A MASS STRANDING OF CETACEANS CAUSED BY NAVAL SONAR IN THE BAHAMAS

KENNETH C. BALCOMB III AND DIANE E. CLARIDGE

INTRODUCTION

With the advent of powerful military sonar systems in recent decades, worldwide attention has focused on the potential effects of sonar on whale behavior and survival, with particular concern over the coincidence of beaked whale (Order Cetacea, Suborder Odontoceti, Family Ziphiidae) mass strandings concurrent with or following naval maneuvers. In this report we provide documentation and discussion of a very significant multi-species mass stranding of cetaceans, predominantly beaked whales, in the northern Bahamas on March 15, 2000 coincident with a US and allied naval transit through the area. We also provide a brief summary of official reports released describing preliminary findings of evidence obtained from specimens that we collected in order to assist in determining the cause of this anomalous stranding. We propose a biophysical explanation for beaked whales sensitivity to underwater sound that could cause them to be more susceptible to injury from powerful sonar systems than other cetaceans. We also offer suggestions for mitigating this problem in future naval training operations.

Front cover: Cuvier's Beaked Whale at High Rock, Grand Bahama. [Photo: Edin Butler]

BACKGROUND

Mead (pers. comm., June 2000) has compiled nineteen records of mass strandings of beaked whales worldwide since 1963, about the time that a new generation of powerful mid-frequency (MF) military sonar was first deployed. Strandings of these "rare" whales prior to 1963 were typically of single individuals, often representing the only records of the existence of these enigmatic animals. Of particular note: four Cuvier's beaked whales (*Ziphius cavirostris*) mass stranded in Bonaire in 1974 (Van Bree and Kristensen, 1974); twelve Cuvier's beaked whales and a Gervais' (Antillean) beaked whale (*Mesoplodon europaeus*) mass stranded in the Canary Islands in 1985, three Cuvier's beaked whales and a northern bottlenose whale (*Hyperoodon ampullatus*) stranded there in 1988, and a total of twenty-four beaked whales (mostly Cuvier's) stranded in the Canary Islands in 1989 (Simmonds and Lopez-Juraco, 1991); twelve Cuvier's beaked whales stranded in Greece in 1996 (Frantzis, 1998); and, in mid-March 2000 at least fifteen beaked whales, two minke whales and a dolphin stranded in the northern Bahamas (this report).

All of these reports note the coincidence of naval maneuvers around the time of the mass strandings and most of them initially reported the whales as swimming ashore alive and subsequently stranding, as opposed to being carcasses drifting in with ocean currents. Although the circumstances of these mass strandings have been observed on multiple occasions, evidence for cause and effect to explain them has been elusive. Since Mead's report was prepared one year ago, there have been two additional reports of mass strandings of beaked whales, at least one of which was coincident with naval activities. This stranding "problem", particularly involving beaked whales, in the wake of naval maneuvers is apparently not going away, and it may be getting worse as new and powerful sonar systems proliferate.

In the case of the March 2000 strandings in the Bahamas, the US Navy after five weeks of well-publicized denial ultimately reported that there **were** coincident naval activities involving an east-to-west transit of US and foreign warships through the Northeast and Northwest Providence Channels, when and where the whales stranded (CINCLANTFLT, Press Release 21

April 2000). It was subsequently reported that "several" of these transiting warships were operating standard, hull mounted tactical sonar within normal mid-range frequencies (MF), power outputs and duty cycles (3.5 kHz and above, 235 dB re 1 microPascal (1uPa) at one meter, pings of one tenth of a second or less on a duty cycle of 24 seconds (CHINFO, June 2000). In January of this year, the Navy (Johnson, 2001) acknowledged that three submarines and seven surface ships were involved in this transit, operating six MF sonars with standard outputs and modes, and that SURTASS LFA (acronym for US Navy LF system) was not involved. No other acoustic details have been released; therefore, we can only estimate (rather than calculate) the whales' received level (RL) sensitivity to the reported MF sonar and the approximate zone of influence for response or injury.

The US Navy conducted an internal review of this transit that showed there was a surface duct approximately 400 to 500 feet (120 to 150 meters) deep in which sound propagated better than it did below that depth. In this surface duct, within a range of 1000 meters from a ship's sonar the sound level reportedly dropped in intensity to less than 180 dB re 1uPa, which has previously been considered a "safe" level for single ping non-serious injury to whales (DOEIS, 1999). We surmise that, with multiple ship's sonar systems operating in the area at 235 dB source level (SL), the sound pressure level from sonar was at times greater than 150 dB re 1uPa **throughout** the NE and NW Providence Channels (from North Eleuthera to Abaco and Grand Bahama) on March 15, 2000. Adjusting for the different reference level for in-air measurement of sound of equivalent acoustic intensity, this level is significantly above the threshold of pain in human hearing, and it approaches the level for TTS (a temporary threshold shift or impairment to hearing that may last from a few minutes to a few days).

It has been argued that cetaceans are adapted to tolerate much higher sound levels than humans before experiencing TTS, and that they are not injured by such levels. Injury is defined as occurring when there is PTS (permanent threshold shift, i.e. permanent impairment or loss of hearing), and it has been presumed that such injury is likely to occur before non-hearing pressure injuries (barotraumas) caused by sound. For industrial scenarios (seismic exploration, oil rig operation, shipping, underwater detonations, etc.), it has been assumed that whales may flee from loud sound before they are injured (see displacement discussion in Richardson, et. al., 1995). Indeed, there are many documented cases of cetacean abandonment of areas that have been subjected to a high level of anthropogenic noise (Perry, 2000).

But, is it reasonable to suppose that whales can escape injurious physical or physiological effects of intense sonar pressure waves traveling at 3000 miles per hour, perhaps from multiple warships cruising at speeds faster than the whales can swim?,...in a sea canyon?

