteristics. The selection of 120dB as a cut point for analyses was determined by a requirement specified by the U.S. National Marine Fisheries Service to monitor presence of mother-calf pairs within that sound isopleth.

Multivariate analyses

A preliminary multivariate analysis was conducted to explore the possibility of assessing the effects of various factors on bowhead whale abundance and distribution within the Central Beaufort Sea. By taking into account temporal and environmental variables that affect bowhead whale distribution, it was hoped that the effects of seismic activities on their distribution could be estimated. Bowhead whale sighting rates over the years 2006–08 were modelled by a suite of anthropogenic and environmental variables using a negative binomial regression (R 2.8.1: R Development Core Team, 2005). The response variable was the number of bowhead whale sightings per 2–min time interval along a transect (hereafter, "segment"), and survey effort in the segment was used as an offset variable to account for differences in survey effort among segments. Only on–transect useable sightings by a primary observer while on systematic surveys were used in the analyses.

Explanatory variables were identified and selected based on their potential to affect bowhead sighting rates and were as follows: year, month, longitude, sightability (subjectively assessed on a scale of 0 to4 where 0 is ideal conditions and 4 is extremely poor conditions), percent ice cover, water depth and exposure to seismic.

[1] No sightings and very little aerial survey effort were obtained in areas estimated to have been exposed to ≥120dB re 1 μPa (rms); therefore, the data presented as ≥120dB represent primarily data where exposure levels were 120-60dB.

Each record in the database contained a value for each variable, as well as the effort and number of bowhead whale sightings in that segment. Year, month and exposure to seismic were categorical variables; sightability, longitude, percent ice cover and depth were regression variables. Average depth was determined for each segment using data from the General Bathymetric Chart of the Oceans (GEBCO, 2003) and depth contours produced by MapInfo software (Pitney Bowes, Inc., 2007). Exposure to seismic was estimated based on the sound source verification data described in **Seismic operations** below. Estimated received levels were grouped into the "exposure" categories not exposed,<120dB and 120–190dB. There were too few segments with received levels 160–190dB to treat them separately. When more than one seismic source was operating at the same time, the highest estimate of received sound level was used for analysis. Segments that were surveyed during post–seismic periods (3min to 24h after cessation of seismic) were excluded.

The ability of models containing different combinations of the above variables to explain variations in bowhead sighting rate data was tested using Akaike's Information Criterion (AIC; Burnham and Anderson, 2002). More details of procedures can be found in Christie et al. (2009).

In the analysis, the variables year, longitude and sightability were included in all candidate models to account for their respective effects on sighting rates while not explicitly testing their explanatory power. In contrast, we were interested in assessing the explanatory ability of the variables month, ice cover, depth and exposure to seismic, and therefore, tested every possible combination of these four variables. In addition to testing all single and additive combinations of test variables, a null model including year, longitude and sightability was run to determine whether the test variables improved overall model fit.

Four interaction terms were tested in addition to the main effects. These interaction terms were exposure×year, exposure×month, exposure×depth and exposure×ice. Only interaction terms containing the variable exposure were included because of interest in the effect of seismic activities on sighting rates. Models including a single interaction term and all possible combinations of main effects were tested using AIC. In total, 36 models were tested.

Density Estimation

Line transect methodology (Buckland *et al*., 2001) was used to convert survey effort and bowhead whale sightings to estimates of density. Probability detection functions $f(0)$ were calculated from the survey data using the program DISTANCE (Thomas *et al*., 2006, version 5.0, release 2). Density estimates included corrections for availability bias $g_a(0)$=0.153 for feeding whales and $g_a(0)$=0.125 for travelling whales. These correction factors were from Thomas *et al*. (2002a) and were based on observations of bowhead whales engaged in those activities during late summer and autumn. It was calculated using the method in Eberhardt (1978).

Vessel survey data

Marine mammal observers were present on all vessels and watched for marine mammals during all daylight periods. Bowheads seen by observers on the source vessel and various support vessels during seismic periods provided information on the closest points of approach to operating seismic vessels.

Acoustic data

A total of 35 Directional Autonomous Seafloor Recorders (DASARs) in 2007 and 40 in 2008 were deployed in five N-S arrays located east and west of the seismic survey area to monitor bowhead vocalizations as they migrated west during seismic and non-seismic periods (Fig. 4). Locations of whale calls around each DASAR array were determined by triangulation of bearings to calls from the individual DASARs (Greene *et al*., 2004). In 2007, the majority of the DASARs were deployed 10-24 August and were retrieved 9-12 October; however, 4 DASARS at site 1 were not recovered prior to freeze-up and were retrieved in August of 2008. In 2008, the majority of the DASARS were deployed 11-21 August and were retrieved 2-8 October. Calls were manually detected during 2007 but in 2008 an automated call detection system was used.

Seismic operations

Shell Offshore, Inc., conducted airgun sound source verification (SSV) tests in the Central Beaufort Sea on 30 August and 14 and 17 September 2007; they conducted production seismic surveys from 18 September through 3 October 2007. On 30 August and 14 September, sounds from two 10in^3 airguns used for shallow hazard surveys were measured; on 17 September, the sounds from the 3,147in^3 array of 24 airguns used during production seismic were measured. All production surveys were conducted within the block outlined in Fig. 2, and shallow hazard surveys were conducted there, and along ~148°40' west longitude shown as a shaded bold line on Fig. 2. During the 18 September to 3 October period, the full airgun array was operated for ~792km of deep-seismic survey lines; an additional ~769km of lead-in, lead-out and ramp up survey was conducted where the source varied from a single mitigation gun to the full array.

In 2008, three companies conducted seismic programs in the Alaskan Beaufort Sea but no more than one of these operations was offshore of the barrier islands at one time. Seismic activity began on 22 July in Camden

Bay and was continuous in some portion of the Beaufort Sea until 9 October. There were short periods without airgun activity during periods of bad weather, while the source vessels moved between survey sites and during shutdowns when marine mammals were sighted in or near the 180 dB re 1 μPa (rms) safety radius from the seismic arrays. SOI conducted large airgun array seismic from the *Gilavar* and shallow hazards and site clearance surveys from the *Henry Christoffersen* and *Alpha Helix*. Eni conducted ocean bottom cable/transition zone seismic surveys in the lagoons and nearshore waters off Oliktok Point (Fig. 3). BP Exploration (Alaska) Inc. also conducted ocean bottom cable seismic surveys in Foggy Island Bay (Fig. 3).

RESULTS

In 2006, 35 useable bowhead whale sightings of 49 whales were made during nine surveys covering 2,861km of useable effort from 26 August to 24 September (Table 1; Fig. 5). In 2007, 81 bowhead whale sightings of 114 whales were made during 16 aerial surveys covering 7,362km of usable effort from 22 August to 8 October (Table 1). In 2008, 92 usable sightings of 131 whales were made during 53 surveys covering 23,927km of useable effort from 6 July to 11 October (Table 1). Bowheads were seen during most surveys where >150km of survey effort was obtained during the main migration period from ~26 August-25 September. Bowheads were scattered throughout the survey area, but in 2007 and 2008, they were most abundant 10-50km west of the Sivulliq prospect (Figs 6 and 7).

Numbers in the survey area

The activities of whales were related to the numbers that were found in all three years. When whales migrated through the study areas without stopping to feed, the numbers detected were generally low and ranged from a few to less than 1,000 whales. Excluding 28-29 August 2008, when a major pulse of whales migrated through the Harrison Bay study area, an average of ~350 bowhead whales was estimated to have been present in the study area during non-feeding periods (Table 2). In comparison, during feeding periods 10-21 September 2007 and 13-19 September 2008, an average of ~2,500 bowhead whales was estimated to have been present in the survey grid near Camden Bay (Table 2).

Activities of whales

The two most common activities of bowhead whales during the late summer and autumn are feeding and travelling (Würsig *et al*., 2002). Travel was a common activity recorded in all three years (27–59% of sightings with activity recorded), and was the predominant activity in 2006 (Fig. 8). However, feeding was the most prevalent activity in both 2007 (50%) and 2008 (43%). Resting, socializing and "other" were observed less frequently.

Headings were recorded for 46 swimming bowhead whales during the feeding period. The mean vector heading was westward (290°T), and although the headings were widely scattered, they were significantly different from random (circular SD=94°T, P=0.043, Rayleigh Test). Twenty-six headings were recorded during travelling periods. The mean vector heading was westward and was significantly different from random (287°T; circular SD=79°T, P=0.02, Rayleigh test; Figure 9A). Similarly, during the feeding period the mean vector heading was westward and was significantly different from random (270°T; circular SD=61°T, P=0.002, Rayleigh test; Figure 9C).

Sample sizes were small when sightings were examined according to seismic exposure category. Headings were westward during periods without seismic present, but they were not significantly different from random during either feeding (247°T, circular SD=91, P=0.42) or travelling (294°T, circular SD=84, P=0.13) periods. Although too few headings were recorded during periods when bowheads were exposed to seismic to conduct meaningful statistical tests, it is worth noting that two of the six sightings recorded as exposed to ≥120dB re 1 μPa in Fig. 9B were east of the seismic operation heading toward it (Fig. 7).

Relative swimming speeds of bowhead whales were recorded for 73 bowhead sightings during late summer and autumn of 2007-8; 48% swam at medium speed, 32% at slow speed, 16% had no forward motion (none) and 4% swam at a fast speed. During the feeding period, 44% of bowhead sightings were recorded as having medium speeds and 33% had slow speed. During the travelling period, 56% were medium speed and 28%, were slow. Activities of whales were not uniform during these feeding and travelling periods. Some whales seen during the feeding period were travelling and some whales seen during the travelling period were feeding. There were no obvious differences in speed related to exposure to seismic sounds (Fig. 10).

