Environmental Assessment of a Marine Geophysical Survey by the R/V *Marcus G. Langseth* off Central America, January–March 2008

Prepared for

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ABSTRACT

Lamont-Doherty Earth Observatory (L-DEO) plans to conduct a marine seismic survey off Central America during January–March 2008 as part of the National Science Foundation's (NSF) MARGINS program. The project will take place in the Exclusive Economic Zone (EEZ) of Costa Rica and Nicaragua; L-DEO has requested clearance to work in these waters. The survey will occur off both the Pacific and the Caribbean coasts of Costa Rica and Nicaragua, where water depths range from <100 m to >2500 m. The seismic study will use a towed array of 36 airguns with a total discharge volume of ~6600 in^3.

L-DEO is requesting an Incidental Harassment Authorization (IHA) from the National Marine Fisheries Service (NMFS) to authorize the incidental, i.e., not intentional, harassment of small numbers of marine mammals should this occur during the seismic survey. The information in this Environmental Assessment (EA) supports the IHA application process, provides information on marine species that are not addressed by the IHA application, and addresses the requirements of Executive Order 12114, "Environmental Effects Abroad of Major Federal Actions". Alternatives addressed in this EA consist of a corresponding program at a different time, along with issuance of an associated IHA; and the no action alternative, with no IHA and no seismic survey.

NSF is the agency of the U.S. Government that is providing the funds to support the research to be undertaken on the proposed cruise. NSF's view is that the Marine Mammal Protection Act (MMPA) does not apply to activities undertaken in the EEZ of a foreign nation. The submission of the IHA application to NMFS does not constitute a waiver of NSF's position.

Numerous species of marine mammals occur off Central America. Several of the cetacean species are listed as ***endangered*** under the U.S. Endangered Species Act (ESA), including the humpback, sei, fin, blue, and sperm whale. In addition, the ***endangered*** West Indian manatee is known to occur in shallow waters along the Caribbean coast of Central America. Listed sea turtle species that occur in Central America include the leatherback, hawksbill, loggerhead, green, and olive ridley turtle. In addition, the Kemp's ridley turtle may occur on the Caribbean coast of Central America.

Potential impacts of the seismic survey on the environment would be primarily a result of the operation of the airgun source. A multibeam echosounder and a sub-bottom profiler will also be operated. Impacts would be associated with increased underwater noise, which may result in avoidance behavior of marine mammals, sea turtles, and fish; and other forms of disturbance. An integral part of the planned seismic program is a monitoring and mitigation program designed to minimize the impacts of the proposed activities on marine animals present during conduct of the proposed research, and to document the nature and extent of any effects. Injurious impacts to marine mammals and sea turtles have not been proven to occur near airgun arrays or echosounders. In any event, the planned monitoring and mitigation measures would minimize the possibility of such effects.

Protection measures designed to mitigate the potential environmental impacts will include the following: ramp ups, minimum of one dedicated observer maintaining a visual watch during all daytime airgun operations, two observers for 30 min before and during ramp ups, passive acoustic monitoring (PAM) via towed hydrophones during both day and night (when practicable), and power downs (or if necessary shut downs) when marine mammals or sea turtles are detected in or about to enter designated safety or exclusion zones. The fact that the airgun array directs the majority of the energy downward, and less energy laterally, is also an inherent mitigation measure. L-DEO and its contractors are committed to apply these measures in order to minimize effects on marine mammals and sea turtles, and other environmental impacts.

With the planned monitoring and mitigation measures, unavoidable impacts to each species of marine mammal and turtle that might be encountered are expected to be limited to short-term localized changes in behavior and distribution near the seismic vessel. At most, effects on marine mammals may be interpreted as falling within the MMPA definition of "Level B Harassment" for those species managed by NMFS. No long-term or significant effects are expected on individual marine mammals, sea turtles, or the populations to which they belong, or on their habitats.

LIST OF ACRONYMS

~	approximately
3D	3-dimensional
CEP	Caribbean Environment Programme
CITES	Convention on International Trade in Endangered Species
cm	centimeter
CPA	Closest Point of Approach
CPUE	Catch per Unit Effort
CRD	Costa Rica Dome
CV	Coefficient of Variation
dB	decibels
DFO	(Canadian) Department of Fisheries and Oceans
EA	Environmental Assessment
EEZ	Exclusive Economic Zone
ESA	(U.S.) Endangered Species Act
ETH	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology in Zurich)
ETP	Eastern Tropical Pacific
EZ	exclusion zone
FAO	(United Nations) Food and Agriculture Organization
GEOMAR	Research Center for Marine Geosciences at the University of Kiel, Germany
GIS	Geographic Information System
h	hour
hp	horsepower
ha	hectares
IATTC	Inter-American Tropical Tuna Commission
ICE	Instituto Costarricense de Electricidad (Costa Rican Energy Institute)
IHA	Incidental Harassment Authorization (under MMPA)
in	inch
INE	Instituto Nicaragüense de Energia
ITCZ	Intertropical Convergence Zone
IUCN	International Union for the Conservation of Nature
IWC	International Whaling Commission
kHz	kilohertz
kt	knot
L-DEO	Lamont-Doherty Earth Observatory of Columbia University
LME	Large Marine Ecosystem
m	meter
MARGINS	continental margins research funded by NSF
MBES	Multibeam Echosounder
MCS	Multichannel Seismic
$mgC/m^2/day$	milligrams of Carbon per square meter per day
mi	mile
min	minute
MCMR	Miskito Coast Marine Reserve
MCPA	Miskito Coast Protected Area
MCS	Multi-Channel Seismic
MMVO	Marine Mammal Visual Observer
MMO	Marine Mammal Observer
MMPA	(U.S.) Marine Mammal Protection Act

MONM	Marine Operations Noise Model
ms	millisecond
MTTS	Masked Temporary Threshold Shift
NATO	North Atlantic Treaty Organization
NECC	North Equatorial Countercurrent
NEPA	(U.S.) National Environmental Policy Act
NMFS	(U.S.) National Marine Fisheries Service
NOAA	(U.S.) National Oceanic and Atmospheric Administration
NRC	(U.S.) National Research Council
NSF	(U.S.) National Science Foundation
NW	northwest
OBS	Ocean Bottom Seismometer
OVSICORI-UNA	Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional
PAM	Passive Acoustic Monitoring
pk	peak
PL	Propagation Loss
ppt	parts per thousand
psi	pounds per square inch
PTS	Permanent Threshold Shift
RAM	Range-dependent Acoustic Model
RL	Received Level
rms	root-mean-square
RP	reproductive patch
rpm	rotations per minute
s	second
scfm	standard cubic feet per minute
SE	southeast
SEL	Sound Exposure Level, in dB re $(1\ \mu\text{Pa})^2 \cdot \text{s}$
SL	Source Level
SPL	Sound Pressure Level, in dB re 1 µPa (equivalent to rms level)
SubFac	Subduction Factory (fundamental initiative under NSF's MARGINS program)
SW	southwest
SWFSC	(NMFS) Southwest Fisheries Science Center
TTS	Temporary Threshold Shift
UCR	Universidad de Costa Rica (University of Costa Rica)
UNEP	United Nations Environment Program
U.S.	United States of America
USFWS	U.S. Fish and Wildlife Service
USN	U.S. Navy
vs.	versus
W	west
WIDECAST	Wider Caribbean Sea Turtle Recovery Team and Conservation Network

I. PURPOSE AND NEED

Lamont-Doherty Earth Observatory (L-DEO), a part of Columbia University, operates the oceanographic research vessel *Marcus G. Langseth* under a cooperative agreement with the U.S. National Science Foundation (NSF). L-DEO plans to conduct a seismic survey in the Pacific Ocean and Caribbean Sea off Central America as part of the Subduction Factory (SubFac) initiative of NSF's MARGINS program. The MARGINS program was developed to facilitate the study of continental margins. The Central American SubFac survey is scheduled to take place from ~5 January through ~7 March 2008.

The seismic study will examine the volcanic arc, backarc, and downgoing plate in the Costa Rican portion of the Central American Focus Site, to determine the inputs, outputs, and controlling processes of subduction zone systems. The study focuses on the central Costa Rican segment of the arc, the site of important transitions in lava chemistry, because the narrow isthmus is well-suited for detailed seismic imaging using onshore-offshore techniques. A systematic understanding of subduction must include a thorough knowledge of the volcanic arc, which in turn is essential in understanding the geochemical recycling processes of the Central American SubFac.

The purpose of this Environmental Assessment (EA) is to provide the information needed to assess the potential environmental impacts associated with the use of a 36-airgun array during the proposed study. The EA was prepared under the National Environmental Policy Act (NEPA) and Executive Order 12114, "Environmental Effects Abroad of Major Federal Actions". The EA addresses potential impacts of the proposed seismic survey on marine mammals, as well as other species of concern near the study area, including sea turtles, fish, and invertebrates. The EA will also provide useful information in support of the application for an Incidental Harassment Authorization (IHA) from the National Marine Fisheries Service (NMFS). The requested IHA would, if issued, allow the non-intentional, non-injurious "take by harassment" of small numbers of marine mammals during the proposed seismic survey by L-DEO off Central America.

NSF is the agency of the U.S. Government that is providing the funds to support the research to be undertaken on the proposed cruise. NSF's view is that the Marine Mammal Protection Act (MMPA) does not apply to activities undertaken in the Exclusive Economic Zone (EEZ) of a foreign nation. The submission of the IHA application to NMFS does not constitute a waiver of NSF's position.

To be eligible for an IHA, the proposed "taking" (with mitigation measures in place) must not cause serious physical injury or death of marine mammals, must have negligible impacts on the species and stocks, must "take" no more than small numbers of those species or stocks, and must not have an unmitigable adverse impact on the availability of the species or stocks for legitimate subsistence uses.

Numerous species of marine mammals occur off Central America. Several of the cetacean species are listed as ***endangered*** under the U.S. Endangered Species Act (ESA), including humpback, sei, fin, blue, and sperm whales. In addition, the ***endangered*** West Indian manatee is known to occur in shallow waters along the Caribbean coast of Central America. Sea turtle species known to occur in Central America include the ***endangered*** leatherback and hawksbill turtles, the ***threatened*** loggerhead turtle, the green turtle (considered ***endangered*** in the breeding colony of Florida and the Pacific coast of Mexico and ***threatened*** elsewhere), and the olive ridley turtle (designated as ***endangered*** in the breeding colony of the Pacific coast of Mexico and ***threatened*** elsewhere). The Kemp's ridley turtle may also occur in the Caribbean.

Protection measures designed to mitigate the potential environmental impacts are also described in this EA as an integral part of the planned activities. With these mitigation measures in place, any impacts on marine mammals and sea turtles are expected to be limited to short-term, localized changes in behavior of small numbers of animals. No long-term or significant effects are expected on individual mammals, turtles, or populations.

II. ALTERNATIVES INCLUDING PROPOSED ACTION

Three alternatives are available: (1) the proposed seismic survey and issuance of an associated IHA, (2) a corresponding seismic survey at an alternative time, along with issuance of an associated IHA, and (3) no action alternative.

Proposed Action

The project objectives and context, activities, and mitigation measures for L-DEO's planned seismic survey are described in the following subsections.

(1) Project Objectives and Context

L-DEO plans to conduct a seismic survey in the Pacific Ocean and Caribbean Sea off Central America as part of the SubFac initiative of NSF's MARGINS program. The SubFac initiative will determine the inputs, outputs, and controlling processes of subduction zone systems by obtaining seismic measurements of magma flux, arc composition, and lower-plate serpentinization at the Central American Focus Site. Subduction zones, which mark sites of convective downwelling of the Earth's lithosphere, exist at convergent plate boundaries where one plate of oceanic lithosphere converges with another plate and sinks below into the mantle. It is at these subduction zones that the oceanic crust and associated sediments are recycled into the deep mantle. Although this mixing of the Earth's crustal and oceanic materials produces ore deposits and new continental crust in the long term, the immediate result is geological activity often expressed as deep, very intense earthquakes and extensive volcanism.

The seismic survey will investigate the volcanic arc, back arc, and downgoing plate in the Costa Rican portion of the Central American Focus Site. The study focuses on the central Costa Rican segment of the arc, the site of important transitions in lava chemistry, because the narrow isthmus (~150 km or 93 mi wide) is well-suited for detailed seismic imaging using onshore-offshore techniques. A systematic understanding of subduction must include a thorough knowledge of the volcanic arc, which in turn is essential in understanding the geochemical recycling processes of the Central American SubFac.

(2) Proposed Activities

(a) Location of the Activities

The Central American SubFac survey will encompass the area from 9.6°–14°N, 82°–83.8°W in the Caribbean Sea and the area 8°–11.5°N, 83.6°–88°W in the Pacific Ocean (Fig. 1). Water depths in the survey areas range from <100 to >2500 m. The seismic survey will take place in the EEZ of Costa Rica and Nicaragua. The survey is tentatively scheduled to occur off the Pacific coast from ~5 January through ~4 February and in the Caribbean Sea from ~5 February through ~7 March 2008. However, the order of the Pacific and Caribbean surveys may be reversed for logistic reasons.

(b) Description of the Activities

The procedures to be used for the Central American SubFac survey will be similar to those used during previous seismic surveys by L-DEO, e.g., off the coast of Newfoundland in the North Atlantic (Holbrook et al. 2003), and will use conventional seismic methodology. The survey will involve one

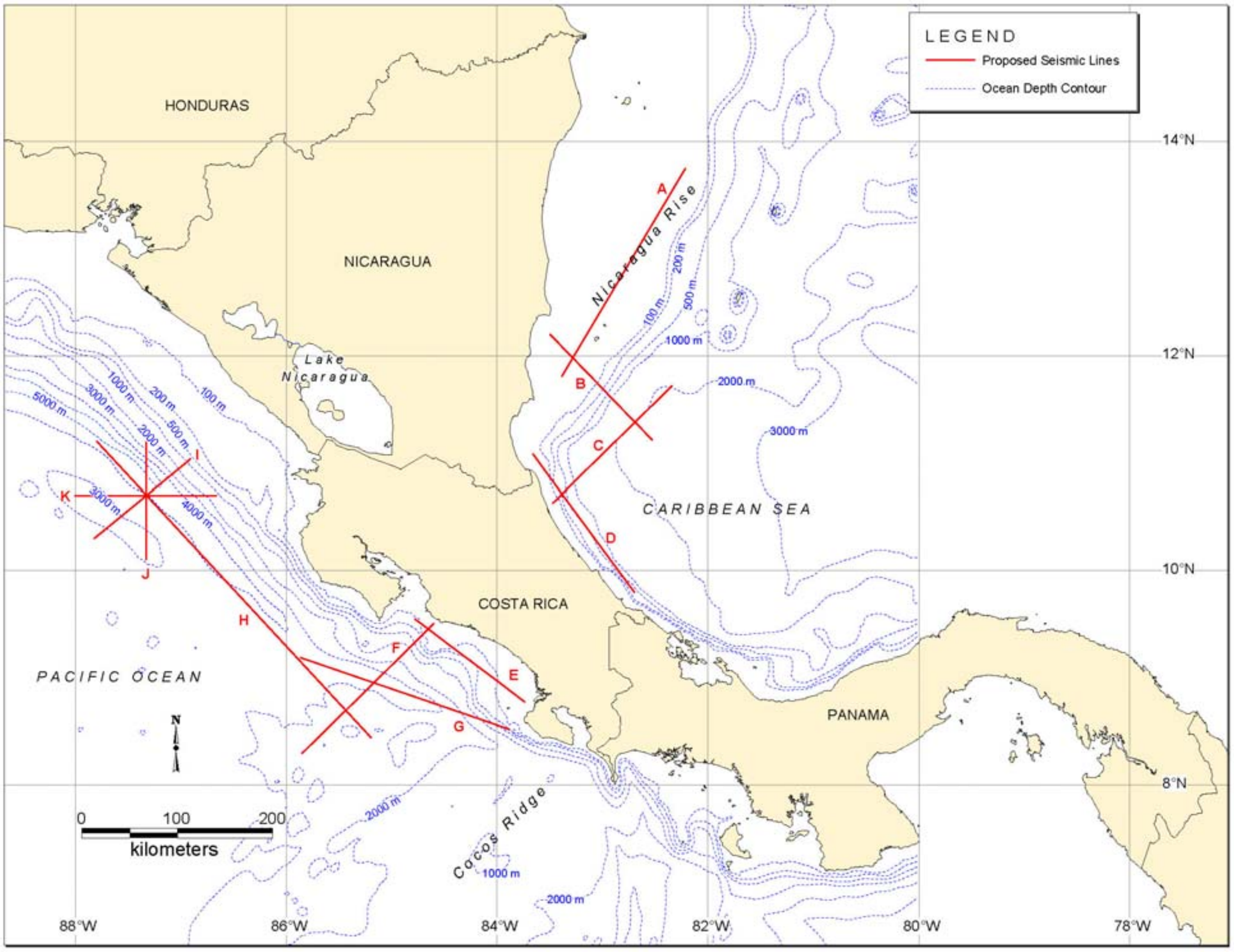

FIGURE 1. Proposed marine seismic transects A–K (not necessarily in the sequence they will be shot) planned for the Central American SubFac survey.

source vessel, the R/V *Marcus G. Langseth*, which will operate in two regions during the proposed survey: the Caribbean Sea and the Pacific Ocean. The *Langseth* will deploy an array of 36 airguns as an energy source and, at times, a receiving system consisting of a 6-km towed hydrophone streamer. As the airgun array is towed along the survey lines, the hydrophone streamer will receive the returning acoustic signals and transfer the data to the on-board processing system. In the Caribbean region, the *Langseth* will also deploy Ocean Bottom Seismometers (OBSs) to receive the returning acoustic signals. In the Pacific Ocean, a second vessel, the R/V *New Horizon*, will deploy and retrieve the OBSs.

To investigate the Central American SubFac, seismic survey transects are proposed across the isthmus in Costa Rica, along the Costa Rican arc and back-arc, the outer rise of the Cocos Plate, and the Nicaragua Rise (Fig. 1). The cross-arc transect will involve offshore as well as onshore (not shown in Fig. 1) shooting from both the Pacific and Caribbean. To understand arc-building processes, the delineation of lateral heterogeneity in crustal thickness and velocity at scales of tens of kilometers is required, both across and along-arc. In order to achieve this, the study will acquire (1) a double-side, onshore-offshore cross-arc profile, (2) an along-arc refraction line, (3) an array of seismometers in the arc to record all onshore and offshore shots and to allow 3-dimensional (3D) tomography, and (4) a refraction survey across the outer rise of the downgoing Cocos Plate (Fig. 1). Onshore seismic operations will not be discussed in detail in the EA.

The marine program will consist of ~2149 km of unique survey lines – 753 km in the Caribbean and 1396 km in the Pacific (Fig. 1; Table 1). With the exception of two lines (D and E) located in shallow to intermediate-depth water (Fig. 1), all lines will be shot twice, once at a ~50-m (20-s) shot spacing for multichannel seismic (MCS) data and once at a ~200-m (80-s) shot spacing for OBS refraction data, for a total of ~3980 km of survey lines (Table 1). The approximate numbers of line kilometers expected to be surveyed in the Pacific and Caribbean in three different water depth categories are shown in Table 2. There will be additional operations associated with equipment testing, startup, line changes, and repeat coverage of any areas where initial data quality is sub-standard.

In addition to the operations of the airgun array, a multibeam echosounder (MBES) will be operated from the *Langseth* continuously throughout the cruise. Also, a sub-bottom profiler (SBP) will be operated by the *Langseth* during most of the survey and during normal operations by the *New Horizon*.

All planned geophysical data acquisition activities will be conducted by L-DEO with on-board assistance by the scientists who have proposed the study. The scientists are headed by Dr. W. Steven Holbrook of the University of Wyoming, with collaboration from Dr. Marino Protti (OVSICORI), Drs. German Leandro and Alan Lopez (ICE), Drs. Percy Denyer, Mauricio Mora, and Walter Montero (UCR), Dr. G. Abers (Boston University), Dr. Ernst Flueh (GEOMAR), Dr. Stephan Husen (ETH), and Dr. Simon Klemperer (Stanford University) [see "List of Acronyms"]. The vessels will be self-contained, and the crew will live aboard the vessels for the entire cruise.

(c) Schedule

For the first part of the cruise, the *Langseth* is expected to depart Puerto Caldera, Costa Rica, on ~5 January 2008 for the study area in the Pacific Ocean (Fig. 1). The seismic survey will commence following the transit and deployment of the streamer and airgun array. Following ~25 days of surveying in the Pacific, all equipment will be recovered, and the vessel will transit through the Panama Canal for arrival in Puerto Limon, Costa Rica, on ~4 February. The OBSs from the *New Horizon* will be shipped over land and loaded onto the *Langseth* in Puerto Limon. The second part of the survey will commence in the Caribbean Sea on ~5 February following the transit and deployment of the streamer, OBSs, and airgun array. The Caribbean survey itself is estimated to last ~25 days. Currently, the vessel is scheduled to arrive at an unspecified port (likely in Costa Rica) on ~7 March. The order of the two surveys may be reversed due to logistics, if necessary. The exact dates of the activities depend on logistics as well as weather conditions, and/or the need to repeat some lines if data quality is substandard.

(d) Source Vessel Specifications

The R/V *Marcus G. Langseth* will be used as the source vessel. The *Langseth* will tow the 36-airgun array and a 6-km streamer containing hydrophones along predetermined lines (Fig. 1). The *Langseth* will also deploy and retrieve the OBSs in the Caribbean study area. Given the presence of the streamer and airgun array behind the vessel, the turning rate of the vessel while the gear is deployed is limited to five degrees per minute. Thus, the maneuverability of the vessel is limited during operations.

The *Langseth* has a length of 71.5 m, a beam of 17.0 m, and a maximum draft of 5.9 m. The *Langseth* was designed as a seismic research vessel, with a propulsion system designed to be as quiet as possible to avoid interference with the seismic signals. The ship is powered by two Bergen BRG-6 diesel engines, each producing 3550 hp which drive the two propellers directly. Each propeller has four blades,

TABLE 1. Estimated line kilometers to be surveyed during the Central American SubFac cruise (see Fig. 1 for locations of transect lines).

Location	Transect Line	km	# of times line is to be surveyed	Total # of km
Caribbean	A	250	2	500
	B	152	2	305
	C	173	2	346
	D	178	1	178
Total		**753**		**1328**
Pacific	E	143	1	143
	F	192	2	384
	G	230	2	460
	H	418	2	837
	I	129	2	258
	J	138	2	276
	K	146	2	293
Total		**1396**		**2652**

TABLE 2. Estimated line kilometers (in km) to be surveyed in different water depth categories during the Central American SubFac cruise.

	Water Depth Category			
Location	Shallow (<100 m)	Intermediate (100 – 1000 m)	Deep (>1000 m)	Total line km
Caribbean	686	238	404	1328
Pacific	111	175	2365	2652
Total	797	413	2769	3980

and the shaft typically rotates at 750 rpm. The vessel also has an 800 hp bowthruster. The operation speed during seismic acquisition is typically 7.4–9.3 km/h (4–5 kt). When not towing seismic survey gear, the *Langseth* can cruise at 20–24 km/h (11–13 kt). The *Langseth* has a range of 25,000 km.

The *Langseth* will also serve as the platform from which vessel-based marine mammal (and sea turtle) observers (MMOs) will watch and listen for animals before and during airgun operations.

Other details of the *Langseth* include the following:

Owner:	National Science Foundation
Operator:	Lamont-Doherty Earth Observatory
Flag:	United States of America
Date Built:	1991 (Refitted in 2006/2007)
Gross Tonnage:	2925
Bottom Mapping Equipment:	Simrad EM120 12 kHz 1ºx1º Deep Sea MBES (150º swath); 3.5 kHz SBP
Compressors for Airguns:	3x 1000 scfm at 2000 psi
Accommodation Capacity:	55 including ~35 scientists

(e) OBS Vessel Specifications

The R/V *New Horizon* will be the dedicated OBS vessel during the Pacific part of the survey and will deploy and retrieve the OBSs. The *New Horizon* has a length of 51.8 m, a beam of 11.0 m, and a maximum draft of 3.7 m. The ship is powered by two 850 hp D398 Caterpillar engines. The typical cruising speed is 18.5 km/h (10 kt) with a maximum speed of 22.8 km/h (12.3 kt). The *New Horizon* has a range of 18,000 km.

Other details of the *New Horizon* include the following:

Owner:	University of California, San Diego
Operator:	Scripps Institution of Oceanography
Flag:	United States of America
Date Built:	1978
Gross Tonnage:	294
Bottom Mapping Equipment:	Knudsen 320 B 3.5/12 kHz SBP Furuno FCV 382 50/200 kHz fathometer
Accommodation Capacity:	12 crew + 19 scientists

(f) Airgun Description

During the survey, the airgun array to be used will consist of 36 airguns, with a total volume of ~6600 in^3. The airguns will comprise a mixture of Bolt 1500LL and 1900LL airguns. The array will consist of four identical linear arrays or "strings" (Fig. 2). Each string will have ten airguns; the first and last airguns in each string are spaced 16 m or 52 ft apart. Nine airguns in each string will be fired simultaneously, while the tenth is kept in reserve as a spare, to be turned on in case of failure of another airgun. The four airgun strings will be distributed across an approximate area of 24×16 m behind the *Langseth* and will be towed ~50–100 m behind the vessel. The firing pressure of the array is 2000 psi. The airgun array will fire in two modes: every 50 m (20 s) or every 200 m (80 s). During firing, a brief (~0.1 s) pulse of sound is emitted. The airguns will be silent during the intervening periods.

The airguns will be towed at a depth of 9 or 12 m. The 12-m tow depth is planned for transect lines C and F (see Fig. 1), whereas all other lines are planned to be shot using the 9-m tow depth. The depth at which the source is towed affects the maximum near-field output and the shape of its frequency spectrum. If the source is towed at 12 m, the effective source level for sound propagating in near-horizontal directions is higher than if the array is towed at 9 m (see. Fig. 3 and 4 below). However, the nominal

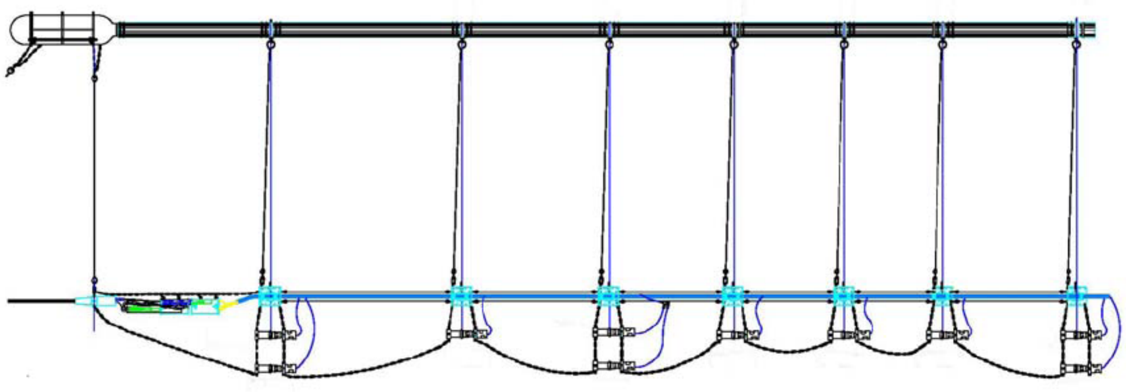

FIGURE 2. One linear airgun array or string.

source levels of the array (or the estimates of the sound that would be measured from a theoretical point source emitting the same total energy as the airgun array) at various tow depths are nearly identical.

Because the actual source is a distributed sound source (36 airguns) rather than a single point source, the highest sound level measurable at any location in the water will be less than the nominal source level. In addition, the effective source level for sound propagating in near-horizontal directions will be substantially lower than the level applicable to downward propagation, because of the directional nature of the sound from the airgun array.

36-Airgun Array Specifications

Energy Source	Thirty-six 2000 psi Bolt airguns of 40–360 in^3
Source output (downward)	0-pk is 82 bar-m (258 dB re 1 µPa·m); pk-pk is 167 bar-m (264 dB)
Towing depth of energy source	12 m
Air discharge volume	~6600 in^3
Dominant frequency components	0–188 Hz

(g) OBS Deployment

A combination of 85 OBSs (150 total deployments) will be used during the project. A total of 60 OBS deployments will take place in the Caribbean (from the *Langseth*), and 90 deployments will take place in the Pacific from the *New Horizon*. The *New Horizon* will conduct a third deployment of the 25 OBSs in the Pacific for their seismicity monitoring program, not specifically addressed in this EA.

(h) Multibeam Echosounder and Sub-bottom Profiler

Along with the airgun operations, two additional acoustical data acquisition systems will be operated during most or all of the *Langseth*'s cruise. The ocean floor will be mapped with the 12-kHz Simrad EM120 MBES and a 3.5-kHz SBP. These sound sources will be operated from the *Langseth* simultaneous with the airgun array.

The Simrad EM120 operates at 11.25–12.6 kHz and is hull-mounted on the *Langseth*. The beamwidth is 1° fore-aft and 150° athwartship. The maximum source level is 242 dB re 1 µPa. For deep-water operation, each "ping" consists of nine successive fan-shaped transmissions, each 15 ms in duration and each ensonifying a sector that extends 1° fore-aft. The nine successive transmissions span an overall cross-track angular extent of about 150°, with 16 ms gaps between the pulses for successive sectors. A receiver in the overlap area between two sectors would receive two 15-ms pulses separated by a 16-ms gap. In shallower water, the pulse duration is reduced to 5 or 2 ms, and the number of transmit beams is also reduced. The ping interval varies with water depth, from ~5 s at 1000 m to 20 s at 4000 m (Kongsberg Maritime 2005).

The SBP is normally operated to provide information about the sedimentary features and the bottom topography that is simultaneously being mapped by the MBES. The energy from the SBP is directed downward by a 3.5 kHz transducer in the hull of the *Langseth*. The output varies with water depth from 50 watts in shallow water to 800 watts in deep water. The pulse interval is 1 s, but a common mode of operation is to broadcast five pulses at 1-s intervals followed by a 5-s pause.

Langseth Sub-bottom Profiler Specifications

Maximum source output (downward)	204 dB re 1 μPa; 800 watts
Normal source output (downward)	200 dB re 1 μPa; 500 watts
Dominant frequency components	3.5 kHz
Bandwidth	1.0 kHz with pulse duration 4 ms 0.5 kHz with pulse duration 2 ms 0.25 kHz with pulse duration 1 ms
Nominal beam width	30 degrees
Pulse duration	1, 2, or 4 ms

The *New Horizon* will also have a SBP that will be used in the Pacific region. The Knudsen 320B echosounder is a dual–frequency system with operating frequencies of 3.5 and 12 kHz. Maximum output power at is 10 kW 3.5 kHz and 2 kW at 12 kHz. Pulse lengths up to 24 ms and bandwidths to 5 kHz are available. Pulse intervals are typically ½ s to ~8 s depending on water depth. The repetition rate is range-dependent with a maximum 1% duty cycle. The source consists of a single 12-kHz transducer plus a lower-frequency (3.5 kHz) transducer array for sub-bottom mapping. The latter consists of 16 elements in a 4×4 array. The 3.5 kHz transducer (TR109) array emits a conical beam with a width of 26°, and the 12 kHz transducer (TC-12/34) emits a conical beam with a width of 30°.

(3) Monitoring and Mitigation Measures

Numerous species of marine mammals and sea turtles are known to occur in the proposed study areas, and there are several turtle nesting beaches that will be in use at the time of the survey. To minimize the likelihood that impacts will occur to the species and stocks, airgun operations will be conducted in accordance with requirements by NMFS and the U.S. Fish and Wildlife Service (USFWS) under the MMPA and the ESA, including obtaining permission for incidental harassment or incidental 'take' of cetaceans and, if present, pinniped, and other endangered species. L-DEO will coordinate all activities with the relevant U.S. federal agencies, and with the governments of Costa Rica and Nicaragua, as the proposed activities will take place in the EEZ of Costa Rica and Nicaragua.

The following subsections provide detailed information about the mitigation measures that are an integral part of the planned activities. The procedures described here are based on protocols used during previous seismic research cruises and on recommended best practices in Richardson et al (1995), Pierson et al. (1998), and Weir and Dolman (2007).

(a) Planning Phase

In designing this proposed seismic survey, L-DEO and NSF have considered potential environmental impacts including seasonal, biological, and weather factors; ship schedules; and equipment availability during a preliminary assessment carried out when ship schedules were still flexible. Part of the considerations was whether the research objectives could be met with a smaller source or with a different survey design that involves less prolonged seismic operations.

(b) Visual Monitoring

Marine mammal visual observers (MMVOs) will be based aboard the seismic source vessel and they will watch for marine mammals and turtles near the vessel during daytime airgun operations and during start-ups of airguns at night. MMVOs will also watch for marine mammals and turtles near the seismic vessel for at least 30 min prior to the planned start of airgun operations after an extended shut down of the airguns. When feasible, observations will also be made during daytime periods when the *Langseth* is underway without seismic operations (e.g., during transits). Based on MMVO observations, airguns will be powered down or, if necessary, shut down completely (see below), when marine mammals or turtles are detected within or about to enter the designated safety or exclusion zone (EZ) [see section (e) below]. The MMVO(s) will continue to maintain watch to determine when the animal(s) are outside the EZ, and airgun operations will not resume until the animal has left that zone.

During seismic operations off Central America, at least three observers will be based aboard the *Langseth*. MMVOs will be appointed by L-DEO with NMFS concurrence. At least one MMVO, and when practical two, will monitor the EZ for marine mammals and turtles during daytime operations and nighttime start ups of the airguns. MMVO(s) will be on duty in shifts of duration no longer than 4 h. The crew will also be instructed to assist in detecting marine mammals and turtles and implementing mitigation requirements (if practical).

The *Langseth* is a suitable platform for marine mammal and turtle observations. When stationed on the observation platform, the eye level will be ~17.8 m above sea level, and the observer will have a good view around the entire vessel. During daytime, the MMVO(s) will scan the area around the vessel systematically with reticle binoculars (e.g., 7×50 Fujinon), Big-eye binoculars (25×150), and with the naked eye. During darkness, night vision devices will be available (ITT F500 Series Generation 3 binocular-image intensifier or equivalent). Laser rangefinding binoculars (Leica LRF 1200 laser rangefinder or equivalent) will be available to assist with distance estimation.

(c) Passive Acoustic Monitoring

Passive acoustic monitoring (PAM) will take place to complement the visual monitoring program. Visual monitoring typically is not effective during periods of bad weather or at night, and even with good visibility, is unable to detect marine mammals when they are below the surface or beyond visual range. Acoustical monitoring can be used in addition to visual observations to improve detection, identification, localization, and tracking of cetaceans. It is only useful when marine mammals call, but it can be effective either by day or by night, and does not depend on good visibility. The acoustic monitoring will serve to alert visual observers (if on duty) when vocalizing cetaceans are detected. It will be monitored in real time so that the visual observers can be advised when cetaceans are detected. When bearings (primary and mirror-image) to calling cetacean(s) are determined, the bearings will be relayed to the visual observer to help him/her sight the calling animal(s).

SEAMAP (Houston, TX) will be used as the primary acoustic monitoring system. This system was also used during several previous L-DEO seismic cruises (e.g., Smultea et al. 2004, 2005; Holst et al.

2005a,b). The PAM system consists of hardware (i.e., hydrophones) and software. The "wet end" of the SEAMAP system consists of a low-noise, towed hydrophone array that is connected to the vessel by a "hairy" faired cable. The array will be deployed from a winch located on the back deck. A deck cable will connect from the winch to the main computer lab where the acoustic station and signal conditioning and processing system will be located. The lead-in from the hydrophone array is ~400 m long, and the active part of the hydrophone array is ~56 m long. The hydrophone array is typically towed at depths <20 m.

While the *Langseth* is in the seismic survey area, the towed hydrophone array will be monitored 24 h per day while at the seismic survey area during airgun operations and also during most periods when the *Langseth* is underway with the airguns not operating. One MMO will monitor the acoustic detection system at any one time, by listening to the signals from two channels via headphones and/or speakers and watching the real-time spectrographic display for frequency ranges produced by cetaceans. MMOs monitoring the acoustical data will be on shift from 1–6 h. All MMOs are expected to rotate through the PAM position, although the most experienced with acoustics will be on PAM duty more frequently.

When a cetacean vocalization is detected, the acoustic MMO will, if visual observations are in progress, contact the MMVO immediately, to alert him/her to the presence of the cetacean(s), if they have not already been see), and to allow a power down or shut down to be initiated, if required. The information regarding the call will be entered into a database. The data to be entered include an acoustic encounter identification number, whether it was linked with a visual sighting, date, time when first and last heard and whenever any additional information was recorded, position and water depth when first detected, bearing if determinable, species or species group (e.g., unidentified dolphin, sperm whale), types and nature of sounds heard (e.g., clicks, continuous, sporadic, whistles, creaks, burst pulses, strength of signal, etc.), and any other notable information. The acoustic detection can also be recorded for further analysis.

(d) MMVO Data and Documentation

MMVOs will record data to estimate the numbers of marine mammals and turtles exposed to various received sound levels and to document apparent disturbance reactions or lack thereof. Data will be used to estimate numbers of animals potentially 'taken' by harassment (as defined in the MMPA). They will also provide information needed to order a power down or shutdown of airguns when marine mammals and turtles are within or near the EZ.

When a sighting is made, the following information about the sighting will be recorded:

1. Species, group size, age/size/sex categories (if determinable), behavior when first sighted and after initial sighting, heading (if consistent), bearing and distance from seismic vessel, sighting cue, apparent reaction to the airguns or vessel (e.g., none, avoidance, approach, paralleling, etc.), and behavioral pace.
2. Time, location, heading, speed, activity of the vessel, sea state, visibility, and sun glare.

The data listed under (2) will also be recorded at the start and end of each observation watch, and during a watch whenever there is a change in one or more of the variables.

All observations, as well as information regarding airgun power down and shutdown, will be recorded in a standardized format. Data accuracy will be verified by the MMVOs at sea, and preliminary reports will be prepared during the field program and summaries forwarded to the operating institution's shore facility and to NSF weekly or more frequently. MMVO observations will provide the following information:

1. The basis for decisions about powering down or shutting down airgun arrays.
2. Information needed to estimate the number of marine mammals potentially 'taken by harassment'. These data will be reported to NMFS and/or USFWS per terms of MMPA authorizations or regulations.
3. Data on the occurrence, distribution, and activities of marine mammals and turtles in the area where the seismic study is conducted.
4. Data on the behavior and movement patterns of marine mammals and turtles seen at times with and without seismic activity.

A report will be submitted to NMFS within 90 days after the end of the cruise. The report will describe the operations that were conducted and sightings of marine mammals and turtles near the operations. The report will be submitted to NMFS, providing full documentation of methods, results, and interpretation pertaining to all monitoring. The 90-day report will summarize the dates and locations of seismic operations, and all marine mammal and turtle sightings (dates, times, locations, activities, associated seismic survey activities). The report will also include estimates of the amount and nature of potential "take" of marine mammals by harassment or in other ways.

(e) Proposed Exclusion Zones

Acoustic Measurement Units.—Received sound levels have been predicted by L-DEO for the 36-airgun array operating in deep water (Fig. 3 and 4) and for a single 1900LL 40 in^3 airgun to be used during power downs (Fig. 5). The predicted received levels depend distance and direction from the airguns, as shown in Figures 3–5. The maximum relevant depth (2000 m), shown on the Figures by the horizontal dashed lines, represents the maximum anticipated depth of dive by any marine mammals, and is relevant for predicting EZs (see below). A detailed description of L-DEO's modeling effort is provided in Appendix A.

The predicted sound contours are shown as sound exposure levels (SEL) in decibels (dB) re 1 $\mu Pa^2 \cdot s$. SEL as used here is a measure of the received energy in one pulse and represents the sound pressure level (SPL) that would be measured if the pulse energy were spread evenly across a 1-s period. Because actual seismic pulses are less than 1 s in duration, this means that the SEL value for a given pulse is lower than the SPL calculated for the actual duration of the pulse. SPL is often referred to as rms or "root mean square" pressure, averaged over the pulse duration. The advantage of working with SEL is that this measure accounts for the total received energy in the pulse, and biological effects of pulsed sounds probably depend mainly on pulse energy rather than SPL. In contrast, SPL for a given pulse depends greatly on pulse duration. A pulse with a given SEL can be long or short depending on the extent to which propagation effects have "stretched" the pulse duration. The SPL will be low if the duration is long and higher if the duration is short, even though the pulse energy (and presumably the biological effects) are the same.

Although SEL may be a better measure than SPL when dealing with biological effects of pulsed sound, SPL is the measure that has been most commonly used in studies of marine mammal reactions to airgun sounds and in NMFS guidelines concerning levels above which "taking" might occur. As noted above, the SPL (= rms) received levels that are used as impact criteria for marine mammals are not directly comparable to pulse energy (SEL). The difference between the SEL and SPL values averages about 5–15 dB, depending on the propagation characteristics of the area and distance from the source. The SPL (i.e., rms sound pressure) for a given pulse is typically 5–15 dB higher than the SEL value for the same pulse as measured at the same location (Greene 1997; McCauley et al. 1998, 2000a; Blackwell et al. 2007; MacGillivray and Hannay 2007; David Hannay, JASCO Research, pers. comm.). Here we assume that rms pressure

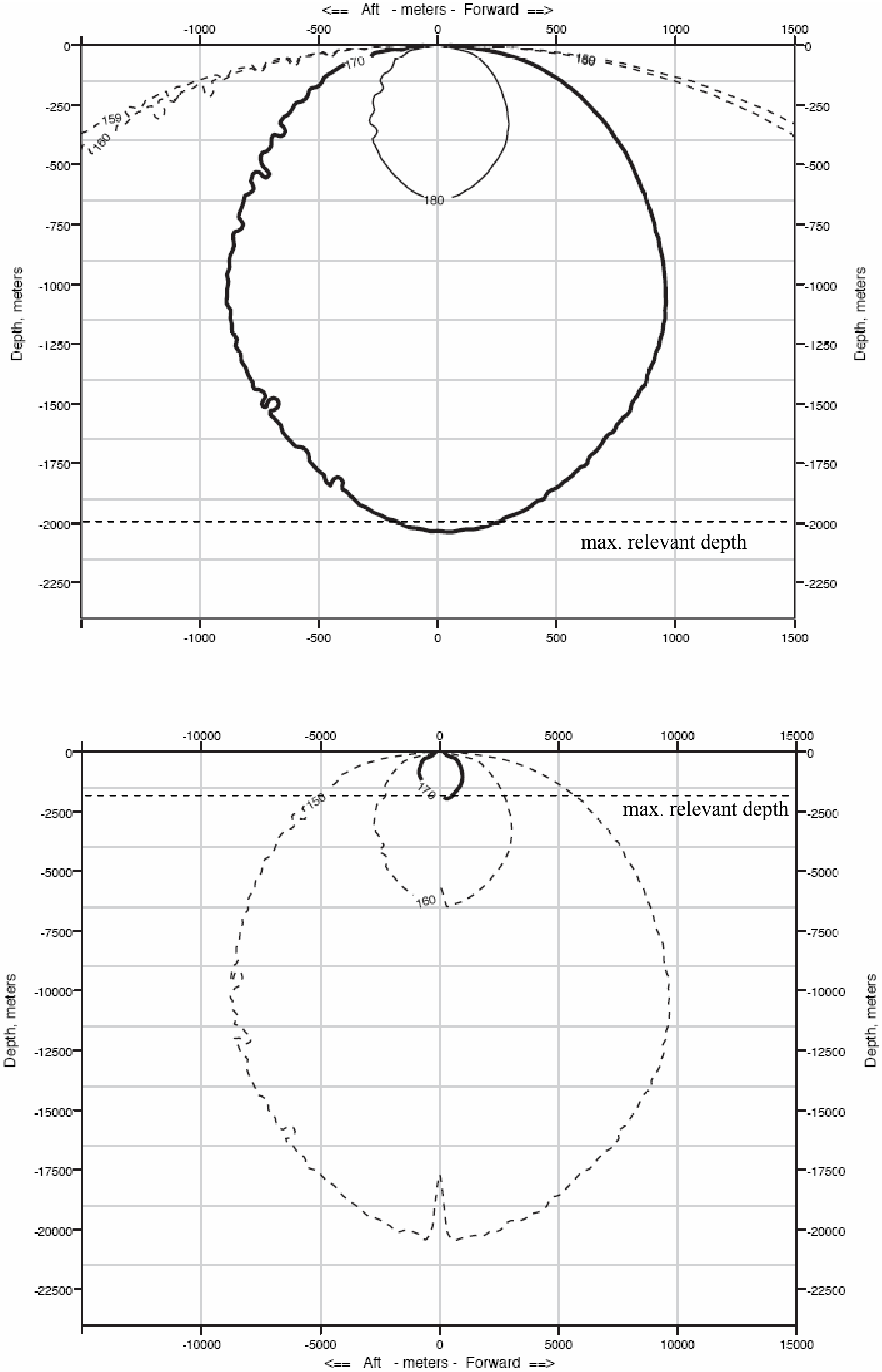

FIGURE 3. Modeled received sound exposure levels (SELs) from the 36-airgun array operating at a 9-m tow depth, as planned for use during much of the Central American SubFac survey during January–March 2008. The rms SPL is expected to average ~10 dB higher than the SEL values.

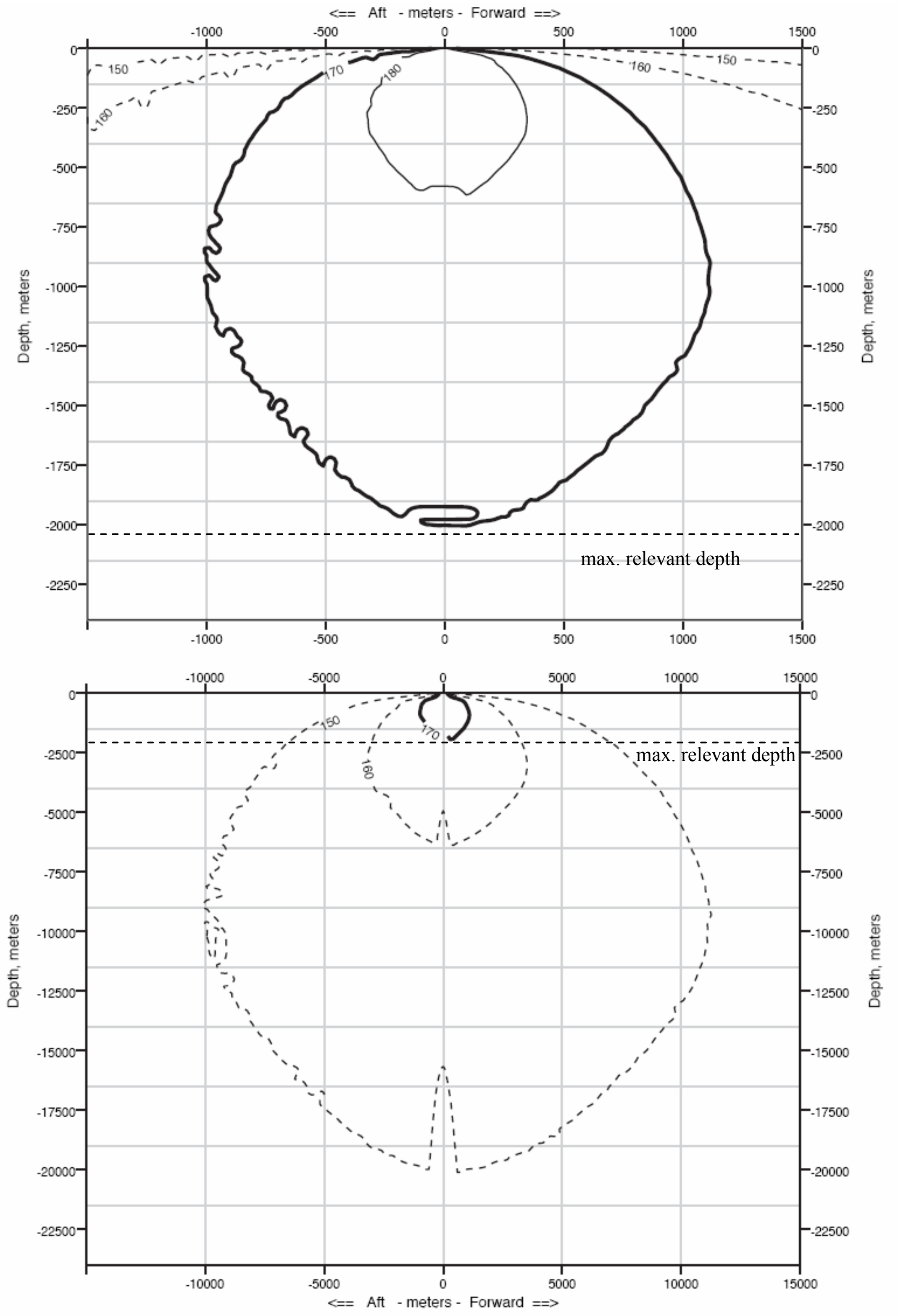

FIGURE 4. Modeled received sound exposure levels (SELs) from the 36-airgun array operating at a 12-m tow depth, as planned for use during parts of the Central American SubFac survey during January–March 2008. The rms SPL is expected to average ~10 dB higher than the SEL values.

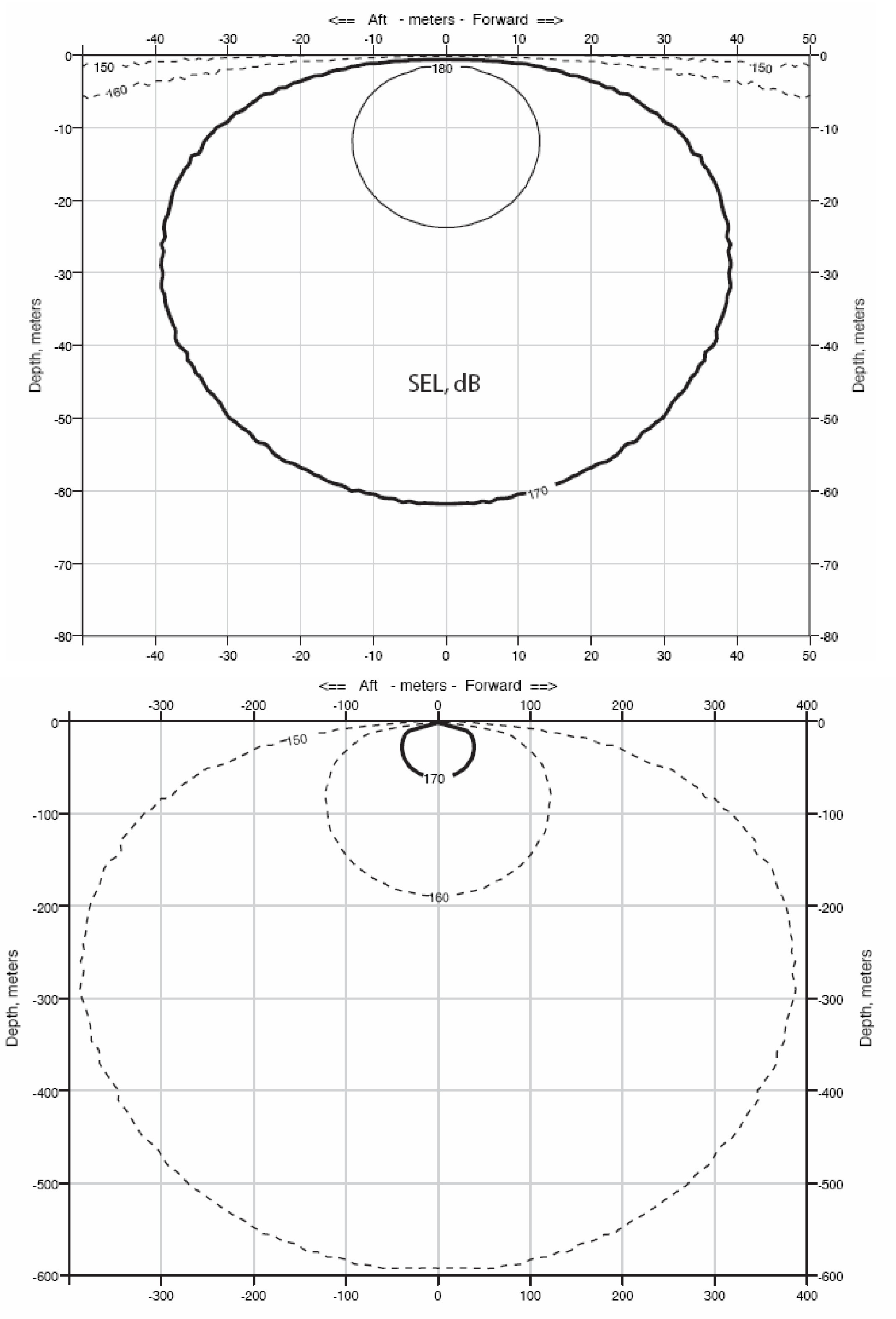

FIGURE 5. Modeled received sound exposure levels (SELs) from a single 40 in^3 airgun operating at a 9-m tow depth, planned for use during power down operations during the Central American SubFac survey during January–March 2008. The rms SPL is expected to average ~10 dB higher than the SEL values.

levels of received seismic pulses will be 10 dB higher than the SEL values predicted by L-DEO's model. Thus, we assume that 170 dB SEL ≈ 180 re 1 μPa_{rms}.

It should be noted that neither the SEL nor the SPL (= rms) measure is directly comparable to the peak or peak-to-peak pressure levels normally used by geophysicists to characterize source levels of airguns. Peak (p or 0-p) and peak-to-peak (p-p) pressure levels for airgun pulses are always higher than the rms dB referred to in much of the biological literature (Greene 1997; McCauley et al. 1998, 2000a). For example, a measured received level of 160 re 1 μPa_{rms} in the far field would typically correspond to to ~170–172 dB re 1 μPa_{p}, and to ~176–178 dB re 1 $\mu Pa_{p\text{-}p}$, *as measured for the same pulse received at the same location* (Greene 1997; McCauley et al. 1998, 2000a). (The SEL value for the same pulse would normally be 145 to 155 dB re 1 $\mu Pa^2 \cdot s$.) The precise difference between rms and peak or peak-to-peak values for a given pulse depends on the distance from source, frequency content, and duration of the pulse, among other factors. However, the rms level is always lower than the peak or peak-to-peak level, and higher than the SEL value, for an airgun-type source.

L-DEO Predicted Sound Levels vs. Distance and Depth.—The depth at which the source is towed impacts the maximum near-field output and on the shape of the frequency spectrum. If the source is towed at a relatively deep depth (e.g., ~12 m), the effective source level for sound propagating in near-horizontal directions is substantially greater than if the array is towed at shallower depths (e.g., ~9 m or 30 ft; see Fig. 4 vs. 3).

Empirical data concerning 180, 170, and 160 dB re 1 μPa_{rms} distances in deep and/or shallow water were acquired for various airgun configurations during the acoustic calibration study of the R/V *Maurice Ewing*'s 20-airgun 8600 in^3 array in 2003 (Tolstoy et al. 2004a,b). The results showed that radii around the airguns where the received level was 160 dB re 1 μPa_{rms} varied with water depth. Similar depth-related variation is likely for the 180-dB re 1 μPa_{rms} safety criterion applicable to cetaceans and the 190-dB re 1 μPa_{rms} radius applicable to pinnipeds (see NMFS 2000), although these were not measured. The L-DEO model does not allow for bottom interactions, and thus is most directly applicable to deep water and to relatively short ranges.

- The empirical data indicated that, for ***deep water*** (>1000 m), the L-DEO model ***overestimates*** the received sound levels at a given distance (Tolstoy et al. 2004a,b). However, to be conservative, the distances predicted by L-DEO's model, as shown in Fig. 3–5, will be applied to deep-water areas during the proposed study (Table 3). As very few, if any, mammals are expected to occur below 2000 m, this depth was used as the maximum relevant depth.
- Empirical measurements indicated that in ***shallow water*** (<100 m), the L-DEO model ***under-estimates*** actual levels. In previous L-DEO projects done since the calibration results were obtained by Tolstoy et al. (2004a,b), the EZs in shallow water were typically adjusted upward from the values predicted by L-DEO's model by factors of 1.3× to 15× depending on the size of the airgun array and the sound level measured (Tolstoy et al. 2004b). During the proposed cruise, similar factors will be applied to the shallow-water radii (Table 3).
- Empirical measurements were not conducted for ***intermediate depths*** (100–1000 m). On the expectation that results would be intermediate between those from shallow and deep water, a correction factor (1.1 to 1.5×) was applied during previous L-DEO cruises to the estimates provided by the model for deep-water situations to obtain estimates for intermediate-depth sites. These correction factors will be used during previous L-DEO surveys and will be used during the proposed study for intermediate depths (Table 3).

TABLE 3. Predicted distances to which sound levels ≥190, 180, 170, and 160 dB re 1 $\mu\text{Pa}_{\text{rms}}$ might be received in shallow (<100 m), intermediate (100–1000 m), and deep (>1000m) water during the Central American SubFac survey, January–March 2008. Predicted radii for "Deep" water are based on Figures 3–5 (derived from L-DEO's model), assuming that received levels on an rms basis are, numerically, 10 dB higher than the SEL values shown in Figures 3–5, and that mammals would not typically occur at depths >2000 m. See text regarding derivation of estimates for "Intermediate" and "Shallow" water depths.

			Predicted RMS Distances (m)			
Source and Volume	**Tow Depth (m)**	**Water Depth**	**190 dB**	**180 dB**	**170 dB**	**160 dB**
Single Bolt airgun 40 in^3	9	Deep	12	40	120	385
		Intermediate	18	60	180	578
		Shallow	150	296	500	1050
4 strings 36 airguns 6600 in^3	9	Deep	300	950	2900	6000
		Intermediate	450	1425	4350	6667
		Shallow	2182	3694	7808	8000
4 strings 36 airguns 6600 in^3	12	Deep	340	1120	3300	7400
		Intermediate	510	1680	4950	8222
		Shallow	2473	4356	8885	9867

Using the distances predicted by L-DEO's deep-water model and the various correction factors, Table 3 shows the distances within which received pulse levels are expected to have diminished to four rms sound levels, considering the 36-airgun array and a single airgun operating in three different water depths. In deep water, the maximum depth considered is 2000 m. The 180 and 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$ distances are the safety criteria as specified by NMFS (2000) and are applicable to cetaceans and pinnipeds, respectively. The 180-dB re 1 $\mu\text{Pa}_{\text{rms}}$ distance will also be used as the EZ for sea turtles, as required by NMFS for previous L-DEO seismic surveys (e.g., Smultea et al. 2005). If marine mammals or turtles are detected within or about to enter the appropriate EZ, the airguns will be powered down (or shut down if necessary) immediately.

Because the predictions in Table 3 are based in part on empirical correction factors derived from acoustic calibration of different airgun configurations than those to be used on the *Langseth* (*cf.* Tolstoy et al. 2004a,b), L-DEO is planning an acoustic calibration study of the *Langseth's* 36-airgun (~6600 in^3) array in the summer of 2007 in the Gulf of Mexico (LGL Ltd. 2006). Distances where sound levels (e.g., 190, 180, 170, and 160 re 1 $\mu\text{Pa}_{\text{rms}}$) are received in deep, intermediate, and shallow water will be determined for various airgun configurations. The empirical data from the 2007 calibration study will be used to refine the EZs used during the Central American SubFac cruise, if the data are appropriate and available at the time of the SubFac survey.

L-DEO is aware that NMFS may release new noise-exposure guidelines soon (NMFS 2005; see http://mmc.gov/sound/plenary2/pdf/gentryetal.pdf for preliminary recommendations concerning the new criteria). L-DEO will be prepared to revise its procedures for estimating numbers of mammals "taken", EZs, etc., as may be required by the new guidelines, if issued.

JASCO Modeled Sound Levels vs. Distance and Depth.—For comparison purposes, received sound fields around the *Langseth*'s 36-airgun array were also predicted by JASCO Research Ltd. (Appendix B). The JASCO model not only takes account of the specific configuration of the airgun array and tow depth to be used (as does the L-DEO model), but it also takes account of bottom conditions and seasonal water-mass properties at sample sites within the proposed study areas in the Western Caribbean and Eastern Tropical Pacific (ETP). Bottom and water-mass properties are known to influence propagation loss.

JASCO's model (Appendix B) is a two-part model including

1. a source model for airgun arrays that predicts the sound levels and frequency characteristics in the near field, allowing for the specific configuration and depths of the airguns, and
2. a propagation model that predicts received levels for various distances, directions, and depths in the water column; it takes into account the water depth, bottom topography, and anticipated sound-velocity profile during the relevant season (winter), as well as the tow depth of the array.

JASCO modeled the expected sound field around the 36-airgun array for three sites in the Caribbean part of the study area (one shallow, one intermediate-depth, and one deep) and for another three sites on the Pacific side of Central America (see Appendix B). The six sites were along the planned seismic survey lines. The model was run for both 9- and 12-m source depth, taking account of aspect-dependence. JASCO's propagation model is based on an implementation of the widely-used Range-dependent Acoustic Model (RAM), with enhancements (Appendix B). From the resulting predicted sound fields at each of the six sample sites, the distances within which received levels were predicted to be as much as 190, 180, 170, and 160 dB re 1 μPa_{rms} were determined, considering received levels at depths down to >2000 m below the water surface (where the water was that deep; Table 4).

The JASCO modeling results are presented here for reference (Table 4 and Appendix B). These model results were not used, however, to define EZs for the study here, nor were they used to estimate the number of marine mammals that would be exposed to specific levels of seismic sound. Instead, the EZs are based on L-DEO model data, corrected based on empirical results from a 2003 Gulf of Mexico calibration study (Tolstoy et al, 2004a,b). The JASCO model results predict shorter ranges to the EZ in nearly every instance, and the data from Tolstoy et al (2004a,b) have been used to support all recent L-DEO projects. Since the JASCO model results have not yet been validated for the *Langseth* arrays, we propose to use these more conservative ranges for the present project as well. Data from the planned 2007 calibration study (LGL Ltd. 2006) will be used to evaluate both the L-DEO and JASCO models to determine how well each predicts actual sound transmission, and if appropriate, to derive more accurate correction factors. The field data will be provided to NMFS for evaluation, and after analysis, will be applied as appropriate to revise the EZs for future surveys. A review of the fit of JASCO's model to empirical data measured durng several recent seismic surveys in the Chukchi Sea is provided in Appendix B.

(f) Mitigation During Operations

Mitigation measures that will be adopted will include (1) speed or course alteration, provided that doing so will not compromise operational safety requirements, (2) power-down procedures, (3) shut-down procedures, (4) ramp-up procedures, and (5) minimize approach to slopes and submarine canyons, if possible, because of sensitivity of beaked whales.

TABLE 4. Alternative predicted distances to which sound levels ≥190, 180, 170, and 160 dB re 1 μPa_{rms} might be received in shallow (<100 m), intermediate (100–1000 m), and deep (>1000 m) water during the Central American SubFac survey, January–March 2008, as modeled by JASCO. For deep water, only the received levels in the top 2000 m of the water column are considered. Distance shown is the higher value of the corresponding "95% max range" and "broadside range" as predicted by JASCO's site-specific propagation modeling (see Annex 4 in Appendix B).

				Predicted RMS Distances (m)			
Source and Volume	**Location**	**Tow Depth (m)**	**Water Depth**	**190 dB**	**180 dB**	**170 dB**	**160 dB**
36 airguns ~6600 in^3	Pacific	9	Deep	321	525	1556	7382
			Intermediate	292	496	2253	7051
			Shallow	254	471	1459	3627
		12 Line F only	Deep	323	620	1871	8503
			Intermediate	314	554	2964	13680
			Shallow	273	459	1639	3827
	Caribbean	9	Deep	290	533	1561	4169
			Intermediate	295	500	1290	4511
			Shallow	288	455	711	2281
		12 Line C only	Deep	315	634	1920	4773
			Intermediate	315	556	1446	5382
			Shallow	310	471	772	3216

Speed or course alteration

If a marine mammal or sea turtle is detected outside the EZ but is likely to enter it based on its position and the relative motion, the vessel's speed and/or direct course may be adjusted, if safety and scientific objectives allow. It should be noted that major course and speed adjustments are often impractical when towing long seismic streamers and large source arrays; thus, alternative mitigation measures often will be required.

Power-down procedures

A power down involves reducing the number of operating airguns, typically to a single airgun (e.g., 40 in^3), to minimize the EZ, so that marine mammals or turtles are no longer in or about to enter this zone. A power down of the airgun array to a reduced number of operating airguns may also occur when the vessel is moving from one seismic line to another. The continued operation of at least one airgun is intended to alert marine mammals and turtles to the presence of the seismic vessel in the area.

If a marine mammal or turtle is detected outside the EZ but is likely to enter it, and if the vessel's speed and/or course cannot be changed, the airguns will be powered down to a single airgun before the animal is within the EZ. Likewise, if a mammal or turtle is already within the EZ when first detected, the airguns will be powered down immediately. If a marine mammal or turtle is detected within or near the smaller EZ around that single airgun (Table 3), all airguns will be shut down (see next subsection).

Following a power down, airgun activity will not resume until the marine mammal or turtle has cleared the EZ. The animal will be considered to have cleared the EZ if it

- is visually observed to have left the EZ, or
- has not been seen within the EZ for 15 min in the case of small odontocetes or pinnipeds, or
- has not been seen within the EZ for 30 min in the case of mysticetes and large odontocetes, including sperm, pygmy sperm, dwarf sperm, and beaked whales, or
- the vessel has moved outside the applicable EZ for turtles, ie., ~8 min [based on the length of time it would take the vessel to leave the modeled deep-water EZ of 1120 m with a speed of 8.3 km/h or 4.5 kt].

Following a power down and subsequent clearing of the EZ, the airgun array will resume operations according to the ramp-up procedures described below.

Shut-down procedures

The operating airgun(s) will be shut down if a marine mammal or turtle is detected within EZ of a single 40 in^3 airgun (Table 3) while the airgun array is at full volume or during a power down. Airgun activity will not resume until the marine mammal or turtle has cleared the EZ or until the MMVO is confident that the animal has left the vicinity of the vessel. Criteria for judging that the animal has cleared the EZ will be as described in the preceding subsection.

Ramp-up procedures

A ramp-up procedure will be followed when the airgun array begins operating after a specified-duration period without airgun operations or when a power down has exceeded that period. It is proposed that, for the present cruise, this period would be ~8 min. This period is based on the modeled 180-dB radius for the 36-airgun array (see Table 3) in relation to the planned speed of the *Langseth* while shooting in deep water (see above). Similar periods (~8–10 min) were used during previous L-DEO surveys.

Ramp up will begin with the smallest airgun in the array (40 in^3). Airguns will be added in a sequence such that the source level of the array will increase in steps not exceeding 6 dB per 5-min period over a total duration of ~20 to 25 min. During ramp-up, the MMVOs will monitor the EZ, and if marine mammals or turtles are sighted, a course/speed change, power down, or shut down will be implemented as though the full array were operational.

Initiation of ramp-up procedures from shutdown requires that the full EZ must be visible by the MMVOs, whether conducted in daytime or nighttime. This requirement likely will preclude start ups at night or in thick fog, because the outer part of the EZ for that array will not be visible during those conditions. Ramp-up is allowed from a power down under reduced visibility conditions only if at least one airgun (e.g., 40 in^3 or similar) has operated continuously with throughout the survey interruption, on the assumption that marine mammals and turtles will be alerted to the approaching seismic vessel by the sounds from the single airgun and could move away if they choose. Ramp up of the airguns will not be initiated if a sea turtle or marine mammal is sighted within or near the applicable EZ during the day or close to the vessel at night.

Minimize Approach to Slopes and Submarine Canyons

Although the sensitivity of beaked whales to airguns is not known, they appear to be sensitive to other sound sources (e.g., mid-frequency sonar; see § IV and Appendix C). Beaked whales tend to concentrate in continental slope areas, and in areas where there are submarine canyons on the slope.

L-DEO will, if possible, avoid airgun operations over or near submarine canyons within the study area, particularly on the Pacific side of Central America.

Alternative Action: Another Time

An alternative to issuing the IHA for the period requested, and to conducting the project then, is to issue the IHA for another time, and to conduct the project at that alternative time. The proposed time for the Central American SubFac cruise (January–March 2008) is the most suitable time logistically for the *Langseth*, the *New Horizon*, and the crew.

During the period of the proposed seismic survey in January–March, most marine mammals will be dispersed throughout the proposed survey area. In addition, the proposed study area is not known to be a critical feeding area for any marine mammal species found there at that time of year. However, a small number of humpback whales are known to calve on the Pacific coast off Costa Rica and Nicaragua at the time of the proposed survey, and some delphinids may also be breeding at that time of year. Because of the nearly year-round presence of humpback whales in the Pacific part of the study area, it is almost impossible to choose a time of year when calving humpbacks of the Northern or Southern Hemisphere populations do not occur in the study area (see § III). In addition, several sea turtle species are known to nest on both the Pacific and Caribbean coasts of Central America at the time of the project and throughout the year.

If the IHA were issued for another date, it might result in less potential effects on certain biota, but would also result in greater potential for effects on other biota. Also, a change in date could result in significant delay and disruption not only of the Central American SubFac cruise, but of additional geophysical studies that are planned by L-DEO and cooperating organizations for the remainder of 2008 and beyond. Ship schedules and OBS availability are carefully planned, and any change in date for one project would affect other projects.

No Action Alternative

An alternative to conducting the proposed activities is the ”No Action” alternative, i.e., do not issue an IHA and do not conduct the operations. If the research is not conducted, the "No Action" alternative would result in no disturbance to marine mammals due to the proposed activities. However, it would also mean that the seismic data to be collected during the Central American SubFac project would not be acquired. The seismic data from that project will be used to determine the inputs, outputs, and controlling processes of subduction zone systems. Those results will be important in understanding earthquakes and volcanos in the study area. Under the “No Action” alternative, this valuable scientific information would not become available.

In addition to forcing cancellation of the planned seismic survey off Central America, the "No Action" alternative could also, in some circumstances, result in significant delay of other geophysical studies that are planned by L-DEO for 2008 and beyond, depending on the timing of the decision.

III. AFFECTED ENVIRONMENT

Physical Environment and Productivity

Pacific Coast of Central America

The planned survey area off the Pacific coast lies within the Central American Coastal Province of the Pacific Coastal Biome (Longhurst 1998) and the Pacific Central American Coastal Large Marine Ecosystem (LME; NOAA 2004). The coast is an active continental margin, so the continental shelf is narrow. For example, the 4000-m depth contour lies only 75–150 km from the coast.

The survey area lies between the westward-flowing South and North Equatorial currents, which are fed by the Peru and California currents, respectively. Between the equatorial currents at 3–10°N is the eastward-flowing North Equatorial Countercurrent (NECC), part of which turns north and becomes the Costa Rica Current when it reaches Central America, and flows along the coast until it turns west off the coast of Mexico and joins the North Equatorial Current. Longshore currents in the survey area are variable, although generally dominated by the reflux of the NECC (Longhurst 1998). The pattern of cyclonic flow exists only in summer-fall, when it flows around the Costa Rica Dome (CRD). The NECC does not extend east of 100°W during February–April (Fiedler 2002).

The CRD is a shoaling of the generally strong and shallow thermocline of the eastern tropical Pacific Ocean. The mean position of the CRD is near 9°N, 90°W; it is 300–500 km in diameter and centered 300 km off the coast between Nicaragua and Costa Rica. The ridge and the CRD extend below the thermocline, to a depth of more than 300 m. Increased biological productivity has been observed at the CRD and attributed to upwelling (Wyrtki 1964; Fiedler et al. 1991; Rodríguez-Fonseca 2001; Fiedler 2002). This is the largest concentration of plankton known in the tropical Pacific Ocean and is highly important for the dynamics of the food resources in the region (Wyrtki 1964, 1967; Wade and Friedrichsen 1979; Fiedler et al. 1991). Several studies have correlated zones of high productivity with concentrations of cetaceans (Volkov and Moroz 1977; Reilly and Thayer 1990; Wade and Gerrodette 1993).

This LME is considered a Class II, moderately high (150–300 $gC/m^2/yr$) productivity ecosystem (NOAA 2004), with a mean productivity is 544 $mgC/m^2/day$ in the coastal region (Sea Around Us 2007). A major factor influencing productivity in waters of the ETP (including the study area) is the Intertropical Convergence Zone (ITCZ) near the equator. At the ITCZ, the northeast and southeast trade winds flow together, causing the vertical ascent of warm moist air and heavy rainfall. In the Pacific, the ITCZ is substantially shifted north of the equator compared to the Atlantic, because of the considerably larger percentage of land that lies in the northern hemisphere in comparison to the southern hemisphere (Brown 1995). July and January are the months with the largest ITCZ effects and fluctuations. The areas near the equator generally experience a drop in productivity during July and January as the productive waters move north with the ITCZ. Consequently, the ITCZ can affect the transport of species from the northern to the southern hemispheres and vice versa (Millero 1996).

Interannual variation in the oceanography of the ETP is greater than in any other area of the world because of the quasi-periodic El Niño–Southern Oscillation (Fiedler 1999; Fiedler and Talley 2006). Interannual variation usually exceeds any seasonal variation in the equatorial and upwelling zones, but is comparable to seasonal variations to the north of the ITCZ (Fiedler and Talley 2006; Pennington et al. 2006).

West Caribbean Sea

The planned survey area off the east coast of Central America lies within the western portion of the Caribbean Sea encompassing the Nicaragua Rise and the Costa Rican arc. The coast is an active continental margin with a narrow continental shelf. The proposed survey lines extend into water depths >2000 m; however most of the West Caribbean Sea survey will take place in relatively shallow depths (Table 2).

The West Caribbean Sea is part of the Caribbean Sea Large Marine Ecosystem (NOAA 2003). It is a tropical sea that covers most of the Caribbean Plate. Its total area is ~2,515,900 km^2 (NOAA 2003), although the survey area encompasses a significantly smaller area in the far west of the region (Fig. 1).

Major ocean currents sweep the region from east to west, including the Caribbean Current, coastal countercurrents, and several large gyres. The hydrography of the Caribbean is dominated by flows of the North Equatorial current and, to a lesser degree (near Trinidad and Tobago), the South Equatorial Current, which filters westward through the Lesser Antilles. Within the Caribbean basin there is a mix of waters from the north and south Atlantic, the predominant water movement being directed through the Caribbean Sea to the Gulf of Mexico, via the Yucatán Current. Oceanic waters near the equator tend to be permanently stratified. The warm surface waters of the Caribbean (25–30°C) rarely mix with the nutrient-rich, cold waters below. The thermocline is generally at a depth of around 50 m.

Caribbean waters are relatively oligotrophic. The Caribbean LME is considered a Class III, low (<150 gC/m^2/yr) productivity ecosystem (NOAA 2003), with a mean of 485 mgC/m^2/day (Sea Around Us 2007). However, certain areas may experience higher productivity due to localized upwelling (see Fig. 6), particularly along the coast. The shallow waters of the Caribbean Sea include some coral reef ecosystems (Glynn 1976; Milliman 1976). Coral reefs in the Caribbean are under significant anthropogenic pressure, including increased sediment loads associated with deforestation, pollution, overfishing, and bleaching due to rising water temperatures that may be linked to global warming (e.g., Amada-Villela et al. 2002; NOAA 2003).

Little information is available on the coral reefs off Nicaragua's Caribbean coast. However, the east coast is home to the largest hard carbonate bank in the Caribbean. It supports several patch and island coral reefs, including Moskitos Cays, Man-of-War Cays, Cayos de Perlas, and Great and Little Corn Islands (Cortés and Hatziolos 2000). Coral cover in Nicaragua is generally low, around 25% with 5% soft corals (Almada-Villela et al. 2002). Several of these locations are close to the proposed seismic survey lines. The Caribbean coastline of Costa Rica consists of sandy beaches with sporadic rocky headlines, as well as offshore carbonate banks to the north that also support coral reefs (Cortés and Hatziolos 2000).

The Wider Caribbean region (which encompasses all of the insular and coastal states and territories bordering the Caribbean Sea) contains a rich variety of complex ecosystems and numerous endemic species. The region represents the greatest concentration of biodiversity in the Atlantic Ocean Basin (CEP 2007).

Areas with Special Status

On both coasts, Nicaragua and Costa Rica have a number of protected areas that include sea turtle nesting beaches (Fig. 7), many of which are monitored and have conservation programs. These protected areas and particular beaches where nesting occurs are described below, as well as in the separate sections for each sea turtle species.

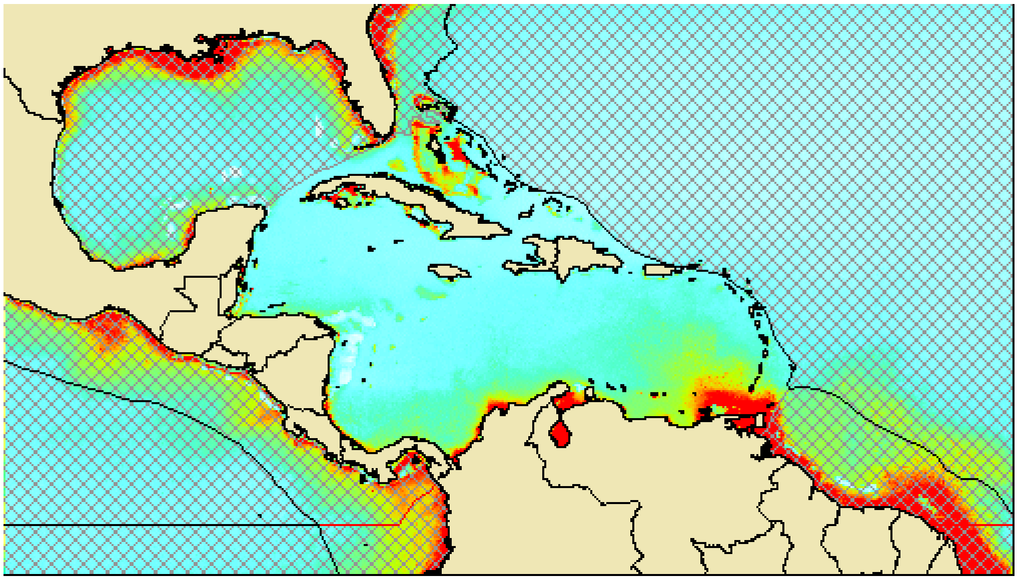

Figure 6. Primary production annual mean off Central America; red areas indicate levels up to 1250 mgC/m^2/day (from Sea Around Us 2007).

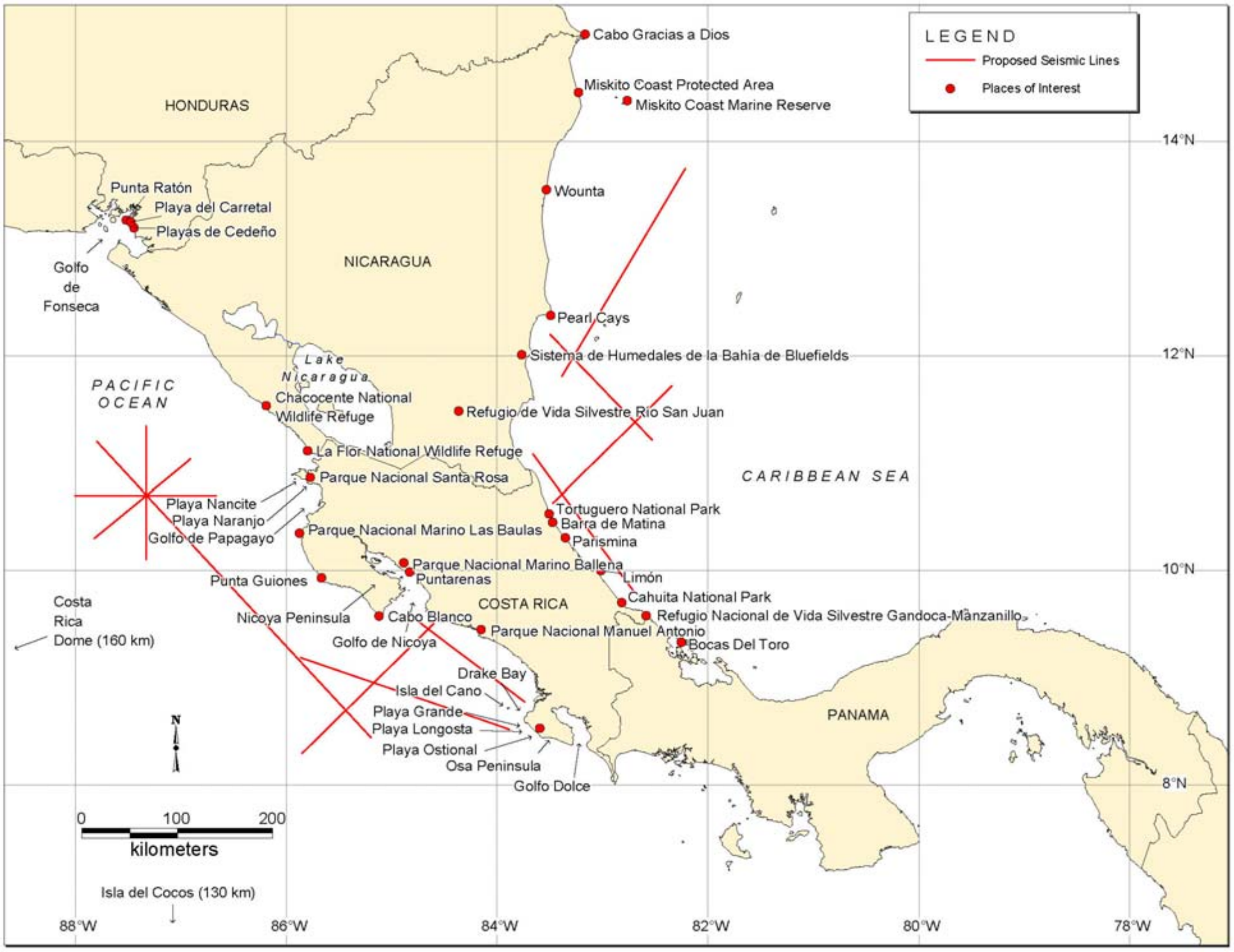

Figure 7. Map of Central America including place names mentioned within the text.

Pacific Coast of Central America

Parque Nacional Santa Rosa is located near the border of Costa Rica with Nicaragua. It encompasses much of the Gulf of Papagayo and two sea turtle nesting beaches, Playa Nancite and Playa Naranjo. Playa Nancite is one of the two most important nesting beaches for olive ridley turtles in the world.

Parque Nacional Marino Las Baulas is located on the northern Nicoya Peninsula. It includes two leatherback turtle nesting beaches, Playa Langosta and Playa Grande. Playa Grande is the fourth largest leatherback nesting beach in the world and is the site of the Las Baulas Leatherback Turtle Project.

Parque Nacional Manuel Antonio is located between the Nicoya Peninsula and the Osa Peninsula. It includes beaches, offshore islands (bird sanctuaries for marine species), and rainforest habitats.

Parque Nacional Marino Ballena is located between the Nicoya Peninsula and the Osa Peninsula. It covers an area of 4500 ha and includes waters out to ~15 km from shore. The park harbors important mangroves and the largest coral reef on the Pacific coast of Central America, green marine iguanas, and nesting olive ridley and hawksbill turtles (May–November). Common and bottlenose dolphins occur offshore, and the bay is the southernmost mating site for the humpback whale (December–April).

Parque Nacional Corcovado is located on the upper two thirds of the Osa Peninsula. It encompasses eight habitats, from mangrove swamp and jolillo palm grove to montane forest. The park protects more than 400 species of birds (20 are endemic), 116 of amphibians and reptiles, and 139 of mammals. Four sea turtle species—green, olive ridley, hawksbill, and leatherback—nest on its beaches.

At Chacocente National Wildlife Refuge in Nicaragua, some 2000–5000 olive ridley turtles nest beginning in July and ending in January (Spotila 2004).

At La Flor National Wildlife Refuges in Nicaragua, 10,000–20,000 olive ridley turtles nest, respectively, beginning in July and ending in January (Spotila 2004).

West Caribbean Sea

Refugio Nacional de Vida Silvestre Gandoca-Manzanillo, located just north of the border with Panama, is a Ramsar site (Wetland of International Importance). It is a coastal lagoon consisting of coral reefs, seagrass beds, beaches, and cliffs with flooded lowland areas between and some mangroves. It is an important sea turtle nesting area.

Cahuita National Park, just north of Gandoca-Manzanillo, was created in 1970 to protect 240 ha of offshore coral reef. It is also an important sea turtle nesting area.

Tortuguero National Park, Costa Rica, about one third of the way down the coast from Nicaragua, was created in 1970 and expanded in 1975, increasing protection for the sea turtles, 35 km of nesting beaches, the adjacent rainforest, and the marine area ~20 km offshore.

Refugio de Vida Silvestre Río San Juan, Nicaragua, is a Wildlife Refuge, Biosphere Reserve, and Ramsar site. It follows the course of the Río San Juan from Lake Nicaragua along the Costa Rican frontier to the city of San Juan del Norte on the Caribbean coast and includes the coastline to the north. The site comprises an array of wetland types, including estuary and shallow marine waters, coastal freshwater lagoon, intertidal marsh, and freshwater. Four species of turtles and the manatee are supported there.

Sistema de Humedales de la Bahía de Bluefields, Nicaragua, is a Ramsar site. It encompasses the "bay", a coastal lagoon associated with the Río Escondido. The site is extremely important for the artisanal fishing, which forms the economic and cultural base of the ethnic groups in the area. It is near the point where the proposed northern track lines cross.

In Nicaragua, the 29,000 km² Miskito Coast Protected Area (MCPA) was designated in 1991 by Government Decree No. 43-91. It has marine and terrestrial components and is considered a stronghold for hawksbill and green sea turtles. The Miskito Coast Marine Reserve (MCMR) component consists of an area defined by a 40 km radius circle around the center (14°23'N, 82°46'W) located on the big island of Miskito Cays. The terrestrial component consists of a 20 km coastal zone band between Cabo Gracias a Dios to the north and Wounta to the south. The Nicaragua Rise track line passes to the east of Miskito Cays.

Additional protected areas in Nicaragua include Cabo Viejo, Bismuna, Pahara, Karatá, Layasiksa, Kukalaya, and Wounta Lagoons (Jameson et al. 2000). These areas were declared protected in 1988. Although not currently under official protective status, the Protected Areas Directorate at the Ministry of the Environment and Natural Resources has identified the following wildlife areas as potential future reserves (Jameson et al. 2000): the mouth of the Rio Grande in Matagalpa, Pearl Lagoon, the Perlas Cays, and Lesser Corn Island. All four of these areas are in the vicinity of the proposed track lines. Bocas del Toro in Panama also has sea turtle nesting beaches (Fig. 7).

Marine Mammals

The distribution and occurrence of marine mammal species are different on the Pacific and Caribbean coasts of Central America; therefore these two areas are discussed separately. Marine mammals that may occur in the proposed survey areas belong to four taxonomic groups: the odontocetes (toothed cetaceans, such as dolphins), mysticetes (baleen whales), pinnipeds (seals and sea lions), and sirenians (the W Indian manatee). Thirty-two species of marine mammals have been documented to occur in Costa Rican waters, most of which are cetaceans (Rodríguez-Herrera et al. 2002). At least 10 of the 32 species are known to occur on the Caribbean side, including the manatee (Rodríguez-Fonseca 2001 and pers. comm.; Rodríguez-Herrera et al. 2002). Twenty-seven species are known to occur on the Pacific side of Costa Rica, including the California and Galápagos sea lions (see Wade and Gerrodette 1993; Ferguson and Barlow 2001; Rodríguez-Fonseca 2001; Rodríguez-Herrera et al. 2002; Rasmussen et al. 2004; Holst et al. 2005a; May-Collado et al. 2005). In addition, there are two other species that could potentially occur in the Pacific study area: the ginkgo-toothed (e.g., Rodríguez-Fonseca 2001) and Longman's beaked whales (e.g., Pitman et al. 1999; Ferguson and Barlow 2001).