Whales evolved from a terrestrial mammalian ancestor and have air-adapted hearing that has been secondarily modified to function well underwater. The middle ear is air filled via the eustachian tube to the larynx, and it requires pressure equalization during ascent and descent, just as it does in human divers. As many readers know from personal experience, pressure trauma in these airspaces can be extremely painful no matter how it is caused (disease, diving, air travel, etc.). Intense sound pressure can also be extremely painful and injurious to humans and animals, and can result in either auditory or non-auditory barotraumas.

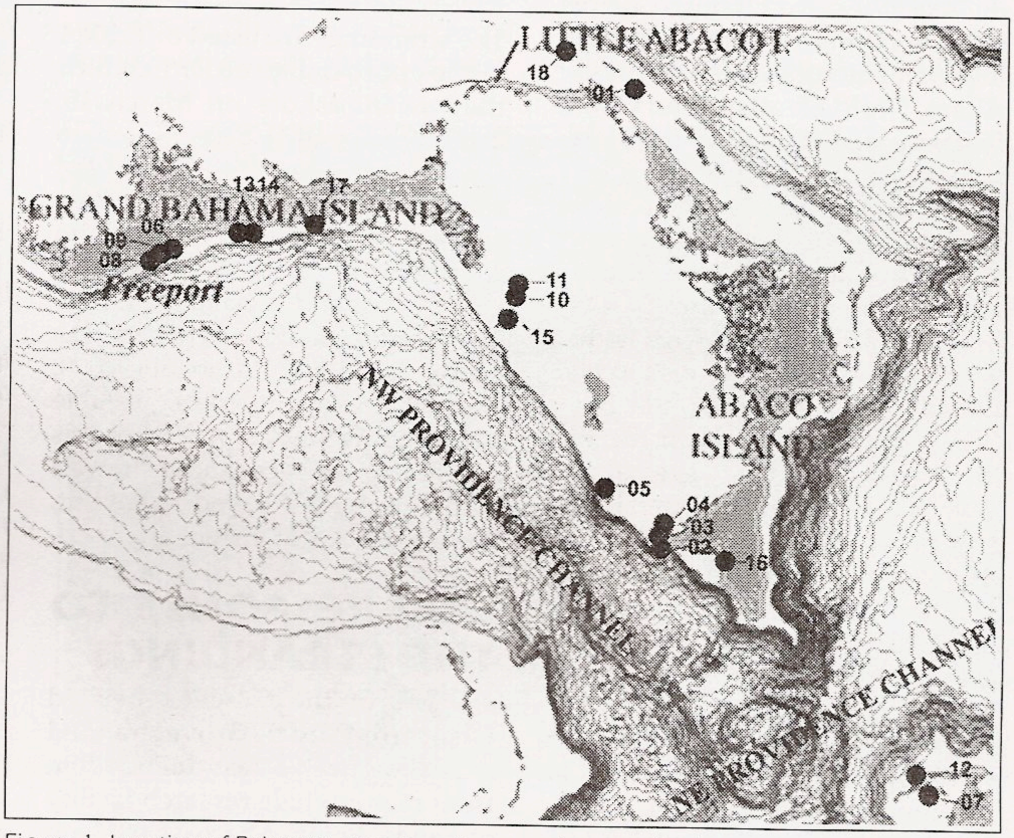

Figure 1. Location of Bahamas strandings in approximate order first seen.

Table 1. Our summary of the cetacean strandings. AB - Dr. Alan Bater; EB - Edin Butler; NMFS – US National Marine Fisheries Service; WHOI - Woods Hole Oceanographic Institution.

Animal ID	Species	Location
BMMS 00-01 Abaco	*Stenella frontalis* immature female	26∞54.307'N 77∞28.974'W
BMMS 00-02 Abaco	*Ziphius cavirostris* immature unk. sex	25∞59.802'N 77∞24.344W
BMMS 00-03 Abaco	*Ziphius cavirostris* sub-adult unk. sex	26∞01.079N 77∞24.150'W
BMMS 00-04 Abaco	*Mesoplodon densirostris* young adult unk. sex	26∞01.271'N 77∞24.049W
BMMS 00-05 Abaco	*Mesoplodon densirostris* young adult prob. female	26∞05.908'N 77∞31.163W
BMMS 00-06 Grand Bahama	*Ziphius cavirostris* juvenile female	26∞37'N 78∞17'W
BMMS 00-07 North Eleuthera (Royal Island)	*Balaenoptera acutorostrata* adult, unk. sex	25∞30'N 76∞47'W
BMMS 00-08 Grand Bahama (Peterson Cay)	*Unidentified Ziphiid* adult female	26∞33'N 78∞31'W
BMMS 00-09 Peterson Cay	*Unidentified Ziphiid* juvenile unk. sex	26∞33'N 78∞31'W
BMMS 00-10 Red Shank Cay	*Ziphius cavirostris* adult male	26∞28'N 77∞46'W
BMMS 00-11 Red Shank Cay	*Ziphius cavirostris* unknown status	26∞28'N 77∞46'W
BMMS 00-12 North Eleuthera (Royal Island)	*Balaenoptera acutorostrata* subadult unk. sex	25∞31'N 76∞49'W
BMMS 00-13 Grand Bahama	*Ziphius cavirostris* adult female	26∞36'N 78∞22'W
BMMS 00-14 Grand Bahama	*Ziphius cavirostris* sub-adult male	26∞36'N 78∞22'W
BMMS 00-15 Water Cay	*Ziphius cavirostris* sub-adult male	26∞26.136'N 77∞45.943'W
BMMS 00-16 Abaco	*Mesoplodon densirostris* sub-adult male	25∞56.447'N 77∞16.553W
BMMS 00-17 Grand Bahama	*Ziphius cavirostris* sub-adult male	26∞35'N 78∞29'W
BMMS00-18 Abaco	*Mesoplodon europaeus* adult male	26∞58.509'N 77∞38.653W