Evidence of displacement

During feeding periods, sighting rates were significantly different among the three sub-areas of the study area (Chi-square test, χ^2=16.6, df=2, P<0.05) with rates being highest in the West and lowest in the Central sub–areas (Table 3). When sighting rates were compared among sub-areas within each received sound level category, sighting rates did not differ significantly among sub-areas at received sound levels <120dB re 1 μPa (rms) (χ^2=4.39, df=2, P=0.11) or when seismic was not present (χ^2=2.37, df=2, P=0.31). However, sighting rates were

significantly higher in the West sub–area than other sub–areas at received sound levels of ≥120dB (χ^2=34.75, *df*=2, *P*<0.001); Fig. 11). The West sub-area is where feeding bowheads were most commonly seen in both 2007 and 2008.

During the travelling period, overall sighting rates did not differ significantly among sub–areas when data from all seismic exposure categories were combined (Chi–square test, χ^2=1.30, *df*=2, *P*=0.52; Table 3). When examined according to presence and level of seismic sounds, sighting rates were not significantly different among sub-areas at received sound levels <120dB (χ^2=0.54, *df*=2, *P*=0.76) and during periods without seismic (χ^2=3.76, *df*=2, *P*=0.15). There were too few data to examine sighting rates in different areas at locations where seismic sounds were ≥120dB. Sighting rates were not significantly different among exposure categories in the West sub-area (Chi–square test, χ^2=1.12, *df*=2, *P*=0.57) but in the Central sub-area, sighting rates were significantly different (Chi–square test, χ^2=11.18, *df*=2, *P*=0.004) with the highest sighting rates during periods with no seismic and the lowest at locations where seismic exposure was estimated to have been ≥120dB. Effort and sightings were too low in the eastern sub-area to test for differences among seismic exposure categories.

Distance of sightings from the centre of the seismic survey area was examined during seismic and non-seismic periods for feeding and travelling bowheads. During feeding periods the average distance from the centre of the seismic survey area not significantly greater during seismic than non-seismic periods (Table 4) (Kruskal–Wallis test, χ^2=0.033, *df*=1, *P*=0.856). In comparison, travelling bowheads tended to be seen significantly farther from the centre of the seismic survey area during seismic periods than non-seismic periods (Kruskal–Wallis test, χ^2=11.75, *df*=1, *P*<0.001, Table 4).

During feeding periods, the average water depth at sighting locations was greater during non-seismic periods (42.9 ± 116.9 m) than during seismic periods with received sound levels ≥120dB (32.7 ± 6.0 m; Kruskal–Wallis test, χ^2=16.6, *df*=2, *P*=0.03; Figure 12).

During travelling periods, there was no statistical difference in the average depth of sightings between periods with no seismic activity and received sound levels ≥120dB rms (Kruskal–Wallis test, χ^2=0.58, *df*=1, *P*=0.45; Fig. 12). Average depth for periods with no seismic activity was 27.8 ± 7.7m versus 29.8 ± 14.8m for periods with received levels ≥120dB rms. Too few data were available to conduct statistical tests of sighting rates within each sub-area with respect to exposure category (Figs 13 and 14).

Multivariate analyses

A total of 5,788 segments (each ~8km of effort) were included in the multivariate analysis, with 154 segments containing 221 bowhead whale sightings. The negative binomial regression fit the data better than a Poisson regression, when the two model types were compared using Akaike's Information Criterion (AIC). Data were not over–dispersed (dispersion parameter < 1), and sample size was large; therefore it was not necessary to use AIC_c or QAIC.

Most models (34 of 36) performed better than the null model containing only non–test variables (sightability, year, longitude). This indicated that test variables (ice, depth, month, exposure) improved overall model–fit and were important predictors of bowhead sighting rates. The highest–ranked model (having the lowest AIC value) included all test variables (depth, ice, month, exposure) and the interaction term exposure×depth (Table 5). According to Burnham and Anderson (2002), only models with ΔAIC≤2.00 receive substantial support; therefore only one model in our candidate model set (the highest–ranked) was well–supported.

To assess the relative explanatory ability of each test variable, average Akaike weights (ω_i) of models that included test variables were compared to those of models not including test variables. Depth, ice and month were equally well–supported (all ω_i = 1.00) and exposure was weakly supported (ω_i = 0.54 versus 0.46 for models not including this variable); however models that included the interaction exposure×depth received substantially more support (ω_i = 0.93) than models without this variable (ω_i = 0.07). Other interaction terms were not well supported by the data.

Weighted parameter estimates, calculated for all variables included in the highest–ranking model, reflected the strength and direction of the relationship between bowhead sighting rates and each variable, including the non–test variables year, sightability, and longitude (Table 6). Parameter estimates for years 2007 and 2008 were negative, indicating that sighting rates were low in these years relative to 2006 (the reference year). Longitude had a very small negative estimate and although we did not explicitly test its predictive power, it likely had little or no effect on sighting rates.

Of the test variables, the parameter estimate for depth had a slight, negative relationship with sighting rates. The shape of this relationship was non–linear which resulted in a small parameter estimate. Sighting rates were negatively associated with ice cover, indicating that bowhead sighting rates were lowest when ice cover was high. Sighting rates were high in September compared to July (the reference month) and October had the lowest sighting rates of all months. Parameter estimates indicated that sighting rates tended to be highest in areas where received sound levels were <120dB re 1μPa (rms). However, sighting rates did not differ between times when no seismic was occurring (not exposed) and times when received levels were ≥120dB.

The interaction term exposure×depth was present in the highest–ranked model, indicating that it substantially improved model fit over models lacking this term.

Vessel-based observations

In 2007, observers on vessels made 26 sightings (51 individuals) of bowhead whales when the airguns were operating. One sighting (3 individuals) was likely exposed to sound levels near 180dB re 1 μPa (rms) while airguns were operating and 7 additional groups (10 individuals) were likely exposed to received seismic sounds >160dB (Table 7). Only one of these groups showed a possible reactions to either the seismic operation or the vessels; two of three whales were breaching (which may or may not have been a reaction to seismic) and levels of seismic sounds (at depth) were estimated to be >170dB. Ten additional sightings (17 individuals) were likely exposed to received levels 140-160dB.

In 2008, observers on vessels made 41 sightings (67 individuals) of bowheads or probable bowheads (unidentified mysticetes) while airguns were operating in the Central Beaufort Sea. The closest sighting to the source vessel was of two unidentified mysticetes at ~3200m ahead of the vessel; no reaction was evident as they swam across the bow of the vessel. Five of the observed groups (7 individuals) may have been exposed to seismic pulses 170-179dB and five other groups (7 individuals) may have been exposed to sound levels 140-159dB.

Sighting rates of cetaceans from all vessels combined increased from 2.9 whales 1,000km^{-1} in areas where exposure to seismic sounds was ≥160dB re 1 μPa (rms) to 4.7 whales 1,000km^{-1} in areas where exposure to seismic sounds was <120dB (Table 8). These rates were not significantly different (Chi-square test, χ^2=3.41, *df*=2, *P*=0.18).

Acoustic data

The acoustic data are currently being analysed and are not ready for presentation. However, some relevant preliminary data are available. Fig. 15 shows call detection rates from the combined sites immediately east and west of the seismic survey area in 2007 and Fig. 16 shows call detection rates from each array in 2008. The black lines at the top of these figures show periods when seismic operations by the *Gilavar*, which operated the large-airgun array, were adjacent to each array. Some bowheads continued to call during seismic periods, but call detection rates were much lower. It is unknown what fraction of the reduction was a result of bowheads moving away from the seismic operation and what fraction was due to the whales that were present being less vocal. However, the rapid increase in call detection rates during periods when seismic operations were suspended suggests that a significant contribution was due to reduced calling. Whale calls often can be detected 15-20km from the DASARs. Calling whales were localised near the DASARs shortly after seismic operations stopped even though it would have taken a minimum of ~4 hours, at a migration speed of ~4.5km/h, for them to arrive near the DASARS from outside of the detection range.

The DASARs were positioned to monitor the main autumn migration corridor of the bowhead whale. The pattern of call locations from the DASARs in 2008 (a light ice year) is similar to the pattern of aerial survey sightings by the BWASP program during years with similar ice conditions from 1998-2008 (Fig. 17), The BWASP surveys cover areas farther offshore than the DASARs (see Monnett and Treacy, 2005) and confirm that the majority of the migration is through waters covered by the DASARs. In 2008, the overall distribution of bowhead whale call locations from the DASARs does not appear to have changed noticeably between periods with and without seismic operations (Fig. 18).

DISCUSSION

Typically, bowheads of the B-C-B stock feed in Canadian waters during the summer and travel through the Alaskan Beaufort Sea during their spring and autumn migration from or toward their wintering areas in the Bering Sea (Moore and Reeves, 1993). During the autumn migration, bowheads occasionally stop to feed, and the most common feeding areas in the Alaskan Beaufort Sea have been found near and east of Kaktovik and near Point Barrow (Landino *et al*., 1994; Ljungblad *et al*., 1986; Lowry, 1993; Lowry *et al*., 2004; Moore and Clarke, 1993; Reeves *et al.*, 1984; Würsig *et al*., 2002). The area in the Central Beaufort Sea where seismic surveys were conducted in 2007 and 2008 has not been heavily used by feeding whales during most earlier years. Long-term studies funded by US Minerals Management Service (Monnett and Treacy, 2005; Treacy *et al*., 2006) have noted relatively low sighting rates of bowheads in that area, though Inupiat traditional knowledge indicates that the Flaxman Island vicinity has historically been a feeding ground.