Information on the occurrence, distribution, population size, and conservation status for each of the 34 marine mammal species that may occur in the proposed project area is presented in Table 5. The status of these species is based on the ESA, the MMPA, the IUCN (International Union for the Conservation of Nature) Red List, the Convention on International Trade in Endangered Species (CITES), and NatureServe (an international network of biological inventories that provides conservation status ranks for Latin America and the Caribbean). Six of the 34 marine mammal species are listed under the ESA as ***endangered***: the sperm, humpback, sei, fin, and blue whale, and the manatee (Table 5).

TABLE 5. The habitat, abundance, and conservation status of marine mammals that may be encountered during the proposed Central American SubFac seismic survey off Central America, January–March 2008.

Species	**Habitat**	**Abun. in NW Atlantic[1]**	**Abun. in ETP[2]**	**ESA[3]**	**IUCN[4]**	**CITES[5]**	**Nature Serve Status[6]**
Odontocetes							
Sperm whale (C,P) (*Physeter macrocephalus*)	Pelagic	13,190[a] 4804	26,053[b]	E	VU	I	G3G4
Pygmy sperm whale (C*,P) (*Kogia breviceps*)	Deeper waters off shelf	395[c]	N.A.	NL	N.A.	II	G4
Dwarf sperm whale (C*,P) (*Kogia sima*)	Deeper waters off shelf	395[c]	11,200[d]	NL	N.A.	II	G4
Cuvier's beaked whale (C*,P) (*Ziphius cavirostris*)	Pelagic	3513[e]	20,000 90,725[bb]	NL	DD	II	G4
Longman's beaked whale (P?) (*Indopacetus pacificus*)	Pelagic	N.A.	291[bb]	NL	DD	II	N.A.
Pygmy beaked whale (P) (*Mesoplodon peruvianus*)	Pelagic	N.A.	25,300[f] 32,678[cc]	NL	DD	II	GNR
Ginkgo-toothed beaked whale (P?) (*Mesoplodon ginkgodens*)	Pelagic	N.A.	25,300[f] 32,678[cc]	NL	DD	II	G3
Gervais' beaked whale (C?) (*Mesoplodon europaeus*)	Pelagic	N.A.	N.A.	NL	DD	II	G3
Blainville's beaked whale (C*, P) (*Mesoplodon densirostris*)	Pelagic	N.A.	25,300[f] 32,678[cc]	NL	DD	II	G4
Rough-toothed dolphin (C?, P) (*Steno bredanensis*)	Mainly Pelagic	2223[g]	145,900	NL	DD	II	G4
Tucuxi (C) (*Sotalia fluviatilis*)	Freshwater and costal waters	49[h] 705[i]	N.A.	NL	DD	II	G4
Bottlenose dolphin (C,P) (*Tursiops truncatus*)	Coastal, shelf and pelagic	43,951[j] 81,588[k]	243,500	NL	DD	II	G5
Pantropical spotted dolphin (C?,P) (*Stenella attenuata*)	Coastal and pelagic	4439	2,059,100	NL	LR-cd	II	G5
Atlantic spotted dolphin (C) (*Stenella frontalis*)	Coastal and shelf	50,978	N.A.	NL	DD	II	G5
Spinner dolphin (C*,P) (*Stenella longirostris*)	Coastal and pelagic	11,971[g]	1,651,100	NL	LR-cd	II	G5

Species	Habitat	Abun. in NW Atlantic[1]	Abun. in ETP[2]	ESA[3]	IUCN[4]	CITES[5]	Nature Serve Status[6]
Clymene dolphin (C?) (*Stenella clymene*)	Pelagic	6086	N.A.	NL	DD	II	G4
Striped dolphin (C*, P) (*Stenella coeruleoalba*)	Coastal and pelagic	94,462	1,918,000	NL	LR-cd	II	G5
Short-beaked common dolphin (P) (*Delphinus delphis*)	Shelf and pelagic	N.A.	3,093,300	NL	N.A.	II[j]	G5
Fraser's dolphin (C*, P) (*Lagenodelphis hosei*)	Pelagic	726[g]	289,300	NL	DD	II	G4
Risso's dolphin (C*, P) (*Grampus griseus*)	Shelf and pelagic	20,479	175,800	NL	DD	II	G5
Melon-headed whale (C*, P) (*Peponocephala electra*)	Pelagic	3451[g]	45,400	NL	N.A.	II	G4
Pygmy killer whale (C*, P) (*Feresa attenuata*)	Pelagic	6[l] 408[g]	38,900	NL	DD	II	G4
False killer whale (C*, P) (*Pseudorca crassidens*)	Pelagic	1038[g]	39,800	NL	N.A.	II	G4
Killer whale (C, P) (*Orcinus orca*)	Coastal	133[g] 6600[m]	8500	NL	LR-cd	II	G4G5
Short-finned pilot whale (C, P) (*Globicephala macrorhynchus*)	Pelagic	31,139[n]	160,200[n]	NL	LR-cd	II	G5
Mysticetes							
Humpback whale (C?, P) (*Megaptera novaeangliae*)	Mainly near-shore waters and banks	10,400[o] 11,570[p]	NE Pacific 1391[q]; SE Pacific ~2900[r]	E	VU	I	G3
Minke whale (C*, P) (*Balaenoptera acutorostrata*)	Coastal	3618[s] 174,000[t]	N.A.	NL	LR-nt	I	G5
Bryde's whale (C?, P) (*Balaenoptera edeni*)	Coastal and pelagic	35[g]	13,000[u]	NL	DD	I	G4
Sei whale (C*, P) (*Balaenoptera borealis*)	Pelagic	12-13,000[v]	N.A.	E	EN	I	G3
Fin whale (C, P) (*Balaenoptera physalus*)	Pelagic	2814 30,000[t]	1851[q]	E	EN	I	G3G4
Blue whale (C*, P) (*Balaenoptera musculus*)	Coastal, shelf, and pelagic	320[w]	1400	E	EN	I	G3G4

Species	Habitat	Abun. in NW Atlantic[1]	Abun. in ETP[2]	ESA[3]	IUCN[4]	CITES[5]	Nature Serve Status[6]
Sirenian							
West Indian manatee (C) (*Trichechus manatus manatus*)	Freshwater and coastal waters	86[x] 340[y]	N.A.	E	VU	I	G2
Pinnipeds							
California sea lion (P) *(Zalophus californianus)*	Coastal	N.A.	237,000–244,000[z]	NL	LR-lc	N.A.	G5
Galápagos sea lion (P?) *(Zalophus wollebaeki)*	Coastal	N.A.	30,000[aa]	NL	VU	N.A.	GNR

Note: Abun. = abundance, NWA = Northwest Alantic Ocean, P = may occur off Pacific coast of proposed project area, C = may occur off Caribbean coast of proposed project area, * = very unlikely to occur in proposed project area, ? = potentially possible but somewhat unlikely to occur in proposed project area, N.A. = Not available or not applicable.

[1] For cetaceans, abundance estimates are given for U.S. Western North Atlantic stocks (Waring et al. 2006) unless otherwise noted.

[2] Abundance estimates for the ETP from Wade and Gerrodette (1993) unless otherwise indicated.

[3] Endangered Species Act (Waring et al. 2006); North Atlantic stock considered only: E = Endangered; NL = Not Listed.

[4] IUCN Red List of Threatened Species (2006). Codes for IUCN classifications: EN = Endangered; VU = vulnerable; LR = Lower Risk, -cd = Conservation Dependent, -nt = Near Threatened, -lc = Least Concern; DD = Data Deficient.

[5] Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC 2007).

[6] NatureServe Status (NatureServe 2005); GNR = unranked, G2 = Imperiled, G3 = Vulnerable, G4 = Apparently secure; G5 = Secure.

[a] g(o) corrected total estimate for the Northeast Atlantic, Faroes-Iceland, and the U.S. east coast (Whitehead 2002).

[b] Whitehead 2002.

[c] This estimate is for *Kogia* sp.

[d] This abundance estimate is mostly for *K. sima* but may also include some *K. breviceps*.

[e] This estimate is for *Mesoplodon* and *Ziphius* spp.

[f] This estimate includes all species of the genus *Mesoplodon* from Wade and Gerrodette (1993).

[g] This estimate is for the northern Gulf of Mexico.

[h] Estimate from a portion of Cayos Miskito Reserve, Nicaragua (Edwards and Schnell 2001).

[i] Estimate from the Cananéia estuarine region of Brazil (Geise et al. 1999).

[j] Estimate for the for the Western North Atlantic coastal stocks (North Carolina (summer), South Carolina, Georgia, Northern Florida, and Central Florida).

[k] Estimate for the for the Western North Atlantic offshore stock.

[l] Based on a single sighting.

[m] Estimate for Icelandic and Faroese waters (Reyes 1991).

[n] This estimate is for *G. macrorhynchus* and *G. melas*.

[o] Estimate for the entire North Atlantic (Smith et al. 1999).

[p] This estimate is for the entire North Atlantic (Stevick et al. 2001, 2003).

[q] Carretta et al. 2007.

[r] Felix et al. 2005.

[s] This estimate is for the Canadian East Coast stock.

[t] Estimate is for the North Atlantic (IWC 2007a).

[u] This estimate is mainly for *Balaenoptera edeni* but may include some *B. borealis*.

[v] Abundance estimate for the North Atlantic (Cattanach et al. 1993).

[w] Minimum abundance estimate (Sears et al. 1990).

[x] Antillean Stock in Puerto Rico only.

[y] Antillean Stock in Belize (Reeves et al. 2002).

[z] Estimate for the U.S. stock (Carretta et al. 2007).

[aa] Reeves et al. 2002.

[bb] Ferguson and Barlow 2001 *in* Barlow et al. 2006.

[cc] This estimate includes all species of the genus *Mesoplodon* (Ferguson and Barlow 2001 *in* Barlow et al. 2006).

Caribbean

Studies on marine mammals inhabiting the Caribbean have been scarce (e.g., Jefferson and Lynn 1994; Rodríguez-Fonseca 2001), and abundance in this area is mostly unknown (Roden and Mullin 2000). Nonetheless, at least one systematic ship-based study employing visual and passive-acoustic survey methods has been undertaken in the eastern Caribbean (Swartz and Burks 2000; Swartz et al. 2001, 2003). In addition, an extensive visual and acoustic survey was conducted in the SE Caribbean Sea off northern Venezuela from the R/V *Maurice Ewing* and the *Seward Johnson II* as part of a marine mammal monitoring program during an L-DEO marine seismic cruise in April-June 2004 (Smultea et al. 2004). Data on the western Caribbean is even more limited.

One mysticete, eight odontocetes, and one sirenian are known to occur in the Caribbean study area (Rodríguez-Fonseca 2001 and pers. comm.; Rodríguez-Herrera et al. 2002). These include the fin, sperm, short-finned pilot, and killer whale; the bottlenose, Atlantic spotted, and clymene dolphin; tucuxi, Gervais' beaked whale, and W Indian manatee. The last four of these species only occur in the Caribbean part of the study area (Table 5). Based on other available information (see Swartz and Burks 2000; Romero et al. 2001; Swartz et al. 2001, 2003; Smultea et al. 2004), an additional five species may potentially occur in the study area (Table 5): two mysticetes (humpback and Bryde's whale) and three delphinids (pantropical spotted, striped, and rough-toothed dolphin). Pinnipeds are unlikely to be seen in the Caribbean part of the study area. Vagrant hooded seals have been seen in the Caribbean (see Rice 1998; Mignucci-Giannoni and Odell 2001; Reeves et al. 2002), but are not considered further here. The Caribbean monk seal (*Monachus tropicalis*) is considered extinct (Debrot 2000; Mignucci-Giannoni and Odell 2001).

Of the ten marine mammal species that are known to occur in the western Caribbean during the proposed study, three are listed as ***endangered*** under the ESA: the sperm and fin whale, and manatee (Table 5). The humpback whale, which could potentially occur in the area, is also listed as ***endangered***.

Pacific

Of the 36 marine mammal species known to occur in the ETP, 29 may occur in the proposed survey area off the W coast of Costa Rica and Nicaragua (Table 5). Five of the 29 species off the W coast are listed under the ESA as ***endangered***: sperm, humpback, blue, fin, and sei whale. The other seven species that are present in the wider ETP but not in the proposed survey area are excluded from Table 5. They include • Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) and Baird's beaked whale (*Berardius bairdii*), which are seen very occasionally (6 and 2 sightings, respectively, in several years of surveys) in the northernmost portions of the ETP (Ferguson and Barlow 2001). • Long-beaked common dolphin (*Delphinus capensis*), which is known to occur in the northernmost areas of the ETP off Baja California, Mexico, and off the coast of Peru (Heyning and Perrin 1994). • Dusky dolphin (*Lagenorhynchus obscurus*), southern right whale dolphin (*Lissodelphis peronii*), Burmeister's porpoise (*Phocoena spinipinnis*), and long-finned pilot whale (*Globicephala melas*) occur near the Peruvian coast but are unlikely to occur in the present study area (Leatherwood et al. 1991; Van Waerebeek et al. 1991; Brownell and Clapham 1999; Olson and Reilly 2002).

Although unlikely, two of the six species of pinnipeds known to occur in the ETP could potentially occur in the proposed project area on rare occasions. These include the California and Galápagos sea lions, which have been documented off W Costa Rica (Acevedo-Gutierrez 1994; Cubero-Parado and Rodríguez 1999; Rodríguez-Herrera et al. 2002; May-Collado 2006, in press). The remaining four pinniped species known from the ETP, the Guadalupe fur seal (*Arctocephalus townsendi*), South American fur seal (*A. australis*), southern sea lion (*Otaria flavescens*), and Galápagos fur seal, are not expected to occur in the survey area because their known ranges are substantially farther north or south of the proposed seismic survey area (Reeves et al. 2002).

Most cetacean research off the west coast of Central America has involved three of the most common, coastal resident species: the bottlenose dolphin, coastal pantropical spotted dolphin, and humpback whale (see review in May-Collado et al. 2005). The remaining marine mammal populations in the region have not been studied in much detail. The most extensive regional distribution and abundance data that encompass the entire study area come primarily from multi-year vessel surveys conducted in the wider ETP by the NMFS Southwest Fisheries Science Center (SWFSC).

Initial systematic studies of cetaceans in the ETP were prompted by the incidental killing of dolphins in the purse-seine fishery for yellowfin tuna, *Thunnus albacares*, in the area (Smith 1983). The main cetacean species that have been affected by the fishery are pantropical spotted and spinner dolphins (Smith 1983). Short-beaked common, striped, bottlenose, Fraser's, and rough-toothed dolphins, as well as short-finned pilot whales, have also been killed in the fishery (e.g., Hall and Boyer 1989). Dolphin mortality was high at the onset of the fishery (Allen 1985), but has dropped considerably (Hall 1998). During the 1960s, the number of dolphins killed by the fishery was estimated at 200,000 to 500,000 per year (Wade 1995). However, in recent years, the bycatch has been less than 2000 dolphins (IATTC 2002) and <0.05% of the population size of each ETP dolphin stock (Bayliff 2004). Nonetheless, populations of offshore spotted dolphins (*S. attenuata attenuata*) and eastern spinner dolphins (*S. longirostris orientalis*) have not yet recovered (Gerrodette and Forcada 2005).

Table 5 summarizes the abundance, habitat, and conservation status of all marine mammal species considered likely to occur in the proposed survey area in the Pacific. Based on a compilation of data from 1979 to 2001, many cetaceans within the Pacific EEZ of Costa Rica occur in both oceanic and coastal waters. However, beaked whales, sperm whales, dwarf/pygmy sperm whales, and baleen whales (except for the humpback whale) occur predominantly in oceanic waters (May-Collado et al. 2005). Bottlenose and pantropical spotted dolphins, as well as the humpback whale, tend to be coastal.

The proposed survey area in the Pacific is part of the "Central American Bight", which extends from Guatemala to Ecuador. Costa Rican waters in particular are one of the most biologically productive regions of the world (Philbrick et al. 2001; Rodríguez-Herrera et al. 2002; May-Collado et al. 2005; Ferguson et al. 2006a). The characteristics that likely make this region so productive are linked to the thermal structure of the water column, including a shallow thermocline (see Fiedler and Talley 2006). Two regions within the ETP that are considered to be important to certain species of cetaceans include the CRD and the countercurrent thermocline ridge at ~10ºN (see Au and Perryman 1985; Reilly 1990; Reilly and Thayer 1990; Fiedler 2002; Ballance et al. 2006).

At least five marine areas are considered ecologically important for different marine mammals off W Costa Rica including areas near the proposed transect lines (e.g., Acevedo and Burkhart 1998; Rodríguez-Fonseca 2001; May-Collado et al. 2005; Ferguson et al. 2006a; Fig. 7). From north to south, the five areas are as follows:

Gulf of Papagayo: This gulf is at the northern end of the Nicoya Peninsula, near the border with Nicaragua.

Punta Guiones to Cabo Blanco, southern Nicoya Peninsula: This area is inshore from the deep-water transect lines.

Costa Rica Dome: The CRD is centered at 9ºN, 90ºW, southwest of the offshore boundary of the planned project area off the Nicoya Peninsula. The CRD is a permanent upwelling front that has a high concentration of nutrients and high productivity. It is thus considered an important feeding habitat for marine mammals, such as blue whales and short-beaked common dolphins (Fiedler 2002; Branch et al. 2006; Ballance et al. 2006). The CRD has also been identified as an area with the highest predicted population density of beaked whales and delphinids (Ferguson et al. 2006a,b).

Quepos-Manuel Antonio National Park region: This region is located at the northern end of the near-shore track line that runs parallel to shore.

Isla del Caño, Golfo Dulce, and Osa Peninsula: This area is at the southern end of the near-shore track line that runs parallel to shore.

Marine mammal species inhabiting these five areas, as well as their seasonal use of the habitats, are described in the species accounts that follow, under the subheading *Pacific*. Information on the distribution and abundance of cetaceans inhabiting the ETP has been summarized in several studies (e.g., Polacheck 1987; Wade and Gerrodette 1993; Ferguson and Barlow 2001). However, for some species, abundance in the proposed seismic survey area could be quite different from that of the wider ETP, depending on local oceanographic variabilities. In addition, procedures used during the various surveys that are cited have differed somewhat, and those differences could affect the results. For example, Polacheck (1987) summarized cetacean abundance in the ETP from 1977 to 1980 for an unspecified season. He calculated encounter rates as the number of schools sighted/ 1000 mi surveyed. His encounter rates do not include any correction factors to account for changes in detectability of species with distance from the survey track line [*f*(0)], for animals at the surface near the trackline but missed [perception bias], or for the diving behavior of the animals [availability bias]. Perception and availability bias, collectively, are often quantified by a factor referred to as *g*(0). Wade and Gerrodette (1993) also calculated encounter rates for cetaceans (number of schools/1000 km surveyed) in the ETP, based on surveys between late July and early December from 1986–1990. Their encounter rates are corrected for *f*(0) but not *g*(0).. Ferguson and Barlow (2001) calculated cetacean densities in the ETP based on summer/fall research surveys in 1986–1996. Their densities are corrected for both *f*(0) and *g*(0).

The densities of Ferguson and Barlow (2001) are shown below for the cetacean species likely to be encountered during the proposed seismic surveys; the calculated mean densities are shown in a later section (see Table 6). As the densities are based on survey data collected from late July to early December, they likely differ from densities in the proposed program area during the planned dates of L-DEO's seismic survey. For example, during L-DEO's Hess Deep survey in mid-July 2003 (LGL Ltd. 2003a,b,c) a single sighting of an unidentified beaked whale was made during the survey, whereas anticipated densities based on the Ferguson and Barlow (2001) data were much higher. Also, densities during L-DEO's survey in the ETP off Central America in late fall 2004 (Holst et al. 2005a) were generally lower during both seismic and non-seismic periods than the numbers reported by Ferguson and Barlow (2001), except for humpback whales. These differences in the number of sightings indicates the likely influence of oceanographic variabilities on the densities of marine mammals in the ETP.

(1) Odontocetes

Sperm Whale (*Physeter macrocephalus*)

Sperm whales are the largest of the toothed whales, with an extensive worldwide distribution (Rice 1989). This species is listed as ***endangered*** under the ESA, but on a worldwide basis it is abundant and not biologically endangered. Sperm whales range as far north and south as the edges of the polar pack ice, although they are most abundant in tropical and temperate waters where temperatures are higher than 59ºF or 15ºC (Rice 1989).

Sperm whales occur singly (older males) or in groups, with a mean group size of 20–30 (Whitehead 2003). Typical social unit sizes range from 3–24 (Christal et al. 1998). Sperm whale distribution is thought to be linked to their social structure. Adult females and juveniles generally occur in tropical and subtropical waters, whereas adult males are commonly alone or in same-sex aggregations, often occurring in higher latitudes outside of the breeding season (Best 1979; Watkins and Moore 1982; Arnbom and Whitehead 1989; Whitehead and Waters 1990). Mature male sperm whales migrate to warmer waters to breed when they are in their late twenties (Best 1979). They spend periods of at least months on the breeding grounds, moving between mixed schools, and spending only hours with each group (Whitehead 1993, 2003). In the Northern Hemisphere, conception may occur from January to August (Rice 1989), although the peak breeding season is from April–June (Best et al. 1984).

Sperm whales undertake some of the deepest-known dives for the longest durations among cetaceans. They can dive to depths of ~2 km for periods of over 1 h; however, most of their foraging dives occur at depths of ~300–800 m for 30–45 min (Whitehead 2002). During a foraging dive, sperm whales typically travel ~3 km horizontally and 0.5 km vertically (Whitehead 2002). The diet of sperm whales consists mainly of mesopelagic and benthic squids and fishes. Sperm whales are thought to forage for prey in a large part of the water column below the scattering layer (Wahlberg 2002).

Caribbean

Sperm whales are common throughout the Caribbean Sea, especially in deep basins north of the continental shelf (Romero et al. 2001; Wardle et al. 2001). Sperm whales are known to occur off the Caribbean coast of Costa Rica (Rodríguez-Fonseca 2001), and Rodríguez-Fonseca and Cubero-Pardo (2001) reported that an individual whale stranded in Limón in 1995. In Venezuelan waters, sperm whales mostly occur in the summer, although males are thought to move through the area seasonally (Romero et al. 2001). Smultea et al. (2004) detected sperm whales acoustically as well as visually during surveys off the Venezuelan coast in April–June. In the northern Caribbean, sperm whales are believed to be more common in the fall and winter (Mignucci-Giannoni 1998). Roden and Mullin (2000) noted a mean group size of <4 individuals for the northern Caribbean.

A telemetry study of a sperm whale in the SE Caribbean conducted by Watkins et al. (2002) showed that most dives were deep dives averaging 990 m and ranged from 420 to 1330 m. Deep dives lasted an average of 44.4 min and ranged from 18.2 to 65.3 min (Watkins et al. 2002). Deep dives occurred during the day and night (Watkins et al. 2002). Shallow dives <200 m were also made (Watkins et al. 2002).

A study of the surface activity of sperm whales in the Caribbean showed that sperm whales traveled at average speeds of 2.6–3.5 km/h or 1.4–1.9 kt (Watkins et al. 1999). Surfacings were made up of two types: short surfacings mainly for respiration, which averaged 7–10.5 min, and extended surfacings for rest or social interactions, which occurred mainly during the daytime (Watkins et al. 1999).

The sperm whale has been hunted until recently in the northeastern Caribbean (Romero et al. 2001). In Dominica, sperm whales that occasionally wash up on shore (two per year on average) are harvested opportunistically (High North Alliance 2003). However, no hunting/harvesting of sperm whales occurs in Costa Rica or Nicaragua.

Pacific

Wade and Gerrodette (1993) estimated sperm whale abundance in the ETP at 22,666, with an encounter rate of 1.02 schools/1000 km of ship survey. Whitehead (2002) updated that estimate to 26,053. Gerrodette and Palacios (1996) reported an abundance of 1360 sperm whales for Costa Rica and 333 for the Central American coast north of Costa Rica. Polacheck (1987) reported average annual encounter rates in the ETP of 0.26–0.36 schools/1000 mi of survey effort in 1977–1980. In the proposed study area, sperm whale densities range from 0 to 0.01/km^2 according to surveys conducted in July–December by Ferguson and Barlow (2001). Polacheck (1987) reported weighted average annual encounter rates of 0.13–1.25 sperm whale schools/1000 mi searched in the proposed study area.

Polacheck (1987) and Wade and Gerrodette (1993) noted that during surveys in the summer and fall, sperm whales were widely distributed in the ETP, although they were generally more abundant in deep “nearshore” waters than far offshore. Rasmussen et al. (2004) and May-Collado et al. (2005) reported sperm whale sightings primarily in deep offshore waters. May-Collado et al. (2005) reported 35 groups of 348 sperm whales off W Costa Rica based on sightings in 1979–2001; mean group size was 9.9 whales. Sperm whales were distributed widely in offshore waters, concentrated off southeast Costa Rica, including waters near Isla del Cocos (May-Collado et al. 2005). Rasmussen et al. (2002) reported one sperm whale sighting in seven years of surveys (1996–2002) off Costa Rica plus surveys in 2001–2002 off Panama. No sperm whales were detected between Puntarenas, Costa Rica, and southern El Salvador during a seismic survey in November–December 2004, during which >3500 km of daytime visual effort and 5200 km of 24-h PAM effort took place (Holst et al. 2005a).

Rodríguez-Fonseca (2001) identified Isla del Caño and the outer part of the Osa Peninsula as an important area in W Costa Rican waters for sperm whales. May-Collado (in press) also noted the occasional occurrence of sperm whales near Isla del Cocos. Rodríguez-Fonseca and Cubero-Pardo (2001) noted that the sperm whale is the cetacean species with the highest frequency of strandings in Costa Rica, with a repoted eight strandings (seven of which were on the Pacific coast) during a 33-year period.

The natural history of sperm whales is better known from a long-term study near the Galápagos Islands located ~700 km southwest of the proposed project area; these data have provided much relevant information about sperm whale behavioral biology (e.g., Whitehead 2002). In the Galápagos Islands, sperm whales usually occur in mixed groups of females and immature animals (Whitehead and Arnbom 1987). Female and immature sperm whales have geographic ranges that are, on average, about 1000 km across, but they occasionally move much further (Dufault and Whitehead 1995; Dufault et al. 1999; Jaquet et al. 2003). Female sperm whales from the Galápagos have been known to travel >3800 km to the Gulf of California (Jaquet et al. 2003). Mature males are seen on the Galápagos breeding ground from April to June, either in close proximity to the mixed groups, or in loose aggregations of males (Christal and Whitehead 1997). The aggregations consist of 10–30 males, and may extend over areas of tens of km (Lettevall et al. 2002). Individual males within aggregations may travel within 1 km of each other and have the same heading (Christal and Whitehead 1997). Mature sperm whales stay within the aggregations from a few days to weeks (Lettevall et al. 2002).

At the Galápagos Islands, sperm whales typically forage at depths of about 400 m, where they feed on squid (Papastavrou et al. 1989; Whitehead 1989; Smith and Whitehead 2000). That depth corresponds with the minimum oxygen layer in the area (Wyrtki 1967), which may facilitate predation on squid (Papastavrou et al. 1989). Papastavrou et al. (1989) noted that sperm whales in the Galápagos started to click regularly when they were 150–300 m deep, indicating that they were echolocating for food (Backus and Schevill 1966; Weilgart and Whitehead 1988; Smith and Whitehead 1993). They also noted that there did not seem to be a diurnal pattern in dive depths, and young calves did not make prolonged, deep dives. Whales typically dove for about 40 min and then spent 10 min at the surface (Papastavrou et al. 1989).

It is not clear whether sperm whales seen in the ETP are part of the Northern or Southern Hemisphere stocks, or whether they should be considered a separate stock (Rice 1977; Berzin 1978). Sperm whales occurring off the Galápagos Islands and near the coast of Ecuador are thought to belong to two different populations (Dufault and Whitehead 1993). Whitehead et al. (1989) suggested that those in the Galápagos may be part of the Northern Hemisphere stock, and the Ecuador whales part of the Southern Hemisphere stock, based on the timing of their breeding seasons. Both populations are considered part of the Southern Hemisphere stock for management purposes (Donovan 1991).

Sperm whales in the ETP were hunted until 1850 off the Galápagos Islands (Shuster 1983) and until the late 1900s off the coast of Peru (Ramirez 1989). A sanctuary has been established in the waters off Ecuador, including the Galápagos Islands, to protect sperm whales (Evans 1991). The Galápagos sperm whale population decreased by 20% per year between the years 1985 and 1995, even though the animals were not hunted during that period (Whitehead et al. 1997). The decline may be attributable to emigration of some whales to coastal waters off Central and South America, in combination with a low recruitment rate of ~0.05 calves/female/year (Whitehead et al. 1997). Those emigrations may have been triggered by heavy whaling in Peruvian waters up until 1981 (Ramirez 1989; Whitehead et al. 1997). Whitehead et al. (1992) estimated a population of ~200 animals in the Galápagos Islands.

Dwarf Sperm Whale (*Kogia sima*) and Pygmy Sperm Whale (*K. breviceps*)

These two species of small whales are distributed widely in the world's oceans, but they are poorly known (Caldwell and Caldwell 1989). The small size of these animals, their non-gregarious nature, and their cryptic behavior make pygmy and dwarf sperm whales difficult to observe. Therefore, these two species are also difficult to distinguish when sighted at sea and are often categorized as *Kogia* sp. (Waring et al. 2006). They are primarily sighted along the continental shelf edge and over deeper waters off the shelf (Hansen et al. 1994; Davis et al. 1998). Barros et al. (1998) suggested that dwarf sperm whales might be more pelagic and dive deeper than pygmy sperm whales. Pygmy sperm whales mainly feed on various species of squid in the deep zones of the continental shelf and slope (McAlpine et al. 1997). Cardona-Maldonado and Mignucci-Giannoni (1999) found squid, mysids, and fish in *Kogia* stomachs. Pygmy sperm whales occur in small groups of up to six individuals, and dwarf sperm whales may form groups of up to 10 animals (Caldwell and Caldwell 1989). Although there are few useful estimates of abundance for pygmy or dwarf sperm whales anywhere in their range, they are thought to be fairly common in some areas.

Caribbean

There are records of these whales throughout the Caribbean, including Cuba, Dominican Republic, Puerto Rico, Virgin Islands, St. Vincent, the southern Netherlands Antilles, and Colombia (Debrot and Barros 1992; Cardona-Maldonado and Mignucci-Giannoni 1999; Romero et al. 2001; Wardle et al. 2001). Dwarf sperm whale sightings were also made by Swartz and Burks (2000) during surveys in the eastern Caribbean. Smultea et al. (2004) reported no sightings of *Kogia* during surveys off Venezuela. *Kogia* are thought to reside in the Caribbean throughout the year (Cardona-Maldonado and Mignucci-Giannoni 1999). Cardona-Maldonado and Mignucci-Giannoni (1999) noted the presence of pregnant females of both species and dwarf sperm whale calves in the Caribbean, indicating that the area is used for breeding and calving. We are unaware of any reports of *Kogia* of the Caribbean coast of Central America, and Rodríguez-Fonseca (2001) did not report *Kogia* for the east coast of Costa Rica. Therefore, encounters in the proposed study area are assumed to be unlikely.

Pacific

Rodríguez-Fonseca (2001) reported the presence of *Kogia* sp. off W Costa Rica, but only the dwarf sperm whale has been positively identified as occurring in that area (Ferguson and Barlow 2001; Jackson et al. 2004; May-Collado et al. 2005). Similarly, the dwarf sperm whale was the only confirmed *Kogia* species off W Costa Rica based on sightings compiled from 1979 to 2001 by May-Collado et al. (2005). Most of the 34 groups of *Kogia* sp. occurred in offshore waters, with frequent sightings ~90–100 km southwest of the Osa Peninsula near the proposed survey lines. No *Kogia* sp. were detected during a seismic survey off Costa Rica and Nicaragua in November–December 2004 (Holst et al. 2005a). The densities of dwarf sperm whales in the proposed study area range from 0–0.027/km^2 during July–December (Ferguson and Barlow 2001). Rodríguez-Fonseca and Cubero-Pardo (2001) reported a stranding of six *K. simus* in 1993 on the Pacific coast .

Cuvier's Beaked Whale (*Ziphius cavirostris*)

This cosmopolitan species is probably the most widespread of the beaked whales, although it is not found in polar waters (Heyning 1989). This species is rarely observed and is mostly known from strandings (Leatherwood et al. 1976; NOAA and USN 2001). Its inconspicuous blow, deep-diving behavior, and its tendency to avoid vessels may help explain the rarity of sightings. On a worldwide basis, there are more recorded strandings for Cuvier's beaked whale than for other beaked whales (Heyning 1989). Since 1960, there have been 41 mass (2 or more animals) strandings of Cuvier’s beaked whales (Brownell et al. 2004 and Taylor et al. 2004 *in* Cox et al. 2006). Several additional mass strandings have been documented subsequently in association with sources of strong noise (e.g., Frantzis 1998; NOAA and USN 2001; Jepson et al. 2003; see § IV, later).

Adult males of this species usually travel alone, but these whales can be seen in groups of up to 15 individuals, with a mean group size of 2.3 (MacLeod and D’Amico 2006). Cuvier's beaked whales typically dive for ~30 min in water up to 1000 m deep, where they are believed to feed on deep-sea fish and squid (Heyning 1989; Palacios et al. 1994). Debrot and Barros (1994) found mysid and squid remains in stomach contents.

Cuvier’s beaked whales rarely are found close to mainland shores, except in submarine canyons or in areas where the continental shelf is narrow and coastal waters are deep (Carwardine 1995). The mostly pelagic species appears to be confined to the warmer side of the 10°C (50°F) isotherm and the deeper side of the 1000-m bathymetric contour (Houston 1991; Robineau and di Natale 1995). They normally avoid boats but are occasionally inquisitive and approachable, especially around Hawaii. Breaching has been observed, though it is probably rare (Carwardine 1995).

Caribbean

In the greater Caribbean, Cuvier's beaked whale is likely the most common beaked whale. Reports exist for several Caribbean locations including Cuba, the Bahamas, Grand Cayman, the Dominican Republic, Puerto Rico, Virgin Islands, St. Martin, Barbados, St. Vincent, Colombia, Bonaire, Aruba, and Curaçao (Romero et al. 2001; Wardle et al. 2001). We are unaware of any reports of this species off the

Caribbean coast of Costa Rica or Nicaragua, and Rodríguez-Fonseca (2001) did not list this beaked whale as present on the east coast of Costa Rica. Therefore, encounters with this species in the proposed study area are unlikely.

Pacific

Cuvier's beaked whales are widely distributed in the ETP, and MacLeod and Mitchell (2006) identified this region as a key area for beaked whales. Wade and Gerrodette (1993) noted an abundance estimate of 20,000 individuals and an encounter rate of 0.67 schools/1000 km. However, the overall abundance from Ferguson and Barlow (2001) as noted by Barlow et al. (2006) is 90,725. Gerrodette and Palacios (1996) reported an abundance of 32,705 ziphids in the EEZ of Costa Rica and 11,386 for the Central American coast north of Costa Rica. Palacios et al. (1994) reported 15 sightings during a 13-month cruise off the Galápagos Islands. In the ETP, group sizes range from one to seven animals (Heyning 1989). Wade and Gerrodette (1993) noted a mean group size of 2.2 in the ETP.

During surveys conducted during July–December, the densities of Cuvier's beaked whales within the proposed study area ranged from 0 to 0.007/km^2 (Ferguson and Barlow 2001). The Cuvier's beaked whale was the most frequent beaked whale identified to species off Costa Rica as reported by May-Collado et al. (2005) for 1979–2001. They reported that 14 of 47 groups of beaked whale sightings were Cuvier's beaked whales; an additional 15 groups were identified as *Ziphius* spp. Ziphiids occurred primarily in offshore deep waters (May-Collado et al. 2005), where some of the proposed seismic survey lines are located. Ferguson et al. (2006b) noted that in the ETP, the mean water depth where Cuvier's beaked whales were sighted was ~3.4 km or 2.1 mi.

No Ziphiids or other beaked whales were identified off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Rodríguez-Fonseca (2001) identified the waters by Isla del Cocos, and Isla del Caño and the outer part of the Osa Peninsula, as two important areas off W Costa Rica for the species.

Longman's Beaked Whale / Tropical Bottlenose Whale (*Indopacetus pacificus*)

Longman's beaked whale, also known as the tropical bottlenose whale, is considered rare on the Pacific side of the project region and would not be expected to occur in the Caribbean region. Although widespread throughout the tropical Pacific, the species is considered rare because of a scarcity of sightings despite a great deal of survey effort (Pitman et al. 1999). Until very recently, Longman's beaked whale was known only from two skulls (Pitman et al. 1987). Recent morphometric and genetic analyses of those two original specimens and an additional four specimens have allowed a more detailed characterization of the species (Dalebout et al. 2003). It seems likely that it is, in fact, the cetacean that has been seen in Indo-Pacific waters and called the "tropical bottlenose whale". Some authorities place the species in the genus *Mesoplodon*, and there now seems to be sufficient information to afford it status as a separate genus (Dalebout et al. 2003).

These whales are thought to prefer warmer waters with temperatures >26ºC, and have been seen in the tropics every month of the year except June, indicating year-round residency (Pitman et al. 1999). Tropical bottlenose whales have been seen in groups of up to 100 individuals, with an average pod size of 19.4 (MacLeod and D'Amico 2006). Pitman et al. (1999) noted a mean group size of 18.5 individuals in the tropics; however, they also noted that group sizes were significantly smaller in the ETP, with an average of only 8.6 individuals. Dives last 18–25 min (Reeves et al. 2002).

Pitman et al. (1999) suggested that several sightings of *Hyperoodon* spp. in the ETP were actually misidentifications (e.g., Wade and Gerrodette 1993) and were, in fact, sightings of tropical bottlenose whales. In the ETP, most tropical bottlenose whale sightings have been made between 3ºN and 10ºN (Pitman et al. 1999). Kinzey et al. (2001) noted one sighting of *I. pacificus* in the ETP at about 135ºW. Jackson et al. (2004) also reported *I. pacificus* in the ETP. The density of tropical bottlenose whales in the Pacific region encompassing the proposed project area ranges from 0 to 0.0004/km^2 (Ferguson and Barlow 2001). No Longman's (or tropical bottlenose) beaked whales were reported by May-Collado et al. (2005) based on compiled sightings off W Costa Rica from 1979–2001. No beaked whales were identified off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a).

Pygmy Beaked Whale (*Mesoplodon peruvianus*)

The pygmy beaked whale is the smallest Mesoplodont (Reyes et al. 1991). This eastern-Pacific species is thought to occur between 25°N and 15°S latitudes, from Baja California to Peru, foraging in mid-to-deep waters (Urbán-Ramírez and Aurioles-Gamboa 1992). However, Pitman and Lynn (2001) noted a stranding record for the species in Chile, at latitude 29°15'S. Reyes et al. (1991) reported 10 records of this species in south-central Peru. Pitman and Lynn (2001) noted that the species may have been known previously as *M.* sp. "A". The pygmy beaked whale is now believed to be widespread in the ETP, but concentrated off central Mexico (Pitman and Lynn 2001). Wade and Gerrodette (1993) reported several sightings for *M. peruvianus* as well as *M.* sp. "A" in the ETP.

Jackson et al. (2004) reported two sightings of *M. peruvianus* within the ETP study area during July–December surveys in 2003. However, Ferguson and Barlow (2001) did not report any pygmy beaked whale sightings in the study area during 10 years of surveys conducted in July–December. Similarly, no pygmy (or *M.* sp "A") beaked whales were reported off W Costa Rica by May-Collado et al. (2005) or Rodríguez-Fonseca and Cubero-Pardo (2001) based on compiled sightings from 1979–2001 and strandings from 1966–1999, respectively. However, May-Collado et al. (2005) documented 17 sightings of *Mesoplodon* spp. during that period. No beaked whales were identified off Costa Rica and Nicaragua during seismic surveys in November–December 2004 (Holst et al. 2005a). Sightings of this species in the proposed Pacific study area are possible, although in low numbers. This species does not occur in the Caribbean.

Ginkgo-toothed Beaked Whale (*Mesoplodon ginkgodens*)

The ginkgo-toothed beaked whale is only known from stranding records (Mead 1989) and would potentially occur only on the Pacific side of the project area. Strandings have been reported for the western and eastern North Pacific, South Pacific, and Indian oceans, and from the Galápagos Islands in the ETP (Palacios 1996a). The species is thought to occupy relatively cool areas in the temperate and tropical Pacific, where upwelling is known to occur, such as in the California and Peru Currents and the equatorial front (Palacios 1996a).

No ginkgo-toothed beaked whales were reported off W Costa Rica by May-Collado et al. (2005) based on compiled sightings from 1979–2001, or by Rodríguez-Fonseca and Cubero-Pardo (2001) using stranding records from 1966–1999. However, May-Collado et al. (2005) documented 17 sightings of *Mesoplodon* spp. during that period. Densities of unidentified *Mesoplodon* sp. in the proposed study area were up to 0.0028/km^2 (Ferguson and Barlow 2001); some of these sightings could have potentially been gingko-toothed beaked whales (see Table 5). No beaked whales were identified off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a).

Gervais' Beaked Whale (*Mesoplodon europaeus*)

The Gervais' beaked whale is mainly oceanic and occurs in tropical and warmer temperate waters of the Atlantic Ocean; it is not known to occur in the Pacific. Its distribution is primarily known from stranding records. It is more frequent in the western than the eastern part of the Atlantic (Mead 1989). According to Debrot and Barros (1992), most records for the Gervais' beaked whale are from Florida. In the Caribbean, there are more records for this species than for Blainville's beaked whale (Rosario-Delestre et al. 1999).

There are records for this species for the Cayman Islands, Bahamas, Cuba, Jamaica, the Dominican Republic, the Virgin Islands, St. Croix, Trinidad and Tobago, Aruba, Bonaire, Curaçao, and it may also frequent Venezuela (Debrot and Barros 1992; Rosario-Delestre et al. 1999; Romero et al. 2001; Wardle et al. 2001). According to NatureServe (2005), the Gervais' beaked whale may also occur in other Caribbean nations, although neither Costa Rica nor any other Central American countries are noted. Rodríguez-Herrera et al. (2002) report this species as present in Costa Rican waters. Data obtained from stranded animals suggest that this species may be more abundant in the Caribbean during winter than during other seasons (Debrot and Barros 1992). However, this species occurs in the Caribbean throughout the year, especially in the Greater Antilles (Rosario-Delestre et al. 1999).

Gervais' beaked whale usually inhabits deep waters (Davis et al. 1998). Food habits of this whale have been poorly studied, although Debrot and Barros (1992) noted that this animal likely feeds in deep water and shows a preference for mesopelagic cephalopods and fish. Stomach contents have been known to include fish, squid, and mysids (Debrot 1998; Debrot et al. 1998).

Blainville's Beaked Whale (*Mesoplodon densirostris*)

Blainville's beaked whale is found in tropical and warmer temperate waters of all oceans (Leatherwood and Reeves 1983; Reeves et al. 2002). It is the *Mesoplodon* species with the widest worldwide distribution (Mead 1989). Houston (1990) reports that Blainville's beaked whale is widely, if thinly, distributed throughout the tropical and subtropical waters of the world. It is rarely sighted, and most of the knowledge on the distribution of this species is derived from stranding data.

There is no evidence that Blainville's beaked whales undergo seasonal migrations. Movements into higher latitudes are likely related to warm currents, such as the Gulf Stream in the North Atlantic. Blainville's beaked whale is mainly a pelagic species, and like other beaked whales, is mainly found in deep waters (Davis et al. 1998). Nonetheless, Blainville's beaked whales may occur more frequently than other beaked whales in coastal areas. These beaked whales are seen in groups of up to 8 individuals, with a mean group size of 3.5 (MacLeod and D'Amico 2006). They appear to feed on mesopelagic squid and fish (Mead 1989), and dives can last up to 45 min.

Caribbean

In the Caribbean, Blainville's beaked whale is not considered abundant (Rosario-Delestre et al. 1999). Nonetheless, it is thought to occur throughout the Caribbean during most of the year (Rosario-Delestre et al. 1999). Blainville's beaked whale has been reported for the Bahamas, Cuba, Grand Cayman Island, and Puerto Rico (Rosario-Delestre et al. 1999; Romero et al. 2001; Wardle et al. 2001). It is also likely to occur in the southern Caribbean, the Colombian Caribbean, and in Venezuelan waters around Margarita Island although its presence there has not yet been confirmed (review by Romero et al. 2001). Swartz and Burks (2000) reported this species during their survey of the SE Caribbean; however, no exact location was given in their report. There is no information available on the occurrence of this species in Costa Rican or Nicaraguan Caribbean waters.

Pacific

In the ETP, Blainville's beaked whales have been sighted in offshore as well as nearshore areas of Central and South America (Pitman et al. 1987; Pitman and Lynn 2001). This species is also known to occur in the southern portion of the ETP, south of 10ºN (Wade and Gerrodette 1993). MacLeod and Mitchell (2006) identified the ETP as a key area for beaked whales.

Off W Costa Rica, May-Collado et al. (2005) reported one sighting of three Blainville's beaked whales in deep offshore waters based on compiled sightings from 1979 to 2001. Ferguson and Barlow (2001) noted densities of Blainville's beaked whales in the proposed survey as high as 0.0013/km^2 (Ferguson and Barlow 2001). In contrast, no beaked whales were identified off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). There were no reported strandings of this species in Costa Rica from 1966 to 1999 (Rodríguez-Fonseca and Cubero-Pardo 2001).

Rough-toothed Dolphin (*Steno bredanensis*)

Rough-toothed dolphins are distributed worldwide in tropical, subtropical, and warm temperate waters (Miyazaki and Perrin 1994). They are generally seen in deep water and in shallower waters around islands. They are typically found in moderate sized groups of 10–20 animals, but groups of up to 300 individuals have been seen (Jefferson 2002). They are deep divers and can dive for up to 15 min (Reeves et al. 2002).

Caribbean

In the western Atlantic, this species occurs between the southeastern U.S. and southern Brazil (Jefferson 2002), including the Caribbean Sea (e.g., Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001). Although Gamboa-Poveda and May-Collado (2006) and Rodríguez-Fonseca (2001) do not mention the presence of this species on the east coast of Costa Rica, May-Collado (in press) notes its occurrence there as frequent. Kuczaj et al. (2005) suggested a resident group of rough-toothed dolphins may inhabit the area off the island of Utila in Honduras. During their study, they photo-identified 16 rough-toothed dolphins in the area. Group sizes ranged from 5 to 20 animals, and most of the dolphins were encountered in waters ranging in depth from 6–122 m (Kuczaj et al. 2005).

Pacific

In the ETP, sightings of rough-toothed dolphins have been reported by Perrin and Walker (1975), Pitman and Ballance (1992), Wade and Gerrodette (1993), Kinzey et al. (1999, 2000, 2001), Ferguson and Barlow (2001), Jackson et al. (2004), and May-Collado et al. (2005). Wade and Gerrodette (1993) estimated rough-toothed dolphin abundance in the ETP at 145,900 based on data from 1986–1990. For 2003, the abundance estimate is 47,921 (Gerrodette et al. 2005). Wade and Gerrodette (1993) reported an encounter rate of 0.86 schools/1000 km in the ETP. The mean group size is 15.46 (Ferguson et al. 2006a). Gerrodette and Palacios (1996) reported an abundance of 3356 rough-toothed dolphins for Costa Rica and 4143 for the Central American coast north of Costa Rica.

May-Collado (in press) reported the occurrence of this species as frequent in the Pacific waters of Costa Rica. Densities of rough-toothed dolphins in the region encompassing the proposed project area range from 0 to 0.0337/km^2 according to Ferguson and Barlow's (2001) surveys conducted during July–December. May-Collado et al. (2005) documented 28 sightings of 513 individuals based on sightings compiled off W Costa Rica from 1979–2001. These sightings were distributed from near to far offshore, including within the proposed project area. Rodríguez-Fonseca (2001) identified Isla del Caño and the outer part of the Osa Peninsula as an important area off W Costa Rican waters for the rough-toothed dolphin. Rasmussen et al. (2002) reported three sightings of rough-toothed dolphins in seven years of surveys (1996–2002) off Costa Rica and from 2001 to 2002 off Panama. None were identified off Costa

Rica and Nicaragua during seismic surveys in November–December 2004 (Holst et al. 2005a).

Tucuxi (*Sotalia fluviatilis*)

The tucuxi inhabits coastal areas from eastern Central America to southern Brazil (Borobia et al. 1991; Carr and Bonde 2000) and is thus limited to the east side of Costa Rica. DiBerardinis et al. (1997) identified aspects of tucuxi habitat as underwater topography and the presence of muddy river runoff. While in fresh water, these animals prefer comparatively deep areas, but in the ocean they prefer shallow water (Romero et al. 2001). They feed on pelagic and demersal fish (Borobia and Barros 1989). These animals form small groups that average four individuals (Vidal et al. 1997). The freshwater Amazonian populations of tucuxi and the coastal marine populations are classified as distinct subspecies. The coastal marine subspecies is identified as *S. f. guianensis* and is the only type of tucuxi known to occur in the study area. The freshwater tucuxi is mainly distributed in the Amazon and Orinoco basins (Vidal et al. 1997).

The tucuxi has been observed on the coast of Nicaragua and Costa Rica, north of its previously reported range (DiBerardinis et al. 1997; Edwards and Schnell 2001; Rodríguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006; May-Collado 2006, in press). Tucuxi have been sighted in groups of 1–15 individuals, and sometimes in association with bottlenose dolphins, off of Gandoca-Manzanilla, Costa Rica, during boat-surveys in April and May 1997 (DiBerardinis et al. 1997). Forestell (1999) noted the presence of up to 20 tucuxi in the area throughout the year from 1997–1990. Most tucuxi were seen in shallow water (~18 m deep) and 500 m from shore. Photographic documentation and sightings of putative tucuxi and bottlenose dolphin hybrids suggests the occurrence of hybridization between those dolphin species in Gandoca-Manzanillo (Forestell 1999; Acevedo et al. 2005). One stranding of a tucuxi has been reported at Playa Manzanillo in 1997 (Rodríguez-Fonseca and Cubero-Pardo 2001).

Edwards and Schnell (2001) estimated that 49 tucuxi inhabited portions of the MCMR, Nicaragua, during boat surveys in March–May of 1996–1998. Coastal areas had the highest density (0.647 individuals/km^2), followed by inlets (0.578/km^2), and then lagoons (0.486/km^2) (Edwards and Schell 2001). In coastal areas, tucuxi were sighted most often within 100 m of shore (54%), and were seldom observed in more than 5 m of water (Edwards and Schnell 2001).

Bottlenose Dolphin (*Tursiops truncatus*)

Bottlenose dolphins are distributed almost worldwide in tropical and temperate marine waters. There are two distinct bottlenose dolphin types: a shallow water type mainly found in coastal waters and a deepwater type mainly found in oceanic waters (Duffield et al. 1983; Hoelzel et al. 1998; Walker et al. 1999). As well as inhabiting different areas, these ecotypes differ in their diving abilities (Klatsky 2004) and prey types (Mead and Potter 1995). The nearshore dolphins usually inhabit shallow waters along the continental shelf and upper slope, at depths <200 m (Davis et al. 1998, 2002). Klatsky (2004) noted that offshore dolphins show a preference for water <2186 m deep. Bottlenose dolphins are reported to regularly dive to depths >450 m for periods of >5 min (Klatsky 2004), and even down to depths of 600–700 m for up to 12 min (Klatsky et al. 2005).

Bottlenose dolphins form groups that are organized on the basis of age, sex, familial relationship, and reproductive condition (Berta and Sumich 1999). Group sizes usually are 2–15 individuals (Shane et al. 1986), although groups of thousands can occur.

Caribbean

In the western North Atlantic, both types of bottlenose dolphins are known to occur (Walker et al. 1999). Bottlenose dolphins are widespread throughout the Caribbean (Jefferson and Lynn 1994; Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001; Campbell et al. 2002; Smultea et al. 2004; Pardo et al. 2005) and are known to occur off the east coast of Costa Rica (DiBerardinis et al. 1997; Rodríguez-Fonseca 2001; Kerr et al. 2005; Gamboa-Poveda and May-Collado 2006; May-Collado 2006, in press; Gamboa-Poveda and May-Collado 2006). An important area for these dolphins is located near Gandoca-Manzanillo (Rodríguez-Fonseca 2001). The bottlenose dolphin is expected to be one of the most commonly sighted species in the proposed study area, especially in shallow water (e.g., Gamboa-Poveda and May-Collado 2006).

Pacific

Bottlenose dolphins are expected to be one of the five most common cetaceans occurring in the proposed Pacific project area, primarily in coastal waters. In the ETP, bottlenose dolphins tend to be more abundant close to the coasts and islands (Scott and Chivers 1990); they also seem to occur more inshore than other dolphin species (Wade and Gerrodette 1993). Gerrodette et al. (2005) estimated the abundance of bottlenose dolphins in the ETP at 277,568 for 2003. For 1986–1990, Wade and Gerrodette (1993) reported an abundance of 243,500. Gerrodette and Palacios (1996) reported an abundance of 12,404 bottlenose dolphins for the EEZ of Costa Rica and 30,144 for the Central American coast north of Costa Rica. Wade and Gerrodette (1993) provided an encounter rate of 1.98 schools/1000 km. Polacheck (1987) noted that the highest encounter rates for bottlenose dolphins in the ETP tended to be in nearshore areas, with average annual encounter rates in 1977–1980 ranging from 0.54–0.88 schools/1000 mi of survey effort. The weighted average annual encounter rates for the proposed study area ranged from 1.44 to 5.06 schools/1000 mi of effort (Polacheck 1987).

Densities of bottlenose dolphins in the general project area can be up to 0.081/km^2 according to surveys conducted by Ferguson and Barlow (2001) during July–December. Off W Costa Rica, May-Collado et al. (2005) reported 176 groups of 3584 bottlenose dolphins with a mean group size of 21.5 individuals based on sightings from 1979–2001. Ferguson et al. (2006a) noted a mean group size of 24.12. May-Collado et al. (2005) found this species concentrated primarily in coastal waters but also in offshore oceanic waters. Rasmussen et al. (2002) reported 44 sightings of bottlenose dolphins in seven years of surveys (1996–2002) off Costa Rica and from 2001 to 2002 off Panama. Eight groups of 69 bottlenose dolphins were identified off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Smith and Whitehead (1999) reported that bottlenose dolphins were frequently seen near the Galápagos Islands.

Rodríguez-Fonseca (2001) identified four important areas in Pacific Costa Rican waters for the species: (1) the area between Punta Guiones and Cabo Blanco, (2) the Quepos-Manuel Antonio National Park region, (3) the Golfo Dulce, and (4) Isla del Cocos. In the Golfo Dulce, they area considered resident, but exhibit localized shifts in distribution (Acevedo and Burkhart 1998).

Studies at Isla del Coco, Costa Rica, showed that bottlenose dolphin feeding and movements are correlated to the spatial distribution of their prey (Acevedo-Gutierrez and Parker 2000). There, dolphin groups (22–27 individuals) feed on fish shoals 500 m from shore, in depths of 100 m (Acevedo and Würsig 1991). At Golfo Dulce, mean dolphin group size is 5.8 and ranges from 1–25 individuals (Acevedo and Burkhart 1998). Feeding is particularly intense during the dry season; during the rainy season, bottlensose dolphins spend more time socializing (Acevedo and Burkhart 1998).

Bottlenose dolphins are commonly reported in strandings in the region. There were seven reported strandings from 1966 to 1999 (Rodríguez-Fonseca and Cubero-Pardo 2001).

Pantropical Spotted Dolphin (*Stenella attenuata*)

Pantropical spotted dolphins have been associated with warm Tropical Surface Water (Au and Perryman 1985; Reilly 1990; Reilly and Fiedler 1994) and occur in both the Pacific and Caribbean study areas (Reeves et al 2002). In contrast to the Gulf of Mexico, where pantropical spotted dolphins occur in deeper waters and rarely over the continental shelf or continental shelf edge (Davis et al. 1998), in the ETP, they occur in coastal and offshore waters.

Baird et al. (2001) found that pantropical spotted dolphins dive deeper at night than during the day and increase their swimming speed after dark. Those results, together with a series of deep dives recorded immediately after sunset, suggest that pantropical spotted dolphins feed primarily at night on organisms associated with the deep-scattering layer as it rises to the surface (Baird et al. 2001). Similarly, Robertson and Chivers (1997) noted that pantropical spotted dolphins likely feed at night on mesopelagic prey, such as fish and squid, when they migrate toward the surface. Those investigators also found seasonal and geographical differences in the prey consumed, suggesting that pantropical spotted dolphins have a flexible diet and may be opportunistic feeders.

Pantropical spotted dolphins are extremely gregarious and form schools of hundreds or even thousands of individuals. These large aggregations contain smaller groups that can consist of only adult females with their young, only juveniles, or only adult males (Perrin and Hohn 1994). The northern stock (north of the equator) of spotted dolphins has reproductive peaks in the spring and autumn, and the southern stock (south of the equator) has a peak corresponding to the spring peak of the northern stock (Barlow 1984). Calving in the southern stock occurs in January, but there may be another calving season six months later (Hohn and Hammond 1985).

Caribbean

In the Caribbean, pantropical spotted dolphins have been observed in the Lesser Antilles, southern Netherlands Antilles, Venezuela, and Columbia (Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001; Smultea et al. 2004; Pardo et al. 2005). Roden and Mullin (2000) noted that most schools of spotted dolphins seen in the northern Caribbean included calves. Jefferson and Lynn (1994) noted that the pantropical spotted dolphin is the most frequently observed dolphin in the SW Caribbean and reported the occurrence of this species off the coast of Central America. Although Rodríguez-Fonseca (2001) did not report any evidence of this species on the Caribbean coast of Costa Rica, the occasional occurrence of this species on the east coast of Costa Rica was reported by Gamboa-Poveda and May-Collado (2006) and May-Collado (2006, in press). Therefore, it is possible that some individuals could be encountered during the proposed survey.

Pacific

The pantropical spotted dolphin is expected to be the one of the most common cetacean species in the proposed project area, primarily in coastal areas (Rasmussen et al. 2004; Holst et al. 2005a; May-Collado et al. 2005). In the eastern Pacific, this species ranges from 25ºN off Baja California, Mexico, to 17ºS, off southern Peru (Perrin and Hohn 1994). Au and Perryman (1985) noted that the species occurs primarily north of the equator, off southern Mexico, and westward along 10ºN. They also noted its occurrence in seasonal tropical waters south of the Galápagos Islands.

Wade and Gerrodette (1993) identified three stocks of spotted dolphins in the ETP: the coastal stock (*S. a. grafmani*) and two offshore (*S. a. attenuata*) stocks (the northeast and the west/south stock) However, recent genetic evidence indicates that there are actually nine genetically distinct stocks of this species in coastal areas from Baja California south to Ecuador (Rosales and Escorza-Treffño 2005).

Spotted dolphins of the coastal stock are most likely to occur in the proposed study area, although individuals of the northeast offshore stock could also occur there.

Much of what is known about the pantropical spotted dolphin in the ETP is related to the tuna purse-seine fishery in that area (Perrin and Hohn 1994). There was an overall stock decline of spotted dolphins from 1960–1980 because of the fishery (Allen 1985). In 1979, the population size of spotted dolphins in the ETP was estimated at 2.9–3.3 million (Allen 1985). For 1986–1990, Wade and Gerrodette (1993) reported an of 2.1 million. Gerrodette and Forcada (2005) noted that the population of offshore northeastern spotted dolphins has not yet recovered from the earlier population declines. The abundance estimate based on data collected from 1979–2000 is ~640,000 northeastern offshore spotted dolphins (Gerrodette and Forcada 2005). Possible reasons for the lack of growth include unreported bycatch, effects of fishing activity on survival and reproduction, and long-term changes in the ecosystem (Gerrodette and Forcada 2005). The estimate for 2003 has been reported as 736,737 (Gerrodette et al. 2005). The mortality rate for 2004 for the tuna fishery was estimated at 0.03% (Bayliff 2004). The sizes of the western/ southern offshore and coastal populations in the ETP were estimated at 627,863 and 149,393 individuals for 2003 (Gerrodette et al. 2005). For the Pacific coast EEZ of Costa Rica, Gerrodette and Palacios (1996) provided an abundance estimate of 8888 spotted dolphins, and for Central American coast north of Costa Rica, the estimate was 29,400.

Gerrodette and Forcada (2005) reported annual encounter rates ranging from 0.385–0.934 schools/100 km for northeast offshore spotted dolphins. Wade and Gerrodette (1993) reported an encounter rate for *S. attenuata* of 4.1 schools/1000 km in the ETP. During 1977–1980, encounter rates of spotted dolphins in the ETP ranged from 3.63–5.56 schools/1000 mi of survey effort (Polacheck 1987). Encounter rates for mixed schools of spinner and spotted dolphins were highest offshore near 10ºN, with average annual encounter rates of 1.03–1.63 schools/1000 mi of effort in 1977–1980 (Polacheck 1987). The weighted average annual encounter rates for the proposed study area ranged from 0.97–2.82 schools/ 1000 mi of effort (Polacheck 1987).

Pantropical spotted dolphins are considered common off W Costa Rica (May-Collado, in press). Densities of spotted dolphins in the region encompassing the proposed project area range from 0.007–0.233/km^2 for the offshore stocks and up to 0.097/km^2 for the coastal stock (Ferguson and Barlow 2001). However, Rodríguez-Fonseca (2001) reported that the oceanic spotted dolphin was less common than the coastal spotted dolphin in Costa Rican waters. Off W Costa Rica, May-Collado et al. (2005) reported 525 groups of 12,311 pantropical spotted dolphins with a mean group size of 29.4 individuals based on sightings from 1979–2001. Ferguson et al. (2006a) noted mean group sizes of 131 and 186 for offshore and unidentified subspecies of pantropical spotted dolphins, respectively, for the ETP. Gerrodette and Forcada (2005) estimated a mean group size of 114 dolphins for the offshore stock. The coastal type is known to be a resident in the Golfo Papagayo where the mean reported group size was 10.2 dolphins; numbers fluctuated seasonally likely in relation to food availability (Rodríguez Saenz and Rodríguez-Fonseca 2004; May-Collado and Morales 2005). In Golfo Dulce, their abundance and distribution also appears to vary seasonally (Acevedo and Burkhart 1998). Rasmussen et al. (2002) reported 353 sightings of spotted dolphins in seven years of surveys from 1996–2002 off Costa Rica and from 2001–2002 off Panama.

Off Costa Rica, several important areas have been identified for the species, including the coastal type *S.a. graffmani*: the Gulf of Papagayo and Cuajiniquil Bay, as well as Dominical, Drake Bay, the Osa Peninsula, and the Golfo Dulce (Acevedo and Burkhart 1998; Rodríguez-Fonseca 2001; Rodríguez Sáenz and Rodríguez-Fonseca 2004; May-Collado and Morales 2005). May-Collado et al. (2005) found this species concentrated primarily in coastal waters but also in offshore oceanic waters. In the Golfo Dulce, Acevedo and Burkhart (1998) reported that spotted dolphins preferred deep waters. Two spotted dolphin strandings on the Pacific coast were included in a list of strandings for Costa Rica during 1966–1999 (Rodríguez-Fonseca and Cubero-Pardo 2001). During a seismic survey off Central America in 2004, eight detections of >200 spotted dolphins were made throughout the project area in both shallow and deep waters (Holst et al. 2005a). Fiedler (2002) reported that spotted dolphins are relatively rare at the CRD.

In the ETP, spotted dolphins feed on fish and squid in the warmest waters, where the thermocline is very strong and slightly deeper than at the CRD (Fiedler 1992). Fiedler (2002) noted that they have evolved a complex feeding association with yellow-fin tuna and birds and apparently depend on the tuna to drive prey from the thermocline up to the surface. Fiedler (2002) suggested that such an association does not function or provide any advantage at the CRD where the thermocline is shallower and weaker than to the west.

Atlantic Spotted Dolphin (*Stenella frontalis*)

Atlantic spotted dolphins are distributed in tropical and warm temperate waters of the western North Atlantic and do not occur in the Pacific (Leatherwood et al. 1976). In the western Atlantic Ocean, their distribution extends from southern New England, south through the Gulf of Mexico and the Caribbean to Venezuela (Leatherwood et al. 1976; Perrin et al. 1994a).

Spotted dolphins usually inhabit shallow waters on the continental shelf inshore of the 250-m isobath (Davis et al. 1998). Although Atlantic spotted dolphins prefer shallow-water habitats, they are not common in nearshore waters (Davis et al. 1996). Davis et al. (1996) found that most dives of Atlantic spotted dolphins were shallow and of short duration, regardless of the time of day. Spotted dolphins usually dove to depths of 4 to <30 m, but the deepest dives recorded were 40–60 m (Davis et al. 1996). Most of the dives were less than 2 min in duration (Davis et al. 1996). Roden and Mullin (2000) noted a mean group size of 30 individuals for the northern Caribbean. Studies of stomach contents showed that spotted dolphins mainly prey on flying fish (Exocoetidae) and epipelagic prey (Perrin et al. 1987; Richard and Barbeau 1994).

Atlantic spotted dolphins are widespread in the Caribbean (Jefferson and Lynn 1994; Avila 1995; Roden and Mullin 2000; Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001; Smultea et al. 2004; Pardo et al. 2005). In the northern Caribbean, the Atlantic spotted dolphin is one of the most commonly sighted species and has been observed there with calves (Roden and Mullin 2000). In the Colombian Caribbean, a population of ~144 individuals was recorded southeast of the Gulf of Morrosquillo, from Crispate Bay to the mouth of the river Sinu (Avila 1995). Bolaños and Boher (2002) reported a recent mass stranding of more than 100 Atlantic spotted dolphins at La Tortuga Island, northeastern Venezuela. Atlantic spotted dolphins have also been sighted off the east coast of Costa Rica (DiBerardinis et al. 1997; Rodríguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006; May-Collado 2006, in press). This species is expected to be one of the most common species in the Caribbean portion of the proposed study area.

Spinner Dolphin (*Stenella longirostris*)

Spinner dolphins are distributed in oceanic and coastal waters and are associated with warm Tropical Surface Water (Au and Perryman 1985; Reilly 1990; Reilly and Fiedler 1994). This species is extremely gregarious and usually forms large schools when in the open sea and small ones in coastal waters (Perrin and Gilpatrick 1994). Spinner dolphins can be seen in groups of 30 to hundreds of individuals, or even thousands (Würsig et al. 2000). They often travel in mixed-groups with pantropical spotted dolphins and other species (Perrin 2002). Spinner dolphins usually feed at night on mesopelagic fish and squid, diving 600 m or deeper to obtain them (Perrin and Gilpatrick 1994). Spinner dolphins can give birth at any time of year. However, Barlow (1984) noted that the eastern Pacific form has a peak in reproduction during March–June, with some regional variation, and that the whitebelly form has peaks in spring and autumn.

Caribbean

In the western Atlantic, spinner dolphins occur along the eastern coast of the U.S. from New Jersey to southern Brazil (Rice 1998); however, their distribution in the Atlantic is poorly known (Culik 2002). Nonetheless, this species is known to occur in the southern Netherlands Antilles and in the Greater and Lesser Antilles (Debrot et al. 1998; Romero et al. 2001; Wardle et al. 2001). Spinner dolphins have been sighted north of Venezuela during several surveys (Jefferson and Lynn 1994; Swartz and Burks 2000; Smultea et al. 2004). Debrot et al. (1998) noted that this species is one of the most common dolphins in the southern Netherlands Antilles. It occurs in the area year-round (Debrot et al. 1998; Romero et al. 2001), although most sightings are made in late spring and summer (Debrot et al. 1998). Spinner dolphins are hunted in some eastern Caribbean nations, including Dominica, Saint Lucia, and Grenada (High North Alliance 2003), although not in Nicaragua or Costa Rica. We are unaware of any published sightings of this species off the Caribbean coast of Central America, and Rodríguez-Fonseca (2001) did not note the presence of this species on the east coast of Costa Rica. Therefore, encounters with this species in the proposed study area are unlikely.

Pacific

In the Pacific, Au and Perryman (1985) noted that the spinner dolphin occurs primarily north of the equator, off southern Mexico, and westward along 10ºN. They also noted its occurrence in seasonal tropical waters south of the Galápagos Islands. In the ETP, three types of spinner dolphins have been identified and two of those are recognized as subspecies: the eastern spinner dolphin, *S. l. orientalis,* considered an offshore species, the Central American spinner, *S. l. centroamericana* (also known as the Costa Rican spinner), considered a coastal species in Costa Rica (Perrin 1990; Dizon et al. 1991), and the 'whitebelly' spinner, which is thought to be a hybrid of the eastern spinner and Gray's spinner (*S. l. longirostris*). The Costa Rican spinner dolphin is typically seen within 150 km from shore, whereas the eastern spinner dolphin is more common in deeper waters offshore (ACS 2007).

Although there is a great deal of overlap between the ranges of eastern and whitebelly spinner dolphins, the eastern form generally occurs in the northeastern portion of the ETP, whereas the whitebelly spinner occurs in the southern portion of the ETP, ranging farther offshore (Wade and Gerrodette 1993; Reilly and Fiedler 1994). Reilly and Fiedler (1994) noted that eastern spinners are associated with waters that have high surface temperatures and chlorophyll and shallow thermoclines, whereas whitebelly spinners are associated with cooler surface temperatures, lower chlorophyll levels, and deeper thermoclines.

The total population of spinner dolphins in the ETP in 1979 was estimated at 0.8–0.9 million (Allen 1985). Wade and Gerrodette (1993) reported an abundance estimate of 1.7 million, and Gerrodette et al. (2005) estimated the abundance at 1.1 million for 2003. Gerrodette and Forcada (2005) note that the population of eastern spinner dolphins has not yet recovered from the earlier population declines. The abundance estimate for 1979–2000 is ~450,000 dolphins (Gerrodette and Forcada 2005), and the estimate for 2003 is 612,662 (Gerrodette et al. 2005). Bayliff (2004) noted a mortality rate in the tuna fishery of 0.03% for 2004. Possible reasons why the population is not recovering include under-reported bycatch, effects of fishing activity on survival and reproduction, and long-term changes in the ecosystem (Gerrodette and Forcada 2005).

Gerrodette and Forcada (2005) reported annual encounter rates for eastern spinner dolphins ranging from 0.141–0.333 schools/100 km for 1979–2000. Wade and Gerrodette (1993) noted an encounter rate for *S. longirostris* of 2.8 schools/1000 km. Polacheck (1987) noted average annual encounter rates in the ETP were 0.41–0.90 schools/1000 mi of effort in 1977–1980. The weighted average annual encounter rates in the proposed study area ranged from 0.33–0.50 schools/1000 mi of effort (Polacheck 1987). In the ETP, spotted and spinner dolphins are often seen together in mixed groups (Au and Perryman 1985). Scott and Cattanach (1998) noted that spinner dolphins form larger groups during the morning than in the afternoon and at night. The encounter rates for mixed schools of spinner and spotted dolphins were highest offshore near 10ºN, and the average annual encounter rates were 1.03–1.63 schools/1000 mi of effort (Polacheck 1987). Polacheck (1987) noted that the highest encounter rates in the ETP occurred southwest of the Galápagos Islands, but spinner dolphins are thought to be rare visitors to the Galápagos Islands (Smith and Whitehead 1999).

Within the proposed survey area, spinner dolphins are likely of the Central American variety, although some eastern spinner dolphins could occur there as well; the whitebelly variety is unlikely to occur in the study area (see Ferguson and Barlow 2001). Rodríguez-Fonseca (2001) reported that the Central American variety is much more common in Costa Rican waters than the eastern spinner dolphin. Data from Ferguson and Barlow (2001) show that the density of *S. l. centroamericana* directly off Costa Rica is 0.148/km^2, and that the densities of all other subspecies and types of spinners are zero; however, the density of *S. l. orientalis* along other parts of the Central American coastline is up to 0.262/km^2. The spinner dolphin is expected to be one of the most abundant cetacean species in the project area.

Spinner dolphins in the project region tend to occur in large groups compared to most other cetaceans. Ferguson et al. (2006a) noted mean group sizes of 108.8, 82.5, and 147.7 for eastern, whitebelly, and unidentified spinner dolphins, respectively. Gerrodette and Forcada (2005) noted a mean group size of 112 dolphins for the eastern stock. Off W Costa Rica, May-Collado et al. (2005) reported 29 groups of 2817 spinner dolphins with a mean group size of 100 based on sightings compiled from 1979–2001. During a seismic survey west of Central America in 2004, three groups of ~1350 spinner dolphins were seen (Holst et al. 2005a). Two of these groups were seen off NW Costa Rica and one off Nicaragua. However, Rasmussen et al. (2002) reported only one sighting of spinner dolphins in seven years of surveys from 1996 to 2002 off Costa Rica and from 2001 to 2002 off Panama.

Rodríguez-Fonseca (2001) identified the Quepos-Manuel Antonio National Park region as an important area in Costa Rican waters for the species. May-Collado (in press) also noted the occurrence of this species around Isla del Cocos. A single spinner dolphin stranding was reported during 1966–1999 at Golfo Dulce (Rodríguez-Fonseca and Cubero-Pardo 2001). May-Collado et al. (2005) reported spinner dolphins primarily in oceanic waters off W Costa Rica from 1979–2001, with small numbers in coastal waters.

Clymene Dolphin (*Stenella clymene*)

Clymene dolphins occur only in the Atlantic where they are usually found in tropical and warm waters. They occur off the eastern U.S. (including the Gulf of Mexico), south to Brazil, and across the Atlantic to West Africa (Mullin et al. 1994a). In the Caribbean, they have been sighted in the Lesser Antilles and southern Netherlands Antilles, and in Venezuela (see Romero et al 2001; Wardle et al. 2001). NatureServe (2005) noted the presence of clymene dolphins in all Central American countries, and Rodríguez-Herrera et al. (2002) also listed this species as present in Costa Rican waters. Rodríguez-Fonseca (2001) noted that this species could possibly occur in Costa Rican waters.

Clymene dolphins inhabit areas where sea surface temperatures are 22.8–29.1ºC and water depths are 704–3064 m or deeper (Mullin et al. 1994a; Davis et al. 1998). They usually feed on small mesopelagic fish and squid (Perrin and Mead 1994). Composition of pods, based on mass strandings, has shown evidence of sexual segregation; groups tend to consist largely of one sex or the other (Jefferson et al. 1995). The estimated pod size for these dolphins is 2 to 100 animals (Mullin et al. 1994a).

Striped Dolphin (*Stenella coeruleoalba*)

Striped dolphins are distributed worldwide in tropical and temperate waters (Perrin et al. 1994b). In some areas, such as the ETP and Gulf of Mexico, they are pelagic and prefer deep water along the edge and seaward of the continental shelf (e.g., Davis et al. 1998). However, in other areas, such as Norway, they also occur in coastal waters (Isaksen and Syvertsen 2002). They prey on small fish and cephalopods (Perrin et al. 1994b). Their distribution appears to be less affected by environmental variables than are the distributions of other dolphin species (Reilly and Fiedler 1994).

Striped dolphins are gregarious (groups of 20 or more are common) and active at the surface (Whitehead et al. 1998). School composition varies and consists of adults, juveniles, or both (Perrin et al. 1994b). Their breeding season has two peaks, one in the summer and one in the winter (Boyd et al. 1999).

Caribbean

Striped dolphins do not appear to be very common in the Caribbean (Debrot et al. 1998; Mignucci-Giannoni 1998). Nonetheless, these animals have been reported in the Greater and Lesser Antilles, southern Netherlands Antilles, Colombia, and Venezuela (Jefferson and Lynn 1994; Romero et al. 2001; Wardle et al. 2001; Smultea et al. 2004; Pardo et al. 2005). Pardo et al. (2005) reported a stranding of one striped dolphin on the coastal region of Santa Marta and Tayrona National Natural Park in the Colombian Caribbean Sea. Although this species is not known to occur in Caribbean Costa Rica (Rodríguez-Fonseca 2001), it is possible that some individuals could be encountered during the proposed study.

Pacific

In the ETP, striped dolphin distribution is associated with cool, upwelling areas along the equator (Au and Perryman 1985). The striped dolphin is expected to occur commonly in deep offshore waters of the proposed project area. Gerrodette et al. (2005) estimated the abundance of striped dolphins in the ETP at 1.5 million for 2003. Wade and Gerrodette (1993) reported an estimated abundance of 1.9 million for 1986–1990. Gerrodette and Palacios (1996) reported an abundance of 37,018 for the EEZ of Costa Rica and 24,907 for the Central American coast north of Costa Rica. The encounter rate during surveys from 1986–1990 was 5.4 schools/1000 km (Wade and Gerrodette 1993). Polacheck (1987) noted that the highest encounter rates in the ETP were off western Mexico. Average annual encounter rates in the ETP were 0.31–0.41 schools/1000 mi of survey effort in 1977–1980 (Polacheck 1987). The weighted average annual encounter rate in the proposed study area was 0.36–0.55 schools/1000 mi effort (Polacheck 1987). Wade and Gerrodette (1993) noted a mean group size of 61 in the ETP, and Ferguson et al. (2006a) noted a mean group size of 55.48.

The striped dolphin is expected to be one of the most abundant cetaceans in the Pacific part of the proposed project area. The reported density of striped dolphins in the region ranges from 0.06 to 0.26/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported 125 sightings of 6162 striped dolphins in the period 1979–2001; mean group size was 48.9 individuals. Mayo-Collado et al. (2005) reported this species nearly exclusively from oceanic waters. However, no striped dolphins were detected off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a).

Rodríguez-Fonseca (2001) identified Isla del Caño and the outer part of the Osa Peninsula to the southeast of the proposed study area, as an important area in Pacific Costa Rican waters for striped dolphins. May-Collado (in press) also noted their occurrence near Isla del Cocos. Three striped dolphin strandings were reported during 1966–1999: two in Puntarenas and one at Golfo Dulce (Rodríguez-Fonseca and Cubero-Pardo 2001).

Short-beaked Common Dolphin (*Delphinus delphis*)

Common dolphins are found in tropical and temperate oceans around the world (Evans 1994). The common dolphin is reportedly one of the most abundant cetacean species off W Costa Rica (May-Collado et al. 2005). The short-beaked common dolphin is widely distributed compared to the long-beaked common dolphin (Heyning and Perrin 1994). No *Delphinus* spp. are known to occur on the Caribbean coast of Costa Rica, and only *D. delphis* is expected to occur on the Pacific coast.

Three stocks of *D. delphis* are recognized in the ETP: northern, central, and southern (Perrin et al. 1985; Perryman and Lynn 1993). Common dolphins seen in the Pacific part of the survey area belong to the central stock. However, dolphins from the southern stock range into CRD waters during extreme environmental events, such as El Niño; such events appear to occasionally result in stock overlap of common dolphins off Costa Rica (Danil and Chivers 2005).

In the ETP, common dolphin distribution is associated with cool, upwelling areas along the equator and off Baja California, Central America, and Peru (Au and Perryman 1985; Reilly 1990; Reilly and Fiedler 1994). Reilly (1990) noted no seasonal changes in common dolphin distribution, although Reilly and Fiedler (1994) observed interannual changes in distribution that were likely attributable to El Niño events.

Common dolphins often travel in large groups; schools of hundreds or even thousands are common. Ferguson et al. (2006a) noted a mean group size of 230, and off W Costa Rica, May-Collado et al. (2005) reported a mean group size of 220.7 dolphins. Groups are composed of subunits of 20–30 closely related individuals (Evans 1994). Scott and Cattanach (1998) noted that they form larger groups in the morning and smaller groups in the later afternoon and at night. Perryman and Lynn (1993) determined that births occurred throughout the year for central common dolphins, and only occurred from January to July for southern common dolphins. Danil and Chivers (2005) reported that common dolphins in and near the CRD give birth throughout the year. Common dolphins feed on small pelagic fish and squid in upwelling-modified water (Fiedler 2002).

The population size of the common dolphin in the ETP in 1979 was estimated at 1.3–3.1 million (Allen 1985). Wade and Gerrodette (1993) noted that the common dolphin is the most numerous cetacean species in the ETP, with an abundance of 3.1 million and an encounter rate of 1.39 schools/1000 km. Gerrodette et al. (2005) reported an abundance estimate of only 1.1 million for 2003. However, abundance estimates of common dolphins have fluctuated from <1 million to >3 million from 1986–2000, with an estimated abundance of 3 million in 2000 (see Gerrodette and Forcada 2002). Gerrodette and Palacios (1996) reported an abundance of 53,796 common dolphins for the EEZ of Costa Rica and 68,668 for the EEZs of the Central American countries north of Costa Rica. Polacheck (1987) noted that encounter rates were highest in nearshore areas at 25ºN and 5ºN of the ETP, and average annual encounter rates were 0.51–1.18 schools/1000 mi of survey effort during 1977–1980. The weighted average annual encounter rates for the proposed study area were 2.38–5.91 schools/1000 mi effort (Polacheck 1987). Polacheck (1987) also noted that there were concentrations of common dolphins offshore near 10ºN and 135–140ºW, but at lower densities.

This species is expected to be one of the most abundant cetaceans in the Pacific part of the project area. The density of short-beaked common dolphins in the region encompassing the proposed project area ranges from 0 to 0.519/km^2 (Ferguson and Barlow 2001). The common dolphin off W Costa Rica is primarily an oceanic species, but has also been reported near shore (May-Collado et al. 2005). May-Collado et al. (2005) reported 82 sightings of 17,875 individuals in the period 1979–2001 off W Costa Rica. However, only one group of 45 short-beaked common dolphins was detected off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Rasmussen et al. (2002) reported one sighting of common dolphins in seven years of surveys from 1996 to 2002 off Costa Rica and from 2001 to 2002 off Panama.

Fraser's Dolphin (*Lagenodelphis hosei*)

Fraser's dolphin is a tropical species that rarely occurs in temperate regions, and then only in relation to temporary oceanographic anomalies such as El Niño events (Perrin et al. 1994c). Fraser's dolphins typically occur in water at least 1000 m deep. They feed on mesopelagic fish, shrimp, and squid, diving to depths of at least 250–500 m (Dolar 2002). They travel in groups ranging from just a few animals to hundreds or even thousands of individuals (Perrin et al. 1994c), often mixed with other species (Culik 2002).

Caribbean

In the western Atlantic, this species ranges from the Gulf of Mexico to Uruguay (Rice 1998). It is believed to occur throughout the Caribbean (NatureServe 2005), although few sightings have been documented (see Romero et al. 2001; Wardle et al. 2001). Bolaños and Villarroel-Marin (2003) reported on a live stranding of two Fraser's dolphins on the central coast of Venezuela in 1999. Swartz and Burks (2000) sighted a group of 70 Fraser's dolphins near Martinique, during a survey in the SE Caribbean. Rodríguez-Fonseca (2001) did not include this species on the list of cetaceans occurring on the Caribbean coast of Costa Rica. Therefore, sightings of this species are unlikely during the Caribbean portion of the proposed survey.

Pacific

Fraser's dolphin may occasionally occur in the proposed project area, although its expected numbers are low based on available data. The species occurs throughout the ETP (Perrin et al. 1973, 1994c). Wade and Gerrodette (1993) showed a mainly equatorial distribution in the ETP, and estimated its abundance in the area at 289,300, with an encounter rate of 0.23 schools/1000 km. Pitman and Ballance (1992) also noted its occurrence in the ETP, and Smith and Whitehead (1999) reported one sighting of 300 individuals in the Galápagos Islands. Wade and Gerrodette (1993) noted a mean group size of 395 for the ETP, and Ferguson et al. (2006a) reported a mean group size of 440.

The density of Fraser's dolphin in the region encompassing the proposed project area ranges from 0 to 0.0056/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported only one sighting of 158 Fraser's dolphins in the period 1979–2001. No Fraser's dolphins were detected off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Rodríguez-Fonseca (2001) identified Isla del Cocos as an important area in Pacific Costa Rican waters for the species.

Risso's Dolphin (*Grampus griseus*)

The Risso's dolphin is primarily a tropical and mid-temperate species distributed worldwide. It generally occurs between 60ºN and 60ºS, where surface water temperatures are above 10ºC (Kruse et al.

1999). Risso's dolphins are primarily pelagic, mostly occurring over steep sections of the continental slope and at subsurface seamounts and escarpments. Risso's dolphins usually occur on the upper continental slope, in waters 350–1000 m deep (Baumgartner 1997; Davis et al. 1998; Baird 2002a). Risso's dolphins occur individually or in small to moderate-sized groups, normally ranging in numbers from two to less than 250, although groups as large as 4000 have been sighted. The majority of groups consist of <50 individuals (Kruse et al. 1999). This species usually feeds on squid and other deepwater prey (Kruse et al. 1999).

Caribbean

There are observations of Risso's dolphins in the Greater and Lesser Antilles, Venezuela, and Colombia (Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001), and NatureServe (2005) notes their occurrence in the wider Caribbean. However, this species was not reported to occur off the east coast of Costa Rica (Rodríguez-Fonseca 2001), nor are we aware of any sightings off the Caribbean coast of Central America. Therefore, encounters with this species in the proposed Caribbean study area are unlikely.

Pacific

Risso's dolphin is likely to occur in deep oceanic waters of the proposed Pacific project area (see May-Collado, in press). Gerrodette et al. (2005) reported an abundance estimate of 76,595 Risso's dolphins for the ETP. For 1986–1990, Wade and Gerrodette (1993) estimated the abundance at 175,800. Gerrodette and Palacios (1996) reported an abundance of 7938 Risso's dolphins for the EEZ of Costa Rica and 4491 for the EEZs of the Central American countries north of Costa Rica. Wade and Gerrodette (1993) noted an encounter rate of 1.45 schools/1000 km in the ETP. Polacheck (1987) noted that the highest encounter rates in the ETP were in (relatively) nearshore areas, and average annual encounter rates were 0.01–0.13 schools/1000 mi of survey effort during 1977–1980. The weighted average annual encounter rates for the proposed study area ranged from 0.23–0.42 schools/1000 mi effort (Polacheck 1987).

The density of Risso's dolphins in the Pacific project area is 0.003–0.023/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported 76 sightings of 880 dolphins in the period 1979–2000, with a mean group size of 11.6 dolphins. Ferguson et al. (2006a) noted a mean group size of 18.64. One group of 25 Risso's was detected off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). May-Collado (in press) also noted the occurrence of this species at Isla del Cocos.

Melon-headed Whale (*Peponocephala electra*)

The melon-headed whale is a pantropical and pelagic species (Perryman et al. 1994). These whales occur mainly between 20ºN and 20ºS; occasional occurrences in temperate regions are likely associated with warm currents (Perryman et al. 1994; Reeves et al. 2002). Melon-headed whales are oceanic and occur in offshore areas (Perryman et al. 1994), as well as around oceanic islands. Mullin et al. (1994b) noted that they are usually sighted in water >500 m deep, and away from the continental shelf. Melon-headed whales tend to travel in large groups of 100 to 500 individuals, but have also been seen in pods of 1500 to 2000 individuals. Melon-headed whales may also form mixed species pods with Fraser's, spinner, and spotted dolphins (Jefferson et al. 1993; Carwardine 1995), and have also been seen in association with Parkinson's petrels, *Procellaria parkinsoni* (Pitman and Ballance 1992). They feed on squid, fish, and shrimp (Jefferson and Barros 1997; Perryman 2002), although squid appear to be the preferred prey of melon-headed whales (Perryman 2002).

Caribbean

In the western Atlantic, melon-headed whales range from the Gulf of Mexico to southern Brazil in the western Atlantic (Rice 1998). They have been sighted throughout the eastern and southern Caribbean (Debrot et al. 1998; Swartz and Burks 2000; Romero et al. 2001; Wardle et al. 2001; Bolaños and Villarroel-Marin 2003). Rodríguez-Fonseca (2001) did not list the melon-headed whale as present on the eastern coast of Costa Rica, and we are unaware of any sightings off the Caribbean coast of Central America. Therefore, encounters with this species during the proposed survey are highly unlikely.