OVERVIEW OF THE BAHAMAS STRANDINGS

At least two minke whales (*Balaenoptera acutorostrata*), one spotted dolphin (*Stenella frontalis*) and fourteen of the beaked whales (Family *Ziphiidae*) live stranded or became temporarily trapped in shallow water along shores and cays of Abaco, North Eleuthera and Grand Bahama coincident with the aforementioned naval transit (Figure 1). The two minke whales and eight of the beaked whales subsequently escaped or were escorted back to sea hours to minutes after first being noticed. It is not known whether any of these escaped or rescued whales survived, but none have been recognized at sea in the following year of dedicated vessel surveys that we have conducted in the NW Providence Channel off south Abaco. Five Cuvier's beaked whales (*Ziphius cavirostris*) and one Blainville's (dense)-beaked whale (*Mesoplodon densirostris*) are known to have died within hours of stranding, and post mortem examinations were conducted on all of them. On the opposite side of Abaco, a spotted dolphin (*Stenella frontalis*) live stranded on Powell Cay and a Gervais' beaked whale (*Mesoplodon europaeus*) stranded on Allans-Pensacola Cay. We collected and froze the dolphin soon after it died in the evening of March 15, but the latter was not reported to us or collected until June 2000 by which time it was decomposed.

The strandings are listed in Table 1 in the approximate order in which they swam ashore on March 15, 2000. Whales BMMS 00-15 and 16 were discovered in the morning of March 16 in fresh condition; whale BMMS 00-17 was discovered on March 20, by which time it was decomposing; and, whale BMMS 00-18 was decomposed when it was reported and collected in June, 2000. This whale is included in our table because it is the first record of this species from Abaco, and it showed evidence of cranial hemorrhage; but, it is otherwise not further analysed.

OUR RESPONSE TO THE STRANDINGS

One of the Cuvier's beaked whales (BMMS 00-03) live stranded in shallow water near the beach in front of our whale research facility at Sandy Point, Abaco at 0815 on March 15, 2000. It appeared healthy, but disoriented, and we were able to turn it around and guide it offshore. Upon release, the whale swam steadily in a large left circle and re-stranded in shallow water repeatedly. Finally, at 0912 it was guided into deep water and did not return. Meanwhile, we learned of another Cuvier's beaked whale (BMMS 00-02) that had completely stranded on the rocky shore at Rocky Point one mile south of our whale research facility at 0730, so we kept it wet until the tide came in sufficiently to re-float and guide it into deep water at 1303. While we were attempting to keep that whale wet and alive, we were notified that a Blainville's beaked whale (BMMS 00-04) had live stranded in shallow water 400 meters north of our whale research facility, so with our neighbors we guided it back to deep water at 1033. Around the same time, we received a call that a dolphin (BMMS 00-01) had live stranded at Powell Cay at 0700 and bystanders were requesting assistance, so one of us (DEC) drove and boated to Powell Cay in response. By midday, concerned that we might be experiencing another mysterious military maneuver/stranding event, one of us (KCB) called a

Samples	Comments
Entire dolphin (frozen)	Entire dolphin to WHOI for UHR-CT & Necropsy
Skin in DMSO	Rescued; sloughed skin for DNA
None	Rescued
None	Rescued
Skin in DMSO	Rescued
Skin, Blood	Died, buried; AB & EB collected samples; sloughed skin for DNA, blood to NMFS
None	Rescued
None	Rescued, Mother
None	Rescued, calf
None	Escaped?
None	Escaped?
None	Rescued
Earbones, tissue samples	Died, buried; AB & NMFS Necropsy; earbone to WHOI; tissues to NMFS; BMMS has head
Earbones, tissue samples	Died, buried; AB & NMFS Necropsy; earbone to WHOI for UHR-CT; tissues to NMFS; BMMS has head
Head, frozen tissue samples	Died, KCB collected; head and earbones to WHOI for UHR-CT; tissues to NMFS; head to be returned to BMMS
Head, frozen tissue samples	Died, KCB & DEC collected; head to WHOI for UHR-CT & dissection; tissues to NMFS; head to be returned to BMMS
Earbones	Died, NMFS collected; earbones to WHOI for UHR-CT
Skull & mandibles	Died, KCB collected; BMMS has head

colleague at the Office of Naval Research and requested that all acoustic recordings made at AUTEC (in Andros) and from other sensors in the region be retained indefinitely for analysis. At 1530, we received a call from Disney personnel at Gorda Cay to assist with another live stranded "dolphin" which was actually another Blainville's beaked whale (BMMS 00-05) that had swum into a mangrove creek. By 1730, we had guided that whale back to deep water as the sun was beginning to set.

The dolphin (BMMS 00-01) at Powell Cay died shortly before sunset, so DEC brought it back to Sandy Point and we put it in a freezer for subsequent analysis. In the evening of March 15, we learned that two Cuvier's beaked whales (BMMS 00-10 & 11) had live stranded at Red Shank Cay between Abaco and Grand Bahama in the afternoon, at least five Cuvier's beaked whales (BMMS 00-06, 08, 09, 13 &14) had stranded on or near Grand Bahama, and two minke whales (BMMS 00-07 & 12) had been seen in very shallow water (conch flats) near Royal Island, North Eleuthera. In total, the day had presented one of the largest multi-species mass strandings of cetaceans (15 animals, four species) ever recorded in the world. Due to the vast expanse of water and the remoteness of many cays and sandbars, we estimated that there most likely were more strandings that had not yet been reported.

On the morning of March 16, 2000 one of us (KCB) conducted an aerial survey of the south and east coastline of Abaco and the cays northwest to the Burrows Group, while the other (DEC) conducted a vessel survey of the southwestern shoreline of Abaco. Our neighbors conducted a flight from Sandy Point to Grand Bahama, offering to report sightings or strandings. Among us, we found a dead Cuvier's beaked whale (BMMS 00-15) on Water Cay in the Burrows Group, a dead Blainville's beaked whale (BMMS

Figure 2. *Mesoploden densirostris* (BMMS 00-16) subadult male, Cross Harbour Creek, Abaco. 16 March 2000.