Although there has been considerable variability in the areas used and the extent of use among years, data collected in the Central Alaskan Beaufort Sea during the late summer and autumn of 2007 and for a short period in 2008 showed a different pattern of use than most years. In 1996-8, bowhead whales seen in the Central Beaufort Sea near Prudhoe Bay tended to swim at medium speed (78%, *n*=468, Miller *et al.*, 1999), their headings were significantly westward (297°T, a.d.=59) and the predominant activity recorded was travel (81%, *n*=136, Miller et al., 1999). In 2007 and 2008, whales swam primarily at medium (48%) and slow speed (32%),

headings were westward but more variable (290°T, a.d.=94) and the predominant activities noted varied between feeding (50% in 2007 and 43% in 2008) and travelling (27% in 2007 and 34% in 2008). Despite these changes in the activities of whales as they passed through the Central Beaufort Sea, acoustic data suggest that the general distribution of bowheads was similar in 2007-8 to other years with low ice cover both during periods with and without seismic activity.

In 1996-8, Miller *et al.* (1999) found that migrating bowheads strongly avoided the area within 20km of seismic operations, and showed less complete, but nonetheless statistically significant avoidance of the areas within 20-30km. Received levels of seismic pulses were typically ~120-130dB at 20km. When data from 2007 and 2008 were combined, there appeared to be small-scale avoidance of the area immediately around the seismic operation during both feeding and travelling periods. Mean sighting distance was significantly farther from the centre of the seismic survey area during seismic periods than during non-seismic periods for travelling bowheads but not for feeding bowheads. This suggests that travelling whales avoided seismic sources at greater distances than feeding whales. During travelling periods, overall sighting rates were not significantly different among the East, Central and West sub-areas or within the West sub-area when examined by seismic exposure category. However, the sighting rates were significantly different among exposure categories in the Central sub-area with the highest sighting rates during periods with no seismic and the lowest during periods when seismic exposure was ≥120dB re 1 μPa (rms) suggesting localized avoidance, more rapid movement through the seismic survey area or that whales were more difficult to detect while there.

During feeding periods in 2007-8, sighting rates were significantly higher in the West sub-area, where feeding was observed, than in the Central and East sub-areas where feeding was not as common. During feeding periods without seismic or at locations with low levels of seismic sounds (i.e., <120dB), sighting rates were not significantly different among the three sub-areas. However, at locations where seismic sounds were estimated to be ≥120dB, sighting rates were significantly higher in the West sub-area and these were the highest sighting rates recorded during the study (Fig. 11). This indicates that feeding bowheads did not avoid areas where seismic sounds were slightly higher than 120dB. The majority of aerial survey effort was in areas where seismic sound levels were >120dB. Little effort was in areas where seismic sounds were estimated to be >160dB re 1 μPa (rms), so the aerial data do not permit a quantitative assessment of whether bowheads avoided areas where seismic sounds were >160dB as has been suggested during the earlier studies by Richardson *et al*. (1986) and Ljungblad *et al*. (1988). The source vessel and its support vessels monitored the area within the 160dB radius of the seismic source and sighting rates were lower, but not significantly so, in areas where seismic sounds were ≥160dB than 120-59dB and <120dB. These data were not broken down into feeding and travelling periods but show that some whales do not avoid the seismic operation when received levels of seismic sounds were >160dB. On a few occasions bowheads were seen much closer to the source vessel apparently tolerating much higher levels of seismic sounds than 160dB during feeding periods. For example, on one occasion in 2007, three bowheads appeared to have tolerated sounds ~180dB, and on three other occasions (5 individuals) whales tolerated sound levels >170dB. Similarly, in 2008 five groups (7 individuals) were seen in areas that were estimated to have been exposed to seismic pulses at 170-79dB.

In 2007-8 fewer whale calls were detected near active seismic operations than in the same area during periods when there was no seismic activity. It is unknown what fraction of this difference is due to whales changing their calling behaviour and what fraction is due to diversion around the operation. The general distribution of whale calls in 2007-8 was similar during seismic and non-seismic periods suggesting that seismic operations did not cause major (i.e., on the order of 50-75km) changes in the migration corridor and whale distribution that would have occurred if whales were diverting when received levels of seismic sounds were 120dB.

If a whale were stationary, it would take an approaching seismic source vessel ~10 h to travel the distance between the 120 and 180dB radius from the source vessel. Miller *et al*. (1999) saw avoidance when whales were exposed to 120-30dB levels of seismic sounds. The nine closest whales sightings during our 2007-8 study tolerated approach of the seismic vessel to a point where received levels were >170dB, so whales had many hours to move away from the path of the seismic vessel had they chosen to do so. Seismic sound levels of 180-90dB re 1 μPa (rms) appear to be well below the level where a few pulses might cause injury to cetacean (Southall *et al*., 2007). Our observations of tolerance of seismic sources are not inconsistent with observations of feeding whales tolerating high levels of seismic sounds while in summer feeding areas in the Canadian Beaufort Sea (LGL Limited, unpublished data ; Miller *et al*., 2005; Richardson *et al*., 1987), and suggest that although bowheads may avoid seismic sources at relatively low received levels and long distances from the seismic source when travelling, they appear to tolerate much higher levels when they have a reason to be in the area, such as the presence of food.

Analyses done to date have not estimated levels of seismic sounds that cause changes in bowhead distribution for feeding whales similar to the analyses done by Miller et al. (1999) for migrating whales, but the available data suggest that avoidance probably occurs when received levels of seismic sounds are ~160dB re 1μPa (rms) with some animals diverting at lower levels and some animals tolerating higher levels. During this study,

travelling whales appeared to divert at lower sound levels than feeding whales but many travelling as well as feeding whales appear to have tolerated levels that substantially exceeded 120dB.

The analyses of 2006-8 data are not complete and further analyses will be conducted. In particular further analyses of the aerial data using multivariate methods may provide more insights into factors that might affect the distance at which whales avoid seismic operations. Further analyses of the acoustic data may provide estimates of the distances, or at least the distances from seismic where animals change their behaviour either by avoiding or changing their calling behaviour, or by a combination of the two. There are a large number of factors, other than food, that might affect bowhead whale distribution relative to seismic operations during their autumn migration. These include, but are not limited to, ice cover, water depth, distance from shore, age, size and breeding status and other sources of disturbance (Koski and Miller, 2002; Moore, 2000; Moore *et al.*, 2000; Treacy *et al*., 2006). These other factors need to be included when assessing potential effects of seismic operations on the distribution and movements of bowhead whales.

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Table 1

Summary of useable survey effort and sightings in the Central Beaufort Sea during summer and early autumn 2006-8. Parentheses indicate less than 500km of useable survey effort. Sighting rates were not calculated (NC) when effort was <250km.

Date	Useable effort (km)	Number of		Raw sightings/ 1000 km
		Sightings	Whales	
2006				
26 Aug	504	3	3	6.0
3 Sep	495	(3)	(3)	(6.1)
4 Sep	435	(8)	(12)	(18.4)
6 Sep	445	(14)	(20)	(31.5)
12 Sep	94	(0)	(0)	NC
13 Sep	404	(4)	(6)	(9.9)
14 Sep	282	(2)	(4)	(7.1)
23 Sep	17	(1)	(1)	NC
24 Sep	135	(0)	(0)	NC
Total 2006	**2,811**	**35**	**49**	**12.45**
2007				
22 Aug	869	4	5	4.6
24 Aug	281	(4)	(4)	(13.8)
3 Sep	339	(5)	(5)	(14.7)
10 Sep	882	16	19	18.1
11 Sep	1,074	18	23	16.8
14 Sep	457	(8)	(15)	(17.5)
18 Sep	708	14	17	19.8
19 Sep	7	(0)	(0)	NC
20 Sep	485	(4)	(4)	(8.2)
21 Sep	1,178	5	17	4.2
26 Sep	47	(0)	(0)	NC
30 Sep	241	(2)	(4)	NC
2 Oct	92	(0)	(0)	NC
3 Oct	551	1	1	1.8
7 Oct	134	(0)	(0)	NC
8 Oct	18	(0)	(0)	NC
Total 2007	**7,362**	**81**	**114**	**11.00**
2008				
6 Jul	636	0	0	0.0
7 Jul	665	1	1	1.5
8 Jul	501	0	0	0.0
9 Jul	732	5	8	6.8
10 Jul	617	0	0	0.0
11 Jul	527	0	0	0.0
12 Jul	704	2	2	2.8
13 Jul	18	(0)	(0)	NC
14 Jul	599	0	0	0.0
22 Jul	220	(0)	(0)	NC
25 Jul	31	(0)	(0)	NC
27 Jul	405	(0)	(0)	(0.0)
2008 continued				
28 Jul	328	(0)	(0)	(0.0)
1 Aug	190	(0)	(0)	NC
2 Aug	471	(0)	(0)	(0.0)
4 Aug	646	0	0	0.0
5 Aug	542	0	0	0.0
6 Aug	398	(0)	(0)	(0.0)
8 Aug	205	(0)	(0)	NC
11 Aug	607	0	0	0.0
16 Aug	189	(0)	(0)	NC
18 Aug	565	0	0	0.0
19 Aug	104	(1)	(1)	NC
23 Aug	701	3	6	4.3
25 Aug	717	1	1	1.4
28 Aug	17	(0)	(0)	NC
29 Aug	795	13	19	16.4
30 Aug	3	(0)	(0)	NC
31 Aug	75	(0)	(0)	NC
5 Sep	466	(0)	(0)	(0.0)
6 Sep	629	7	11	11.1
9 Sep	328	(0)	(0)	(0.0)
10 Sep	444	(0)	(0)	(0.0)
12 Sep	908	6	7	6.6
13 Sep	755	12	17	15.9
14 Sep	41	(0)	(0)	NC
18 Sep	516	7	11	13.6
19 Sep	1,090	17	25	15.6
22 Sep	292	(2)	(2)	(6.8)
23 Sep	193	(1)	(2)	NC
24 Sep	113	(2)	(3)	NC
25 Sep	680	3	3	4.4
26 Sep	727	1	1	1.4
27 Sep	983	2	2	2.0
28 Sep	582	1	2	1.7
29 Sep	693	2	3	2.9
1 Oct	197	(0)	(0)	NC
2 Oct	455	(1)	(1)	(2.2)
6 Oct	428	(0)	(0)	(0.0)
8 Oct	144	(0)	(0)	NC
9 Oct	389	(2)	(3)	(5.1)
10 Oct	325	(0)	(0)	(0.0)
11 Oct	338	(0)	(0)	(0.0)
Total 2008	**23,927**	**92**	**131**	**3.85**

Table 2

Estimated numbers of bowhead whales in the Central Beaufort Sea 22 August - 30 September 2006-8. Estimates calculated using DISTANCE software (Thomas *et al.*, 2006). Densities are corrected for both *f*(0) and *g*(0) biases. Numbers in parentheses should be interpreted with caution due to low survey effort; no estimate is shown (NC) if effort <250km.