Pacific

The melon-headed whale likely occurs in small numbers in the Pacific part of the proposed project area. Au and Perryman (1985) and Perryman et al. (1994) reported that it occurs primarily in equatorial waters, although Wade and Gerrodette (1993) noted its occurrence in non-equatorial waters. Perrin et al. (1976) reported on a capture of the species in a tuna purse seine off Central America.

Wade and Gerrodette (1993) estimated the abundance of this species in the ETP at 45,400, with an encounter rate of 0.10 schools/1000 km. The density of this species in the proposed project area can range up to 0.0577/km^2 (Ferguson and Barlow 2001). Ferguson et al. (2006a) reported the mean group size as 257.7. Off W Costa Rica, May-Collado et al. (2005) reported two sightings of 445 animals in the period 1979–2000. All of these animals were far offshore with the nearest one to a proposed seismic survey line >100 km to the south. No melon-headed whales were detected off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Three melon-headed whale strandings occurred on the Pacific coast during 1966–1999; >200 individuals stranded at Nicoya Peninsula in 1976, and two individual strandings occurred on the northern coast in 1970 (Rodríguez-Fonseca and Cubero-Pardo 2001).

Pygmy Killer Whale (*Feresa attenuata*)

Pygmy killer whales are pantropical (Ross and Leatherwood 1994; Rice 1998). They tend to travel in groups of 15–50 individuals, although herds of a few hundred have been sighted (Ross and Leatherwood 1994). The remains of fishes and squids have been found in the stomachs of stranded pygmy killer whales, and they are suspected to attack and sometimes eat other dolphins (Donahue and Perryman 2002).

Caribbean

In the western Atlantic, pygmy killer whales inhabit deep, warm waters from the Gulf of Mexico to Uruguay (Rice 1998). They are fairly uncommon in the Caribbean, but sightings have been made throughout the eastern and southern Caribbean, including Puerto Rico, the British Virgin Islands, Dominica, St. Vincent, as well as Venezuela (see Romero et al. 2001; Wardle et al. 2001; Bolaños and Villarroel-Marin 2003). They may also occur in the Colombian Caribbean (Romero et al. 2001). Rodríguez-Fonseca (2001) did not note the presence of this species on the east coast of Costa Rica, and we are also unaware of any sightings off the Caribbean coast of Central America. Therefore, encounters with this species during the proposed survey are highly unlikely. This species is hunted in some eastern Caribbean nations (High North Alliance 2003), although no hunting occurs in the proposed project area.

Pacific

The pygmy killer whale may occasionally occur in small numbers in the Pacific part of the proposed project area. Pygmy killer whales have been sighted in the ETP (Van Waerebeek and Reyes 1988; Pitman and Ballance 1992; Wade and Gerrodette 1993) and appear to occur sporadically along the equator and the coast of Central America (Wade and Gerrodette 1993). In warmer water, they are usually seen close to the coast (Wade and Gerrodette 1993), but they are also found in deep waters. Pygmy killer whales tend to travel in groups of 15–50, although pods of a few hundred have been sighted (Ross and Leatherwood 1994). Wade and Gerrodette (1993) noted a mean group size of 28, and Ferguson et al. (2006a) reported a mean group size of 30.

Wade and Gerrodette (1993) estimated the abundance of this species in the ETP at 39,800, with an encounter rate of 0.21 schools/1000 km. The density of this species in the proposed project area can range up to 0.01/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported no sightings of this species in 1979–2000. No pygmy killer whales were seen off Costa Rica and Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). There has been a report of a stranding on the coast of Ecuador (Félix et al. 1995).

False Killer Whale (*Pseudorca crassidens*)

False killer whales are widely distributed, though not abundant anywhere (Carwardine 1995). They are found in all tropical and warmer, temperate oceans, especially in deep offshore waters (Odell and McClune 1999), although sightings have been reported for both shallow (<200 m) and deep (>2000 m) waters. They are gregarious and form strong social bonds (Stacey and Baird 1991). They travel in pods of 20–100 individuals (Baird 2002b), although groups of several hundred are sometimes observed. Recently stranded groups ranged from 28 to over 1000 animals. False killer whales feed primarily on fish and cephalopods, but have been known to attack small cetaceans, California sea lions (S.F. MacLean, LGL Ltd., pers. comm.), and even a humpback whale (Jefferson et al. 1993).

Caribbean

False killer whales are seen infrequently in the Caribbean, but they are known to occur throughout the area (NatureServe 2005), with sightings in Cuba, Puerto Rico, Dominica, St. Vincent, the Grenadines, Tobago, the western Caribbean, and the central coast of Venezuela (see Romero et al. 2001; Wardle et al. 2001). However, we are unaware of any sightings off the Caribbean coast of Central America, and Rodríguez-Fonseca (2001) did not note the presence of this species on the east coast of Costa Rica. Therefore, encounters with this species during the proposed survey are highly unlikely.

Pacific

False killer whales have been sighted in the ETP, where they chase or attack *Stenella* and *Delphinus* dolphins during tuna fishing operations (Perryman and Foster 1980). Palacios (1996b) observed false killer whales attacking a group of 20–25 sperm whales in the Galápagos Islands. Generally, the prey of the false killer whale has been reported to include fish and squid; however, in the Galápagos Islands, their feeding habits and diving behavior are mostly unknown (Stacey et al. 1994). In the ETP, they are usually seen far offshore (Wade and Gerrodette 1983). Along W Costa Rica, false killer whales are occasionally to commonly observed (Rasmussen et al. 2004; Martínez-Fernandez et al. 2005).

Wade and Gerrodette (1993) and Ferguson et al. (2006a) noted a mean group size of 11 in the ETP. They noted the occurrence of false killer whales especially along the equator, and estimated their abundance in the ETP at 39,800, with an encounter rate of 0.31 schools/1000 km. The density of this species in the proposed project area can range up to 0.021/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported nine sightings of 253 animals in 1979–2000; mean group size was 36.2 animals. Martínez-Fernandez et al. (2005) observed four groups off Costa Rica during monthly strip-transect surveys from December 2004–June 2005; the mean group size was 13.2. One group of 12 animals was sighted during a seismic survey off Costa Rica and Nicaragua in November–December 2004 (Holst et al. 2005a). Rasmussen et al. (2002) reported seven sightings of false killer whales in seven years of surveys (1996–2002) off Costa Rica and in 2001–2002 off Panama.

Four areas important for the species have been identified in Pacific Costa Rican waters for the species (Rodríguez-Fonseca 2001; Martínez-Fernandez et al. 2005): (1) Isla del Cocos, (2) the Quepos-Manuel Antonio National Park region, (3) the coast of Drake Bay, and (4) the Golfo Dulce. Acevedo-Gutierrez et al. (1997) made 15 sightings of false killer whales in Golfo Dulce and at Isla del Cocos; mean group size was 16, with a range of 13–14 in Golfo Dulce and 5–34 at Isla del Cocos. May-Collado et al. (2005) reported sightings in both neritic and oceanic waters. Martínez-Fernández et al. (2005) postulated that the presence of false killer whales in Pacific coastal waters of Costa Rica may be influenced by the seasonality (e.g., wet and dry seasons) of the area.

Killer Whale (*Orcinus orca*)

Killer whales are cosmopolitan and globally abundant; they have been observed in all oceans of the world (Ford 2002). Although they prefer cold waters, they have been reported in tropical and offshore waters (Heyning and Dahlheim 1988). High densities occur in high latitudes, especially in areas where prey is abundant. Mitchell (1975) noted that the greatest abundance is found within 800 km of major continents

Killer whales are segregated socially, genetically, and ecologically into three distinct groups, residents, transients, and offshore animals. Resident groups feed exclusively on fish, while transients feed exclusively on marine mammals. Offshore killer whales are less known, and their feeding habits are uncertain. They have been known to attack sperm whales in the Galápagos Islands (e.g., Arnbom et al. 1987; Pitman et al. 2001). Killer whale movements generally appear to follow the distribution of prey. Killer whales often travel in close-knit matrilineal groups of a few to tens of individuals (Dahlheim and Heyning 1999).

Caribbean

Killer whales are seen irregularly in the Caribbean. Sightings, mainly anecdotal, have been reported for the Bahamas, Cayman Islands, Cuba, Dominican Republic, St. Lucia, Dominica, St. Vincent and the Grenadines, Puerto Rico and the Virgin Islands, and Trinidad and Tobago (see Romero et al. 2001; Ward et al. 2001). Killer whales are also known to occur along Costa Rica's Caribbean coast (Rodríguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006), but sightings are infrequent.

Pacific

Killer whales are found throughout the ETP (Pitman and Ballance 1992; Wade and Gerrodette 1993), but are most densely distributed near the coast from 35ºN to 5ºS (Dahlheim et al. 1982). Dahlheim et al. (1982) noted the occurrence of a cluster of sightings at two offshore locations in the ETP. One location was bounded by 7–14ºN and 127–139ºW, and the other was within a band between the equator and 5ºN and from the Galápagos Islands to 115ºW. The pods contained up to 75 individuals, with a mean group size of 5.3 (Dahlheim et al. 1982). A group of 20–22 killer whales was seen preying on a blue whale calf in the CRD in 2003, ~230 km west of Nicaragua (Gilpatrick et al. 2005). An estimated 8500 killer whales occur in the ETP, and the encounter rate was found to be 0.43 schools/1000 km (Wade and Gerrodette 1993).

The density of killer whales in the proposed project area ranges from 0 to 0.0007/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported seven sightings of 25 animals in 1979–2000; sightings were made in offshore oceanic waters west of the proposed seismic survey area. May-Collado et al. (2005) noted that the mean group size was the smallest among the delphinids seen, at 3.51 animals; Ferguson et al. (2006a) reported a mean group size of 5.45.

No killer whales were detected off Costa Rica or Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Rasmussen et al. (2002) reported two sightings in seven years of surveys (1996–2002) off Costa Rica and in 2001–2002 off Panama. Rasmussen et al. (2004) reported killer whales pursuing humpback whales off the W coast of C Rica. Rodríguez-Fonseca (2001) identified two important areas in Pacific Costa Rican waters for the species: the area between Punta Guiones and Cabo Blanco, and Isla del Caño and the outer part of the Osa Peninsula. One killer whale stranding was reported in 1993 for the Osa Peninsula (Rodríguez-Fonseca and Cubero-Pardo 2001).

Short-finned Pilot Whale (*Globicephala macrorhynchus*)

The short-finned pilot whale can be found in tropical and warmer temperate waters (Leatherwood and Reeves 1983; Bernard and Reilly 1999), generally south of 50ºN and north of 40ºS (Jefferson et al. 1993; Rice 1998). Davis et al. (1998) noted that it is mainly pelagic and occurs in deep waters usually in areas ~1000 m or 3281 ft deep, where it feeds on squid. Changes in the distribution of the short-finned pilot whale likely are influenced by the distribution of its prey.

Short-finned pilot whales appear to form relatively stable, matrilineal groups of up to several hundred individuals (Jefferson et al. 1993; Olson and Reilly 2002). They are generally nomadic, but may be resident in certain locations including California and Hawaii (Olson and Reilly 2002). There do not appear to be fixed migrations, but general north–south or inshore–offshore movements occur in relation to prey distribution or incursions of warm water. Short-finned pilot whales are primarily adapted to feeding on squid (Hacker 1992), although they also take some fishes.

Caribbean

Short-finned pilot whales are thought to be fairly common in the Caribbean and have been sighted in many parts of that region, including the Lesser Antilles, southern Netherlands Antilles, Columbia, Venezuela (see Romero et al. 2001; Wardle et al. 2001; Smultea et al. 2004; Pardo et al. 2005), and Costa Rica (Rodríguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006; May-Collado 2006, in press). They likely occur in the area year-round (Debrot et al. 1998); however, little detailed information is available on either their status or abundance in the region (Wardle et al. 2001). Calves have also been seen in the southern Netherlands Antilles (Debrot et al. 1998), as well as in the northern Caribbean (Roden and Mullin 2000). The short-finned pilot whale is harvested in parts of the eastern Caribbean (High North Alliance 2003), although not in the proposed project area.

Pacific

Short-finned pilot whales are likely to be seen in the proposed project area off the W Coast of Central America. Pilot whales have a wide distribution throughout the ETP, but are most abundant in cold waters where upwelling occurs (Wade and Gerrodette 1993). Wade and Gerrodette (1993) estimated the abundance of pilot whales in the ETP at 160,200 based on data from 1986–1990. The number of pilot whales appears to be greater for 1998–2000, with an estimate of 589,315 for 2000 (Gerrodette and Forcada 2002). Gerrodette and Palacios (1996) reported an abundance of 8541 pilot whales for the EEZ of Costa Rica and 3811 for the EEZs of the Central American countries north of Costa Rica. Wade and Gerrodette (1993) provided an encounter rate of 1.7 schools/1000 km for the ETP. Polacheck (1987) noted that encounter rates for pilot whales in the ETP were highest inshore and that average annual encounter rates were 0.33–0.88 schools/1000 mi of survey effort in 1977–1980. Weighted average annual encounter rates for the proposed study area were 0.59–2.55 schools/1000 mi (Polacheck 1987). Offshore concentrations may also occur, but at lower densities (Polacheck 1987). Smith and Whitehead (1999) reported that pilot whales were only rarely seen off the Galápagos Islands. Wade and Gerrodette (1993) and Ferguson et al. (2006a) reported a mean group size of 18 in the ETP.

Off W Costa Rica, pilot whales are considered common (May-Collado, in press). The density of this species in the proposed project area can range up to 0.03/km^2 (Ferguson and Barlow 2001). May-Collado et al. (2005) reported 68 sightings of 967 animals in 1979–2001; mean group size was 14.2 animals. Sightings were made primarily in offshore oceanic waters, but a fair number also occurred in neritic waters. Four groups of 30 whales were detected during a seismic survey off Costa Rica and Nicaragua in November–December 2004 (Holst et al. 2005a).

Rodríguez-Fonseca (2001) identified the area between Punta Guiones and Cabo Blanco as an important area in Pacific Costa Rican waters for the species. May-Collado (in press) also noted the occurrence of this species at Isla del Cocos. Three pilot whales stranded at Playa Ostional in 1995 (Rodríguez-Fonseca and Cubero-Pardo 2001).

(2) Mysticetes

Humpback Whale (*Megaptera novaeangliae*)

The humpback whale, classified as ***endangered*** under the U.S. ESA, has a near-cosmopolitan distribution. Although it is considered to be a mainly coastal species, it often traverses deep pelagic areas while migrating. Its migrations between high-latitude summering grounds and low-latitude wintering grounds are reasonably well known (Winn and Reichley 1985). In fact, the humpback whale has the longest known migration movements of any mammal, with one-way distances up to 8461 km (Rasmussen et al. 2007).

Humpback whales are often sighted singly or in groups of two or three; however, in their breeding and feeding ranges, they may occur in groups of up to 15 (Leatherwood and Reeves 1983). Roden and Mullin (2000) noted an average group size of 1.8 for the northern Caribbean. Humpbacks feed on krill and small schooling fish, primarily in high-latitude waters during summer; there is little feeding during winter in tropical waters, where calving and mating occur. Locations of wintering areas appear to be influenced by water temperatures; Rasmussen et al. (2007) noted that all wintering areas are found in warm waters (21.1–28.3ºC).

Male humpbacks sing a characteristic song when on the wintering grounds (Winn and Reichley 1985); singing also occasionally occurs in higher-latitude areas. The singing is generally thought to attract females and/or establish territories (Payne and McVay 1971; Winn and Winn 1978; Darling et al. 1983; Glockner 1983; Mobley et al. 1988; Clapham 1996). Humpback whales produce sounds in the frequency range of 20 Hz to 8.2 kHz, although songs have dominant frequencies of 120–4000 Hz (review by Thomson and Richardson 1995). Some harmonic components can extend to frequencies above 24 kHz (Au et al. 2006).

Caribbean

The majority of humpbacks from the North Atlantic population overwinter in the West Indies (Smith et al. 1999). Smith et al. (1999) noted that at least 7100 whales of the North Atlantic population of 9300–12,100 whales are thought to breed in the Caribbean. Stevick et al. (2003) reported that the most precise estimate for the West Indies breeding population of humpbacks is 10,752, and that the average rate of increase of this population over a 14-year period was 0.031.

In the Caribbean, humpback whale distribution is associated with shallow banks. For example, Swartz et al. (2001, 2003) noted that ~71% of visually detected whales were seen in shelf waters (<100 m or 328 ft deep). Nonetheless, humpbacks are also known to occur in deep waters in the Caribbean (see Roden and Mullin 2000; Swartz et al. 2001, 2003).

The Greater Antilles and the northern Lesser Antilles have large concentrations of humpback whales (Reeves et al. 2001a). The peak breeding season in this area extends from mid-February to mid-March (Mignucci-Giannoni 1998). The principal breeding and calving areas in the West Indies include Silver Bank, Navidad Bank off Hispaniola, Mona Passage off Puerto Rico, and Anguilla and Virgin Banks (Winn et al. 1975; Balcomb and Nichols 1982; Whitehead and Moore 1982; Mattila and Clapham 1989; Mattila et al. 1989).

The abundance and distribution of humpback whales for the southern Caribbean Sea are mostly unknown, but humpbacks have been sighted in the Lesser Antilles and along the coast of Venezuela (Swartz and Burk 2000; Romero et al. 2001; Wardle et al. 2001; Swartz et al. 2001, 2003). However, the density of whales in this area is expected to be low, since intense hunting used to occur there (Reeves et al. 2001a). In most of the Caribbean, hunting of humpbacks ceased in 1927 due to depleted numbers of whales (Swartz et al. 2001, 2003). However, humpback whale are still subject to a limited hunt in the southeast Caribbean, in St. Vincent and the Grenadines (IWC 2007b).

Humpback whales have not been reported to occur off the Caribbean coast of Central America (Rodríguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006; May-Collado 2006, in press). However, there is a remote possibility that an individual could be seen in the proposed West Caribbean study area.

Pacific

The worldwide population of humpback whales is divided into various northern and southern ocean populations (Mackintosh 1965). Geographical overlap of these populations has been documented only off Central America near Costa Rica (Acevedo and Smultea 1995; Rasmussen et al. 2004, 2007). Genetic analyses suggest gene flow (either past or present) through the North and South Pacific (e.g., Baker et al. 1993; Caballero et al. 2001; Medrano-González et al. 2001). The humpback whale is one of the most abundant cetaceans off the Pacific coast of Costa Rica during the winter breeding season of northern hemisphere humpbacks, and during the southern-winter breeding period for southern hemisphere humpbacks (e.g., Rasmussen et al. 2004; May-Collado et al. 2005).

Largely due to its coastal winter distribution, the humpback whale is one of the best-described cetacean species off Costa Rica. Photo-identification studies of individual humpback whales have been ongoing off W Costa Rica since the 1980s and more recently off Nicaragua as well (e.g., Steiger et al. 1991; Rasmussen et al. 2002, 2004, 2007). These studies combined with others have linked Costa Rican humpbacks with both the northern and southern hemispheres, although animals from the different populations generally occur there at opposite times of the year during their respective winter breeding/calving periods.

The North Pacific stock is estimated at over 6000 individuals (Calambokidis et al. 1997). Most northeastern Pacific humpbacks spend the northern winter off Baja California and mainland Mexico, and summer off the western coast of North America from California to Alaska (Urbán and Aguayo 1987; Urbán et al. 2000). The northern-hemisphere humpbacks occur in the Mexican Pacific from as early as September through the winter to mid-May (Urbán and Aguayo 1987). A small number of whales inhabiting the eastern North Pacific are known to winter as far south as Nicaragua and Costa Rica (Steiger et al. 1991; Calambokidis et al. 2000; Rasmussen et al. 2002, 2004, 2007; Holst et al. 2005a). Although Central America, including the project area, is not considered a major wintering area for humpback whales, they have been reported there regularly during the northern winter (Steiger et al. 1991; Acevedo and Smultea 1995; Rasmussen et al 2002, 2004, 2007; May-Collado et al. 2005). The North Pacific humpback whale is the most abundant mysticete in the region during the northern winter, particularly from January to March (Steiger et al. 1991; Rasmussen et al. 2002, 2004; May-Collado et al. 2005). By early spring (April), most of these humpbacks have migrated north to feeding grounds (Steiger et al. 1991; Rasmussen et al. 2002, 2004; May-Collado et al. 2005).

The southeastern Pacific stock of humpback whales was recently estimated at ~2881 to 2917 individuals (Félix et al. 2005). Breeding/calving areas occur largely in coastal areas from 4º30'S (Peru) to 9ºN (Central America) during the southern winter (i.e., the northern-hemisphere summer). The largest concentrations occur off Colombia and Ecuador (Flórez-González 1991; Flórez-González et al. 1998; Scheidat et al. 2000; Félix and Haase 2001). Individuals occur in Columbia as early as mid-June, with peak numbers from August to October (Flórez-González 1991). Humpback whales may migrate between these breeding areas within a season and perhaps between years (Flórez-González et al. 1998). These southern-hemisphere whales then migrate south to feed off Antarctica during December–April (Flórez-González 1991; Flórez-González et al. 1998; Scheidat et al. 2000; Felix and Haase 2001; May-Collado et al. 2005). Off W Costa Rica, humpbacks from the southern hemisphere are seen in June–October, with a peak in numbers during August to early October (Rasmussen et al. 2004, 2007; May-Collado et al. 2005).

Rasmumssen et al. (2007) reported 207 humpback whale sightings off Central America during surveys in the austral winters of 2001–2004. Based on eight years (1996–2003) of survey effort off Costa Rica and three years (2001–2002) off Panama, Rasmussen et al. (2004) noted 177 sightings. May-Collado et al. (2005) reported 186 sightings of 246 humpbacks in 1979–2001. Eleven groups of 16 humpbacks were seen during a seismic survey off Costa Rica and Nicaragua in November–December 2004 (Holst et al. 2005a). This includes a small concentration of humpback whales (8 groups totaling 12 whales) seen in the Gulf of Fonseca near the Honduras/El Salvador/Nicaragua borders in early December. Two of these individuals were also recorded singing, a behavior associated predominantly with the winter breeding season. Small concentrations of humpbacks were seen in the same region later that winter in 2005 (J. Calambokidis, pers. comm. to LGL, Dec. 2005).

May-Collado et al. (2005) reported that all humpback sightings off W Costa Rica over a 20-year period were in nearshore shallow waters in the neritic zone, primarily during the northern winter. They reported heaviest concentrations around Osa Peninsula in southern Costa Rica, where most studies have taken place since the 1980s (e.g., Steiger et al. 1991; Rasmussen et al. 2002, 2004, 2207). Rodríguez-Fonseca (2001) and May-Collado et al. (2005) identified several important areas in Pacific Costa Rican waters for the species: the Gulf of Papagayo at the southern end of the proposed survey area, Isla del Caño, the outer part of the Osa Peninsula, and the Golfo Dulce. Specific humpback calving areas in the proposed project region are not well documented. However, a humpback whale calf stranded at Playa Flamingo in 1998 and subsequently died (Rodríguez-Fonseca and Cubero-Pardo 2001). Holst et al. (2005a) sighted a humpback mother-calf pair off northwestern Costa Rica on 25 November 2004.

Systematic vessel-based surveys of the ETP have occurred during July–December. Although Jackson et al. (2004) did not encounter any humpbacks in the proposed survey area during surveys in July–December 2003, Ferguson and Barlow (2001) reported the maximum density of humpback whales in the proposed project area as 0.004/km^2 for July–December. While on these wintering grounds, humpbacks occur predominantly in coastal waters. The planned seismic survey is proposed to occur between the beginning of January and early March, mainly in offshore waters, west of Costa Rica and southern Nicaragua. However, only one of the proposed survey lines off the Pacific coast occurs in nearshore waters; Line E is located parallel to the coast between the southern tip of the Nicoya Peninsula south to the northern tip of the Osa Peninsula (Fig. 1 and 7). The location of this line overlaps one of the highest reported concentrations of humpback whales off W Costa Rica, off the northern Osa Peninsula (May-Collado et al. 2005). If possible, Line E will be surveyed at a time when the fewest number of whales are expected to be in the area (i.e., in early January or late March).

Minke Whale (*Balaenoptera acutorostrata*)

Minke whales have a cosmopolitan distribution at ice-free latitudes (Stewart and Leatherwood 1985), and also occur in some marginal ice areas. In at least some areas, minke whales migrate northward during spring and summer and can be seen in pelagic water at this time; however, they also occur in coastal areas (Stewart and Leatherwood 1985). Minke whales seem able to find and exploit small and transient concentrations of prey (including both fish and invertebrates) as well as the more stable concentrations that attract multi-species assemblages of large predators. Minke whales are relatively solitary, but can occur in aggregations of up to 100 animals when food resources are concentrated.

Caribbean

In the Caribbean, minke whales have been sighted in various nations, including the Bahamas, the Dominican Republic, Anguilla, Antigua, Guadeloupe, and perhaps in Venezuela (see Romero et al. 2001; Wardle et al. 2001). Their vocalizations have also been recorded near Puerto Rico (Mellinger et al. 2000). Although May-Collado (2006, in press) noted that minke whales could be encountered in the area, minke whales are not known to occur off the east coast of Costa Rica (Rodriguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006). Therefore, they are not expected to be encountered during the proposed Caribbean survey.

Pacific

Minke whales are likely to be rare in the Pacific part of the survey area. The general distribution of minke whales includes W Costa Rica (e.g., Reeves et al. 2002), and this species has been found there on occasion (Rodríguez-Herrera et al. 2002). Further, one probable minke was observed off west-central Panama during a survey in November–December 2004 (Holst et al. 2005a). However, no minke whales were found in the proposed project region over a 10-year period by Ferguson and Barlow (2001) during July–December surveys or by Jackson et al. (2004) during July–December surveys in 2003. Rasmussen et al. (2002) did not report seeing any minke whales in seven years of surveys (1996–2002) off Costa Rica or in 2001–2002 off Panama. May-Collado et al. (2005) also did not report any minkes based on compiled sightings off W Costa Rica from 1979–2001, nor have minkes been reported among compiled strandings off Costa Rica (Rodríguez-Fonseca and Cubero-Pardo 2001). Therefore, it seems unlikely that this species will be encountered during the Pacific portion of the proposed seismic survey.

Bryde's Whale (*Balaenoptera edeni*)

Bryde’s whale is found in tropical and subtropical waters throughout the world, but rarely in latitudes above 35º. It typically inhabits areas with high productivity, such as the Caribbean Sea (Reeves et al. 2002). Bryde’s whale does not undertake long migrations, although it may move closer to the equator in winter and toward temperate waters in the summer (Best 1975 *in* Cummings 1985). Debrot (1998) noted that this species is sedentary in the tropics.

Bryde's whale is pelagic as well as coastal, and occurs singly or in groups of up to five. Hoyt (1984) noted that group size varied with season; 55% were seen individually, 27% in pairs, and 18% in groups of three or more. Romero et al. (2001) noted that 78% of all sightings off Venezuela were of single animals.

Early limited studies suggested that Bryde's whales produce “moans” in the frequency range 70–930 Hz (reviewed by Thomson and Richardson 1995). Recent data from the ETP and elsewhere indicate that the predominant frequencies are in the lower part of this range, and down to about 20 Hz (Oleson et al. 2003; Heimlich et al. 2005).

Caribbean

The Bryde’s whale is the most common mysticete in the tropics (Debrot 1998). Bryde's whale has been sighted throughout much of the Caribbean Sea, including St. Croix, the Dominican Republic, Grenada, Curaçao, Aruba, Colombia, and Venezuela (see Romero et al. 2001; Wardle et al. 2001; Pardo et al. (2005). Although Romero et al. (2001) noted the occurrence of this species in the area year-round, it appears to be common in the area in summer and late fall (Debrot et al. 1998). To our knowledge, Bryde’s whales have not been reported off the Caribbean coast of Central America although they could occur there(e.g., Rodriguez-Fonseca 2001; Gamboa-Poveda and May-Collado 2006; May-Collado 2006. in press). Therefore, it is possible that some individuals could occur in the proposed seismic survey area.

The presence of Bryde's whales has been associated with the abundance of sardines (*Sardinella anchovia*) in Venezuela (Evans et al. 1979 *in* Romero et al. 2001). It has been suggested that the whales feed in the area for several months in the late spring and early summer, and then migrate south in the winter, although some individuals likely stay year-round (Evans et al. 1979 *in* Romero et al. 2001). Bryde's whales in the southern Netherlands Antilles are part of a Venezuelan stock, which is associated with areas of upwelling and biological productivity in the area; they are associated with tuna schools (Debrot 1998; Debrot et al. 1998).

Pacific

In the eastern Pacific, Bryde’s whales occur from Baja California to Chile (Clarke and Aguayo 1965 *in* Cummings 1985; Aguayo 1974; Gallardo et al. 1983). They are common throughout the ETP, with a concentration near the equator east of 110ºW, decreasing west of 140ºW (Lee 1993; Wade and Gerrodette 1993). Wade and Gerrodette (1993) estimated the Bryde’s whale population size in the ETP at 13,000, based on data collected from 1986–1990, with an encounter rate of 0.84 schools/1000 km. The abundance estimate for 2000 was 10,411 (Gerrodette and Forcada 2002). Gerrodette and Palacios (1996) reported an abundance of 289 Bryde’s whales for the EEZ of Costa Rica and 42 for the Central American coast north of Costa Rica. This species has also been sighted off Columbia and Ecuador (Gallardo et al. 1983), and may occur around the Galápagos Islands (Clarke and Aguayo 1965 *in* Gallardo et al. 1983). The International Whaling Commission (IWC) recognizes a cross-equatorial or Peruvian stock of Bryde's whales (Donovan 1991).

The Bryde’s whale is relatively common off W Costa Rica as compared with most other baleen whales (May-Collado et al. 2005). Over the year, it is the second-most abundant mysticete and is a common year-round resident off NW and SW Costa Rica in the EEZ (May-Collado et al. 2005). The density of this species in the proposed project area in July–December ranges from 0 to 0.0015/km^2 (Ferguson and Barlow 2001). Off W Costa Rica, May-Collado et al. (2005) reported at least 8 and possibly up to 24 sightings of at least 11 (possibly up to 43) Bryde’s whales in 1979–2000; these numbers are uncertain because it is now surmised that early reports of Bryde’s/sei whales in this region were most likely Bryde's whales. Both categories of sightings occurred from coastal to ocean waters off W Costa Rica, including the proposed survey area. Rasmussen et al. (2002) reported one sighting of a Bryde's whale in seven years of surveys (1996–2002) off Costa Rica and from 2001 to 2002 off Panama. Jackson et al. (2004) also encountered a Bryde's whale near the study area during July–December 2003 surveys. However, no Bryde's whales were detected off Costa Rica or Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). One Bryde's whale stranding on the central Pacific coast at Playa Bandera was reported during 1966–1999 (Rodríguez-Fonseca and Cubero-Pardo 2001).

Sei Whale (*Balaenoptera borealis*)

Sei whales have a cosmopolitan distribution, with a marked preference for temperate oceanic waters (Gambell 1985a). Sei whales are thought to migrate between summer feeding areas at high latitudes and wintering areas at low latitudes (Jonsgård 1966; Jonsgård and Darling 1977). A small number of individuals have been sighted in the Northeast Atlantic between October and December, indicating that some animals may remain at higher latitudes during winter (Evans 1992). Sei whales are pelagic, and generally are not found in coastal waters (Harwood and Wilson 2001).

Sei whale populations were depleted by whaling, and their current status is generally uncertain (Horwood 1987). The global population size is thought to be small; the sei whale is listed under the ESA as ***endangered***, and it is a CITES Appendix I species (Table 5).

Caribbean

The sei whale is considered rare in the Caribbean (Notarbartolo di Sciara 1983). Leatherwood and Reeves (1983) even doubted that sei whales occur in the Caribbean Sea. However, there have been several sightings in the Caribbean, including Venezuela (Mead 1977; see review by Romero et al. 2001; Wardle et al. 2001; also see NatureServe 2005). This species is an occasional visitor rather than a resident in this area (Romero et al. 2001). Because the Venezuelan coast is influenced by the South and North Equatorial currents, the animals that were sighted in this area were thought to have been migrating whales from the Southern Hemisphere stock sighted during the austral winter (Mitchell and Chapman 1977). We are not aware of any reports of this species off the east coast of Costa Rica or Nicaragua.

Pacific

The sei whale is unlikely to occur in the Pacific portion of the proposed project region based on its generally more temperate distribution and the paucity of confirmed sightings in the region. The sei whale has not been confirmed off W Costa Rica during 22 years of dedicated marine mammal surveys conducted there by the SWFSC (T. Gerrodette, pers. comm. 2003 *in* May-Collado et al. 2005). Although it is reported as having been documented off Costa Rica (Rodríguez-Herrera et al. 2002), the reliability of the identification is uncertain. Sei whales may have been sighted during surveys in the greater ETP (Wade and Gerrodette 1993; Kinzey et al. 1999, 2000, 2001); however, it is difficult to distinguish sei whales from Bryde's whales. Because sei whales generally have a more northerly and temperate distribution (Leatherwood et al. 1988), Wade and Gerrodette (1993) classified any tentative sei whale observations in the ETP as Bryde's whale sightings, as did May-Collado et al. (2005) for sightings off W Costa Rica. Sei whales may also have been sighted near the Galápagos Islands (Clarke 1962 *in* Gallardo et al. 1983), although Clarke and Aguayo (1965 *in* Gallardo et al. 1983) suggested that those sightings could have been Bryde's whales.

Neither Ferguson and Barlow (2001) nor Jackson et al. (2004) positively identified any sei whales in the proposed project area during surveys conducted during July–December. Similarly, none were detected off Costa Rica or Nicaragua during a seismic survey seismic cruise in November–December

2004 (Holst et al. 2005a). Similarly, Rasmussen et al. (2002) did not report them in seven years of surveys (1996–2002) off Costa Rica in 2001–2002 off Panama.

Fin Whale (*Balaenoptera physalus*)

Fin whales are widely distributed in all the world's oceans (Gambell 1985b), but typically occur in temperate and polar regions. Fin whales appear to have complex seasonal movements and are likely seasonal migrants (Gambell 1985b). Fin whales mate and calve in temperate waters during the winter, but migrate to higher latitudes during the summer to feed (Mackintosh 1965). Whales from the northern and southern populations do not occur near the equator at the same time, because the seasons are opposite (Gambell 1985b). The North Pacific population summers from the Chukchi Sea to California and winters from California southward (Gambell 1985b). If fin whales occurred in the Pacific part of the project area, they would probably be from the North Pacific population. Fin whales from the Southern Hemisphere are usually distributed south of 50ºS in the summer, and in the austral winter they migrate as far north as Peru (Gambell 1985b). The Chile–Peruvian stock of the Southern Hemisphere fin whale population winters west of North Chile and Peru from 110ºW to 60ºW (Gambell 1985b).

Fin whales occur in coastal and shelf waters, as well as in oceanic waters. Sergeant (1977) proposed that fin whales tend to follow steep slope contours, either because they detect them readily or because biological productivity is high along steep contours. Fin whales are typically observed alone or in pairs, but on feeding grounds up to 20 individuals can occur together (Gambell 1985b). They feed on euphausiids, copepods, squid, and small schooling fish. In the Northern Hemisphere, the peak breeding season is in December and January (Gambell 1985b).

The diving behavior of fin whales in the western North Atlantic was reviewed by Stone et al. (1992) with the objective of evaluating the likelihood of detection by aerial and shipboard surveys. Fin whales in their study area blew about 50 times per hour, and the average dive time was ~3 min. Because fin whales do not usually remain submerged for long periods, have tall blows and a conspicuous surfacing profile, and often occur in groups of several animals, they are less likely to be overlooked than most other species.

Probably at least in part because of their initially high abundance, wide distribution and diverse feeding habits, fin whales seem not to have been as badly depleted by commercial whaling as were the other large whales in the North Atlantic. However, this species is listed as ***endangered*** under the ESA and by IUCN, and it is a CITES Appendix I species (Table 5).

Caribbean

In the North Atlantic, fin whales are found in the summer from Baffin Bay, Spitsbergen, and the Barents Sea south to North Carolina and the coast of Portugal (Rice 1998). In the winter, they have been sighted from Newfoundland to the Gulf of Mexico and the Caribbean, and from the Faroes and Norway south to the Canary Islands (Rice 1998). There are few records for the Caribbean (see review by Romero et al. 2001; Wardle et al. 2001), however fin whales may occur off the east coast of Costa Rica (Rodríguez-Fonseca pers. comm.). A calf stranded at Playa Tortuguero in 1995 and subsequently died (Rodríguez-Fonseca and Cubero-Padro 2001).

Pacific

Fin whales are considered very rare off the Pacific coast of Costa Rica and in the proposed survey area. Despite >30 years of SWFSC and other surveys and stranding records in the region, there have been no confirmed records of fin whales (May-Collado et al. 2005). A possible sighting of a fin whale in this region occurred off the Osa Peninsula in 1997; however, the species was not confirmed (May-Collado et al. 2005). Rodríguez-Herrera et al. (2002) list the fin whale as having been documented off Costa Rica.

No confirmed fin whale sightings were made in the proposed study area during 10 years of survey effort in July–December by Ferguson and Barlow (2001) or by Jackson et al. (2004) during July-December surveys in 2003. Similarly, none were detected off Costa Rica or Nicaragua during a seismic cruise in November–December 2004 (Holst et al. 2005a). On the apparently rare occasion when a fin whale might occur in the project region during the proposed survey period, it would presumably be a winter-breeding individual from the North Pacific stock.

Blue Whale (*Balaenoptera musculus*)

The blue whale is widely distributed throughout the world's oceans and occurs in coastal, shelf, and oceanic waters. Its distribution, at least during times of the year when feeding is a major activity, is specific to areas that provide large seasonal concentrations of euphausiids (krill), which are the blue whale's main prey (Yochem and Leatherwood 1985). Blue whale density has also been associated with deep waters areas that have high levels of chlorophyll-*a* (Branch et al. 2006). Blue whales may move back and forth between feeding grounds to follow plankton fronts along the continental shelf (Evans 1980).

Blue whales usually occur alone or in small groups (Leatherwood and Reeves 1983). All populations of blue whales have been exploited commercially, and many have been severely depleted as a result. The blue whale is listed as ***endangered*** under the ESA and by IUCN, and is listed in CITES Appendix I (Table 5).

Caribbean

Although blue whales are globally distributed, their occurrence in the Caribbean is likely infrequent, and they are unlikely to be seen in the project area. Nonetheless, they are reported to occur in Colombian as well as Venezuelan waters (NatureServe 2005).

Pacific

Blue whales are occasionally sighted in pelagic waters off the western coast of the proposed project area, and they could potentially occur there during the proposed seismic survey period. The nearest historical blue whale sighting to the Costa Rican coast was ~150 km away based on sightings reported from research vessels (1976–1999, n = 327) and U.S. tuna boats (1971–1990, n = 191) in the NOAA/NMFS/SWFSC sightings database (from Fig. 14 of Fiedler 2002).

In the ETP, blue whales have been sighted along Baja California, near Costa Rica particularly the CRD, at and near the Galápagos Islands, and along the coasts of Ecuador and northern Peru (Aguayo 1974; Clarke 1980; Donovan 1984; Reilly and Thayer 1990; Mate et al. 1999; Palacios 1999; Palacios et al. 2005; Branch et al. 2006). They are known to occur in pelagic and coastal waters (Leatherwood and Reeves 1983; Yochem and Leatherwood 1985), and are most often found in cool, productive waters where upwelling occurs (Reilly and Thayer 1990). Palacios (1999) noted that blue whales were distributed to the west and southwest of the Galápagos Islands where the water is enriched. When hydrophones were set out to record whale calls in the ETP, some sounds were attributed to blue whales (Stafford et al. 1999a, 2005).

The timing of the migration of blue whales from the California stock to areas close to the CRD, centered at 9ºN, 90ºW, during the winter calving/breeding season suggests that they may feed in the latter area, as it is biologically productive (Mate et al. 1999). Whales have been sighted off the coast of Central

America, and especially in the CRD, throughout the year (Wade and Friedrichsen 1979; Reilly and Thayer 1990; Wade and Gerrodette 1993; Chandler and Calambokidis 2004). Similarly, Rodríguez-Fonseca (2001) identified the CRD as an important area for blue whales off Costa Rica. Year-round recordings of blue whale calls from 1996–2004 near the CRD indicate peaks in calls during the northern winter and spring months, with considerable interannual variability (Palacios et al. 2005). The authors suggest that observed seasonal declines in blue whale calls are linked to redistribution of this wintering population in response to expanding productive habitat.

Reilly and Thayer (1990) suggested that blue whales that occur in the CRD may be migrant animals from the northern or southern hemispheres or they may be a resident population. Reilly and Thayer (1990) also suggested that the whales seen along the equator are likely part of the southeast Pacific population, which occupies the coastal shelf of South America and the Antarctic (Mackintosh 1966). However, the whales could also be resident in the area, exploiting food resources in the CRD and near the South American coastline (Mate et al. 1999; Palacios 1999). Based on call similarities, Stafford et al. (1999b) linked the whales near the CRD to the population that feeds off California at the same time of year.

The blue whale population in the ETP in the summer/fall was estimated at 1415, with an encounter rate of 0.20 schools/1000 km (Wade and Gerrodette 1993). Gerrodette and Palacios (1996) reported an abundance of 48 blue whales for the EEZ of Costa Rica and 94 for the EEZs of the Central American countries north of Costa Rica. Sightings of blue whales in the ETP, including equatorial waters, may include the pygmy blue whale (Berzin 1978; Donovan 1984). Berzin (1978) noted that the distribution of the pygmy blue whale is much wider than previously thought; however, this subspecies is difficult to distinguish from the larger blue whale (Donovan 1984).

The density of blue whales in the proposed project area is low, with a maximum of 0.0005/km^2 in the proposed study area as observed during surveys in July–December (Ferguson and Barlow 2001). May-Collado et al. (2005) reported three groups of four blue whales off W Costa Rica based on compiled sightings from 1979–2001. Both sightings were in deep oceanic waters, one in the proposed seismic survey region off west-central Costa Rica. Jackson et al. (2004) also sighted at least one blue whale near the study area during surveys in July–December 2003. No blue whales were detected off Costa Rica or Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a).

(3) Sirenian

West Indian Manatee - Antillean Stock (*Trichechus manatus manatus*)

In Central America, the W Indian manatee occurs only on the east coast; it may occur inshore of some parts of the project area, but is unlikely to occur far enough offshore to be near the seismic ship. This species occurs in rivers, estuaries, lagoons, and coastal waters from the southeastern U.S. to Brazil. Lefebvre et al. (1989) indicated that W Indian manatees have a patchy coastal distribution that is dependent on suitable habitat, including vegetation and fresh water. In the northern Gulf of Mexico, Fertl et al. (2005) noted that manatees were most common in estuarine habitats and rare in open ocean. In a 5-year study in the coastal zone of Belize, Auil (2004) considered the nearshore systems of lagoon and rivers as primary manatee habitat. Auil (2004) also found that nearshore sites had higher probability of manatee observations than offshore sites, and manatees were more likely to be observed in the wet season (May to mid-November) compared to the dry season (November to April). Manatees swim slowly just below or at the surface of the water, and thus they are vulnerable to collisions with boats operating in shallow water. They feed on a variety of sea grasses and other vegetation.

The W Indian manatee is subdivided into two subspecies, the Florida manatee (*Trichechus manatus latirostris*) and the Antillean manatee (*T. m. manatus*). The Antillean stock of the W Indian manatee is listed under the ESA as ***endangered***, and is a CITES Appendix I species (Table 5). The manatee is the one species of marine mammal occurring in the area of concern that, in the U.S, is managed by the USFWS rather than NMFS.

The Antillean manatee occurs in the Greater Antilles, northern and eastern South America, as well as Central America and eastern Mexico (Lefebvre et al. 1989). The Antillean manatee was relatively common in Costa Rica until the 1950s, but is considered rare now (Reynolds et al. 1995). Fragmented populations of the manatee now exist over the manatee's once vast Caribbean–West Atlantic range (Smethurst and Nietschmann 1999). Jiménez (1999 *in* May-Collado 2006) noted two populations of manatees in Costa Rica: one on the northeastern coast (near Tortuguero) and one on the southeast coast close to Panama. Tortuguero, in the northeastern coastal plain of Costa Rica, harbors the largest, although small, concentration of manatees in the country, especially in Ca O Servulo, but even there the numbers are small (Reynolds et al. 1995). An aerial survey in July 1991 yielded 3 sightings: 1 manatee in Ca O Servulo and 2 just north of the mouth of the Rio Sixaola on the Panama border (Reynolds et al. 1995). From 1996 to 1998, Smethurst and Nietschmann (1999) made 29 sightings of manatees in Tortuguero and learned about 61 other sightings through interviews with residents and reports from the Area de Conservación Tortuguero.

Although excellent manatee habitat exists in Costa Rica, areas where manatees are most abundant lie adjacent to countries with more manatees (Reynolds et al. 1995). For example, Carr (1992 *in* Reynolds et al. 1995) observed 71 manatees in Nicaragua; similarly, Mou Sue et al. (1990 *in* Reynolds et al. 1995) found 42–72 manatees exist in Panama. The nearshore coastal region of Belize is home to the largest recorded number of Antillean manatees in the Caribbean (Morales-Vela et al. 2000; Auil 2004). Morales-Vela et al. (2000) conducted three aerial surveys in Belize and Chetumal Bay, Mexico, in January and May 1994 and January 1996, and total manatee counts were 266, 207, and 171, respectively. During a five year study in the coastal zone of Belize, Auil (2004) sighted 229 manatees in rivers in the dry seasons (winter months), and 49 manatees were sighted in the wet seasons (summer months).

(4) Pinnipeds

Pinnipeds are not expected to occur regularly in the proposed project regions. Subsequent to the extinction of the monk seal from the Caribbean, there has been no resident species of pinniped in that area. Vagrant hooded seals have also been sighted in the Caribbean (see Rice 1998; Mignucci-Giannoni and Odell 2001; Reeves et al. 2002), but any occurrence off the Caribbean coast of Central America would be extremely rare. This species will not be considered further.

Pinnipeds are also unlikely to be encountered during the Pacific portion of the seismic survey. Of the six species of pinnipeds found within the ETP, two are considered to have low potential to occur within the Pacific part of the survey area as rare vagrants: the California sea lion and the Galápagos sea lion (Table 5). These species have been documented occasionally off W Costa Rica; the California sea lion is the more likely to be seen off the W coast of the survey area. The remaining four pinniped species known from the ETP, the Guadalupe fur seal, South American fur seal, southern sea lion, and Galápagos fur seal, are not expected to occur in the study area. No pinnipeds were observed off Costa Rica/Nicaragua during a seismic survey in November–December 2004 (Holst et al. 2005a). Similarly, Jackson et al. (2004) did not encounter any pinnipeds in the proposed study area.

The normal southernmost range of the California sea lion is considerably north of the proposed survey area. However, the California sea lion has been documented off W Costa Rica on at least seven occasions including, from north to south, on the Nicoya and Osa peninsulas, in Golfo Dulce, and at Isla del Cocos (Acevedo 1994; Acevedo-Gutierrez 1996; Cubero-Pardo and Rodríguez 1999; Rodríguez-Herrera et al. 2002; May-Collado 2006, in press). The California sea lion is normally distributed from southern Mexico north to southwestern Canada and is considered as the subspecies *Z. c. californianus* (other subspecies are found on the Galápagos Islands and in Japan, although the latter is likely extinct). The breeding areas of the California sea lion are on islands located in southern California, western Baja California, and the Gulf of California. Although encounters with the species are possible in the proposed study area, it is unlikely that it would be seen there.

Galápagos sea lions occur on and near the Galápagos Islands. However, the Galápagos sea lion has been documented occasionally off W Costa Rica, including at Isla del Cocos (Acevedo-Gutierrez 1994; Rodríguez-Herrera et al. 2002). As there are no reports of that species along the Central American coast, its presence in the proposed survey area, although possible, is unlikely.

Sea Turtles

Of the world's seven species of sea turtles, six species are known to occur near the proposed study site in the Caribbean Sea (loggerhead, green, hawksbill, Kemp's ridley, olive ridley, and leatherback), while five species may be found in the proposed Pacific Ocean study area (loggerhead, green, hawksbill, olive ridley, and leatherback). These six species of sea turtles have special status under the ESA, CITES, and the IUCN Red List. The green, loggerhead, and olive ridley turtles are listed as ***threatened***, and the hawksbill, Kemp's ridley and leatherback are listed as ***endangered*** under the ESA (as is the population of green turtles in Florida and along the Pacific coast of Mexico, and the olive ridley turtle population on the Pacific coast of Mexico). The IUCN Red List classifies green, loggerhead, and olive ridley turtles as ***endangered***, and hawksbill, Kemp's ridley, and leatherback turtles as ***critically endangered***. All six species of turtles are on Appendix I of CITES.

Sea turtles share a common life cycle with slight variations between species (see Miller 1997). All species migrate between foraging areas and mating areas. Migration routes may exceed 2600 km, but most sea turtles travel <1000 km (Miller 1997). Females lay clutches of ~100 eggs in buried nests on beaches. Females may return to the beach to deposit up to 10 clutches in a season. Most species nest every two to four years. The eggs incubate for about two months, and then the hatchlings move into the sea where they begin their extended pelagic phase of development. Later, juveniles of most species enter the coastal zone or move into bays and estuaries, where they mature 10 to 50 years later.

Mature turtles spend most of their time at sea and generally only return to land to nest. Most species are widely distributed, but their habitat preferences vary. Some occur only in coastal areas or near islands, while others may occur in the open ocean. Given the wide-ranging nature of some sea turtles, there are substantial uncertainties about their migration routes and seasonal distributions of various age and sex classes of some populations.

The Pacific survey area is in water depths up to 4600 m and extends from ~190 km offshore almost to the shoreline. Several sea turtle nesting beaches occur on the Pacific coast close to the proposed near-shore transect, including beaches near the Nicoya and Osa Peninsulas in Costa Rica, as well as the Gulf of Papagayo. The Caribbean survey area extends from shore out to ~2700 m water depth, 143 km from shore. Sea turtle nesting beaches that are located close to the proposed survey lines on the Caribbean coast include those at Tortuguero National Park and Gandoca/Manzanilo in Costa Rica.

Costa Rica, Nicaragua, and the United States are all signatories of the Inter-American Convention for the Protection and Conservation of Sea Turtles, and all but Nicaragua have ratified the Convention.

The general descriptions of sea turtles below are mainly based on information from Márquez (1990) and United Nations Environment Program (UNEP) technical reports (Horrocks 1992; Sybesma 1992; Barmes et al. 1993; UNEP 1993; d'Auvergne and Eckert 1993).

Loggerhead turtle (*Caretta caretta*)

The loggerhead turtle is a widely distributed species occurring in coastal tropical and subtropical waters around the world. The global population is estimated at 43,320–44,560 nesting females (Spotila 2004). Loggerhead turtles (juveniles and adults) are suspected to take long migrations using warm water currents such as the Gulf Stream that bring them far from their breeding grounds. Loggerheads may be seen in the open seas during these migrations, and may actually remain in pelagic existence for many years (e.g., for up to 12 years in the North Atlantic Gyre). Loggerheads prefer to feed in coastal bays and estuaries, and in the shallow waters along the continental shelves of the Atlantic, Pacific, and Indian oceans. Adult loggerheads feed on a variety of benthic fauna like conchs, crabs, shrimp, sea urchins, sponges, and fish. During the migration through the open sea, they eat jellyfish, pteropods, floating mollusks, floating egg clusters, flying fish, and squid.

Major nesting areas are located in the southeastern U.S., Yucatán Peninsula of Mexico, Columbia, Cuba, South Africa, eastern Australia, and Japan (Márquez 1990; EuroTurtle 2006). During or shortly after the March to August breeding season, females disperse to distant feeding grounds via poorly delineated migration routes.

Western Caribbean Sea

The greatest concentration of loggerheads occurs in the Atlantic and the adjacent Caribbean Sea. While the largest nesting concentration of loggerheads in the world occurs in Florida, with more than 20,000 nesting females (Spotila 2004), additional concentrations occur in the Caribbean, with Mexico's Yucatán Peninsula and Quintana Roo particularly notable. Nesting beaches for loggerheads are also present in Costa Rica at Parismina, Tortuguero, and Gandoca/Manzanilo, and at Bocas del Toro in Panama, where nesting typically occurs from March to May. Spotila (2004) provided an estimate of just 60 nesting loggerhead females in the Caribbean and Gulf of Mexico. The proposed survey is expected to occur in this area at the beginning of the nesting season, in early March.

Pacific Coast of Central America

While the loggerhead turtle is found in eastern Pacific waters, nesting in the Pacific is largely restricted to Japan and eastern Australia (CCC 2003; Spotila 2004). The size structure of loggerheads in coastal and nearshore waters of the eastern and western Pacific suggest that Pacific loggerheads have a pelagic stage similar to that in the Atlantic (NMFS 2002); loggerheads spend the first 2–6 years of their lives at sea. Large aggregations (thousands) of mainly juveniles and subadult loggerheads are found off the southwestern coast of Baja California (Nichols et al. 2000). When mature, they return to breed at the western Pacific beaches where they were hatched.

L-DEO conducted a marine seismic program in the Eastern Tropical Pacific (ETP) off Costa Rica and Nicaragua during November–December 2004, and ~179 sea turtle sightings were reported. However, no loggerheads were confirmed (Holst et al. 2005a). Nesting loggerheads are not likely to be encountered in the Pacific study area, although non-breeding animals may occur there.

Olive ridley (*Lepidochelys olivacea*)

Olive ridley turtles are pantropical, occurring in waters with temperatures of at least 20ºC or 68ºF; they have a large range in the Pacific, Indian, and South Atlantic oceans. They travel between breeding and feeding grounds in continental coastal waters and are rare around oceanic islands. The worldwide population of olive ridley turtles is estimated at 2 million nesting females (Spotila 2004). As discussed in some detail below, olive ridleys are unlikely to be encountered in the Caribbean portion of the project. The Pacific portion of the project includes areas that are very important to this species. Although olive ridley turtles will be nesting in the area at the time of the survey, the project has been scheduled outside of the peak nesting season.

Most olive ridleys nest synchronously in huge colonies called "arribadas", with several thousand females nesting at the same time; others nest alone, out of sequence with the arribada (Kalb and Owens 1994). The arribadas usually last from three to seven nights (Aprill 1994). Satellite telemetry of nesting cohorts (small groups of females that arrive at the nesting beach at the same time) indicates that an arribada is not a social event, but rather an aggregation of turtles reacting in a similar way to as-yet-unknown common stimuli (Plotkin et al. 1991). Most females lay two clutches of eggs with an internesting period of 1–2 months (Plotkin et al. 1994b). Radio-tracking studies have shown that females that nested in arribadas remain within 5 km of the beach most of the time during the inter-nesting period (Kalb and Owens 1994).

Reasons for the timing of, and even the occurrence of, arribadas are not clear. Chaves et al. (1994) reported that arribadas follow a lunar cycle, with nesting during the new moon, in the darkest nights, starting during the high tide. At Playa La Flor, Nicaragua, during August 1993–January 1994, six arribadas occurred, arriving every 23–30 days without relation to the moon phase (Ruiz 1994). During the same period, turtles emerged during the day and night in September and October, but only at night in the other months (Cerna et al. 1996). In some cases, an arribada will skip a month. In a study of inter-nesting behavior at Nancite, Costa Rica, in 1990 and 1991, Plotkin et al. (1995) noted that there were arribadas in September and November, but not in October, contrary to expectations. In 1991, there were arribadas in each month from September to December. Hatching success of olive ridley nests in arribada beaches is low. Especially when the arribadas are large, many of the eggs are destroyed by the turtles themselves (Alvarado 1990).

Although most mating is generally assumed to occur near nesting beaches, Pitman (1990) observed olive ridleys mating at sea, as far as 1850 km from the nearest mainland, during every month of the year except March and December. However, there was a sharp peak in offshore mating activity during August and September, corresponding with peak breeding activity in mainland populations. Turtles observed during NMFS/SWFC dolphin surveys during July–December 1998 and 1999 were captured; 50 of 324 were involved in mating (Kopitsky et al. 2002). Aggregations of turtles[1], sometimes >100 individuals, have been observed as far offshore as 120°W, ~3000 km from shore (Arenas and Hall 1991).

Outside of the breeding season, the turtles disperse, but little is known of their behavior. Neither males nor females migrate to one specific foraging area, but exhibit a nomadic movement pattern and occupy a series of feeding areas in oceanic waters (Plotkin et al. 1994a,b). Typically, turtles will feed during the morning and bask on the water's surface in the afternoon. Olive ridleys are primarily carnivorous, feeding on crabs, jellyfish, and fish eggs. They feed on algae if no other food is available. They are generally thought to be surface feeders, but have been caught in trawls at depths of 80–110 m (NMFS and USFWS 1998).

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[1] Of sea turtles observed at sea, 75% were olive ridleys.

Western Caribbean Sea

While olive ridley turtles do occur in the Atlantic Ocean and along the Atlantic coast of South America [including nesting sites on the north coast of Venezuela (Sternberg 1981) and Surinam (EuroTurtle 2006)], they do not typically penetrate into the western Caribbean. Therefore, olive ridley turtles are unlikely to be encountered during the Caribbean component of the proposed survey.

Pacific Coast of Central America

The Pacific population migrates from their nesting grounds in Mexico and Central America to the North Pacific (NMFS 2002). The post-nesting migration routes of olive ridleys tracked via satellite from Costa Rica traversed thousands of kilometers of deep oceanic waters ranging from Mexico to Peru, and more than 3000 km out into the central Pacific (Plotkin et al. 1994a). The olive ridley is considered the most abundant sea turtle in the open ocean waters of the ETP (Pitman 1990).

Several large nesting sites are located on Costa Rica's Pacific coast with a total of ~60 nesting beaches identified. Two of the most important Pacific beaches are located on the Nicoya Peninsula: Playa Nancite at Santa Rosa National Park and Playa Ostional (EuroTurtle 2006). Playa Ostional and Playa Nancite are considered the two most important nesting beaches for olive ridleys in the world; 500,000 turtles occur at Playa Ostional and up to 100,000 may be found at Playa Nancite each year (Spotila 2004). Nesting occurs from May to December at Nancite and year round at Ostional, although the biggest arribadas (~120,000 turtles) occur during the rainy season, May–October (Chaves et al. 1994).

In Nicaragua, two major nesting sites exist: Chacocente and La Flor National Wildlife Refuges, where some 2000–5000 and 10,000–20,000 olive ridley turtles nest, respectively, beginning in July and ending in January (Spotila 2004). During August 1993–January 1994 at Playa La Flor, six arribadas occurred, arriving every 23–30 days (Ruiz 1994). They were 2–4 days in length, with turtle numbers ranging from 1393 to 8886 per arribada. The highest numbers occurred in early October (8886), early November (6400), and late November (5189). In late December, 1650 turtles nested, and none came in January. In 1994, the largest arribadas took place in August and September (Cerna et al. 1996). Other nesting sites in Nicaragua (Masachapa and Pochomil) are considered to no longer be active (Spotila 2004).

In Honduras, to the north of the survey area, olive ridleys nest on many islands in the Gulf of Fonseca and on the mainland from the border with Nicaragua to Punta Novillo, located on the west side of Isla Zacate Grande. Over half of the nesting occurs at three mainland sites: Punta Raton, Cedeño, and El Carretal (C. Lagueux, Univ. Florida, pers. comm. *in* NMFS and USFWS 1998). Cornelius (1982) cited an estimate of 3000 nesting females for all of Pacific Honduras and reported that the population was declining. In 1987, olive ridleys laid an estimated 2000 clutches in Pacific Honduras, i.e. ~1000 nesting females (C. Lagueux, pers. comm. *in* NMFS and USFWS 1998).

Females and males begin to aggregate in reproductive patches (RP) near their nesting beaches two months before the nesting season, and most mating is generally assumed to occur near the nesting beaches (NMFS 2002). Off Playa Nancite, Costa Rica (close to the border with Nicaragua), they either copulate en route to the beach or in shallow water (<200 m or 656 ft deep) off the beach (Plotkin et al. 1994b). A detailed study of the RP off Playa Nancite during July–September 1991 and 1992 showed that the RP comprises mature reproductive males and females engaged in courtship, mating, or waiting for the next period of synchronous nesting. Females move in and out of the RP but always return. The RP is usually in water 12–40 m deep and within 3 km of Playa Nancite (Kalb et al. 1995). Eggs hatch 45–51 days after laying.

Solitary nesting also occurs, but numbers are much lower than in arribadas, and there are other differences in behavior. Mehta et al. (2000) studied solitary nesting at Ostional from July to December 1998. Peak nesting activity occurred in August (~2600 nests) and October (~3500), with a decrease in September (~1000). Radio-tracking studies showed that females that nest solitarily have a shorter inter-nesting period (~2 weeks) than do arribada females, and solitary nesters are less likely to stay near Nancite during the internesting period than are arribada females (Kalb and Owens 1994).

During the November–December 2004 L-DEO marine seismic program conducted in the ETP (Holst et al. 2005a), ~179 sea turtles were observed and 84 turtles were positively identified as olive ridley turtles, the greatest number for any observed species during the cruise. Nesting olive ridley turtles will also be in the study area during the proposed survey.

Green sea turtle (*Chelonia mydas*)

Green sea turtles are widely distributed in tropical and subtropical waters near continental coasts and around islands. Some authorities treat the black turtle (*Chelonia agassizii*) as a separate species, but most now recognize the black turtle as a subspecies of green turtle. Green turtles are known to swim and feed in the coastal waters of at least 140 countries (Spotila 2004) and nest in ~80 of those. Large nesting colonies are found in Costa Rica, among many other widespread locations (Spotila 2004). Green turtles typically show nest site fidelity and nest in the same spot as their last clutch, or at the same beach from which they hatched. Hatchlings are epipelagic (surface dwelling in the open sea) for ~1–3 years. They live in bays and along protected shorelines, and feed during the day on seagrass and algae (Bjorndal 1982). Juvenile and sub-adult green turtles may travel thousands of kilometers before they return to breeding and nesting grounds (Carr et al. 1978). Green sea turtles typically migrate along coastal routes from rookeries to feeding grounds, although some populations conduct trans-oceanic migrations (e.g., Ascension Island to Brazil). The worldwide green sea turtle population is estimated at 88,520 nesting females (Spotila 2004).

Western Caribbean Sea

The largest nesting site for green turtles in the Western Hemisphere is at Tortuguero, Costa Rica, with an estimated 22,500 nesting females (Spotila 2004). Other minor nesting sites occur in the area, including Costa Rica's Gandoca-Manzanillo Wildlife Refuge, and Barra de Matina, north of Limón (CCC 2003). Meylan et al. (1991) reported that more than 70 green turtles captured at Bocas del Toro, Panama, had been tagged in Tortuguero. Many of the captured animals were mated pairs, suggesting that Bocas del Toro was an important point on the migration route of Tortuguero-bound turtles (Meylan et al. 1991; Meylan and Meylan 1994); Panama is also believed to provide important developmental habitat and adult foraging range (Taft and Carranza 2000). The largest green turtle foraging area is believed to be off the east coast of Nicaragua (Lagueux 1998).

The season of peak breeding in the Caribbean generally occurs from April to October (EuroTurtle 2006), with a peak in August. Therefore, nesting green turtles are not expected to be encountered during the survey. Nonetheless, adult green turtles are present in these areas year-round.

Pacific Coast of Central America

In the eastern Pacific, the primary nesting grounds are located in Michoacán, Mexico, with an estimated 850 nesting females, and the Galápagos Islands, Ecuador, with an estimated 1400 nesting females (Spotila 2004). Nesting occurs in Michoacán between August and January, with a peak in October–November, and on the Galápagos Islands between December and May with a peak in February (Alvarado and Figueroa 1995). In Central America, small numbers of green turtles nest at major nesting sites of other species, primarily olive ridleys, in Nicaragua at La Flor National Wildlife Refuge (Ocean Resources Foundation 1998), and in Costa Rica at Playa Ostional, Playa Naranjo (NMFS and USFWS 1997), Playa Nancite, and Rio Oro on the Osa Peninsula (Govan 1998). Nesting of green turtles at Rio Oro peaks between November and December (Govan 1998). Green turtles also nest in very small numbers in El Salvador (Hasbún and Vásquez 1999).

Adult green turtles may be present in the region year-round, and small numbers are caught accidentally during longline fishing and shrimp trawling (e.g., Seguara and Arauz 1995; Arauz et al. 1998). In Pacific waters of Costa Rica, Segura and Arauz (1995) reported that 2 of 31 turtles caught as bycatch during October 1991-February 1992 were green turtles, and Arauz et al. (1998) noted that 9.6% of 281 turtles caught during an observer program on shrimp trawlers were green turtles. During observations made during a marine seismic survey in the ETP in 2004 (Holst et al. 2005a), two sea turtles were tentatively identified as green turtles out of ~179 turtle sightings. The proposed survey may overlap with the presence of some nesting green turtles in Pacific Costa Rican waters.

Hawksbill sea turtle (*Eretmochelys imbricata*)

Hawksbill turtles are the most tropical of all sea turtles, but have been known to occur as far north as Cape Cod, U.S. They occur in the waters of at least 82 nations and nest on the beaches of ~ 60 of those (Spotila 2004). The hawksbill is a solitary nester, and population trends or estimates are difficult to determine. However, a minimum of 20,000–26,000 females are thought to nest annually (Spotila 2004); since females nest once every three years, the total adult female population is estimated at 60,000–78,000 females (Spotila 2004).

Nesting is confined to areas where water temperature is 25º–35ºC (77º–95ºC) and occurs in the spring and summer. Hawksbill turtles nest on low and high-energy beaches, often sharing high-energy locations with green turtles. Hawksbill turtles most commonly perform short-distance movements between nesting beaches and offshore feeding banks, although long-distance movements are also known. Posthatchlings are believed to be pelagic, taking shelter in weed lines around convergence zones, and they re-enter coastal waters once attaining a length of ~20–25 cm (8–10 in).

Hawksbill turtles are observed in shallow waters with seagrass or algal meadows, and are most common where reef formations are present. They live in clear, littoral waters of mainland and island shelves. Hawksbill turtles feed on a variety of prey, including corals, tunicates, algae, and sponges.

Western Caribbean Sea

The most important nesting beaches for hawksbill turtles in the North Atlantic are along the Yucatán Peninsula, southern Cuba, and a few Caribbean islands (EuroTurtle 2006). A total of 5000–6000 females nest in the region, with 40–50 of those in Belize and 2–800 in Mexico (Spotila 2004). Minor nesting sites for hawksbill turtles include Tortuguero (mean of 7.82 nests/season between 1972–2000), Parismina, Gandoca-Manzanillo Wildlife Refuge (38 nests in 1998 and an average of 5.5 nests per season between 1994–2000), Barra de Matina in Costa Rica, and Pearl Cays in Nicaragua (Chacón 2000, 2003; Chacón and Quiros 2003; WCS 2004). Nesting may occur year-round although it peaks between June and August. Troëng et al. (2001) found that the species may show a nesting pattern with two reproductive peaks—the first in May to late July and the second in October. Campbell et al. (2000) and Lagueux et al. (2003) report that the extensive continental shelf on the Caribbean coast of Nicaragua provides nesting, foraging, and developmental habitat for all life stages of hawksbill turtles. During the proposed survey, small numbers of breeding hawksbill turtles may be encountered in the Caribbean study area.

Pacific Coast of Central America

No major nesting sites for hawksbill turtles occur on the Pacific coast of Central America (EuroTurtle 2006), although a few hawksbills are known to nest at the La Flor National Wildlife Refuge in Nicaragua (Ocean Resource Foundation 1998) and at Punta Banco, Caña Blanca, and Playa Caletas in Costa Rica (Gaos et al. 2006). Hawksbill turtles also reportedly nested at Barra de Santiago in El Salvador three decades ago, but today only occur there sporadically (Hasbún and Vásquez 1999). Chiriqui Beach in western Panama was once famous for its huge nesting colony of hawksbill turtles (Spotila 2004), but was essentially abandoned by 1990 due to overharvesting. Efforts to restore the beach have progressed and in recent years several hundred nests have been observed (Spotila 2004). The nesting season of the hawksbill turtle is approximately six months in duration; nesting generally occurs from June to December, preceded by courtship and mating.

During observations made during a marine seismic survey in the ETP in 2004 (Holst et al. 2005a), none of the ~179 turtle sightings were identified as hawksbill turtles. Nesting hawksbill turtles are not expected to be encountered during the proposed survey in the Pacific study area.

Kemp's ridley turtle (*Lepidochelys kempii*)

Kemp's ridley turtles have a more restricted distribution than most other sea turtles. Adult Kemp's ridley turtles usually only occur in the Gulf of Mexico, but juveniles and immature individuals range between the tropics and temperate coastal areas of the NW Atlantic, as far as New England. Occasionally individuals may be carried by the Gulf Stream as far as northern Europe, although those individuals are considered lost to the breeding population. Adult Kemp's ridley turtles migrate along the coast between nesting beaches and feeding areas. They feed on crabs, shrimp, gastropods, clams, urchins, jellyfish, squid eggs, and fish. Kemp's ridley turtles nest only along the Mexican Gulf Coast, with nesting concentrated at Rancho Nuevo (Spotila 2004). The total population of adult females in the Gulf of Mexico is estimated at about 5000 (Spotila 2004). Adult female Kemp's ridley turtles rarely leave the Gulf of Mexico, and adult male turtles remain near the nesting beaches all year (Spotila 2004). Therefore, encounters in the western Caribbean can be considered rare and unlikely during the proposed survey. Kemp's ridley turtles do not occur off the Pacific coast of Central America.

Leatherback turtle (*Dermochelys coriacea*)

Leatherback turtles are the most widely distributed sea turtles and range far from their tropical and subtropical breeding grounds. Leatherbacks are highly pelagic and approach coastal waters only during the reproductive season (EuroTurtle 2006). They appear to migrate along bathymetric contours ranging from depths of 200–3500 m. There is evidence that leatherbacks are associated with oceanic front systems, such as shelf breaks and the edges of oceanic gyre systems where their prey is concentrated (Lutcavage 1996). Leatherbacks feed mainly on jellyfish, tunicates, and other epipelagic soft-bodied invertebrates (Hartog and van Nierop 1984; Davenport and Balazs 1991). This species is one of the deepest divers in the ocean, with dives deeper than 1000 m (Eckert et al. 1988). Leatherbacks dive continually and spend only short periods of time at the surface (Eckert et al. 1986; Southwood et al. 1998). Hatchling leatherbacks are also pelagic, but nothing is known about their distribution for the first four years (Musick and Limpus 1997). The global female leatherback turtle population is estimated at 35,860 (Spotila 2004).

Western Caribbean Sea

Leatherbacks occur in the Caribbean only during the mating and nesting period from March to July; outside of the breeding season leatherbacks feed in the open ocean. During the breeding season, the Caribbean coast of Costa Rica receives ~400 nesting females at Tortuguero/Limón and 300 at Gandoca/

Manzanillo (Spotila 2004). Chacón (2000) reported that 599 leatherbacks nest at Gandoca from February to September 1998, and that they represented the most abundant species on the beach. Panama's Bocas del Toro is estimated to be home to ~200 nesting females (Spotila 2004). Small numbers of leatherback turtles may be encountered in the proposed study area during the time of the survey.

Pacific Coast of Central America

In the Pacific, leatherbacks nest along the west coast of Mexico and Central America from September to March. Females may lay up to nine clutches in a season (although six is more common), and the incubation period is 58–65 days. At Playa Grande, Costa Rica, and in French Guiana, the mean internesting period is 9 days (Lux et al. 2003). Recent estimates of the number of nesting females in the eastern Pacific population are 1600–1700 (NMFS 2002).

In Costa Rica, leatherbacks nest at Playa Naranjo in Santa Rosa National Park, Rio Oro on the Osa Peninsula, and at various beaches in Las Baulas National Park including Playa Langosta and Playa Grande (see EuroTurtle 2006). At Playa Naranjo, track counts were 312–1212 during several months of the nesting season in 1983–84, 1989–90, and 1990–91 (Araúz-Almengor and Morera-Avila 1994). Playa Grande is the fourth-largest leatherback nesting colony in the world (NMFS 2002). However, the number of leatherback turtles nesting in Las Baulas National Park has been declining steadily. During the 1988–89 nesting season, ~1500 females nested; that had declined to ~800 in 1990–91 and 1991–92, and to 193 in 1993–94 (Williams et al. 1996). Only 117 turtles nested in 1998–99 (Spotila 2000 *in* NMFS 2002). Spotila (2004) reports that between 59 and 435 leatherbacks nest at Las Baulas each year depending on the El Nino–La Nina cycle; this site is reportedly the largest nesting colony of leatherbacks in the East Pacific.

Leatherbacks also nest in Nicaragua, Panama, El Salvador, and Guatamala. In Guatemala, leatherbacks nest in limited numbers (2–3 nests per night from November to December), although most of the eggs are collected by local residents (NMFS 2002). Nesting occurs in El Salvador sporadically in the dry months between November and February (Hasbún and Vásquez 1999). During an aerial survey in January–February 1999, Sarti et al. (2000) recorded 4, 0, 61, and 11 nestings in El Salvador, Honduras, Nicaragua, and Costa Rica, respectively. (The most important nesting beaches in Costa Rica, Playa Grande and Playa Langosta, were not surveyed.)

During a marine seismic survey in the ETP, November–December 2004, only one of the ~179 turtle sightings was identified as a leatherback turtle (Holst et al. 2005a). Small numbers of nesting leatherbacks may occur in the area during the time of the survey.

IV. ENVIRONMENTAL CONSEQUENCES

Proposed Action

(1) Direct Effects on Marine Mammals and Sea Turtles and Their Significance

The material in this section includes a summary of the anticipated effects (or lack thereof) on marine mammals and sea turtles of the airgun source to be used by L-DEO. A more detailed general review of airgun effects on marine mammals appears in Appendix C. That Appendix is similar to corresponding parts of previous EAs and associated IHA applications concerning other L-DEO seismic surveys since 2003, but was updated in 2007. Appendix D contains a general review of seismic noise and sea turtles. This section also includes a discussion of the potential impacts of operations by L-DEO's MBES and SBP.

Finally, this section includes estimates of the numbers of marine mammals that might be affected by the proposed activity during the Central American SubFac seismic survey scheduled to occur from January to March 2008. A description of the rationale for L-DEO's estimates of the potential numbers of harassment "takes" during the planned seismic program is also provided.

(a) Summary of Potential Effects of Airgun Sounds

The effects of sounds from airguns might include one or more of the following: tolerance, masking of natural sounds, behavioral disturbance, and at least in theory, temporary or permanent hearing impairment, or non-auditory physical or physiological effects (Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007). However, it is unlikely that there would be any cases of temporary or especially permanent hearing impairment, or any significant non-auditory physical or physiological effects. Also, behavioral disturbance is expected to be limited to relatively short distances.

Tolerance

Numerous studies have shown that pulsed sounds from airguns are often readily detectable in the water at distances of many kilometers. For a summary of the characteristics of airgun pulses, see Appendices A and C (c). Several studies have shown that marine mammals at distances more than a few kilometers from operating seismic vessels often show no apparent response—see Appendix C (e). That is often true even in cases when the pulsed sounds must be readily audible to the animals based on measured received levels and the hearing sensitivity of that mammal group. Although various baleen whales, toothed whales, and (less frequently) pinnipeds have been shown to react behaviorally to airgun pulses under some conditions, at other times mammals of all three types have shown no overt reactions. In general, pinnipeds and small odontocetes seem to be more tolerant of exposure to airgun pulses than are baleen whales.

Masking

Masking effects of pulsed sounds (even from large arrays of airguns) on marine mammal calls and other natural sounds are expected to be limited, although there are very few specific data of relevance. Some whales are known to continue calling in the presence of seismic pulses. The airgun sounds are pulsed, with quiet periods between the pulses, and whale calls often can be heard between the seismic pulses (e.g., Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999; Nieukirk et al. 2004; Smultea et al. 2004). Although there has been one report that sperm whales cease calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994), a more recent study reports that sperm whales off northern Norway continued calling in the presence of seismic pulses (Madsen et al. 2002). That has also been shown during recent work in the Gulf of Mexico and Caribbean Sea (Smultea et al. 2004; Tyack et al. 2006). Masking effects of seismic pulses are expected to be negligible in the case of the smaller odontocete cetaceans, given the intermittent nature of seismic pulses. Dolphins and porpoises commonly are heard calling while airguns are operating (e.g., Gordon et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b). Also, the sounds important to small odontocetes are predominantly at much higher frequencies than are airgun sounds. Masking effects, in general, are discussed further in Appendix C (d).

Disturbance Reactions

Disturbance includes a variety of effects, including subtle changes in behavior, more conspicuous changes in activities, and displacement. Based on NMFS (2001, p. 9293) and NRC (2005), we assume that simple exposure to sound, or brief reactions that do not disrupt behavioral patterns in a potentially significant manner, do not constitute harassment or "taking". By potentially significant, we mean "in a manner that might have deleterious effects to the well-being of individual marine mammals or their populations".

Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors. If a marine mammal does react briefly to an underwater sound by changing its behavior or moving a small distance, the impacts of the change are unlikely to be significant to the individual, let alone the stock or the species as a whole. However, if a sound source displaces marine mammals from an important feeding or breeding area for a prolonged period, impacts on the animals could be significant. Given the many uncertainties in predicting the quantity and types of impacts of noise on marine mammals, it is common practice to estimate how many mammals were present within a particular distance of industrial activities, or exposed to a particular level of industrial sound. That likely overestimates the numbers of marine mammals that are affected in some biologically-important manner.

The sound criteria used to estimate how many marine mammals might be disturbed to some biologically-important degree by a seismic program are based on behavioral observations during studies of several species. However, information is lacking for many species. Detailed studies have been done on humpback, gray, bowhead, and sperm whales, and on ringed seals. Less detailed data are available for some other species of baleen whales, sperm whales, small toothed whales, and sea otters.

Baleen Whales.—Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable. Whales are often reported to show no overt reactions to pulses from large arrays of airguns at distances beyond a few kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, as reviewed in Appendix C (e), baleen whales exposed to strong noise pulses from airguns often react by deviating from their normal migration route and/or interrupting their feeding and moving away. In the case of migrating gray and bowhead whales, the observed changes in behavior appeared to be of little or no biological consequence to the animals. They simply avoided the sound source by displacing their migration route to varying degrees, but within the natural boundaries of the migration corridors.

Studies of gray, bowhead, and humpback whales have determined that received levels of pulses in the 160–170 dB re 1 μPa_{rms} range seem to cause obvious avoidance behavior in a substantial fraction of the animals exposed. In many areas, seismic pulses from large arrays of airguns diminish to those levels at distances ranging from 4.5–14.5 km from the source. A substantial proportion of the baleen whales within those distances may show avoidance or other strong disturbance reactions to the airgun array. Subtle behavioral changes sometimes become evident at somewhat lower received levels, and studies summarized in Appendix C (e) have shown that some species of baleen whales, notably bowhead and humpback whales, at times show strong avoidance at received levels lower than 160–170 dB re 1 μPa_{rms}.

Responses of *humpback whales* to seismic surveys have been studied during migration and on the summer feeding grounds, and there has also been discussion of effects on the Brazilian wintering grounds. McCauley et al. (1998, 2000a) studied the responses of humpback whales off Western Australia to a full-scale seismic survey with a 16-airgun, 2678-in^3 array, and to a single 20-in^3 airgun with source level 227 dB re 1 $\mu Pa{\cdot}m_{p\text{–}p}$. McCauley et al. (1998) documented that avoidance reactions began at 5–8 km from the array, and that those reactions kept most pods about 3–4 km from the operating seismic boat. McCauley et al. (2000a) noted localized displacement during migration of 4–5 km by traveling pods and 7–12 km by cow-calve pairs. Avoidance distances with respect to the single airgun were smaller but consistent with the results from the full array in terms of the received sound levels. Mean avoidance distance from the airgun corresponded to a received sound level of 140 dB re 1 µPa_{rms}; this was the level at which humpbacks started to show avoidance reactions to an approaching airgun. The standoff range, i.e., the closest point of approach (CPA) of the whales to the airgun, corresponded to a received level of 143 dB 1 µPa_{rms}. The initial avoidance response generally occurred at distances of 5–8 km from the airgun array and 2 km from the single airgun. However, some individual humpback whales, especially males, approached within distances 100–400 m, where the maximum received level was 179 dB re 1 µPa_{rms}.

Humpback whales on their summer feeding grounds in southeast Alaska did not exhibit persistent avoidance when exposed to seismic pulses from a 1.64-L (100 in^3) airgun (Malme et al. 1985). Some humpbacks seemed "startled" at received levels of 150–169 dB re 1 µPa. Malme et al. (1985) concluded that there was no clear evidence of avoidance, despite the possibility of subtle effects, at received levels up to 172 re 1 µPa on an approximate rms basis.

It has been suggested that South Atlantic humpback whales wintering off Brazil may be displaced or even strand upon exposure to seismic surveys (Engel et al. 2004). The evidence for this was circumstantial, subject to alternative explanations (IAGC 2004), and not consistent with results from direct studies of humpbacks exposed to seismic surveys in other areas and seasons. After allowance for data from subsequent years, there was "no observable direct correlation" between strandings and seismic surveys (IWC 2007d).

Results from *bowhead whales* show that responsiveness of baleen whales to seismic surveys can be quite variable depending on the activity (migrating vs. feeding) of the whales. Bowhead whales migrating west across the Alaskan Beaufort Sea in autumn, in particular, are unusually responsive, with substantial avoidance occurring out to distances of 20–30 km from a medium-sized airgun source, where received sound levels were on the order of 130 dB re 1 µPa_{rms} [Miller et al. 1999; Richardson et al. 1999; see Appendix C (e)]. However, more recent research on bowhead whales (Miller et al. 2005a) corroborates earlier evidence that, during the summer feeding season, bowheads are not as sensitive to seismic sources. In summer, bowheads typically begin to show avoidance reactions at a received level of about 160–170 dB re 1 µPa_{rms} (Richardson et al. 1986; Ljungblad et al. 1988; Miller et al. 1999). There are no data on reactions of wintering bowhead whales to seismic surveys.

Reactions of migrating and feeding (but not wintering) *gray whales* to seismic surveys have been studied. Malme et al. (1986, 1988) studied the responses of feeding Eastern Pacific gray whales to pulses from a single 100-in^3 airgun off St. Lawrence Island in the northern Bering Sea. They estimated, based on small sample sizes, that 50% of feeding gray whales ceased feeding at an average received pressure level of 173 dB re 1 µPa on an (approximate) rms basis, and that 10% of feeding whales interrupted feeding at received levels of 163 dB. Those findings were generally consistent with the results of experiments conducted on larger numbers of gray whales that were migrating along the California coast, and on observations of Western Pacific gray whales feeding off Sakhalin Island, Russia (Johnson et al. 2007).

We are not aware of any information on reactions of *Bryde's whales* to seismic surveys. However, other species of *Balaenoptera* (blue, sei, fin, and minke whales) have occasionally been reported in areas ensonified by airgun pulses. Sightings by observers on seismic vessels off the United Kingdom from 1997–2000 suggest that, at times of good sightability, numbers of rorquals seen are similar when airguns are shooting and not shooting (Stone 2003). Although individual species did not show any significant displacement in relation to seismic activity, all baleen whales combined were found to remain significantly further from the airguns during shooting compared with periods without shooting (Stone 2003). In a study off Nova Scotia, Moulton and Miller (in press) found little or no difference in sighting rates and initial sighting distances of balaenopterid whales when airguns were operating vs. silent. However, there were indications that these whales were more likely to be moving away when seen during airgun operations.

Data on short-term reactions (or lack of reactions) of cetaceans to impulsive noises do not necessarily provide information about long-term effects. It is not known whether impulsive noises affect reproductive rate or distribution and habitat use in subsequent days or years. However, gray whales continued to migrate annually along the west coast of North America despite intermittent seismic exploration and much ship traffic in that area for decades (Appendix A *in* Malme et al. 1984). The Western Pacific gray whale population did not seem affected by a seismic survey in its feeding ground during a prior year (Johnson et al. 2007). Bowhead whales continued to travel to the eastern Beaufort Sea each summer despite seismic exploration in their summer and autumn range for many years (Richardson et al. 1987). Populations of both gray and bowhead whales grew substantially during this time. In any event, the brief exposures to sound pulses from the proposed airgun source are highly unlikely to result in prolonged effects.

Toothed Whales.—Little systematic information is available about reactions of toothed whales to noise pulses. With the exception of sperm whales, few studies similar to the more extensive baleen whale/seismic pulse work summarized above and (in more detail) in Appendix C have been reported for toothed whales. Controlled exposure experiments on sperm whales took taken place in the Gulf of Mexico in 2002 and 2003 (see Miller et al. 2006; Tyack et al. 2006), and there is an increasing amount of information about responses of various odontocetes to seismic surveys based on monitoring studies (e.g., Stone 2003; Smultea et al. 2004; Bain and Williams 2006; Holst et al. 2006; Moulton and Miller in press).

Seismic operators and marine mammal observers sometimes see dolphins and other small toothed whales near operating airgun arrays, but there is a tendency for most delphinids to show limited avoidance of seismic vessels operating large airgun systems. Some dolphins and porpoises seem to be attracted to the seismic vessel and floats, and some ride the bow wave of the seismic vessel even when large arrays of airguns are firing. Nonetheless, small toothed whales sometimes move away, or maintain a somewhat greater distance from the vessel, when a large array of airguns is operating than when it is silent (e.g., Goold 1996a,b,c; Calambokidis and Osmek 1998; Stone 2003). In most cases the avoidance radii for delphinids appear to be small, on the order of 1 km or less. The beluga may be a species that (at least at times) shows long-distance avoidance of seismic vessels. Aerial surveys during seismic operations in the southeastern Beaufort Sea recorded much lower sighting rates of beluga whales within 10–20 km of an active seismic vessel. These results were consistent with the low number of beluga sightings reported by observers aboard the seismic vessel, suggesting that some belugas might be avoiding the seismic operations at distances of 10–20 km (Miller et al. 2005a). No other odontocete is known to show avoidance at such distances.

Captive bottlenose dolphins and beluga whales exhibited changes in behavior when exposed to strong pulsed sounds similar in duration to those typically used in seismic surveys (Finneran et al. 2000, 2002, 2005; Finneran and Schlundt 2004). However, the animals tolerated high received levels of sound (>200 dB re 1 $\mu\mathrm{Pa}{\cdot}\mathrm{m}_{p\text{–}p}$) before exhibiting aversive behaviors. For pooled data at 3, 10, and 20 kHz, sound exposure levels during sessions with 25, 50, and 75% altered behavior were 180, 190, and 199 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$, respectively (Finneran and Schlundt 2004).

Results for porpoises depend on species. Dall's porpoises seem relatively tolerant of airgun operations (MacLean et al. 2005; Bain and Williams 2006), whereas the limited available data suggest that harbor porpoises show stronger avoidance (Stone 2003; Bain and Williams 2006). This apparent difference in responsiveness of these two porpoise species is consistent with their relative responsiveness to boat traffic in general (Richardson et al. 1995).

Sperm whales show considerable tolerance of airgun pulses. In most cases the whales do not show strong avoidance, and they continue to call (see Appendix C for review). However, controlled exposure experiments in the Gulf of Mexico indicate that foraging effort is apparently somewhat reduced upon exposure to airgun pulses from a seismic vessel operating in the area, and there may be a delay in diving to foraging depth (Miller et al. 2006; Tyack et al. 2006).