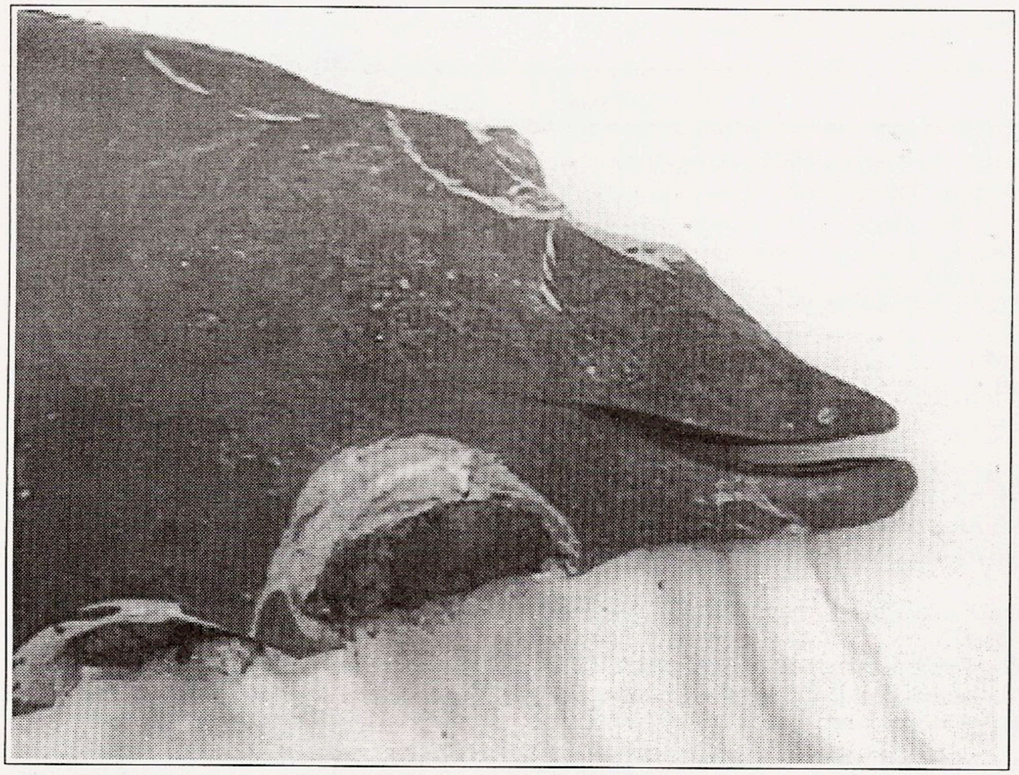

Figure 3. *Ziphius cavirostris* (BMMS 00-15) illustrating shark bites inflicted *in vivo*. For scale, distance from eye to tip of rostrum approximately 70 cm.

00-16) in Cross Harbour Creek, and a naval warship transiting west near Grand Bahama with a large rectangular/oblong shaped object in tow. In the afternoon, we conducted a necropsy of the Blainville's beaked whale (BMMS 00-15), noting it was in very fresh condition (Figure 2) but with what appeared to be bands of hemorrhage (bruising) in the lungs. We froze the head and preserved many organ samples for later analysis.

On March 17, 2000 one of us (KCB) went by boat with an assistant to examine the Cuvier's beaked whale (BMMS 00-15) on Water Cay. It was in a remarkably good state of preservation because the whale had apparently exsanguinated from shark bites while alive (Figure 3). We collected the head and froze it for later analysis.

On March 18 and 19, one of us (KCB) went to Grand Bahama to assist a Freeport veterinarian (Dr. Alan Bater) and a US National Marine Fisheries Service (NMFS) veterinary pathologist with necropsy of two of the Cuvier's beaked whales (BMMS 00-13 & 14) that had stranded at Gold Rock Beach. These specimens, however, were decomposing and of little forensic value in themselves (Figure 4).

On March 20, we conducted an aerial survey of the southern coastline of Grand Bahama, the Berry Islands and the northeast coast of Andros, spotting only one additional decomposing Cuvier's beaked whale (BMMS 00-17) on Grand Bahama that was being examined by members of the NMFS response group. We also sighted several additional naval warships in the area (Figure 5).

On March 30, we airlifted our fresh frozen and preserved specimen materials to Boston for ultra high resolution computerized tomography (UHR-CT) analysis of the crania and ears at Harvard Medical School, and subsequent dissection at Woods Hole Oceanographic Institution.

Because our resources were limited and the analyses expensive, we fully cooperated with the US National Marine Fisheries Service and the US Navy by providing our fresh specimen materials to Harvard Medical School, Woods Hole Oceanographic Institution and NMFS for forensic analysis. Our conditions for doing this were: 1) that the investigation into the cause of the stranding would be objective, timely and transparent; 2) that the results be released to the public; 3) that we be included in scientific reporting of findings concerning the incident; 4) and, that the specimens be returned to us in the Bahamas for ultimate curation.

FINDINGS OF EVIDENCE FROM OUR SPECIMENS

[*Preliminary* findings of UHR-CT scans and dissections, from NOAA Fisheries Press Releases and reports to scientific committees]

On June 14, 2000, a NOAA Fisheries status report of preliminary findings of postmortem examinations on six of the beaked whale heads from the NW Providence Channel strandings indicated that there was evidence of injuries consistent with an intense acoustic or pressure event (NOAA Fisheries, 2000). A subsequent report by the NMFS investigators to the International Whaling Commission Scientific Committee stated, "The current consensus of the necropsy findings is that there were significant cranial lesions among the beaked whales but not in the single delphinid. The findings suggest that some pressure wave occurred that had characteristics especially significant or traumatic for beaked whales... In summary, the findings in the beaked whale heads examined to date are that hemorrhages were found in the inner ears and some cranial spaces. Acoustic fats also show varying degrees of hemorrhage. These pathologies are consistent with impulse trauma that may have compromised hearing or the vestibular system, but was not immediately or directly fatal." Concerning the best preserved beaked whale (our *Mesoplodon densirostris* Md 00-16) the evidence "consisted of intra-cochlear and subarachnoid hemorrhage with clots in the lateral ventricles." It also had, "renal capsular hemorrhage, possible lung hemorrhage, bruising of the larynx, and heart lesions (often seen in strandings)" (Rowles, et. al., 2000).