Survey no.	Date	Effort (km)	Sightings	Density (/1000 km^2)	Est. no. whales	95% C.I.
2006 Camden Bay - travelling						
1	26 Aug	504	3	23.0	130	44 - 216
2	3 Sep	495	(3)	(22.9)	(130)	(27 - 233)
3	4 Sep	435	(8)	(82.8)	(469)	(265 - 673)
4	6 Sep	445	(14)	(114.7)	(649)	(318 - 980)
5	12 Sep	94	(0)	NC	NC	--
6	13 Sep	404	(4)	(34.8)	(345)	(148 - 542)
7	14 Sep	282	(2)	(15.7)	(116)	(27 - 205)
8	23 Sep	17	(1)	NC	NC	--
9	24 Sep	135	(0)	NC	NC	--
2007 Harrison Bay - travelling						
1	22 Aug	869	4	11.5	109	32 - 365
2	24 Aug	290	4	(68.9)	(653)	(163 - 2,617)
3	3 Sep	339	5	(58.8)	(916)	(325 - 2,582)
2007 Camden Bay - feeding						
4	10-11 Sep	1,809	33	127.2	3,047	1,465 - 6,338
5	11-14 Sep	605	11	179.0	4,826	1,513 - 15,397
6	18-19 Sep	715	14	132.5	3,176	1,651 - 6,109
7	20 Sep	488	4	(13.9)	(332)	(63 - 1,755)
8	21 Sep	1,178	6	86.2	2,065	323 - 13,214
2007 Camden Bay - travelling						
9	26 Sep	51	0	NC	NC	--
10	30 Sep	241	3	NC	NC	--
2008 Camden Bay - travelling						
22	23 Aug	701	3	56.1	318	76 - 1,330
35	22 Sep	292	(2)	(22.4)	(402)	(52 - 3,094)
36	23 Sep	125	(0)	NC	NC	--
37	25 Sep	449	(1)	(14.6)	(261)	(28 - 2,427)
38	26 Sep	671	2	19.6	350	57 - 2,138
39	28 Sep	582	1	11.3	202	21 - 1,873
2008 Camden Bay - feeding						
31	13 Sep	737	12	124.6	2,229	856 - 5,805
32	14 Sep	39	(0)	NC	NC	--
33	18 Sep	288	(6)	(140.3)	(2,510)	(546 - 11,532)
34	19 Sep	868	16	110.0	1,968	544 - 7,116
2008 Harrison Bay - travelling						
23	25 Aug	717	1	10.2	187	28 - 1,234
24	28, 29 Aug	812	11	126.7	2319	470 - 11,450
25	30, 31 Aug	78	(0)	NC	NC	--
26	5 Sep	466	(2)	(47.3)	(866)	(118 - 6,337)
36	23 Sep	68	(1)	NC	NC	--
52	24 Sep	113	(2)	NC	NC	--
53	25, 27 Sep	1,167	4	18.9	346	120 - 995
54	29 Sep	693	1	10.6	194	29 - 1,317
2008 Harrison Bay - feeding						
27	6 Sep	629	6	81.8	1496	461 - 4,860
28	9 Sep	328	(0)	(0.0)	(0)	--
29	10 Sep	383	(0)	(0.0)	(0)	--
30	12 Sep	908	7	24.3	444	151 - 1,304
32	14 Sep	7	(0)	NC	NC	--
33	18 Sep	228	(1)	NC	NC	--
51	19 Sep	219	(1)	NC	NC	--

Table 3

Sighting rates of bowhead whales by sub–areas during aerial surveys in the Central Beaufort Sea, during feeding and travelling periods in late summer and autumn of 2007–8.

	Subarea		
	West	Central	East
Feeding period			
Sightings	50	33	24
Effort (km)	2468	3956	1748
Sightings 1000km^{-1}	20.3	8.3	13.7
Travelling period			
Sightings	14	25	8
Effort (km)	3890	4760	1677
Sightings 1000km^{-1}	3.6	5.3	4.8

Table 4

Distances (km) of bowhead whale sightings from the centre of the seismic survey area during feeding and travelling periods. Data collected during aerial surveys of the Central Beaufort Sea in 2007–8.

Activity period	*n*	Distance from seismic (km)			
Seismic state		Minimum	Maximum	Mean	SE
Feeding periods					
Seismic	53	10.5	102.1	51.4	2.96
Non-seismic	56	15.7	104.8	49.6	2.76
Traveling periods					
Seismic	15	13.1	83.7	51.5	5.65
Non-seismic	34	1.2	68.6	27.3	2.50

Table 5

Confidence model set and null model with associated model weights. The highest ranking model (ΔAIC=0.00) is shown in bold.

Test variables	Non-test variables[a]	K[b]	ΔAIC[c]	ω*i* [d]
Exposure+depth+ice+month+exposure×depth	**Sightability+year+long**	**15**	**0.00**	**0.62**
Ice+depth+month	Sightability+year+long	11	2.31	0.20
Exposure+depth+ice+month+exposure×year	Sightability+year+long	15	3.67	0.10
Exposure+depth+ice+month	Sightability+year+long	13	4.35	0.07
Exposure+depth+ice+month+exposure×ice	Sightability+year+long	15	8.20	0.01
Null	Sightability+year+long	6	66.20	0.00

[a] Variables included in every model
[b] Number of parameters used in model
[c] AIC*i* -AICmin
[d] Akaike weight or probability that a model is the best approximating model among those considered

Table 6

Weighted parameter estimates and unconditional variance estimator for variables included in the highest ranking model.

Variable	Class	Weighted estimate	Unconditional variance estimator
Intercept		-4.97	0.79
Year[a]	2007	-1.78	0.19
	2008	-2.14	0.20
Sightability		-0.95	0.02
Longitude		-0.02	0.00
Exposure[b]	<120dB re 1 µPa (rms)	0.44	0.52
	Not exposed	-0.01	0.34
Depth		-0.01	0.00
Ice		-0.23	0.00
Month[c]	August	0.08	0.20
	September	1.15	0.21
	October	-0.13	0.54
Exposure×depth[d]	<120dB re 1 µPa (rms)	-0.02	0.02
	Not exposed	0.01	0.01

[a]Year has 3 classes, with 2006 as the reference

[b]Exposure has 3 classes, with 120-90 dB as the reference

[c]Month has 4 classes, with July as the reference

[d]Exposure×depth was present in one model; therefore, SE is given

Table 7

Estimated exposure levels in dB re 1 µPa (rms) for bowhead whales seen from vessels during periods when airguns were operating in the Central Beaufort Sea in 2007-8. Sound exposure was estimated from empirical sound source equations for the relevant sound source, location and year.

Exposure levels[a]	2007		2008	
	Sightings	Individuals	Sightings	Individuals
~180	1	3	0	0
170-179	3	5	5	7
160-169	4	5	0	0
150-159	8	14	2	4
140-149	2	3	3	3
130-139	0	0	0	0
120-129	0	0	2	4
<120	8	21	29	49
All	26	51	41	67

[a] The 180dB distances for operation of the large airgun arrays were 2.25-2.90km. Data for exposure levels ~180dB come mainly from the source vessel and data for <180dB come mainly from support vessels.

Table 8

Sighting rates of cetaceans from vessels in the Beaufort Sea during summer and autumn in 2006-8.

Estimated seismic sound levels in dB re 1ąPa (rms)	Number of sightings	Effort (km)	Sighting rate (number 1,000km^{-1})
≥160	12	4,182	2.87
120 - 159	23	6,395	3.60
<120	106	22,773	4.65

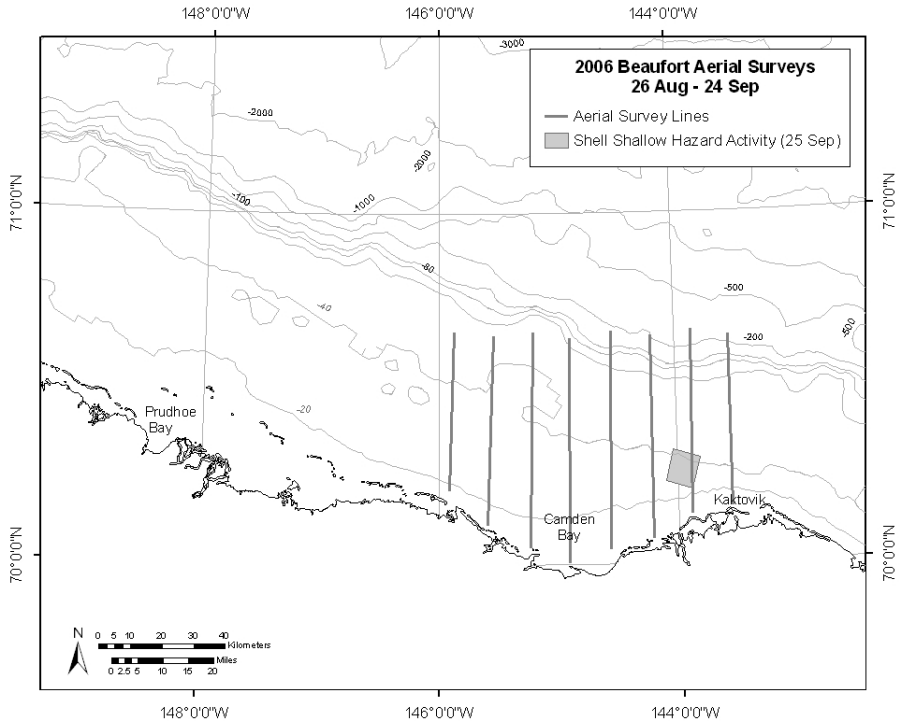

Fig. 1. Locations of aerial transects surveyed in the Central Alaskan Beaufort Sea 26 August - 24 September 2006. Note that the area shown is smaller than in Figs 2 and 3.