There are no specific data on the behavioral reactions of beaked whales to seismic surveys. Most beaked whales tend to avoid approaching vessels of other types (e.g., Würsig et al. 1998). They commonly dive for an extended period when approached by a vessel (e.g., Kasuya 1986). It is likely that these beaked whales would normally show strong avoidance of an approaching seismic vessel, but this has not been documented explicitly.

Odontocete reactions to large arrays of airguns are variable and, at least for delphinids and some porpoises, seem to be confined to a smaller radius than has been observed for mysticetes (Apppendix C). A ≥170 dB re 1 μPa_{rms} disturbance criterion (rather than ≥160 dB re 1 μPa_{rms}) is considered appropriate for delphinids (and pinnipeds), which tend to be less responsive than other cetaceans.

Pinnipeds.—Pinnipeds are not likely to show a strong avoidance reaction to the airgun sources that will be used. Visual monitoring from seismic vessels has shown only slight (if any) avoidance of airguns by pinnipeds, and only slight (if any) changes in behavior—see Appendix C (e). Ringed seals frequently do not avoid the area within a few hundred meters of operating airgun arrays (e.g., Harris et al. 2001; Moulton and Lawson 2002; Miller et al. 2005a). However, initial telemetry work suggests that avoidance and other behavioral reactions by two other species of seals to small airgun sources may at times be stronger than evident to date from visual studies of pinniped reactions to airguns (Thompson et al. 1998). Even if reactions of any pinnipeds that might be encountered in the present study area are as strong as those evident in the telemetry study, reactions are expected to be confined to relatively small distances and durations, with no long-term effects on pinniped individuals or populations. As for delphinids, a ≥170 dB disturbance criterion is considered appropriate for pinnipeds, which tend to be less responsive than many cetaceans. It should also be noted that pinnipeds are not likely to be encountered often, if at all, during the present study.

Sea Turtles.—The limited available data indicate that sea turtles will hear airgun sounds and will sometimes exhibit behavioral changes and/or localized avoidance (see Appendix D). For example, Holst et al. (2006) noted that sea turtles were seen significantly farther from an operating seismic vessel when compared with sightings when the airguns were not firing. To the extent that there are any impacts on sea turtles, seismic operations in or near areas where turtles concentrate are likely to have the greatest impact. There are no specific data that demonstrate the consequences to sea turtles if seismic operations with large or small arrays of airguns occur in important areas at biologically important times of year.

The MMVOs stationed on the *Langseth* will watch for sea turtles, and airgun operations will be shut down if a turtle enters the designated EZ.

Hearing Impairment and Other Physical Effects

Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds, but there has been no specific documentation of this for marine mammals exposed to sequences of airgun pulses. The current NMFS policy regarding exposure of marine mammals to high-level sounds is that cetaceans and pinnipeds should not be exposed to impulsive sounds ≥180 and 190 dB re 1 μPa$_{rms}$, respectively (e.g., NMFS 2000). Those criteria have been used in defining the EZs planned for the proposed seismic program. However, those criteria were established before there were any data on the minimum received levels of sounds necessary to cause temporary auditory impairment in marine mammals. As discussed in Appendix C (f) and summarized here,

- the 180-dB re 1 μPa$_{rms}$ criterion for cetaceans is probably quite precautionary, i.e., lower than necessary to avoid temporary threshold shift (TTS), let alone permanent auditory injury, at least for delphinids and other small odontocetes.
- the minimum sound level necessary to cause permanent hearing impairment is higher, by a variable and generally unknown amount, than the level that induces barely-detectable TTS.
- the level associated with the onset of TTS is often considered to be a precautionary estimate of the level below which there is no danger of permanent damage.

NMFS is developing new noise exposure criteria for marine mammals that account for the now-available scientific data on TTS, the expected offset between the TTS and PTS thresholds, differences in the acoustic frequencies to which different marine mammal groups are sensitive, and other relevant factors. For preliminary information about this process, and about the structure of the new criteria see NMFS (2005), D. Wieting *in* http://mmc.gov/sound/plenary2/pdf/plenary2summaryfinal.pdf, and Miller et al. (2005b).

Several aspects of the planned monitoring and mitigation measures for this project are designed to detect marine mammals occurring near the airguns to avoid exposing them to sound pulses that might , at least in theory, cause hearing impairment (see "Mitigation Measures" *in* § II). In addition, many cetaceans and (to a limited degree) sea turtles are likely to show some avoidance of the area with high received levels of airgun sound (see above). In those cases, the avoidance responses of the animals themselves will reduce or (most likely) avoid any possibility of hearing impairment.

Non-auditory physical effects may also occur in marine mammals exposed to strong underwater pulsed sound. Possible types of non-auditory physiological effects or injuries that theoretically might occur in mammals close to a strong sound source include stress, neurological effects, bubble formation, and other types of organ or tissue damage. It is possible that some marine mammal species (i.e., beaked whales) may be especially susceptible to injury and/or stranding when exposed to strong pulsed sounds. However, as discussed below, there is no definitive evidence that any of these effects occur even for marine mammals in close proximity to large arrays of airguns. It is especially unlikely that any effects of these types would occur during the present project given the brief duration of exposure of any given mammal and the planned monitoring and mitigation measures (see below). The following subsections discuss in somewhat more detail the possibilities of TTS, permanent threshold shift (PTS), and non-auditory physical effects.

Temporary Threshold Shift.—TTS is the mildest form of hearing impairment that can occur during exposure to a strong sound (Kryter 1985). While experiencing TTS, the hearing threshold rises and a sound must be stronger in order to be heard. At least in terrestrial mammals, TTS can last from minutes or hours to (in cases of strong TTS) days. For sound exposures at or somewhat above the TTS threshold, hearing sensitivity in both terrestrial and marine mammals recovers rapidly after exposure to the noise ends. Few data on sound levels and durations necessary to elicit mild TTS have been obtained for marine mammals, and none of the published data concern TTS elicited by exposure to multiple pulses of sound.

For toothed whales exposed to single short pulses, the TTS threshold appears to be, to a first approximation, a function of the energy content of the pulse (Finneran et al. 2002, 2005). Given the available data, the received energy level of a single seismic pulse (with no frequency weighting) might need to be ~186 dB re 1 $\mu Pa^2 \cdot s$ (i.e., 186 dB SEL or ~221–226 dB re 1 $\mu Pa{\cdot}m_{p-p}$) in order to produce brief, mild TTS. Exposure to several strong seismic pulses that each have received levels near 175–180 dB SEL might result in slight TTS in a small odontocete, assuming the TTS threshold is (to a first approximation) a function of the total received pulse energy. The distances from the *Langseth*'s airguns at which the received energy level (per pulse) would be expected to be ≥175–180 dB SEL are the distances shown in the 190 dB re 1 μPa_{rms} column in Table 3 (given that the rms level close to an airgun array is ~10–15 dB higher than the SEL value for the same pulse). The specific radius would depend on the depth of the water and the tow depth of the airgun array (9 vs. 12 m). For an odontocete closer to the surface, the maximum radius with ≥175–180 dB SEL or ≥190 dB re 1 μPa_{rms} would be smaller.

For baleen whales, there are no data, direct or indirect, on levels or properties of sound that are required to induce TTS. The frequencies to which baleen whales are most sensitive are lower than those to which odontocetes are most sensitive, and natural background noise levels at those low frequencies tend to be higher. As a result, auditory thresholds of baleen whales within their frequency band of best hearing are believed to be higher (less sensitive) than are those of odontocetes at their best frequencies (Clark and Ellison 2004). From this, it is suspected that received levels causing TTS onset may also be higher in baleen whales. In any event, no cases of TTS are expected given three considerations: (1) the relatively low abundance of baleen whales expected in most parts of the planned program area; (2) the strong likelihood that baleen whales would avoid the approaching airguns (or vessel) before being exposed to levels high enough for there to be any possibility of TTS; and (3) the mitigation measures that are planned.

In pinnipeds, TTS thresholds associated with exposure to brief pulses (single or multiple) of underwater sound have not been measured. Evidence from more prolonged exposures suggests that some pinnipeds may incur TTS at lower received levels than do small odontocetes exposed for similar durations, on the order of 171 dB SEL (Kastak et al. 1999, 2005; Ketten et al. 2001). However, very few, if any, pinnipeds are expected to occur in or near the planned study area.

NMFS (1995, 2000) concluded that cetaceans and pinnipeds should not be exposed to pulsed underwater noise at received levels exceeding, respectively, 180 and 190 dB re 1 μPa_{rms}. Those sound levels were ***not*** considered to be the levels above which TTS might occur. Rather, they were the received levels above which, in the view of a panel of bioacoustics specialists convened by NMFS before TTS measurements for marine mammals started to become available, one could not be certain that there would be no injurious effects, auditory or otherwise, to marine mammals. As summarized above, data that are now available imply that TTS is unlikely to occur unless odontocetes (and probably mysticetes as well) are exposed to airgun pulses stronger than 180 dB re 1 μPa_{rms}.

Permanent Threshold Shift.—When PTS occurs, there is physical damage to the sound receptors in the ear. In some cases, there can be total or partial deafness, whereas in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges.

There is no specific evidence that exposure to pulses of airgun sound can cause PTS in any marine mammal, even with large arrays of airguns. However, given the possibility that mammals close to an airgun array might incur TTS, there has been further speculation about the possibility that some individuals occurring very close to airguns might incur PTS. Single or occasional occurrences of mild TTS are not indicative of permanent auditory damage in terrestrial mammals. Relationships between TTS and

PTS thresholds have not been studied in marine mammals, but are assumed to be similar to those in humans and other terrestrial mammals. PTS might occur at a received sound level at least several decibels above that inducing mild TTS if the animal were exposed to strong sound pulses with rapid rise time—see Appendix C (f). The specific difference between the PTS and TTS thresholds has not been measured for marine mammals exposed to any sound type. However, based on data from terrestrial mammals, a precautionary assumption is that the PTS threshold for impulse sounds (such as airgun pulses as received close to the source) is at least 6 dB higher than the TTS threshold on a peak-pressure basis, and probably more than 6 dB.

Given the higher level of sound necessary to cause PTS as compared with TTS, it is even less likely that PTS could occur. In fact, even the levels immediately adjacent to the airguns may not be sufficient to induce PTS, especially because a mammal would not be exposed to more than one strong pulse unless it swam immediately alongside the airgun for a period longer than the inter-pulse interval. Baleen whales generally avoid the immediate area around operating seismic vessels, as do some other marine mammals and sea turtles. The planned monitoring and mitigation measures, including visual monitoring, PAM, power downs, and shut downs of the airguns when mammals are seen within the EZ, will minimize the already-minimal probability of exposure of marine mammals to sounds strong enough to induce PTS.

Non-auditory Physiological Effects.—Non-auditory physiological effects or injuries that theoretically might occur in marine mammals exposed to strong underwater sound include stress, neurological effects, bubble formation, and other types of organ or tissue damage. However, studies examining such effects are very limited. If any such effects do occur, they would probably be limited to unusual situations when animals might be exposed at close range for unusually long periods. It is doubtful that any single marine mammal would be exposed to strong seismic sounds for sufficiently long that significant physiological stress would develop.

Until recently, it was assumed that diving marine mammals are not subject to the bends or air embolisms. This possibility was explored at a workshop (Gentry [ed.] 2002) held to discuss whether the stranding of beaked whales in the Bahamas in 2000 (Balcomb and Claridge 2001; NOAA and USN 2001) might have been related to bubble formation in tissues caused by exposure to noise from naval sonar. However, the opinions were inconclusive. Jepson et al. (2003) first suggested a possible link between mid-frequency sonar activity and acute and chronic tissue damage that results from the formation *in vivo* of gas bubbles, based on the beaked whale stranding in the Canary Islands in 2002 during naval exercises. Fernández et al. (2005a) showed those beaked whales did indeed have gas bubble-associated lesions as well as fat embolisms. Fernández et al. (2005b) also found evidence of fat embolisms in three beaked whales that stranded 100 km north of the Canaries in 2004 during naval exercises. Examinations of several other stranded species have also revealed evidence of gas and fat embolisms (e.g., Arbelo et al. 2005; Jepson et al. 2005a; Méndez et al 2005). Most of the afflicted species were deep divers. There is speculation that gas and fat embolisms may occur if cetaceans ascend unusually quickly when exposed to aversive sounds, or if sound in the environment causes the destabilization of existing bubble nuclei (Potter 2004; Arbelo et al. 2005; Fernández et al. 2005a; Jepson et al. 2005b; Cox et al. 2006). Even if gas and fat embolisms can occur during exposure to mid-frequency sonar, there is no evidence that that type of effect occurs in response to airgun sounds.

In general, little is known about the potential for seismic survey sounds to cause auditory impairment or other physical effects in marine mammals. Available data suggest that direct physiological effects, if they occur at all, would be limited to short distances and probably to projects involving large arrays of airguns.

However, the available data do not allow for meaningful quantitative predictions of the numbers (if any) of marine mammals that might be affected in those ways. Marine mammals that show behavioral avoidance of seismic vessels, including most baleen whales, some odontocetes, and some pinnipeds are especially unlikely to incur auditory impairment or other physical effects. It is not known whether aversive behavioral responses to airgun pulses by deep-diving species could lead to indirect physiological problems as apparently can occur upon exposure of some beaked whales to mid-frequency sonar (Cox et al. 2006). The planned mitigation measures [§ II (3)], including shut downs of the airguns, will reduce any such effects that might otherwise occur.

Sea Turtles.—The limited available data indicate that the frequency range of best hearing sensitivity of sea turtles extends from roughly 250–300 Hz to 500–700 Hz; the sensitivity deteriorates at lower or higher frequencies. However, there is some sensitivity to frequencies as low as 60 Hz, and probably as low as 30 Hz. Thus, there is substantial overlap in the frequencies that sea turtles detect vs. the frequencies in airgun pulses. We are not aware of measurements of the absolute hearing thresholds of any sea turtle to waterborne sounds similar to airgun pulses. In the absence of relevant absolute threshold data, we cannot estimate how far away an airgun array might be audible to a sea turtle. TTS apparently occurred in loggerhead turtles exposed to many pulses from a single airgun ≤65 m away (see Moein et al. [1994] and Appendix D). This suggests that sounds from an airgun array might cause temporary hearing impairment in sea turtles if they do not avoid the (unknown) radius where TTS occurs. However, exposure duration during the planned surveys would be much less than during the study by Moein et al. (1994). Also, recent monitoring studies show that some sea turtles do show localized movement away from approaching airguns (Holst et al. 2005a, 2006). At short distances from the source, received sound level diminishes rapidly with increasing distance. In that situation, even a small-scale avoidance response could result in a significant reduction in sound exposure.

As noted above, the MMVOs stationed on the *Langseth* will also watch for sea turtles, and airgun operations will be shut down if a turtle enters the designated EZ.

Strandings and Mortality

Marine mammals close to underwater detonations of high explosives can be killed or severely injured, and the auditory organs are especially susceptible to injury (Ketten et al. 1993; Ketten 1995). Airgun pulses are less energetic and have slower rise times, and there is no proof that they can cause serious injury, death, or stranding even in the case of large airgun arrays. However, the association of mass strandings of beaked whales with naval exercises (see Appendix C) and, in one case, an L-DEO seismic survey, has raised the possibility that beaked whales exposed to strong pulsed sounds may be especially susceptible to injury and/or behavioral reactions that can lead to stranding. Appendix C (g) provides additional details.

Seismic pulses and mid-frequency sonar pulses are quite different. Sounds produced by airgun arrays are broadband with most of the energy below 1 kHz. Typical military mid-frequency sonars operate at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time. Thus, it is not appropriate to assume that there is a direct connection between the effects of military sonar and seismic surveys on marine mammals. However, evidence that sonar pulses can, in special circumstances, lead to physical damage and mortality (Balcomb and Claridge 2001; NOAA and USN 2001; Jepson et al. 2003; Fernández et al. 2004, 2005a; Cox et al. 2006), even if only indirectly, suggests that caution is warranted when dealing with exposure of marine mammals to any high-intensity pulsed sound.

There is no conclusive evidence of cetacean strandings as a result of exposure to seismic surveys. Speculation concerning a possible link between seismic surveys and strandings of humpback whales in

Brazil (Engel et al. 2004) was not well founded (IAGC 2004; IWC 2006). In September 2002, there was a stranding of two Cuvier's beaked whales in the Gulf of California, Mexico, when the L-DEO vessel *Maurice Ewing* was operating a 20-airgun, 8490 in^3 array in the general area. The link between the stranding and the seismic survey was inconclusive and not based on any physical evidence (Hogarth 2002; Yoder 2002). Nonetheless, that plus the incidents involving beaked whale strandings near naval exercises suggests a need for caution in conducting seismic surveys in areas occupied by beaked whales. No injuries of beaked whales are anticipated during the proposed study, because of the proposed monitoring and mitigation measures.

(b) Possible Effects of Mid-Frequency Multibeam Echosounder Signals

The Simrad EM120 12-kHz MBES will be operated from the source vessel during the planned study. Details about this equipment were provided in § II (h). Sounds from the MBES are very short pulses, occurring for 15 ms once every 5–20 s, depending on water depth. Most of the energy in the sound pulses emitted by this MBES is at frequencies centered at 12 kHz. The beam is narrow (1º) in fore-aft extent and wide (150º) in the cross-track extent. Each ping consists of nine successive fan-shaped transmissions (segments) at different cross-track angles. Any given mammal at depth near the trackline would be in the main beam for only one or two of the nine segments. Also, marine mammals that encounter the Simrad EM120 are unlikely to be subjected to repeated pulses because of the narrow fore–aft width of the beam and will receive only limited amounts of pulse energy because of the short pulses. Animals close to the ship (where the beam is narrowest) are especially unlikely to be ensonified for more than one 15 ms pulse (or two pulses if in the overlap area). Similarly, Kremser et al. (2005) noted that the probability of a cetacean swimming through the area of exposure when an MBES emits a pulse is small. The animal would have to pass the transducer at close range and be swimming at speeds similar to the vessel in order to be subjected to sound levels that could cause TTS.

Navy sonars that have been linked to avoidance reactions and stranding of cetaceans (1) generally have a longer pulse duration than the Simrad EM120, and (2) are often directed close to horizontally vs. downward for the Simrad EM120. The area of possible influence of the Simrad EM120 is much smaller—a narrow band below the source vessel. The duration of exposure for a given marine mammal can be much longer for a navy sonar.

Masking

Marine mammal communications will not be masked appreciably by the MBES signals given its low duty cycle and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of baleen whales, the signals (12 kHz) do not overlap with the predominant frequencies in the calls, which would avoid significant masking.

Behavioral Responses

Behavioral reactions of free-ranging marine mammals to military sonars and other sound sources appear to vary by species and circumstance. Observed reactions have included silencing and dispersal by sperm whales (Watkins et al. 1985), increased vocalizations and no dispersal by pilot whales (Rendell and Gordon 1999), and the previously-mentioned beachings by beaked whales. During exposure to a 21–25 kHz whale-finding sonar with a source level of 215 dB re 1 μPa·m, gray whales showed slight avoidance (~200 m) behavior (Frankel 2005). However, all of those observations are of limited relevance to the present situation. Pulse durations from those sonars were much longer than those of the MBES, and a given mammal would have received many pulses from the naval sonars. During L-DEO's operations, the individual pulses will be very short, and a given mammal would not receive many of the downward-directed pulses as the vessel passes by.

Captive bottlenose dolphins and a white whale exhibited changes in behavior when exposed to 1 s pulsed sounds at frequencies similar to those that will be emitted by the MBES used by L-DEO, and to shorter broadband pulsed signals. Behavioral changes typically involved what appeared to be deliberate attempts to avoid the sound exposure (Schlundt et al. 2000; Finneran et al. 2002; Finneran and Schlundt 2004). The relevance of those data to free-ranging odontocetes is uncertain, and in any case, the test sounds were quite different in either duration or bandwidth as compared with those from an MBES.

We are not aware of any data on the reactions of pinnipeds to sounds at frequencies similar to the 12 kHz frequency of the *Langseth*'s MBES. Based on observed pinniped responses to other types of pulsed sounds, and the likely brevity of exposure to the MBES sounds, pinniped reactions are expected to be limited to startle or otherwise brief responses of no lasting consequence to the animals. Also, few, if any, pinnipeds will be encountered during this project.

NMFS (2001) has concluded that momentary behavioral reactions "do not rise to the level of taking". Thus, brief exposure of cetaceans or pinnipeds to small numbers of signals from the MBES would not result in a "take" by harassment.

Hearing Impairment and Other Physical Effects

Given recent stranding events that have been associated with the operation of naval sonar, there is concern that mid-frequency sonar sounds can cause serious impacts to marine mammals (see above). However, the MBES proposed for use by L-DEO is quite different than sonars used for navy operations. Pulse duration of the MBES is very short relative to the naval sonars. Also, at any given location, an individual marine mammal would be in the beam of the MBES for much less time given the generally downward orientation of the beam and its narrow fore-aft beamwidth; navy sonars often use near-horizontally-directed sound. Those factors would all reduce the sound energy received from the MBES rather drastically relative to that from the sonars used by the navy.

Given the maximum source level of 242 dB re 1 μPa_{rms} (see § II), the received level for an animal within the MBES beam 100 m below the ship would be about 202 dB re 1 μPa_{rms}, assuming 40 dB of spreading loss over 100 m. Given the narrow beam, only one pulse is likely to be received by a given animal. The received energy level from a single pulse of duration 15 ms would be about 184 dB re 1 $\mu Pa^2 \cdot s$, i.e., 202 dB + 10 log (0.015 s). That would be below the TTS threshold for an odontocete exposed to a single non-impulsive sonar transmission (Schlundt et al. 2000; Finneran et al. 2005) and even further below the anticipated PTS threshold.

Sea Turtles

It is unlikely that echosounder operations during the planned seismic surveys would significantly affect sea turtles through masking, disturbance, or hearing impairment. Any effects would be negligible given the brief exposure and the fact that frequency of the MBES is far above the range of optimal hearing by sea turtles (see Appendix D).

(c) Possible Effects of the Sub-bottom Profiler Signals

An SBP will be operated from the source vessel during the planned study. Details about this equipment were provided in § II (h). Sounds from the SBP are very short pulses, occurring for 1, 2, or 4 ms once every second. Most of the energy in the sound pulses emitted by this SBP is at mid frequencies, centered at 3.5 kHz. The beam width is ~30° and is directed downward.

Sound levels have not been measured directly for the SBP on the *Langseth*, but Burgess and Lawson (2000) measured sounds propagating more or less horizontally from a similar unit with similar source output (205 dB re 1 µPa·m). The 160 and 180 dB re 1 μPa_{rms} radii, in the horizontal direction, were estimated to be, respectively, near 20 m and 8 m from the source, as measured in 13 m water depth. The corresponding distances for an animal in the beam below the transducer would be greater, on the order of 180 m and 18 m, assuming spherical spreading.

The SBP on the *Langseth* has a stated maximum source level of 204 dB re 1 µPa · m (see § II). Thus, the received level would be expected to decrease to 160 and 180 dB about 160 m and 16 m below the transducer, respectively, again assuming spherical spreading. Corresponding distances in the horizontal plane would be lower, given the directionality of this source (30° beam width) and the measurements of Burgess and Lawson (2000).

Kremser et al. (2005) noted that the probability of a cetacean swimming through the area of exposure when a SBP emits a pulse is small, and if the animal was in the area, it would have to pass the transducer at close range in order to be subjected to sound levels that could cause TTS.

Masking

Marine mammal communications will not be masked appreciably by the SBP signals given their directionality and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of most odontocetes, the signals do not overlap with the predominant frequencies in the calls, which would avoid significant masking.

Behavioral Responses

Marine mammal behavioral reactions to other pulsed sound sources are discussed above, and responses to the SBP are likely to be similar to those for other pulsed sources if received at the same levels. However, the pulsed signals from the SBP are somewhat weaker than those from the MBES. Therefore, behavioral responses are not expected unless marine mammals are very close to the source, e.g., about 160 m below the vessel or a lesser distance to the side.

Also, NMFS (2001) has concluded that momentary behavioral reactions “do not rise to the level of taking”. Thus, brief exposure of cetaceans to small numbers of signals from the SBP would not result in a “take” by harassment.

Hearing Impairment and Other Physical Effects

Source levels of the SBP are lower than those of the airguns and the MBES, which are discussed above. Sound levels from a SBP similar to the one on the *Langseth* were estimated to decrease to 180 dB re 1 μPa_{rms} at 8 m horizontally from the source (Burgess and Lawson 2000) and at ~18 m downward from the source. Furthermore, received levels of pulsed sounds that are necessary to cause temporary or especially permanent hearing impairment in marine mammals appear to be higher than 180 dB (see earlier). Thus, it is unlikely that the SBP produces pulse levels strong enough to cause hearing impairment or other physical injuries even in an animal that is (briefly) in a position near the source.

The SBP is usually operated simultaneously with other higher-power acoustic sources. Many marine mammals will move away in response to the approaching higher-power sources or the vessel itself before the mammals would be close enough for there to be any possibility of effects from the less intense sounds from the SBP. In the case of mammals that do not avoid the approaching vessel and its various sound sources, mitigation measures that would be applied to minimize effects of other sources [see § II(3)] would further reduce or eliminate any minor effects of the SBP.

Sea Turtles

It is very unlikely that SBP operations during the planned seismic program would significantly affect sea turtles through masking, disturbance, or hearing impairment. Any effects likely would be negligible given the brief exposure and relatively low source level.

(2) Mitigation Measures

Several mitigation measures are built into the proposed seismic program as an integral part of the planned activities. These measures include the following: ramp ups, minimum of one dedicated observer maintaining a visual watch during all daytime airgun operations, two observers for 30 min before and during ramp-ups during the day and at night (and when possible at other times), PAM during the day and night when practicable, and power downs (or if necessary shut downs) when mammals or turtles are detected in or about to enter designated EZ. These mitigation measures are described earlier in this document, in § II(3). The fact that the 36-airgun array, as a result of its design, directs the majority of the energy downward, and less energy laterally, is also an inherent mitigation measure.

Previous and subsequent analysis of the potential impacts take account of these planned mitigation measures. It would not be meaningful to analyze the effects of the planned activities without mitigation, as the mitigation (and associated monitoring) measures are a basic part of the activities.

(3) Numbers of Marine Mammals that Might be "Taken by Harassment"

All anticipated takes would be "takes by harassment", involving temporary changes in behavior. The mitigation measures to be applied will minimize the possibility of injurious takes. (However, as noted earlier, there is no specific information demonstrating that injurious "takes" would occur even in the absence of the planned mitigation measures.) In the sections below, we describe methods to estimate "take by harassment" and present estimates of the numbers of marine mammals that might be affected during the proposed Central American SubFac seismic program. The estimates of "take by harassment" are based on consideration of the number of marine mammals that might be disturbed appreciably by ~1328 km of seismic surveys in the western ***Caribbean*** and 2652 km in the eastern ***Pacific***. The main sources of distributional and numerical data used in deriving the estimates are described in the next subsection.

The anticipated radii of influence of the MBES are less than those for the airgun array. It is assumed that, during simultaneous operations of the airgun array and echosounders, any marine mammals close enough to be affected by the echosounders would already be affected by the airguns. However, whether or not the airguns are operating simultaneously with the echosounders, marine mammals are expected to exhibit no more than short-term and inconsequential responses to the echosounders given their characteristics (e.g., narrow downward-directed beam) and other considerations described in § II and IV, above. Such reactions are not considered to constitute "taking" (NMFS 2001). Therefore, no additional allowance is included for animals that might be affected by sound sources other than airguns.

(a) Basis for Estimating "Take by Harassment" for the Central American SubFac survey

Extensive marine mammal surveys have been conducted in the ETP over numerous years (e.g., Polacheck 1987; Wade and Gerrodette 1993; Kinzey et al. 1999, 2000, 2001; Ferguson and Barlow 2001; Smultea and Holst 2003; Jackson et al. 2004; Holst et al. 2005a; May-Collado et al. 2005). Therefore, for the ***Pacific*** portion of the proposed seismic survey, marine mammal density data were readily available. The most comprehensive data available for the region encompassing the proposed survey area are from

Ferguson and Barlow (2001) and Holst et al. (2005a). The Ferguson and Barlow (2001) surveys took place from late July to early December across a large area of the ETP. For our density estimates, we only used data from areas in or adjacent to the proposed study location. These areas included ten 5°× 5° survey blocks from the Ferguson and Barlow (2001) surveys: 118, 119, 137, 138, 139, 140, 158, 159, 160, and 161. These blocks included survey effort in all water depths, but primarily deeper than 100 m. Similarly, survey data from all water depths were included from Holst et al. (2005a), although most effort (>93%) occurred in water >100 m deep. Survey data collected by Holst et al. (2005a) were the result of a marine mammal monitoring and mitigation program during L-DEO's seismic survey off Costa Rica and Nicaragua in November-December 2004. Only data collected during non-seismic periods were combined with data from Ferguson and Barlow (2001) to calculate mean densities for the proposed study area. However, data collected by Holst et al. (2005a) during seismic and non-seismic periods were used to estimate allowances for sightings not identified to species.

The proposed survey off the Pacific coast of Central America is presently scheduled to occur in the January-to-March 2008 period. Therefore, the representativeness of the data collected by Holst et al. (2005a) in November–December and especially by Ferguson and Barlow (2001) in July–December is uncertain. For some species, the densities derived from past surveys may not be representative of the densities that will be encountered during the proposed seismic survey. As an example of potential uncertainty of the data, the number of cetaceans sighted during L-DEO's 2003 Hess Deep seismic operations (see Smultea and Holst 2003) was considerably lower (only one sighting) than expected based on the Ferguson and Barlow (2001) data. The Hess Deep survey occurred in mid-July, and was apparently not well represented by the Ferguson and Barlow (2001) data collected largely during the autumn in other years. Similarly, the densities calculated by Holst et al. (2005a) were generally lower for dolphins and greater for humpbacks compared with those determined by Ferguson and Barlow (2001).

Despite the above caveats, the Ferguson and Barlow (2001) and Holst et al. (2005a) data still represent the best available data for estimating numbers of marine mammals potentially exposed to the proposed seismic sounds. Table 6 shows the densities that were derived from Ferguson and Barlow (2001) and Holst et al. (2005a), which we used to estimate numbers of marine mammals potentially exposed. The densities reported by Ferguson and Barlow (2001) and Holst et al. (2005a) were corrected for both detectability [*f*(0)] and availability [*g*(0)] biases, and therefore, are relatively unbiased. To provide some allowance for uncertainties in these data, "best estimates" and "maximum estimates" of the numbers potentially affected have been derived (Table 7).

For the ***Caribbean*** portion of the Central American SubFac program, we were unable to find published data on marine mammal densities in or immediately adjacent to the proposed seismic survey area. The closest quantitative surveys were conducted in the SE Caribbean (Swartz and Burks 2000; Swartz et al. 2001; Smultea et al. 2004). Most of the survey effort by Swartz and Burks (2000) and Swartz et al. (2001) took place during March and April near the islands on the east side of the Caribbean Sea and near the north and northeast coasts of Venezuela in water depths <1000 m. Survey data from Smultea et al. (2004) were collected north of Venezuela during April–June in association with a previous L-DEO seismic survey. The proposed survey is scheduled to occur sometime in January to early March in the western Caribbean Sea, a location and time of year in which the species densities are likely different from those during the above-mentioned surveys in the SE Caribbean. Therefore, the representativeness of the data is uncertain, but they are the best available at this time.

The data from Smultea et al. (2004) were deemed to be more representative of the proposed study area than those from Swartz and Burks (2000) and Swartz et al. (2001), because Smultea et al. (2004) reported separate densities for different water depth categories, whereas the other surveys did not.

TABLE 6. Densities of cetaceans along the Pacific coast of Costa Rica and Nicaragua in the region of the proposed survey scheduled to take place, January–March 2008. Densities are from Ferguson and Barlow (2001) and Holst et al. (2005a). Densities are corrected for $f(0)$ and $g(0)$ biases. Species in italics (except for *Mesoplodon* sp.) are listed as endangered under the U.S. ESA.

Species	**Average Density (# / km^2)**		**Maximum Density (# / km^2)**	
	Density[a]	**CV[b]**	**Density[a]**	**CV[b]**
Odontocetes				
Sperm whale	*0.0032*	*0.21*	*0.0108*	*0.65*
Pygmy sperm whale	0.0000	-1.00	0.0000	-1.00
Dwarf sperm whale	0.0194	0.36	0.0333	0.45
Cuvier's beaked whale	0.0061	0.33	0.0110	0.76
Tropical bottlenose whale	0.0001	0.83	0.0004	0.94
Pygmy beaked whale	0.0000	-1.00	0.0000	-1.00
Blainville's beaked whale	0.0002	0.83	0.0013	0.83
Mesoplodon sp. (unidentified)	0.0016	0.48	0.0040	0.65
Rough-toothed dolphin	0.0162	0.33	0.0432	0.76
Bottlenose dolphin	0.0362	0.08	0.1078	0.72
Spotted dolphin	0.1338	0.11	0.3425	0.31
Spinner dolphin	0.0829	0.24	0.3559	0.36
Costa Rican spinner dolphin	0.0064	0.94	0.1522	0.94
Striped dolphin	0.1815	0.004	0.3675	0.51
Short-beaked common dolphin	0.1781	0.14	0.6363	0.31
Fraser's dolphin	0.0016	0.83	0.0065	0.94
Risso's dolphin	0.0118	0.24	0.0295	0.45
Melon-headed whale	0.0082	0.57	0.0596	0.83
Pygmy killer whale	0.0025	0.65	0.0105	0.94
False killer whale	0.0030	0.68	0.0217	0.83
Killer whale	0.0002	0.54	0.0008	0.76
Short-finned pilot whale	0.0122	0.19	0.1684	0.72
Mysticetes				
Humpback whale	*0.0002*	*0.57*	*0.0046*	*0.64*
Minke whale	0.0000	-1.00	0.0000	-1.00
Bryde's whale	0.0009	0.35	0.0031	0.50
Sei whale	*0.0000*	*-1.00*	*0.0000*	*-1.00*
Fin whale	*0.0000*	*-1.00*	*0.0000*	*-1.00*
Blue whale	*0.0002*	*0.47*	*0.0007*	*0.57*

[a] Densities for each species include allowance for sightings not identified to species.

[b] CV (Coefficient of Variation) is a measure of a number's variability. The larger the CV, the higher the variability. It is estimated by the equation $0.94 - 0.162\log_e n$ from Koski et al. (1998), but likely underestimates the true variability.

TABLE 7. Estimates of the number of individual marine mammals that may be exposed to sound levels >160 dB (>170 dB delphinids only) during L-DEO's seismic program on the Pacific coast off Central America, January –March 2008. Received levels are expressed in dB re 1 μPa (rms, averaged over pulse duration). Best estimates are based on mean densities; maximum estimates are based on maximum densities[a]. Species in italics are listed as endangered under the U.S. ESA.

Species	Best Estimate		Percent of Regional Population[b]	Maximum Estimate[c]		Requested Take Authorization[c]
Physeteridae						
Sperm whale	71		0.3	239		**239**
Pygmy sperm whale	0		0.0	0		**0**
Dwarf sperm whale	428		3.8	856		**856**
Ziphiidae						
Cuvier's beaked whale	151		0.8	302		**302**
Tropical bottlenose whale	2		N.A.	9		**9**
Pygmy beaked whale	0		N.A.	0		**0**
Blainville's beaked whale	3		N.A.	29		**29**
Delphinidae						
Rough-toothed dolphin	357	(194)	0.2	954	(519)	**954**
Bottlenose dolphin	800	(435)	0.3	2380	(1295)	**2380**
Spotted dolphin	2952	(1606)	0.1	7560	(4112)	**7560**
Spinner dolphin	1830	(996)	0.1	7856	(4273)	**7856**
Costa Rican spinner dolphin	141	(77)	N.A.	3358	(1827)	**3358**
Striped dolphin	4005	(2178)	0.2	8110	(4412)	**8110**
Short-beaked common dolphin	3931	(2138)	0.1	14045	(7639)	**14045**
Fraser's dolphin	35	(19)	0.0	144	(78)	**144**
Risso's dolphin	260	(141)	0.1	651	(354)	**651**
Melon-headed whale	180	(98)	0.4	1315	(715)	**1315**
Pygmy killer whale	56	(30)	0.1	231	(126)	**231**
False killer whale	67	(36)	0.2	479	(261)	**479**
Killer whale	5	(3)	0.1	17	(9)	**17**
Short-finned pilot whale	270	(147)	0.2	3717	(2022)	**3717**
Balaenopteridae						
Humpback whale	4		0.4	101		**101**
Minke whale	0		0.0	0		**0**
Bryde's whale	21		0.2	68		**68**
Sei whale	0		0.0	0		**0**
Fin whale	0		0.0	0		**0**
Blue whale	4		0.3	15		**15**
Pinnipeds						
California sea lion	0		0.0	0		**0**
Galápagos sea lion	0		0.0	0		**0**

[a] Best and maximum estimates based on densities in Table 6.

[b] Percentage based on best estimates. Population estimates are from Table 5. N.A. indicates that regional population estimates are not available.

[c] Includes adjustments for at least 2x the best estimate.

However, there was no shallow-water effort during surveys by Smultea et al. (2004). Densities from a survey off Yucatán, Mexico (Holst et al. 2005b), were used for shallow water, as those data were deemed more appropriate than densities for deeper waters from the SE Caribbean surveys. Therefore, for the Central American SubFac survey, mean densities for intermediate and deep water are those for non-seismic periods from Smultea et al. (2004), and for shallow water, densities for non-seismic periods from Holst et al. (2005b) were used (Table 8). Densities were available for striped, Atlantic spotted, and bottlenose dolphins, as well as short-finned pilot whales, and were corrected for detectability [*f*(0)] and availability [*g*(0)] biases and for unidentified sightings by the original authors. To allow for the possibility of encountering small numbers of individuals of other species in the survey area, even though they were not recorded during previous surveys, we adjusted the 'maximum estimates' based on mean group size, if available (e.g., Swartz and Burks 2000).

(b) Potential Number of "Takes by Harassment"

Best and Maximum Estimates of the Number of Individuals that may be Exposed to ≥160 dB.— The number of different individuals likely to be exposed to airgun sounds with received levels ≥160 dB re 1 µPa$_{rms}$ on one or more occasions can be estimated by considering the total marine area that would be within the 160-dB radius around the operating airgun array on at least one occasion. Most of the proposed lines (9 of 11) will be surveyed twice, although it is unknown how much time will pass between the first and the second transit along each line. Therefore, some of the same individuals may be approached by the operating airguns and come within the 160-dB distance on two occasions. However, this also means that some different marine mammals could occur in the area during the second pass. Thus, the best estimates in this section are based on a single pass of all survey lines (including a 15% contingency for airgun operations during turns), and maximum estimates are based on maximum densities (i.e., for the ***Pacific***) or on at least two times the best estimate. Table 8 shows the best and maximum estimates of the number of marine mammals that could potentially be affected during the Caribbean portion of the seismic survey.

The potential number of different individuals that might be exposed to received levels ≥160 dB re 1 µPa$_{rms}$ was calculated separately for the ***Pacific*** and ***Caribbean*** study areas. For the ***Caribbean*** portion of the Central American SubFac survey, the number of potentially-affected individuals was calculated for each of three water depth categories (shallow, <100 m or <328 ft; intermediate-depth, 100–1000 m or 328–3281 ft; and deep, >1000 m. However, for the ***Pacific*** area, no distinction was made between different water depth categories for several reasons: (1) <5% of the proposed survey in the ***Pacific*** will take place in water <100 m deep, (2) most of the effort (>93%) during surveys by Holst et al. (2005a) took place in waters deeper than 100 m, and (3) Ferguson and Barlow (2001) did not present depth-specific densities.

The number of different individuals potentially exposed to ≥160 dB re 1 µPa$_{rms}$ in each area was calculated by multiplying

- the expected species density, either "mean" (i.e., best estimate) or "maximum", for a particular water depth, times
- the anticipated minimum area to be ensonified to that level during airgun operations in each water depth category. The 160-dB re 1 µPa$_{rms}$ distances were as predicted by L-DEO's model, with adjustments based on Tolstoy et al. (2004a,b) for shallow and intermediate-depth water.

TABLE 8. Average densities in three different water depth categories and estimates of the number of individual marine mammals that may be exposed to sound levels >160 dB (>170 dB delphinids only) during L-DEO's seismic program on the Caribbean coast off Central America, January–March 2008. Received levels are expressed in dB re 1 µPa (rms, averaged over pulse duration). Species in italics are listed as endangered under the ESA.

	Average Density (# / km^2)								
Species	**Shallow[a] (<100 m)**	**Inter.[b] (100-1000 m)**	**Deep[b] (>1000 m)**	**Best Estimate[c]**		**Percent of Regional Population[d]**	**Maximum Estimate[e]**		**Requested Take Authorization**
Physeteridae									
Sperm whale	-	-	-	*3*		*0.02*	*5*		***5***
Dwarf sperm whale	-	-	-	0		0.00	0		**0**
Pygmy sperm whale	-	-	-	0		0.00	0		**0**
Ziphiidae									
Cuvier's beaked whale	-	-	-	0		0.00	0		**0**
Gervais' beaked whale	-	-	-	2		N.A.	4		**4**
Blainville's beaked whale	-	-	-	0		0.00	0		**0**
Delphinidae									
Rough-toothed dolphin	-	-	-	0	0	0.00	9	0	**9**
Tucuxi	-	-	-	0	0	0.00	0	0	**0**
Bottlenose dolphin	0.0215	0.0086	0.0015	194	(174)	0.15	389	(347)	**389**
Pantropical spotted dolphin	-	-	-	0	0	0.00	37	0	**37**
Atlantic spotted dolphin	0.0182	0.0216	0.0024	220	(180)	0.43	440	(360)	**440**
Spinner dolphin	-	-	-	0	0	0.00	0	0	**0**
Clymene dolphin	-	-	-	0	0	0.00	29	0	**29**
Striped dolphin[f]	-	0.0000	0.0043	15	(7)	0.02	31	(13)	**31**
Fraser's dolphin	-	-	-	0	0	0.00	0	0	**0**
Risso's dolphin	-	-	-	0	0	0.00	0	0	**0**
Melon-headed whale	-	-	-	0	0	0.00	0	0	**0**
Pygmy killer whale	-	-	-	0	0	0.00	0	0	**0**
False killer whale	-	-	-	0	0	0.00	0	0	**0**
Killer whale	-	-	-	5	(4)	0.08	10	(8)	**10**
Short-finned pilot whale	-	0.0038	0.0012	18	(10)	0.06	36	(20)	**36**
Balaenopteridae									
Humpback whale	-	-	-	*1*		*0.14*	*3*		***3***
Minke whale	-	-	-	0		0.00	0		**0**
Bryde's whale	-	-	-	2		0.01	3		**3**
Sei whale	-	-	-	*0*		*0.00*	*0*		***0***
Fin whale	-	-	-	*1*		*0.05*	*2*		***2***
Blue whale	-	-	-	*0*		*0.00*	*0*		***0***
Sirenia									
West Indian Manatee	-	-	-	*0*		*0.00*	*0*		***0***

Note: '-' means that the species is not expected to occur in that water depth category within the study area; N.A. means not available.

[a] Densities from Holst et al. (2005b), adjusted for unidentified dolphins.

[b] Intermediate-depth densities from Smultea et al. (2004), adjusted for unidentified dolphins.

[c] Based on average densities for the three different water depth categories.

[d] Percentage based on best estimates. Population estimates are from Table 4.

[e] Maximum estimates are based on 2x best estimates (see text).

[f] Low probability of sighting this species within the proposed survey area.

The area expected to be ensonified was determined by entering the planned survey lines into a MapInfo Geographic Information System (GIS), using the GIS to identify the relevant areas by "drawing" the applicable 160 dB buffer (see Table 3) around each seismic line (depending on the water and tow depth), and then calculating the total area within the buffers. Areas where overlap occurred were included only once to determine the minimum area expected to be ensonified to ≥160 dB at least once.

Applying the approach described above, ~19,193 km^2 would be within the 160 dB isopleth on one or more occasions during the ***Pacific*** portion of the survey, and 12,643 km^2 would be ensonified on one or more occasions during the ***Caribbean*** portion of the survey. However, this approach does not allow for turnover in the mammal populations in the study area during the course of the study. This might somewhat underestimate actual numbers of individuals exposed, although the conservative distances used to calculate the area may offset the understimate. In addition, the approach assumes that no cetaceans will move away or toward the trackline (as the *Langseth* approaches) in response to increasing sound levels prior to the time the levels reach 160 dB re 1 μPa$_{rms}$. Another way of interpreting the estimates that follow is that they represent the number of individuals that are expected (in the absence of a seismic program) to occur in the waters that will be exposed to ≥160 dB re 1 μPa$_{rms.}$

The 'best estimate' of the number of individual marine mammals that might be exposed to seismic sounds with received levels ≥160 dB re 1 μPa$_{rms}$ during the ***Pacific*** portion of the proposed survey is 15,572 (Table 7). That total includes 79 ***endangered*** whales (71 sperm, 4 humpback, and 4 blue whales), 156 beaked whales, and 21 Bryde's whale (Table 7). Striped, short-beaked common, and pantropical spotted dolphins are expected to be the most common species in the Pacific part of the study area; the best estimates for those species are 4005, 3931, and 2952, respectively (Table 7). Estimates for other species are lower (Table 7). The 'maximum estimate' for the ***Pacific*** is 52,438 individual marine mammals. Most of these would be dolphins (Table 7), for which the ≥160 dB criterion used here is probably unnecessarily low, resulting in overestimates of numbers affected. The maximum estimate of 101 humpback whales is likely a more realistic estimate of the number of individuals that might be exposed to seismic sounds ≥160 dB re 1 μPa$_{rms}$ during the ***Pacific*** survey, as these estimates are based on density data from July–December and not from the peak breeding/calving period in January–March.

The 'best estimate' of the number of individual marine mammals that might be exposed to seismic sounds with received levels ≥160 dB re 1 μPa$_{rms}$ during the ***Caribbean*** portion of the proposed survey is 461 (Table 8). That total includes 5 ***endangered*** whales (3 sperm, 1 humpback, 1 fin whale), 2 beaked whales, and 2 Bryde's whale (Table 8). Atlantic spotted and bottlenose dolphins are expected to be the most common species in the Caribbean part of the study area; the best estimates for those species are 220 and 194, respectively (Table 8). Estimates for other species are lower (Table 8). The 'maximum estimate' for the ***Caribbean*** is 998 individual marine mammals.

Best and Maximum Estimates of the Number of Individual Delphinids that might be Exposed to ≥170 dB.—The 160-dB criterion, on which the preceding estimates are based, was derived from studies of baleen whales. Odontocete hearing at low frequencies is relatively insensitive, and delphinids generally appear to be more tolerant of strong low-frequency sounds than are most baleen whales. As summarized in Appendix C (e), delphinids commonly occur within distances where received levels would be expected to exceed 160 dB re 1 μPa$_{rms}$. There is no generally accepted alternative "take" criterion for delphinids exposed to airgun sounds. However, we assume that only those delphinids exposed to ≥170 dB re 1 μPa$_{rms}$, on average, would be affected sufficiently to be considered "taken by harassment". ("On average" means that some individuals might react significantly upon exposure to levels somewhat <170 dB re 1 μPa$_{rms}$, but others would not do so even upon exposure to levels somewhat >170 dB.) The area ensonified by levels ≥170 dB re 1 μPa_{rms} was determined (as described above for levels ≥160 dB re 1 μPa_{rms}) and was multiplied by the marine mammal density for the particular water depth (if applicable) in order to obtain best and maximum estimates.

The best and maximum estimates of the numbers of exposures to ≥170 dB re 1 μPa_{rms} for all delphinids during the ***Pacific*** portion of the survey are 8098 and 27,641, respectively (Table 7). The best estimates of the numbers of individuals that might be exposed to ≥170 dB re 1 μPa_{rms} for the three most abundant delphinid species are 2178 striped dolphins, 2138 short-beaked common dolphins, and 1606 spotted dolphins. The best and maximum estimates of the numbers of exposures to ≥170 dB re 1 μPa_{rms} for all delphinids during the ***Caribbean*** portion of the survey are 374 and 749, respectively (Table 8). The best estimates of the numbers of individuals that might be exposed to ≥170 dB re 1 μPa_{rms} for the two most abundant delphinid species are 174 bottlenose dolphins and 180 Atlantic spotted dolphins. These values are based on the predicted 170 dB radii around each of the array types to be used during the study and are considered to be more realistic estimates of the number of individual delphinids that may be affected.

(4) Conclusions

The proposed seismic program will involve towing an airgun array that introduces pulsed sounds into the ocean, along with, at times, simultaneous operation of an MBES and SPB. The survey will employ a 36-airgun array typical of airgun arrays used for typical high-energy seismic surveys. The total airgun discharge volume is ~6600 in^3. However, the intervals between pulses (20 s or 80 s) will be longer than during typical industry surveys. Routine vessel operations, other than the proposed airgun operations, are conventionally assumed not to affect marine mammals sufficiently to constitute "taking". No "taking" of marine mammals is expected in association with echosounder operations given the considerations discussed in § IV(1)(b), i.e., echosounder signals are beamed downward, the beam is narrow, the pulses are extremely short, etc.

(a) Cetaceans

Strong avoidance reactions by several species of mysticetes to seismic vessels have been observed at ranges up to 6–8 km and occasionally as far as 20–30 km from the source vessel. However, reactions at the longer distances appear to be atypical of most species and situations. Mysticetes are likely to be encountered in very low numbers, if at all, during the planned program in the ***Caribbean*** portion of the Central American SubFac survey. During the ***Pacific*** portion of the survey, humpback, blue, and Bryde's whales are expected to occur, albeit in relatively low numbers (see 'Best Estimate' in Table 7).

Reactions of odontocetes to seismic pulses, or at least the reactions of delphinids, are expected to extend to lesser distances than are those of mysticetes. Odontocete low-frequency hearing is less sensitive than that of mysticetes, and delphinids are often seen from seismic vessels. In fact, there are documented instances of dolphins approaching active seismic vessels. However, delphinids as well as some other types of odontocetes sometimes show avoidance responses and/or other changes in behavior near operating seismic vessels.

Taking into account the mitigation measures that are planned (see § II), effects on cetaceans are generally expected to be limited to avoidance of the area around the seismic operation and short-term changes in behavior, falling within the MMPA definition of "Level B harassment". Furthermore, the estimated numbers of animals potentially exposed to sound levels sufficient to cause appreciable disturbance are generally low percentages of the population sizes in the respective regions. For the ***Pacific***, the best estimates of the number of individual mammals (n = 15,572 for all species combined) that would be exposed to sounds ≥160 dB re 1 μPa$_{rms}$ represent, on a species-by-species basis, no more than 0.8% of the population (except in the case of the dwarf sperm whale, where 3.8% of the population potentially could be affected; Table 7). This includes an estimated 71 endangered sperm whales (0.3% of the population), 4 endangered humpback whales (0.3%), 4 endangered blue whales (0.3%), and 151 beaked whales representing no more than 0.8% of the population (Table 7). Large numbers of dolphins may be present within the area to be exposed to ≥160 dB re 1 μPa$_{rms,}$ but the population sizes of species likely to occur in the operating area are also large, and the numbers within the ≥160-dB zones are small relative to the population sizes (Table 7). Also, these delphinids are not expected to be disturbed appreciably at received levels below 170 dB re 1 μPa$_{rms}$. The percentages of the delphinids expected to be exposed to sounds >170 dB re 1 μPa$_{rms}$ in the ***Pacific*** are ≤0.2% of the population size for all delphinid species.

For the ***Caribbean***, the best estimates of the number of individual mammals (*n* = 461 for all species combined) that would be exposed to sounds ≥160 dB re 1 μPa$_{rms}$ represent no more than 0.5% of any population (Table 8). This includes an estimated 3 endangered sperm whales or 0.02% of the population, 1 endangered fin whale (0.05%), 1 endangered humpback (<0.1%), and 2 Gervais' beaked whales representing an unknown fraction of the population (Table 8). However, delphinids are not expected to be disturbed appreciably at received levels below 170 dB re 1 μPa$_{rms}$. The percentages of the delphinids expected to be exposed to sounds >170 dB re 1 μPa$_{rms}$ are <0.4% of the population size for all delphinid species.

Although low numbers of tucuxi could be present in the nearshore waters during the seismic survey off the ***Caribbean*** coast, they are expected to be far enough inshore such that they will not be exposed to strong (if any) airgun sound. Tucuxi distribution is very patchy on the east coast of Costa Rica and Nicaragua. At least two of the proposed survey lines are located near areas where tucuxi are known to occur. However, tucuxi generally occur <500 m from shore in waters ≤18 m deep. The northern end of Line A ends offshore from MCMR, and the southern tip of Line D approaches Gandoca-Manzanillo, but not within depths of 100 m or within 500 m from shore. Therefore, no tucuxi are expected to be encountered or exposed to strong sounds.

Varying estimates of the numbers of marine mammals that might be exposed to strong airgun sounds during the proposed program have been presented, depending on the specific exposure criteria (≥160 vs. ≥170 dB) and assumed density [most likely (best) vs. maximum]. The requested numbers of authorized "takes" are based on the maximum estimated numbers of individuals that might be exposed to levels ≥160 re 1 μPa$_{rms}$. Actual numbers exposed to this level are expected to be lower, and these relatively short-term exposures are unlikely to result in any long-term negative consequences for the individuals or their populations.

The many cases of apparent tolerance by cetaceans of seismic exploration, vessel traffic, and some other human activities show that co-existence is possible. Mitigation measures such as controlled speed, course alternation, look-outs, non-pursuit, ramp ups, power downs, and shut downs when marine mammals are seen within defined ranges should further reduce short-term reactions, and minimize any effects on hearing sensitivity. In all cases, the effects are expected to be short-term, with no lasting biological consequence.

(b) Pinnipeds

No pinnipeds are expected to be encountered in the ***Caribbean***, and the likelihood of encountering sea lions or other pinnipeds in the ***Pacific*** study area is also very low.

(c) Sirenians

Manatees are not the subject of this IHA Application to NMFS, since they are managed (in the U.S.) by the USFWS. However, it is unlikely that manatees would be affected by the planned airgun or echosounder operations. Although some of the proposed seismic transect lines approach the coast, manatees are rare in waters deep enough for operations by a seismic survey vessel of the type to be used in this project. Even if manatees did occur near the proposed activities, it is unlikely that there would be more than short-term effects on their behavior or distribution.

(5) Direct Effects on Fish and Their Significance

One reason for the adoption of airguns as the standard energy source for marine seismic surveys is that, unlike explosives, they have not been associated with large-scale fish kills. However, existing information on the impacts of seismic surveys on marine fish populations is very limited (see Appendix E). There are three types of potential effects of exposure to seismic surveys: (1) pathological, (2) physiological, and (3) behavioral. Pathological effects involve lethal and temporary or permanent sub-lethal injury. Physiological effects involve temporary and permanent primary and secondary stress responses, such as changes in levels of enzymes and proteins. Behavioral effects refer to temporary and (if it occurs) permanent changes in exhibited behavior (e.g., startle and avoidance behavior). The three categories are interrelated in complex ways. For example, it is possible that certain physiological and behavioral changes could potentially lead to an ultimate pathological effect on individuals (i.e., mortality).

The specific received sound levels at which permanent adverse effects to fish potentially could occur are little studied and largely unknown. Furthermore, the available information on the impacts of seismic surveys on marine fish is from studies of individuals or portions of a population; there have been no studies at the population scale. Thus, available information provides limited insight on possible real-world effects at the ocean or population scale. This makes drawing conclusions about impacts on fish problematic because ultimately, the most important aspect of potential impacts relates to how exposure to seismic survey sound affects marine fish populations and their viability, including their availability to fisheries.

The following sections provide a general synopsis of available information on the effects of exposure to seismic and other anthropogenic sound as relevant to fish. The information comprises results from scientific studies of varying degrees of rigor plus some anecdotal information. Some of the data sources may have serious shortcomings in methods, analysis, interpretation, and reproducibility that must be considered when interpreting their results (see Hastings and Popper 2005). Potential adverse effects of the program's sound sources on marine fish are then noted.

Pathological Effects.—The potential for pathological damage to hearing structures in fish depends on the energy level of the received sound and the physiology and hearing capability of the species in question (see Appendix E). For a given sound to result in hearing loss, the sound must exceed, by some specific amount, the hearing threshold of the fish for that sound (Popper et al. 2005). The consequences of temporary or permanent hearing loss in individual fish on a fish population is unknown; however, it likely depends on the number of individuals affected and whether critical behaviors involving sound (e.g. predator avoidance, prey capture, orientation and navigation, reproduction, etc.) are adversely affected.

Little is known about the mechanisms and characteristics of damage to fish that may be inflicted by exposure to seismic survey sounds. Few data have been presented in the peer-reviewed scientific literature. As far as we know, there are only two valid papers with proper experimental methods, controls, and careful pathological investigation implicating sounds produced by actual seismic survey airguns with adverse anatomical effects. One such study indicated anatomical damage and the second indicated TTS in fish hearing. The anatomical case is McCauley et al. (2003), who found that exposure to airgun sound caused observable anatomical damage to the auditory maculae of "pink snapper" (*Pagrus auratus*). This damage in the ears had not been repaired in fish sacrificed and examined almost two months after exposure. On the other hand, Popper et al. (2005) documented only TTS (as determined by auditory brainstem response) in two of three fishes from the Mackenzie River Delta. This study found that broad whitefish (*Coregonus nasus*) that received a sound exposure level of 177 dB re 1 μPa^2·s showed no hearing loss. During both studies, the repetitive exposure to sound was greater than would have occurred during a typical seismic survey. However, the substantial low-frequency energy produced by the airgun arrays [less than ~400 Hz in the study by McCauley et al. (2003) and less than ~200 Hz in Popper et al. (2005)] likely did not propagate to the fish because the water in the study areas was very shallow (~9 m in the former case and <2 m in the latter). Water depth sets a lower limit on the lowest sound frequency that will propagate (the "cutoff frequency") at about one-quarter wavelength (Urick 1983; Rogers and Cox 1988).

Except for these two studies, at least with airgun-generated sound treatments, most contributions rely on rather subjective assays such as fish "alarm" or "startle response" or changes in catch rates by fishers. These observations are important in that they attempt to use the levels of exposures that are likely to be encountered by most free-ranging fish in actual survey areas. However, the associated sound stimuli are often poorly described, and the biological assays are varied (Hastings and Popper 2005).

Wardle et al. (2001) suggested that in water, acute injury and death of organisms exposed to seismic energy depends primarily on two features of the sound source: (1) the received peak pressure and (2) the time required for the pressure to rise and decay. Generally, as received pressure increases, the period for the pressure to rise and decay decreases, and the chance of acute pathological effects increases. According to Buchanan et al. (2004), for the types of seismic airguns and arrays involved with the proposed program, the pathological (mortality) zone for fish would be expected to be within a few meters of the seismic source. Numerous other studies provide examples of no fish mortality upon exposure to seismic sources (Falk and Lawrence 1973; Holliday et al. 1987; La Bella et al. 1996; Santulli et al. 1999; McCauley et al. 2000a,b, 2003; Bjarti 2002; Hassel et al. 2003; Popper et al. 2005).

Some studies have reported, some equivocally, that mortality of fish, fish eggs, or larvae can occur close to seismic sources (Kostyuchenko 1973; Dalen and Knutsen 1986; Booman et al. 1996; Dalen et al. 1996). Some of the reports claimed seismic effects from treatments quite different from actual seismic survey sounds or even reasonable surrogates. Saetre and Ona (1996) applied a 'worst-case scenario' mathematical model to investigate the effects of seismic energy on fish eggs and larvae. They concluded that mortality rates caused by exposure to seismic surveys are so low, as compared to natural mortality rates, that the impact of seismic surveying on recruitment to a fish stock must be regarded as insignificant.

Physiological Effects.—Physiological effects refer to cellular and/or biochemical responses of fish to acoustic stress. Such stress potentially could affect fish populations by increasing mortality or reducing reproductive success. Primary and secondary stress responses of fish after exposure to seismic survey sound appear to be temporary in all studies done to date (Sverdrup et al. 1994; McCauley et al. 2000a,b). The periods necessary for the biochemical changes to return to normal are variable, and depend on numerous aspects of the biology of the species and of the sound stimulus (see Appendix E).

Behavioral Effects.—Behavioral effects include changes in the distribution, migration, mating, and catchability of fish populations. Studies investigating the possible effects of sound (including seismic survey sound) on fish behavior have been conducted on both uncaged and caged individuals (Chapman and Hawkins 1969; Pearson et al. 1992; Santulli et al. 1999; Wardle et al. 2001; Hassel et al. 2003).

Typically, in these studies fish exhibited a sharp "startle" response at the onset of a sound followed by habituation and a return to normal behavior after the sound ceased.

There is general concern about potential adverse effects of seismic operations on fisheries, namely a potential reduction in the "catchability" of fish involved in fisheries. Although reduced catch rates have been observed in some marine fisheries during seismic testing, in a number of cases the findings are confounded by other sources of disturbance (Dalen and Raknes 1985; Dalen and Knutsen 1986; Løkkeborg 1991; Skalski et al. 1992; Engås et al. 1996). In other airgun experiments, there was no change in catch per unit effort (CPUE) of fish when airgun pulses were emitted, particularly in the immediate vicinity of the seismic survey (Pickett et al. 1994; La Bella et al. 1996). For some species, reductions in catch may have resulted from a change in behavior of the fish, e.g., a change in vertical or horizontal distribution, as reported in Slotte et al. (2004).

In general, any adverse effects on fish behavior or fisheries attributable to seismic testing may depend on the species in question and the nature of the fishery (season, duration, fishing method). They may also depend on the age of the fish, its motivational state, its size, and numerous other factors that are difficult, if not impossible, to quantify at this point, given such limited data on effects of airguns on fish, particularly under realistic at-sea conditions.

(6) Direct Effects on Invertebrates and Their Significance

The existing body of information on the impacts of seismic survey sound on marine invertebrates is very limited. However, there is some unpublished and very limited evidence of the potential for adverse effects on invertebrates, thereby justifying further discussion and analysis of this issue. The three types of potential effects of exposure to seismic surveys on marine invertebrates are pathological, physiological, and behavioral. Based on the physical structure of their sensory organs, marine invertebrates appear to be specialized to respond to particle displacement components of an impinging sound field and not to the pressure component (Popper et al. 2001; see also Appendix F).

The only information available on the impacts of seismic surveys on marine invertebrates involves studies of individuals; there have been no studies at the population scale. Thus, available information provides limited insight on possible real-world effects at the regional or ocean scale. The most important aspect of potential impacts concerns how exposure to seismic survey sound ultimately affects invertebrate populations and their viability, including availability to fisheries.

The following sections provide a synopsis of available information on the effects of exposure to seismic survey sound on species of decapod crustaceans and cephalopods, the two taxonomic groups of invertebrates on which most such studies have been conducted. The available information is from studies with variable degrees of scientific soundness and from anecdotal information. A more detailed review of the literature on the effects of seismic survey sound on invertebrates is provided in Appendix F.

Pathological Effects.—In water, lethal and sub-lethal injury to organisms exposed to seismic survey sound could depend on at least two features of the sound source: (1) the received peak pressure, and (2) the time required for the pressure to rise and decay. Generally, as received pressure increases, the period for the pressure to rise and decay decreases, and the chance of acute pathological effects increases. For the type of airgun array planned for the proposed program, the pathological (mortality) zone for crustaceans and cephalopods is expected to be within a few meters of the seismic source; however, very few specific data are available on levels of seismic signals that might damage these animals. This premise is based on the peak pressure and rise/decay time characteristics of seismic airgun arrays currently in use around the world.

Some studies have suggested that seismic survey sound has a limited pathological impact on early developmental stages of crustaceans (Pearson et al. 1994; Christian et al. 2003; DFO 2004). However, the impacts appear to be either temporary or insignificant compared to what occurs under natural conditions. Controlled field experiments on adult crustaceans (Christian et al. 2003, 2004; DFO 2004) and adult cephalopods (McCauley et al. 2000a,b) exposed to seismic survey sound have not resulted in any significant pathological impacts on the animals. It has been suggested that exposure to commercial seismic survey activities has injured giant squid (Guerra et al. 2004), but there is no evidence to support such claims.

Physiological Effects.—Physiological effects refer mainly to biochemical responses by marine invertebrates to acoustic stress. Such stress potentially could affect invertebrate populations by increasing mortality or reducing reproductive success. Any primary and secondary stress responses (i.e., changes in haemolymph levels of enzymes, proteins, etc.) of crustaceans after exposure to seismic survey sounds appear to be temporary (hours to days) in studies done to date (Payne et al. 2007). The periods necessary for these biochemical changes to return to normal are variable and depend on numerous aspects of the biology of the species and of the sound stimulus.

Behavioral Effects.—There is increasing interest in assessing the possible direct and indirect effects of seismic and other sounds on invertebrate behavior, particularly in relation to the consequences for fisheries. Changes in behavior could potentially affect such aspects as reproductive success, distribution, susceptibility to predation, and catchability by fisheries. Studies investigating the possible behavioral effects of exposure to seismic survey sound on crustaceans and cephalopods have been conducted on both uncaged and caged animals. In some cases, invertebrates exhibited startle responses (e.g., squid in McCauley et al. 2000a,b). In other cases, no behavioral impacts were noted (e.g., crustaceans in Christian et al. 2003, 2004; DFO 2004). There have been anecdotal reports of reduced catch rates of shrimp shortly after exposure to seismic surveys; however, other studies have not observed any significant changes in shrimp catch rate (Andriguetto-Filho et al. 2005). Parry and Gason (2006) reported no changes in rock lobster CPUE during or after seismic surveys off western Victoria, Australia, from 1978–2004. Any adverse effects on crustacean and cephalopod behavior or fisheries attributable to seismic survey sound depend on the species in question and the nature of the fishery (season, duration, fishing method).

(7) Direct Effects on Seabirds and Their Significance

Investigations into the effects of airguns on seabirds are extremely limited. Stemp (1985) conducted opportunistic observations on the effects of seismic exploration on seabirds, and Lacroix et al. (2003) investigated the effect of seismic surveys on molting long-tailed ducks in the Beaufort Sea, Alaska. Stemp (1985) did not observe any effects of seismic testing, although he warned that his observations should not be extrapolated to areas with large concentrations of feeding or molting birds. In a more intensive and directed study, Lacroix et al. (2003) did not detect any effects of nearshore seismic exploration on molting long-tailed ducks in the inshore lagoon systems of Alaska's North Slope. Both aerial surveys and radio-tracking indicated that the proportion of ducks that stayed near their marking location from before to after seismic exploration was unaffected by proximity to seismic survey activities. Seismic activity also did not appear to change the diving intensity of long-tailed ducks significantly.

Birds might be affected slightly by seismic sounds from the proposed study, but the impacts are not expected to be significant to individual birds or their populations. The types of impacts that are possible are summarized below:

Localized, temporary displacement and disruption of feeding.—Such displacements would be similar to those caused by other large vessels that passed through the area. Any adverse effects would be negligible.

Modified prey abundance.—It is unlikely that prey species for birds will be affected by seismic activities to a degree that affects the foraging success of birds. If prey species exhibit avoidance of the ship, the avoidance is expected to be transitory and limited to a very small portion of a bird's foraging range.

Disturbance to breeding birds.—A vessel (seismic or otherwise) that approaches too close to a breeding colony could disturb adult birds from nests in response either to sonic or to visual stimuli. There is no potential for this because the planned surveys will not occur close to land.

Egg and nestling mortality.—Disturbance of adult birds from nests can lead to egg or nestling mortality *via* temperature stress or predation. There is no potential for this considering the distance that the seismic survey will occur from major colonies.

Chance injury or mortality.—Many species of marine birds feed by diving to depths of several meters or more. Flocks of feeding birds may consist of hundreds or even thousands of individuals. Also, some species of seabirds (particularly alcids) escape from boats by diving when the boat gets too close. It is possible that, during the course of normal feeding or escape behavior, some birds could be near enough to an airgun to be injured by a pulse. Although no specific information is available about the circumstances (if any) under which this could occur, the negligible aversive reactions of birds to airguns (see above) suggest that a bird would have to be very close to any airgun to receive a pulse with sufficient energy to cause injury, if that is possible at all.

Induced injury or mortality.—A seismic survey could attract seabirds if it disorients, injures, or kills prey species, or otherwise increases the availability of prey species to the birds. Birds drawn too close to an airgun could be at risk of injury. However, available evidence from other seismic surveys using airguns has not shown a pattern of fish (or other prey) kills from airguns [see § IV (5) and IV (6), above]. Thus, the potential that birds would be attracted and subsequently injured by the proposed seismic surveys appears very low.

(8) Indirect Effects on Marine Mammals, Sea Turtles, and Their Significance

The proposed airgun operations will not result in any permanent impact on habitats used by marine mammals or sea turtles, or to the food sources they use. The main impact issue associated with the proposed activities will be temporarily elevated noise levels and the associated direct effects on marine mammals and sea turtles, as discussed above.

During the seismic study, only a small fraction of the available habitat would be ensonified at any given time. Disturbance to fish species and invertebrates would be short-term and fish are expected to return to their pre-disturbance behavior once the seismic activity ceased [see § IV(5) and IV(6), above]. Thus, the proposed survey would have little, if any, impact on the abilities of marine mammals or sea turtles to feed in the area where seismic work is planned.

Some mysticetes feed on concentrations of zooplankton. A reaction by zooplankton to a seismic impulse would only be relevant to whales if it caused a concentration of zooplankton to scatter. Pressure changes of sufficient magnitude to cause that type of reaction would probably occur only very close to the source. Impacts on zooplankton behavior are predicted to be negligible, and that would translate into negligible impacts on those mysticetes that feed on zooplankton.

(9) Cumulative Effects

Cumulative effects refer to the impacts on the environment that result from a combination of past, existing, and imminent projects and human activities. Causal agents of cumulative effects can include multiple causes, multiple effects, effects of activities in more than one locale, and recurring events.

Human activities are limited in offshore waters of the proposed seismic survey areas in Central America. However, some vessel traffic and commercial fishing occur within each of the proposed areas. These activities, when conducted separately or in combination with other activities, could affect marine mammals and sea turtles in the study areas.

(a) Oil and Gas Industry

Pacific

Despite the fact that Central America has few energy resources, the region is a major avenue for oil transportation because of the Panama Canal. In 1997, 32 million tonnes of oil products passed through the canal for dispersal at points in North and South America and across the Pacific; approximately 0.6 Mb/d pass through the Panama Canal (Rodrigue 2007).

Nicaragua does not currently have any oil production, but exploration for petroleum resources began in 1930. On the Pacific coast, the offshore Sandino Basin has been the focus of exploratory efforts (Fig. 8). In the 1970s, thousands of kilometers of seismic data were shot and several exploration wells were drilled (INE 2006). In 1990, a 2D seismic survey was conducted that shot 1360 km of marine seismic surveys (INE 2006). However, no commercial development has begun in Nicaragua's offshore zone. In May 2003, the Nicaraguan government issued exploration and production contracts to a number of U.S. firms granting them 6-year leases to explore. Those contracts included 19 offshore blocks on the Pacific coast, for a total of 3423 km^2 awarded to Industria Oklahoma Nicaragua, and 12 blocks in offshore Pacific area, covering 4000 km^2, awarded to Hellen Greathouse Year 2000 Trust (Alexander's Gas & Oil Connection 2003). The government's stated goal is to produce 50,000 bpd of petroleum and 2 mm cfpd of natural gas (Alexander's Gas & Oil Connection 2002).

Costa Rica, despite establishing oil and gas licensing blocks in 1994 and opening them to bid to foreign companies in 1997, effectively produces zero amounts of oil. In 2002, the then-newly-elected President Abel Pacheco de la Espriella essentially declared Costa Rica free of oil exploration and development. It is unclear how the election of President Oscar Arias Sanchez in 2006 may change that *de facto* policy.

Caribbean

The Caribbean Sea is an important petroleum processing and shipping area with several refineries and storage facilities. The oil and gas industry in this area is characterized by production and pumping platforms, tanker traffic, seismic surveys, explosive removal of platforms from expired lease areas, and both aircraft and vessel support. Sources of pollution from oil and gas activities include oil spills from tankers, overflows, routine discharges (produced water, drilling muds and cuttings) and, potentially, blowouts and platform fires. Oil pollution can have an impact on the ecology of coastal and marine ecosystems such as coral reefs, mangrove forests, shellfish, fish, marine mammals, and sea turtles. In the Caribbean basin, 50% of the 1 million tons of oil that enter the marine environment annually come from tankers and other ships (Patin 2003).

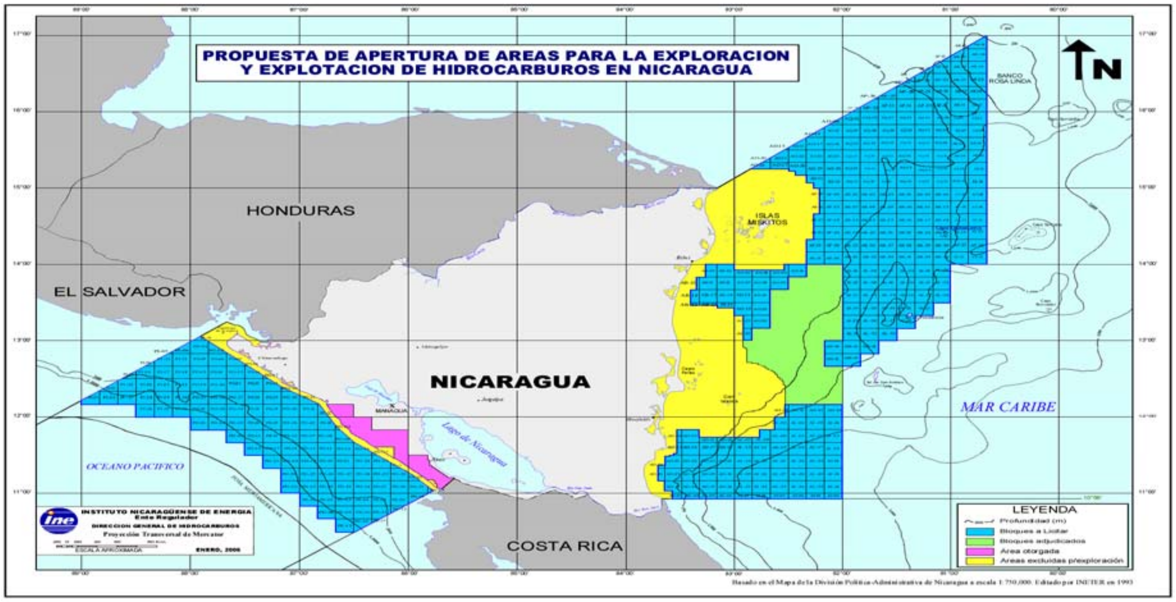

FIGURE 8. Oil and gas lease areas for lease offshore Nicaragua (Instituto Nicaraguense de Energia 2006).

In 2003, the Nicaraguan government issued licenses for oil and gas exploration in two offshore blocks in the Mosquitia Basin in the southwestern portion of the Nicaragua Rise (see Fig. 8). Plans for the region include 1000 km of new 2-D seismic on each concession, followed by 100 km^2 of 3-D and ultimately an exploration well on each site. Preliminary estimates place potential reserves at 7 billion barrels of oil. Additional prospects on the Isabel Bank may yield 3.5 billion barrels of oil (see Fig. 8). MKJ Xploration Inc., Metairie, LA, recently (2006) signed oil and gas concessions with the Nicaraguan government for blocks in the Caribbean Sea (OGJ 2006). Exploration is planned to begin as soon as permits are obtained.

As described above for its west coast, Costa Rica also has limited oil exploration and development on the east coast. In 1994, Costa Rica passed the Hydrocarbons Law that divided the country into 27 oil and natural gas exploration blocks. These blocks were opened to bidding in 1997. One site—Talamaca—in southeastern Costa Rica has been the focus of a great deal of controversy because of planned offshore drilling. The exploration company—Harken-MKJ—had its offshore drilling plans denied in February 2002. Under President Abel Pacheco de la Espriella, Costa Rica had a *de facto* moratorium on oil exploration.

(b) Shipping and Vessel Noise

Vessel noise could affect marine animals in the proposed study area. Shipping noise generally dominates ambient noise at frequencies from 20 to 300 Hz (Richardson et al. 1995). Baleen whales are thought to be more sensitive to sound at these low frequencies than are toothed whales. There may be some localized avoidance by marine mammals of commercial ships operating routinely in and near the proposed seismic program area. The main vessel traffic in the proposed study area will consist fishing vessels, as well as other commercial (cargo) and pleasure vessels. Several major international marine trade routes pass through the study area and lead to and from the Panama Canal (e.g., NOAA 2004), which connects the Pacific with the Atlantic Ocean.

On the Pacific coast, both Nicaragua and Costa Rica have port facilities. Nicaragua has three Pacific seaports, all operated by the government-run Port Authority: Corinth, Puerto Sandino, and San Juan del Sur (Industry Canada 2006). The most suitable for commercial shipping is at Corinto (on the northern coastline), whereas the port at Puerto Sandino is used primarily for the import of crude petroleum and bulk cargo. The port at San Juan del Sur (southern coastline) has limited capacity and uses barges to load and unload cargo. Costa Rica has a number of Pacific ports. Several are located in the Golfo de Nicoya, including Caldera, Puntarenas, and Puerto Punta Morales. The primary Pacific port is Caldera, located ~100 km from the capital of San Jose. Caldera is the main port for international shipments. Puntarenas was originally constructed for the export of coffee and to serve the railroad, and is now a major port for visiting cruise ships, with most visiting from November to April. Puerto Punta Morales was constructed for the exclusive export of sugar, alcohol, and molasses. Numerous marinas serve the sport fishing and pleasure vessel industry. Marina Flamingo in Guanacaste, also in Costa Rica's northwest, has facilities for 70 sport fishing and sailboats. Whale watching is developing into a popular tourist activity in Central America, although it is still in its early stages compared to Mexico and the United States.

On the Caribbean coast of Nicaragua and Costa Rica, ports are less developed as compared with those on the Pacific coast. Nicaragua's three Caribeean ports include Puerto Cabezas, El Bluff/Bluefields, and El Rama (Industry Canada 2006). Costa Rica's main Caribbean port is Puerto Limon, the capital of Limon province. This port developed as a major banana export port and is now a popular cruise ship destination.

The Panama Canal is one of the world's major shipping routes and is a significant focus for marine shipping to the south of Costa Rica. Grains account for ~43% of goods shipped through the canal, whereas containers and petroleum products account for 11 and 10%, respectively (Rodrigue 2007). An average of 35 vessels transit the canal each day, for an annual total of ~13,000 vessels (Rodrigue 2007).

There is also an increasing number of vessels off of Central America associated with the whalewatching industry. In 2001, there were 25 tour operators in Costa Rica. The number of people that participated in whalewatching grew from 2034 in 1991 to 90,720 in 1994 (Hoyt 1991).

The proposed seismic survey will consist of ~1328 line km in the Caribbean and ~2652 km in the Pacific, which will be small proportions of the combined vessel traffic for the proposed study areas.

(c) Fishing

The primary contributions of fishing to potential cumulative impacts on marine mammals and sea turtles involve direct removal of prey items, noise, and potential entanglement. There may be some localized avoidance by marine mammals of fishing vessels near the seismic area. Also, entanglement in fishing gear can lead to mortality of some marine mammals and sea turtles.

Pacific

Commercial and sport fishing takes place offshore from Nicaragua and Costa Rica in the ETP. Primary commercial species include shrimps and prawns, sharks and rays, tuna, and perch-like fishes (FAO 2003; Sea Around Us 2007; Table 9). The Gulf of Fonseca is an important shrimp nursery (NOAA 2004). Most of the commercial fishing is done by bottom-trawling, but mid-water trawling, purse seining, boat seining, and handlines are also used (Sea Around Us 2007).

In Costa Rica, sport fishing occurs off the Nicoya Peninsula, with vessels heading north into the offshore area. Marlin, sailfish, tuna, dorado, wahoo, and roosterfish are all caught by sport fishing vessels (Fishcostarica.com 2007). Marlin can be caught throughout the year, although the peak is November–

TABLE 9. Eastern Central Pacific total commercial fishery production (mt) for Nicaragua and Costa Rica, 1996-2001.

COUNTRY	SPECIES	1996	1997	1998	1999	2000	2001
COSTA RICA	Shrimps, prawns	6,675	5,718	4,956	5,419	3,619	3,628
	Spiny and rock lobsters	7	7	3	4	14	17
	Crabs, sea-spiders	3	50	9	8	4	3
	Sharks, rays, chimaeras	3,486	5,548	7,632	7,833	12,757	9,551
	Tunas, bonitos, billfish	5,147	3,938	3,279	3,299	3,552	4,019
	Herrings, sardines, anchovies	438	1,175	906	1,788	1,628	2,207
	Unidentified marine fishes	7,543	10,564	7,727	9,612	3,978	3,544
	Miscellaneous coastal fishes	529	631	1,122	921	618	450
	Miscellaneous pelagic fishes					8,370	11,221
	Squids, cuttlefish, octopus	47	69	7	78	78	77
	Miscellaneous molluscs	65	109	62	55	42	
	TOTAL (mt)	23,940	27,809	25,703	29,017	34,660	34,717
NICARAGUA	Shrimps, prawns	3,228	4,134	5,901	5,893	6,232	6,688
	Spiny and rock lobsters	101	152	66	131	476	652
	Sharks, rays, chimaeras				160	110	200
	Tunas, bonitos, billfish				3,340	3,730	
	Unidentified marine fishes	3,580	4,595	5,442	926	757	1,270
	Miscellaneous coastal fishes				2,700	2,000	2,745
	Miscellaneous pelagic fishes				710	2,540	2,470
	TOTAL (mt)	6,909	8,881	11,409	13,860	15,845	14,025

Data Source: FAO (2003)

March and August–September. Sailfish can be caught year-round with a peak from May to August, whereas tuna is also a year-round fish with a peak from August to October. Dorado is a focus of the sport fishery from May to October, and wahoo fishing peaks in July–August. Roosterfish are also caught year-round, although their peak is November–March.

Although hundreds of thousands of dolphins used to be killed in the tuna fishery annually, the bycatch has been drastically reduced, and in recent years has been less than 2000 dolphins (IATTC 2002) and <0.05% of the population size of each ETP dolphin stock (Bayliff 2004).

Caribbean

Costa Rica does not have a large-scale commercial fishery in the Caribbean (only two vessels fish for large pelagic species) and, under specific legislation, the first ~22 km from the coast (territorial waters) are reserved solely for small-scale artisanal fishing. Furthermore, large areas of the Caribbean coastal zone have been designated as National Parks, protecting land as well as marine areas, where small-scale fishing is prohibited or severely restricted. The small-scale artisanal fishery involves 228 small boats or dugout canoes ~9 m in length and fitted with high-powered outboard motors (FAO 2004).

Recreational fishing, especially for marine species at the mouths of rivers and in coastal lagoons, is of growing importance in Costa Rica. Large pelagic species are not often fished in the Caribbean. Important species for sport fishing are snook, tarpon, wahoo, dolphinfish, snapper, and barracuda. A number of sport fishing camping sites have been built around the coastal lagoons in the northern part of the Caribbean to accommodate foreign tourists who come to fish mainly for tarpon and snook. Some 50 or so aluminium or fiberglass vessels 6–8 m in length and fitted with outboard motors are used for this type of fishing (FAO 2004).

The total commercial catch in 2001–2003 for the Caribbean Costa Rica was 480–675 tonnes. Landings from 1953 to 2003 consisted of 84% spiny lobster, 10% *Penaeus* shrimps, and 6% serranid finfish, e.g., sea basses and groupers. Swordfish, marlin, and dolphin each comprised <1% of the catch. Type of gear used is mainly traps (36% of all gear types used in 1950–2003), bottom trawls (26%), mid-water trawls (18%), bagnets (5%), hooks (5%), and gillnets (2.5%) (Sea Around Us 2007).

In Nicaragua, the lobster fishery is currently the most valuable single-species fishery and also the main provider of local employment. The fishery is based on the extensive reef areas that lie 15–100 km offshore, and Nicaraguan fishermen operate along most of the coast from the Miskito Cays to the Costa Rican border. The artisanal fishery takes place along the coast, around reefs and cays, and the commercial fishery is concentrated at locations farther from shore, in deeper waters. There is a substantial fishery in the south of Nicaragua, based on diving and trapping boats sailing from Bluefields and Corn Island, near the point where the proposed northern track lines cross.

Total catch in Nicaragua in 2001–2003 was 10,219–10,544 tonnes. Landings from 1950 to 2003 consisted primarily of 55% *Penaeus* shrimps, 34% spiny lobster, 5% snooks, 2% serranid finfish, e.g., sea basses and groupers, and 2% snappers. Type of gear used is mainly bottom trawls (54% of all gear types used in 1950–2003), traps (31%), mid-water trawls (5%), hooks (5%), and bagnets, purse seines, handlines, and gillnets (each ~1%) (Sea Around Us 2007).

(d) Hunting and Incidental Mortality

Certain cetaceans are currently hunted in some parts of the Caribbean, although subsistence use is generally limited. Species that may be hunted in the Caribbean include the endangered humpback whale, as well as pygmy killer whales, short-finned pilot whales, and dolphins (e.g., spinner dolphins). The sperm whale has been hunted until recently in some parts of the Caribbean (Romero et al. 2001). In Dominica, sperm whales that occasionally wash up on shore (two per year on average) are harvested opportunistically (High North Alliance 2003). However, hunting areas in the Caribbean are northeast of the area where the seismic survey is planned.

The short-finned pilot whale is the most heavily hunted cetacean in the Caribbean. It is harvested in the Lesser Antilles, especially St. Vincent and St. Lucia (east of the waters where the planned seismic survey will occur). The harvest averages 300–450 animals annually (High North Alliance 2003). Humpback whales (up to four per year) are hunted by Bequian subsistence users on the islands of St. Vincent and the Grenadines (IWC 2007b). Historically, there was hunting for humpbacks from Grenada and from Trinidad and Tobago, but whaling ceased by the mid-1920s (Romero and Hayford 2000; Reeves et al. 2001a,b).

Costa Rica and Nicaragua are members of the International Whaling Commission; El Salvador and Honduras are not members (IWC 2007c). None of those nations are whaling countries. No commercial or subsistence whaling is practiced in Costa Rican, Nicaraguan, El Salvadorian, or Honduran territorial waters. However, it is estimated that <2000 dolphins are still being killed each year by tuna fishing fleets in the Pacific Ocean west of Mexico and Central America (IATTC 2002). Some dolphins are also killed for shark bait (May-Collado 2006).

(e) Cumulative Impacts to Sea Turtles

Major threats to sea turtles include hunting and poaching, the collection of eggs, coastal development, increased tourism including beaches obstructed with lights and chairs, beach sand mining, pedestrian traffic, oil spills, ship strikes, entanglement in fishing gear and bycatch, ingestion of plastic and marine garbage, and destruction of feeding habitat in coral reefs and seagrass beds (Horrocks 1992; Marcovaldi et al. 2003).

Sea turtle bycatch in longline fishing operations was evaluated off the Pacific coast of Costa Rica from October 1991–February 1992 (Segura and Arauz 1995). A total of 31 sea turtles were caught during 13 of 27 longline deployments, 29 of which were olive ridleys and 2 were green turtles (Segura and Arauz 1995). The mortality rate of olive ridleys was 10.3% (Segura and Arauz 1995).

During an observer program on shrimp trawlers along the Pacific coast of Costa Rica, 281 turtles were caught in nets during 2557 h of observation (Arauz et al. 1998). Most of the captured turtles were olive ridleys (90%), followed by green turtles (9.6%), and hawksbills (0.4%). Arauz et al. (1998) estimated the mortality rates attributable to shrimp nets to be 37.6% for olive ridleys and 50% for green turtles. Along the Pacific coast of Costa Rica alone, the annual incidental catch of turtles by the shrimp fleet is estimated at 15,631 turtles. Arauz et al. (1998) noted that Costa Rica has the highest recorded average CPUE rate for sea turtles in the world and suggested that countries in the ETP use Turtle Excluder Devices to reduce turtle bycatch.