Figure 4 *Ziphius cavirostris* (BMMS 00-13) Gold Rock beach, Grand Bahama, 19 March 2000. Carcass has been buried and exhumed.

A NOAA Fisheries status report on the one-year anniversary of the stranding in the Bahamas stated, "The team has reached no final conclusions. The pattern of stranding suggests that only a source of intense pressure or acoustic energy moving from south to north through the Northwest Providence Channel could have been responsible. No source fitting this description other than Navy sonar has yet been found. Individual strandings coincided closely in time and space with the passage of Navy ships. The team believes it is highly likely that sonars were linked to this stranding. The specific aspect of the sonar signal, and the mechanism by which it acts, has not been identified. Experiments to determine these mechanisms will not be completed for another year. The scientific investigation is an ongoing high priority for both NOAA Fisheries and the U.S. Navy." (NOAA, Press Release March 26th, 2001)

DISCUSSION

During nine years of photo-identification study of beaked whales off Abaco Island (1991-2000), we found Blainville's and Cuvier's beaked whales year-round, with many individuals seen repeatedly, strongly suggesting significant occupancy of these species in the area. We reported these findings to consultants developing the AUTEC Environmental Review (1997), to the Chief of Naval Operations (OP 45, Environmental Protection, Safety, and Occupational Health Division), and to the Office of Naval Research.

We were astonished when the March 15, 2000 mass strandings commenced, and we quickly responded and reported on the catastrophe via the internet (www.whaleresearch.com and via the scientific discussion group MARMAM) because of the multi-species nature of the stranding event(s), and our concern that it was not due to natural causes. Cetacean strandings in the Bahamas are rare, usually on the order of one to two animals discovered each year in the entire archipelago. Mass

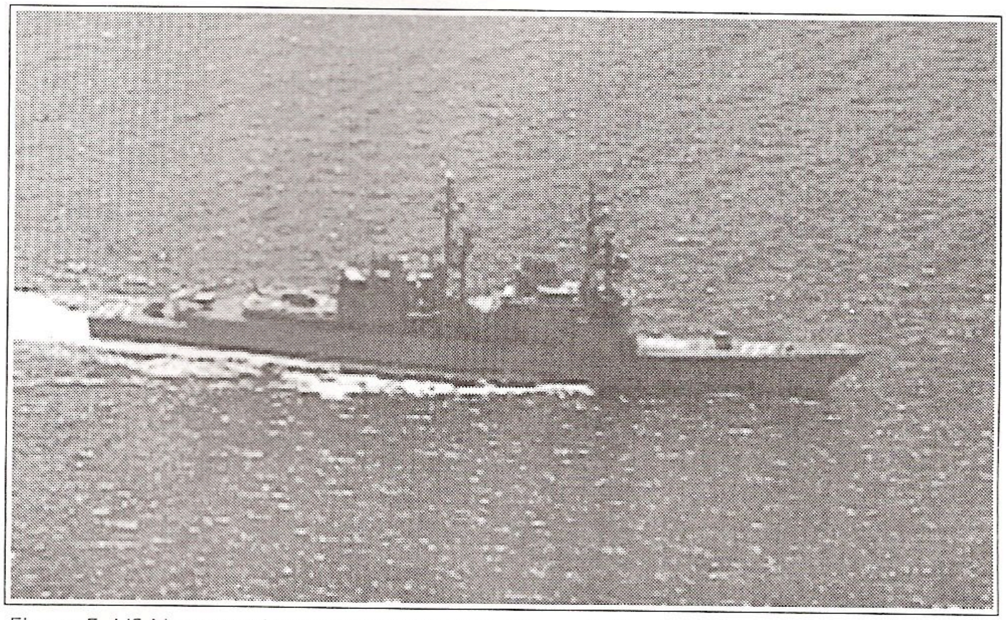

Figure 5. US Navy warship in NW Providence Channel, March 2000

year in the entire archipelago. Mass strandings have only been reported twice before in the Bahamas, and both were involving beaked whales: four Cuvier's beaked whales stranded near Norman's Cay in the Exumas in February 1968 (Caldwell and Caldwell, 1971); and, three Blainville's beaked whales live stranded on Rum Cay on March 18, 1998 (Vernon, pers. comm.). We have yet to ascertain whether there were any naval maneuvers in Exuma Sound in February 1968; but, we have learned that there was a Canadian Low Frequency Active (LFA) sonar test in Exuma Sound not far from Rum Cay in early March 1998 two weeks prior to the Rum Cay stranding. Dr. Vernon, a veterinarian who conducted a necropsy on two of the Rum Cay whales, reported that he believed they "lost sonar control i.e. cerebella dysfunction." The muscle mass and internal organs evidenced "massive hemorrhage along with emphysematous gas throughout." (Vernon ltr to Bahamas National Trust, dated May 11, 1998.)

By mid-day on March 15, 2000 we were already skeptical that what we were witnessing was a natural mass stranding, and we were very suspicious that something was causing these animals to flee from their natural habitat. We considered it likely that the only evidence available to surmise cause would be behavioral or derive from stranding pattern analysis, but fortunately we were also able to obtain and properly curate fresh specimens for forensic examination. In the field, many factors were considered that might be causal, and we concluded that there must have been an enormous acoustic event or series of acoustic events that triggered a behavioral flight response by several species, but predominantly Cuvier's beaked whales, such as had been suggested in previous reports of mass strandings of these whales in the Canary Islands, Bonaire, and Greece.