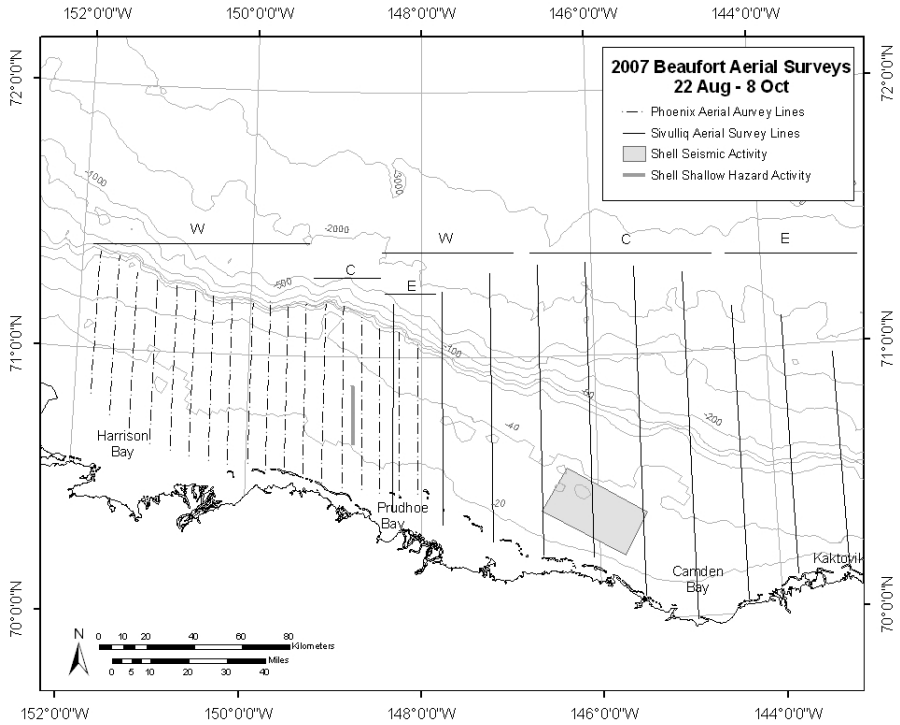

Fig. 2. Locations of aerial transects surveyed in the Central Alaskan Beaufort Sea 22 August - 8 October 2007.

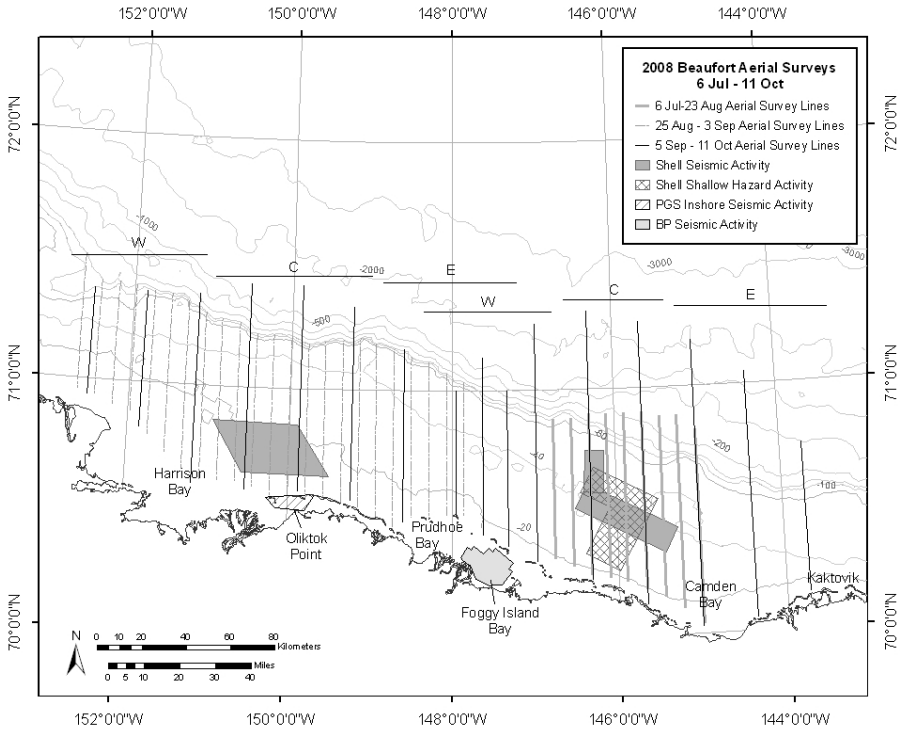

Fig. 3. Locations of aerial transects surveyed in the Central Alaskan Beaufort Sea 6 July - 11 October 2008.

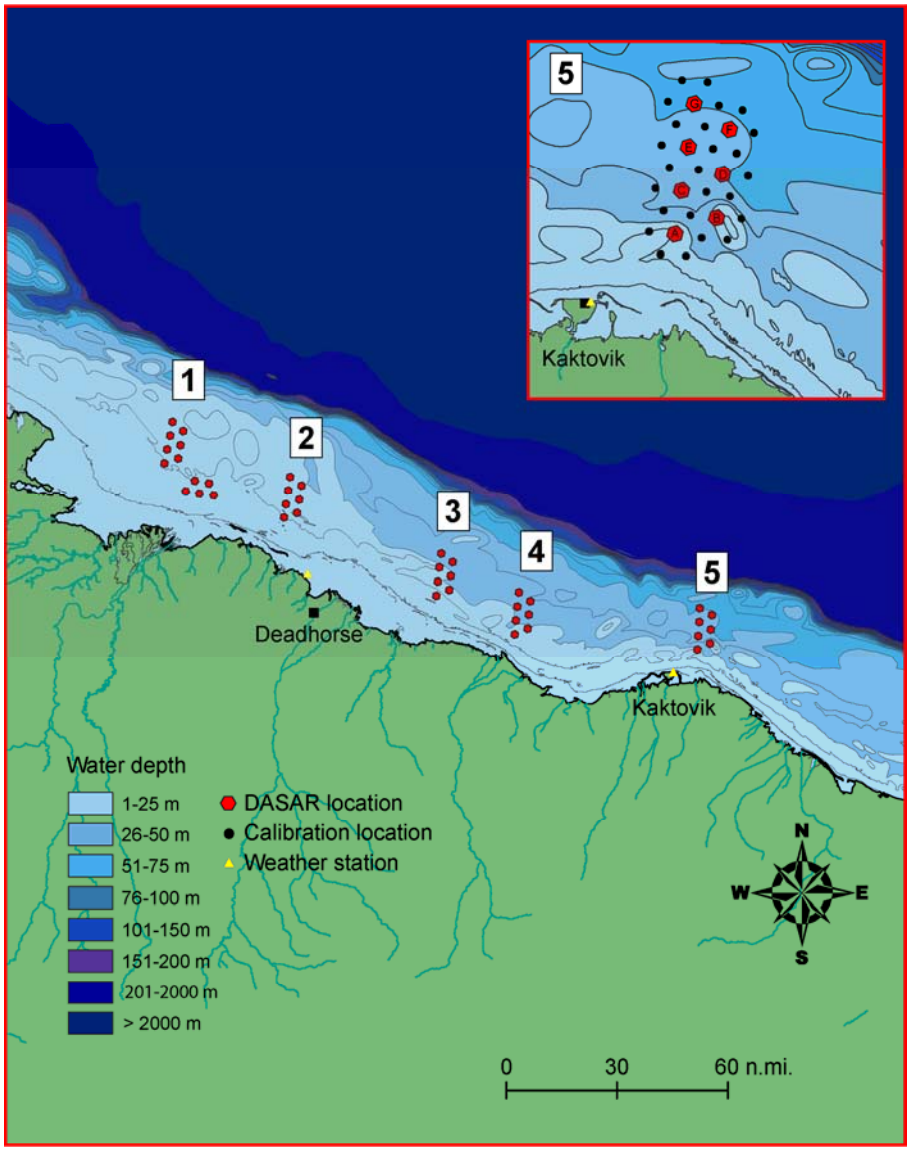

Fig. 4. DASAR deployment locations during the 2007-8 field seasons (azimuthal equidistant projection). The five sites are labeled 1–5 from west to east, and A–G from south to north (see inset). The five DASARS located southeast of array 1 were deployed by Eni only in 2008.