The United Nations Environment Program (UNEP) has organized a Wider Caribbean Sea Turtle Recovery Team and Conservation Network (WIDECAST). Since 1992, many recommendations of the WIDECAST action plan for sea turtle recovery in the Caribbean (Horrocks 1992) have been implemented.

(10) Unavoidable Impacts

It is expected that unavoidable impacts to the species of marine mammals and turtles occurring in the proposed study area in Central America will be limited to short-term, localized changes in behavior of individuals. For cetaceans, some of the changes in behavior may be sufficient to fall within the MMPA definition of "Level B Harassment" (behavioral disturbance; no serious injury or mortality). No long-term or significant impacts are expected on any of these individual marine mammals or turtles, or on the populations to which they belong. Effects on recruitment or survival are expected to be (at most) negligible.

Alternative Action: Another Time

An alternative to issuing the IHA for the period requested, and to conducting the project then, is to issue the IHA for another time, and to conduct the project at that alternative time. The proposed time for the Central American SubFac cruise (January–March 2008) is the most suitable time logistically for the *Langseth*, the *New Horizon*, and the crew. Issuing the IHA for a later time would delay the cruise; this would disrupt the schedule for the scientific projects scheduled to be conducted by the *Langseth* in 2008.

During the periods of the proposed activity off Central America in January–March 2008, most species of marine mammals will be dispersed throughout the area. The proposed study area is not known to be a critical feeding area for any of the species of marine mammals that are found there at that time of year. However, a small number of humpback whales are known to calf on the Pacific coast off Costa Rica and Nicaragua at the time of the proposed survey, and some delphinids may also be breeding at that time of year. Because of the nearly year-round presence of humpback whales off the Pacific coast, it is nearly impossible to choose a time of year when calving humpbacks do not occur in the area. Therefore, postponing the survey would likely not change the potential impacts of this project on marine mammals. The survey also overlaps the nesting season of some turtle species; however, postponing the project could result in the survey occurring at a time of year when more turtle species or greater numbers are nesting.

Postponing the survey will also significantly delay of geophysical studies that are planned by L-DEO for 2008. Each of the studies planned by L-DEO has its own individual scientific rationale and has undergone rigorous scientific merit review. Each study has been judged to be of sufficient scientific value to warrant expenditure of significant federal funds. Inability to proceed with one or more of these studies would result in loss of important scientific data and knowledge, and further disruption to planned ship and investigator schedules.

No Action Alternative

The No Action Alternative would result in cancellation of the proposed activities, and thus no disturbance by the planned activities to marine mammals in Central America. Each of the studies planned by L-DEO has its own individual scientific rationale and has undergone rigorous scientific merit review. Each study has been judged to be of sufficient scientific value to warrant expenditure of significant federal funds. Inability to proceed with one or more of these studies would result in loss of important scientific data and knowledge, and further disruption to planned ship and investigator schedules. The seismic data from the Central American SubFac survey are needed to determine the inputs, outputs, and controlling processes of subduction zone systems, by examining the volcanic arc, backarc, and downgoing plate in the Costa Rican portion of the Central American Focus Site. The "No Action" alternative would deprive the scientific community of these data.

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VI. LITERATURE CITED

Acevedo, A. and M.A. Smultea. 1995. First records of humpback whales including calves at Golfo Dulce and Isla del Coco, Costa Rica, suggesting geographical overlap of northern and southern hemisphere populations. **Mar. Mamm. Sci**. 11(4):554-560.

Acevedo, A. and B. Würsig. 1991. Preliminary observations on bottlenose dolphins, Tursiops truncatus, at Isla del Coco, Costa Rica, **Aquat. Mamm.** 17:148-151.

Acevedo, A., A. DiBerardinis, S. Larkin, K. Larkin, and P. Forestell. 2005. Social interactions between tucuxi and bottlenose dolphins in Gandoca-Manzanillo, Costa Rica. **LAJAM** 4(1):49-54.

Acevedo-Gutierrez, A. 1994. First record of a sea lion, *Zalophus californianus*, at Isla del Coco, Costa Rica. **Mar. Mamm. Sci.** 10(4):484-485.

Acevedo-Gutierrez, A. 1996. Lista de mamíferos marinos en Golfo Dulce e Isla del Coco, Costa Rica. **Rev. Biol. Trop.** 44(2):933- 934.

Acevedo-Gutierrez, A. and S. Burkhart. 1998. Seasonal distribution of bottlenose (*Tursiops truncatus*) and pantropical spotted (*Stenella attenuata*) dolphins (Cetacea:Delphinidae) in Golfo Dulce, Costa Rica. **Rev. Biol. Trop**. 46 (Supl. 6):91-101.

Acevedo-Gutierrez, A. and E.N. Parker. 2000. Surface behavior of bottlenose dolphins is related to spatial arrangment of prey. **Mar. Mamm. Sci.** 16(2):287-298.

Acevedo-Gutierrez, A, B. Brennan, P. Rodríguez, and M. Thomas. 1997. Resightings and behavior of false killer whales (*Pseudorca crassidens*) in Costa Rica. **Mar. Mamm. Sci.** 13(2):307-313.

ACS. 2007. American Cetacean Society fact sheet: spinner dolphin, S*tenella longirostris*. http://www.acsonline.org/factpack/SpinnerDolphin.htm

Aguayo, A.L. 1974. Baleen whales off continental Chile. p. 209-217 *In:* W.E. Schevill (ed.), The whale problem: a status report. Harvard University Press, Cambridge, MA.

Alexander's Gas & Oil Connection. 2002. Nicaragua allows US companies to explore oil and gas deposits. http://www.gasandoil.com/goc/company/cnl23224.htm

Alexander's Gas & Oil Connection. 2003. Nicaragua awards exploration and production contracts to US firms. http://www.gasandoil.com/goc/company/cnl32415.htm

Allen, R.L. 1985. Dolphins and the purse-seine fishery for yellowfin tuna. p. 236-252 *In*: J.R. Beddington, R.J.H. Beverton and D.M. Lavigne (eds.), Marine mammals and fisheries. George Allen & Unwin, London, U.K. 354 p.

Almada-Villela, P., M. Mcfield, P. Kramer, P.R. Kramer, and E. Arias-Gonzalez. 2002. Status of Coral Reefs of Mesoamerica - Mexico, Belize, Guatemala, Honduras, Nicaragua, and El Salvador. p. 303-324 *In:* C.R. Wilkinson (ed.), Status of coral reefs of the world: 2002. GCRMN Report, Australian Institute of Marine Science, Townsville.

Alvarado, J. and A. Figueroa. 1995. East Pacific green turtle, *Chelonia mydas*. p. 24-36 *In*: P.T. Plotkin (ed.), National Marine Fisheries Service and U.S. Fish and Wildlife Service status reviews for sea turtles listed under the Endangered Species Act of 1973. NMFS, Silver Spring, MD. 139 p.

Alvarado, M.A. 1990. The results of more than two years of turtle egg harvests at Ostional, Costa Rica. p. 175-178 *In*: T.H. Richardson, J.I. Richardson, and M. Donnelly (compilers), Proc. 10th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFC-278. 286 p.

Andriguetto-Filho, J.M., A. Ostrensky, M.R. Pie, U.A. Silva, and W.A. Boeger. 2005. Evaluating the impact of seismic prospecting on artisanal shrimp fisheries. **Cont. Shelf Res.** 25:1720-1727.

Aprill, M. L. 1994. Visitation and predation of the Olive Ridley Sea Turtle, *Lepidochelys olivacea*, at nest sites in Ostional, Costa Rica. p. 3-6 *In*: K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (comp.), Proc. 14th Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Arauz, R.M., R. Vargas, I. Narango, and C. Gamboa. 1998. Analysis of the incidental capture and mortality of sea turtles in the shrimp fleet of Pacific Costa Rica. p. 1-3 *In*: S.P. Epperly and J. Braun (comp.), Proc. 17th Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-415. 294 p.

Araúz-Almengor, M. and R. Morera-Avila. 1994. Status of the marine turtles *Dermochelys coriacea*, *Chelonia agassizii*, and *Lepidochelys olivacea* at Playa Naranjo, Parque Nacional Santa Rosa, Costa Rica. p. 175 *In*: K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (comp.), Proc. 14th Symp. Sea Turtle Biol. Cons. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Arbelo, M., M. Méndez, E. Sierra, P. Castro, J. Jaber, P. Calabuig, M. Carrillo, and A. Fernández. 2005. Novel "gas embolic syndrome" in beaked whales resembling decompression sickness. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Arenas, P. and M. Hall. 1991. The association of sea turtles and other pelagic fauna with floating objects in the eastern tropical Pacific Ocean. p. 7-10 *In*: M. Salmon and J. Wyneken (comp.), Proc. 11th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-302. 195 p.

Arnbom, T., V. Papastavrou, L. Weilgart, and H. Whitehead. 1987. Sperm whales react to an attack by killer whales. **J. Mammal.** 68(2):450-453.

Arnbom, T. and H. Whitehead. 1989. Observations on the composition and behaviour of groups of female sperm whale near the Galápagos Islands. **Can. J. Zool.** 67(1):1-7.

Au, D.K.W. and W.L. Perryman. 1985. Dolphin habitats in the eastern tropical Pacific. **Fish. Bull.** 83(4):623-643

Au, W.W.L., A.A. Pack, M.O. Lammers, L.M. Herman, M.H. Deakos, and K. Andrews. 2006. Acoustic properties of humpback whale songs. **J. Acoust. Soc. Am.** 120(2):1103-1110.

Auil, N.E. 2004. Abundance and distribution trends of the West Indian manatee in the coastal zone of Belize: implications for conservation. M.Sc. Thesis, Texas A&M University, Galveston, Texas. 83 p.

Avila, J.M. 1995. Abundance of species *Sotalia fluviatilis*, Cispata Bay, Colombian Caribbean, using line transect methods. Abstr. 11th Bienn. Conf. Biol. Mar. Mamm., 14-16 Dec., Orlando, FL.

Backus, R.H. and W.E. Schevill. 1966. *Physeter* clicks. p. 510-528 *In*: K.S. Norris (ed.), Whales, dolphins, and porpoises. Univ. Calif. Press, Berkeley, CA.

Baker, C.S., A. Perry, J.L. Bannister, M.T Weinrich, R.B. Abernethy, J. Calambokidis, J. Lien, R.H. Lambertsen, J. Urbán Ramirez, O. Vasquez, P.J. Clapham, A. Alling, S.J. O'Brien, and S.R. Palumbi. 1993. Abundant mitochondrial DNA variation and world-wide population structure in humpback whales. **Proc. Nat. Acad. Sci. USA** 90:8239-8243.

Bain, D.E. and R. Williams. 2006. Long-range effects of airgun noise on marine mammals: responses as a function of received sound level and distance. **Int. Whal. Comm. Working Pap.** SC/58/E35. 13 p.

Baird, R.W. 2002a. Risso's dolphin. p. 1037-1039 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

Baird, R.W. 2002b. False killer whale. p. 411-412 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

Baird, R.W., A.D. Ligon, S.K. Hooker, and A.M. Gorgone. 2001. Subsurface and nighttime behaviour of pantropical spotted dolphins in Hawai'i. **Can. J. Zool.** 79(6):988-996.

Balcomb, K.C. and G. Nichols. 1982. Humpback whale censuses in the West Indies. **Rep. Int. Whal. Comm.** 32:401-406.

Balcomb, K.C., III and D.E. Claridge. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. **Bahamas J. Sci.** 8(2):2-12.

Ballance, L.T., R.L. Pitman, and P.C. Fiedler. 2006. Oceanographic influences on seabirds and cetaceans in the eatern tropical Pacific: a review. **Prog. Oceanogr.** 69:360-390.

Barlow, J. 1984. Reproductive seasonality in pelagic dolphins (*Stenella* spp.): implications for measuring rates. **Rep. Int. Whal. Comm Spec. Iss.** 6:191-198.

Barlow, J., M.C. Ferguson, W.F. Perrin, L. Ballance, T. Gerrodette, G. Joyce, C.D. Macleod, K. Mullin, D.L. Palka, and G. Waring. 2006. Abundance and densities of beaked and bottlenose whales (familyZiphiidae). **J. Cetacean Res. Manage.** 7(3):263-270.

Barmes, T., K.L. Eckert, and J. Sybesma. 1993. WIDECAST sea turtle recovery action plan for Aruba. *In:* K.L. Eckert (ed.), CEP Technical Report No. 25. UNEP Caribbean Environment Program, Kingston, Jamaica. 58 p.

Barros, N.B., D.A. Duffield, P.H. Ostrom, D.K. Odell, and V.R. Cornish. 1998. Nearshore vs. offshore ecotype differentiation of *Kogia breviceps* and *K. simus* based on hemoglobin, morphometric and dietary analyses. Abstr. World Mar. Mamm. Sci. Conf., Monaco, 20-24 Jan. 1998.

Baumgartner, M.F. 1997. The distribution of Risso's dolphin (*Grampus griseus*) with respect to the physiography of the Northern Gulf of Mexico. **Mar. Mamm. Sci.** 13(4):614-638.

Bayliff, W.H. (ed.) 2004. 2002 Annual report. Inter-American Tropical Tuna Commission, La Jolla, California. 96 p.

Bernard, H.J. and S.B. Reilly. 1999. Pilot whales *Globicephala* (Lesson, 1828). p. 245-279 *In*: S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 6. The second book of dolphins and the porpoises. Academic Press, San Diego, CA. 486 p.

Berta, A. and J.L. Sumich. 1999. Marine mammals/evolutionary biology. Academic Press, San Diego, CA. 494 p.

Berzin, A.A. 1978. Whale distribution in tropical eastern Pacific waters. **Rep. Int. Whal. Comm.** 28:173-177.

Best, P.B. 1979. Social organization in sperm whales, *Physeter macrocephalus*. p. 227-289 *In:* H.E. Winn and B.L. Olla (eds.), Behavior of marine animals, Vol. 3. Plenum, New York, NY.

Best, P.B., P.A.S. Canham, and N. Macleod. 1984. Patterns of reproduction in sperm whales, *Physeter macrocephalus*. **Rep. Int. Whal. Comm., Spec. Iss.** 6:51-79.

Bjarti, T. 2002. An experiment on how seismic shooting affects caged fish. Faroese Fisheries Laboratory, University of Aberdeen. 41 p.

Bjorndal, K.A. 1982. The consequences of herbivory for the life history pattern of the Caribbean green turtle, *Chelonia mydas*. p. 111-116 *In:* K.A. Bjorndal (ed.), Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Blackwell, S.B., R.G. Norman, C.R. Greene Jr. and W.J. Richardson. 2007. Acoustic measurements. p. 4-1 to 4-52 *In:* H. Patterson et al., Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July-September 2006: 90-day report. LGL Rep. P891-1. Rep. from LGL Alaska Res. Assoc. Inc., Anchorage, AK, and Greeneridge Sciences Inc., Santa Barbara, CA, for Shell Offshore Inc., Houston, TX, Nat. Mar. Fish. Serv., Silver Spring, MD, and U.S. Fish & Wildl. Serv., Anchorage, AK. 199 p. Available at http://www.nmfs.noaa.gov/pr/pdfs/permits/shell_90day_report.pdf.

Bolaños, J. and S. Boher. 2002. Sobre un varamiento masivo de delfin manchado del Atlantico (*Stenella frontalis*) en la Isla la Tortuga, nororiente de Venezuela. PT/Serie Informes Tecnicos MARN-ONDB-DGF-DFA 412, Caracas. (On a mass stranding of more than a hundred Atlantic spotted dolphins in la Tortuga Island, northeastern Venezuela).

Bolaños, J. and A. Villarroel-Marin. 2003. Three new records of cetacean species for Venezuelan waters. **Caribbean J. Sci.** 30(2):230-232.

Booman, C., J. Dalen, H. Leivestad, A. Levsen, T. van der Meeren, and K. Toklum. 1996. Effecter av luftkanonshyting på egg, larver og yngel. **Fisken og Havet** 1996(3):1-83. (Norwegian with English summary).

Borobia, M. and N.B. Barros. 1989. Notes on the diet of marine *Sotalia fluviatilis*. **Mar. Mamm. Sci**. 5(4):395-399.

Borobia, M., S. Siciliano, L. Lodi, and W. Hoek. 1991. Distribution of the South American dolphin *Sotalia fluviatilis*. **Can. J. Zool.** 69:1025-1039.

Bowles, A.E., M. Smultea, B. Würsig, D.P. DeMaster, and D. Palka. 1994. Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island Feasibility Test. **J. Acoust. Soc. Am.** 96:2469-2484.

Boyd, I.L., C. Lockyer, and H.D. March. 1999. Reproduction in marine mammals. p. 218-286 *In:* J.E. Reynolds III and S.A. Rommel (eds.), Biology of marine mammals. Smithsonian Institution Press, Washington and London. 578 p.

Branch, T.A., D.M. Palacios, K.M. Stafford, C. Allison, J.L. Bannister, C.L.K. Burton, K.C.S. Jenner, M-N.M. Jenner, B. Maughan, T. Miyashita, M.G. Morrice, V.J. Sturrock, R.C. Anderson, A.N. Baker, P.B. Best, P. Borsa, S. Childerhouse, K.P. Findlay, A.D. Ilangakoon, M. Joergensen, B. Kahn, B. Maughan, Y.A. Mikhalev, Oman Whale and Dolphin Research Group, D. Thiele, D. Tormosov, K. Van Waerebeek, and R.M. Warneke. 2006. Past and present distribution of blue whales in the Southern Hemisphere and northern Indian Ocean. Paper SC/58/SH16 presented to the IWC Scientific Committee, June 2006 (unpublished). 27 p. Paper available from the IWC Secretariat: secretariat@iwcoffice.org.

Brown, J. 1995. Ocean circulation. Pergamon Press, New York, NY.

Brownell, R.L., Jr. and P.J. Clapham. 1999. Burmeister's porpoise *Phocoena spinipinnis* Burmeister, 1865. p. 393-410 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 6. The second book of dolphins and the porpoises. Academic Press, San Diego, CA. 486 p.

Brownell, R.L., T. Yamada, J.G. Mead, and A.L. van Helden. 2004. Mass strandings of Cuvier's beaked whales in Japan: US Naval acoustic link? Paper SC/56/E37 presented to the IWC Scientific Committee, July 204, Sorrento, Italy. 10 p + Addendum. [Paper available from the Office of this Journal].

Buchanan, R.A., J.R. Christian, V.D. Moulton, B. Mactavish, and S. Dufault. 2004. 2004 Laurentian 2-D seismic survey environmental assessment. Rep. from LGL Ltd., St. John's, Nfld., and Canning & Pitt Associates, Inc., St. John's, Nfld., for ConocoPhillips Canada Resources Corp., Calgary, Alta. 274 p.

Caballero, S., H. Hamilton, C. Jaramillo, J. Capella, L. Flórez-González, C. Olavarria, H. Rosenbaum, F. Guhl, and C.S. Baker. 2001. Genetic characterisation of the Colombian Pacific Coast humpback whale population using RAPD and mitochondrial DNA sequences. **Mem. Queensl. Mus.** 47(2):459-464.

Calambokidis, J. and S.D. Osmek. 1998. Marine mammal research and mitigation in conjunction with air gun operation for the USGS 'SHIPS' seismic surveys in 1998. Draft Rep. from Cascadia Research, Olympia, WA, for U.S. Geol. Surv., Nat. Mar. Fish. Serv., and Minerals Manage. Serv.

Calambokidis, J., G.H. Steiger, J.M. Straley, T. Quinn, L.M. Herman, S. Cerchio, D.R. Salden, M. Yamaguchi, F. Sato, J.R. Urban, J. Jacobsen, O. von Ziegesar, K.C. Balcomb, C.M. Gabriele, M.E. Dahlheim, N. Higashi, S. Uchida, J.K.B. Ford, Y. Miyamura, P. Ladron de Guevara, S.A. Mizroch, L. Schlender, and K. Rasmussen. 1997. Abundance and population structure of humpback whales in the North Pacific basin. Final Contract Report 50ABNF500113 to Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA, 92038. 72. p.

Calambokidis, J., G.H Steiger, K. Rasmussen, J. Urbán R., K.C. Balcomb, P. Ladrón De Guevara, M. Salinas Z., J. K. Jacobsen, C.S. Baker, L.M. Herman, S. Cerchio, and J.D. Darling. 2000. Migratory destinations of humpback whales from the California, Oregon and Washington feeding ground. **Mar. Ecol. Prog. Ser.** 192:295-304.

Caldwell, D.K. and M.C. Caldwell. 1989. Pygmy sperm whale *Kogia breviceps* (de Blainville, 1838): dwarf sperm whale *Kogia simus* Owen, 1866. p. 235-260 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 4. River dolphins and the larger toothed whales. Academic Press, San Diego, CA. 444 p.

Campbell, C.L., C.J. Lagueux, and W.A. Coy. 2000. Hawksbill (*Eretmochelys imbricata*) nesting on the Pearl Cays of Nicaragua. p. 246-247 *In*: Mosier, A, A. Foley, and B. Brost (comp.), Proc. 20th Ann. Symp. Sea Turtle Biol. Cons. NOAA Tech. Mem. NMFS-SEFSC-477. 369 p.

Campbell, G.S., B.A. Bilgre, and R.H. Defran. 2002. Bottlenose dolphins (*Tursiops truncates*) in Turneffe Atoll, Belize: occurrence, site fidelity, group size and abundance. **Aquatic Mamm.** 28(2): 170-180.

Cardona-Maldonado, M.A. and A.A. Mignucci-Giannoni. 1999. Pygmy and dwarf sperm whales in Puerto Rico and the Virgin Islands, with a review of *Kogia* in the Caribbean. **Caribbean J. Sci.** 35(1-2):29-37.

Carr, T. and R.K. Bonde. 2000. Tucuxi (*Sotalia fluviatilis*) occurs in Nicaragua, 800 km north of its previously known range. **Mar. Mamm. Sci.** 16(2):447-452.

Carr, A., M.H. Carr and A.B. Meylan. 1978. The ecology and migrations of sea turtles. The west Caribbean green turtle colony. **Bull. Am. Mus. Hist.** 162(1):1-46.

Carretta, J.V., K.A. Forney, M.M. Muto, J. Barlow, J. Baker, B. Hanson, and M.S. Lowry. 2007. U.S. Pacific marine mammal stock assessments: 2006. Dep. Of Comm. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-398. 312 p.

Carwardine, M. 1995. Whales, dolphins and porpoises. Dorling Kindersley Publishing, Inc., NY. 256 p.

Cattanach, K.L., J. Sigurjónsson, S.T. Buckland, and T. Gunnlaugsson. 1993. Sei whale abundance in the North Atlantic, estimated from NASS-87 and NASS-89 data. **Rep. Int. Whal. Comm.** 43:315-321.

Cerna, J., C. Guti (Errez), P. Martinez, B. Quintero, and G.A. Ruiz. 1996. Research on *L. olivacea* in La Flor, Rivas, Nicaragua. p. 58-61 *In*: J.A. Keinath, D.E. Barnard, J.A. Musick, and B.A. Bell (comp.), Proc. 15th Annu. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 355 p.

CCC. 2003. Information on sea turtles and threats to their survival. http://www.cccturtle.org/sea-turtle-information.php

CEP. 2007. Biological diversity in the wider Caribbean region. http://www.cep.unep.org/marine-issues/plonearticlemultipage.2005-10-12.3537186879/plonearticle.2005-10-12.4456635765/

Chacón, D. 2000. Reproduction and conservation of the leatherback turtle, *Dermochelys coriacea* (Testudines: Dermochelyidae), on Playa Gandoca, Costa Rica: the nineties. p. 246-247 *In*: Mosier, A, A. Foley, and B. Brost (comp.), Proc. 20th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-477. 369 p.

Chacón, D. 2003. Nesting of the hawksbill turtle in the southern Caribbean coast of Costa Rica. p. 135-136 *In*: Seminoff, J.A. (comp.), Proc. 22nd Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-503. 308 p.

Chacón, D. and W. Quiros. 2003. Ecovolunteer program: an economic alternative supporting sea turtle conservation at Gandoca Beach, Costa Rica. p. 135-136 *In*: Seminoff, J.A. (comp.), Proc. 22nd Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-503. 308 p.

Chapman, C.J. and A.D. Hawkins. 1969. The importance of sound in fish behaviour in relation to capture by trawls. **FAO Fish. Rep.** 62:717-729.

Chandler, T.E. and J. Calambokidis. 2004. Costa Rica Dome blue whale cruise report. Unpublished report, 6 p. Available at http://www.cascadiaresearch.org/reports/CRUISE%20REPORT.pdf.

Chaves, A., N. Bolanos, and G. Marin. 1994. Ostional Biological Station: A site for research and education. p. 208-209 *In* K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (comp.), Proc. 14th Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Christal, J. and H. Whitehead. 1997. Aggregations of mature male sperm whales on the Galápagos Islands breeding ground. **Mar. Mamm. Sci.** 13(1):59-69.

Christal, J., H. Whitehead, and E. Lettevall. 1998. Sperm whale social units: variation and change. **Can. J. Zool.** 76(8):1431-1440.

Christian, J.R., A. Mathieu, D.H. Thomson, D. White, and R.A. Buchanan. 2003. Effect of seismic energy on snow crab (*Chionoecetes opilio*). Rep. by LGL Limited, St. John's, Nfld., for Environmental Studies Research Fund (ESRF), Calgary, Alb. 56 p.

Christian, J.R., A. Mathieu, and R.A. Buchanan. 2004. Chronic effects of seismic energy on snow crab (*Chionoecetes opilio*). Environmental Studies Research Funds Report No. 158, Calgary, AB. March.

Clapham, P.J. 1996. The social and reproductive biology of humpback whale: an ecological perspective. **Mamm. Rev**. 26(1):27-49.

Clarke, R. 1980. Catches of sperm whales and whalebone whales in the southeast Pacific between 1908 and 1975. **Rep. Int. Whal. Comm.** 30:285-288.

Clark, C.W. and W.T. Ellison. 2004. Potential use of low-frequency sounds by baleen whales for probing the environment: evidence from models and empirical measurements. p. 564-582 *In:* J.A. Thomas, C.F. Moss and M. Vater (eds.), Echolocation in bats and dolphins. Univ. Chicago Press, Chicago, IL.

Cornelius, S.E. 1982. Status of sea turtles along the Pacific coast of Middle America. p. 211-219 *In*: K.A. Bjorndal (ed.), Biology and conservation of sea Turtles. Smithsonian Inst. Press, Washington, DC. 583 p.

Cortés, J. and M.E. Hatziolos. 1998. Status of coral reefs of Central America: Pacific and Caribbean coasts. Chapter 11 *In*: C. Wilkinson (ed.), Status of coral reefs of the world: 1998. Australian Institute of Marine Science. Available at http://www.aims.gov.au/pages/research/coral-bleaching/scr1998/scr-11.html.

Cox, T.M., T.J. Ragen, A.J. Read, E. Vos, R.W. Baird, K. Balcomb, J. Barlow, J. Caldwell, T. Cranford, L. Crum, A. D'Amico, G. D'Spain, A. Fern ndez, J. Finneran, R. Gentry, W. Gerth, F. Gulland, J. Hildebrand, D. Houser, T. Hullar, P.D. Jepson, D. Ketten, C.D. MacLeod, P. Miller, S. Moore, D.C. Mountain, D. Palka, P. Ponganis, S. Rommel, T. Rowles, B. Taylor, P. Tyack, D. Wartzok, R. Gisiner, J. Mead, and L. Benner. 2006. Understanding the impacts of anthropogenic sound on beaked whales. **J. Cetac. Res. Manage.** 7(3):177-187.

Cubero-Pardo, P. and J. Rodríguez F. 2000. *Zalophus californianus* (Pinnipedia:Otariidae) en Costa Rica. **Rev. Biol. Trop.** 48(1):273.

Culik, B.M. 2002. Review on small cetaceans: distribution, behaviour, migration and threats. Available at http://www.cms.int/reports/small_cetaceans/index.htm

Cummings, W. C. 1985. Bryde's whale. p. 137–154 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, London, U.K. 362 p.

Dahlheim, M.E. and J.E. Heyning. 1999. Killer whale *Orcinus orca* (Linnaeus, 1758). p. 281-322 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 6. The second book of dolphins and the porpoises. Academic Press, San Diego, CA. 486 p.

Dahlheim, M.E., S. Leatherwood, and W.F. Perrin. 1982. Distribution of killer whales in the warm temperate and tropical eastern Pacific. **Rep. Int. Whal. Comm.** 32:647-653.

Dalebout, M.L., G.J.B. Ross, C.S. Baker, R.C. Anderson, P.B. Best, V.G. Cockcroft, H.L. Hinsz, V. Peddemors, and R.L. Pitman. 2003. Appearance, distribution, and genetic distinctiveness of Longman's beaked whale, *Indopacetus pacificus*. **Mar. Mamm. Sci.** 19(3):421-461.

Dalen, J. and G.M. Knutsen. 1986. Scaring effects in fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. p. 93-102 *In*: H.M. Merklinger (ed.), Progress in underwater acoustics. Plenum, NY. 839 p.

Dalen, J. and A. Raknes. 1985. Scaring effects on fish from three dimensional seismic surveys. Inst. Mar. Res. Rep. FO 8504/8505, Bergen, Norway. [Norwegian, Engl. summ.]

Dalen, J., E. Ona, A.V. Soldal, and R. Saetre. 1996. Seismiske undersøkelser til havs: en vurdering av konsekvenser for fisk og fiskerier [Seismic investigations at sea; an evaluation of consequences for fish and fisheries]. **Fisken og Havet** 1996:1-26. (in Norwegian, with an English summary).

Danil, K. and S.J. Chivers 2005. Habitat-based sptail and temporal variability in life history characteristics of female common dolphins (*Delphinus delphis*) in the eastern tropical Pacific. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Darling, J.D., K.M. Gibson, and G.K. Silber. 1983. Observations on the abundance and behavior of humpback whales (*Megaptera novaeangliae*) off West Maui, Hawaii, 1977-1979. p. 210-222 *In:* R. Payne (ed.), Communication and behavior of whales. AAAS Selected Symposia 76, Westview Press, Boulder, CO. 643 p.

d'Auvergne, C. and K.L. Eckert. 1993. WIDECAST sea turtle recovery action plan for St. Lucia. *In:* K.L. Eckert (ed.), CEP Technical Report No. 26. UNEP Caribbean Environment Program, Kingston, Jamaica. 70 p.

Davenport, J. and G.H. Balazs. 1991. 'Fiery bodies' - are pyrosomas an important component of the diet of leatherback turtles? **Brit. Herp. Soc. Bull.** 31:33-38.

Davis, R.W., G.J. Worthy, B. Würsig, and S.K. Lynn. 1996. Diving behavior and at-sea movements of an Atlantic spotted dolphin in the Gulf of Mexico. **Mar. Mamm. Sci.** 12(4):569-581.

Davis, R.W., G.S. Fargion, N. May, T.D. Leming, M. Baumgartner, W.E. Evans, L.J. Hansen, and K. Mullin. 1998. Physical habitat of cetaceans along the continental slope in the north-central and western Gulf of Mexico. **Mar. Mamm. Sci.** 14(3):490-507.

Davis, R.W., J.G. Ortega-Ortiz, C.A. Ribic, W.E. Evans, D.C. Biggs, P.H. Ressler, R.B. Cady, R.R. Leben, K.D. Mullin, and B. Würsig. 2002. Cetacean habitat in the northern oceanic Gulf of Mexico. **Deep-Sea Res. I** 49(1):121-142.

Debrot, A.O. 1998. New cetacean records for Curaçao, Netherlands Antilles. **Caribbean J. Sci.** 34(1-2):168-169.

Debrot, A.O. 2000. A review of the extinct West Indian monk seal, *Monachus tropicalis* (Carnivora:Phocidae), for the Netherlands Antilles. **Mar. Mamm. Sci.** 16(4):834-837.

Debrot, A.O. and N.B. Barros. 1992. Notes on a Gervais' beaked whale, *Mesoplodon europaeus and* a dwarf sperm whale, *Kogia simus,* stranded in Curaçao, Netherlands Antilles. **Mar. Mamm. Sci.** 8(2):172-178.

Debrot, A.O. and N.B. Barros. 1994. Additional cetacean records for the Leeward Dutch Antilles. **Mar. Mamm. Sci.** 10:359-368.

Debrot, A.O., J.A. De Meyer, and P.J.E. Dezentjé. 1998. Additional records and a review of the cetacean fauna of the Leeward Dutch Antilles. **Caribbean J. Sci.** 34(3-4):204-210.

DFO. 2004. Potential impacts of seismic energy on snow crab. Canadian Science Advisory Secretariat Habitat Status Report 2004/003.

DiBerardinis, A., S. Larkin, and V. Schott. 1997. Identification of *Sotalia fluviatilis* (Tucuxi) outside of previously reported range. Talamanca Dolphin Foundation, Manzanillo, Talamanca, Costa Rica. Available at www.dolphinlink.org/scientific_documentation_page.htm

Dizon, A.E., S.O. Southern, and W.F. Perrin. 1991. Molecular analysis of mtDNA types in exploited populations of spinner dolphins (*Stenella longirostris*). **Rep. Int. Whal. Comm. Spec. Iss.** 13:183-202.

Dolar, M.L.L. 2002. Fraser's dolphin – *Lagenodelphis hosei*. p. 485-487 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego. 1414 p.

Donahue, M.A. and W.L. Perryman. 2002. Pygmy killer whale – *Feresa attenuata*. p. 1009-1010 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego. 1414 p.

Donovan, G.P. 1984. Blue whales off Peru, December 1982, with special reference to pygmy blue whales. **Rep. Int. Whal. Comm.** 34:473-476.

Donovan, G.P. 1991. A review of IWC stock boundaries. **Rep. Int. Whal. Comm. Spec. Iss.** 13:39-68.

Dufault, S. and H. Whitehead. 1993. Assessing the stock identity of sperm whales in the eastern equatorial Pacific. **Rep. Int. Whal. Comm.** 43:469-475.

Dufault, S. and H. Whitehead. 1995. The geographic stock structure of female and immature sperm whales in the South Pacific. **Rep. Int. Whal. Comm.** 45:401-405.

Dufault, S., H. Whitehead, and M. Dillon. 1999. An examination of the current knowledge on the stock structure of sperm whales (*Physeter macrocephalus*) worldwide. **J. Cetac. Res. Manage.** 1(1):1-10.

Duffield, D.A., S.H. Ridgway, and L.H. Cornell. 1983. Hematology distinguishes coastal and offshore forms of dolphins (*Tursiop*s). **Can. J. Zool.** 61(4):930-933.

Eckert, S.A., K.L. Eckert, and G.L. Kooyman. 1986. Diving patterns of two leatherback sea turtles (*Dermochelys coriacea*) during the interesting intervals at Sandy Point, St. Croix, U.S. Virgin Islands. **Herpetologica** 42:381-388.

Eckert, S.A., D.W. Nellis, K.L. Eckert, P. Ponganis, and G.L. Kooyman. 1988. Diving and foraging behaviour of leatherback sea turtles (*Dermochelys coriacea*). **Can J. Zool.** 67:2834-2840.

Edwards, H.H. and G.D. Schnell. 2001. Status and ecology of *Sotalia fluviatilis* in the Cayos Miskito Reserve, Nicaragua. **Mar. Mamm. Sci.** 17:445-472.

Engås, A, S. Løkkeborg, E. Ona, and A.V. Soldal. 1996. Effects of seismic shooting on local abundance and catch rates of cod (*G. morhua*) and haddock (*M. aeglefinus*). **Can. J. Fish. Aquat. Sci.** 53:2238-2249.

Engel, M.H., M.C.C. Marcondes, C.C.A. Martins, F.O. Luna, R.P. Lima, and A. Campos. 2004. Are seismic surveys responsible for cetacean strandings? An unusual mortality of adult humpback whales in Abrolhos Bank, northeastern coast of Brazil. Working Paper SC/56/E28. Int. Whal. Comm., Cambridge, U.K. 8 p.

EuroTurtle. 2006. Sea turtle outlines. http://www.euroturtle.org

Evans, P.G.H. 1980. Cetaceans in British waters. **Mamm. Rev.** 10:1-46.

Evans, D. 1991. Ecuadorian whale sanctuary is created providing protection for the Galápagos Islands. **Ambio** 20(2):97.

Evans, P.G.H. 1992. Status review of cetaceans in British and Irish waters. UK Mammal Society Cetacean Group Report, University of Oxford. 100 p.

Evans, W.E. 1994. Common dolphin, white-bellied porpoise *Delphinus delphis* Linnaeus, 1758. p. 191-224 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first Book of dolphins. Academic Press, San Diego, CA. 416 p.

Evans, W.E., J.R. Jehl, Jr., and F.H. Wolfson. 1979. Current studies on distribution and abundance of cetaceans in Venezuela. **Rep. Int. Whal. Comm. Working Pap.** 13:1–6.

Falk, M.R. and M.J. Lawrence. 1973. Seismic exploration: its nature and effect on fish. Fisheries and Marine Service, Resource Management Branch, Fisheries Operations Directorate: Technical Report CENT-73-9.

FAO. 2003. World Fisheries and Aquaculture Atlas. CD-Rom.

FAO. 2004. Fishery country profile: Costa Rica. Food and Agriculture Organization of the United Nations FID/ CP/CRI. http://www.fao.org/fi/fcp/en/CRI/profile.htm.

Félix, F. and B. Haase. 2001. Towards an estimate of the southeastern Pacific humpback whale stock. **J. Cetacacean Res. Manage.** 3(1):55-58.

Félix, F., B. Haase, and J. Samaniego. 1995. First record of pygmy killer whale *Feresa attenuata* (Cetacea, Delphinidae) and dwarf sperm whale *Kogia simus* (Cetacea, Physeteridae) on the Ecuadorean continental coast. **Estud. Oceanol.** 14:77-85. [In Spanish].

Felix, F., C. Castro, B. Haase, P. Forestell, and M. Scheidat. 2005. New estimate of the southeastern Pacific humpback whale stock. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Ferguson, M.C. and J. Barlow. 2001. Spatial distribution and density of cetaceans in the Eastern Tropical Pacific Ocean based on summer/fall research vessel surveys in 1986-96. Admin. Rep. LJ-01-04, SWFSC, NMFS, La Jolla, CA. 61 p.

Ferguson, M.C., J. Barlow, P. Fiedler, S.B. Reilly, and T. Gerrodette. 2006a. Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. **Ecol. Model.** 193(2006): 645-662.

Ferguson, M.C., J. Barlow, S.B. Reilly, and T. Gerrodette. 2006b. Predicting Cuvier's (*Ziphiuscavirostris*) and *Mesoplodon* beaked whale population density from habitat characteristics in the Eastern Tropical Pacific Ocean. **J. Cetacean Res. Manage.** 7(3): 287-299

Fernández, A., M. Arbelo, R. Deaville, I.A.P. Patterson, P. Castro, J.R. Baker, E. Degollada, H.M. Ross, P. Herráez, A.M. Pocknell, E. Rodríguez, F.E. Howie, A. Espinosa, R.J. Reid, J.R. Jaber, V. Martin, A.A. Cunningham and P.D. Jepson. 2004. Pathology: whales, sonar and decompression sickness (reply). **Nature** 428(6984).

Fernández, A., J.F. Edwards, F. Rodriquez, A.E. de los Monteros, P. Herráez, P. Castro, J.R. Jaber, V. Martin, and M. Arbelo. 2005a. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (Family Ziphiidae) exposed to anthropogenic sonar signals. **Vet. Pathol.** 42(4):446-457.

Fernández, A., M. Méndez, E. Sierra, A. Godinho, P. Herráez, A.E. De los Monteros, F. Rodrigues, and M. Arbelo. 2005b. New gas and fat embolic pathology in beaked whales stranded in the Canary Islands. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Fertl, D., A.J. Schiro, G.T. Regan, C.A. Beck, N. Adimey, L. Price-May, A. Amost, G.A.J. Worthy, and R. Crossland. 2005. Manatee occurrence in the northern Gulf of Mexico, west of Florida. **Gulf Carib. Res.** 17:69-94.

Fiedler, P.C. 1992. Seasonal climatologies and variability of eastern tropical Pacific surface waters. NOAA Tech. Rept. NMFS 109. 65 p.

Fiedler, P.C. 2002. The annual cycle and biological effects of the Costa Rica Dome. **Deep-Sea Res. I** 49:321-338.

Fiedler, P.C. and L.D. Talley. 2006. Hydrography of the eastern tropical Pacific: a review. **Prog. Oceanogr.** 69(2–4): 143-180.

Fiedler, P.C., V. Philbrick, and F.P. Chavez. 1991. Oceanic upwelling and productivity in the eastern tropical Pacific. **Limn. Ocean.** 36:834-850.

Finneran, J.J. and C.E. Schlundt. 2004. Effects of intense pure tones on the behavior of trained odontocetes. TR 1913, SSC San Diego, San Diego, CA.

Finneran, J.J., C.E. Schlundt, D.A. Carder, J.A. Clark, J.A. Young, J.B. Gaspin, and S.H. Ridgway. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. **J. Acoust. Soc. Am.** 108(1):417-431.

Finneran, J.J., C.E. Schlundt, R. Dear, D.A. Carder, and S.H. Ridgway. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. **J. Acoust. Soc. Am.** 111(6):2929-2940.

Finneran, J.J., D.A. Carder, C.E. Schlundt, and S.H. Ridgway. 2005. Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. **J. Acoust. Soc. Am.** 118(4):2696-2705.

Fishcostarica.com. 2007. Costa Rica fishing – saltwater and freshwater sport fishing. http://www.fishcostarica.com.

Flórez-González, L. 1991. Humpback whale *Megaptera novaeangliae* in the Gorgona Island, Colombian Pacific breeding waters: Population and pod characteristics. **Mem. Queensl. Mus.** 30(2):291-295.

Flórez-González, L., J. Capelía A., B. Haase, G.A. Bravo, F. Félix, and T. Gerrodette. 1998. Changes in winter destinations and the northernmost record of southeastern Pacific humpback whales. **Mar. Mamm. Sci.** 14(1):189-196.

Ford, J.K.B. 2002. Killer whale. p. 669-675 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

Barlow, J. and K.A. Forney. In prep. Abundance and density of cetaceans in the California Current ecosystem. Submitted to **Fish. Bull.**

Forestell, P.H., A.M. Wright, A. DiBerardinis, S. Larkin, and V. Schot. 1999. Sex and the single Tucuxi: observation of interspecies mating between free-ranging bottlenose (*Tursiops truncatus*) and tucuxi (*Sotalia fluviatilis*) dolphins in Costa Rica. Abstr. 13th Bien. Conf. Biol. Mar. Mamm., 28 Nov-3 Dec., Wailea, Maui, Hawaii.

Frankel, A.S. 2005. Gray whales hear and respond to a 21–25 kHz high-frequency whale-finding sonar. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Frantzis, A. 1998. Does acoustic testing strand whales? **Nature** 392(6671):29.

Gallardo, V.A., D. Arcos, M. Salamanca, and L. Pastene. 1983. On the occurrence of Bryde's Whales (*Balaenoptera edeni* Anderson, 1878) in an upwelling area off central Chile. **Rep. Int. Whal. Comm.** 33:481-488.

Gambell, R. 1985a. Sei whale *Balaenoptera borealis* Lesson, 1828. p. 155-170 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, London, U.K. 362 p.

Gambell, R. 1985b. Fin whale *Balaenoptera physalus* (Linnaeus, 1758). p. 171-192 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, London, U.K. 362 p.

Gamboa-Poveda, M. and L.J. May-Collado. 2006. Insights on the occurrence, residency, and behaviour of two coastal dolphins from Gandoca-Manzanillo, Costa Rica: *Sotalia guianensis* and *Tursiops truncatus* (Family Delphinidae). Paper SC/58/SM4 presented to the IWC Scientific Committee, June 2006 (unpublished). 9 p. Paper available from the IWC Secretariat: secretariat@iwcoffice.org.

Gaos, A., R. Arauz, and I. Yañez. 2006. Hawksbill turtles on the Pacific coast of Costa Rica. **Mar. Turtle Newsl.** 112(14). Available at http://www.seaturtle.org/mtn/archives/mtn112/mtn112p14.shtml.

Geise, L., N. Gomes, and R. Cerqueira. 1999. Behaviour, habitat use and population size of *Sotalia fluviatilis* (Gervais, 1853) (Cetacea, Delphinidae) in the Cananéia Estuary Region, SÃO Paulo, **Brazil. Rev. Bras. Biol.** Vol.59 no. 2.

Gentry, R. (ed.). 2002. Report of the workshop on acoustic resonance as a source of tissue trauma in cetaceans, Silver Spring, MD, April 2002. NMFS. 19 p. Available at http://www.nmfs.noaa.gov/pr/pdfs/acoustics/cetaceans.pdf

Gerrodette, T. and J. Forcada. 2002. Estimates of abundance of western/southern spotted, whitebelly spinner, striped and common dolphins, and pilot, sperm and bryde's whales in the Eastern Tropical Pacific Ocean. SWFSC Admin. Rep LJ-02-20. 24 p.

Gerrodette, T. and J. Forcada. 2005. Non-recovery of two spotted and spinner dolphin populations in the eastern tropical Pacific Ocean. **Mar. Ecol. Prog. Ser.** 291:1-21.

Gerrodette, T. and D.M. Palacios. 1996. Estimates of cetacean abundance in EEZ waters of the Eastern Tropical Pacific. NMFS, SWFSC, Admin. Rep. JL-96-10, 27 p.

Gerrodette, T., G. Watters, and J. Forcada. 2005. Preliminary estimates of 2003 dolphin abundance in the the Eastern Tropical Pacific. NMFS, SWFSC, Admin. Rep. JL-05-10-05. 26 p.

Gilpatrick, J.W., Jr., R.L. Pitman, L.T. Ballance, R. LeDuc, and H. Fearnbach. 2005. Killer whales prey upon a blue whale calf on the Costa Rica Dome: genetics, morphometrics and composition of the herd. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Glockner, D.A. 1983. Determining the sex of humpback whales (*Megaptera novaeangliae*) in their natural environment. p. 447-466 *In:* R. Payne (ed.), Communication and behavior of whales. AAAS Selected Symposia 76, Westview Press, Boulder, CO. 643 p.

Glynn, P.N. 1976. Aspects of the ecology of coral reefs in the Western Atlantic Region. p. 271-324 *In:* O.A. Jones and R. Endea (eds.), Biology and geology of coral reefs, Vol. 2. Academic Press, New York, NY.

Goold, J.C. 1996a. Acoustic assessment of common dolphins off the west Wales coast, in conjunction with 16th round seismic surveying. Rep. from School of Ocean Sciences, Univ. Wales, Bangor, Wales, for Chevron UK Ltd, Repsol Explor. (UK) Ltd., and Aran Energy Explor. Ltd. 22 p.

Goold, J.C. 1996b. Acoustic assessment of populations of common dolphin *Delphinus delphis* in conjunction with seismic surveying. **J. Mar. Biol. Assoc. U.K.** 76:811-820.

Goold, J.C. 1996c. Acoustic cetacean monitoring off the west Wales coast. Rep. from School of Ocean Sciences, Univ. Wales, Bangor, Wales, for Chevron UK Ltd, Repsol Explor. (UK) Ltd, and Aran Energy Explor. Ltd. 20 p.

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M.P. Simmonds, R. Swift, and D. Thompson. 2004. A review of the effects of seismic surveys on marine mammals. **Mar. Technol. Soc. J.** 37(4):16-34. Available at http://www.pelagosinstitute.gr/en/pelagos/pdfs/Gordon%20et%20al.%202004,%20Review%20of%20Seismic%20Surveys%20Effects.pdf

Govan, H. 1998. Community turtle conservation at Rio Oro on the Pacific coast of Costa Rica. **Mar. Turtle Newsl.** 80:10-11.

Greene, C.R., Jr., with J.S. Hanna and R.W. Blaylock. 1997. Physical acoustics measurements. p. 3-1 to 3-63 *In*: W.J. Richardson (ed.), Northstar marine mammal monitoring program, 1996: marine mammal and acoustical monitoring of a seismic program in the Alaskan Beaufort Sea. LGL Rep. TA2121-2. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 245 p.

Greene, C.R., Jr., N.S. Altman, and W.J. Richardson. 1999. Bowhead whale calls. p. 6-1 to 6-23 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1998. LGL Rep. TA2230-3. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 390 p.

Guerra, A., A.F. González, and F. Rocha. 2004. A review of the records of giant squid in the north-eastern Atlantic and severe injuries in *Architeuthis dux* stranded after acoustic explorations. Paper presented at the International Council for the Exploration of the Sea (ICES) Annual Science Conference, 22–25 September 2004, Vigo, Spain. ICES CM 2004/CC:29.

Hacker, S.E. 1992. Stomach contents of four short-finned pilot whales (*Globicephala macrorhynchus*) from the Southern California Bight. **Mar. Mamm. Sci.** 8(1):76-81.

Hall, M.A. 1998. An ecological view of the tuna-dolphin problem: impacts and trade-offs. **Rev. Fish Biol.** 8(1):1-34.

Hall, M.A. and S.D. Boyer. 1989. Estimates of incidental mortality of dolphins in the eastern Pacific fishery for tropical tunas in 1987. **Rep. Int. Whal. Comm.** 39:321-322.

Hansen, L.J., K.D. Mullin, and C.L. Roden. 1994. Preliminary estimates of cetacean abundance in the U.S. Atlantic Exclusive Economic Zone from 1992 vessel surveys. Southeast Fisheries Science Center, Miami Laboratory. Contribution No. MIA-93/94-58.

Harris, R.E., G.W. Miller, and W.J. Richardson. 2001. Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. **Mar. Mamm. Sci.** 17(4):795-812.

Hartog, J.C. den and M.M. van Nierop. 1984. A study of the gut contents of six leathery turtles, *Dermochelys coriacea* (Linnaeus) (Reptilia: Testudines: Dermochelyidae) from British waters and from the Netherlands. **Zool. Verh.** 209(1984):1-36.

Hastings, M.C. and A.N. Popper. 2005. Effects of sound on fish. Prepared by Jones & Stokes, Sacramento, CA, for California Department of Transportation, Sacramento, CA. 28 January.

Harwood, J. and B. Wilson. 2001. The implications of developments on the Atlantic Frontier for marine mammals. **Cont. Shelf Res.** 21:1073-1093.

Hasbún, C.R. and M. Vásquez. 1999. Sea Turtles of El Salvador. **Mar. Turtle Newsl.** 85:7-9.

Hassel, A., T. Knutsen, J. Dalen, S. Løkkeborg, K. Skaar, Ø. Østensen, E.K. Haugland, M. Fonn, Å. Høines, and O.A. Misund. 2003. Reaction of sandeel to seismic shooting: a field experiment and fishery statistics study. Institute of Marine Research, Bergen, Norway.

Heimlich, S.L., D.K. Mellinger, S.L. Nieukirk, and C.G. Fox. 2005. Types, distribution, and seasonal occurrence of sounds attributed to Bryde's whales (*Balaenoptera edeni*) recorded in the eastern tropical Pacific, 1999-2001. **J. Acoust. Soc. Am.** 118(3): 1830-1837.

Heyning, J.E. 1989. Cuvier's beaked whale *Ziphius cavirostris* G. Cuvier, 1823. p. 289-308 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 4. River dolphins and the larger toothed whales. Academic Press, San Diego, CA. 444 p.

Heyning, J.E. and M.E. Dahlheim. 1988. *Orcinus orca.* **Mammal. Spec.** 304:1-9.

Heyning, J.E. and W.F. Perrin. 1994. Evidence for two species of common dolphins (genus *Delphinus*) from the Eastern North Pacific. **Contribut. Sci.** 442:1-35.

High North Alliance. 2003. Whaling today – Caribbean. http://www.highnorth.no/iwc2000/briefings/Whaling.htm #Caribbean.

Hoelzel, A.R., C.W. Potter, and P.B. Best. 1998. Genetic differentiation between parapatric 'nearshore' and 'offshore' populations of the bottlenose dolphin. **Proc. R. Soc Lond. B** 265:1177-1183.

Hogarth, W.T. 2002. Declaration of William T. Hogarth in opposition to plaintiff's motion for temporary restraining order, 23 October 2002. Civ. No. 02-05065-JL. U.S. District Court, Northern District of California, San Francisco Div.

Hohn, A.A. and P.S. Hammond. 1985. Early postnatal growth of the spotted dolphin, *Stenella attenuata*, in the offshore eastern tropical Pacific. **Fish. Bull.** 83(4):553-566.

Holbrook, W.S., P. Paramo, S. Pearse, and R.W. Schmitt. 2003. Thermohaline fine structure in an oceanographic front from seismic reflection profiling. **Science** 301(5634):821-824.

Holliday, D.V., R.E. Piper, M.E. Clarke, and C.F. Greenlaw. 1987. The effects of airgun energy release on the eggs, larvae, and adults of the northern anchovy (*Engraulis mordax*). American Petroleum Institute, Washington, DC. Tracer Applied Sciences.

Holst, M., M.A. Smultea, W.R. Koski, and B. Haley 2005a. Marine mammal and sea turtle monitoring during Lamont-Doherty Earth Observatory's marine seismic program in the Eastern Tropical Pacific Ocean off Central America, November–December 2004. LGL Rep. TA2822-30. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 125 p.

Holst, M., M.A. Smultea, W.R. Koski, and B. Haley. 2005b. Marine mammal and sea turtle monitoring during Lamont-Doherty Earth Observatory's marine seismic program off the Northern Yucatán Peninsula in the Southern Gulf of Mexico, January–February 2005. LGL Rep. TA2822-31. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 96 p.

Holst, M., W.J. Richardson, W.R. Koski, M.A. Smultea, B. Haley, M.W. Fitzgerald, and M. Rawson. 2006. Effects of large and small-source seismic surveys on marine mammals and sea turtles. Abstract. Presented at Am. Geophys. Union - Soc. Explor. Geophys. Joint Assembly on Environ. Impacts from Marine Geophys. & Geological Studies - Recent Advances from Academic & Industry Res. Progr., Baltimore, MD, May 2006.

Horrocks, J.A. 1992. WIDECAST Sea Turtle Recovery Action Plan for Barbados. *In:* K.L. Eckert (ed.). CEP Technical Report No. 12. UNEP Caribbean Environment Program, Kingston, Jamaica. 61 p.

Horwood, J. 1987. The sei whale: population biology, ecology, and management. Croom Helm, Beckenham, Kent, U.K. 375 p.

Houston, J. 1990. Status of Blainville's beaked whale, *Mesoplodon densirostris*, in Canada. **Nature** 104(1):117-120.

Houston J. 1991. Status of Cuvier's beaked whale, *Ziphius cavirostris*, in Canada. **Can. Field Nat.** 105(2):215-218.

Hoyt, E. 1984. The whale watcher's handbook. Doubleday, Garden City, NY. 208 p.

Hoyt, E. 1991. Whale watching: wolrdwide tourism numbers, expenditures, and expanding socioeconomic benefits. International Fund for Animal Welfare. Yarmouth Port, MA. Available at http://www.ifaw.org/ifaw/dfiles/file_106.pdf.

IAGC. 2004. Further analysis of 2002 Abrolhos Bank, Brazil humpback whale strandings coincident with seismic surveys. Intern. Assoc. Geophys. Contr., Houston, TX.

IATTC. 2002. Annual report of the Inter-American Tropical Tuna Commission 2000. IATTC, La Jolla, CA. 171 p.

Industry Canada. 2006. Nicaragua country commercial guide 2004, Chapter 2 - Economic trends and outlook Nicaragua. http://strategis.ic.gc.ca/epic/site/imr-ri.nsf/en/gr126555e.html.

INE. 2006. Propuesta de aperture de areas para la exploracion y explotacion de hidrocarburos en Nicaragua. http://www.internationalpavilion.com/Houston_Theatre_pres_06/Nicaragua_06.ppt.

Isaksen, K. and P.O. Syvertsen. 2002. Striped dolphins, *Stenella coeruleoalba*, in Norwegian and adjacent waters. **Mammalia** 66(1):33-41.

IUCN. 2006. 2006 IUCN Red List of Threatened Species. http://www.iucnredlist.org

IWC. 2007a. Whale population estimates. http://www.iwcoffice.org/conservation/estimate.htm.

IWC. 2007b. Catch limits & catches taken. http://www.iwcoffice.org/conservation/catches.htm.

IWC. 2007c. IWC members and commissionaires. http://www.iwcoffice.org/commission/members.htm.

IWC. 2007d. Report of the standing working group on environmental concerns. Annex K to Report of the Scientific Committee. **J. Cetacean Res. Manage.** 9(Suppl.):227-260.

Jackson, A., T. Gerrodette, S. Chivers, M. Lynn, P. Olson, and S. Rankin. 2004. Marine mammal data collected during a survey in the Eastern Tropical Pacific Ocean aboard the NOAA ships *Mcarthur II* and *David StarrJordan*, July 29–December 10, 2003. NOAA Tech. Memo. TM-NMFS-SWFSC-366. National Marine Fisheries Service, Southwest Fisheries Science Center, La Jolla, CA. 98 p.

Jameson, S.C., L.J. Trott, M.J. Marshall, and M.J. Childress. 2000. Nicaragua: Caribbean coast. *P.* 517-530 *In:* C. Sheppard (ed.), Seas at the millennium: an environmental evaluation, Volume 1. Elsevier Science, Amsterdam.

Jaquet, N., D. Gendron, and A. Coakes. 2003. Sperm whales in the Gulf of California: residency, movements, behavior, and the possible influence of variation in food supply. **Mar. Mamm. Sci.** 19(3):545-562.

Jefferson, T.A. 2002. Rough-toothed dolphin – *Steno bredanensis.* p. 1055-1059 *In*: W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego. 1414 p.

Jefferson, T.A. and S K. Lynn. 1994. Marine mammal sightings in the Caribbean Sea and Gulf of Mexico, summer 1991. **Caribbean J. Sci.** 30(1–2):83–89.

Jefferson, T.A. and N.B. Barros. 1997. *Peponocephala electra*. **Mammal. Spec.** 553:1-6.

Jefferson, T.A., S. Leatherwood, and M.A. Webber. 1993. FAO Species identification guide. Marine mammals of the world. UNEP/FAO, Rome.

Jefferson, T.A., D.K. Odell, and K.T. Prunier. 1995. Notes on the biology of the Clymene dolphin (*Stenella clymene*) in the northern Gulf of Mexico. **Mar. Mamm. Sci.** 11(4):564-573.

Jepson, P.D., M. Arbelo, R. Deaville, I.A.P. Patterson, P. Castro, J.R. Baker, E. Degollada, H.M. Ross, P. Herráez, A.M. Pocknell, F. Rodríguez, F.E. Howie, A. Espinosa, R.J. Reid, J.R. Jaber, V. Martin, A.A. Cunningham, and A. Fernández. 2003. Gas-bubble lesions in stranded cetaceans. **Nature** 425(6958):575-576.

Jepson, P.D., D.S. Houser, L.A. Crum, P.L. Tyack, and A. Fernández. 2005a. Beaked whales, sonar and the “bubble hypothesis”. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Jepson, P.D. R. Deaville, I.A.P. Patterson, A.M. Pocknell, H.M. Ross, J.R. Baker, F.E. Howie, R.J. Reid, A. Colloff, and A.A. Cunningham. 2005b. Acute and chronic gas bubble lesions in cetaceans stranded in the United Kingdom. **Vet. Pahol.** 42(3):291-305.

Johnson, S.R., W.J. Richardson, S.B. Yazvenko, S.A. Blokhin, G. Gailye, M.R. Jenkerson, S.K. Meier, H.R. Melton, M.W. Newcomer, A.S. Perlov, S.A. Rutenko, B. Würsig, C.R. Martin, and D.E. Egging. 2007. A western gray whale mitigation and monitoring program for a 3-D seismic survey, Sakhalin Island, Russia. **Environ. Monit. Assess.** DOI 10.1007/s10661-007-9813-0.

Jonsgård, Å. 1966. The distribution of Balaenopteridae in the North Atlantic Ocean. p. 114-124 *In:* K.S. Norris (ed.), Whales, dolphins, and porpoises. University of California Press, Berkeley and Los Angeles.

Jonsgård, Å. and K. Darling. 1977. On the biology of the eastern North Atlantic sei whale, *Balaenoptera borealis* Lesson. **Rep. Int. Whal. Comm., Spec. Iss.** 1:124-129.

Kalb, H. and D. Owens. 1994. Differences between solitary and arribada nesting olive ridley females during the interesting period. p. 68 *In* K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (comp.), Proc. 14th Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Kalb, H., R. Valverde, and D. Owens. 1995. What is the reproductive patch of the olive ridley sea turtle? p. 57-60 *In*: J.I Richardson and T.H. Richardson (comp.), Proc. 12th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-361. 274 p.

Kastak, D., R.L. Schusterman, B.L. Southall, and C.J. Reichmuth. 1999. Underwater temporary threshold shift induced by octave-band noise in three species of pinnipeds. **J. Acoust. Soc. Am.** 106:1142-1148.

Kastak, D., B.L. Southall, R.J. Schusterman, and C.R. Kastak. 2005. Underwater temporary threshold shift in pinnipeds: effects of noise level and duration. **J. Acoust. Soc. Am.** 118(5):3154-3163.

Kasuya, T. 1986. Distribution and behavior of Baird's beaked whales off the Pacific coast of Japan. **Sci. Rep. Whales Res. Inst.** 37:61-83.

Kerr, K.A., R.H. Defran, and G.S. Campbell. 2005. Bottlenose dolphins (*Tursiops truncates*) in the Drowned Cayes, Belize: group size, site fidelity and abundance. **Caribbean J. Sci.** 41(1):172-177.

Ketten, D.R. 1995. Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. p. 391-407 *In:* R.A. Kastelein, J.A. Thomas and P.E. Nachtigall (eds.), Sensory systems of aquatic mammals. De Spil Publ., Woerden, Netherlands. 588 p.

Ketten, D.R., J. Lien, and S. Todd. 1993. Blast injury in humpback whale ears: evidence and implications. **J. Acoust. Soc. Am.** 94(3, Pt. 2):1849-1850.

Ketten, D.R., J. O'Malley, P.W.B. Moore, S. Ridgway, and C. Merigo. 2001. Aging, injury, disease, and noise in marine mammal ears. **J. Acoust. Soc. Am.** 110(5, Pt. 2):2721.

Kinzey, D., T. Gerrodette, J. Barlow, A. Dizon, W. Perryman, P. Olson, and A. Von Saunder. 1999. Marine mammal data collected during a survey in the eastern tropical Pacific Ocean aboard the NOAA ships *McArthur* and *David Starr Jordan* and the UNOLS ship *Endeavor* July 31-December 9, 1998. NOAA Tech. Memo. NMFS, U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-283. 113 p.

Kinzey, D., T. Gerrodette, J. Barlow, A. Dizon, W. Perryman, and P. Olson. 2000. Marine mammal data collected during a survey in the eastern tropical Pacific Ocean aboard the NOAA ships *McArthur* and *David Starr Jordan*, July 28-December 9, 1998. NOAA Tech. Memo. NMFS, U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-293. 89 p.

Kinzey, D., T. Gerrodette, A. Dizon, W. Perryman, P. Olson, and S. Rankin. 2001. Marine mammal data collected during a survey in the eastern tropical Pacific Ocean aboard the NOAA ships *McArthur* and *David Starr Jordan*, July 28-December 9, 2000. NOAA Tech. Memo. NMFS, U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-303. 100 p.

Klatsky, L.J. 2004. Movement and dive behavior of bottlenose dolphins (*Tursiops truncatus*) near the Bermuda Pedestal. M.Sc. thesis, San Diego State University, CA. 31 p.

Klatsky, L., R. Wells, and J. Sweeney. 2005. Bermuda's deep diving dolphins – movements and dive behavior of offshore bottlenose dolphins in the Northwest Atlantic Ocean near Bermuda. Abstracts of the 16th Biennial Conference on the Biology of Marine Mammals, San Diego, CA, 12-16 December 2005.

Kongsberg Maritime. 2006. EM 120 Multibeam echo sounder. ttp://www.km.kongsberg.com/KS/WEB/NOKBG0397.nsf/AllWeb/57CA49472DCE0190C1256C39003C1BCE/$file/160930ai_EM120_Product_description_lr.pdf?OpenElement.

Kopitsky, K., R.L. Pitman, and P.H. Dutton. 2002. Reproductive ecology of olive ridleys in the open ocean in the eastern tropical Pacific. p. 90-91. *In*: A. Mosier, A. Foley, and B. Brost (compilers), Proc.20th Annu. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-477. 369 p.

Koski, W.R., D.H. Thomson, and W.J. Richardson. 1998. Descriptions of marine mammal populations. p. 1-182 plus Appendices *In:* Point Mugu Sea Range marine mammal technical report. Rep. from LGL Ltd., King City, Ont., for Naval Air Warfare Center, Weapons Div., Point Mugu, CA, and Southwest Div. Naval Facilities Engin. Command, San Diego, CA. 322 p.

Kostyuchenko, L.P. 1973. Effects of elastic waves generated in marine seismic prospecting on fish eggs in the Black Sea. **Hydrobiol. J.** 9:45-48.

Kremser, U., P. Klemm, and W.D. Kötz. 2005. Estimating the risk of temporary acoustic threshold shift, caused by hydroacoustic devices, in whales in the Southern Ocean. **Antarctic Sci.** 17(1):3-10.

Kruse, S., D.K. Caldwell, and M.C. Caldwell. 1999. Risso's dolphin *Grampus griseus* (G. Cuvier, 1812). p. 183-212 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 6. The mecond book of dolphins and the porpoises. Academic Press, San Diego, CA. 486 p.

Kryter, K.D. 1985. The effects of noise on man, 2nd ed. Academic Press, Orlando, FL. 688 p.

Kuczaj, S., D. Yeater, and S. Brown. 2005. Behavioral observations of a possible resident population of rough-toothed dolphins (*Steno bredanenis*) off the coast of Utila, Honduras. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

LaBella, G., C. Froglia, A. Modica, S. Ratti, and G. Rivas. 1996. First assessment of effects of air-gun seismic shooting on marine resources in the central Adriatic Sea. Society of Petroleum Engineers, Inc. International Conference on Health, Safety and Environment, New Orleans, Louisiana, U.S.A., 9-12 June 1996.

Lacroix, D.L., R.B. Lanctot, J.A. Reed, and T.L. McDonald. 2003. Effect of underwater seismic surveys on molting male long-tailed ducks in the Beaufort Sea, Alaska. **Can. J. Zool.** 81:1862-1875.

Lagueux, C.J. 1998. Demography of marine turtles harvested by Miskitu Indians of Atlantic Nicaragua. p. 90 *In*: R. Byles and Y. Fernandez (comp.), Proc. 16th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-412.

Lagueux, C.J., C.L. Campbell, W.A. McCoy, B.A. Schroeder, and G.H. Balazs. 2003. Migration routes and dive patterns of post-nesting hawksbills from the Pearl Cays, Nicaragua. p. 54 *In*: Seminoff, J.A. (comp.), Proc. 22nd Ann. Symp. Sea Turtle Biol. Conserv. NMFS-SEFSC-503. 308 p.

Leatherwood, S. and R.R. Reeves. 1983. The Sierra Club handbook of whales and dolphins. Sierra Club, San Francisco, CA.

Leatherwood, S., D.K. Caldwell, and H.E. Winn. 1976. Whales, dolphins, and porpoises of the Western North Atlantic. A guide to their identification. NOAA Tech. Rep. NMFS Circ. 396. U.S. Dep. Comm., Washington, DC.

Leatherwood, S., R.R. Reeves, W.F. Perrin, and W.E. Evans. 1988. Whales, dolphins and porpoises of the Eastern North Pacific and Adjacent Arctic Waters. Dover Publications, New York, NY. 245 p.

Leatherwood, S., J.S. Grove, and A.E. Zuckerman. 1991. Dolphins of the genus *Lagenorhynchus* in the tropical South Pacific. **Mar. Mamm. Sci.** 7(2):194-197.

Lee, T. 1993. Summary of cetacean survey data collected between the years of 1974 and 1985. NOAA Tech. Memo. NMFS-SWFSC-181. 184 p.

Lefebvre, L.W., T.J. O'Shea, G.B. Rathbun, and R.C. Best. 1989. Distribution, status, and biogeography of the West Indian manatee. p. 567-610 *In:* C.A. Woods (ed.), Biogeography of the West Indies: past, present, and future. Sandhill Crane Press, Gainesville, FL.

Lettevall, E., C. Richter, N. Jaquet, E. Slotten, S. Dawson, H. Whitehead, J. Christal, and P.M. Howard. 2002. Social structure and residency in aggregations of male sperm whales. **Can. J. Zool.** 80(7):1189-1196.

LGL Ltd. 2003a. Request by Lamont-Doherty Earth Observatory for an Incidental Harassment Authorization to allow the incidental take of cetaceans and pinnipeds during a marine seismic program in the Hess Deep area of the eastern tropical Pacific Ocean, March-April 2003. LGL Rep. TA2822-1. Rep. From LGL Ltd., King City, ON, for Lamont-Doherty Earth Observatory, Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 94 p.

LGL Ltd. 2003b. Environmental Assessment of a marine seismic survey by the R/V *Maurice Ewing* in the Hess Deep area of the eastern tropical Pacific Ocean. LGL Rep. TA2822-4. Rep. from LGL Ltd, King City, ON, for Lamont-Doherty Earth Observatory, Columbia Univ., Palisades, NY, and Nat. Sci. Found., Arlington, VA. 101 p.

LGL Ltd. 2003c. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic study in the Hess Deep area of the Eastern Equatorial Tropical Pacific, July 2003. LGL Rep. TA2822-16. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory, Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 68 p.

LGL Ltd. 2006. Request by Lamont-Doherty Earth Observatory for an Incidental Harassment Authorization to allow the incidental take of marine mammals during seismic testing in the northern Gulf of Mexico, fall 2006. LGL Rep. TA4295-1 prep. for Lamont-Doherty Earth Observatory, Palisades, NY.

Ljungblad, D.K., B. Würsig, S.L. Swartz, and J.M. Keene. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. **Arctic** 41(3):183-194.

Løkkeborg, S. 1991. Effects of geophysical survey on catching success in longline fishing. **ICES CM B** 40:9 p.

Longhurst, A.R. 1998. Ecological geography of the sea. Academic Press, San Diego, CA. 398 p.

Lux, J., R.Reina, and L. Stokes. 2003. Nesting activity of leatherback turtles (*Dermochelys coriacea*) in relation to tidal and lunar cycles at Playa Grande, Costa Rica. p. 215-216 *In*: J.A. Seminoff (comp.), Proc. 22nd Annu. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-503. 308 p.

Lutcavage, M.E. 1996. Planning your next meal: Leatherback travel routes and ocean fronts. p. 174-178 *In*: J.A. Keinath, D.E. Barnard, J.A. Musick, and B.A. Bell (comp.), Proc. 15th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 355 p.

MacGillivray, A. and D. Hannay. 2007. Field measurements of airgun array sound levels. p. 4-1 to 4-19 *In:* D. Ireleand et al., Marine mammal monitoring and mitigation during open water seismic exporation by GX Technology in the Chukchi Sea, October-November 2006: 90-day report. LGL Rep. P909-1. Rep. from LGL Alaska Res. Assoc. Inc., Anchorage, AK; LGL Ltd., King City, Ont., and JASCO Res. Ltd., Victoria, B.C., for GX Technology, Houston, TX; U.S. Nat. Mar. Fish. Serv., Silver Spring, MD; and U.S. Fish & Wildl. Serv., Anchorage, AK. 118 p. Available at http://www.nmfs.noaa.gov/pr/pdfs/permits/gxt_90day_report.pdf.

Mackintosh, N.A. 1965. The stocks of whales. Fishing News, London.

Mackintosh, N.A. 1966. The distribution of southern blue and fin whales. p. 125-144 *In:* K.S. Norris (ed.), Whales, dolphins and porpoises. University of California Press, Berkeley and Los Angeles, CA. 789 p.

MacLean, S.A. and W.R. Koski. 2005. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic program in the Gulf of Alaska, August-September 2004. LGL Rep. TA2822-28. Rep. from LGL Ltd., King City, Ont., Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 102 p.

MacLeod, C.D. and G. Mitchell. 2006. Key areas for beaked whales worldwide. **J. Cetacean Res. Manage.** 7(3): 309-322.

MacLeod, C.D. and A. D'Amico. 2006. A review of beaked whale behaviour and ecology in relation to assessing and mitigating impacts of anthropogenic noise. **J. Cetacean Res. Manage.** 7(3): 211-221

Madsen, P.T., B. Mohl, B.K. Nielsen, and M. Wahlberg. 2002. Male sperm whale behavior during exposures to distant seismic survey pulses. **Aquat. Mamm.** 28(3):231-240.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack, and J.E. Bird. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration. BBN Rep. 5586. Rep. from Bolt Beranek & Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Var. pag. NTIS PB86-218377.

Malme, C.I., P.R. Miles, P. Tyack, C.W. Clark, and J.E. Bird. 1985. Investigation of the potential effects of underwater noise from petroleum industry activities on feeding humpback whale behavior. BBN Rep. 5851; OCS Study MMS 85-0019. Rep. from BBN Labs Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Var. pag. NTIS PB86-218385.

Malme, C.I., B. Würsig, J.E. Bird, and P. Tyack. 1986. Behavioral responses of gray whales to industrial noise: feeding observations and predictive modeling. Outer Cont. Shelf Environ. Assess. Progr., Final Rep. Princ. Invest., NOAA, Anchorage, AK 56(1988):393-600. BBN Rep. 6265. 600 p. OCS Study MMS 88-0048; NTIS PB88-249008.

Malme, C.I., B. Würsig, J.E. Bird, and P. Tyack. 1988. Observations of feeding gray whale responses to controlled industrial noise exposure. p. 55-73 *In*: W.M. Sackinger, M.O. Jeffries, J.L. Imm and S.D. Treacy (eds.), Port and ocean engineering under arctic conditions, vol. II. Geophysical Inst., Univ. Alaska, Fairbanks, AK. 111 p.

Marcovaldi, M.A., J. Thomé, and J.G. Frazier. 2003. Marine turtles in Latin America and the Caribbean: a regional perspective of successes, failures, and priorities for the future. **Mar. Turtle Newsle.** 100:38-42.

Márquez, M.R. 1990. Sea turtles of the world. An annotated and illustrated catalogue of sea turtle species known to date. FAO Fisheries Synopsis No. 125, Vol 11. Rome. 81 p. Available at: http://www.sefsc.noaa.gov/seaturtlepublications.jsp.

Martínez-Fernández, D., A. Montero-Cordero, L. May-Collado, and J. Calambokidis. 2005. Occurrence of *Pseudorca crassidens* in the Pacific coastal waters of Costa Rica. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Mate, B.R., B.A. Lagerquist, and J. Calambokidis. 1999. Movements of North Pacific blue whales during the feeding season off southern California and their southern fall migration. **Mar. Mamm. Sci.** 15(4):1246-1257.

Mattila, D.K. and P.J. Clapham. 1989. Humpback whales and other cetaceans on Virgin Bank and in the northern Leeward Islands, 1985 and 1986. **Can. J. Zool.** 67(9):2201-2211.

Mattila, D.K., P.J. Clapham, S.K. Katona, and G.S. Stone. 1989. Population composition of humpback whales on Silver Bank. **Can. J. Zool.** 67(2):281-285.

May-Collado, L.J. 2006. Los mamiferos marinos de Costa Rica. Reporte para el Gobierno de Costa Rica y Conservacion Internacional. LJMCR01. Available at http://delphinids.com/Publications_files/Mamiferos%20marinosLJMCR01.pdf.

May-Collado, L.J. In press. Marine mammals. Chapter 7 *In* Marine biodiversity of Costa Rica, Central America. Wehrmann, I. & J. Cortes (eds), Monographiae biologicae. Kluwer Academic Press. Available at http://delphinids.com/Marine%20Mammals%20of%20Costa%20Rica_files/List%20of%20Marine%20Mammals%20of%20Costa%20Rica.doc

May-Collado, L.J. and A.R. Morales. 2005. Presencia y patrones de comportamiento del delfin manchado costero, *Stenella attenuata graffmani* (Cetcea:Delphinidae) en el Golfo de Papagayo, Costa Rica. **Rev. Biol. Trop.** 53:265-276.

May-Collado, L., T. Gerrodette, J. Calambokidis, K. Rasmussen, and I. Sereg. 2005. Patterns of cetacean sighting distribution in the Pacific Exclusive Economic Zone of Costa Rica based on data collected from 1979-2001. **Rev Biol. Trop.** 53:249-263.

McAlpine, D.F., L.D. Murison, and E.P. Hoberg. 1997. New records for the pygmy sperm whale, *Kogia breviceps* (Physeteridae) from Atlantic Canada with notes on diet and parasites. **Mar. Mamm. Sci.** 13(4):701-704.

McCauley, R.D., M.-N. Jenner, C. Jenner, K.A. McCabe, and J. Murdoch. 1998. The response of humpback whales (*Megaptera novangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. **APPEA (Austral. Petrol. Product. Explor. Assoc.) J.** 38:692-707.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, and K. McCabe. 2000a. Marine seismic surveys: Analysis of airgun signals; and effects of air gun exposure on humpback whales, sea turtles, fishes and squid. Rep. from Centre for Marine Science and Technology, Curtin Univ., Perth, W.A., for Austral. Petrol. Prod. Assoc., Sydney, N.S.W. 188 p.

McCauley, R.D., J. Fewtrell, A.J. Duncan, M.-N. Jenner, M-N., C. Jenner, R.I.T. Prince, A. Adhitya, K. McCabe, and J. Murdoch. 2000b. Marine seismic surveys - a study of environmental implications. **APPEA (Austral. Petrol. Product. Explor. Assoc.) J.** 40:692-708.

McCauley, R.D., J. Fewtrell, and A.N. Popper. 2003. High intensity anthropogenic sound damages fish ears. **J. Acoust. Soc. Am.** 113(1):638-642.

McDonald, M.A., J.A. Hildebrand, and S.C. Webb. 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. **J. Acoust. Soc. Am.** 98(2 Pt.1):712-721.

Mead, J.G. 1977. Records of sei and Bryde's whales from the Atlantic coast of the United States, the Gulf of Mexico, and the Caribbean. **Rep. Int. Whal. Comm., Spec. Iss.** 1:113–116.

Mead, J.G. 1989. Beaked whales of the genus *Mesoplodon*. p. 349-430 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 4, River dolphins and the larger toothed whales. Academic Press, San Diego, CA. 444 p.

Mead, J.G. and C.W. Potter. 1995. Recognizing two populations of the bottlenose dolphins (*Tursiops truncatus*) off the Atlantic coast of North America: morphological and ecological considerations. **IBI Reports** 5:31-44.

Medrano-González, L., C.S. Baker, M.R. Robles-Saavedra, J. Murrell, M.J. Vazquez-Cuevas, B.C. Congdon, J.M. Straley, J. Calambokidis, J. Urban-Ramirez, L. Forez-González, C. Olavarria-Barrera, A. Aguagyo-Lobo, J. Nolasco-Soto, R.A. Juarez-Salas, and K. Villavicencio-Llamosas. 2001. Trans-ocenaic population genetic structure of humpback whales in the North and South Pacific. **Mem. Qld. Mus.** 47(2):465-479.

Mehta, S., A. Russel, and R. Arauz. 2000. Solitary nesting activity in the Ostional Wildlife Refuge, Costa Rica and the impact of poaching (during solitary nesting) and harvesting (during arribadas) on olive ridley sea turtle nests (*Lepidochelys olivacea*). p. 69-71 *In*: H.J. Kalb and T. Wibbels (compilers), Proc.19th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-443. 291 p.

Mellinger, D.K., C.D. Carson, and C.W. Clark. 2000. Characteristics of minke whale (*Balaenoptera acutorostrata*) pulse trains recorded near Puerto Rico. **Mar. Mamm. Sci.** 16(4):739-756

Méndez, M., M. Arbelo, E. Sierra, A. Godinho, M.J. Caballero, J. Jaber, P. Herráez, and A. Fernández. 2005. Lung fat embolism in cetaceans stranded in Canary Islands. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm. 12-16 Dec. 2005, San Diego, CA.

Meylan, A. and P. Meylan. 1999. Corroboration of the developmental habitat hypothesis for marine turtles. p. 68 *In:* S. Epperly and J. Braun (eds.), Proc. 17th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-415.

Meylan, P.A., A.B. Meylan, and R. Yeomans. 1991. Interception of Tortuguero-bound green turtles at Bocas Del Toro Province, Panama. p. 74 *In*: Salmon, M. and J. Wyneken (comp.), Proc. 11th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-302. 195 p.

Mignucci-Giannoni, A.A. 1998. Zoogeography of cetaceans off Puerto Rico and the Virgin Islands. **Caribbean J. Sci.** 34(3-4):173-190.

Mignucci-Giannoni A.A. and D.K. Odell. 2001. Tropical and subtropical records of hooded seals (*Cystophora cristata*) dispel the myth of extant Caribbean monk seals (*Monachus tropicalis*). **Bull. Mar. Sci.** 68(1):47-58.

Miller, G.W., R.E. Elliott, W.R. Koski, V.D. Moulton, and W.J. Richardson. 1999. Whales. p. 5-1 to 5-109 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1998. LGL Rep. TA2230-3. Rep. from LGL Ltd., King City, ON, and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 390 p.

Miller, G.W., V.D. Moulton, R.A. Davis, M. Holst, P. Millman, A. MacGillivray, and D. Hannay. 2005a. Monitoring seismic effects on marine mammals—southeastern Beaufort Sea, 2001-2002. p. 511-542 *In*: S.L. Armsworthy, P.J. Cranford, and K. Lee (eds.), Offshore oil and gas environmental effects monitoring/ Approaches and technologies. Battelle Press, Columbus, OH.

Miller, J.D. 1997. Reproduction in sea turtles. p. 51-81 *In*: P.L. Lutz and J.A. Musick (eds.), The biology of sea turtles. CRC Press, Boca Raton, FL. 432 p.

Miller, J.H., A.E. Bowles, R.L. Gentry, W.T. Ellison, J.J. Finneran, C.R. Greene Jr., D. Kastak, D.R. Ketten, P.E. Nachtigall, W.J. Richardson, B.L. Southall, J.A. Thomas, and P.L. Tyack. 2005b. Strategies for weighting exposure in the development of acoustic criteria for marine mammals. **J. Acoust. Soc. Am.** 118(3, Pt.2): 2019. Presentation to 150th Meet. Acoust. Soc. Am., Minneapolis, MN, Oct. 2005. Available at http://www.oce.uri.edu/faculty_pages/miller/Noise_Weighting_10_18_2005.ppt.

Miller, P.J., P.L. Tyack, M.P. Johnson, P.T. Madsen, and R. King. 2006. Techniques to assess and mitigate the environmental risk posed by use of airguns: recent advances from academic research program. Abstract. Presented at Am. Geophys. Union - Soc. Explor. Geophys. Joint Assembly on Environ. Impacts from Marine Geophys. & Geological Studies - Recent Advances from Academic & Industry Res. Progr., Baltimore, MD, May 2006.

Millero, F.J. 1996. Chemical oceanography, 2nd edit. CRC Press, Boca Raton, FL.

Milliman, J.D. 1976. Caribbean coral reefs. p. 1-50 *In:* O.A. Jones and R. Endean (eds.), Biology and geology of coral reefs, Vol. 1. Academic Press, New York, NY.

Mitchell, E.D. 1975. Report on the meeting on small cetaceans, Montreal, April 1-11, 1974. **J. Fish. Res. Board Can.** 32:914-91.

Mitchell, E. and D.G. Chapman. 1977. Preliminary assessment of stocks of northwest Atlantic sei whale (*Balaenoptera borealis*). **Rep. Int. Whal. Comm. Spec. Iss.** 1:117–120.

Miyazaki, N. and W.F. Perrin. 1994. Rough-toothed dolphin *Steno bredanensis* (Lesson, 1828). p. 1-21 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Mobley, J.R., Jr., L.M. Herman, and A.S. Frankel. 1988. Responses of wintering humpback whales (*Megaptera novaeangliae*) to playback of recordings of wintering and summer vocalizations and of synthetic sounds. **Behav. Ecol. Sociobiol.** 23(4):211-223.

Moein, S.E., J.A. Musick, J.A. Keinath, D.E. Barnard, M. Lenhardt, and R. George. 1994. Evaluation of seismic sources for repelling sea turtles from hopper dredges. Rep. from Virginia Inst. Mar. Sci., [Gloucester Point], VA, for U.S. Army Corps of Engineers. 33 p.

Morales-Vela, B. D. Olivera-Gomez, J.E. Reynolds III, and G.B. Rathbun. 2000. Distribution and habitat use by manatees (*Trichechus manatus manatus*) in Belize and Chetumal Bay, Mexico. **Biol. Cons.** 95(1): 67-75.

Moulton, V.D. and J.W. Lawson. 2002. Seals, 2001. p. 3-1 to 3-48 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of WesternGeco's open water seismic program in the Alaskan Beaufort Sea, 2001. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for WesternGeco, Houston, TX, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. LGL Rep. TA2564-4.

Moulton, V.D. and G.W. Miller. In press. Marine mammal monitoring of a seismic survey on the Scotian Slope, 2003. **Can. Tech. Rep Fish. Aquat. Sci.** 13 p.

Mullin, K.D., L.V. Higgins, T.A. Jefferson, and L.J. Hansen. 1994a. Sightings of the Clymene dolphin (*Stenella clymene*) in the Gulf of Mexico. **Mar. Mamm. Sci.** 10(4):464-470.

Mullin, K.D., T.A. Jefferson, L.J. Hansen, and W. Hoggard. 1994b. First sightings of melon-headed whales (*Peponocephala electra*) in the Gulf of Mexico. **Mar. Mamm. Sci.** 10(3):342-348.

Musick, J.A. and C.J. Limpus. 1997. Habitat utilization and migration in juvenile sea turtles. p. 137-163 *In*: P.L. Lutz and J.A. Musick (eds.), The biology of sea turtles. CRC Press, Boca Raton, FL. 432 p.

NatureServe. 2005. InfoNatura. http://www.natureserve.org/infonatura.

Nichols, W.J., A. Resendiz, and C. Mayoral-Russeau. 2000. Biology and conservation of loggerhead turtles (*Caretta caretta*) in Baja California, Mexico. p. 169-171 *In*: H.J. Kalb and T. Wibbels (comp.), Proc. 19th Annu. Symp. Sea Turtle Biol. Conserva. NOAA Tech. Memo. NMFS-SEFSC-443. 291 p.

Nieukirk, S.L., K.M. Stafford, D.K. Mellinger, R.P. Dziak, and C.G. Fox. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. **J. Acoust. Soc. Am.** 115:1832-1843.

NMFS. 1995. Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. **Fed. Regist.** 60(200, 17 Oct.):53753-53760.

NMFS. 2000. Small takes of marine mammals incidental to specified activities; marine seismic-reflection data collection in southern California/Notice of receipt of application. **Fed. Regist.** 65(60, 28 Mar.):16374-16379.

NMFS. 2001. Small takes of marine mammals incidental to specified activities; oil and gas exploration drilling activities in the Beaufort Sea/Notice of issuance of an incidental harassment authorization. **Fed. Regist**. 66(26, 7 Feb.):9291-9298.

NMFS. 2002. Endangered Species Act Section 7 Consultation Biological Opinion: authorization of pelagic fisheries under the Fishery Management Plan for Pelagic Fisheries of the Western Pacific Region. National Marine Fisheries Service, Southwest Region, Pacific Islands Area Office. 365 p.

NMFS. 2005. Endangered fish and wildlife; Notice of Intent to prepare an Environmental Impact Statement. **Fed. Regist.** 70(7, 11 Jan.):1871-1875.

NMFS and USFWS. 1997. Recovery plan for U.S. Pacific populations of the East Pacific green turtle (*Chelonia mydas*). U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service and U.S. Department of the Interior, U.S. Fish and Wildlife Service. Prepared by the Sea Turtle Recovery Team.