The U.S. National Marine Fisheries Service and the U.S. Navy came to a similar conclusion for the March 2000 stranding, based on the biological results of examination of our specimens which indicated that the injuries were all consistent with an intense acoustic or pressure event. It is important to emphasize that grossly the animals appeared healthy, and were in good body condition but disoriented and hemorrhaging internally. It is also important to note that while the damages observed might be considered survivable, the beaked whales that were not assisted died within a very few hours of live stranding, and at least one was mortally injured by sharks while it was near shore. Perhaps the assisted whales also died or were killed by sharks after being returned to sea while the sonar exercise was still ongoing.

Our experience in the Bahamas mass stranding event and our review of details of the Greek strandings (D'Amico, 1998) caused us to wonder what specific acoustic phenomena and sound pressure levels are of particular significance to beaked whales, and what is the underlying biophysical explanation for the traumas observed in such strandings. It has also caused us to wonder about the effectiveness of the U.S. Navy's mitigation efforts, and the accuracy of their information about whale distribution, social structure, normal behavior and aversion.

Is 180 dB re 1uPa RL safe for cetaceans?

Considering the similar biological damage (ear and cranial hemorrhage) to beaked whales over great distance, and considering that it is not likely that all of the whales examined were within 1000 meters of a navy sonar on March 15 in the Bahamas, the damage pattern strongly suggests to us that beaked whales may have a particular sensitivity to sonar acoustic stimuli at received levels well below the 180 dB RL previously considered safe for cetaceans. This "safe" level is based in part upon US Navy experiments with dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) that indicated TTS (i.e. recoverable hearing loss) varies from 182 to 193 dB RL, in the 20 to 75 kHz range, where their best hearing threshold is 40-45 dB (Schlundt, et. al., 2000). Nobody knows what the hearing frequency range, response threshold, or TTS are for beaked whales, but they have been presumed to be similar to dolphins. For general reference, typical ocean ambient noise levels in the Bahamas range from about 40 dB re 1uPa in sea state 0 with no shipping, to about 68 dB in sea state 6 with heavy shipping; and, most of the acoustic energy of ambient noise is below 1000 Hz (NUWC, 1997). It should be noted that the decibel scale is logarithmic, meaning a difference of 10 dB is tenfold, 20 dB is 100 fold, 30 dB 1000 fold, etc., i.e. relative to a calm day, on a windy day with heavy shipping the sound level is about 1000 times noisier, and the so-called "safe" level is one hundred trillion times noisier.

Certainly the flight response in beaked whales is initiated at received levels well below 180 dB re 1uPa considered "safe" for hearing. This was well demonstrated in the Greek incident reported by D'Amico (1998, Figure 2.2 and Annex F). If one takes into account how fast a beaked whale can swim (about 15 km per hour, maximum), the first whale to strand forty kilometers away one hour later must have been at least 25 km from the ship when the acoustic trial commenced! At that distance, which happens to coincide with the first caustic or convergence zone of refracted sound from the source, the RL was calculated by the Navy (D'Amico, 1998, Annex G) to be approximately 140 dB re 1uPa. The NATO sonar equipment was transmitting 4 seconds of HFM and CW 450-700 Hz, and 2.8-

3.3 kHz every 60 seconds.

Similarly in the Bahamas, a sound level of 180 dB RL re 1uPa is demonstrably not safe for avoiding flight response by beaked whales or other cetaceans (two minke whales and a dolphin also stranded in this incident). It is remarkable that so many whales representing at least three species swam into extremely shallow water and stranded on March 15, nearly coincident in time but up to 200 kilometers apart! Aversion **evidently and repeatedly** occurred for these cetaceans at levels of somewhere between 140 and 180 dB RL re 1 uPa (probably nearer the former) of the mid-frequency sonar signals (1/10 second 3.5 kHz transmitted every 24 seconds from multiple ships) in the whales' habitat.

Is there a biophysical explanation for beaked whale sensitivity to sonar?

Aside from potential auditory trauma, we have been concerned about the potentially damaging non-auditory *resonance* bioeffects of underwater sound, such as had been previously reported in U.S. Navy sponsored studies: vestibular dysfunction in immersed laboratory animals at 160 dB RL at lung resonance frequencies (Jackson and Kopke, 1998); and, hemorrhage in lungs, liver and other organ systems at 170-184 dB at lung resonance frequencies (Dalecki, 1998; Dalecki, et. al., 1998). Lung resonance can be calculated from body mass (Dalecki, 1998), or from airspace volume (Andreeva, 1964). The NATO report on the stranding in Greece addressed the *potential* for resonance effect damage, but was inconclusive because appropriate samples were not collected for analysis. Readers of that report might wonder whether either frequency range "caused" the whales to strand, since neither matched the **reported** resonance frequency (290 Hz) in that instance for Cuvier's beaked whales' airspaces at an arbitrarily chosen 500 meters depth. In this respect the NATO report could be construed as misleading because beaked whales normally swim from the surface to 1500 meters depth while foraging, and it is lung or airspace resonance throughout this range of depths that should have been calculated as follows:

$f_o = (1/2\mathrm{p}R) \div ((3\mathrm{g}P_o + 4\mathrm{m})/\mathrm{r})$ as derived from Andreeva (1964; from Barham (1973)). There are also several functional anatomical facts to consider.