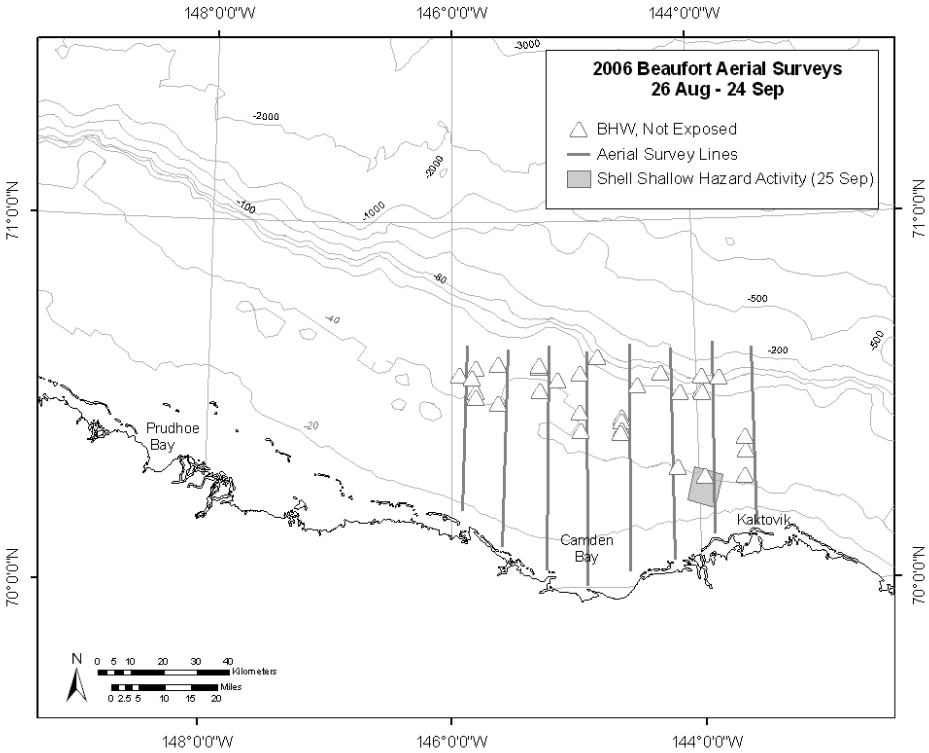

Fig. 5. Bowhead whale sightings during aerial surveys 26 August - 24 September 2006.

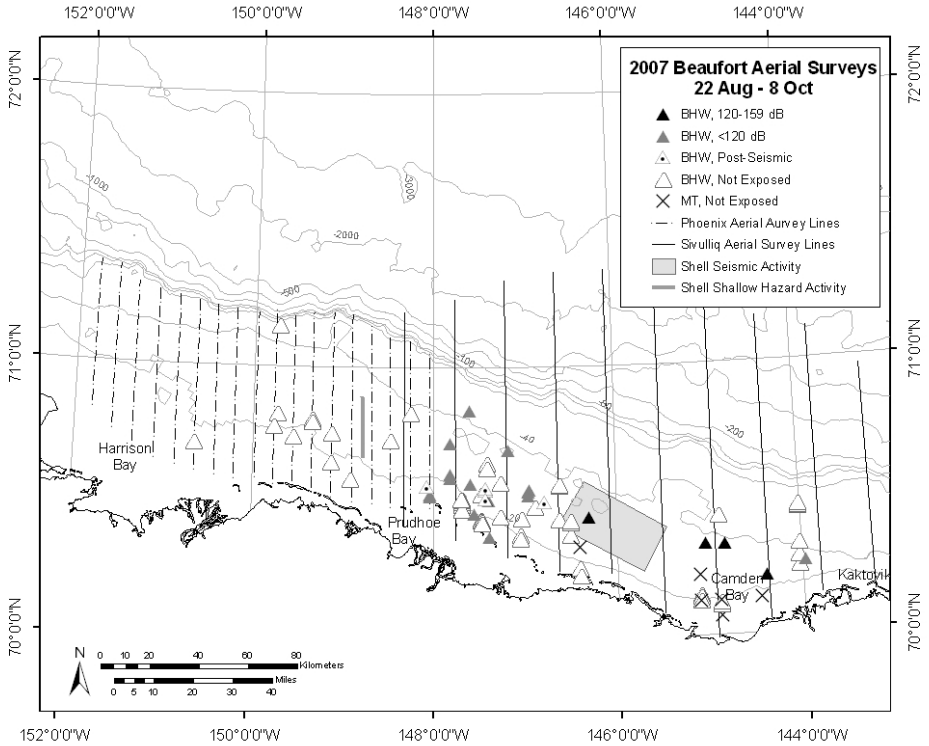

Fig. 6. Bowhead whale sightings during aerial surveys 22 August - 8 October 2007.

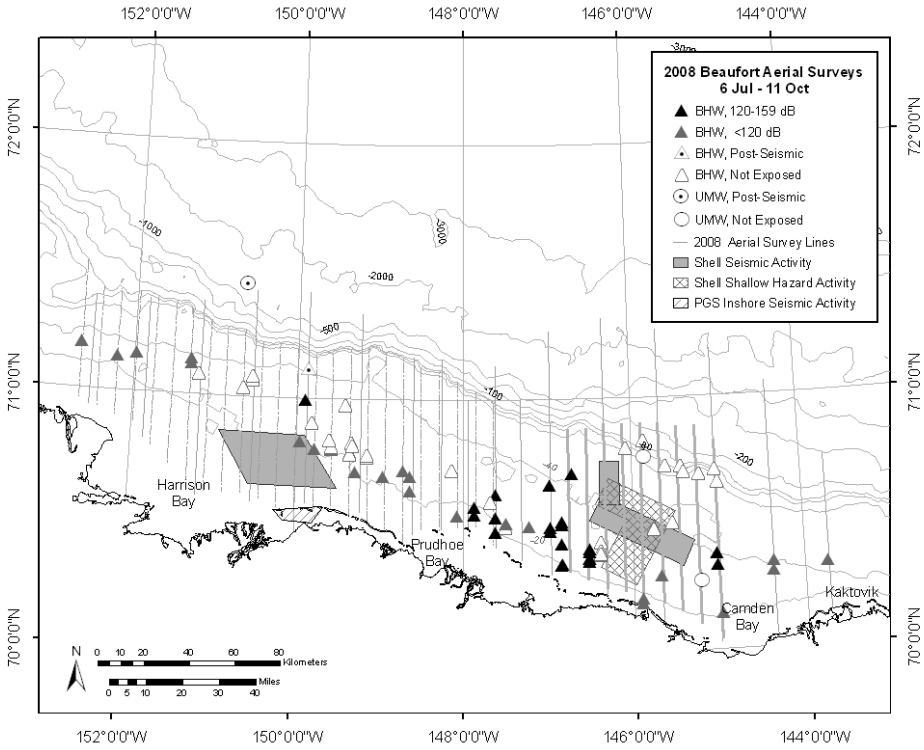

Fig. 7. Bowhead whale sightings during aerial surveys 6 July - 11 October 2008.

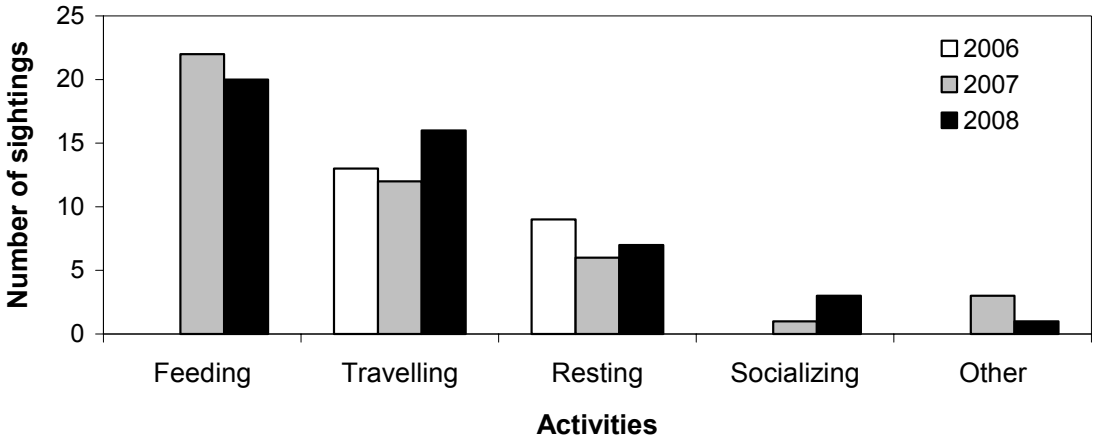

Fig. 8. Activities of bowhead whales in the Central Beaufort Sea late summer and autumn 2006-8.