NMFS and USFWS. 1998. Recovery plan for U.S. Pacific populations of the olive ridley turtle (*Lepidochelys olivacea*). Nat. Mar. Fish. Service, Silver Spring, MD. 53 p.

NOAA. 2003. LME 12: Caribbean Sea. http://na.nefsc.noaa.gov/lme/text/lme12.htm

NOAA. 2004. LME 11: Pacific Central American Coastal LME. http://na.nefsc.noaa.gov/lme/text/lme11.htm

NOAA and USN. 2001. Joint interim report: Bahamas marine mammal stranding event of 15-16 March 2000. U.S. Dep. Commer., Nat. Oceanic Atmos. Admin., Nat. Mar. Fish. Serv., Sec. Navy, Assis. Sec. Navy, Installations and Envir. 51 p. Available at http://www.awionline.org/oceans/Noise/Interim_Bahamas_Report.pdf.

Notarbartolo di Sciara, G. 1983. Bryde's whale (*Balaenoptera edeni* Anderson, 1878) off Eastern Venezuela (Cetacea, Balaenopteridae). Tech. Rep. 83-153. Hubbs-Sea World Res. Inst., San Diego, CA. 16 p.

Nowacek, D.P., L.H. Thorne, D.W. Johnston, and P.L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. **Mammal Rev.** 37(2):81-115.

NRC. 2005. Marine mammal populations and ocean noise/Determining when noise causes biologically significant effects. U.S. Nat. Res. Counc., Ocean Studies Board, Committee on Characterizing Biologically Significant Marine Mammal Behavior (D.W. Wartzok, J. Altmann, W. Au, K. Ralls, A. Starfield, and P.L. Tyack). Nat. Acad. Press, Washington, DC. 126 p.

Odell, D.K. and K.M. McClune. 1999. False killer whale *Pseudorca crassidens* (Owen, 1846). p. 213-243 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals. Vol. 6. The second Book of dolphins and the porpoises. Academic Press, San Diego, CA. 486 p.

Ocean Resource Foundation. 1998. Construction on Playa La Flor National Wildlife Refuge-Nicaragua. http://www.orf.org/currents001b.htm

OGJ. 2006. Nicaragua signs MKJ to Caribbean blocks. **Oil & Gas Journal Online** April 25 2006. Available at: http://www.ogj.com/articles/article_display.cfm?Section=ONART&C=ExplD&ARTICLE_ID=253514&p=7

Oleson, E.M., J. Barlow, G. Gordon, S. Rankin, and J.A. Hildebrand. 2003. Low frequency calls of Bryde's whales. **Mar. Mamm. Sci.** 19(2):407-419.

Olson, P.A. and S. B. Reilly. 2002. Pilot whales. p. 898-893 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

Palacios, D.M. 1996a. On the specimen of the ginkgo-toothed beaked whale, *Mesoplodon ginkgodens*, from the Galápagos Islands. **Mar. Mamm. Sci.** 12(3):444-446.

Palacios, D.M. 1996b. Attack by false killer whales (*Pseudorca crassidens*) on sperm whales (*Physeter macrocephalus*) in the Galápagos Islands. **Mar. Mamm. Sci.** 12(4):582-587.

Palacios, D.M. 1999. Blue whale (*Balaenoptera musculus*) occurrence off the Galápagos Islands, 1978-1995. **J. Cetac. Res. Manage.** 1(1):41-51.

Palacios, D.M, P. Rodríguez, B. Brennan, and K. Marshall. 1994. Notes on the Cuvier's beaked whale (*Ziphius cavirostris*), with observations of a dead specimen. **Not. Galápagos** 54:29-31.

Palacios, D.M. K.M. Stafford, and F.B. Schwing. 2005. Temporal variations in blue whale acoustic detections in relation to environmental conditions in the northeastern tropical Pacific, 1996-2002. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Papastavrou, V., S.C. Smith, and H. Whitehead. 1989. Diving behaviour of the sperm whale, *Physeter macrocephalus*, off the Galápagos Islands. **Can. J. Zool.** 67(4):839-846.

Pardo, M.A., J.M. Avila, and G.A. Jáuregui. 2005. New records of cetacean species in the coast region of Santa Marta and Tayrona National Natural Park TNNP (Colombian Caribbean Sea) related with some particular environmental features of the area. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec., San Diego, CA.

Parry, G.D. and A. Gason. 2006. The effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia. **Fish. Res.** 79:272-284.

Patkin, S. 1999. Enviromental impact of the offshore oil and gas industry. EcoMonitor Publishing, NY.

Payne, J.F., C.A. Andrews, L.L. Fancey, A.L. Cook, and J.R. Christian. 2007. Pilot study on the effects of seismic air gun noise on lobster (*Homarus americanus*). Canadian Technical Report of Fisheries and Aquatic Sciences No. 2712:v + 46 p.

Payne, R.S. and S. McVay. 1971. Songs of humpback whales. **Science** 173(3997):585-597.

Pearson, W.H., J.R. Skalski, and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on behaviour of captive rockfish (*Sebastes* spp.). **Can. J. Fish. Aquat. Sci.** 49(7):1343-1356.

Pearson, W., J. Skalski, S. Sulkin, and C. Malme. 1994. Effects of seismic energy releases on the survival and development of zoeal larvae of Dungeness crab (*Cancer magister*). **Mar. Environ. Res**. 38: 93-113.

Pennington, J.T., K.L. Mahoney, V.S. Kuwahara, D.D. Kolber, R. Calienes, and F.P. Chavez. 2006. Primary production in the eastern tropical Pacific: a review. **Prog. Oceanogr**. 69 (2-4), 285-317.

Perrin, W.F. 1990. Subspecies of *Stenella longirostris* (Mammalia: Cetacea, Delphinidae). **Proc. Biol. Soc. Wash.** 103(2):453-463.

Perrin, W.F. 2002. Spinner dolphin – *Stenella longirostris*. p. 1174-1178 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego. 1414 p.

Perrin, W.F. and J.W. Gilpatrick, Jr. 1994. Spinner dolphin. p. 99-128 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Perrin, W.F. and A.A. Hohn. 1994. Pantropical spotted dolphin *Stenella attenuat*a. p. 71-98 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Perrin, W.F. and J.G. Mead. 1994. Clymene dolphin *Stenella clymene* (Gray, 1846). p. 161-171 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, London, U.K. 416 p.

Perrin, W.F. and W.A. Walker. 1975. The rough-toothed porpoise, *Steno bredanensis*, in the eastern tropical Pacific. **J. Mammal.** 56:905-907.

Perrin, W.F., P.B. Best, W.H. Dawbin, K.C. Balcomb, R. Gambell, and G.J.B. Ross. 1973. Rediscovery of Fraser's dolphin *Lagenodelphis hosei*. **Nature** 241(5388):345-350.

Perrin, W.F., J.M. Coe, and J.R. Zweifel. 1976. Growth and reproduction of the spotted porpoise, *Stenella attenuata*, in the offshore eastern tropical Pacific. **Fish. Bull.** 74(2):229-269.

Perrin, W.F., M.D. Scott, G.J. Walker, and V.L. Cass. 1985. Review of geographical stocks of tropical dolphins (*Stenella* spp. and *Delphinus delphis*) in the eastern Pacific. NOAA Tech. Rep. NMFS 28. 28 p.

Perrin, W.F., E.D. Mitchell, J.G. Mead, D.K. Caldwell, M.C. Caldwell, P.J.H. Van Bree, and W.H. Dawbin. 1987. Revision of the spotted dolphins, *Stenella* spp. **Mar. Mamm. Sci.** 3(2):99-170.

Perrin, W.F., D.K. Caldwell, and M.C. Caldwell. 1994a. Atlantic spotted dolphin *Stenella frontalis* (G. Cuvier, 1829). p. 173-190 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Perrin, W.F., C.E. Wilson, and F.I. Archer II. 1994b. Striped dolphin *Stenella coeruleoalba* (Meyen, 1833). p. 129-159 *In:* S. H. Ridgway and R. J. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Perrin, W.F., S. Leatherwood, and A. Collet. 1994c. Fraser's dolphin *Lagenodelphis hosei* Fraser, 1956. p. 225-240 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, London, U.K. 416 p.

Perryman, W.L. 2002. Melon-headed whale – *Peponocephala electra*. p. 733-735 *In:* W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

Perryman, W.L. and T.C. Foster. 1980. Preliminary report of predation by small whales, mainly the false killer whale, *Pseudorca crassidens*, on dolphins (*Stenella* spp. and *Delphinus delphis*) in the eastern tropical Pacific. NOAA, NMFS, Southwest Fisheries Center Administrative Report LJ-80-05. 9 p.

Perryman, W.L. and M.S. Lynn. 1993. Identification of geographic forms of common dolphin (*Delphinus delphis*) from aerial photogrammetry. **Mar. Mamm. Sci.** 9(2):119-137.

Perryman, W.L., D.W.K. Au, S. Leatherwood, and T.A. Jefferson. 1994. Melon-headed whale *Peponocephala electra* Gray, 1846. p. 363-386. *In*: S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals. Volume 5. The first book of dolphins. Academic Press. 416 p.

Philbrick, V.A., P.C. Fiedler, J.T. Fluty, and S.B. Reilly. 2001. Report of oceanographic studies conducted during the 2000 eastern tropical Pacific Ocean survey on the research vessels *David Starr Jordan* and *McArthur*. U.S. Department of Commerce. NOAA Tech. Memo. NMFS-SWFSC-309. 20 p.

Pickett, G.D., D.R. Eaton, R.M.H. Seaby, and G.P. Arnold. 1994. Results of bass tagging in Poole Bay during 1992. Laboratory Leaflet Number 74. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research, Lowestoft, UK.

Pierson, M.O., J.P. Wagner, V. Langford, P. Birnie, and M.L. Tasker. 1998. Protection from, and mitigation of, the potential effects of seismic exploration on marine mammals. Chapter 7 *In*: M.L. Tasker and C. Weir (eds.), Proceedings of the seismic and marine mammals workshop, London, 23–25 June 1998.

Pitman, R.L. 1990. Pelagic distribution and biology of sea turtles in the eastern tropical Pacific. p. 143-148 *In*: T.H. Richardson, J.I. Richardson, and M. Donnelly (compilers), Proc. 10th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFC-278. 286 p.

Pitman, R.L. and L.T. Ballance. 1992. Parkinson's petrel distribution and foraging ecology in the eastern tropical Pacific: Aspects of an exclusive feeding relationships with dolphins. **Condor** 94(4):825-835.

Pitman, R.L. and M.S. Lynn. 2001. Biological observations of an unidentified Mesoplodont whale in the eastern tropical Pacific and probable identity: *Mesoplodon peruvianus*. **Mar. Mamm. Sci.** 17(3): 648-657.

Pitman, R.L., A. Aguayo L., and J. Urbán R. 1987. Observations of an unidentified beaked whale (*Mesoplodon* sp.) in the eastern tropical Pacific. **Mar. Mamm. Sci.** 3(4):345-352.

Pitman, R.L., D.M. Palacios, P.L.R. Brennan, B.J. Brennan, K.C. Balcomb, III, and T. Miyashita. 1999. Sightings and possible identity of a bottlenose whale in the tropical Indo-Pacific: *Indopacetus pacificus*? **Mar. Mamm. Sci.** 15(2): 513-518.

Pitman, R.L., L.T. Ballance, S.I. Mesnick, and S.J. Chivers. 2001. Killer whale predation on sperm whales: observations and implications. **Mar. Mamm. Sci.** 17(3):494-507.

Plotkin, P.T., R.A. Byles, D.C. Rostal, and D.W. Owens. 1991. Arribadas: social events or simply aggregations? Preliminary results from satellite telemetry. p. 95-96 *In*: M. Salmon and J. Wyneken (comp.), Proc. 11th Annu. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-302. 195 p.

Plotkin, P.T., R.A. Byles, and D.W. Owens. 1994a. Post-breeding movements of male olive ridley sea turtles *Lepidochelys olivacea* from a nearshore breeding area. p. 119 *In*: K.A. Bjorndal, A.B. Bolten, D.A. Johnson, and P.J. Eliazar (comp.), Proc. 14th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Plotkin, P.T., R.A. Byles, and D.W. Owens. 1994b. Migratory and reproductive behavior of *Lepidochelys olivacea* in the eastern Pacific Ocean. p. 138 *In*: B.A. Schroeder and B.E. Witherington (comp.), Proc. 13th Annu. Symp. Sea Turtle Biol. and Conserv. NOAA Tech. Memo. NMFS-SEFSC-341. 281 p.

Plotkin, P.T., R.A. Byles, D.C. Rostal, and D.W. Owens. 1995. Investigation of cohort cohesiveness in mass emergent nesting behavior of *Lepidochelys olivacea*. p. 94-95 *In*: Richardson, J.I and T.H. Richardson (comp.), Proc. 12th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-361. 274 p.

Polacheck, T. 1987. Relative abundance, distribution and inter-specific relationship of cetacean schools in the Eastern Tropical Pacific. **Mar. Mamm. Sci.** 3(1):54-77.

Popper, A.N., M. Salmon, and K.W. Horch. 2001. Acoustic detection and communication by decapod crustaceans. **J. Comp. Physiol. A** 187: 83-89.

Popper, A.N., M.E. Smith, P.A. Cott, B.W. Hanna, A.O. MacGillivray, M.E. Austin, and D.A. Mann. 2005. Effects of exposure to seismic airgun use on hearing of three fish species. **J. Acoust. Soc. Am.** 117:3958-3971.

PortFocus. 2003. Costa Rica. Available at http://portfocus.com/costa_rica/zz_marinas/index.html.

Potter, J.R. 2004. A possible mechanism for acoustic triggering of decompression sickness symptoms in deep-diving marine mammals. Paper presented to the 2004 IEEE International Symposium on Underwater Technology, Taipei, Taiwan, 19-23 April 2004. Available at http://www.zifios.com/documentos-oficiales/documentos/Singapore_John_R_Potter_UT04.pdf.

Ramirez, A.P. 1989. Captura de cachalotes en Paita: 1976-1981. **Bol. Lima** 63:81-88. [In Spanish].

Rasmussen, K., J. Calambokidis, and G.H. Steiger. 2002. Humpback whales and other marine mammals off Costa Rica and surrounding waters, 1996-2002. Report of the Oceanic Society 2002 field season in cooperation with elderhostel volunteers. Cascadia Research, Olympia, WA. 32 p.

Rasmussen, K., J. Calambokidis, and G.H. Steiger. 2004. Humpback whales and other marine mammals off Costa Rica and surrounding waters, 1996-2003. Report of the Oceanic Society 2003 field season in cooperation with elderhostel volunteers. Cascadia Research, Olympia, WA. 24 p.

Rasmussen, K., D.M. Palacios, J. Calambokidis, M.T. Saborio, L. Dalla Rosa, E.R. Secchi, G.H. Steiger, J.M. Allen, and G.S. Stone. 2007. Southern Hemisphere humpback whales wintering off Central America: insights from water temperature into the longest mammalian migration. **Biol. Lett.** 3:302-305.

Reeves, R.R., S.L. Swartz, S.E. Wetmore, and P.J. Clapham. 2001a. Historical occurrence and distribution of humpback whales in the eastern and southern Caribbean Sea, based on data from American whaling logbooks. **J. Cetac. Res. Manage.** 3(2):117-129.

Reeves, R.R., J.A. Kahn, R.R. Olsen, S.L. Swartz and T.D. Smith. 2001b. History of whaling in Trinidad and Tobago. **J. Cetac. Res. Manage.** 3(1):45-54.

Reeves, R.R., B.S. Stewart, P.J. Clapham, and J.A. Powell. 2002. Guide to marine mammals of the world. Chanticleer Press, New York, NY.

Reilly, S.B. 1990. Seasonal changes in distribution and habitat differences among dolphins in the eastern tropical Pacific. **Mar. Ecol. Prog. Ser.** 66(1-2):1-11.

Reilly, S.B. and V.G. Thayer. 1990. Blue whale (*Balaenoptera musculus*) distribution in the eastern tropical Pacific. **Mar. Mamm. Sci.** 6:265-277.

Reilly, S.B. and P.C. Fiedler. 1994. Interannual variability of dolphin habitats in the eastern tropical Pacific. I: Research vessel surveys, 1986-1990. **Fish. Bull.** 92(2):434-450.

Rendell, L.E. and J.C.D. Gordon. 1999. Vocal response of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. **Mar. Mamm. Sci.** 15(1):198-204.

Reyes, J.C. 1991. The conservation of small cetaceans: a review. Report prepared for the Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals. UNEP/CMS Secretariat, Bonn.

Reyes, J.C., J.G. Mead, and K. Van Waerebeek. 1991. A new species of beaked whale *Mesoplodon peruvianus* sp. n. (Cetacea: Ziphiidae) from Peru. **Mar. Mamm. Sci.** 7(1):1-24.

Reynolds, J.E., III, W.A. Szelistowski, and M.A. León. 1995. Status and conservation of manatees *Trichechus manatus manatus* in Costa Rica. **Biol. Cons.** 71: 193-196.

Rice, D.W. 1989. Sperm whale *Physeter macrocephalus* Linnaeus, 1758. p. 177-233 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 4. River dolphins and the larger toothed whales. Academic Press, San Diego, CA. 444 p.

Rice, D.W. 1998. Marine mammals of the world, systematics and distribution. Spec. Publ. 4. Soc. Mar. Mammal., Allen Press, Lawrence, KS. 231 p.

Rice, D.W. 1998. Marine Mammals of the World, Systematics and Distribution. Spec. Publ. 4. Soc. Mar. Mammal., Allen Press, Lawrence, KS. 231 p.

Richard, K.R. and M.A. Barbeau. 1994. Observations of spotted dolphins feeding nocturnally on flying fish. **Mar. Mamm. Sci.** 10(4):473-477.

Richardson, W.J., B. Würsig, and C.R. Greene. 1986. Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. **J. Acoust. Soc. Am.** 79(4):1117-1128.

Richardson, W.J., R.A. Davis, C.R. Evans, D.K. Ljungblad, and P. Norton. 1987. Summer distribution of bowhead whales, *Balaena mysticetus*, relative to oil industry activities in the Canadian Beaufort Sea, 1980-84. **Arctic** 40(2):93-104.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. Marine mammals and noise. Academic Press, San Diego. 576 p.

Richardson, W.J., G.W. Miller, and C.R. Greene Jr. 1999. Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. **J. Acoust. Soc. Am.** 106(4, Pt. 2):2281.

Robertson, K.M. and S.J. Chivers. 1997. Prey occurrence in pantropical spotted dolphins, *Stenella attenuata*, from the eastern tropical Pacific. **Fish. Bull.** 95(2):334-348.

Robineau, D. and A. di Natale. 1995. *Ziphius cavirostris* - Cuvier-Schnabelwal. p. 526-543 In: D. Robineau, R. Duguy and M. Klima (eds.), Handbuch der Säugetiere Europas. Meeressäuger. Teil IB: Wale und Delphine 2. Aula-Verlag, Wiesbaden.

Roden, C.L. and K.D. Mullin. 2000. Sightings of cetaceans in the northern Caribbean Sea and adjacent waters, winter 1995. **Caribbean J. Sci.** 36(3-4):280-288.

Rodrigue, J-P. 2007. The strategic space of international transportation. http://people.hofstra.edu/ geotrans/eng/ch5en/conc5en/ch5c1en.html. Accessed on 19 February 2007.

Rodríguez-Fonseca, J. 2001. Diversity and distribution of Costa Rica's cetaceans (Cetacea: Delphinidae, Physeteridae, Ziphiidae and Balaenopteridae). **Rev. Biol. Trop.** 49, Suppl. 2:135-143. (Spanish, Engl. summ.)

Rodríguez-Fonseca, J. and P. Cubero-Pardo. 2001. Cetacean strandings in Costa Rica (1966-1999). **Rev. Biol. Trop**. 49(2):667-672.

Rodríguez-Herrera, B., F.A. Chinchilla, and L.J. May-Collado. 2002. Lista de especies, endemismo y conservación de los de mamiferos de Costa Rica. **Rev. Mex. Mastozoologia** 6:19-41.

Rodríguez Saenz, K. and J. Rodríguez-Fonseca. 2004. Avistamientos del delfín manchado, *Stenella attenuata* (Cetacea: Delphinidae) en Bahia Culebra, Costa Rica, 1999-2000. **Rev. Biol. Trop.** 52, Suppl. 2. Available at www.scielo.sa.cr/scielo.

Rogers, P. and M. Cox. 1988. Underwater sound as a biological stimulus. p. 131-149 *In*: J. Atema., R.R. Fay, A.N. Popper, and W.N. Tavolga (eds.), The sensory biology of aquatic animals. Springer-Verlag, New York, NY.

Romero, A. and K. Hayford. 2000. Past and present utilisation of marine mammals in Grenada, West Indies. **J. Cetacean Res. Manage.** 2(3):223-226.

Romero, A., A.I. Agudo, S.M. Green, and G. Notarbartolo di Sciara. 2001. Cetaceans of Venezuela: their distribution and conservation status. NOAA Tech. Rep. NMFS 151. U.S. Dep. Comm., Seattle, WA. 60 p.

Rosales, M.L. and S. Escorza-Trefiño. 2005. Population structure and sex biased dispersal of spotted dolphins (*Stenella attenuata*) in the eastern tropical Pacific. 2005. Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12-16 Dec. 2005, San Diego, CA.

Rosario-Delestre, R., M.A. Rodríguez-López, A.A. Mignucci-Giannoni, and J.G Mead. 1999. New Records of beaked whales (*Mesoplodon* spp.) for the Caribbean. **Caribbean J. Sci.** 35(1-2):144-148.

Ross, G. J.B. and S. Leatherwood. 1994. Pygmy killer whale *Feresa attenuata* Gray, 1874. p. 387-404 *In:* S.H. Ridgway and R.J. Harrison (eds.), Handbook of marine mammals, Vol. 5. The first book of dolphins. Academic Press, San Diego, CA. 416 p.

Ruiz, G.A. 1994. Sea turtle nesting population at Playa La Flor, Nicaraugua: An olive ridley “arribada” beach. p. 129-130 *In*: K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (comp.), Proc. 14th Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 323 p.

Saetre, R. and E. Ona. 1996. Seismike undersøkelser og på fiskeegg og -larver en vurdering av mulige effecter pa bestandsniva. [Seismic investigations and damages on fish eggs and larvae; an evaluation of possible effects on stock level]. **Fisken og Havet** 1996:1-17, 1-8. (in Norwegian, with an English summary).

Santulli, A., A. Modica, C. Messina, L. Ceffa, A. Curatolo, G. Rivas, G. Fabi, and V. D'Amelio. 1999. Biochemical responses of European sea bass (*Dicentrarchus labrax* L.) to the stress induced by off shore experimental seismic prospecting. **Mar. Pollut. Bull.** 38(12):1105-1114.

Sarti, L., S Eckert, P. Dutton, A. Barragán, and N. García. 2000. The current situation of the leatherback population on the Pacific coast of Mexico and Central America, abundance and distribution of the nestings: an update. p. 85-87 *In*: H.J. Kalb and T. Wibbels (comp.), Proc. 19th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-443. 291 p.

Scheidat, M., C. Castro, J. Denkinger, J. González, and D. Adelung. 2000. A breeding area for humpback whales (*Megaptera novaeangliae*) off Ecuador. **J. Cetacean Res. Manage.** 2(3):165-171.

Schlundt, C.E., J.J. Finneran, D.A. Carder, and S.H. Ridgway. 2000. Temporary shift in masking hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. **J. Acoust. Soc. Am.** 107(6):3496-3508.

Scott, M.D. and K.L. Cattanach. 1998. Diel patterns in aggregations of pelagic dolphins and tunas in the eastern Pacific. **Mar. Mamm. Sci.** 14(3):401-428.

Scott, M.D. and S.J. Chivers. 1990. Distribution and herd structure of bottlenose dolphins in the eastern tropical Pacific Ocean. p. 387-402. *In:* S. Leatherwood and R.R. Reeves (eds.), The bottlenose dolphin. Academic Press, San Diego, CA. 653 p.

Sea Around Us. 2007. Sea Around Us Project. http://www.seaaroundus.org

Sears, R., J.M. Williamson, F.W. Wenzel, M. Bérubé, D. Gendron, and P. Jones. 1990. Photographic identification of the blue whale (*Balaenoptera musculus*) in the Gulf of St. Lawrence, Canada. **Rep. Int. Whal. Comm., Spec. Iss.** 12:335-342.

Segura, A. and R.M. Arauz. 1995. By-catch capture of sea turtles by two kinds of experimental longline gears in Pacific Costa Rica waters. p. 125-127 *In*: J.I. Richardson and T.H. Richardson (comp.), Proc. 12th Ann. Workshop Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-361. 274 p.

Sergeant, D.E. 1977. Stocks of fin whales *Balaenoptera physalus* L. in the North Atlantic Ocean. **Rep. Int. Whal. Comm.** 27:460-473.

Shane, S.H., R.S. Wells, and B. Würsig. 1986. Ecology, behavior and social organization of the bottlenose dolphin: a review. **Mar. Mamm. Sci.** 2:34-63.

Shuster, G.W. 1983. The Galápagos Islands: a preliminary study of the effects of sperm whaling on a specific whaling ground. **Rep . Int. Whal. Comm. Spec. Iss.** 5:81-82.

Skalski, J.R., W.H. Pearson, and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (*Sebastes* spp). **Can. J. Fish. Aquatic Sci.** 49:1357-1365.

Slotte, A., K. Hansen, J. Dalen, and E. Ona. 2004. Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. **Fish. Res.** 67:143-150.

Smethurst, D. and B. Nietschmann. 1999. The distribution of manatees (*Trichechus manatus*) in the coastal waterways of Tortuguero, Costa Rica. **Biol. Cons.** 89(3):267-274.

Smith, T.D. 1983. Changes in size of three dolphin (*Stenella* spp.) populations in the eastern tropical Pacific. **Fish. Bull.** 81(1):1-13.

Smith, S.C. and H. Whitehead. 1993. Variations in the feeding success and behaviour of Galápagos sperm whales (*Physeter macrocephalus*) as they relate to oceanographic conditions**. Can. J. Zool.** 71(10):1991-1996.

Smith, S.D. and H. Whitehead. 1999. Distribution of dolphins in Galápagos waters. **Mar. Mamm. Sci.** 15(2)550-555.

Smith, S.C. and H. Whitehead. 2000. The diet of Galápagos sperm whales *Physeter macrocephalus* as indicated by fecal sample analysis. **Mar. Mamm. Sci.** 16(2):315-325.

Smith, T.D., J. Allen, P.J. Clapham, P.S. Hammond, S. Katona, F. Larsen, J. Lien, D. Mattila, P. Palsbøll, J. Sigurjónsson, P.T. Stevick, and N. Øien. 1999. An ocean-basin-wide mark-recapture study of the North Atlantic humpback whale (*Megaptera novaeangliae*). **Mar. Mamm. Sci.** 15(1):1-32.

Smultea, M.A. and M. Holst. 2003. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic study in the Hess Deep area of the Eastern Equatorial Tropical Pacific, July 2003. LGL Rep. TA2822-16. Rep. from LGL Ltd., King City, ON, for Lamont-Doherty Earth Observatory, Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 68 p.

Smultea, M.A., M. Holst, W.R. Koski, and S. Stoltz. 2004. Marine mammal monitoring during Lamont-Doherty Earth Observatory’s seismic program in the Southeast Caribbean Sea and adjacent Atlantic Ocean, April–

June 2004. LGL Rep. TA2822-26. Rep. From LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 106 p.

Smultea, M.A., W.R. Koski, and T.J. Norris. 2005. Marine mammal monitoring during Lamont-Doherty Earth Observatory's marine seismic study of the Blanco Fracture Zone in the Northeastern Pacific Ocean, October-November 2004. LGL Rep. TA2822-29. Rep. From LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 89 p.

Southwood, A.L., R.D. Andrews, D.R. Jones, M.E. Lutcavage, F.V. Paladino, and N.H. West. 1998. Heart rate and dive behaviour of the leatherback sea turtle during the interesting interval. p.100-101 *In*: S.P. Epperly and J. Braun (comp.), Proc. 17th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-415. 294 p.

Spotila, J.R. 2004. Sea turtles: a complete guide to their biology, behavior, and conservation. The Johns Hopkins University Press and Oakwood Arts. Baltimore and London.

Stacey, P.J. and R.W. Baird. 1991. Status of the false killer whale, *Pseudorca crassidens*, in Canada. **Can. Field-Nat.** 105(2):189-197.

Stacey, P.J., S. Leatherwood, and R.W. Baird. 1994. *Pseudorca crassidens*. **Mammal. Species** 456:1-6.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox. 1999a. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. **J. Acoust. Soc. Am.** 106(6):3687-3698.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox. 1999b. An acoustic link between blue whales in the eastern tropical Pacific and the Northeast Pacific. **Mar. Mamm. Sci**. 15(4):1258-1268.

Stafford, K.M., S.E. Moore, and C.G. Fox. 2005. Diel variation in blue whale calls recorded in the eastern tropical Pacific. **Anim. Behav.** 69(4): 951-958.

Steiger, G.H., J. Calambokidis, R. Sears, K.C. Balcomb, and J.C. Cubbage. 1991. Movement of humpback whales between California and Costa Rica. **Mar. Mamm. Sci.** 7(3):306-310.

Stemp, R. 1985. Observations on the effects of seismic exploration on seabirds. p. 217-231 *In* G.D. Greene, F.R. Engelhardt, and R.J. Paterson (eds.), Proceedings of the Workshop on the Effects of Explosives Use in the Marine Environment, 29–31 January 1985. Tech. Rep. 5, Canada Oil and Gas Lands Administration, Environmental Protection Branch, Ottawa, ON.

Sternberg, J. 1981. The worldwide distribution of sea turtle nesting beaches. Sea Turtle Rescue Fund, Center for Environmental Education, Washington D.C.

Stevick, P.T., J. Allen, P.J. Clapham, N. Friday, S.K. Katona, F. Larsen, J. Lien, D.K. Mattila, P.J. Palsbøll, R. Sears, J. Sigurjónsson, T.D. Smith, G. Vikingsson, J. Øien, and P.S. Hammond. 2001. Trends in abundance of North Atlantic humpback whales, 1979-1993. Paper SC/53/NAH2 presented to the International Whaling Commission Scientific Committee.

Stevick, P.T., J. Allen, P.J. Clapham, N. Friday, S.K. Katona, F.Larsen, J. Lien, D.K. Mattila, P.J. Palsbøll, J. Sigurjónsson, T.D. Smith, N. Øien, and P.S. Hammond. 2003. North Atlantic humpback whale abundance and rate of increase four decades after protection from whaling. **Mar. Ecol. Prog. Ser.** 258:263-273.

Stewart, B.S. and S. Leatherwood. 1985. Minke whale *Balaenoptera acutorostrata* Lacépède, 1804. p. 91-136 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, London, U.K. 362 p.

Swartz, S.L. and C. Burks. 2000. Cruise Results. Windwards Humpback (*Megaptera novaeangliae*) survey. NOAA ship Gordon Gunter Cruise GU-00-01. 9 February to 3 April 2000. NOAA Tech. Memo. NMFS-SEFSC-438. 32 p.

Swartz, S.L., A. Martinez, T. Cole, P.J. Clapham, M.A. McDonald, J.A. Hildebrand, E.M. Oleson, C. Burks, and J. Barlow. 2001. Visual and acoustic survey of humpback whales (*Megaptera novaeangliae*) in the eastern and southern Caribbean Sea: preliminary findings. NOAA Tech. Memo. NMFS-SEFSC-456. 45 p.

Swartz, S.L., T. Cole, M.A. McDonald, J.A. Hildebrand, E.M. Oleson, A. Martinez, P.J. Clapham, J. Barlow, and M.L. Jones. 2003. Acoustic and visual survey of humpback whale (*Megaptera novaeangliae*) distribution in the eastern and southeastern Caribbean Sea. **Caribbean J. Sci.** 39(2):195-208.

Stone, C.J. 2003. The effects of seismic activity on marine mammals in UK waters 1998-2000. JNCC Report 323. Joint Nature Conservancy, Aberdeen , Scotland. 43 p.

Stone, G.S., S.K. Katona, A. Mainwaring, J.M. Allen, and H.D. Corbett. 1992. Respiration and surfacing rates of fin whales (*Balaenoptera physalus*) observed from a lighthouse tower. **Rep. Int. Whal. Comm.** 42:739-745.

Sverdrup, A., E. Kjellsby, P.G. Krüger, R. Fløysand, F.R. Knudsen, P.S. Enger, G. Serck-Hanssen, and K.B. Helle. 1994. Effects of experimental seismic shock on vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the Atlantic salmon. **J. Fish Biol.** 45:973-995.

Sybesma, J. 1992. WIDECAST Sea Turtle Recovery Action Plan for the Netherlands Antilles. *In:* K.L. Eckert (ed.), CEP Technical Report No. 11. UNEP Caribbean Environment Program, Kingston, Jamaica. 63 p.

Taft, L.K. and R. S. Carranza. 2000. The cooperative agreement for the conservation of sea turtles of the Caribbean coast of Costa Rica, Nicaragua and Panama. p. 208-210 *In*: Kalb, H.J. and T. Wibbels (comp.), Proc. 19th Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Mem. NMFS-SEFSC-443. 291 p.

Taylor, B., J. Barlow, R. Pitman, L. Balance, T. Klinger, D. DeMaster, J. Hildebrand, J. Urban, D. Palacios, and J. Mead. 2004. A call for research to assess risk of acoustic impact on beaked whale populations. Paper SC/56/E36 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy. 4 p. [Paper available from the Office of this Journal].

Thompson, D., M. Sjöberg, E.B. Bryant, P. Lovell, and A. Bjørge. 1998. Behavioural and physiological responses of harbour (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals to seismic surveys. Abstr. World Mar. Mamm. Sci. Conf., Monaco.

Thomson, D.H. and W.J. Richardson. 1995. Marine mammal sounds. p. 159-204 *In*: W.J. Richardson, C.R. Greene, Jr., C.I. Malme and D.H. Thomson, Marine mammals and noise. Academic Press, San Diego, CA. 576 p.

Tolstoy, M., J. Diebold, S. Webb, D. Bohnenstiehl, and E. Chapp. 2004a. Acoustic calibration measurements. Chapter 3 *In*: W.J. Richardson (ed.), Marine mammal and acoustic monitoring during Lamont-Doherty Earth Observatory's acoustic calibration study in the northern Gulf of Mexico, 2003. Revised ed. Rep. from LGL Ltd., King City, ON, for Lamont-Doherty Earth Observ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. Available at: http://www.nmfs.noaa.gov/pr/pdfs/permits/lamont_report_gulf.pdf.

Tolstoy, M., J.B. Diebold, S.C. Webb, D.R. Bohenstiehl, E. Chapp, R.C. Holmes, and M. Rawson. 2004b. Broadband calibration of R/V *Ewing* seismic sources. **Geophys. Res. Lett.** 31:L14310.

Troëng, S. 2001. Decline in the hawksbill turtle *Eretmochelys imbricata* in Caribbean Costa Rica. p. 338-339 *In:* M. Coiné (comp.), Proc. 21st Ann. Symp. Sea Turtle Biol. Conserv. NOAA Tech. Memo. NMFS-SEFSC-528. 368 p.

Tyack, P., M. Johnson, and P. Miller. 2006. Response of sperm whales to airgun sounds in the Gulf of Mexico. Pages 215-168 *In:* A.E. Jochens et al., Sperm whale seismic study in the Gulf of Mexico. Summary Report, 2002-2004. OCS Study MMS 2006-034. Rep. from Texas A&M Univ., College Station, TX, for U.S. Minerals Manage. Serv., Gulf of Mexico OCS Reg., New Orleans, LA.

UNEP. 1993. Sea Turtle Recovery Action Plan for St. Vincent and the Grenadines. CEP Technical Report No. 27. UNEP Caribbean Environment Program, Kingston, Jamaica.

UNEP-WCMC. 2007. UNEP-WCMC Species Database: CITES-Listed Species. http://www.cites.org/

Urbán, R.J. and A.L. Aguayo. 1987. Spatial and seasonal distribution of the humpback whale, *Megaptera novaeangliae*, in the Mexican Pacific. **Mar. Mamm. Sci.** 3(4):333-344.

Urbán, R.J., A. Jaramillo L., A. Aguayo L., P. Ladrón de Guevara P., M. Salinas Z., C. Alvarez F., L. Medrano G., J.K. Jacobsen, K.C. Balcomb, D.E. Claridge, J. Calambokidis, G.H. Steiger, J.M Straley, O. von Ziegesar, J.M. Waite, S. Mizroch, M.E. Dahlheim, J.D. Darling, and C.S. Baker. 2000. Migratory destinations of humpback whales wintering in the Mexican Pacific. **J. Cetac. Res. Manage.** 2(2):101-110.

Urbán-Ramírez, J. and D. Aurioles-Gamboa. 1992. First record of the pygmy beaked whale *Mesoplodon peruvianus* in the North Pacific. **Mar. Mamm. Sci.** 8(4):420-425.

Urick, R.J. (1982) "Sound propagation in the sea." Peninsula Publ., Los Altos, CA.

Van Waerebeek, K. and J.C. Reyes. 1988. First record of the pygmy killer whale, *Feresa attenuata* Gray, 1975 from Peru, with a summary of distribution in the eastern Pacific. **Z. Säugetierkunde** 53:253-255.

Van Waerebeek, K., J. Canto, J. Gonzalez, J. Oporto, and J.L. Brito. 1991. Southern right whale dolphins, *Lissodelphis peronii* off the Pacific coast of South America. **Z. Säugetierkunde** 56:284-295.

Vidal, O., J. Barlow, L.A. Hurtado, J. Torre, P. Cendon, and Z. Ojeda. 1997. Distribution and abundance of the Amazon river dolphin (*Inia geoffrensis*) and the Tucuxi (*Sotalia fluviatilis*) in the upper Amazon river. **Mar. Mamm. Sci.** 13(3):427-445.

Volkov, A.F. and I.F. Moroz. 1977. Oceanological conditions of the distribution of Cetacea in the eastern tropical part of the Pacific Ocean. **Rep. Int. Whal. Comm** 27:186-188.

Wade, L.S. and G.L. Friedrichsen. 1979. Recent sightings of the blue whale, *Balaenoptera musculus*, in the northeastern tropical Pacific. **Fish. Bull.** 76(4):915-919.

Wade, P.R. 1995. Revised estimates of incidental kill of dolphins (Delphinidae) by the purse-seine tuna fishery in the eastern tropical Pacific, 1959−1972. **Fish. Bull.** 93:345−354.

Wade, P.R. and T. Gerrodette. 1993. Estimates of cetacean abundance and distribution in the Eastern Tropical Pacific. **Rep. Int. Whal. Comm.** 43:477-493.

Wahlberg, M. 2002. The acoustic behaviour of diving sperm whales observed with a hydrophone array. **J. Exp. Mar. Biol. Ecol.** 281(1-2):53-62.

Walker, J.L., C.W. Potter, and S.A. Macko. 1999. The diets of modern and historic bottlenose dolphin populations reflected through stable isotopes. **Mar. Mamm. Sci.** 15(2):335-350.

Ward, N., A. Moscrop, and C. Carlson. 2001. Elements for the development of a marine mammal action plan for the wider Caribbean: A review of marine mammal distribution. United Nations Environment Programme. UNEP(DEC)/CAR IG.20/INF.3 First Meeting of the Contracting Parties (COP) to the Protocol Concerning Specifically Protected Areas and Wildlife (SPAW) in the Wider Caribbean Region. Havana, Cuba, 24-25 September 2001.

Wardle, C.S., T.J. Carter, G.G. Urquhart, A.D.F. Johnstone, A.M. Ziolkowski, G. Hampson, and D. Mackie. 2001. Effects of seismic air guns on marine fish. **Cont. Shelf Res.** 21(8-10):1005-1027.

Waring, G.T., E. Josephson, C.P. Fairfield, and K. Maze-Foley (eds.) 2006. U.S. Atlantic and Gulf of Mexico marine mammal stock assessments -- 2005. NOAA Tech. Memo. NMFS-NE-194. 346 p

Watkins, W.A. and K.E. Moore. 1982. An underwater acoustic survey for sperm whales (*Physeter catodon*) and other cetaceans in the southeast Caribbean. **Cetology** 46:1-7.

Watkins, W.A., K.E. Moore, and P. Tyack. 1985. Sperm whale acoustic behaviors in the southeast Caribbean. **Cetology** 49:1-15.

Watkins, W.A., M.A. Daher, N.A. DiMarzio, A. Samuels, D. Wartzok, K.M. Fristrup, D.P. Gannon, P.W. Howey, R.R. Maeiefski, and T.R. Spradlin. 1999. Sperm whale surface activity from tracking by radio and satellite tags. **Mar. Mamm. Sci.** 15(4):1158-1180.

Watkins, W.A., M.A. Daher, N.A. DiMarzio, A. Samuels, D. Wartzok, K.M. Fristrup, P.W. Howey, and R.R. Maeiefski. 2002. Sperm whale dives tracked by radio tag telemetry. **Mar. Mamm. Sci.** 18(1):55-68.

WCS. 2004. Endangered sea turtles make a dramatic turnaround: poaching nearly eliminated in Central American nesting ground. http://www.sciencedaily.com/releases/2004/01/040127083014.htm.

Weilgart, L.S. and H. Whitehead. 1988. Distinctive vocalizations from mature male sperm whales (*Physeter macrocephalus*). **Can. J. Zool.** 66(9):1931-1937.

Weir, C.R. and S.J. Dolman. 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. **J. Int. Wild. Law Pol. 10**:1-27.

Whitehead, H. 1989. Formations of foraging sperm whales, *Physeter macrocephalus*, off the Galápagos Islands. **Can. J. Zool.** 67(9):2131-2139.

Whitehead, H. 1993. The behavior of mature male sperm whales on the Galápagos breeding grounds. **Can. J. Zool.** 66:1931-1937.

Whitehead, H. 2002. Estimates of the current global population size and historical trajectory for sperm whales. **Mar. Ecol. Prog. Ser.** 242:295-304.

Whitehead, H. 2003. Sperm Whales: Social Evolution in the Ocean. University of Chicago Press, Chicago, IL. 431 p.

Whitehead, H. and T. Arnbom. 1987. Social organization of sperm whales off the Galápagos Islands, February-April 1985. **Can. J. Zool.** 65(4):913-919.

Whitehead, H. and M.J. Moore. 1982. Distribution and movements of West Indian humpback whales in winter. **Can. J. Zool.** 60(9):2203-2211.

Whitehead, H. and S. Waters. 1990. Social organization and population structure of sperm whales off the Galápagos Islands, Ecuador (1985-1987). **Rep. Int. Whal. Comm., Spec. Iss.** 12:249-257.

Whitehead, H., L. Weilgart, and S. Waters. 1989. Seasonality of sperm whales off the Galápagos Islands, Ecuador. **Rep. Int. Whal. Comm.** 39:207-210.

Whitehead, H., S. Waters, and T. Lyrholm. 1992. Population structure of female and immature sperm whales (*Physeter macrocephalus*) off the Galápagos Islands. **Can. J. Fish. Aquatic Sci.** 49(1):78-84.

Whitehead, H., J. Christal, and S. Dufault. 1997. Past and distant whaling and the rapid decline of sperm whales off the Galápagos Islands. **Conserv. Biol.** 11(6):1387-1396.

Whitehead, H., W.D. Bowen, S.K. Hooker, and S. Gowans. 1998. Marine mammals. p. 186-221 *In:* W.G. Harrison and D.G. Fenton (eds.), The Gully: a scientific review of its environment and ecosystem. Dep. Fish. Oceans, Ottawa, Ont. Canadian Stock Assessment Secretariat Research Document 98/83.

Williams, K.L., A.C. Steyermark, C.C. Hurd, A.J. Schwandt, F.V. Paladino, and J.R. Spotila. 1996. Population ecology , nesting and success of leatherback turtles, *Dermochelys coriacea*, at Las Baulas de Guanacaste National Park, Costa Rica. p. 340 *In*: J.A. Keinath, D.E. Barnard, J.A. Musick, and B.A. Bell (comp.), Proc. 15th Annu. Symp. Sea Turtle Biol. and Conserv. NOAA Tech. Memo. NMFS-SEFSC-351. 355 p.

Winn, H.E. and L.K. Winn. 1978. The song of the humpback whale *Megaptera novaeangliae* in the West Indies. **Mar. Biol.** 47(2):97–114.

Winn, H.E. and N.E. Reichley. 1985. Humpback whale *Megaptera novaeangliae* (Borowski, 1781). p. 241-273 *In:* S.H. Ridgway and R. Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, London, U.K. 362 p.

Winn, H.E., R.K. Edel, and A.G. Taruski. 1975. Population estimate of the humpback whale (*Megaptera novaeangliae*) in the West Indies by visual and acoustic techniques. **J. Fish. Res. Board Can.** 32(4):499-506.

Würsig, B., S.K. Lynn, T.A. Jefferson, and K.D. Mullin. 1998. Behaviour of cetaceans in the northern Gulf of Mexico relative to survey ships and aircraft. **Aquat. Mamm.** 24(1):41-50.

Würsig, B., T.A. Jefferson, and D.J. Schmidly. 2000. The marine mammals of the Gulf of Mexico. Texas A&M Univ. Press, College Station, TX. 232 p.

Wyrtki, K. 1964. Upwelling in the Costa Rica Dome. **Fish. Bull.** 63(2):355-372.

Wyrtki, K. 1967. Circulation and water masses in the eastern equatorial Pacific Ocean. **Int. J. Oceanol. Limn.** 1(2):117-147.

Yochem, P.K. and S. Leatherwood. 1985. Blue whale. p. 193-240 *In:* S.H. Ridgway and R Harrison (eds.), Handbook of marine mammals, Vol. 3. The sirenians and baleen whales. Academic Press, New York. 362 p.

Yoder, J.A. 2002. Declaration of James A. Yoder in opposition to plaintiff's motion for temporary restraining order, 28 October 2002. Civ. No. 02-05065-JL. U.S. District Court, Northern District of California, San Francisco Division.

APPENDIX A:

L-DEO MODELING FOR MARINE SEISMIC SOURCE ARRAYS FOR SPECIES MITIGATION[2]

(a) Summary

To ensure that U.S. academic marine seismic activity does not adversely affect marine wildlife stocks, federal regulations controlling the levels of sound to which those stocks may be exposed are closely followed. These regulations include the establishment of various safety or exlusion zones, which are defined by a priori modeling of the propagation of sound from the proposed seismic source array. To provide realistic results, modeling must include free surface and array effects. This is best accomplished when the near field signature of each airgun array element is propagated separately to the far field and the results summed there. The far field signatures are analyzed to provide measurements that characterize the source's energy as a function of distance and direction. The measure currently required for marine wildlife mitigation is root-mean-square (rms). While rms is an appropriate measure for lengthy signals, it may not accurately represent the energy and impact of a short, impulsive signal. When a comparison is made between rms and several other metrics, it is apparent that rms is the least consistent.

(b) Introduction

Modern marine seismic profiling is typically carried out using arrays of airguns as the acoustic source. Unlike single airguns or explosive sources, the physical extent and distributed quality of these arrays produce an asymmetric pressure field, which cannot be described accurately by a simple, rule-of-thumb approach.

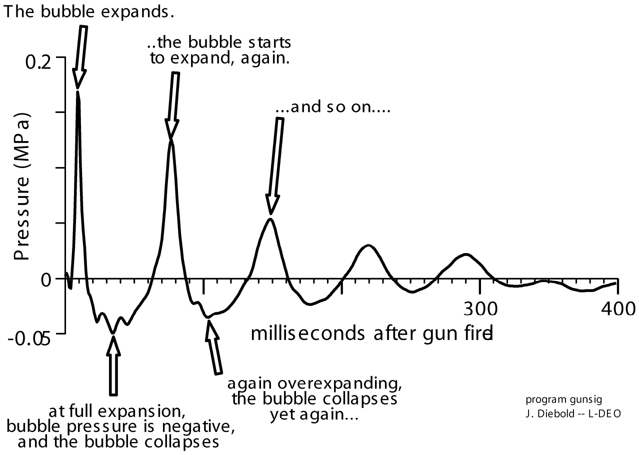

Figure B-1. Recording of a single airgun pulse made during R/V *Maurice Ewing* tests, 1990.

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[2] By **John Diebold**, L-DEO, revised May 2006.

This wavetrain can be seen in its true form only very close to the airgun and it is called the "near field" signal. Airguns are usually towed at a shallow depth (3–9 m) beneath the sea surface, from which sound waves are negatively reflected, and at any significant distance from the airgun, both the direct and its negatively reflected "ghost" are seen, one right after the other. This ghosting imposes a strong and very predictable filter on the received arrivals.

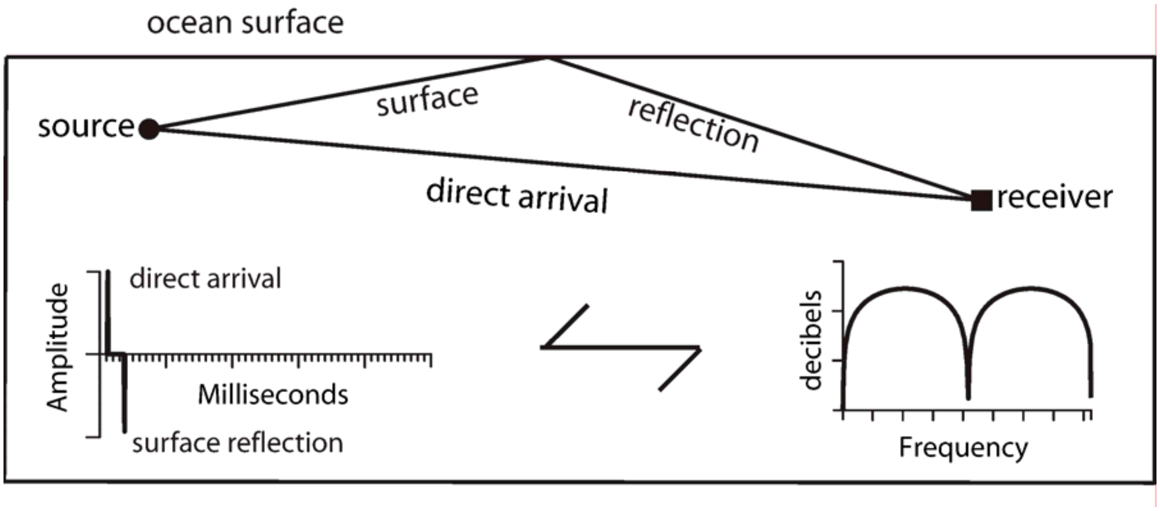

Figure B-2. Top: pathways for direct and surface-reflected arrivals used in modeling. Bottom: direct and ghosted arrival amplitudes in the time domain can be considered an operator whose spectrum is predictable, and which acts as a filter on the spectrum of the intrinsic near field source, whatever that may be.

The time interval between the arrivals of the direct and surface-reflected signals depends on the position of observation; it is greatest at any position directly beneath the source. Depending on the location of the point of observation relative to the source array, the appearance and strength of the signal can be extremely variable. In the comparison below, two observation points were chosen, equally distant from a 20-airgun array.

The differences here are caused by two effects. One is directionality resulting from the physical dimensions of the array. The other effect is that the surface ghosting imposes a strong filter on the near field source signatures, and the shape of this filter is controlled by the relative positions of sources and receivers.

(c) Modeling

Since the sum of the direct and the surface-reflected signals varies according to position, modeling can only be carried out correctly when near-field source signatures are used, and propagation along all of the pathways between the source and the receiver is considered separately. In the simple half-space model illustrated above (Fig. 3), there are only two pathways. When an array of sources is used, travel time, spreading and reflection losses are calculated for each pathway and for each source element separately. According to the exact distance between the point of observation and the particular airgun, each element's near-field signal is appropriately scaled in amplitude and shifted in time. Then the process is repeated to produce the free surface "ghost" signal of each airgun, and the results are summed.

For R/V *Maurice Ewing* mitigation, the near-field signatures were calculated by extrapolation from a set of measured signals received from Teledyne in 1981. Results of this modeling have been compared to a great number of published signals, and the amplitudes of the library's signals adjusted to provide a close match. Since peak values are highly dependent on an impulsive signal's high frequency content, the comparisons are most accurately made in the spectral domain.

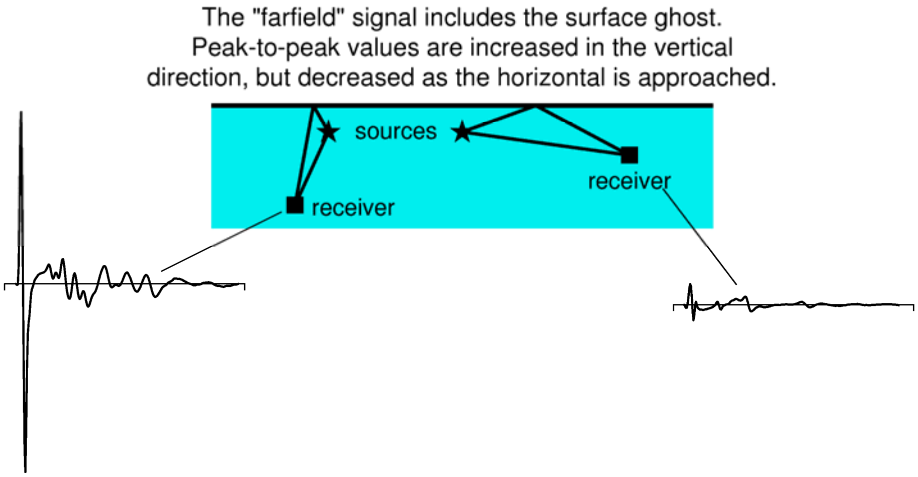

Figure B-3. The far field signature of a 20-airgun array modeled at two receiver positions equidistant from the center of the array. Differences are due to array directivity and surface ghosting effects.

Few, if any, of the published examples include airguns with volumes as large as those often included in *Ewing*'s source arrays. There are several very good reasons for this (and for the inclusion of such sizes in *Ewing* arrays.) Principal among these was the observation by W. Dragoset of Western Geophysical [pers. comm., 1990] that the characteristics of the Bolt 1500C air exhaust ports are such that throttling occurs when air chambers above a certain size are used. The result of this is that peak amplitudes increase only slightly, so that the efficiency of these airguns diminishes with increasing volume. On the other hand, bubble pulse periods do increase according to theory, so that the benefit of larger sizes in array tuning is undiminished. The decrease in efficiency was borne out during testing of *Ewing*'s airguns during the 1990 shakedown legs (Fig. 4).

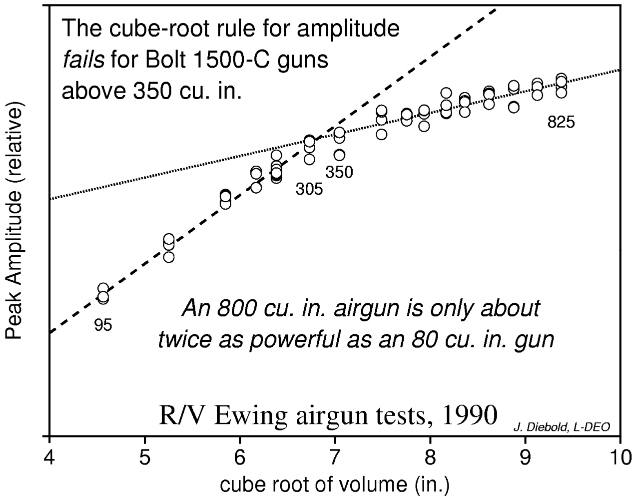

Figure B-4. R/V *Ewing* test results, 1990.

Near-field signatures can be created by a number of commercially available modeling packages, all based in part on the work of Ziolkowski (1978). Those packages were not used for *Ewing* modeling for two reasons: cost and accuracy. As Figure 5 demonstrates, PGS' Nucleus/Masomo software does not accurately model the large Bolt airguns used in *Ewing* arrays:

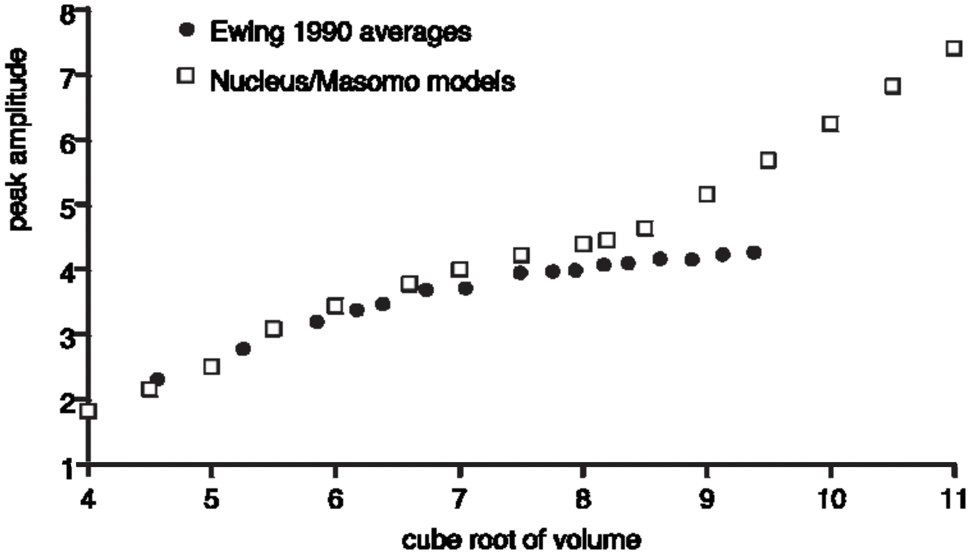

Figure B-5. Nucleus/Masomo overestimates peak values for large Bolt airguns.

The R/V *Langseth* will have source arrays that are quite different than *Ewing*'s: (1) maximum airgun volume will be much smaller, (2) two different kinds of airguns will be combined, (3) airguns will be towed closer together, and (4) two-element "clusters" will be included. The latter three of these features are unsupported by the homebrew modeling used for *Ewing* arrays, and we are currently using PGS' Nucleus/Masomo software for this purpose [http://www.pgs.com/business/products/nucleus/]. Some of the examples below have been created using the simpler *Ewing*models, however.

The modeling procedure can be summarized as follows:

1) Define the airgun array in terms of the size and relative location of each airgun [X, Y, Z].
2) Create near field ["notional"] signatures for each airgun.
3) Decide upon a 2D mesh of points, for example within a plane intersecting the center of the airgun array. A typical mesh is 100 x 50.
4) For each of the points in the mesh, create the signal that would be observed there when every airgun in the array was fired simultaneously.
5) For that signal, determine the desired statistic: Peak-to-peak dB, Peak dB, rms dB, maximum psi, etc.
6) Contour the mesh.

Most of the work lies in step 4) which has steps of its own:

a) For each of the airguns in the array, determine the distances, and thus the time-of-flight between the airgun and the mesh point, as well as the free surface ghost "image" of the airgun and the mesh point.
b) Scale and shift this airgun's near-field signal, dividing by the point-to-point distance and moving forward in time according to time-of-flight.
c) Scale and shift the near-field signal's ghost image, as above, in addition multiplying by the free surface reflection coefficient [typically between -.9 and -.95].

d) Sum the results. For the *Ewing* 20-airgun array, 40 scaled and shifted signals were created and summed for each mesh point.

(d) Units

Exploration industry standard units for seismic source pressures are Bar-meters; an intuitively attractive measure in atmospheres [bars] at one meter from the center of the source array. In SI units, 10 Bar = 1 megaPascal = 10^{-12} µPascal. To convert Bar-m to decibels with respect to µPascal–m we use this formula:

$$\text{dB [wrt } \mu\text{Pascal –m]} = 220 * 20 \log^{10}(\text{B-m})$$

A variety of means are used to characterize the strength of seismic source signals. Peak, peak-to-peak and total energy levels are easy to measure, but historically, all of the research on acoustic avoidance behavior of marine mammals has quantified the sound levels in terms of rms, a measure which is entirely appropriate for many acoustic signals found in the marine environment (e.g., shipping noise, Navy sonar, etc.). Although it is less appropriate for impulsive airgun signals, the rms measure has been used in most published studies anyway (cf. Malme et al. 1983a,b), so that meaningful comparisons could be made. The protocols used for the rms calculation in most published research are diagrammed below (Fig. 6), applied to the signal predicted by our modeling for a point 4000 m aft of *Ewing*'s 20 airgun array, at a depth of 1200 m.

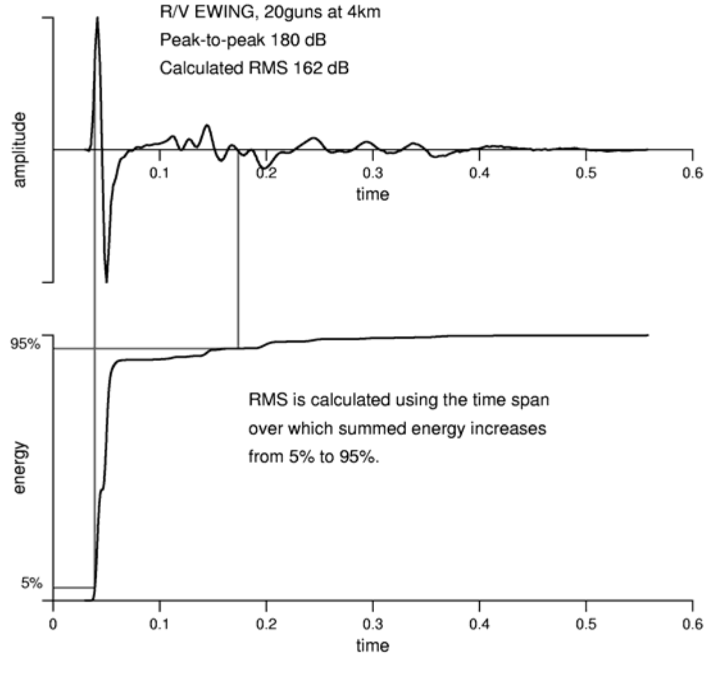

Figure B-6. The "standard" 90% rms calculation. Energy is summed as a function of time for the entire signal. From this result, the times at which 5% and 95% of the total energy are attained define the RMS integration window.

This difference between the peak-to-peak and rms dB levels for the same signal falls within the 16-18 dB averages reported for impulsive airgun signals by Greene (1997) and McCauley (1998).

(e) Calculating the safety zone

R/V *Ewing* source arrays were intended and designed for 2D seismic reflection and refraction work, and were, consequentially, highly directional, focusing energy downwards and in line with the ship's track direction.

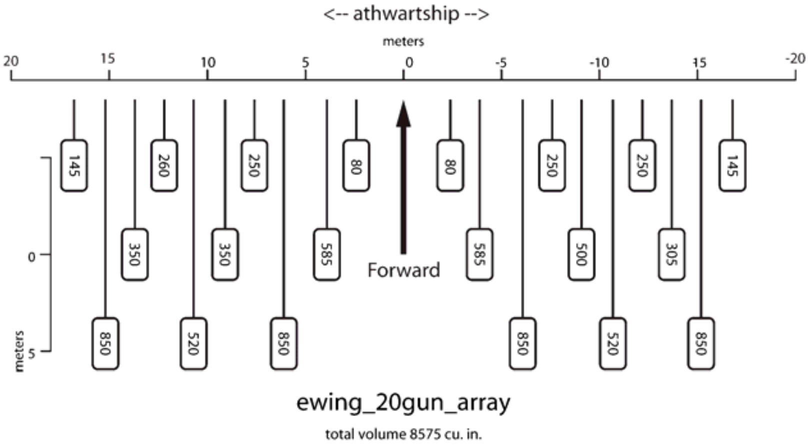

Figure B-7. Plan view of the 20-airgun array used to calculate Fig. 3, 4, and 6. Tow depth is 7.5 m.

The rms calculation is applied to the mesh point signatures resulting from the modeling process described above. When the 90% rms levels are contoured, the directional nature of the standard R/V *Ewing* source array is obvious (Fig. 8).

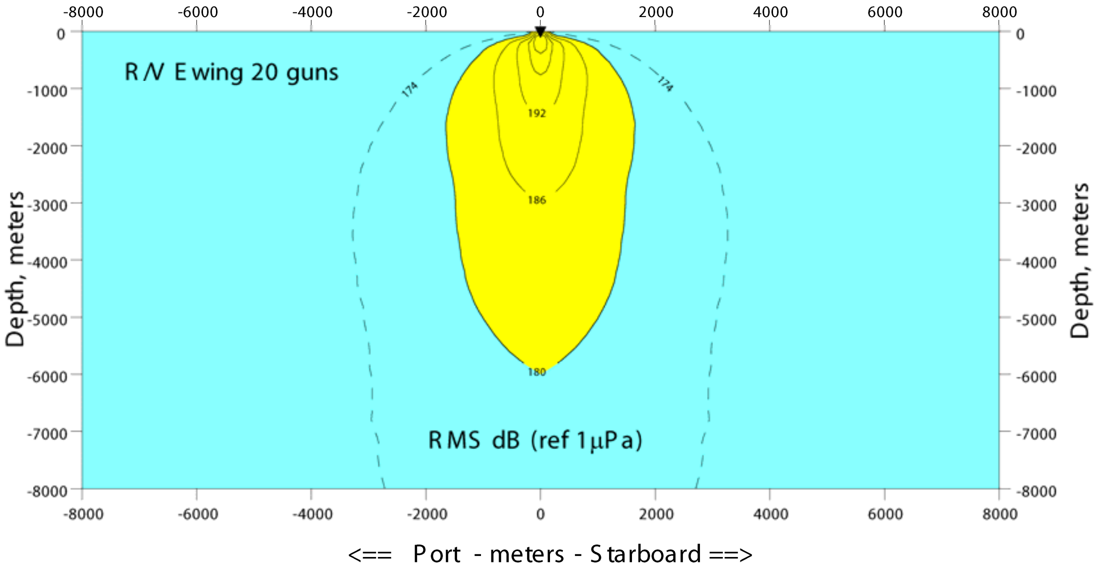

Figure B-8a. 90% rms isopleths calculated in the crosstrack direction for a 20-airun array. Yellow denotes rms values >180 dB.

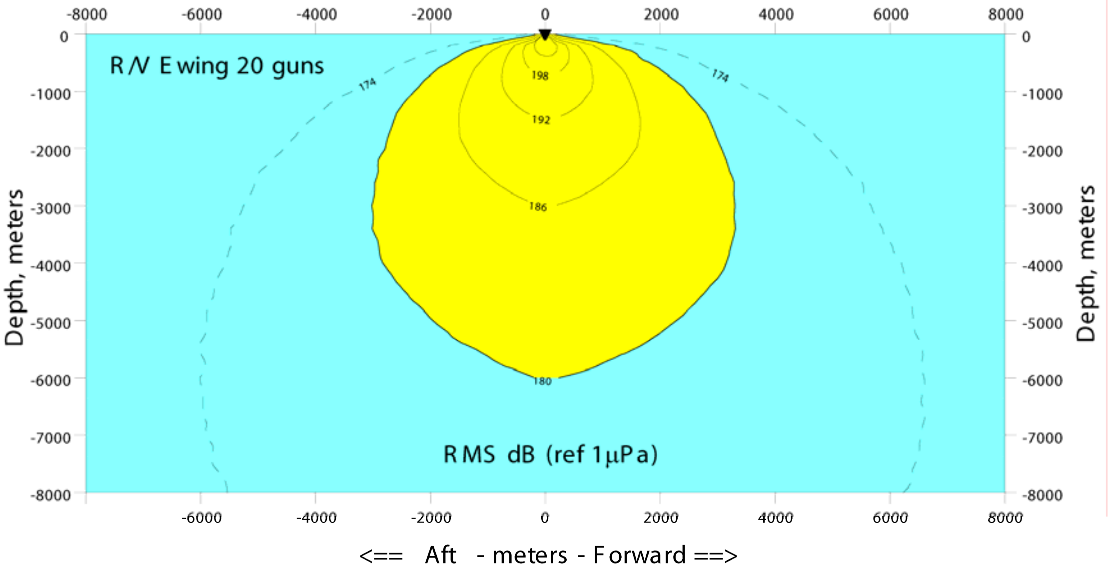

Figure B-8b. 90% rms isopleths calculated in the along track direction for a 20-airun array. Yellow denotes RMS values >180 dB.

Since the fore-and-aft extent of *Ewing*'s array is smaller than the athwartship dimension, directionality is less marked in front of and behind the array. The distances therefore to the 180 dB contours, or isopleths, are greater in the fore-and-aft than athwartship directions, and we use these worst case distances to determine the EZ.

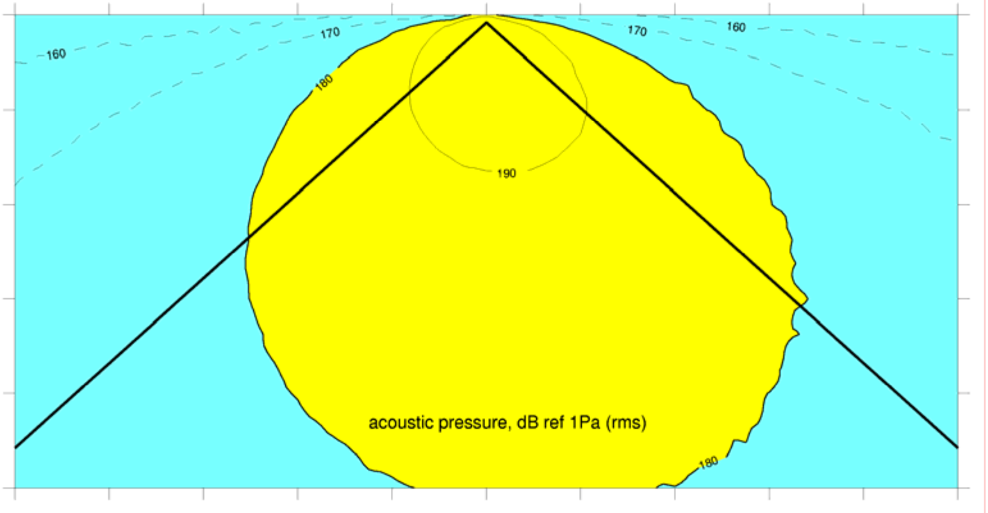

Figure B-9. The pathways in offset and depth which intersect maximum-radius isopleths. These are used to calculate radii for various 90% rms levels.

This modeling approach includes two important simplifications: (1) the assumption of a homogeneous water column (i.e., raypaths are linear), and (2) that interactions with the seafloor are not included. In deep water (i.e., 1000 m and greater] our predicted distances are conservatively greater than those determined by actual calibration (Tolstoy et al. 2004). In shallow water (100 m and less) water column reverberations and constructive interference contribute to increase actual levels over those predicted by the modeling techniques described here.

Problems with 90% rms

The biggest pitfall in the 90% rms measure is that the rms value can vary tremendously for signals having similar energy content. If the signal is only a little less “ringy” than the *Ewing* 20 airgun example shown above, the 90% energy time span will be much smaller, which greatly increases the RMS value. The better the “tuning” of a seismic source array, the more impulsive its signature and the shorter its 90% energy window. The resulting problems can be illustrated using a simple source – a two-gun “cluster” as modeled by Nucleus/Masomo. Signals are calculated at hundreds of mesh points, 90% rms is calculated for each signal, and the resulting levels were contoured (Fig. 10).

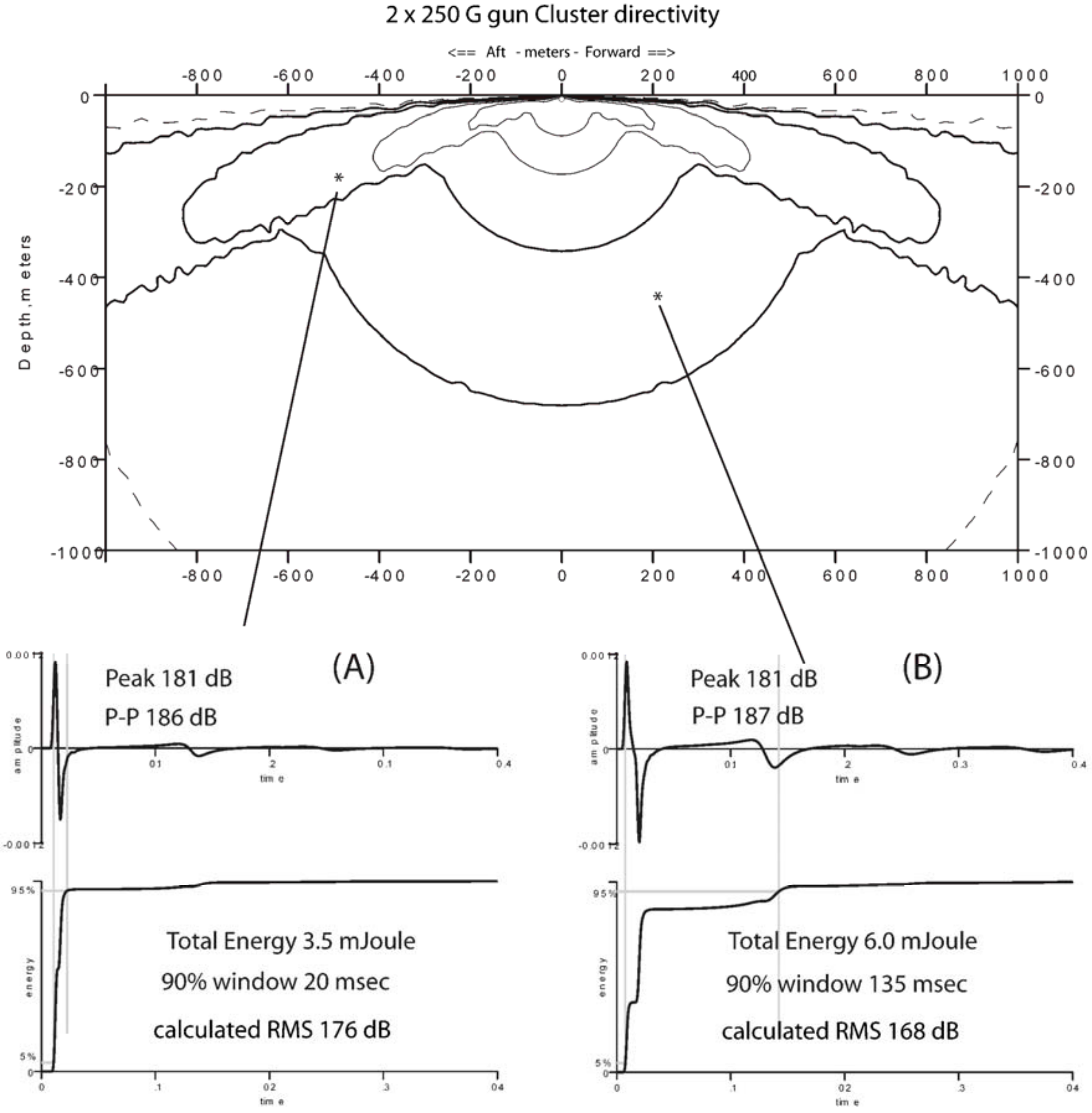

Figure B-10. Modeled results from a simple 2-airgun cluster source.

Unlike the *Ewing* example presented earlier, the rms contours for this source are pathologically variable. To investigate the reason for this, two signatures, (A) and (B), were calculated at equal distances from the source array, but in high and low rms zones, respectively. These signals have identical peak levels, but greatly different rms values. The difference is almost entirely due to the varying length of the automatically determined 90% rms integration window. This change in window length is in turn due to the effects of surface ghosting, which diminish the bubble pulse in the left-hand signal (A), thus reducing the 90% energy time span. Paradoxically, the right-hand signal (B), which has higher peak-to-peak and total energy levels, has a greatly lower rms value. This is almost entirely due to large variations in the automatically calculated 90% rmswindow length. A contour plot of 90% rms window length shows that for this source, they vary between 5 and 137 milliseconds (Fig. 11).

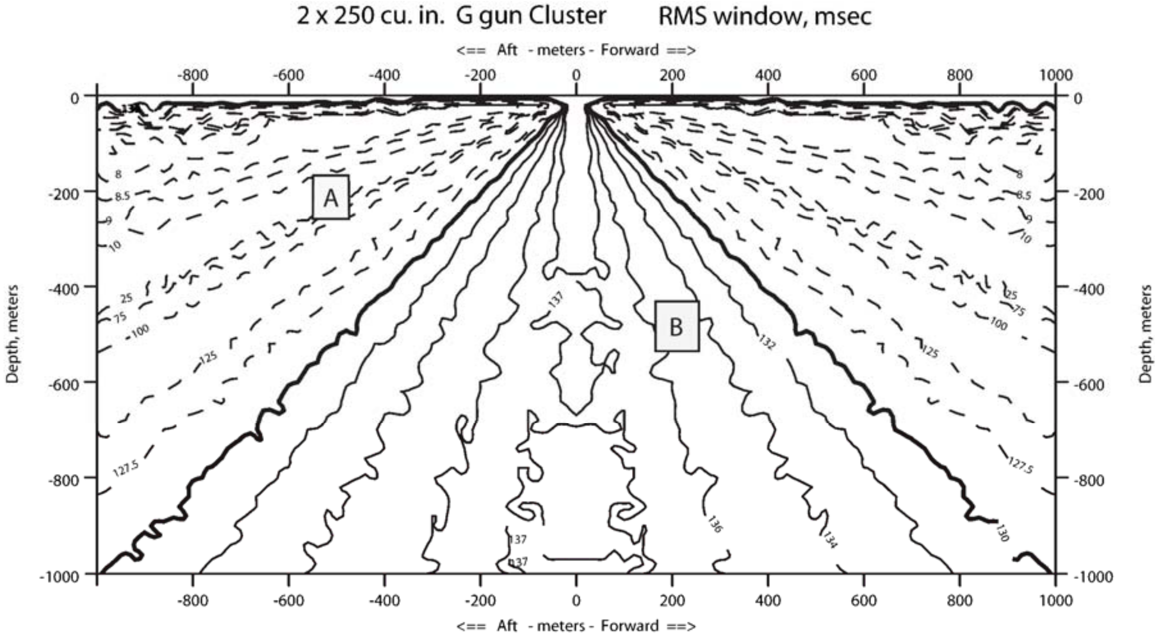

Figure B-11. The locations from which signals (A) and (B) were extracted are shown for reference.

Other measures may be far more appropriate for quantifying airgun signal levels and predicting their effect on marine creatures.

Sound exposure level (SEL) is equal to rms but with an added factor which is intended to minimize the time windowing effect, and to produce a measure more meaningful for the effects of noise on mammalian ears:

$DB_{SEL} = dB_{rms} + 10 * \text{Log}_{10}$ (window), where the window has units of seconds.

For rms window lengths less than one second, this additive factor varies between –30 dB for a rms window length of 1 millisecond, to zero, for a window length of one second.

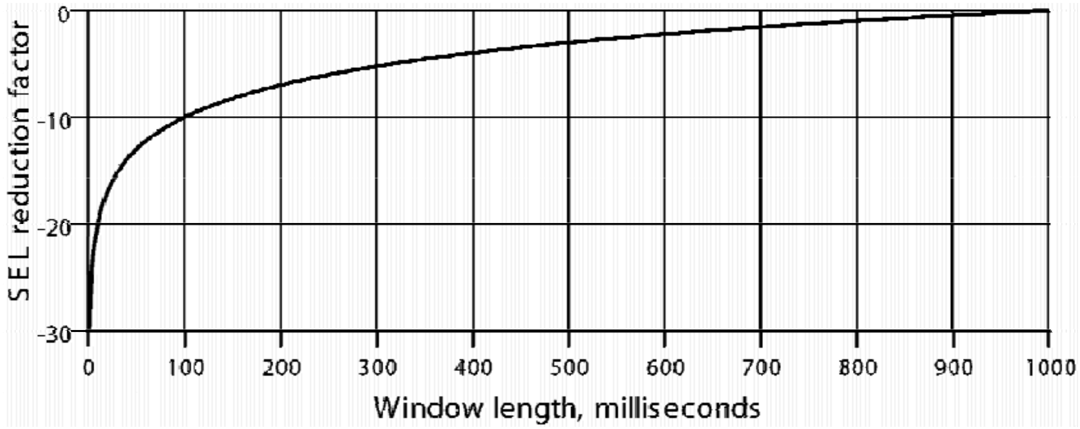

Figure B-12.

Calculation of SEL for the two cluster signatures shown above shows the effect of the calculation's window length correction factor:

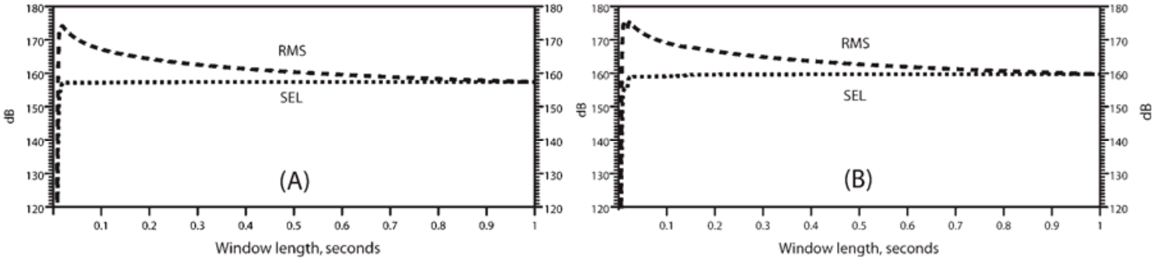

Figure B-13.

While rms varies continually with window length, SEL tends to approach a stationary level; in this case 157 dB for signal (A), and 160 dB for (B). The effect is to eliminate the dependence of the determined level upon window size; as long as the entire signal is captured, the calculated SEL will be pretty much the same. SEL is considered by many researchers (cf. Patterson 1991) to be a better predictor of hearing threshold shifts than is rms or peak level.

Neither rms nor SEL include frequency content, and there are many ways to look at this. Within the exploration seismic community, the cumulative energy flux is a standard measure (Johnston et al. 1988).

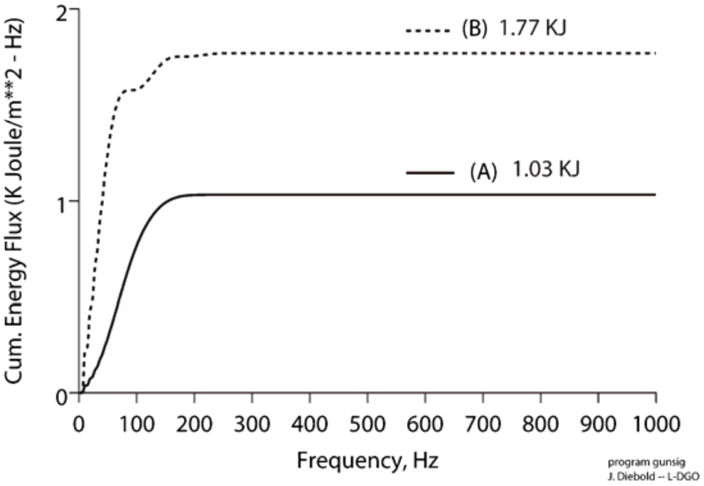

Figure B-14.

Two features are immediately apparent from this plot: first, most of the energy in both signals is present at frequencies below several hundred Hz, and second, signal (B) whose 90% rms level is less than half that of signal (A), actually contains appreciably more total energy. When the total energy of a short, impulsive signal, such as that created by an airgun array in deep water, is expressed in terms of dB, the result is usually equal to SEL.

The 90% rms measure currently used to characterize possible impact on marine mammals may be severely flawed, especially when marine seismic source arrays are physically compact and/or well-tuned. An energy-based metric would produce more consistent results, and can be implemented in either time or frequency domains.

Table B-1.

	A	B	%, A/B
rms	176	168	166.67%
Peak	181	181	100.00%
P-P	186	187	91.67%
SEL	157	160	75.00%
Energy	3.5	6	58.33%
Energy	1.03	1.77	58.19%

The seismic sources planned and under construction for R/V *LANGSETH* are much more highly tuned than those deployed by R/V *Ewing*. Although the total energy content in the signal produced by *Langseth*'s largest array is smaller than that of the "standard" *Ewing* 20-airgun array, 90% rms values of modeled signatures are much higher, due entirely to the rms window length imposed by the improved tuning. Therefore, we propose to use SEL values, at least until new metrics are imposed. The question is: how to convert from SEL to equivalent rms?

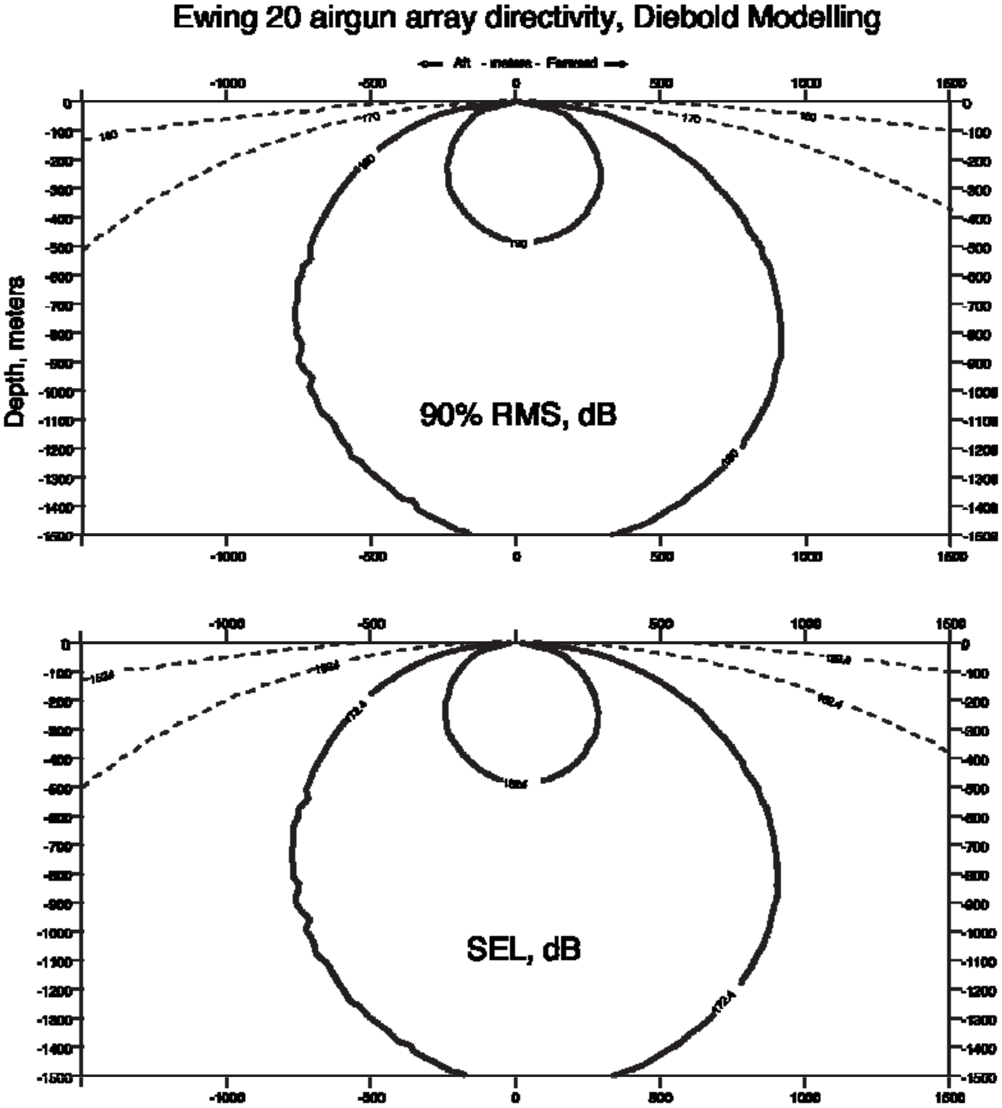

Figure B-15. Here we have matched the rms and SEL contours nearly perfectly by using an SEL value equal to rms – 7.6 dB, an offset corresponding to the normal 90% energy window length of about 174 msec. Current IHA applications have used an SEL "discount" of 15 dB, which is equivalent to an rms window of about 32 msec. It might be more appropriate to use a discount factor which corresponds to the natural mammal hearing integration time – it has been suggested, for example [Peter Tyack, pers. comm.] that this is about 200 msec for dolphins. This would be equivalent to an rms – SEL discount of 7 dB.