Lung volumes vary individually with animal size, and they also vary with ambient pressure that changes dramatically with depth, so it is useful to perform the resonance calculations in a computer-based spreadsheet (we used Microsoft Excel 97). In order to perform these calculations for various depths the following must be considered:

a. Lung volume at the surface. [estimated 100 liters for adult Cuvier's beaked whale]

b. Boyle's Law PV=constant; therefore, lung volume will decrease with increasing depth. [In fact, below 100 meters depth virtually all of the respiratory air in the lungs is forced into laryngeal and cranial airspaces, wherein its volume *continues* to decrease with increasing depth until it is about a total volume of one liter or less at 100 or more atmospheres of pressure].

c. Functional anatomy of beaked whales. These remaining airspaces (b. above) are bilaterally adjacent to the earbones and base of the brain (via the large foramen for the oversize VIII cranial nerve) in cetaceans; and, their diminishing volume at depth is compensated for by retia mirabilia (an anastomosing vascular network that engorges with blood like a penile corpus cavernosum).

Following the Navy's example and formulae (D'Amico, 1988, Annex H), the frequencies of powerful low and mid-frequency sonars precisely match the equivalent bubble resonance frequencies of these cranial airspaces in beaked whales at predictable depths from the surface to the benthos of the water column. If the whales' tissues respond anything like laboratory animal tissues, ensonifying them at levels of 160 to 170 dB re 1uPa of resonant frequency can cause vertigo and hemorrhage, and it is probably as painful to the whales as it would be to humans. If this is what is happening, it is no wonder these animals flee such sounds once they are heard at sufficiently high levels of appropriate frequency to initiate these traumas. The resonance effect may only occur within a specific depth range during a whale's dive, but when the whale passes through that range and the damage is done, the physiological and behavioral situation can rapidly deteriorate into a non-survivable response (stranding) if a shoreline is nearby. Unfortunately, the Greek mass stranding incident passed into relative obscurity because the NATO Bioacoustics Panel did not further investigate resonance effects, and because suitable specimen materials were not collected for discovering evidence that could be relevant to the problem.

The biophysical explanation in the preceding paragraph could be considered largely theoretical, except that there *is* evidence of such hemorrhage in the organ systems and ears of our specimens from the Bahamas. In order to investigate whether there is additional anatomical evidence in support of the biophysical explanation, we prepared an endocast of the right pterygoid sac (one of two bilaterally symmetrical cranial airspaces) of one of the Cuvier's beaked whale specimens from the Bahamas incident (Figure 6), and determined that its volume closely matched the calculated volume used in the resonance formulae. Because most of the cranial

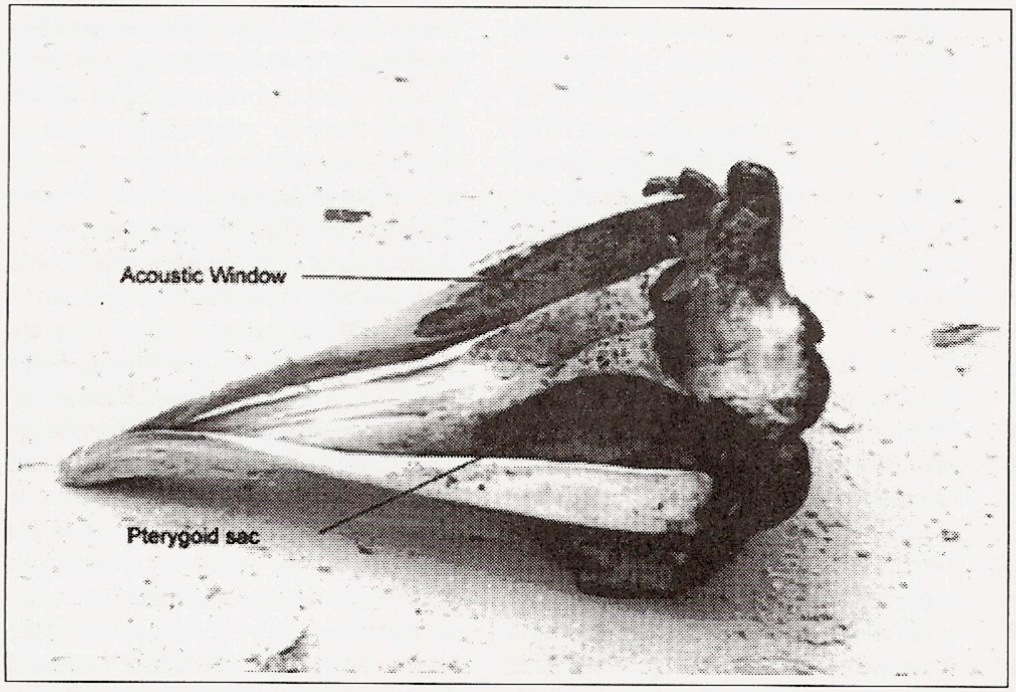

Figure 6 *Ziphius cavirostris* (BMMS 00-13) cranium and mandibles, ventral view showing Acoustic Window and similarly shaped pterygoid sac.

hemorrhage observed in our specimens was in tissues adjacent to this pterygoid sac and at its most posterior end where it is enveloped in a unique cul-de-sac of sesamoid bone and dense earbone that keep it open during the deepest part of a dive, we consider both the anatomical evidence and the forensic evidence supportive of our biophysical explanation.