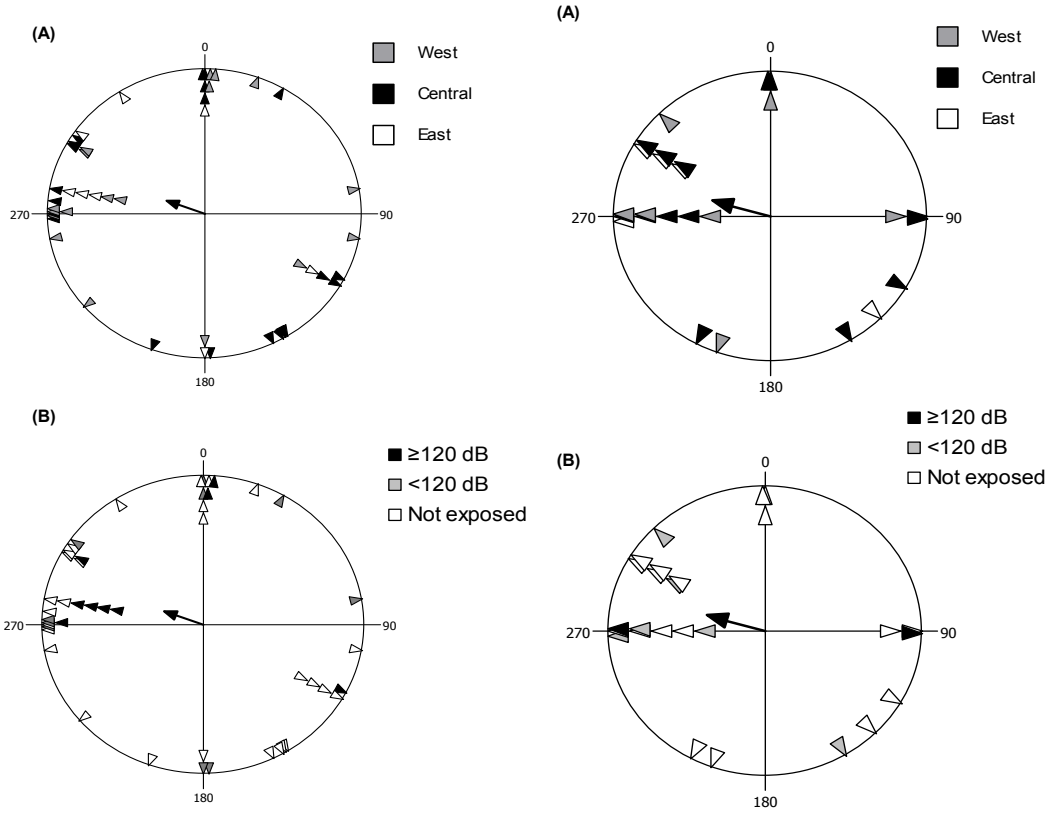

Fig. 9. Headings of bowhead whale sightings during feeding periods by (A top left panel) survey sub–area and (B bottom left panel) received sound levels of seismic pulses in dB re 1µPa (rms) and during travelling periods by (A top right panel) survey sub–area and (B bottom right panel) received sound levels of seismic pulses in dB re 1µPa (rms). Data from aerial surveys of the Central Beaufort Sea in 2007–8.

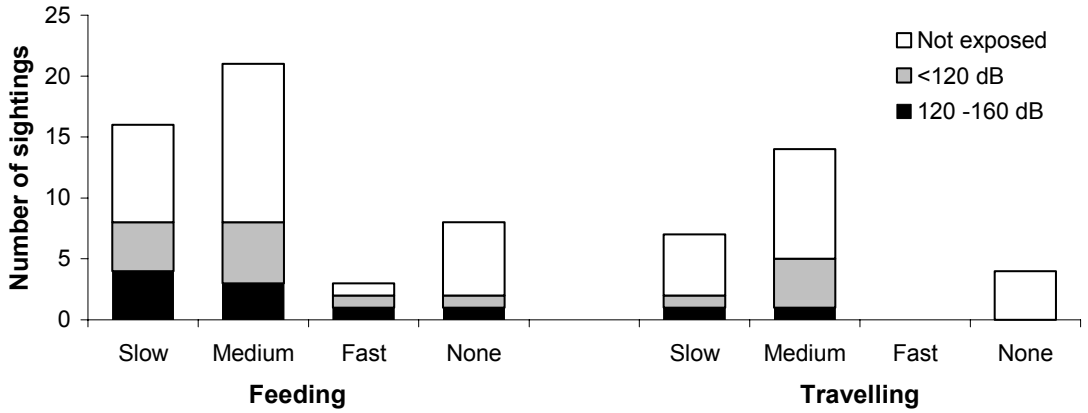

Fig. 10. Speeds of movement recorded for bowhead whale sightings during feeding and travelling periods according to received sound level categories measured in dB re 1 µPa (rms). Data collected during aerial surveys in the Central Beaufort Sea, 2007–2008.

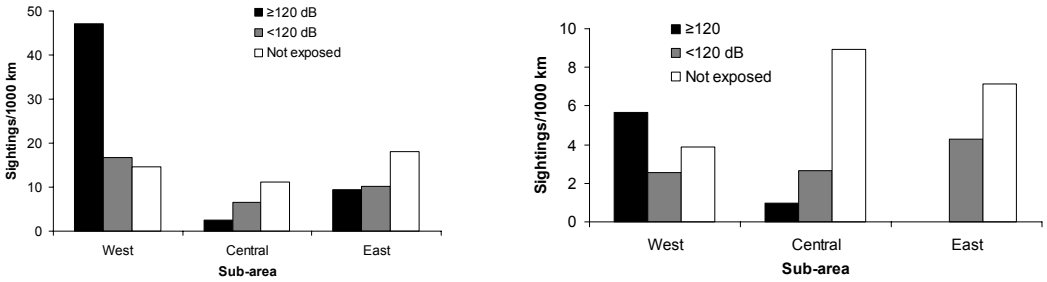

Fig . 11. Comparison of bowhead whale sighting rates during feeding (left) and travelling (right) periods by sub–areas. Received sound level is indicated by shading. Data were collected during aerial surveys in the Central Beaufort Sea in late summer and autumn of 2007–08.

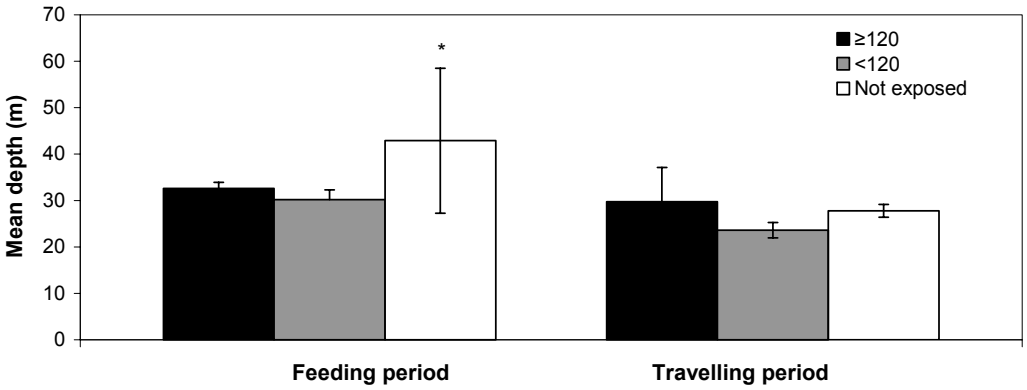

Fig. 12. Average water depth (±SE) at bowhead whale sightings made during feeding and travelling periods according to sound exposure category measured in dB re 1 µPa (rms). Asterisk indicates a significant difference among mean water depth during feeding periods. Data collected during aerial surveys of the Central Beaufort Sea in late summer and autumn 2007–2008.

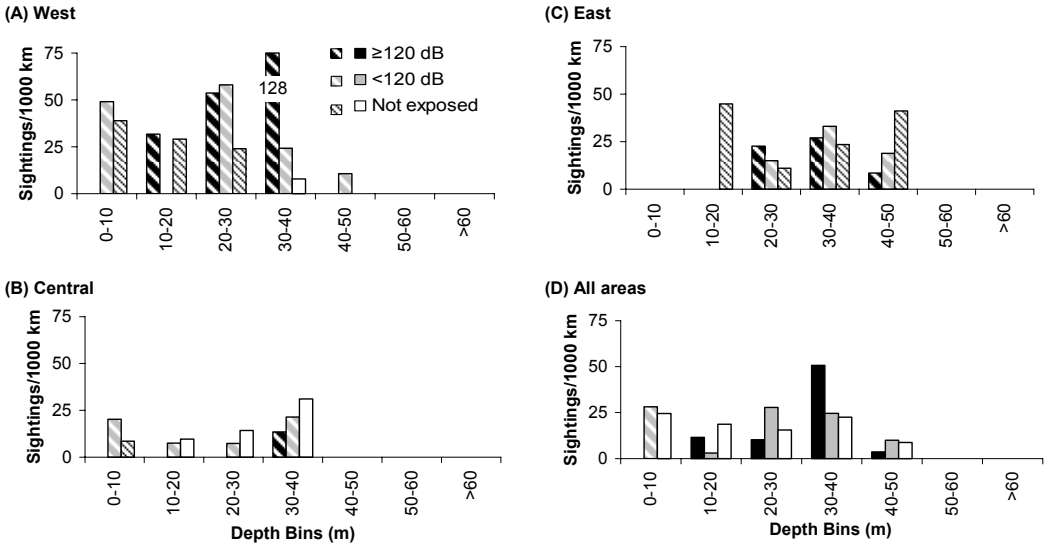

Fig. 13. Bowhead whale sighting rates by 10–m water–depth bins during aerial surveys of the Central Beaufort Sea during feeding periods in 2007–08 in the (A) West, (B) Central, (C) East and (D) All sub–areas. Estimated received levels of seismic pulses in dB re 1 µPa (rms) indicated by shading. Bars with cross–hatching represent depth bins with <250km of effort. Numbers over bars indicate values that exceed the y–axis scale.

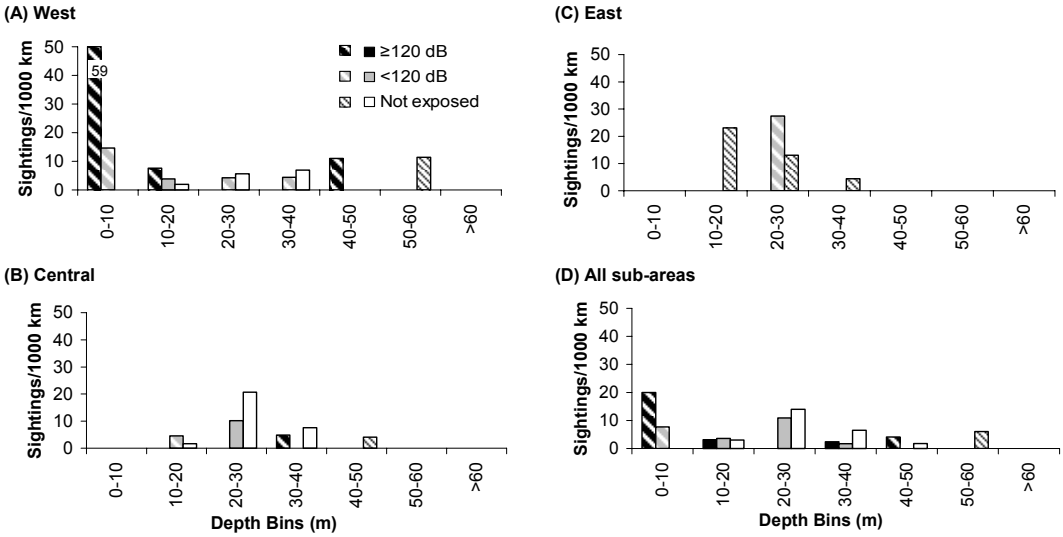

Fig. 14. Bowhead whale sighting rates by 10–m water–depth bins during aerial surveys of the Central Beaufort Sea during travelling periods in 2007-8 in the (A) West, (B) Central, (C) East and (D) All sub–areas. Estimated received levels of seismic pulses in dB re 1µPa (rms) indicated by shading. Bars with cross–hatching represent depth bins with <250km of effort. Numbers over bars indicate values that exceed the y–axis scale.