Other metrics

When geophysicists investigate signal quality, they are likely to plot spectral energy on a linear frequency scale, as specified in Johnston et al. (1988):

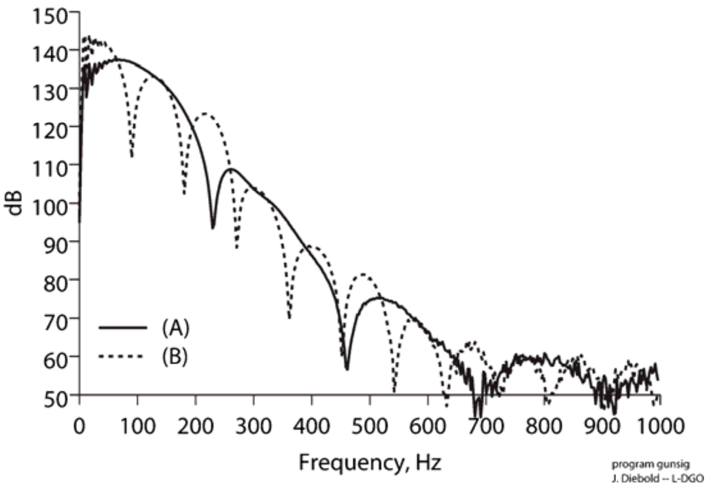

Figure B-16.

In studies of noise and its effect on marine animals, a spectral display in terms of 1/3 octave energy levels is often preferred. To obtain such a display, spectral power is integrated within specified bands whose width increases logarithmically with frequency.

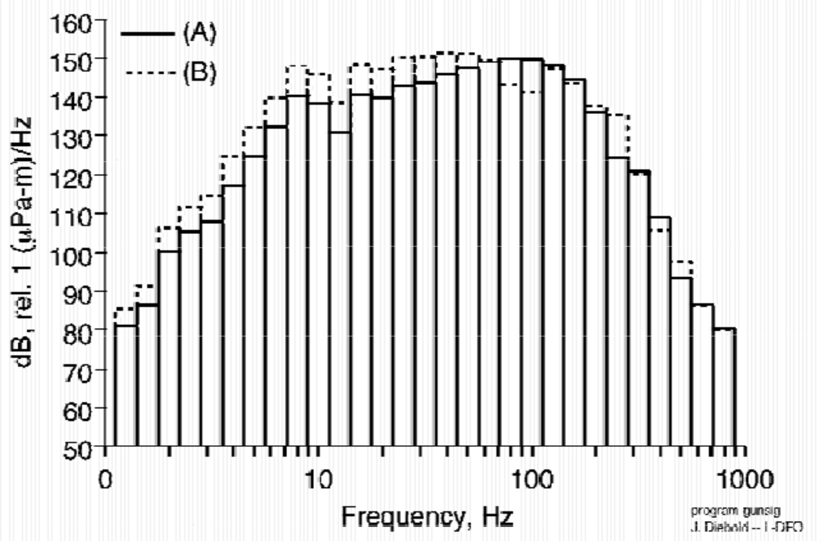

Figure B-17.

It is clear from this display that despite its higher calculated 90% rms level, signal (A) has lower energy than (B) at most frequencies, especially between zero and 100 Hz, where ghosting effects play a major role.

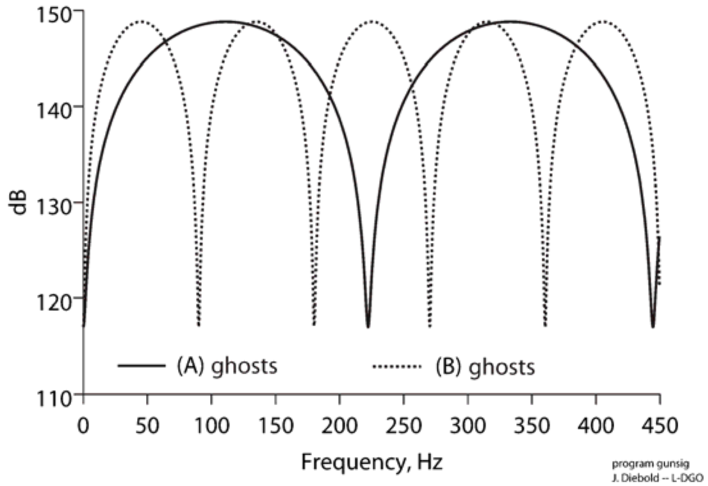

Figure B-18.

The time lag between direct and surface-reflected paths for signal (A) is much smaller than that for signal (B). Therefore the ghost-induced shaping filter superimposed on signal (A) cuts out much of the low-frequency energy seen in signal (B).

If we plot the ghost shaping filters in the third-octave display described above, it is readily apparent that most of the differences between (A) and (B) in the previous third-octave plot are due to ghosting effects:

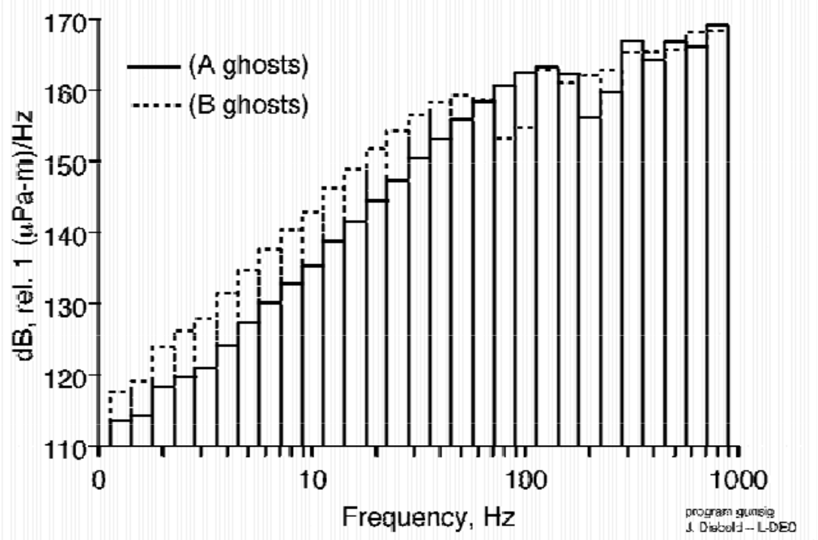

Figure B-19.

(f) Literature Cited

Finneran, J.J., C.E. Schlundt, R. Dear, D.A. Carder, and S.H. Ridgeway. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. **J. Acoust. Soc. Am.** 111:2929-2940.

Greene, C.R., Jr., with J.S. Hanna and R.W. Blaylock. 1997. Physical acoustics measurements. p. 3-1 to 3-63 *In*: W.J. Richardson (ed.), Northstar marine mammal monitoring program, 1996: marine mammal and acoustical monitoring of a seismic program in the Alaskan Beaufort Sea. LGL Rep. TA2121-2. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 245 p.

Johnston, R.C., D.H. Reed, and J.F. Desler. 1988. Special report on marine seismic energy source standards. **Geophysics** 53:566-575.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyak, and J.E. Bird. 1983a. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. BBN Report 5366, Report from Bolt Beranek & Newman Inc., Cambridge, MA for US Minerals Management Service, Anchorage, AK, NTIS PB86-174174.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack, and J.E. Bird. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration. BBN Report 5851, Report from BBN Laboratories Inc., Cambridge, MA for US Minerals Management Service, Anchorage, AK, NTIS PB86-218385.

McCauley, R.D., M.-N. Jenner, C. Jenner, K.A. McCabe, and J. Murdoch. 1998. The response of humpback whales (*Megaptera novangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. **Austral. Petrol. Product. Explor. Assoc. (APPEA) J.** 38:692-707.

Parkes, G. and L. Hatton. 1986. The Marine Seismic Source. D. Reidel publishing Company.

Patterson, J.H. 1991. Effects of peak pressure and energy of impulses. **J. Acoust. Soc. Am.** 90:205-208.

Tolstoy, M., J.B. Diebold, S.C. Webb, D.R. Bohenstiehl, E. Chapp, R.C. Holme, and M. Rawson. 2004. Broadband calibration of R/V *Ewing* seismic sources. **Geophys. Res. Lett.** 31:L14310.

Ziolkowski, A. 1970. A method for calculating the output waveform from an air gun. **Geophys. J. R. Astr. Soc.** 21**:**137-161.

APPENDIX B:

JASCO UNDERWATER SOUND MODELING REPORT [3]

(a) Project Description

Safety zones for marine mammals are commonly defined by the areas within which specific sound level thresholds are exceeded. During all seismic survey data acquisition, Lamont-Doherty Earth Observatory (L-DEO) implements a safety-zone monitoring program for marine mammals and sea turtles. In effect, the survey airguns are powered down to a single airgun, or shut down entirely, every time a marine mammal or sea turtle is detected within or about to enter its defined safety zone.

This report describes a site-specific modeling study that was carried out to determine the levels of underwater sound expected to result from the L-DEO's Central America SubFac (Subduction Factory) survey. This cruise is scheduled to occur in the Western Caribbean Sea and Eastern Pacific Ocean off the coasts of Costa Rica and Nicaragua from January–March 2008. The study presented herein provides a scientifically rigorous forecast of the safety zones based on full numerical modeling of the acoustic propagation in a complex, multi-layered, inhomogeneous environment. This approach takes account of the specific properties of the water column and bottom in the planned areas of operation, insofar as they are known. The advantages of this approach over a free-field or adjusted free-field approach are discussed, as are the potential sources of uncertainty in the full model predictions.

Section b describes the types of seismic surveys that are typically carried out and how a seismic airgun generates a noise impulse. Section c discusses the methodology that was used to predict the sound levels and describes the configuration of the airgun array planned for use by L-DEO and used for the modeling study. Section d describes the source locations and modeling parameters required by the propagation model. Finally, the results of the modeling study are presented in section e and discussed in section f.

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[3] By **Scott Carr, Kate Collins, Isabelle Gaboury, Alex MacGillivray, and Stephen Turner**, JASCO Research Ltd., September 2006.

(b) Seismic Survey Overview

Marine seismic airgun surveys are capable of high-resolution three-dimensional imaging of the Earth's crust, down to several kilometers depth, and have thus become an essential tool for geophysicists studying the Earth's structure. Seismic airgun surveys may be divided into two types, 2-D and 3-D, according to the type of data that they acquire. 2-D surveys are so-called because they only provide a two-dimensional cross-sectional image of the Earth's structure and are characterized by large spacing between survey lines, on the order of a kilometer or more. 3-D surveys, on the other hand, employ very dense line spacing, of the order of a few hundred meters, to provide a three-dimensional volumetric image of the Earth's structure.

A typical airgun survey, either 2-D or 3-D, is operated from a single survey ship that tows both the seismic source and receiver apparatus. The seismic source itself is an airgun array consisting of many individual airguns that are fired simultaneously in order to project a high-amplitude seismo-acoustic pulse into the ocean sub-bottom. The receiver equipment consists of one or more streamers, often several kilometers in length, that contain hundreds of sensitive hydrophones for detecting echoes of the seismic pulse reflected from sub-bottom features.

Airgun arrays are broadband acoustic sources that project energy over a wide range of frequencies, from under 10 Hz to over 5 kHz. However, airgun arrays are designed to produce most of their energy below 200 Hz, which are the frequencies useful for seismic profiling. Most of the underwater sound generated by a seismic survey is due to the airgun array; in comparison, the survey vessel itself contributes very little to the overall sound field. The array consists of many airguns that are configured in such a way as to project the maximum amount of seismic energy vertically into the Earth. However, a significant portion of the sound energy from the array escapes horizontally and at other off-vertical angles, and propagates into the surrounding environment. The frequency spectrum of the sound propagating near-horizontally can differ from that of the sound directed downward.

Airgun Operating Principles

An airgun is a pneumatic sound source that creates predominantly low-frequency acoustic impulses by generating bubbles of compressed air in water. The rapid release of highly compressed air (typically at pressures of ~2000 psi) from the airgun chamber creates an oscillating air bubble in the water. The expansion and oscillation of this air bubble generates a strongly-peaked, high-amplitude acoustic impulse that is useful for seismic profiling. The main features of the pressure signal generated by an airgun, as shown in FIGURE B. 1, are the strong initial peak and the subsequent bubble pulses. The amplitude of the initial peak depends primarily on the firing pressure and chamber volume of the airgun, whereas the period and amplitude of the bubble pulse depends on the volume and firing depth of the airgun.

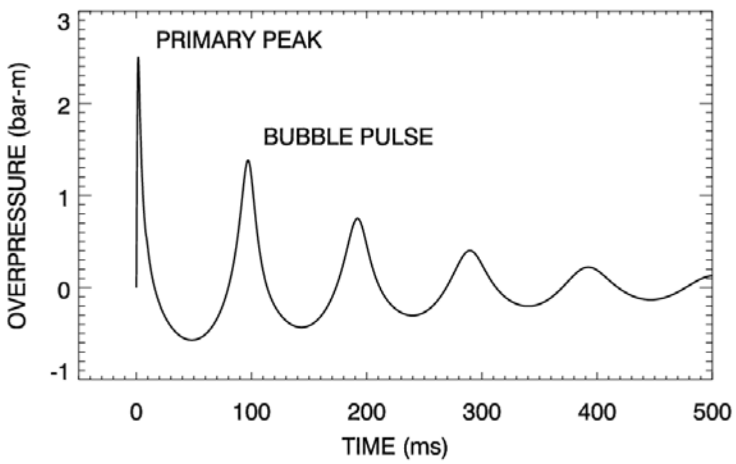

FIGURE B. 1: Overpressure signature for a single airgun, showing the primary peak and the bubble pulse.

Airguns are designed to generate most of their acoustic energy at frequencies less than ~200 Hz, which is the frequency range most useful for seismic penetration beneath surficial seabed sediment layers. In general, the frequency output of an airgun depends on its volume: larger airguns generate lower-frequency impulses. However, due to the impulsive nature of the source, airguns inevitably generate sound energy at higher frequencies, above 200 Hz, as well — although the energy output at these frequencies is substantially less than at low frequencies.

Zero-to-peak source levels for lone airguns are typically between 220 and 235 dB re 1µPa @ 1m (0-p) (~1–6 bar·m)[4], with larger airguns generating higher peak pressures than smaller ones. The peak pressure of an airgun, however, only increases with the cubic root of the chamber volume. Furthermore, the amplitude of the bubble pulse also increases with the volume of the airgun — and for the geophysicist the bubble pulse is an undesirable feature of the airgun signal since it smears out sub-bottom reflections. In order to increase the pulse amplitude (to see deeper into the Earth), geophysicists generally combine multiple airguns together into arrays. Airgun arrays provide several advantages over single airguns for deep geophysical surveying:

- The peak pressure of an airgun array in the vertical direction increases nearly linearly with the number of airguns.
- Airgun arrays are designed to project maximum peak levels toward the seabed (i.e., directly downward), whereas single airguns produce nearly omnidirectional sound.
- By utilizing airguns of several different volumes, airgun arrays may be "tuned" to increase the amplitude of the primary peak and simultaneously decrease the relative amplitude of the bubble pulses.

Airgun Array Source Levels

The far-field pressure generated by a seismic airgun array is substantially greater than that of an individual airgun. An array of 30 airguns, for example, may have a zero-to-peak source level of

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[4] Source level in dB re 1 µPa @ 1 m = 20 log (pressure in bar·m) + 220

255 dB re 1μPa @ 1m (0-p) (~56 bar·m) in the vertical direction. This apparently high value for the source level can lead to erroneous conclusions about the impact on marine mammals and fish for the following reasons:

- Peak source levels for seismic survey sources are usually quoted relative to the vertical direction; however, due to the directional dependence of the radiated sound field, source levels off to the sides of the array are generally lower.
- Far field source levels do not apply in the near field of the array where the individual airguns do not add coherently; sound levels in the near field are, in fact, lower than would be expected from far field estimates.

The acoustic source level of a seismic airgun array varies considerably in both the horizontal and vertical directions due to the complex configuration of airguns composing the array. One must account for this variability in order to correctly predict the sound field generated by an airgun array. If the source signatures of the individual airguns are known, then it is possible to accurately compute the source level of an array in any direction by summing up the contributions of the array elements with the appropriate time delays, according to their relative positions. This is the basis for the airgun array source model discussed in the next section.

(c) Modeling Methodology

Two models are used in this Appendix to forecast the underwater acoustic fields resulting from the operation of the seismic array in a particular area. The Airgun Array Source Model (AASM) described below predicts the source level (SL) and directionality of a seismic airgun array. An acoustic propagation model is then used to estimate the acoustic field at any point far from the source. The propagation model uses parameters of the environment in the specific area of concern, including the expected sound speed profile, the bathymetry, and the bottom geoacoustic properties to produce site specific estimates of the radiated noise field as a function of range and depth. JASCO uses the Marine Operations Noise Model (MONM) described below to predict the transmission loss in various directions from representative source locations. The received level (RL) at any 3-dimensional location away from the source is calculated by combining the source level (SL) and transmission loss (TL) using the following relation:

$$RL = SL - TL$$

Acoustic transmission loss and received sound levels are a function of depth, range, bearing, and environmental properties. The received levels estimated by MONM, like the source levels from which they are computed, are equivalent to sound exposure level (SEL) over the duration of a single source pulse. SEL is expressed in units of dB re $1\mu Pa^2 \cdot s$.

The safety and disturbance criteria currently applied to marine seismic surveys by the U.S. National Marine Fisheries Service are based on the rms (root-mean-square) sound pressure level (SPL) metric as adapted for impulsive sound sources. Cetaceans are not to be exposed to received levels >180 dB re 1 μPa_{rms}, and pinnipeds are not to be exposed to RL >190 dB re 1 μPa_{rms}. Also, NMFS assumes that marine mammals may be disturbed if exposed to RL >160 dB re 1 μPa_{rms}. Therefore, a method is required to convert the modeled SEL levels to rms SPL (see below).

Airgun Array Source Model

The current study makes use of a full-waveform airgun array source signature model developed by JASCO, called AASM, in order to compute the source level and directionality of Lamont-Doherty Earth Observatory's (L-DEO) airgun arrays. The airgun model is based on the physics of the oscillation and radiation of airgun bubbles, as described by Ziolkowski (1970). The model solves a set of parallel differential equations that govern the airgun bubble oscillations.

In addition to the basic bubble physics, the source model also accounts for non-linear pressure interactions between airguns, port throttling, bubble damping, and GI-gun behavior, as described by such authors as Dragoset (1984), Laws et al. (1990), and Landro (1992). The source model includes four empirical parameters that are tuned so that the model output matches observed airgun behavior. The model parameters were fitted to a large library of real airgun data using a "simulated annealing" global optimization algorithm. These airgun data were obtained from a previous study (Racca and Scrimger 1986) that measured the signatures of Bolt 600/B airguns ranging in volume from 5 in^3 to 185 in^3.

The airgun array source model requires several inputs, including the array layout, volumes, towing depths, and firing pressure. Prior to modeling an array, the cluster-gun elements were moved apart by a small distance (20 cm total) since the JASCO airgun model does not yet account for coalescing airgun bubbles. This minor change in the array layout is not expected to significantly alter the source level or directionality of the array. The output of the source model is a set of "notional" signatures for the array elements. The notional signatures are the pressure waveforms of the individual airguns, in the absence of the other array elements, at a standard reference distance of 1 meter.

After the source model is executed, the resulting notional signatures are summed together with the appropriate phase delays to obtain the far-field source signature of the array. The far-field array signature, in turn, is filtered into $^1/_3$-octave pass bands to compute the source level of the array as a function of frequency band, f_c, and propagation azimuth, θ:

$SL = SL(f_c, \theta)$

The interaction between the signals from individual airguns creates a directionality pattern in the overall acoustic emission from the array. This directionality is particularly prominent at frequencies in the mid-range of several tens to several hundred Hz: at lower frequencies the array appears omni-directional, while at higher frequencies the pattern of lobes becomes too finely spaced to resolve.

The propagation model calculates transmission loss from an equivalent point-like acoustic source to receiver locations at various distances, depths, and bearings. However, an airgun array consists of many sources and so the point-source assumption is not valid in the near field, where the array elements do not add coherently. The maximum extent of the near field of an array is given by the expression

$$R_{nf} < \frac{L^2}{4\lambda}$$

where λ is the sound wavelength and L is the longest dimension of the array (Lurton 2002, §5.2.4). Along the diagonal of the airgun array, $L \approx 29$ meters and so the maximum near field range is 140 meters at 1 kHz (R_{nf} is less for lower frequencies). Beyond this range it is assumed that an array radiates like a point source and can be treated as such for the purpose of propagation modeling.

R/V *Langseth* Airgun Arrays – Central America SubFac Cruise

The R/V *Langseth* will employ a single standard airgun array configuration towed at two different depths depending on the survey trackline being shot. The airgun array that will be operated from the *Langseth* during the Central America SubFac cruise will consist of 36 airguns, with a total discharge volume of 6600 in^3. The array is made up of four identical linear arrays or strings, with 10 airguns on each string (FIGURE B. 2). For each operating string, nine airguns will be fired simultaneously, while the tenth will be kept in reserve as a spare, to be turned on in case of failure of another airgun.

The 36-airgun array will consist of a mixture of Bolt 1500LL and 1900LLX airguns, ranging in size from 40 to 360 in^3. The airguns will fire for a brief (~0.1 s) pulse every 50 m or every 200 m, depending on the line then being shot. At normal operating speed, that is equivalent to a shot interval of about 20 s or 80 s, depending on the line. The source will be silent during the intervening periods. The airgun array will be towed ~50–100 m behind the seismic vessel at a depth of 9–12 m.

The nominal specification of the airgun source planned for use is given below:

	36-Airgun Array (4 strings)
Energy Source	Thirty-six 2000 psi Bolt airguns of 40–360 in^3
Source output (downward)	9 m depth: 258 dB re 1 µPa @ 1 m 0-Peak level
	12 m depth: 257 dB re 1 µPa @ 1 m 0-Peak level
Towing depth of source	9 or 12 m
Air discharge volume	~6600 in^3

The highest sound level measurable at any location in the water from the airguns will be less than the nominal source level, because the pressure signatures of the airguns do not add coherently in the near field. For example, the highest measurable levels would occur close to the 2 × 360 in^3 cluster airguns within the array. At these locations the received sound level would be dominated almost entirely by the nearest 2 × 360 in^3 cluster and would be about 235 dB re µPa at a distance of 1 m.

TABLE B. 1 lists the two proposed airgun array configurations, along with the total volume, number of airguns, array layout, and nominal tow depths. Note that the firing volume (6600 in^3) is less than the total volume of airguns in the water (7320 in^3). This is because four airguns (one per string) are used as spares, to be operated only in case of a dropout by another airgun.

The two arrays listed in TABLE B. 1 were modeled using the JASCO airgun array source signature model to compute notional source signatures and also 1/3-octave band source levels as a function of azimuth angle. For each of the airgun arrays, broadside and endfire overpressure signatures and corresponding power spectrum levels are shown in FIGURE B. 3. Horizontal 1/3-octave band directionality plots for the array at the two possible tow depths are provided in Annex 1.

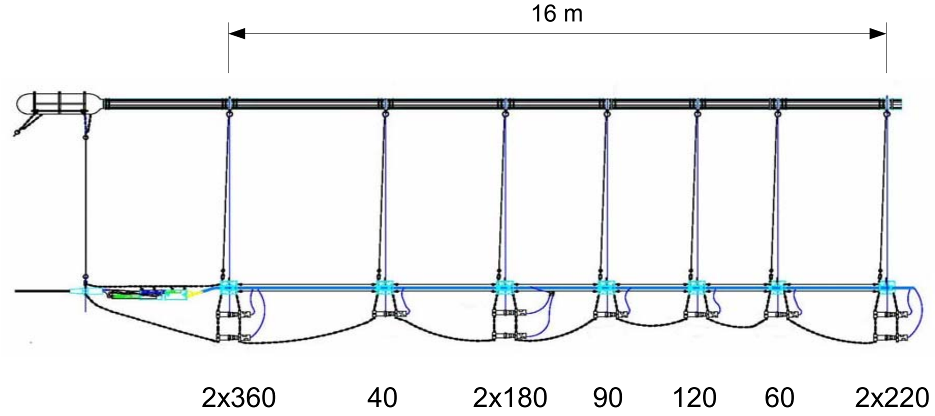


FIGURE B. 2: Diagram of R/V *Langseth* standard 1650 in^3 subarray design for 2-D and 3-D reflection or refraction surveys. Volumes of individual airguns are shown in cubic inches (in^3). Note that one of the 180 in^3 airguns is an inactive spare (in case of an airgun dropout) and so the nominal firing volume of the subarray is actually 1650 in^3 even though the total volume of the 10 airguns is 1830 in^3.

TABLE B. 1: Descriptions of R/V *Langseth* airgun array configurations for the Central America SubFac cruise. Parentheses in second column indicate total number of active airguns plus spares.

Array description	No. airguns operating (present)	Total vol. (in^3)	Shot vol. (in^3)	Array configuration as operated	Tow depth (m)
4-string array for 2D reflection	36(40)	7320	6600	4 x 1650 in^3 subarray	9
4-string array for 2D refraction	36(40)	7320	6600	4 x 1650 in^3 subarray	12

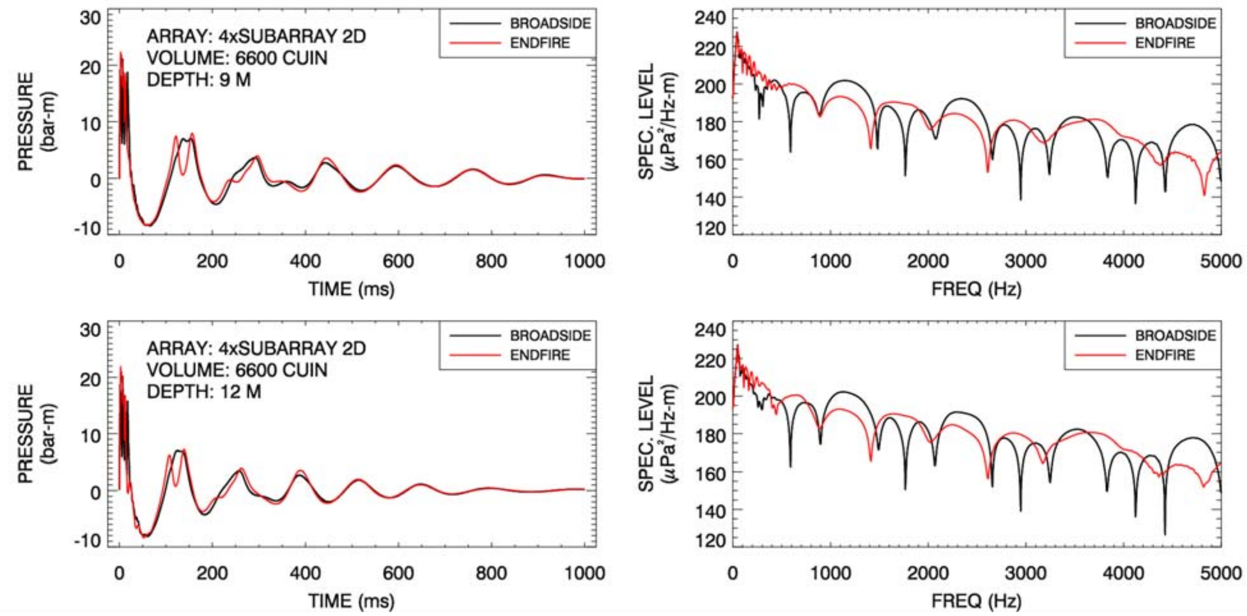


FIGURE B. 3: Predicted broadside and endfire overpressure signatures, with associated frequency spectra, for R/V *Langseth* airgun arrays. Note that the array volume given in the plot annotations is the active shot volume.

Sound Propagation Model

The modeled directional ⅓-octave source levels for the airgun array were used as input for the acoustic propagation software MONM (Marine Operations Noise Model), which computes the sound field radiated from the source. MONM, a proprietary application developed by JASCO Research, is an advanced modeling package whose algorithmic engine is a modified version of the widely-used the Range Dependent Acoustic Model, RAM (Collins et al. 1996).

RAM is based on the parabolic equation method using the split-step Padé algorithm to efficiently solve range dependent acoustic problems. RAM assumes that outgoing energy dominates over scattered energy and computes the solution for the outgoing wave equation. An uncoupled azimuthal approximation is used to provide two-dimensional transmission loss values in range and depth. RAM has been enhanced by JASCO to approximately model shear wave conversion at the sea floor using the equivalent fluid complex density approach of Zhang and Tindle (1995).

Because the modeling takes place over radial planes in range and depth, volume coverage is achieved by creating a fan of radials that is sufficiently dense to provide the desired tangential resolution. This *n* × *2-D* approach is modified in MONM to achieve greater computational efficiency by not over-sampling the region close to the source.

The desired coverage is obtained through a process of tessellation, whereby the initial fan of radials has a fairly wide angular spacing (5 degrees was used in this study), but the arc length between adjacent radials is not allowed to increase beyond a preset limit before a new radial modeling segment is started, bisecting the existing ones. The new radial need not extend back to the source because its starting acoustic field at the bisection radius is "seeded" from the corresponding range step of its neighboring traverse. In this study, the arc length limit was set at 1.5 km for larger modeling regions and 1 km for a smaller area, keeping the density of radials high at all ranges from the source.

The tessellation algorithm also allows the truncation of radials along the edges of a bounding quadrangle of arbitrary shape, further contributing to computational efficiency by enabling the modeling region to be more closely tailored to an area of relevance. MONM has the capability of modeling sound propagation from multiple directional sources at different locations and merging their acoustic fields into an overall received level at any given location and depth. This feature was not required in the present single-source study. The received sound levels at any location within the region of interest are computed from the ⅓-octave band source levels by subtracting the numerically modeled transmission loss at each ⅓-octave band center frequency, and summing incoherently across all frequencies to obtain a broadband value. The received levels, like the source levels from which they are computed, are equivalent to sound exposure level (SEL) over the duration of a single pulse or equivalently the rms level over a fixed 1-second time window.

Estimating 90% rms SPL from SEL

Existing U.S. safety zone requirements for impulsive sound sources are based on the rms sound pressure level metric. An objective definition of pulse duration is needed when measuring the rms level for a pulse. Following suggestions by C.I. Malme, Greene (1997) and McCauley et al. (1998), pulse duration is conventionally taken to be the interval during which 90% of the pulse energy is received. Although one can easily measure the 90% rms SPL *in situ*, this metric is extremely difficult to model in general since the adaptive integration period, implicit in the definition of the 90% rms level, is highly sensitive to the specific multipath arrival pattern from an acoustic source. To accurately predict the 90% rms level, it is necessary to model full-waveform acoustic propagation; for low frequencies in highly range dependent environments, this problem is beyond the capability of available modeling codes. Thus, accurate direct forecasting of the 90% rms SPL at any significant range from the source is not feasible at present.

Accurate estimates of airgun array safety zones must take into account the acoustic energy that is returned to the water column by bottom and surface reflections. This is especially important in the case of shallow water, as illustrated by the measurements of Tolstoy et al. (2004). If multipath reflections were taken into account, the resultant temporal spreading of the received seismic pulse would most certainly change the received pulse duration, rms estimates, and safety zones. The MONM algorithm does not attempt to predict the rms pressure directly; rather it models the propagation of acoustic energy in ⅓-octave bands in a realistic, range-dependent acoustic environment. When these ⅓-octave band levels are summed, the result is a broadband level that is equivalent to the sound exposure for a single airgun array pulse. For *in situ* measurements the SEL, pulse duration, and 90% rms SPL can all be measured, and SPL is related to SEL via a simple relation that depends only on the rms integration period T:

$$\mathrm{SPL}_{\mathrm{RMS90}} = \mathrm{SEL} - 10\log(T) - 0.458$$

Here the last term accounts for the fact that only 90% of the acoustic pulse energy is delivered over the standard integration period. In the absence of *in situ* measurements, however, the integration period is difficult to predict with any reasonable degree of accuracy. The best that can be done is to use a heuristic value of T, based on field measurements in similar environments, to estimate an rms level from the modeled SEL. Safety zones estimated in this way are approximate since the true time spreading of the pulse has not actually been modeled. For this study, the integration period T has been assumed equal to a pulse width of 0.1 s resulting in the following approximate relationship between rms sound pressure level and SEL:

$$\mathrm{SPL}_{\mathrm{rms90}} = \mathrm{SEL} + 10$$

In various studies where the SPL_{rms90}, SEL, and duration have been determined for individual airgun pulses, the average offset between SPL and SEL has been found to be 10–15 dB, with considerable within-study as well as between-study variation. For situations where the offset is ~15 dB, the SPL_{rms90} would be ~5 dB higher than calculated here, but the duration would be shorter than assumed here, and the received energy (SEL) would be equivalent.

(d) MONM Parameters

Source Locations

Six sites were selected as representative source locations for sound propagation modeling based on the previously-proposed seismic tracklines (which have since been updated, see Figure 1 in § I of EA). Three locations were chosen in the Caribbean Sea and three in the Pacific Ocean. For each of these two areas, one site was in shallow (<100 m) water on the continental shelf, one site was in intermediate-depth water (100–1000 m) on the continental slope, and one site was in deep water (>1000 m). The geographic locations of the six source points used for the modeling runs are listed in TABLE B. 2 and shown on the map in Annex 2.

TABLE B. 2: Assumed source locations and tow depths

Source Location No.	Latitude (N)	Longitude (W)	Water Depth (m)	Array Depth (m)	Array Heading (deg T)
1	12.3068	83.1943	24	9 & 12	139
2	10.6865	83.3664	482	9 & 12	224
3	11.1874	82.8676	2040	9 & 12	224
4	8.8953	83.9000	65	9 & 12	305
5	9.3361	84.7361	340	9 & 12	225
6	8.9874	86.5433	3100	9 & 12	314

Model Receiver Depths

From the chosen source positions, the model can generate a grid of acoustic levels over any desired area as well as at any depth in the water column. To create a map of noise level contours, a choice must be made of the depths at which to "sample" the modeled acoustic field. For each site modeled in this study, noise contour results were mapped at the depths shown in TABLE B. 3.

TABLE B. 3: Receiver depths at the six sites

Site No.	Receiver Depths (m)
1	10 & 20
2	10, 20, 50, 100 & 200
3	10, 20, 50, 100, 200, 500, 1000 & 2000
4	10, 20 & 50
5	10, 20, 50, 100 & 200
6	10, 20, 50, 100, 200, 500, 1000, 2000 & 3000

Bathymetry and Acoustic Environment

Bathymetry

The relief of the sea floor is one of the most crucial parameters affecting the propagation of underwater sound, and detailed bathymetric data are therefore key to accurate modeling. For each of the six modeling sites, the bathymetry data used for this modeling were extracted from the 2004 version of the SRTM30 Plus dataset, a database of bottom depth measurements with worldwide coverage and 30 arc-seconds resolution.

Geoacoustic Properties

Geoacoustic models for the east and west coasts of Costa Rica were derived using data from the Ocean Drilling Program (ODP) and Deep Sea Drilling Program (DSDP). Core locations that were used in deriving the models are shown in FIGURE B. 4. Data from these cores were used, along with sediment properties provided in the review article by Hamilton (1980), to generate geoacoustic models for each of the six sites. These geoacoustic parameters were selected as physically realistic estimates for the sites in question based on the available data and may not represent the most conservative propagation scenario for the area as a whole. The parameters used for each of the six sites are listed in Tables A.4 – A.7.

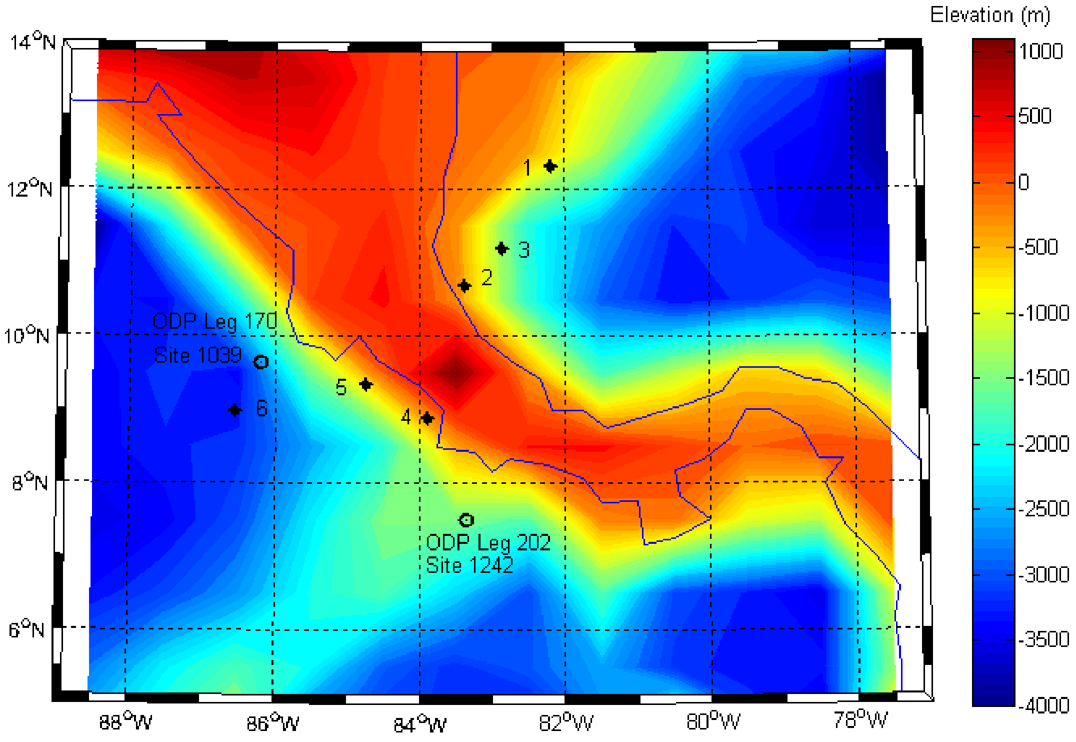


FIGURE B. 4: Locations of cores used to create geoacoustic models. Color-coded depths are in meters. Note that core sites do not correspond directly to the six modelling sites.

Geoacoustic data for sediments at modeling Sites 1 and 2 are taken from a seismic-stratigraphic analysis of the western Colombian Basin (Bowland 1993). This region is characterized by oceanic plateau underneath about 3000 m of sediment. The top 1000 m of sediment is composed of volcanogenic turbidites, containing formanifera fossils and calcerous clay. The basement rocks are composed of basalt flows and sills with inter-bedded sedimentary rocks.

TABLE B. 4: Geoacoustic model inputs for Sites 1 and 2

	Layer 1	**Layer 2**
Type of layer	Volcanogenic turbidites	Volcanogenic and carbonate turbidites
Thickness (m)	1000	2500
Sound Speed (m/s)	1559.0	2898.0
Sound speed gradient (m/s /m)	0.66	0.86
Density (g/cm^3)	1.42	1.60
Attenuation (dB/λ)	0.11	5.0
Shear wave parameters		
Velocity (m/s)	290	
Attenuation (dB/λ)	3.9	

Geoacoustic data for sediments at Site 3 are extrapolated from the information we have for Sites 1 and 2, based on the assumption that sediment becomes coarser in deeper water.

TABLE B. 5: Geoacoustic model inputs for Site 3

	Layer 1	**Layer 2**
Type of layer	Volcanogenic turbidites	Volcanogenic and carbonate turbidites
Thickness (m)	1000	2500
Sound Speed (m/s)	1559.0	2898.0
Sound speed gradient (m/s /m)	0.66	0.86
Density (g/cm^3)	1.42	1.60
Attenuation (dB/λ)	0.13	5.0
	Shear wave parameters	
Velocity (m/s)	290	
Attenuation (dB/λ)	3.9	

Geoacoustic data for sediments at Sites 4 and 5 are taken from ODP Leg 202, Site 1242, with additional information from seismic lines (Bialas et al. 1996). The core taken at Site 1242 consisted of fine-grained, homogeneous, hemipelagic sediments that represent the upper Pliocene, Pleistocene and Holocene intervals. Bialas et al (1996) describe these sediments as continuing to depths down to 1000 m below the seabed, where they overlie a large margin wedge of well-consolidated ophiolite rocks.

TABLE B. 6: Geoacoustic model inputs for Sites 4 and 5

	Layer 1	**Layer 2**
Type of layer	Fine-grained hemipelagic sediments	Well-consolidated ophiolites
Thickness (m)	1000	2000
Sound Speed (m/s)	1606.0	2111.0
Sound speed gradient (m/s /m)	1.32	2.13
Density (g/cm^3)	1.60	1.60
Attenuation (dB/λ)	0.165	5.0
Shear wave parameters		
Velocity (m/s)	116	
Attenuation (dB/λ)	2	

Geoacoustic data for sediments at Site 6 are taken from ODP Leg 205, Site 1039 drill core, which was taken to depth 404 m below sea floor. The composition of the core from top to bottom is turbidite up to about 100 m, followed by a shallow layer of diatomaceous ooze with sand and ash layers from the Pleistocene age. Silty clay with ash layers from the Pliocene age, siliceous nannofossil ooze, and calcareous clay from the Miocene-early Pliocene age make up a layer ~200 m thick. Pyroxene gabbro intrusions with plagioclase glomerocrysts compose the final 100 m of the core.

TABLE B. 7: Geoacoustic model inputs for Site 6

	Layer 1	**Layer 2**	**Layer 3**
Type of layer	Turbidite, sand and ash	Silty clay, calcareous clay	Pyroxene Gabbro intrusions
Thickness (m)	100	200	100
Sound Speed (m/s)	1583.4	1867.83	2177.28
Sound speed gradient (m/s /m)	1.22	0.35	0.66
Density (g/cm^3)	1.34	1.46	1.6
Attenuation (dB/λ)	0.16	0.2	2.6
Shear wave parameters			
Velocity (m/s)	127		
Attenuation (dB/λ)	1.7		

Sound Speed Profiles

Sound speed profiles in the ocean for each of the six modeling locations were derived from the U.S. Naval Oceanographic Office's Generalized Digital Environmental Model (GDEM) database (Teague et al. 1990). The latest release of the GDEM database (version 3.0) provides average monthly profiles of temperature and salinity for the World's oceans on a latitude/longitude grid with 0.25 degree resolution. Profiles in GDEM are provided at 78 fixed depth points up to a maximum depth of 6800 meters. The profiles in GDEM are based on historical observations of global temperature and salinity from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS).

The L-DEO Central America SubFac cruise is currently scheduled to take place during winter (January–March) 2008. Given the nearly equatorial climatic conditions of the survey locations, the specific season will have little effect on the modeled safety zones. For each acoustic model scenario, a representative T/S profile was extracted from the GDEM database and converted to speed of sound in seawater using the equations of Coppens (1981):

$$
\begin{aligned}
c(z,T,S) &= 1449.05 + 45.7T - 5.21t^2 - 0.23t^3 \\
&\quad + (1.333 - 0.126t + 0.009t^2)(S - 35) + \Delta \\
\Delta &= 16.3Z + 0.18Z^2 \\
Z &= z/1000(1 - 0.0026\cos 2\phi) \\
t &= T/10
\end{aligned}
$$

where *z* is depth in meters, *T* is temperature in degrees Celsius, *S* is salinity in psu and φ is latitude. For continental shelf sites, where the water depth at the source was less than that at some nearby sites included in the modeling area, sound speed profiles were extrapolated to the maximum modeling depth by splicing data points from neighboring grid cells. FIGURE B. 5 shows the six sound speed profiles that were used for modeling at each of the survey locations.

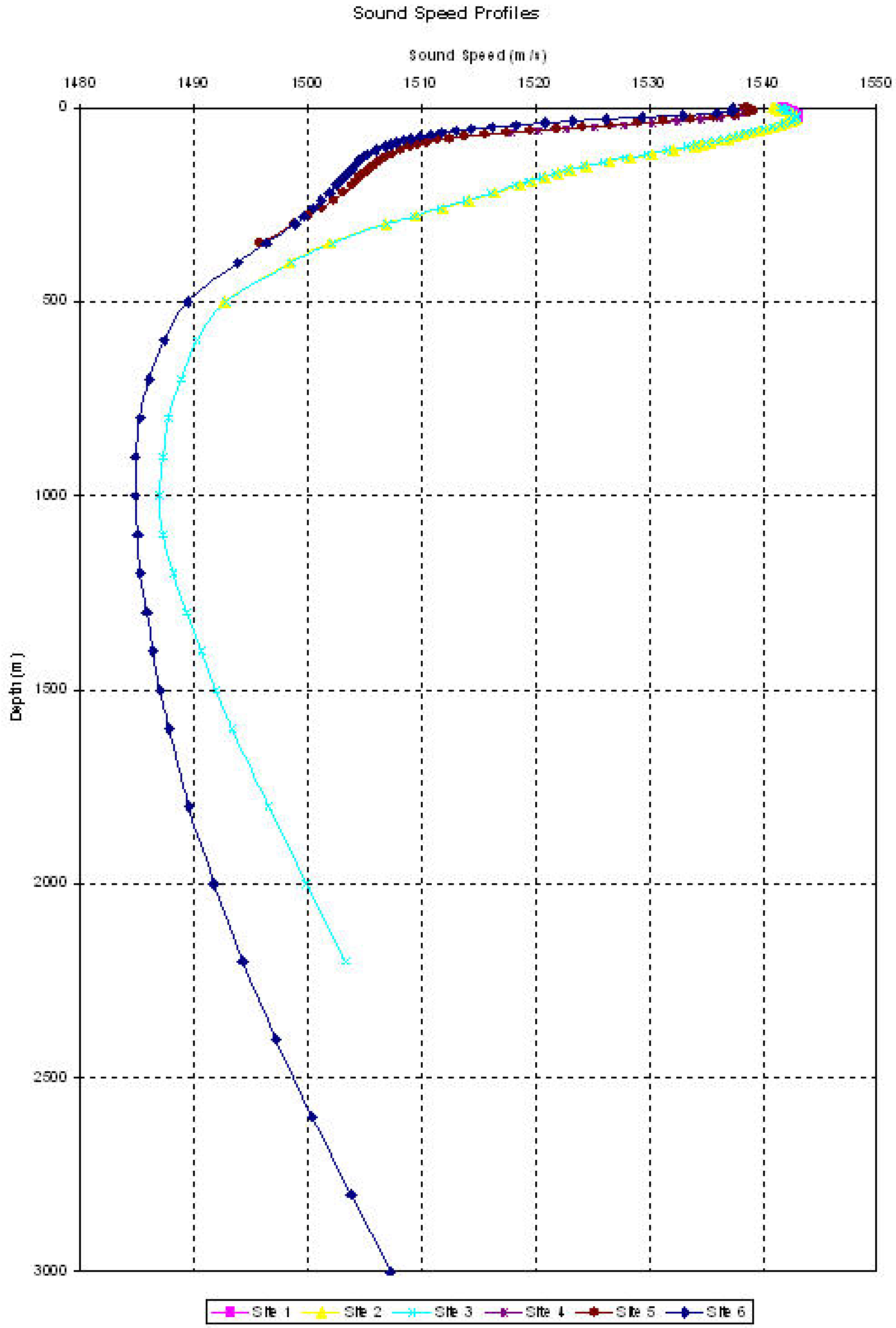


FIGURE B. 5: Plots of the sound speed versus depth profiles used for each of the modeling locations.

Deep Water

In deep water (greater than 2000 m), the deep sound channel allows refracted sounds to travel long distances without losses from reflection at the bottom. This phenomenon occurs because of the upward-refracting sound speed profile below the deep sound channel. In the Atlantic, the deep sound channel typically occurs at depths between 800 m and 1100 m between the Tropics of Cancer and Capricorn (Clay & Medwin 1977).

In the Caribbean, the seasonal variability in the maximum depth of the surface mixed layer ranges from 30 m during summer months to around 75 m in winter. Mixed layer depths appear to be consistently shallower (i.e., <30 m) on the Pacific side of Central America (De Boyer Montégut et al. 2004). Sound can be refracted toward the surface if there is a slight increase in sound speed with depth and can travel at shallow depth with reflection from the surface. Scattering loss at the surface will increase with sea state. Below the shallow duct a shadow zone is created, with weak sound energy from diffraction, diffusion, scattering, and reflection. This situation is uncommon and does not happen with low frequency sounds (sound whose wavelength is greater than the depth of the surface duct).

FIGURE B. 6 and FIGURE B. 7 show mean temperature and salinity from GDEM, and derived sound speed profiles, for the locations under consideration in this study. Note that the depth of the surface mixed layer is somewhat less at these near-shore sites. On the western side of Costa Rica, typical mixed layer depths are near 15 m year-round. Near the eastern coast, the mixed layer is expected to be approximately 30 m thick in the winter, and almost non-existent in mid-summer. In both cases, the sound speed minimum occurs near 1000 m.

Shallow Water

In shallow water (less than 200 m), sound speed profiles tend to be downward refracting or nearly constant with depth, resulting in repeated bottom interaction. Long-range propagation is complicated and difficult to predict due to spatially and temporally varying water and bottom properties. Low frequencies (less than 1000 Hz) are the most affected by bottom loss and high frequencies (above 10 kHz) by scattering loss. There is less bottom interaction in the winter than in the summer since the surface waters are less warm and thus sound speed is lower. The optimum frequency for propagation in shallow water is highly dependent on depth, partially dependent on sound speed profile, and weakly dependent on bottom type. In 100-m water, frequencies of 200–800 Hz likely would travel the farthest. As can be seen from FIGURE B. 6 and FIGURE B. 7, seasonal variations do occur although the seasonal variations in near-surface temperature and sound speed are not large.

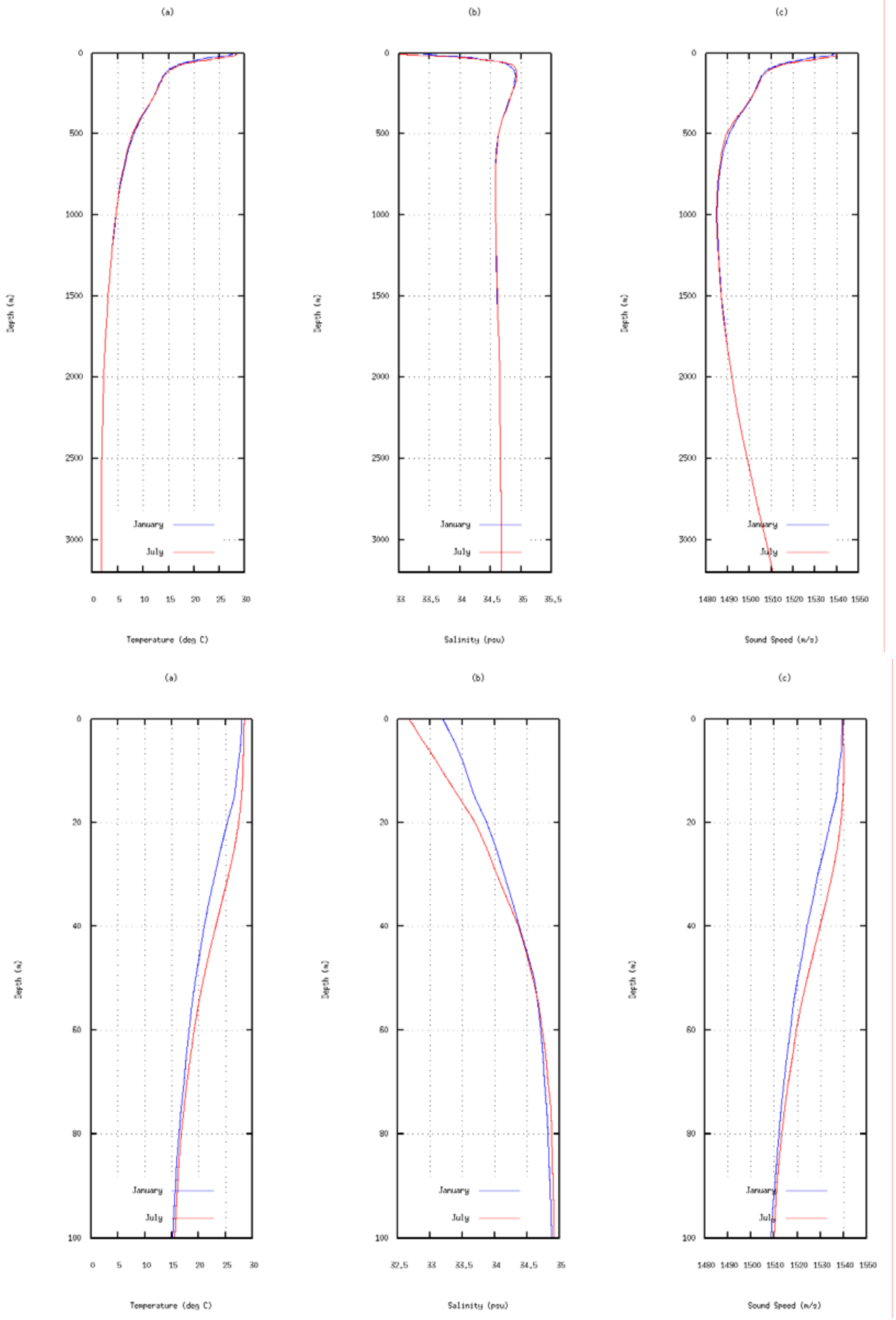


FIGURE B. 6: Profiles of temperature, salinity, and sound speed in the full (top) and upper 100 m (bottom) of the water column at 9ºN, 86ºW (between the two Pacific Ocean sites) in winter and summer conditions.

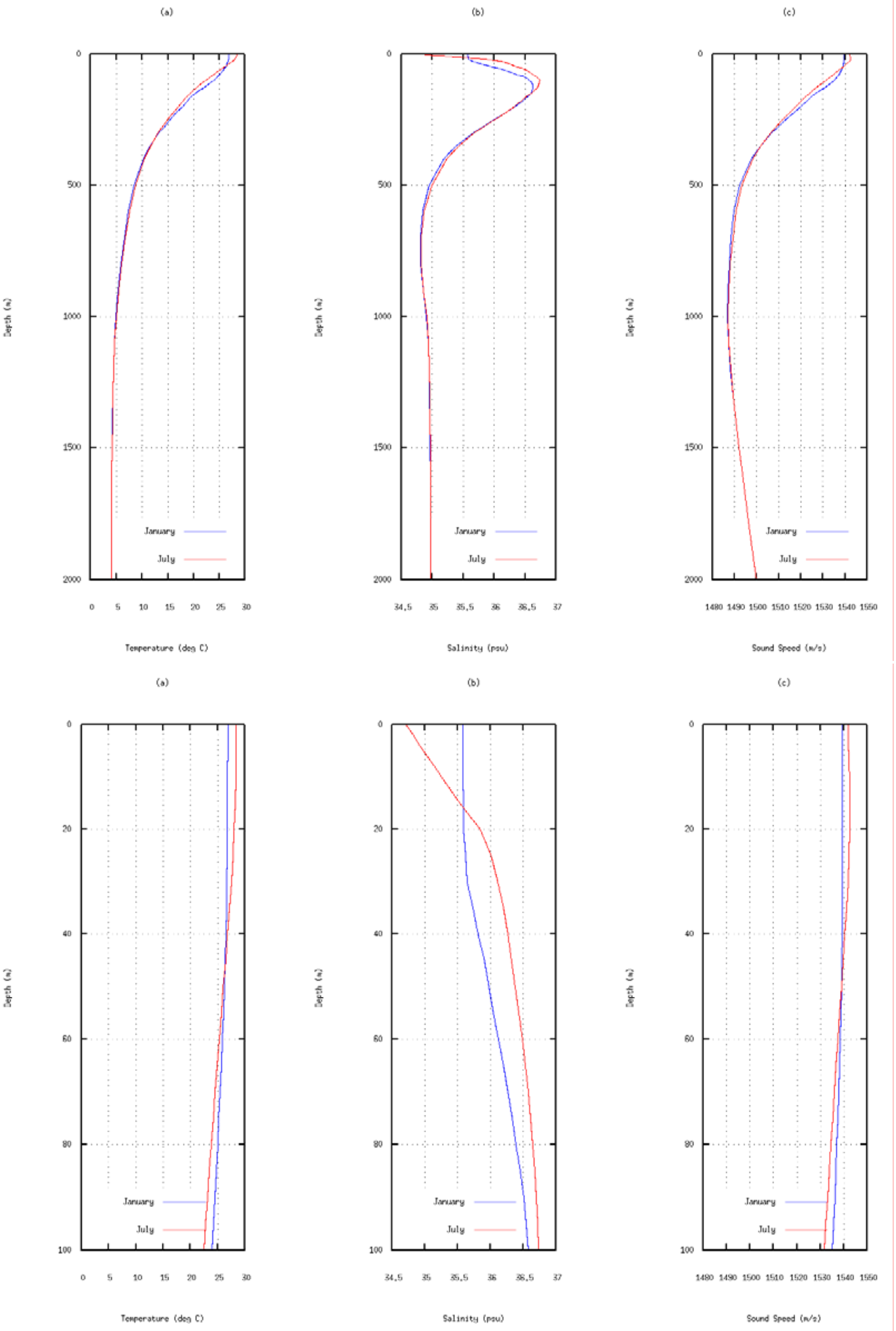


FIGURE B. 7: Profiles of temperature, salinity, and sound speed in the full (top) and upper 100 m (bottom) of the water column at 11ºN, 83ºW (roughly in the center of the Caribbean sites) in winter and summer.

(e) Model Results

The MONM propagation model was run in the full *n* × *2-D* sense as described in section c. Geographically rendered maps of the received sound levels in dB re $\mu Pa^2 \cdot s$ for the six modeled source locations are shown in Annex 3, FIGURE B. 18 through FIGURE B. 29. The acoustic level values in the model output represent the sound exposure level (SEL) metric, a suitable measure of the impact of an impulsive sound because it reflects the total acoustic energy delivered over the duration of the event at a receiver location. To determine the rms sound pressure levels required in defining safety zones and "take estimates", a pulse duration of 0.1 s was assumed, resulting in a conversion factor of +10 dB. Thus, rms levels (in dB re 1μPa) were taken to be 10 dB higher than SEL values in dB re $1\mu Pa^2 \cdot s$.

Annex 4 summarizes the results of the acoustic modeling in terms of radii to specified threshold levels between 160 dB and 190 dB re 1 μPa_{rms} for all modeled depth strata. For each sound level threshold, two different statistical estimates of the safety zones are provided: the 95% radius and the maximum broadside radius. Given a regularly gridded spatial distribution of modeled received levels, the 95% radius is defined as the radius of a circle that encompasses 95% of the grid points whose value is equal to or greater than the threshold value. This definition is meaningful in terms of impact because, regardless of the geometrical shape of the noise footprint for a given threshold level, it always provides a range beyond which no more than 5% of a uniformly distributed population would be exposed to sound at or above that level. The maximum broadside radius is the radius of a 60 degree angular sector, centered on the broadside axis of the array, that encompasses all grid points whose value is equal to or greater than the threshold value. Modeled sound levels were sampled at several depths at each site, up to the lesser of 2000 m or the seafloor depth. This was done on the assumption that, at sites deeper than 2000 m, mammals would not dive deeply enough to be exposed to sounds at greater depths.

TABLE B. 8 summarizes, for each of the six sites, the predicted radii within which received levels of ≥180 and ≥190 dB re 1 μPa_{rms} level might be received at one or more of the sampled depths. The six sites are assumed to be representative of locations in shallow (<100 m), intermediate (100–1000 m), and deep water (>1000 m) in the Pacific and Caribbean regions. TABLE B. 9 and TABLE B. 10 summarize the maximum predicted 95% and broadside radii to threshold levels from 190 dB to 160 dB re 1 μPa_{rms} across all depth regimes for the Caribbean and Pacific regions respectively.

Table B. 8: Estimated ranges to 180 and 190 dB re 1 µPa$_{rms}$ sound levels thresholds in shallow (<100 m), intermediate (100–1000 m), and deep (>1000 m) water during operation of the 4-string 36-airgun array. For deep water, only the received levels in the top 2000 m of the water column (the usual depths for marine mammals and sea turtles) are considered. Each entry is the higher of the corresponding "95% max range" and "broadside range" shown in Annex 4.

Source and Volume	Location	Tow Depth (m)	Water Depth	Predicted Safety Radii (m)	
				180 dB	190 dB
4 strings 36 airguns 6600 in^3	Pacific	9	Deep	525	321
			Interm.	496	292
			Shallow	471	254
		12 Line F only	Deep	620	323
			Interm.	554	314
			Shallow	459	273
	Caribbean	9	Deep	533	290
			Interm.	500	295
			Shallow	455	288
		12 Line C only	Deep	634	310
			Interm.	556	315
			Shallow	471	315

TABLE B. 9: Summary of maximum ranges for all depth regimes in the Caribbean.

SEL	SPL$_{rms}$	95% Range (km)	Broadside Range (km)
180	190	0.317	0.323
170	180	0.620	0.521
160	170	2.964	2.380
150	160	8.503	13.680

TABLE B. 10: Summary of maximum ranges for all depth regimes in the Pacific.

SEL	SPL$_{rms}$	95% Range (km)	Broadside Range (km)
180	190	0.315	0.308
170	180	0.634	0.555
160	170	1.92	1.526
150	160	5.382	4.265

(f) Discussion

Comparison of Free-field predictions to MONM

Seismic industry estimates of the sound fields around their airgun arrays are typically based on "free-field" sound level calculations that assume uniform sound spreading in an infinite, homogenous ocean. These free-field estimates neglect specific environmental effects, such as water column refraction and bottom reflections, both of which are taken into account in MONM. As a rule of thumb, free-field models may be considered accurate inside a zone, centered at the source, with radius approximately half the water depth (see FIGURE B.8). Within that zone, the contribution from multipath reflections is much less than that from the direct-path signal, and environmental effects do not contribute significantly to the received sound field. This zone of validity includes the region directly below the airgun array, where the highest sound levels are encountered. Due to the simplifying assumptions involved in the free-field calculation, free-field models can be used to generate full-waveform (i.e., time-domain) field predictions with relatively little computational cost. However, they cannot reliably predict received sound levels beyond a limited range, especially in shallow areas where the local environment has significant (and site-specific) effects on propagation (see Urick 1982). Because free-field models do not allow for local conditions, they are generally unable to provide realistic estimates of radii to lower dB levels such as the 160 dB disturbance criterion defined by NMFS.

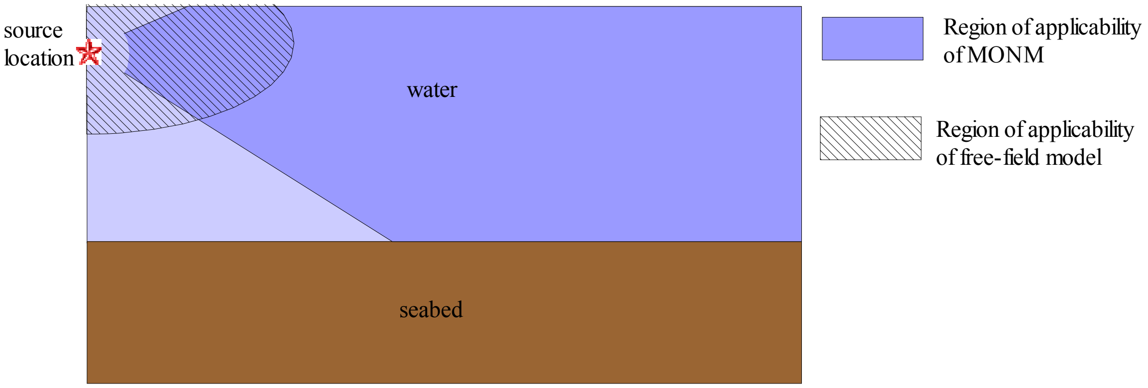


FIGURE B. 8: Stylized diagram showing approximate regions of applicability of the MONM and free-field models.

MONM, on the other hand, can account for much of the complexity of the ocean environment, including the effects of an inhomogeneous water column, arbitrary layering in the sub-bottom, and sloping bathymetry, provided these environmental factors are adequately known for the site and season in question. These effects are especially important at long range from the source and in shallow water where free-field models are most inaccurate. This increase in accuracy, however, comes at a significant computational cost and so MONM uses two simplifying approximations to make the hundreds of kilometers of transmission loss computations feasible:

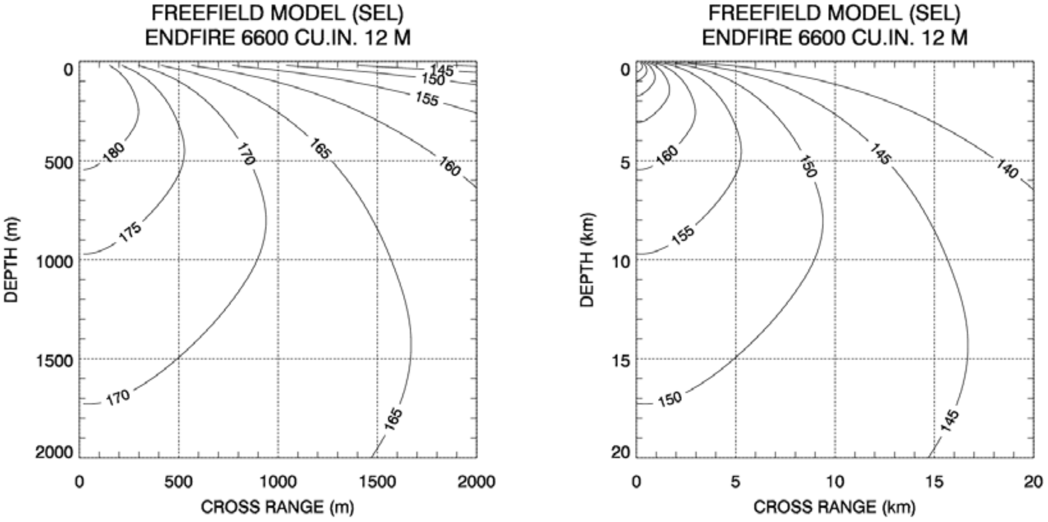
1. MONM calculates transmission loss in the frequency domain, at ⅓-octave band center frequencies, and broadband received levels are computed by incoherently summing the ⅓-octave transmission loss calculations with the ⅓-octave band source levels for the airgun array. This approximation is required in order to make three-dimensional broadband field calculations computationally practical over areas of hundreds of square kilometers. The ⅓-

octave band modeling approach is widely used in the acoustics community to characterize the energy of the sound field produced by broadband sources although it cannot be used to replicate the acoustic signal in the time-domain (this would require modelling at a much finer frequency resolution).

2. Although it fully handles planar directivity, MONM currently neglects the vertical directionality of the airgun array and assumes that the source radiates at all vertical angles with the same (azimuth dependent) intensity as in the horizontal direction. This approximation is necessary because RAM computes transmission loss for an omni-directional, point-like acoustic source. It is also reasonable because, beyond a very short range, the vertically projected component of the array's acoustic energy contributes negligibly to the received level at shallow propagation angles. It is only in the vertical direction below the array, where free-field models produce more accurate predictions, that MONM systematically underestimates received levels. JASCO is currently in the process of modifying MONM's capabilities to fully account for the vertical directionality of airgun array sources. This change will render this horizontal source level approximation unnecessary in future applications of MONM.

As long as environmental conditions are well defined, RAM provides physically accurate predictions of transmission loss for long-range propagation. This is borne out by numerical comparisons of RAM with benchmark acoustic propagation models (Collins et al. 1996; Hannay and Racca 2005).

If we were to neglect the propagation modeling component of MONM, the source modelling component alone produces results that are consistent with free-field models such as L-DEO's. To illustrate this point, MONM's own integrated airgun array source model was used to perform a free-field sound level calculation using a method similar to that employed by L-DEO (*cf.* Appendix B). JASCO's airgun array source model is a time-domain source waveform model that can be used to make free-field received level predictions independently of any particular acoustic propagation model. Figure B.9 shows the sound levels predicted by the free-field model in the forward endfire direction from the planned 36-airgun array. It is apparent from the Figure that the free-field calculations predict very low received levels in the region near the sea-surface, horizontally away from the source position. As well, one can see that the free-field contours less than 170 dB SEL penetrate well into the sub-bottom, even for deep water locations. Comparison of these predictions with those from L-DEO's free-field model appearing in the main body of this document show that the predicted received levels are very similar, generally within 1–2 dB. However, these free-field predictions cannot be extended with any degree of generality to propagation in an environment that includes an inhomogeneous water column and reflections from a lower boundary. A free-field model is, by definition, ignorant of the presence of boundaries or gradients in the medium and predicts received levels based on a fixed spreading loss law.



(a) (b)

FIGURE B. 9: Free-field SEL predictions for the 36-gun, 6600 in^3 airgun array in the forward endfire direction at 12 meters tow-depth, for distances out to (a) 2000 m from the source, and (b) 20 km from the source.

Tolstoy et al. (2004) measured the radii to certain received levels for various configurations of airgun arrays operating in the northern Gulf of Mexico and compared these empirical results with corresponding values predicted by L-DEO's free-field model. For shallow water, measured distances substantially exceeded distances predicted by the free-field model, as one would expect. Conversely, for deep water, measured distances tended to be less than those predicted by that model. From these results empirical to predicted ratios were determined and have subsequently been used as correction factors when estimating "safety zones" (180 and 190 dB re 1 μPa_{rms}) and "disturbance zones" (e.g., 160 dB re 1 μPa_{rms}) for various other airgun configurations operated by L-DEO and other NSF-sponsored researchers. Those adjustments of the basic free-field approach were expected to produce more reliable estimates than would the free-field model itself, at least when applied to the region where the correction factors were determined (northern Gulf of Mexico), or to a region with similar propagation conditions. However, that approach makes no allowance for differences in propagation conditions among regions, which are known to be substantial. A model such as MONM, unlike the free-field models, allows for site-specific propagation conditions by taking account of known or estimated environmental conditions in the area of interest.

Uncertainty in MONM predictions

Accurately predicting the sound field from a seismic airgun array using MONM requires prior knowledge about the ocean environment, including bathymetry, sound speed in the water column, and geoacoustic parameters for the sub-bottom. If reasonably accurate values are used for these parameters, then the well-established propagation model on which MONM is based should produce accurate estimates of the sound field. However, when high-quality environmental data are unavailable, one must try to estimate these parameters based on available knowledge about the environment. This is especially true for geoacoustic parameters in the sub-bottom, which are seldom known with a high degree of confidence. For the current study, we have assumed average acoustic properties at each location, based on available environmental knowledge, for both sound speed profiles in water and geoacoustic parameters for the sub-bottom.

Three primary types of environmental parameters are used as input to MONM, and the relative sensitivity of the sound level predictions to those parameters depends primarily on the water depth. It is well established that, in deep water, MONM's predictions and those of any similar propagation model are most strongly influenced by the sound speed profile in water. In contrast, in shallow water MONM and similar models are most strongly influenced by the geoacoustic properties of the sub-bottom and by variations in bathymetry. For the current study the best-available environmental data at each location were used as input to the acoustic model, as discussed in section d. Sound speed profiles in the water column were based on average historical temperature and salinity from the GDEM database; however, these parameters vary over time in the ocean and anomalous conditions could lead to lower (or higher) transmission loss conditions. Bathymetry data with nominal 30 arc-second (~1 km) resolution were interpolated from the global SRTM database; however, global databases like SRTM are an agglomeration of many different datasets which may be of lower resolution and sometimes contain errors. Geoacoustics in the bottom were based on geological descriptions of a limited number of ODP sediment cores, and the acoustic parameters were estimated from average sediment properties from literature sources. For shallow sites, MONM should give results comparable to those from other state-of-the art models, and superior to results from less mathematically complete models. However, MONM's predictions in shallow water environments are very sensitive to the bottom parameters, and it is in shallow waters therefore that the predictions have the highest uncertainty.

MONM's predictions of received sound levels from three planned seismic studies in the Alaskan Chukchi Sea have recently been compared with *in situ* Ocean Bottom Hydrophone data acquired during those projects. Publicly available summaries of the preliminary results show that measured levels generally exceeded predicted levels for that range. Measured distances to the 160–190 dB re 1 μPa_{rms} received levels ranged between 1.1 and 1.9 times the predicted distances (Austin et al. 2006; Blackwell 2006; Turner et al. 2006).

- One reason for the under-predictions of received levels and of radii for specified sound levels in the Chukchi Sea was an apparent underestimation of the sound speed in the sub-bottom.[5] It is important to note in this context that there is very little published information concerning the sub-bottom properties of the Chukchi Sea; indeed the geoacoustic parameters for the Chukchi modeling were based on a single sediment core.
- Also, the acoustic measurements had to be acquired at locations and (to some degree) water depths different from those for which the model had been run, in part because of the presence of ice in some areas when the measurements were taken. A better match between the predicted and observed sound fields would be expected if the Chukchi model predictions were re-run considering the actual locations where empirical data were acquired (and using better estimates of the bottom sound speed).
- Lastly, the Chukchi modeling runs were consistently performed for a receiver depth of 10 m as this was the agreed reporting depth, whereas the measurements were always taken at the seafloor. Given that the water sound velocity profiles in the region at the time of the measurements created downward refracting propagation conditions, there is clear evidence that sound levels should be higher at the hydrophones than at the 10m modelled depth. This provides an additional explanation for the under-estimation of the measurement results by the model.

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[5] Waveform modeling along a single transect showed that the modeled pressure amplitudes differed by less than 2 dB from measured values. However, the number of strong propagating modes evident in the measurements was 7 while only 4 were apparent in the modeled waveforms. This leads to the conclusion that the estimated sound speed in the sub-bottom (as used for the model predictions in the Chukchi Sea) was too low, since the number of modes depends on the bottom sound speed in the upper few hundred meters of sediment.

The most extensive validation to date of the accuracy of MONM predictions in shallow waters has been performed for a region off Sakhalin Island, Russia, as part of an environmental impact mitigation program that involved forecasting industrial noise from subsea construction operations (Hannay and Racca 2005). That study included benchmark assessment against other models, transmission loss measurements in controlled conditions, and comparison of model predictions to measured levels at multiple locations during an operation involving several sources. In that situation the match between modeled locations and measurement sites was very close and the relatively good initial knowledge of the seafloor geoacoustic properties was further refined based on the comparison of model results to controlled measurements. The results of that work showed that the model predicted consistently, to within a few dB, the received sound levels over areas of many tens of square kilometers, from multiple concurrent sources at wide separations, in a shallow water environment characterized by very complex bathymetry. The model tended to be conservative when compared to real life aggregate measurements of noise from an operation primarily because the source levels are generally representative of the noisiest regime for each vessel involved. From the standpoint of transmission loss estimation, however, the model was found to exhibit no systematic bias relative to the measured values within the margin of uncertainty. The results of MONM in that application have been used successfully as a planning tool for construction scheduling and subsequently verified in extensive monitoring trials.

(g) Literature Cited

Austin, M., M. Laurinolli, and D. Hannay. 2006. Preliminary Acoustic Level Measurements of Airgun Sources from GX Technology Corporation's 2006 Arctic Span Seismic Survey." Technical report from JASCO Research Ltd. submitted by GXT to NOAA. Available at http://www.nmfs.noaa.gov/pr/permits/incidental.htm, September 2006.

Bialas, S. J. Ye. E.R. Flueh, A. Stavenhagen, and R. von Huene. 1996. Crustal structure of the Middle American Trench off Costa Rica from wide-angle seismic data. **Tectonics** 15(5):1006-1021.

Blackwell, S. 2006. Field report for validation measurements of sound produced by airguns on M/V *Gilavar* in the Chukchi Sea on 21 July 2006. (Rev. 3, 6 Aug. 2006). Technical report from Greeneridge Sciences Inc. submitted by Shell to NOAA. Available at http://www.nmfs.noaa.gov/pr/permits/incidental.htm, September 2006.

Bowland, C.L. 1993. Depositional History of the western Colombian Basin, Caribbean Sea, revealed by seismic stratigraphy. **Geol. Soc. Am. Bull.** 105:1321-1345.

Clay, C.S. and H. Medwin. 1977. Acoustical Oceanography. New York: John Wiley.

Collins, M.D., R.J. Cederberg, D.B. King, and S.A. Chin-Bing. Comparison of algorithms for solving parabolic wave equations. **J. Acoust. Soc. Am.** 100(1):178-182.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. **J. Acoust. Soc. Am.** 69(3):862–863.

de Boyer Montégut, C., G. Madec, A.S. Fischer, A. Lazar, and D. Iudicone. 2004. Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. **J. Geophys. Res.** 109:C12003

Dragoset, W.H. 1984. A comprehensive method for evaluating the design of airguns and airgun arrays. 16th Annual Proc. Offshore Tech. Conf. 3:75-84.

Greene, C.R., Jr. 1997. Physical acoustics measurements. p. 3-1 to 3-63 *In:* W.J. Richardson (ed.), Northstar marine mammal monitoring program, 1996: marine mammal and acoustical monitoring of a seismic program in the Alaskan Beaufort Sea. LGL Rep. 2121-2. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 245 p.

Hamilton, E.L. 1980. Geoacoustic modeling of the sea floor. **J. Acoust. Soc. Am.** 68(5). 1313-1340.

Hannay, D.E. and R.G. Racca. 2005. Acoustic model validation. Technical report by JASCO Research Ltd. for Sakhalin Energy Investment Company. Available at http://www.sakhalinenergy.com/en/documents/doc_33_jasco.pdf

Landro, M. 1992. Modeling of GI gun signatures. **Geophys. Prosp.** 40 (7):721-747.

Laws, M., L. Hatton, and M. Haartsen. 1990. Computer modeling of clustered airguns. **First Break** 8(9):331–338.

Lurton, X. 2002. An Introduction to Underwater Acoustics: Principles and Applications. Springer, Chichester, U.K. 347 p.

Mackenzie, K. 1981. Nine-term equation for the sound speed in the oceans. **J. Acoust. Soc. Am.** 70(3):807-812.

McCauley, R.D., M.-N. Jenner, C. Jenner, K.A. McCabe, and J. Murdoch. 1998. The response of humpback whales (*Megaptera novaeangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. **APPEA J.** 38:692-707.

Racca, R.G. and J.A. Scrimger. 1986. Underwater Acoustic Source Characteristics of Air and Water Guns. Contractor report by JASCO Research Ltd., Victoria, B.C, for DREP Contract No. 06SB 97708-5-7055.

Teague, W. J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the generalized digital environmental model and Levitus climatologies. **J. Geophys. Res.** 95(C5):7167-7183.

Tolstoy, M., J.B. Diebold, S.C. Webb, D.R. Bohnenstiehl, E. Chapp, R.C. Holmes, and M. Rawson. 2004. Broadband calibration of R/V *Ewing* seismic sources. **Geophys. Res. Let.** 31. L14310, doi: 10.1029/2004GL020234.

Turner S., M. Zyko,v and A. MacGillivra. 2006. Preliminary Acoustic Level Measurements of Airgun Sources from ConocoPhillips' 2006 Seismic Survey in Alaskan Chukchi Sea. Technical report from JASCO Research Ltd. submitted by ConocoPhillips to NOAA. Available at http://www.nmfs.noaa.gov/pr/permits/incidental.htm, September 2006.

Urick, R.J. 1982. Sound propagation in the sea. Peninsula Publ., Los Altos, CA.

Ziolkowski, A. 1970. A Method for Calculating the Output Pressure Waveform from an Air Gun. **Geophys. J. R. Astr. Soc.** 21:137–161.

Zhang, Z. and C. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. **J. Acoust. Soc. Am.** 98:3391-3396.

(h) Annex 1: Airgun Array $^{1}/_{3}^{\text{rd}}$-Octave Band Source Levels

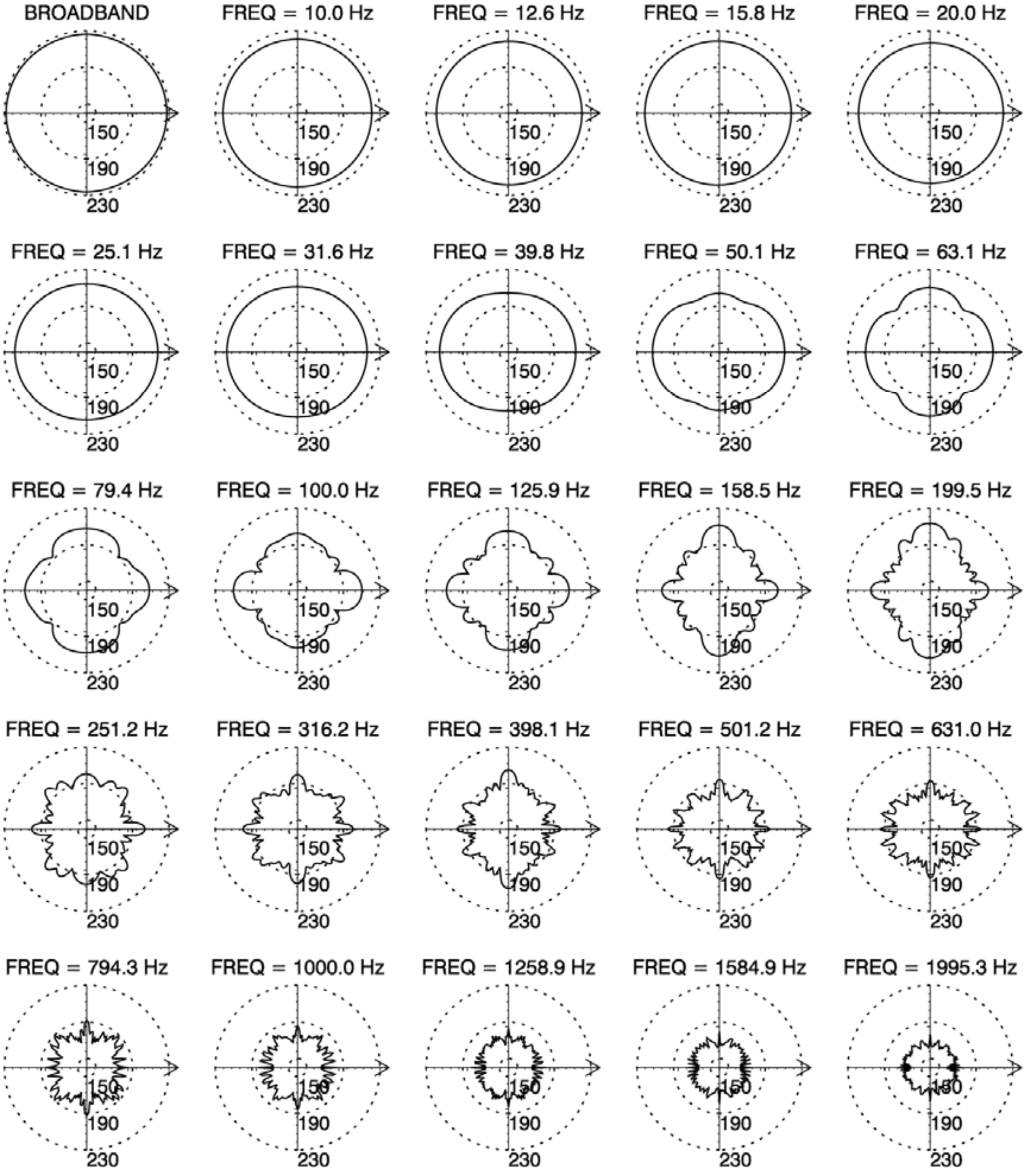


FIGURE B. 10: Directionality of the predicted airgun array source levels (dB re μPa^2 · s) for *Langseth* 2D-Reflection source (4 x 1650 in^3) at 9 m tow depth in third octave bands. Band center frequencies are indicated in the plot annotation.

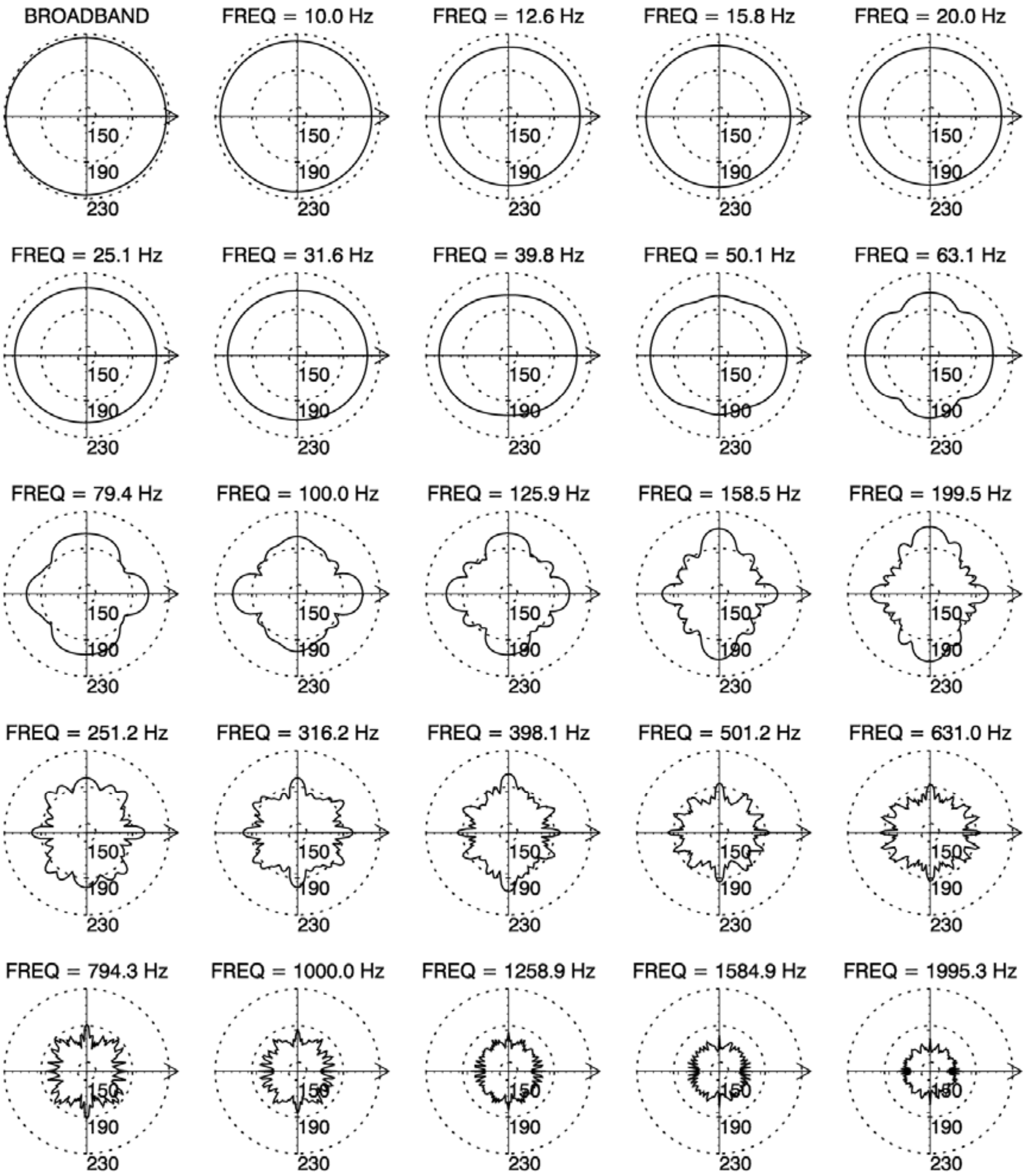


FIGURE B. 11: Directionality of the predicted airgun array source levels (dB re µPa^2 · s) for *Langseth* 2D-Reflection source (4 x 1650 in^3) at 12 m tow depth in third octave bands. Band center frequencies are indicated in the plot annotation.