Is a beaked whale's auditory system more sensitive than a dolphin's? While preparing the endocast of the pterygoid sac as described in the preceding discussion, and reviewing our notes and photographs on dissections of other beaked whales (see Balcomb, 1989), we observed that the air-filled pterygoid space in these whales is shaped like and precisely mediad the "pan bone" region of the mandible, the famed Norris' Acoustic Window (Ridgeway, 1999). This elegant "jaw hearing" idea of Norris (1968) is now well established (Brill, et. al., 1988), but in delphinids the pterygoid sinuses are laterally and ventrally encapsulated with a thin laminate of bone and they are much smaller than in ziphiids. We propose that the relatively enormous open-sided airspace that has evolved in ziphiids could serve not only as an air reservoir for the middle ear, but also as an "acoustic mirror" that effectively would increase the sensitivity of "jaw hearing" over that of delphinids and other cetaceans that lack it. Such hearing advantage at depth would support the surmise that these whales evolved as sensitive listeners more than active echolocaters of their primary prey (squid). Functionally, this pterygoid mirror would be similar to those proposed for the parabaloid premaxillary sac and the frontal sac in another famous theory of Norris (Norris and Harvey, 1972; Cranford, 1999) concerning the sound production mechanism in the nose of sperm whales. In our proposal, however, it is only hearing that is involved and there is only one mirror (the pterygoid sac) for each ear, instead of two for the nose. Concurrently, reduced or absent posterior mandibular and maxillary dentition would reduce the beaked whales' tissue density interference in the receiving sound path. The plasticity of an unossified lateral wall of the pterygoid sac would of course also permit it to function well as an air reservoir for the middle ear in deep diving. As respiratory air is forced into the cranial region from the compressed thorax in a dive, the pterygoid sacs and contiguous large bore eustachian tube would permit the "terrestrial" ear to function normally. In our theory, we think it probable that deep diving provided the evolutionary impetus for development of this feature, and improved hearing sensitivity may be serendipitous.

One of our esteemed colleagues, Dr. Darlene Ketten of Woods Hole Oceanographic Institution, is currently decalcifying the earbones of the Bahamian beaked whales to histologically examine the cochlea, whose basilar membranes, spiral laminae and sensory hair cells will for the first time reveal the frequency range of hearing of a ziphiid species (see Ketten, 1992). This examination may also forensically reveal the identity of the damaging frequency(ies) [the smoking gun of permanent threshold shift, PTS, from damaged sensory hair cells] in the Bahamas exercise *if* there was hearing damage.

SUMMARY

Whether or not there is PTS injury demonstrated for any whales that stranded in the Bahamas coincident with the Navy sonar incident of March 15, 2000, the whales certainly fled from the area and many, if not all, of them died. The aversive and injurious impacts of intense low and mid-frequency sonar, either of standard (1/10 sec MF as in the Bahamas) or of long duration (4-6 second, LFA and MF, as in Greece), on beaked whales in particular is occurring at significant distances well beyond the current mitigation distance (1 km) used by the US Navy. This impact distance can be easily calculated for the well-documented strandings, such as in Greece and the Bahamas, and it is 20 kilometers or more – near caustics well over the horizon of shipboard observers. Multiple sonar "pings" and oceanographic and topographic conditions undoubtedly contributed to efficient sound propagation and regions of enhancement in the Bahamas situation, but the whales' sensitivity was not only behavioral, it was physiological and could reasonably be expected whenever similar received levels of similar frequencies of similar duration occur. None of the Cuvier's beaked whales that we had documented in our nine-year study have returned since the March 15 naval exercise, and none of the "rescued" whales have been seen again, either. We consider it entirely plausible that most, if not all, of the local population of this species was killed on that day; or, at the very least, there has been a very serious displacement of these whales. In the long run, we simply cannot expect cetaceans to habituate to pressure induced vestibular dysfunction, cerebral hemorrhage and cochlear squeeze, etc. that is resulting from some naval sonar operations. Mitigation of naval activities during peacetime exercise appears to be the only reasonable solution to this problem.

Within vital defense requirements for early detection of threat from submarines, what can be done? First, the Navy's inaccurate AIM model of cetacean distribution and abundance should be overhauled and its purposes featured in "whale sensitivity training" for fleet commanders and personnel. Second, the mitigation distance for high source level LF and MF sonar operations should be increased from 1 kilometer to the distance coinciding with the first or second caustic, provided that the RL at that distance does not exceed a demonstrably safe level for precluding injury to cetaceans that inhabit the area. And third, commanders should avoid conducting sonar exercises in relatively confining oceanographic canyons and areas of high acoustic reflectivity where the sound field may behave unexpectedly and boundary effects dramatically increase the local RL. Finally, for training purposes, many sonar exercises can be simulated or conducted at lower SL than combat operating levels. Somehow we must find a way for whales to survive and live in relative peace, as humans increasingly exploit and dominate the seas and prepare for war.

ACKNOWLEDGEMENTS

Thanks to the US Navy's concern, it was revealed that a major naval transit (Gap exercise) was in the area at the time of the Bahamas strandings. Both the US Navy and the US National Marine Fisheries Service have assembled expert teams to determine what happened that may be of etiological significance in these strandings. We thank Michael Braynen, Director of the Bahamas Department of Fisheries for the attention he gave this important event and his speedy authorization for specimen collection and permits for exportation. We also thank Dr. Alan Bater for informing us of the Grand Bahama specimens, Bill Anspach for donating flight time, Earthwatch volunteers for untiring assistance with rescues and necropsies, Dave Ellifrit and Marta Azzolin for expertly coordinating volunteers, the residents of Sandy Point for timely help and freezer storage, Erika Moultrie for attempting to locate photographs of the Peterson Cay whales, Paul Adams for locating photographs of the whales stranded at Red Shank Cay, George Sweeting and family for rescuing both minke whales at Royal Island, and the Abaco Cruisers Net for communications assistance. We are extremely grateful for the expert assistance with resonance calculations provided by Earthwatch volunteers William T. Sperry, Maria Carnevale, and Dr. Andrea Lorek. Financial support for the Bahamas Marine Mammal Survey derives from Earthwatch Institute and tax-deductible contributions from the public.

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Kenneth C Balcomb III and Diane E Claridge, PO Box AB-20714, Marsh Harbour, Abaco.

Editorial Figure (see p. 1). A section of the sea wall along the north coast of New Providence about half-a-mile east of Caves Point. In order to protect the road a low concrete wall was built, which encouraged further beach erosion, leading to damage to the wall. The wall has since been heightened several times and is now topped with unstable gabions which are breaking apart. The crude steps in the foreground show the height to which the wall has been raised so far. Both wall and road will be continually eroded unless the road is set back and a broad beach is allowed to develop.