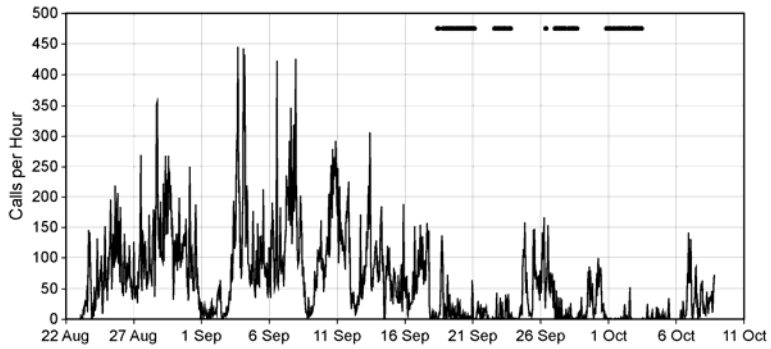

Fig. 15. Hourly call detection rate at DASAR sites 3 and 4 combined in 2007. These sites were west and east, respectively, of seismic operations that began on 18 September. Black lines at the top of the plot indicate hours during which seismic acquisition was ongoing.

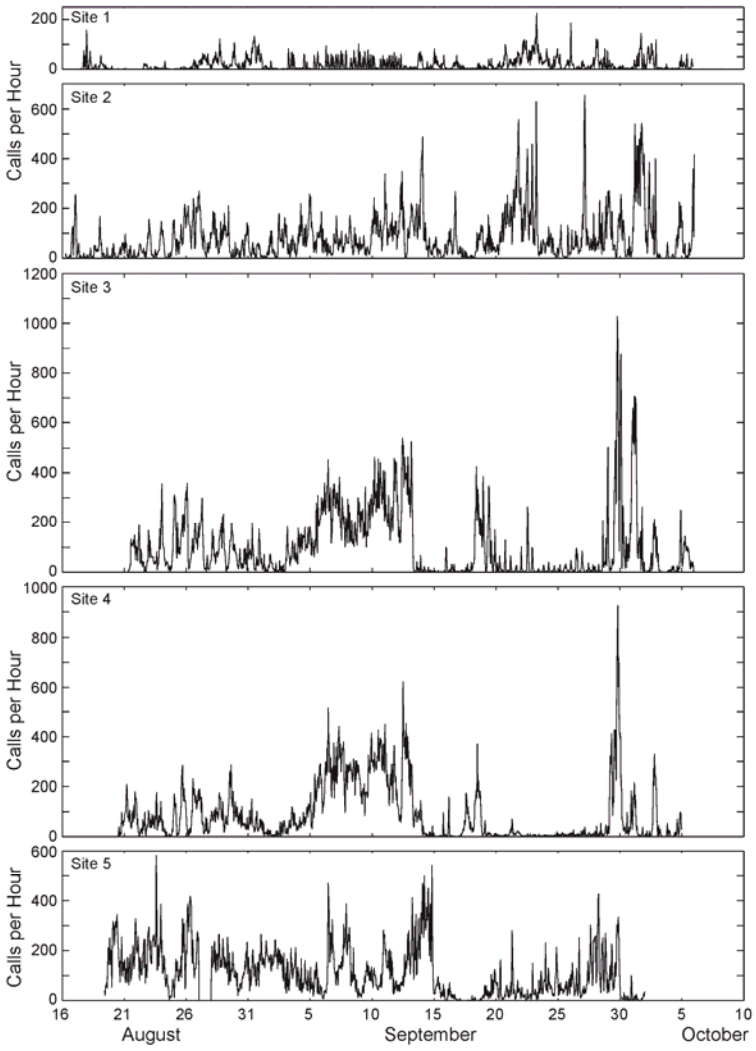

Fig. 16. Hourly call detection rates (preliminary data) at all five sites over the entire field season in 2008. Seismic acquisition was ongoing at and near Site 1 from 3 to 12 September and 30 September to October and between Sites 3 and 5 from 13 to 28 September.

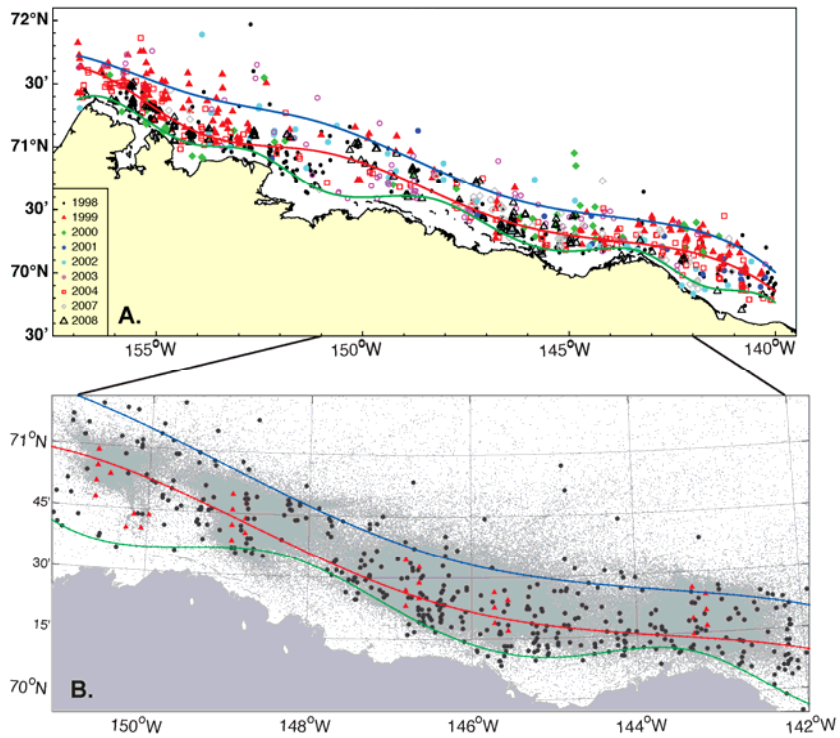

Fig. 17. (A) BWASP sightings in the years 1998–2004, 2007 and 2008 (preliminary data) which were all low-ice years. The middle line shows the median distance from shore for whale sightings, the inshore line is the 10th percentile and the offshore line is the 90th percentile. Aerial survey coverage diminishes in far offshore areas. (B) Comparison of the call locations obtained in 2008 (gray dots) with the BWASP sightings in (A). See Fig. 4 for the functional DASAR locations. Note that the longitude range on the two maps is different.

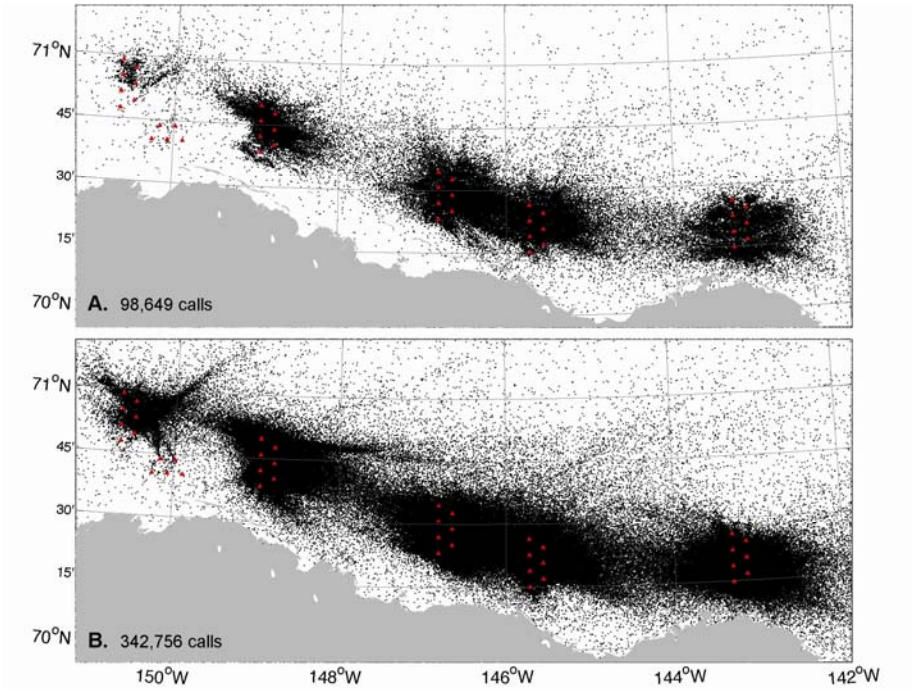

Fig. 18. Locations of bowhead whale calls (preliminary data) determined from DASARS deployed in the Central Beaufort Sea in 2008 during periods (A) without seismic and (B) with seismic operations. Seismic operations >50 km outside of the map boundary are not considered in (A).