(i) Annex 2: Source Locations and Study Area

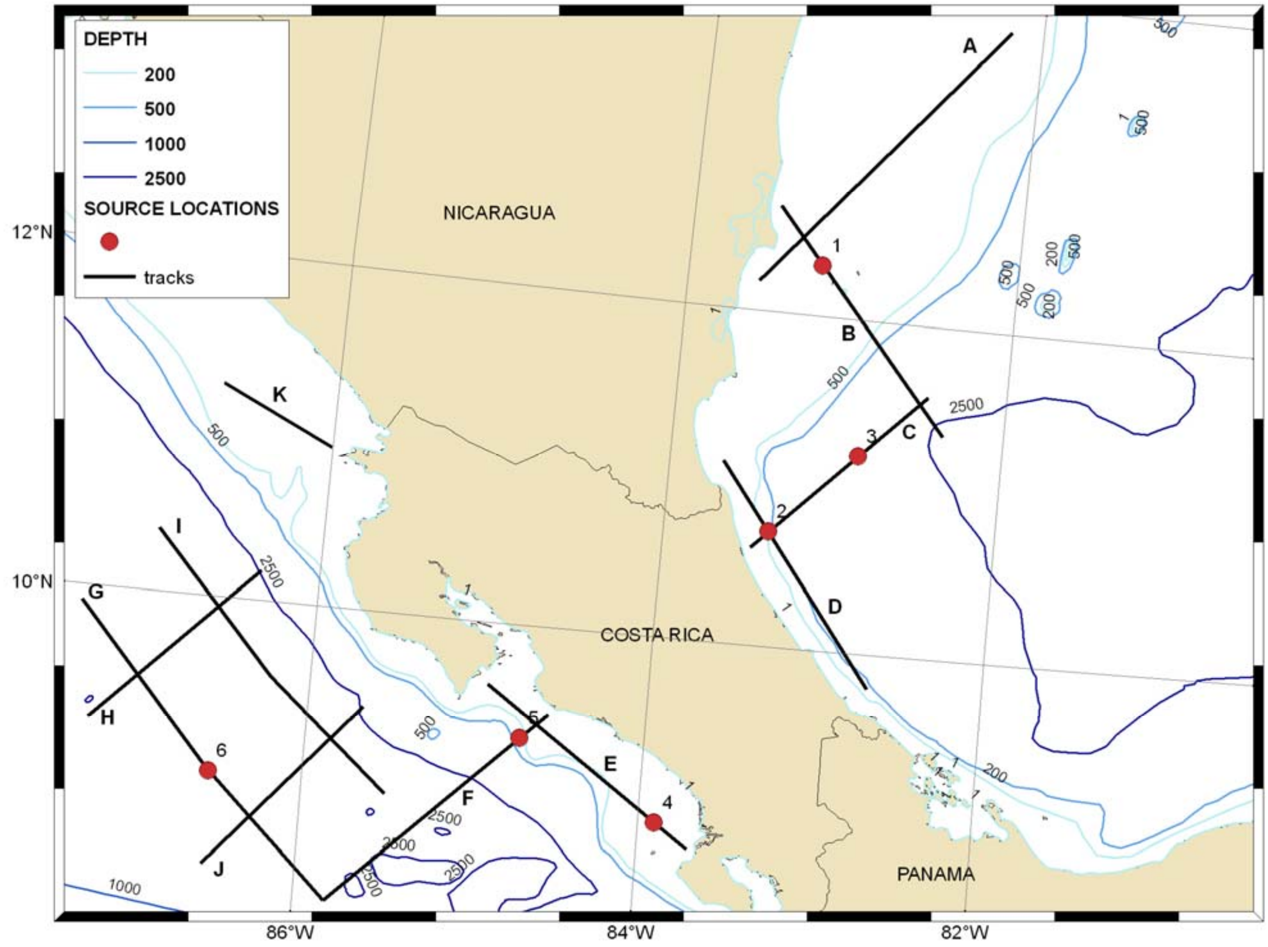
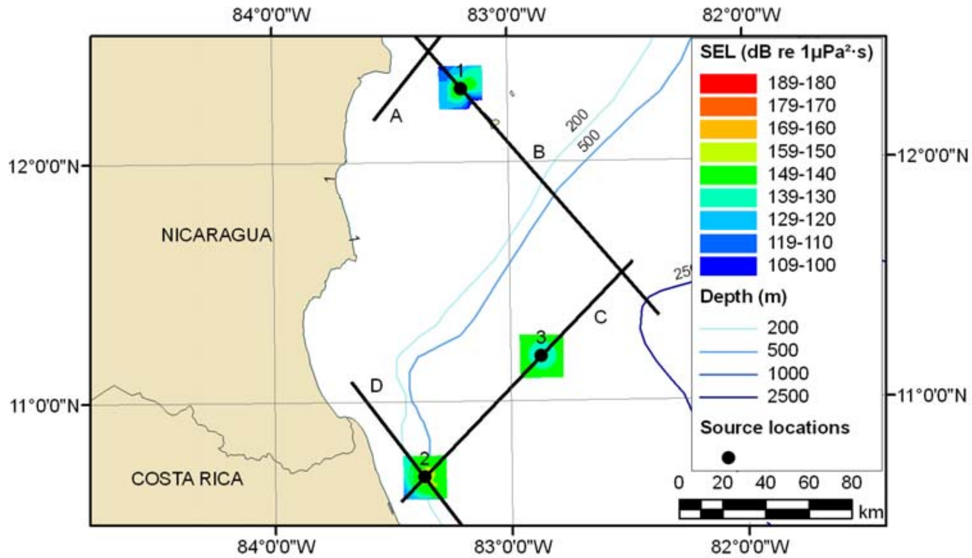


FIGURE B. 12: Previously-planned tracklines A–K and modeled source positions for Caribbean and Pacific (for current plan, see Figure 1 in § I of the EA).

(j) Annex 3: Sound Maps

(a) Eastern Sites



(b) Western Sites

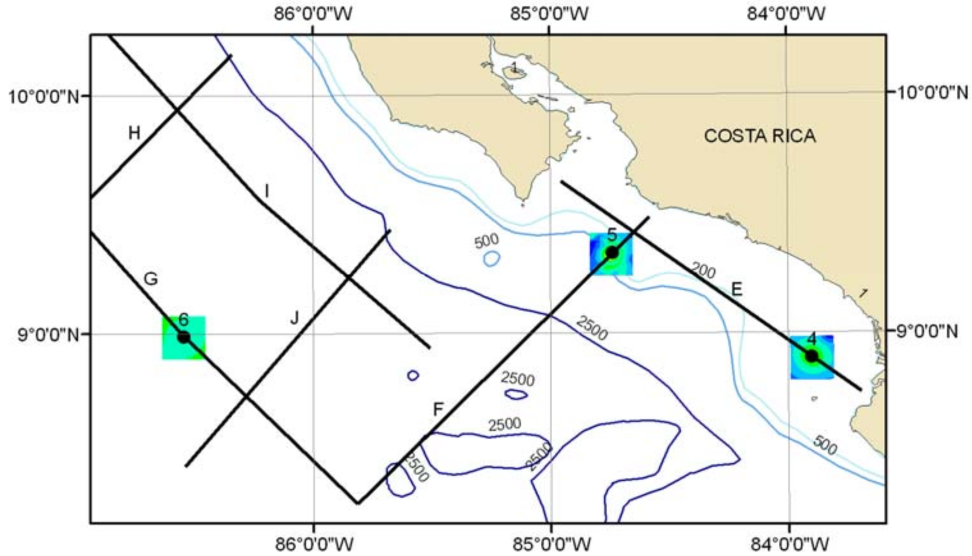


FIGURE B. 13: Overview of predicted received sound exposure level (dB re μPa^2 · s) at 50 m depth if the 36-airgun array were operating at 9-m depth at 6 modeled locations. Received rms levels would be ~10 dB higher than shown here.

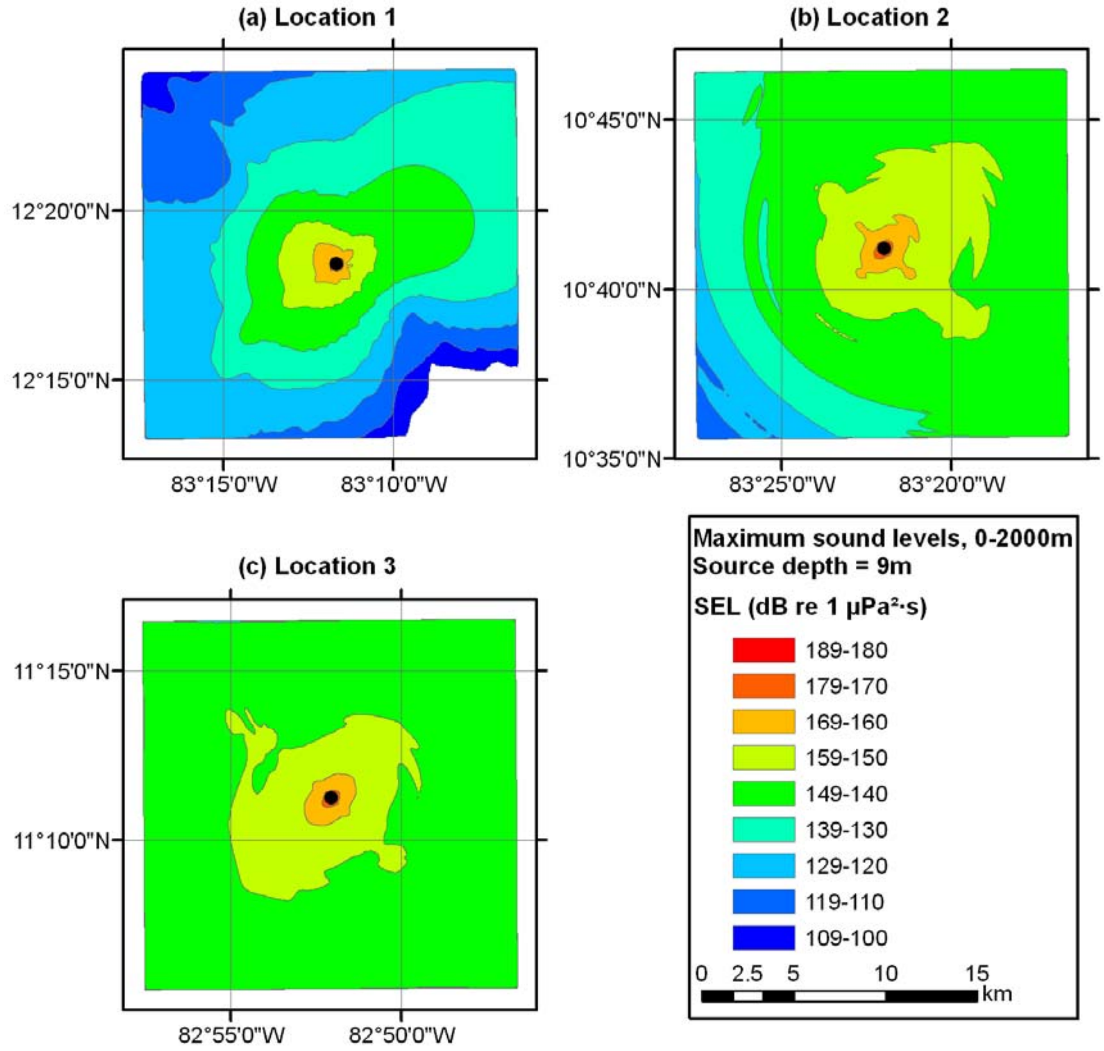


FIGURE B. 14: Predicted maximum sound exposure levels (dB re $\mu Pa^2 \cdot s$) in the water column, between near-surface and the shallower of bottom depth or 2000 m, during operations at 9-m depth at modeled locations in the Caribbean Sea. Received rms levels would be ~10 dB higher than shown here.

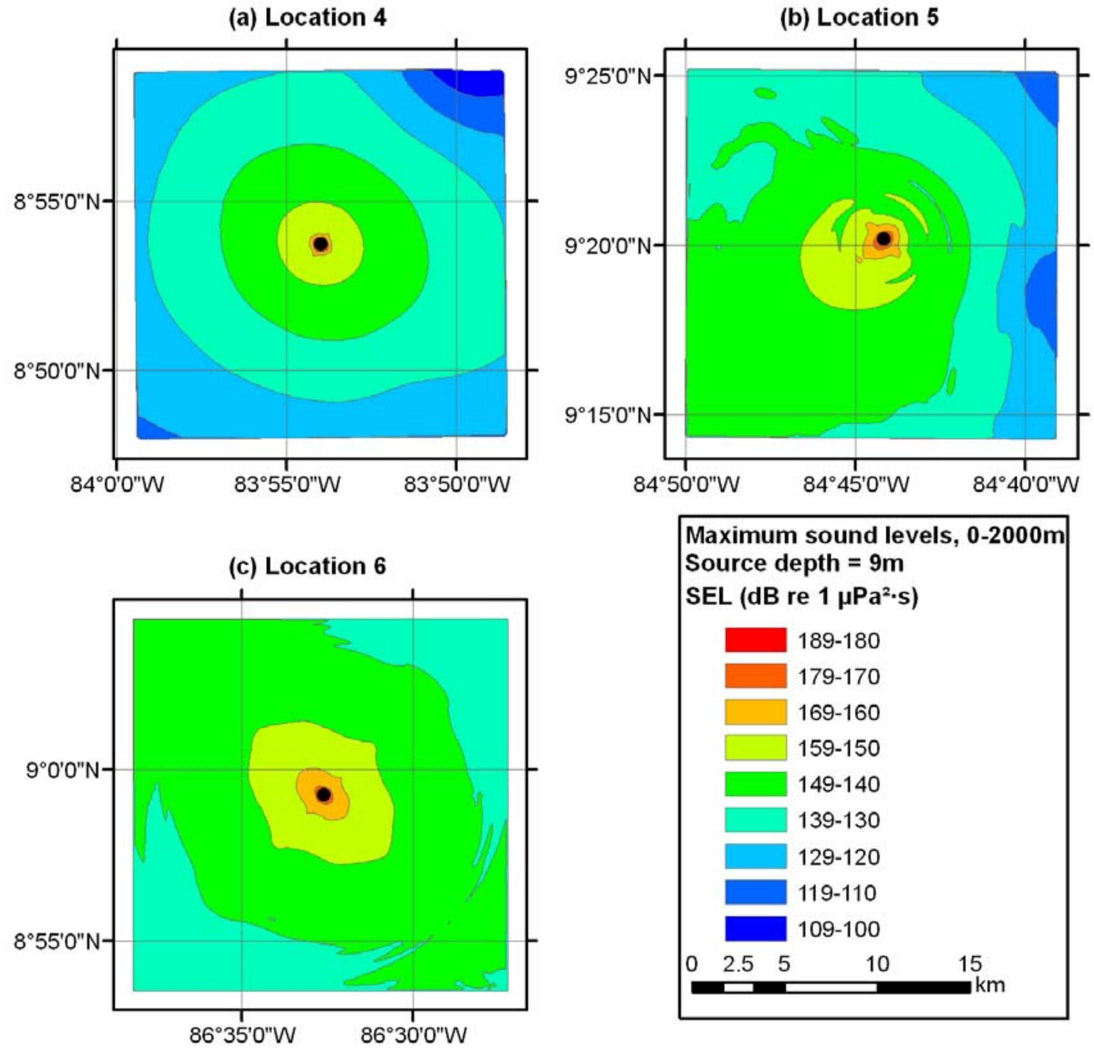


FIGURE B. 15: Predicted maximum sound exposure levels (dB re µPa^2 · s) in the water column, between near-surface and the shallower of bottom depth or 2000 m, during operations at 9-m depth at modeled locations in the Pacific Ocean. Received rms levels would be ~10 dB higher than shown here.

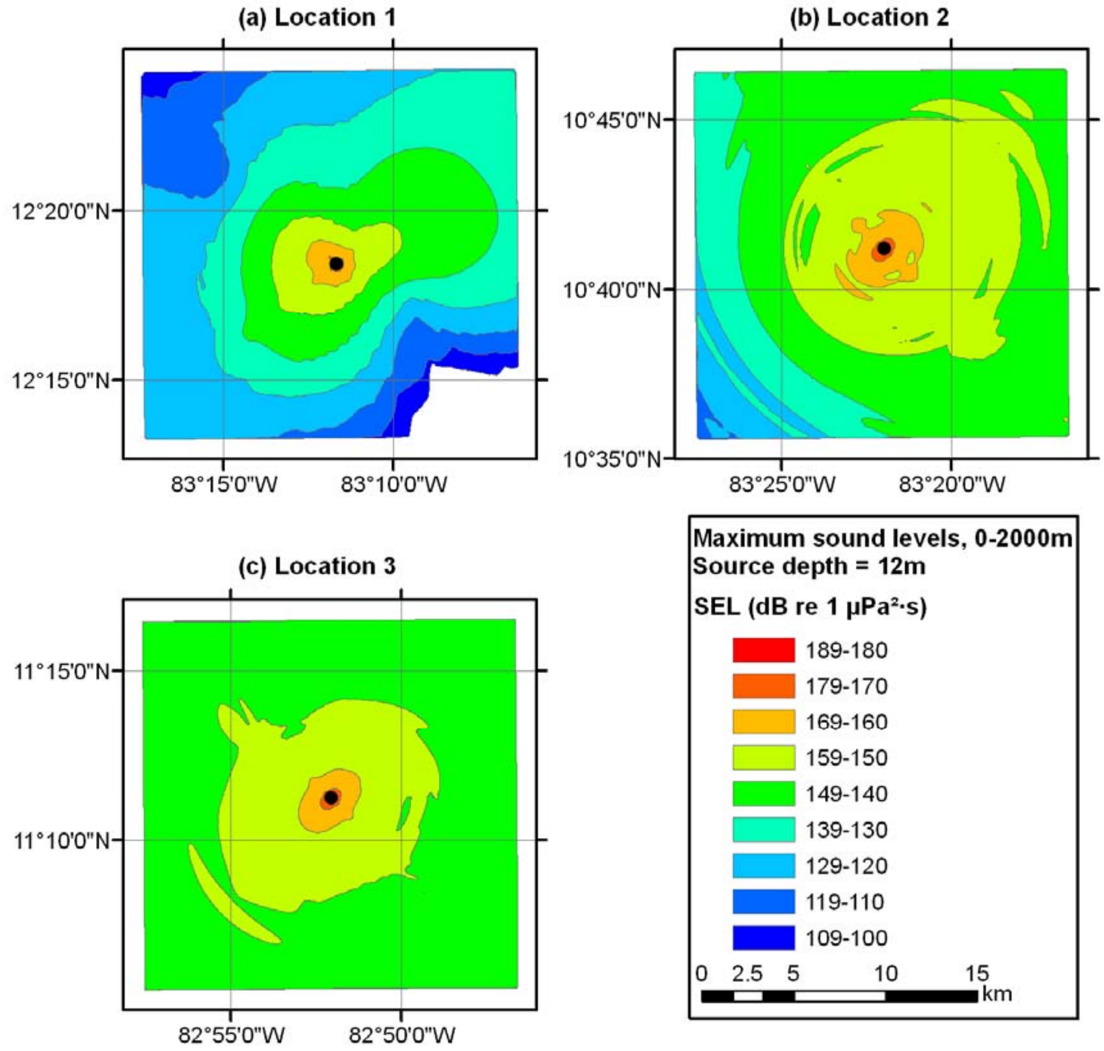


FIGURE B. 16: Predicted maximum sound exposure levels (dB re µPa^2 · s) in the water column, between near-surface and the shallower of bottom depth or 2000 m, during operations at 12-m depth at modeled locations in the Caribbean Sea. Received rms levels would be ~10 dB higher than shown here.

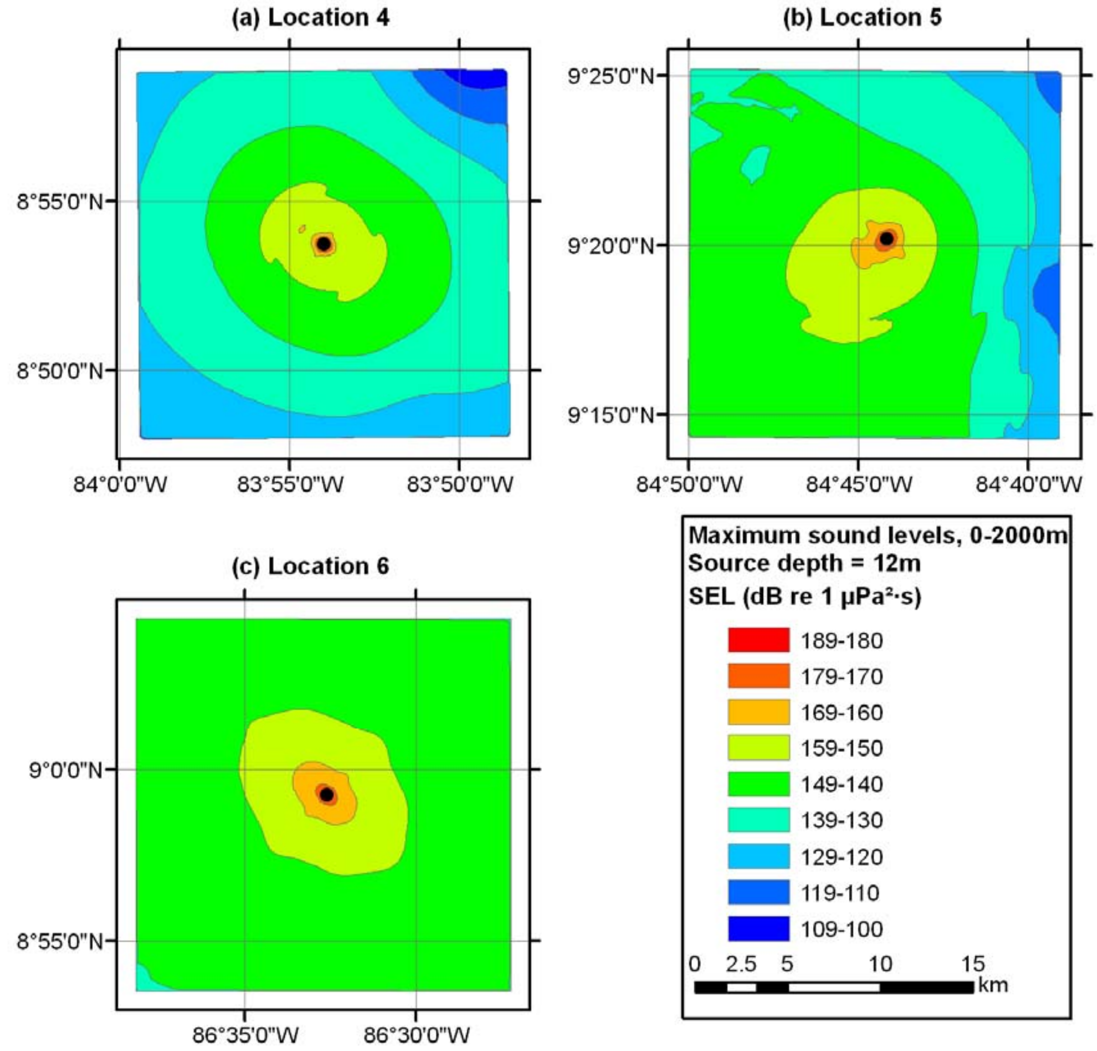


FIGURE B. 17: Predicted maximum sound exposure levels (dB re µPa^2 · s) in the water column, between near-surface and the shallower of bottom depth or 2000 m, during operations at 12-m depth at modeled locations in the Pacific Ocean. Received rms levels would be ~10 dB higher than shown here.

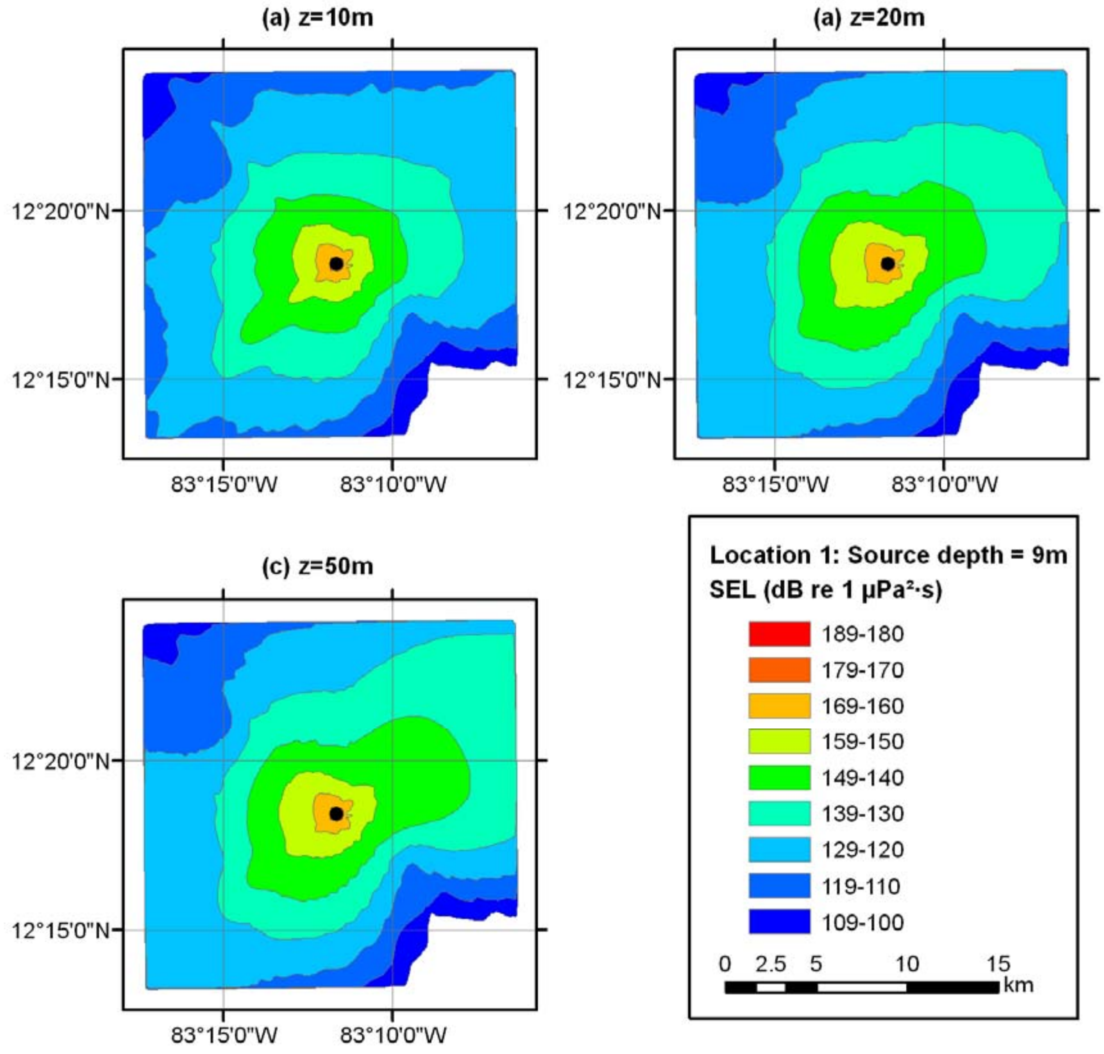


FIGURE B. 18: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at three depths in the water column during operations at 9-m depth at Site 1. Received rms levels would be ~10 dB higher than shown here.

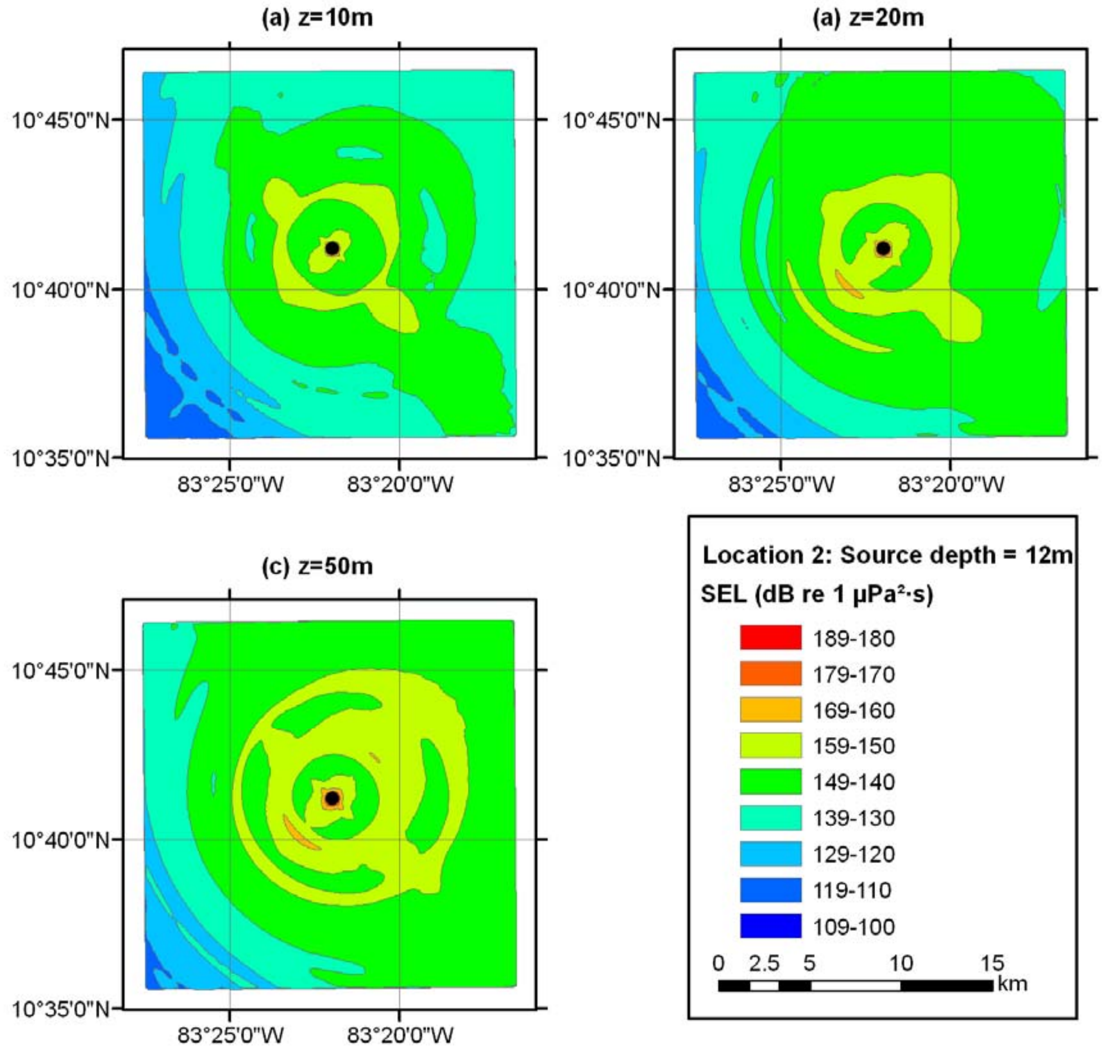


Figure B. 19: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at three depths in the water column during operations at 12-m depth at Site 2. Received rms levels would be ~10 dB higher than shown here.

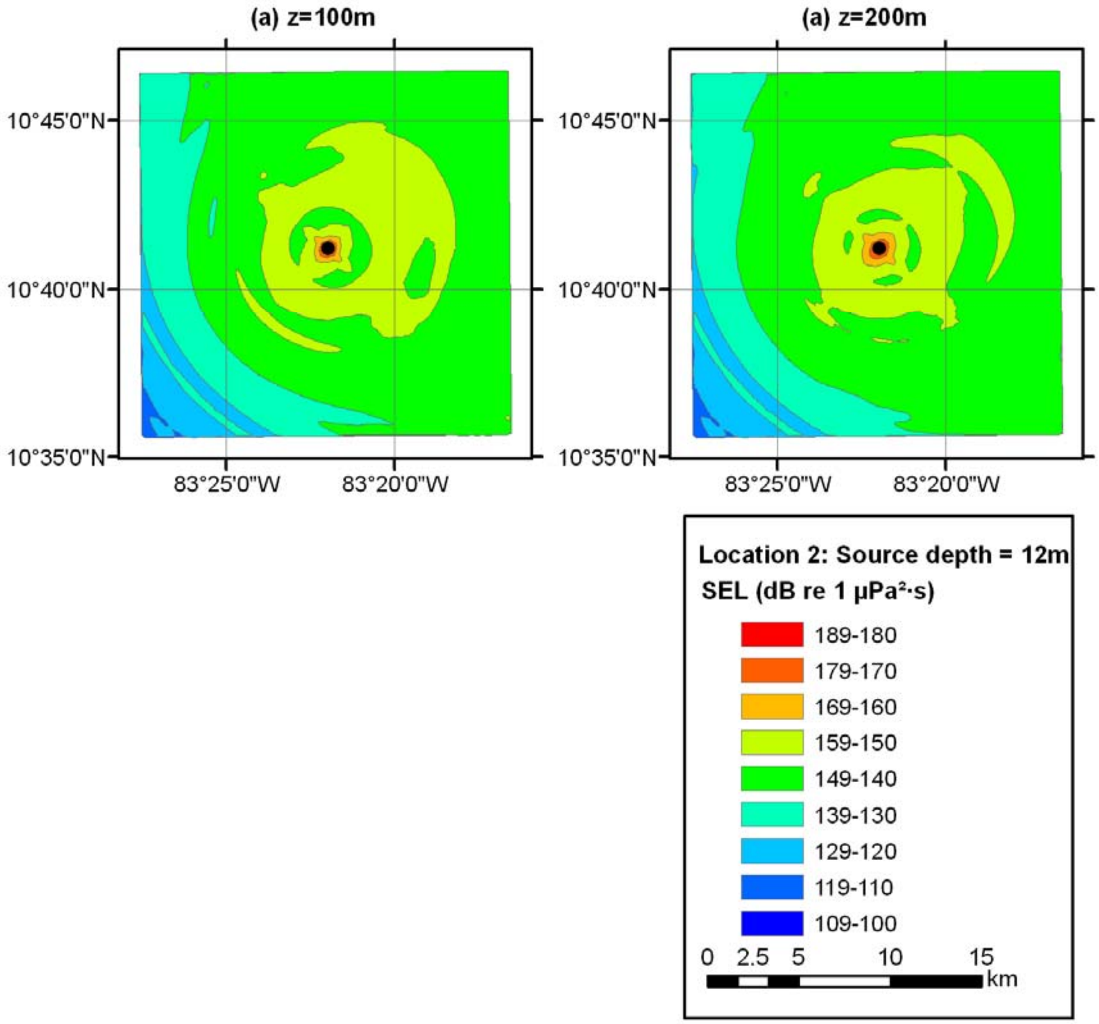


FIGURE B. 20: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at Site 2 (100 and 200 m depths).

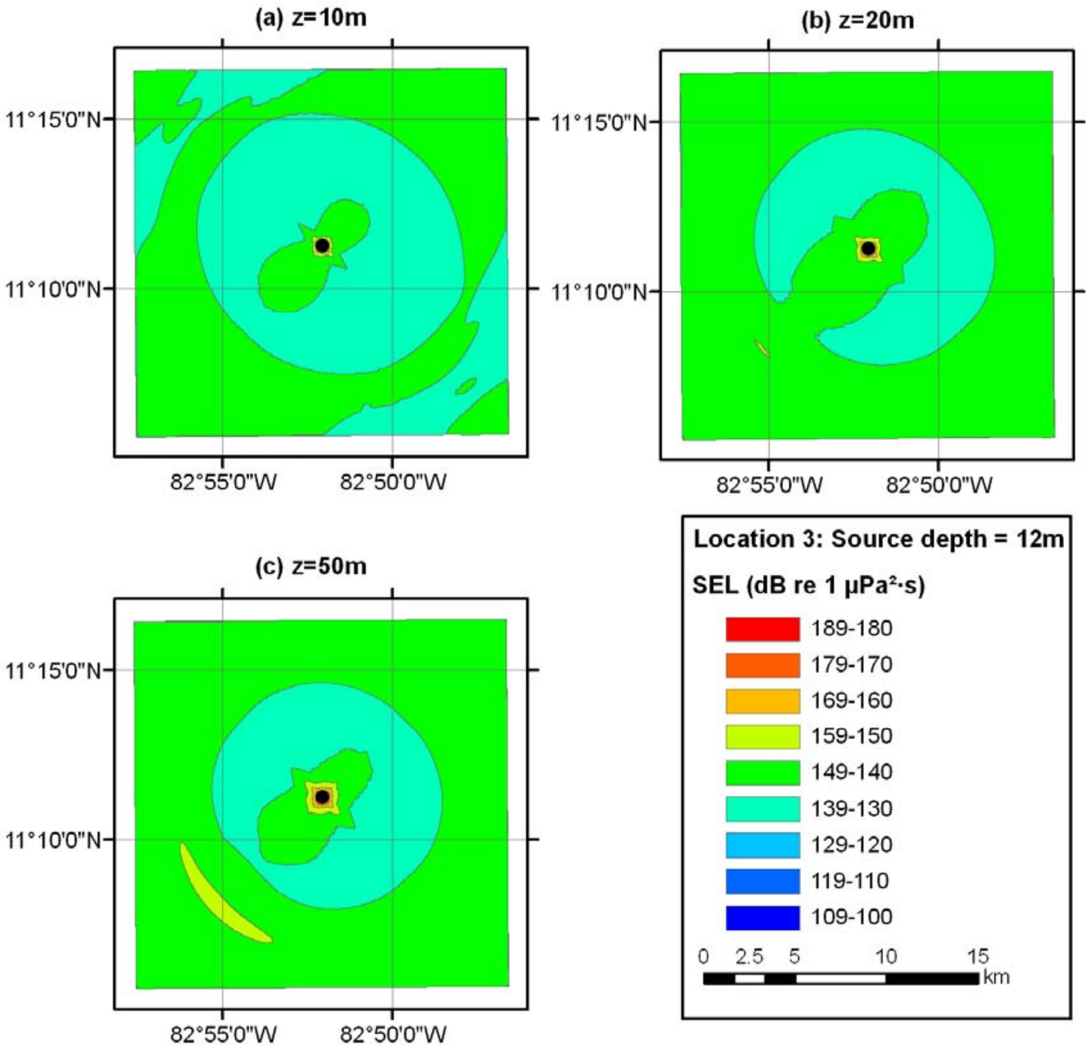


FIGURE B. 21: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at three depths in the water column during operations at 12-m depth at Site 3. Received rms levels would be ~10 dB higher than shown here.

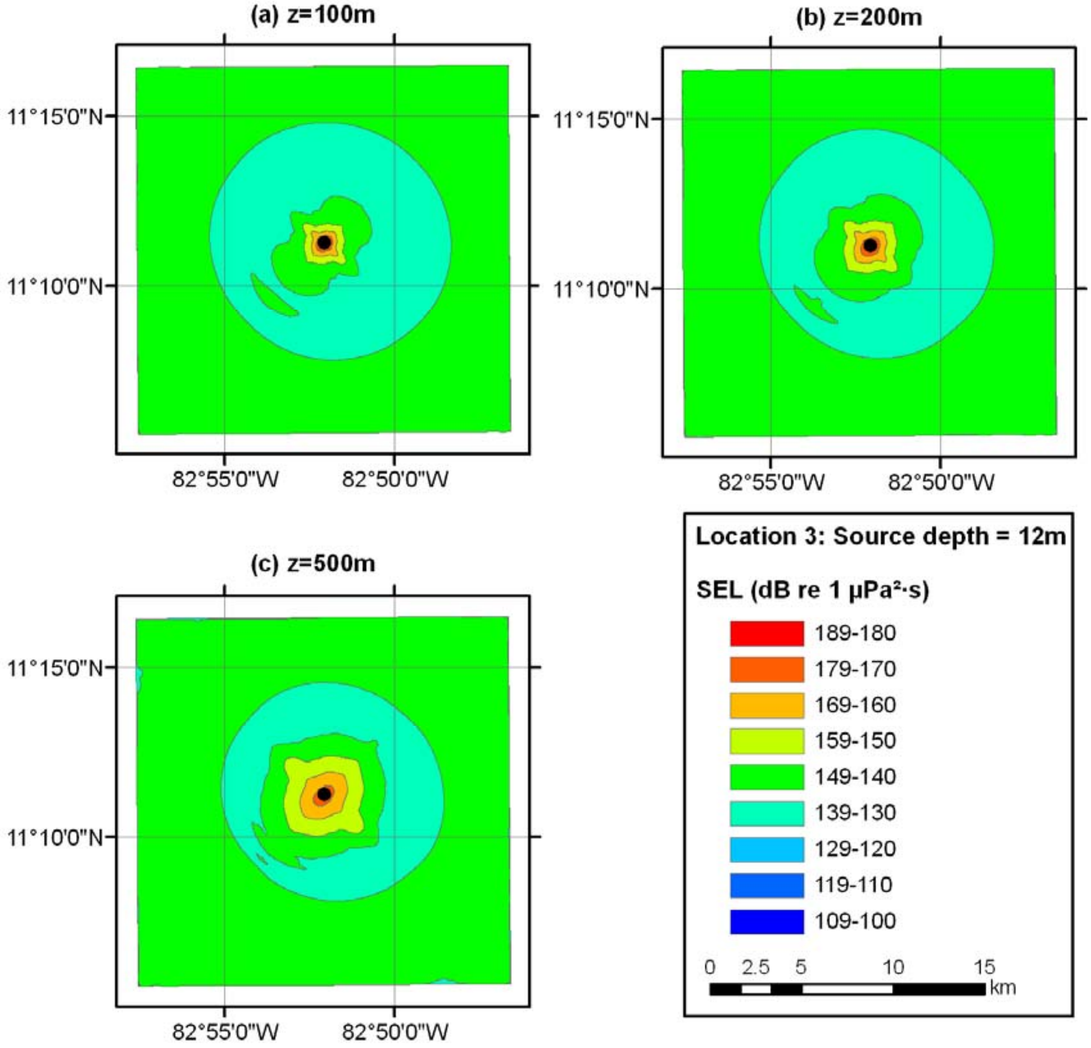


FIGURE B. 22: Predicted sound exposure levels (dB re µPa^2 · s) at Site 3 (100, 200 and 500 m depths).

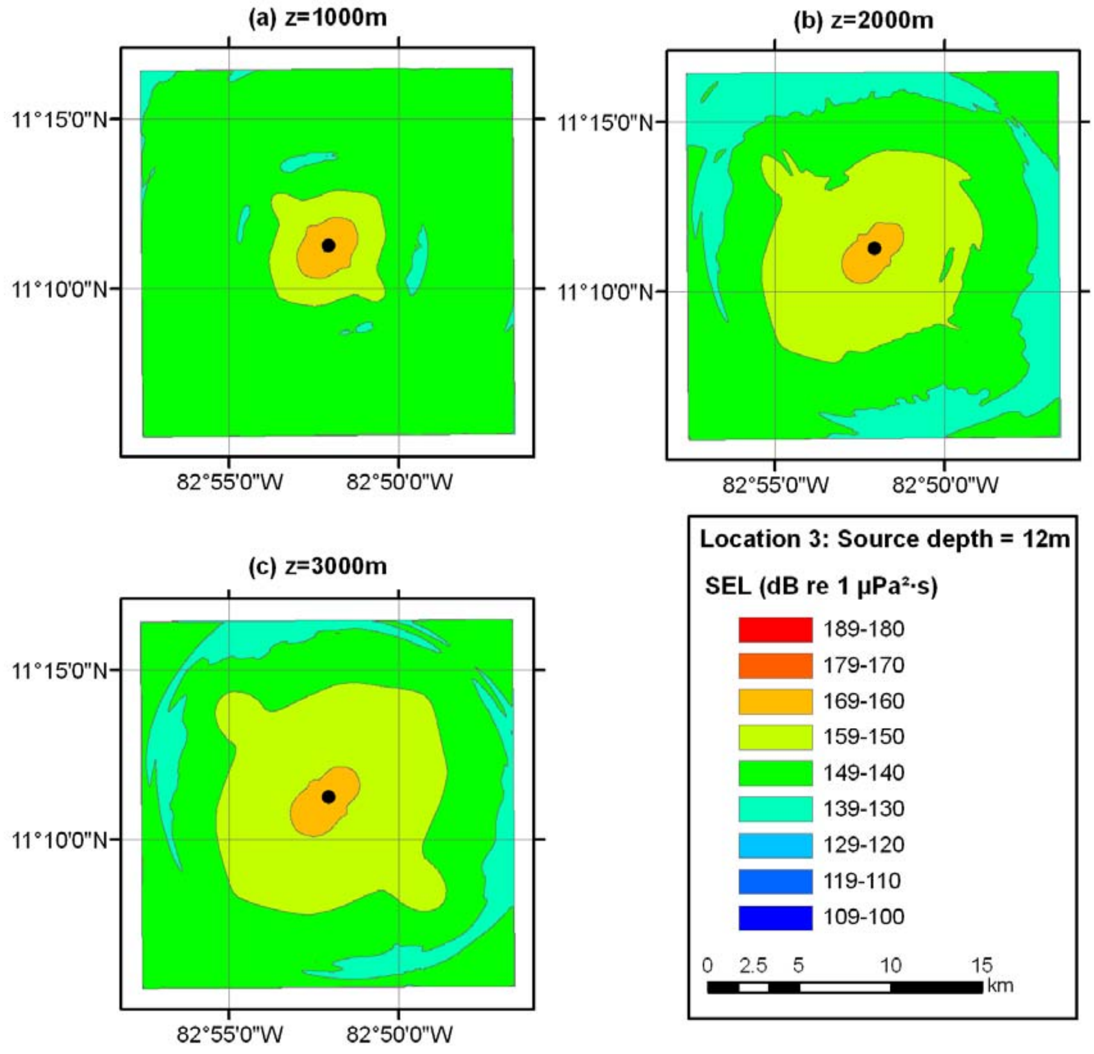


FIGURE B. 23: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at Site 3 (1000, 2000 and 3000 m depths).

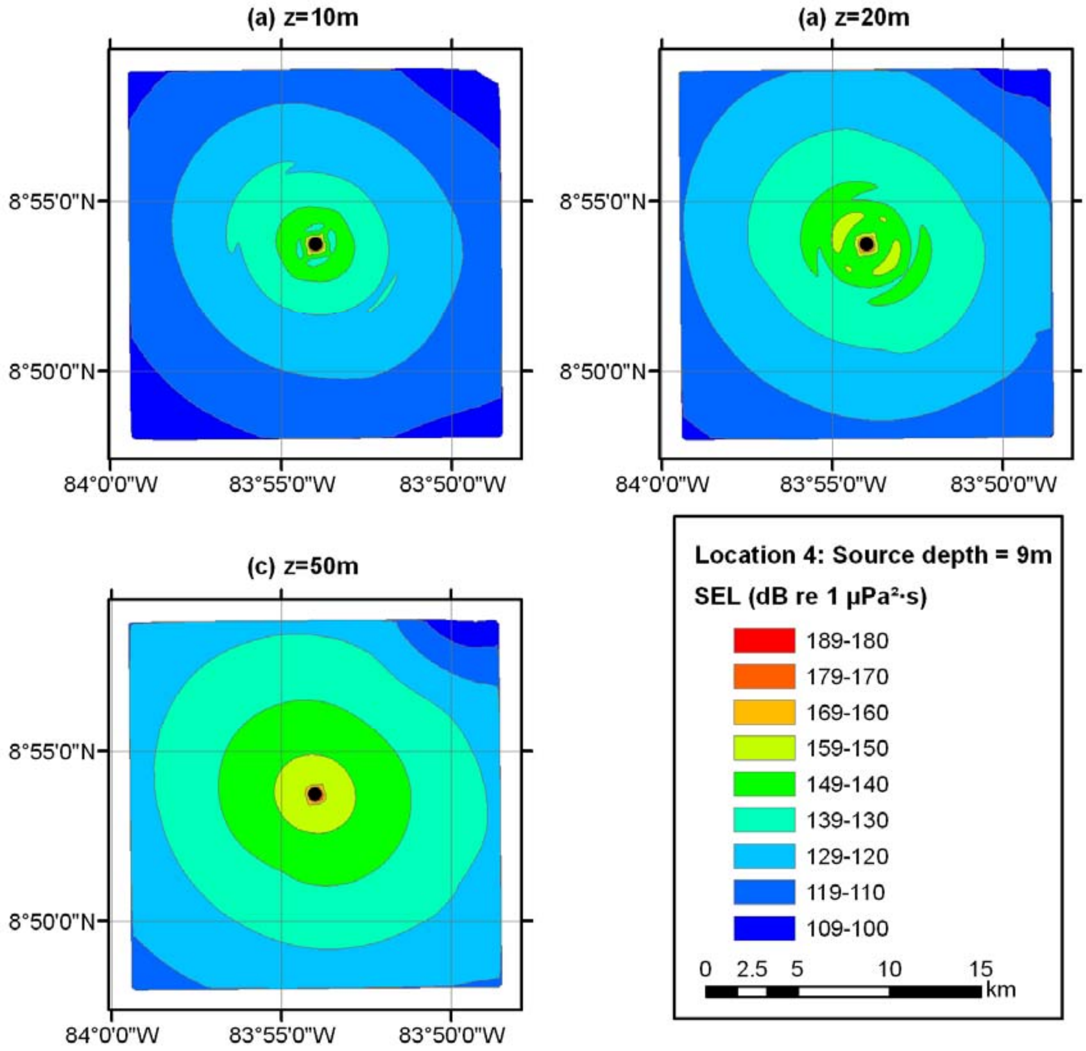


FIGURE B. 24: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at three depths in the water column during operations at 9-m depth at Site 4. Received rms levels would be ~10 dB higher than shown here.

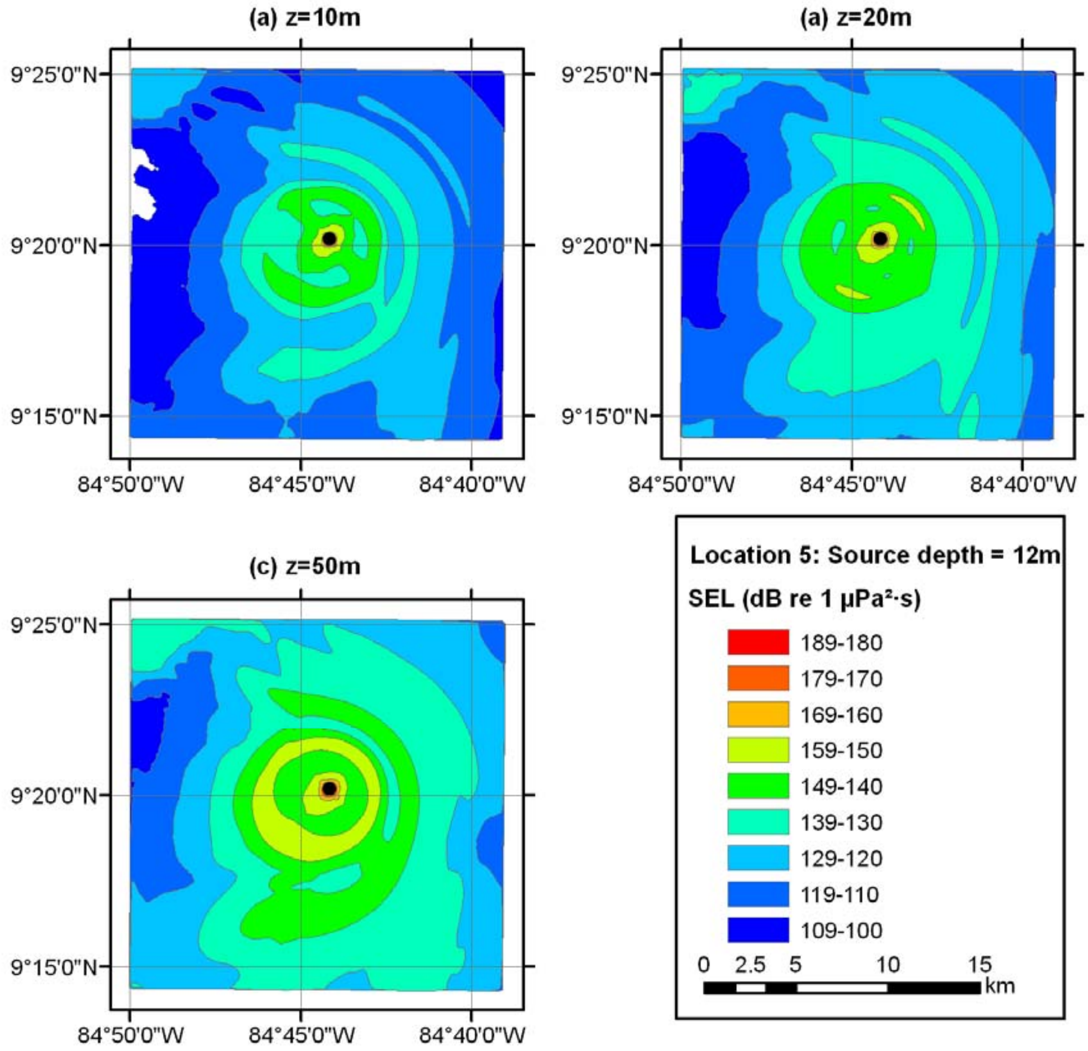


FIGURE B. 25: Predicted sound exposure levels (dB re µPa^2 · s) at three depths in the water column during operations at 12-m depth at Site 5. Received rms levels would be ~10 dB higher than shown here.

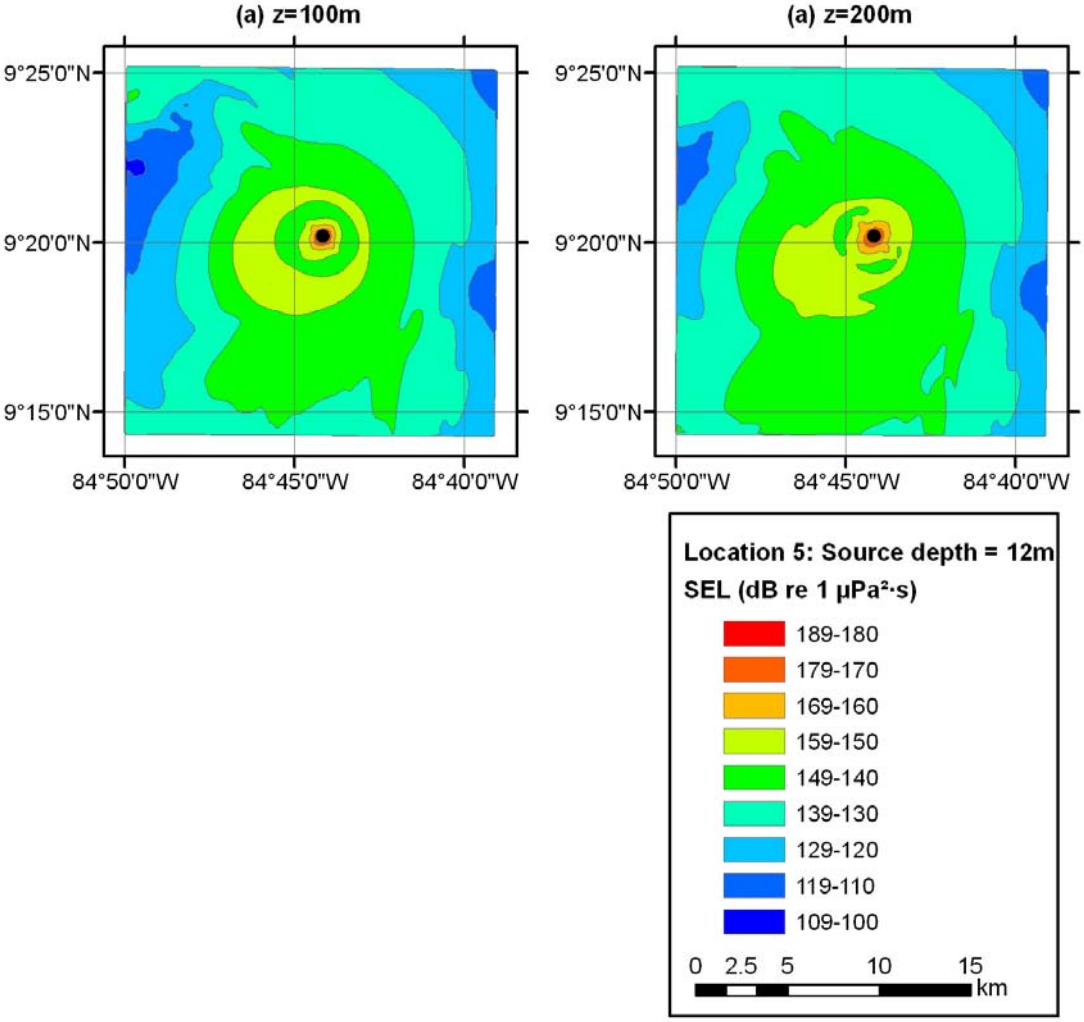


FIGURE B. 26: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at Site 5 (100 and 200 m depths).

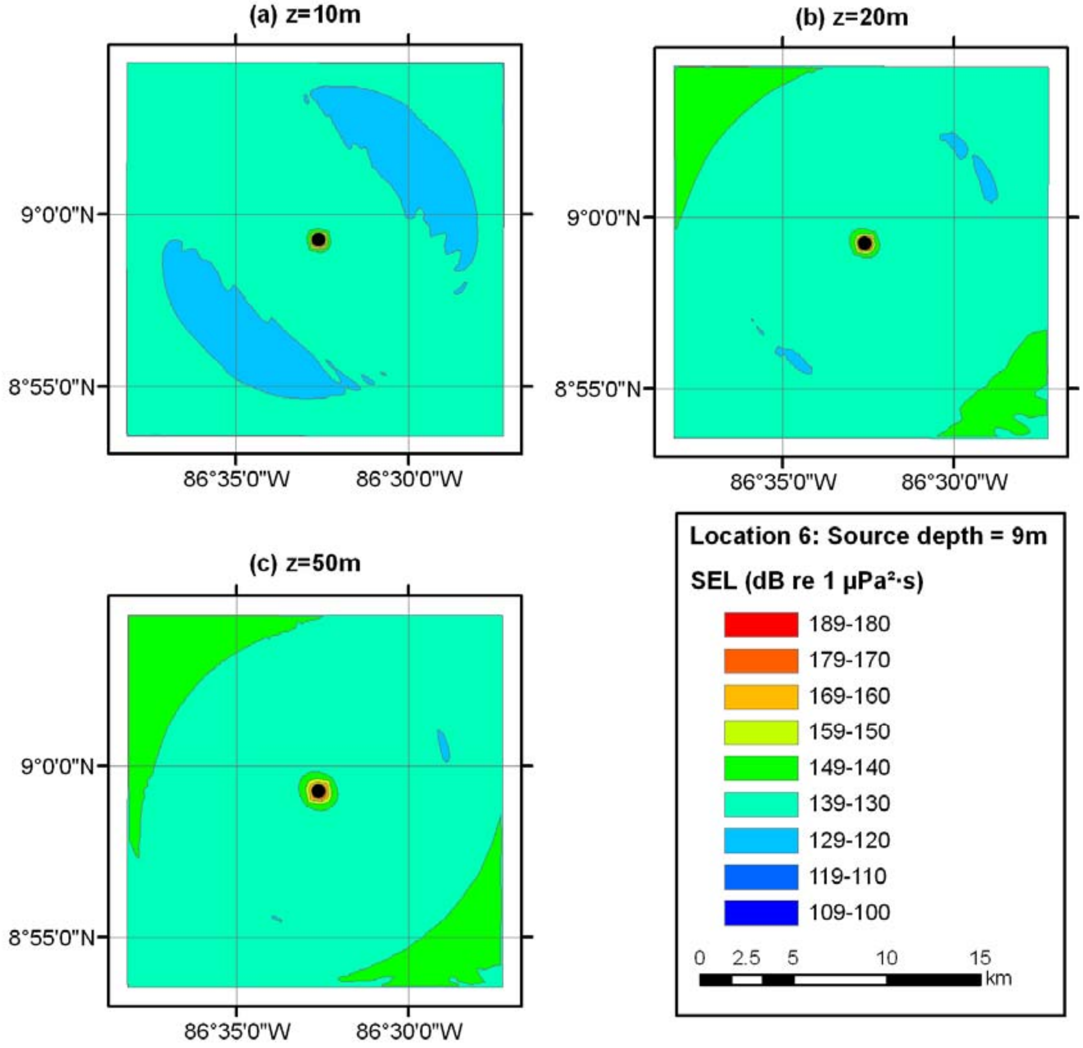


FIGURE B. 27: Predicted sound exposure levels (dB re µPa$^2 \cdot$ s) at three depths in the water column during operations at 9-m depth at Site 6. Received rms levels would be ~10 dB higher than shown here.

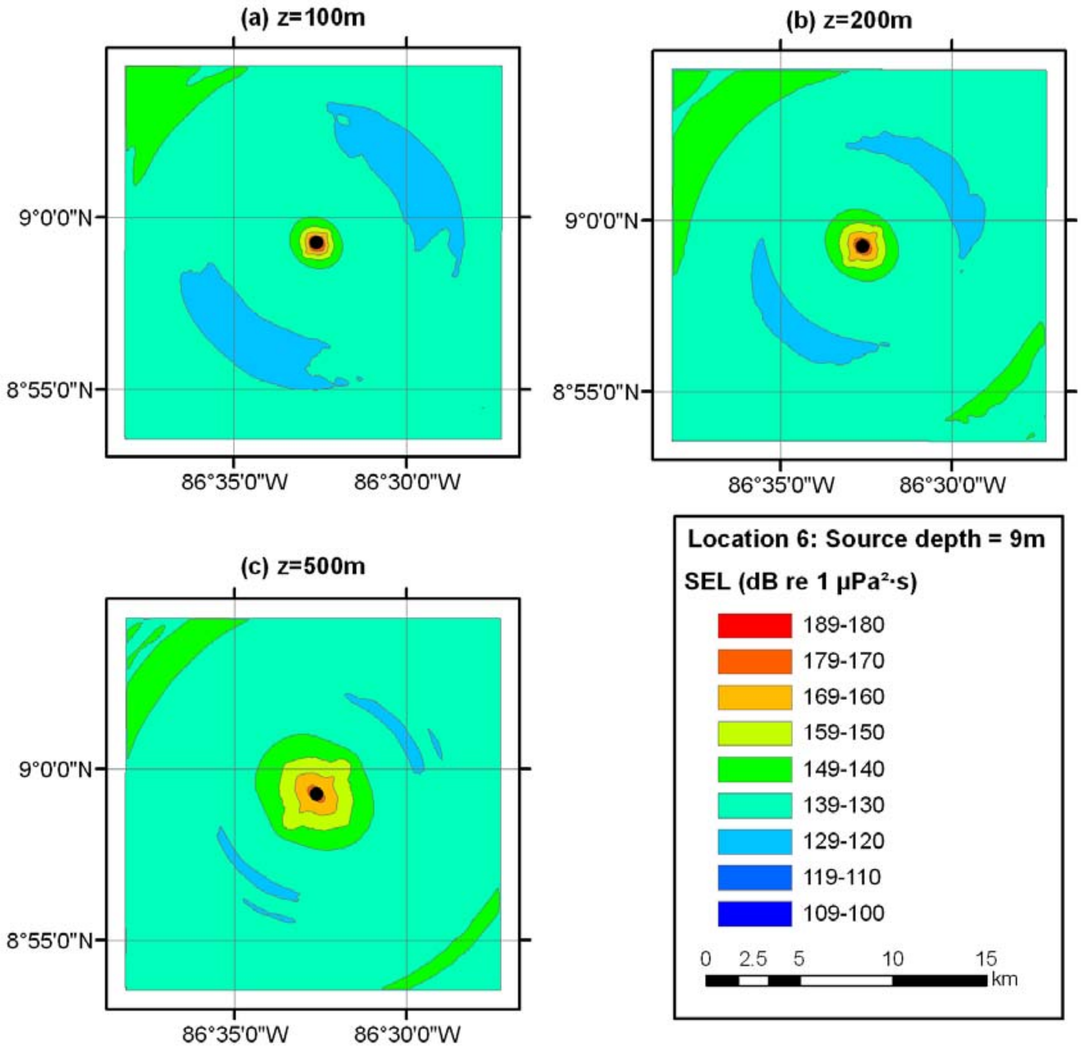


FIGURE B. 28: Predicted sound exposure levels (dB re μPa^2 · s) at Site 6 (100, 200 and 500 m depths).

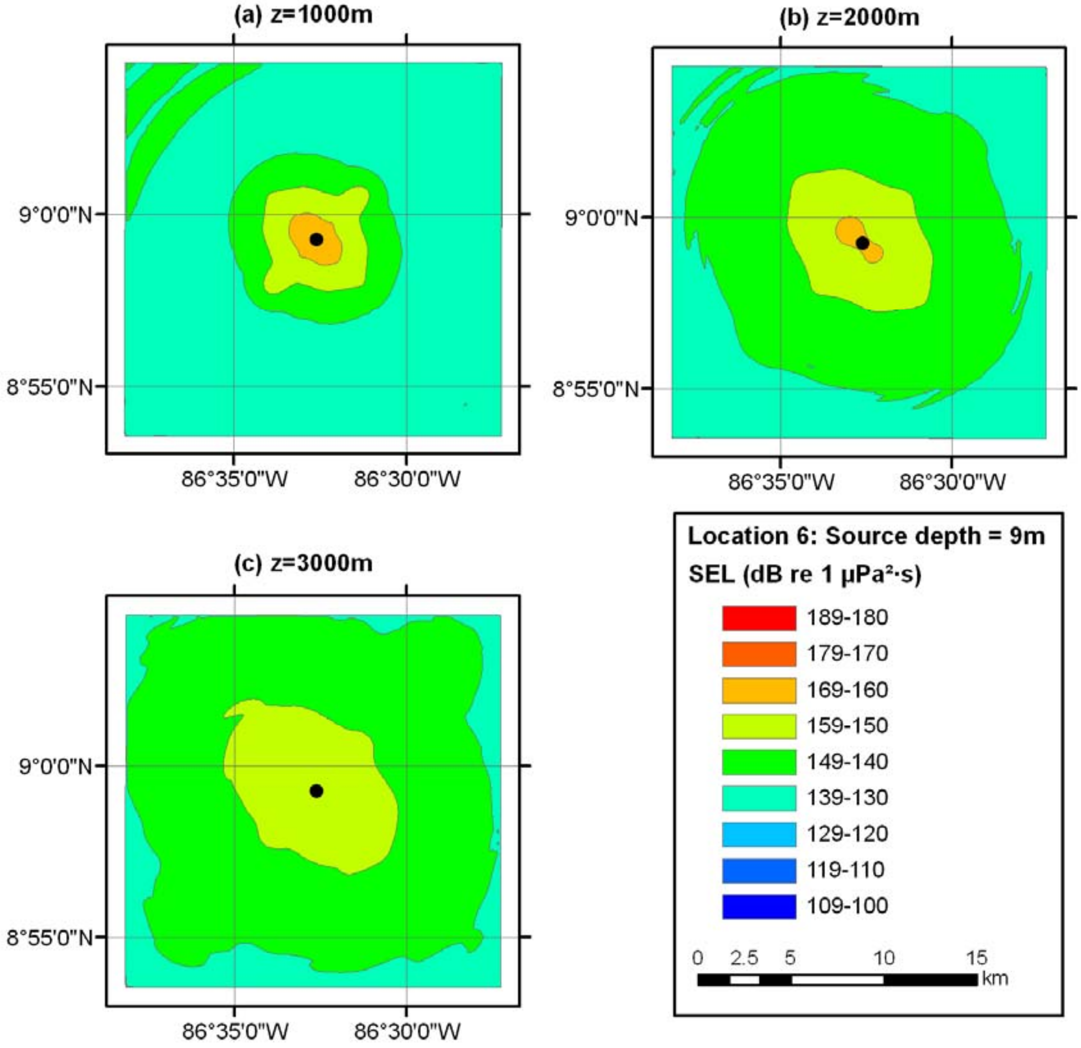


FIGURE B. 29: Predicted sound exposure levels (dB re µPa^2 · s) at Site 6 (1000, 2000 and 3000 m depths).

(k) Annex 4: Predicted ranges to various received levels

The "95% Range" and "Broadside Range" columns consider received levels at depths down to 2000 m below the surface (deep sites) or, for other sites, to the deepest modeled depth.

Array depth = 9m

Site No.1												
Lat	12.3068° N		**Water Depth (m)**	24								
Long	83.1943° W		**Array Depth (m)**	9								
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.254	0.231	0.254	0.254	0.254	n/a					
170	180	0.385	0.471	0.385	0.382	0.382						
160	170	1.302	1.459	1.208	1.302	1.302						
150	160	3.000	3.627	2.476	3.000	2.958						

Site No. 2												
Lat	10.6865° N		**Water Depth (m)**	482								
Long	83.3664° W		**Array Depth (m)**	9								
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.292	0.272	0.182	0.261	0.292	0.277	0.196	n/a			
170	180	0.496	0.456	0.338	0.369	0.404	0.441	0.496				
160	170	0.933	2.253	0.412	0.480	0.611	0.749	0.933				
150	160	6.744	7.051	5.168	5.634	5.997	6.256	6.744				

Site No. 3

Lat	11.1874° N	**Water Depth (m)**	2040
Long	82.8676° W	**Array Depth (m)**	9

SEL	SPL_{rms}	95% Range (km)	Broadside Range (km)	95% Range (km) at Receiver Depth (m)								
				10	20	50	100	200	500	1000	2000	3000
180	190	0.310	0.321	0.310	0.307	0.297	0.280	0.231	0.181	0.115		
170	180	0.525	0.449	0.335	0.348	0.383	0.427	0.485	0.525	0.285	0.256	0.260
160	170	1.556	1.271	0.384	0.451	0.583	0.724	0.908	1.199	1.510	1.556	1.760
150	160	5.843	7.382	0.560	0.723	0.937	1.164	1.487	2.222	3.196	5.843	6.416

Site No. 4

Lat	8.8953° N	**Water Depth (m)**	65
Long	83.9000° W	**Array Depth (m)**	9

SEL	SPL_{rms}	95% Range (km)	Broadside Range (km)	95% Range (km) at Receiver Depth (m)								
				10	20	50	100	200	500	1000	2000	3000
180	190	0.288	0.273	0.181	0.261	0.288	n/a					
170	180	0.400	0.455	0.339	0.368	0.400						
160	170	0.567	0.711	0.415	0.466	0.567						
150	160	2.121	2.281	0.591	1.881	2.121						

Site No. 5													
Lat	9.3361° N	**Water Depth (m)**	340										
Long	84.7361° W	**Array Depth (m)**	9										
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**									
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.295	0.270	0.170	0.251	0.295	0.279	0.207	n/a			
170	180	0.500	0.483	0.338	0.367	0.398	0.439	0.500				
160	170	0.896	1.290	0.415	0.468	0.562	0.684	0.896				
150	160	4.511	3.803	0.886	1.125	3.976	4.511	3.754				

Site No. 6													
Lat	8.9874° N	**Water Depth (m)**	3100										
Long	86.5433° W	**Array Depth (m)**	9										
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**									
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.290	0.268	0.180	0.255	0.290	0.273	0.189				
170	180	0.533	0.465	0.336	0.363	0.396	0.437	0.494	0.533	0.227		
160	170	1.561	1.319	0.398	0.438	0.528	0.662	0.884	1.220	1.516	1.561	0.368
150	160	4.169	3.809	0.485	0.556	0.706	0.919	1.280	2.133	3.231	4.169	5.050

Array depth = 12 m

Site No. 1

Lat	12.3068° N	**Water Depth (m)**	24
Long	83.1943° W	**Array Depth (m)**	12

SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.273	0.259	0.272	0.273	0.273	n/a					
170	180	0.441	0.459	0.427	0.441	0.441						
160	170	1.550	1.639	1.303	1.550	1.550						
150	160	3.370	3.827	2.654	3.311	3.370						

Site No. 2

Lat	10.6865° N	**Water Depth (m)**	482
Long	83.3664° W	**Array Depth (m)**	12

SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.314	0.303	0.220	0.286	0.314	0.305	0.248	n/a			
170	180	0.554	0.521	0.352	0.380	0.424	0.476	0.554				
160	170	2.964	2.38	0.437	2.964	2.950	0.825	1.020				
150	160	7.472	13.68	5.237	5.767	7.472	6.827	7.210				

Site No. 3

Lat	11.1874º N	**Water Depth (m)**	2040
Long	82.8676º W	**Array Depth (m)**	12

SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.317	0.323	0.315	0.317	0.307	0.298	0.259	0.200	0.150	0.101	0.118
170	180	0.620	0.493	0.340	0.359	0.405	0.462	0.541	0.620	0.312	0.270	0.276
160	170	1.871	1.535	0.407	0.491	0.643	0.793	0.990	1.355	1.744	1.871	2.155
150	160	8.503	7.866	0.630	7.893	8.503	1.271	1.615	2.398	3.468	6.326	6.936

Site No. 4

Lat	8.8953º N	**Water Depth (m)**	65
Long	83.9000º W	**Array Depth (m)**	12

SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.310	0.308	0.225	0.286	0.310	n/a					
170	180	0.422	0.471	0.353	0.381	0.422						
160	170	0.617	0.772	0.439	0.499	0.617						
150	160	3.216	2.642	1.764	1.960	3.216						

Site No. 5												
Lat	9.3361° N	**Water Depth (m)**	340									
Long	84.7631° W	**Array Depth (m)**	12									
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.315	0.299	0.218	0.282	0.315	0.302	0.251	n/a			
170	180	0.556	0.555	0.351	0.379	0.419	0.470	0.556				
160	170	0.980	1.446	0.440	0.519	0.608	0.743	0.980				
150	160	5.382	4.265	0.965	3.376	4.071	4.696	5.382				

Site No. 6												
Lat	8.9874° N	**Water Depth (m)**	3100									
Long	86.5433° W	**Array Depth (m)**	12									
SEL	**SPL$_{rms}$**	**95% Range (km)**	**Broadside Range (km)**	**95% Range (km) at Receiver Depth (m)**								
				10	**20**	**50**	**100**	**200**	**500**	**1000**	**2000**	**3000**
180	190	0.315	0.296	0.222	0.284	0.315	0.304	0.244				
170	180	0.634	0.514	0.348	0.376	0.414	0.468	0.551	0.634			
160	170	1.920	1.526	0.411	0.459	0.565	0.712	0.964	1.365	1.754	1.920	1.330
150	160	4.773	4.194	0.512	0.593	0.760	0.995	1.391	2.304	3.515	4.773	6.662

APPENDIX C:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON MARINE MAMMALS [6]

The following subsections review relevant information concerning the potential effects of airgun sounds on marine mammals. This information is included here as background for the briefer summary of this topic included in § IV of the EA. This background material is little changed from corresponding subsections included in IHA applications and EAs submitted to NMFS for previous NSF funded seismic surveys from 2003 to date. Much of this information has also been included in varying formats in other reviews, assessments, and regulatory applications prepared by LGL Ltd., environmental research associates. Because this review is intended to be of general usefulness, it includes references to types of marine mammals that will not be found in some specific regions.

(a) Categories of Noise Effects

The effects of noise on marine mammals are highly variable, and can be categorized as follows (based on Richardson et al. 1995):

1. The noise may be too weak to be heard at the location of the animal, i.e., lower than the prevailing ambient noise level, the hearing threshold of the animal at relevant frequencies, or both;
2. The noise may be audible but not strong enough to elicit any overt behavioral response, i.e., the mammals may tolerate it;
3. The noise may elicit behavioral reactions of variable conspicuousness and variable relevance to the well being of the animal; these can range from subtle effects on respiration or other behaviors (detectable only by statistical analysis) to active avoidance reactions;
4. Upon repeated exposure, animals may exhibit diminishing responsiveness (habituation), or disturbance effects may persist; the latter is most likely with sounds that are highly variable in characteristics, unpredictable in occurrence, and associated with situations that the animal perceives as a threat;
5. Any man-made noise that is strong enough to be heard has the potential to reduce (mask) the ability of marine mammals to hear natural sounds at similar frequencies, including calls from conspecifics, echolocation sounds of odontocetes, and environmental sounds such as surf noise or (at high latitudes) ice noise. However, intermittent airgun or echosounder pulses could cause masking for only a small proportion of the time, given the short duration of these pulses relative to the inter-pulse intervals;
6. Very strong sounds have the potential to cause temporary or permanent reduction in hearing sensitivity, or other physical effects. Received sound levels must far exceed the animal's hearing threshold for any temporary threshold shift to occur. Received levels must be even higher for a risk of permanent hearing impairment.

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(b) Hearing Abilities of Marine Mammals

The hearing abilities of marine mammals are functions of the following (Richardson et al. 1995; Au et al. 2000):

1. Absolute hearing threshold at the frequency in question (the level of sound barely audible in the absence of ambient noise). The "best frequency" is the frequency with the lowest absolute threshold.
2. Critical ratio (the signal-to-noise ratio required to detect a sound at a specific frequency in the presence of background noise around that frequency).
3. The ability to localize sound direction at the frequencies under consideration.
4. The ability to discriminate among sounds of different frequencies and intensities.

Marine mammals rely heavily on the use of underwater sounds to communicate and to gain information about their surroundings. Experiments also show that they hear and may react to many man-made sounds including sounds made during seismic exploration.

Baleen Whales (Mysticetes)

The hearing abilities of baleen whales have not been studied directly. Behavioral and anatomical evidence indicates that they hear well at frequencies below 1 kHz (Richardson et al. 1995; Ketten 2000). Baleen whales also reacted to sonar sounds at 3.1 kHz and other sources centered at 4 kHz (see Richardson et al. 1995 for a review). Frankel (2005) noted that gray whales reacted to a 21–25 kHz whale-finding sonar. Some baleen whales react to pinger sounds up to 28 kHz, but not to pingers or sonars emitting sounds at 36 kHz or above (Watkins 1986). In addition, baleen whales produce sounds at frequencies up to 8 kHz and, for humpbacks, to >15 kHz (Au et al. 2001). The anatomy of the baleen whale inner ear seems to be well adapted for detection of low-frequency sounds (Ketten 1991, 1992, 1994, 2000). The absolute sound levels that they can detect below 1 kHz are probably limited by increasing levels of natural ambient noise at decreasing frequencies. Ambient noise energy is higher at low frequencies than at mid frequencies. At frequencies below 1 kHz, natural ambient levels tend to increase with decreasing frequency.

The hearing systems of baleen whales are undoubtedly more sensitive to low-frequency sounds than are the ears of the small toothed whales that have been studied directly. Thus, baleen whales are likely to hear airgun pulses farther away than can small toothed whales and, at closer distances, airgun sounds may seem more prominent to baleen than to toothed whales. However, baleen whales have commonly been seen well within the distances where seismic (or other sound sources) sounds would be detectable and yet often show no overt reaction to those sounds. Behavioral responses by baleen whales to seismic pulses have been documented, but received levels of pulsed sounds necessary to elicit behavioral reactions are typically well above the minimum detectable levels (Malme et al. 1984, 1988; Richardson et al. 1986, 1995; McCauley et al. 2000a; Johnson et al. 2007).

Toothed Whales (Odontocetes)

Hearing abilities of some toothed whales (odontocetes) have been studied in detail (reviewed in Chapter 8 of Richardson et al. [1995] and in Au et al. [2000]). Hearing sensitivity of several species has been determined as a function of frequency. The small to moderate-sized toothed whales whose hearing has been studied have relatively poor hearing sensitivity at frequencies below 1 kHz, but extremely good sensitivity at, and above, several kHz. There are very few data on the absolute hearing thresholds of most of the larger, deep-diving toothed whales, such as the sperm and beaked whales. However, Mann et al. (2005) and Cook et al. (2006) reported that a Gervais' beaked whale showed evoked potentials from 5 to 80 kHz, with the best sensitivity at 40–80 kHz.

Despite the relatively poor sensitivity of small odontocetes at the low frequencies that contribute most of the energy in pulses of sound from airgun arrays, the sounds are sufficiently strong that their received levels sometimes remain above the hearing thresholds of odontocetes at distances out to several tens of kilometers (Richardson and Würsig 1997). However, there is no evidence that small odontocetes react to airgun pulses at such long distances, or even at intermediate distances where sound levels are well above the ambient noise level (see below).

The multibeam echosounders operated from oceanographic vessels to survey deep areas and sub-bottom profilers emit pulsed sounds at 12–15.5 kHz and 2.5–18 kHz, respectively. Those frequencies are within or near the range of best sensitivity of many odontocetes. Thus, sound pulses from the multibeam echosounder and sub-bottom profiler will be readily audible to these animals when they are within the narrow angular extent of the transmitted sound beam. Some vessels operate higher frequency (e.g., 24–455 kHz) multibeam echosounders designed to map shallower waters, and some of those will also be audible to odontocetes.

Seals and Sea Lions (Pinnipeds)

Underwater audiograms have been obtained using behavioral methods for three species of phocinid seals, two species of monachid seals, two species of otariids, and the walrus (reviewed in Richardson et al. 1995: 211*ff*; Kastak and Schusterman 1998, 1999; Kastelein et al. 2002). In comparison with odontocetes, pinnipeds tend to have lower best frequencies, lower high-frequency cutoffs, better auditory sensitivity at low frequencies, and poorer sensitivity at the best frequency.

At least some of the phocid (hair) seals have better sensitivity at low frequencies (≤1 kHz) than do odontocetes. Below 30–50 kHz, the hearing thresholds of most species tested are essentially flat down to about 1 kHz, and range between 60 and 85 dB re 1 μPa. Measurements for a harbor seal indicate that, below 1 kHz, its thresholds deteriorate gradually to ~97 dB re 1 μPa at 100 Hz (Kastak and Schusterman 1998). The northern elephant seal appears to have better underwater sensitivity than the harbor seal, at least at low frequencies (Kastak and Schusterman 1998, 1999).

For the otariid (eared) seals, the high frequency cutoff is lower than for phocinids, and sensitivity at low frequencies (e.g., 100 Hz) is poorer than for hair seals (harbor or elephant seal).

The underwater hearing of a walrus has been measured at frequencies from 125 Hz to 15 kHz (Kastelein et al. 2002). The range of best hearing was 1–12 kHz, with maximum sensitivity (67 dB re 1 μPa) occurring at 12 kHz (Kastelein et al. 2002).

Manatees and Dugong (Sirenians)

The West Indian manatee can apparently detect sounds from 15 Hz to 46 kHz, based on use of behavioral testing methods (Gerstein et al. 1999). Thus, manatees may hear, or at least detect, sounds in the low-frequency range where most seismic energy is released. It is possible that they are able to feel these low-frequency sounds using vibrotactile receptors or because of resonance in body cavities or bone conduction.

Based on measurements of evoked potentials, manatee hearing is apparently best around 1–1.5 kHz (Bullock et al. 1982). However, behavioral testing suggests their best sensitivity is at 6–20 kHz (Gerstein et al. 1999). The ability to detect high frequencies may be an adaptation to shallow water, where the propagation of low frequency sound is limited (Gerstein et al. 1999).

Sea Otter and Polar Bear (Fissipeds)

No data are available on the hearing abilities of sea otters (Ketten 1998), although the in-air vocalizations of sea otters have most of their energy concentrated at 3–5 kHz (McShane et al. 1995; Thomson and Richardson 1995; Richardson et al. 1995). Sea otter vocalizations are considered to be most suitable for short-range communication among individuals (McShane et al. 1995). Airborne sounds include screams, whines or whistles, hisses, deep-throated snarls or growls, soft cooing sounds, grunts, and barks (Kenyon 1975; McShane et al. 1995).

Data on the specific hearing capabilities of polar bears are also largely lacking. A recent study, and the only known testing of in-air hearing of polar bears, conducted measurements using auditory evoked potentials while tone pips were played to anesthetized bears (Nachtigall et al. 2007). Hearing was tested in ½ octave steps from 1 to 22.5 kHz, and best hearing sensitivity was found between 11.2 and 22.5 kHz. These data suggest that polar bears have sensitive hearing over a wide frequency range.

Data suggest that the frequencies of some medium- and high-frequency sounds may be audible to polar bears. However, polar bears' usual behavior (e.g., remaining on the ice, at the water surface, or on land) reduces or avoids their exposure to those sounds. Sea otters may be able to detect some low- and medium-frequency sounds, but as with polar bears, their largely water surface- and land-oriented behavior would reduce their exposure to those sounds.

(c) Characteristics of Airgun Pulses

Airguns function by venting high-pressure air into the water. The pressure signature of an individual airgun consists of a sharp rise and then fall in pressure, followed by several positive and negative pressure excursions caused by oscillation of the resulting air bubble. The sizes, arrangement, and firing times of the individual airguns in an array are designed and synchronized to suppress the pressure oscillations subsequent to the first cycle. The resulting downward-directed pulse has a duration of only 10–20 ms, with only one strong positive and one strong negative peak pressure (Caldwell and Dragoset 2000). Most energy emitted from airguns is at relatively low frequencies. For example, typical high-energy airgun arrays emit most energy at 10–120 Hz. However, the pulses contain some energy up to 500–1000 Hz and above (Goold and Fish 1998; Potter et al. 2006). Substantial high-frequency energy output of up to 150 kHz was found during tests of 60-in^3 and 250-in^3 airguns (Goold and Coates 2006). In fact, the output of those airguns covered the entire frequency range known to be used by marine mammals. The output included substantial energy levels that would be clearly audible to most, if not all, cetacean species (Goold and Coates 2006). Other recent studies—including controlled studies of sperm whales in the Gulf of Mexico (Tyack et al. 2006a,b)—have also found that airguns exposed animals to significant sound energy above 500 Hz (Goold and Fish 1998; Sodal 1999). Those data increase concerns about the potential impacts of seismic sounds on odontocetes with poor low-frequency hearing but good higher-frequency hearing.

The pulsed sounds associated with seismic exploration have higher peak levels than other industrial sounds (except explosions) to which whales and other marine mammals are routinely exposed. The peak-to-peak source levels of the 2- to 20-airgun arrays used by Lamont-Doherty Earth Observatory (L-DEO) from the R/V *Maurice Ewing* during previous projects ranged from 236 to 263 dB re 1 µPa at 1 m, considering the frequency band up to about 250 Hz. The peak-to-peak source level for the 36-airgun array used on the *Langseth* is 265 dB re 1 µPa at 1 m. These are the nominal source levels applicable to downward propagation. The effective source levels for horizontal propagation are lower than those for downward propagation when numerous airguns spaced apart from one another are used. The only man-made sources with effective source levels as high as (or higher than) a large array of airguns are explosions and high-power sonars operating near maximum power.

Levels of anthropogenic underwater sounds, including those produced by seismic surveys, have been increasing worldwide. Concurrently, there is growing concern by the general public, researchers, government entities, and others regarding exposure of marine mammals to these sounds (e.g., Hildebrand 2004; Marine Technological Society 2004; Simmonds et al. 2006). In a comparison of anthropogenic underwater sound sources, airgun arrays worldwide were estimated to introduce 3.9 x 10^{13} Joules of energy into the ocean, second only to underwater nuclear explosions and ranking above military sonars (Moore and Angliss 2006). As a result, there has been increasing interest and studies on methods to estimate the numbers of animals exposed to various sound levels and to mitigate exposure to these sounds (e.g., Hollingshead and Harrison 2005).

Recent attention has focused on developing sound exposure criteria appropriate to the acoustic sensitivities of various marine mammal groups and species (e.g., Hollingshead and Harrison 2005; Miller et al. 2005a). These exposure criteria have important implications for identifying appropriate "safety or exclusion zones" and sound exposure limits, including balancing mitigation with goals of geophysical seismic studies (e.g., Barton et al. 2006). Various empirical data are being collected, and modeling and predictions of the propagation and received levels of airgun sounds are being developed and applied (e.g., Breitzke 2006; Diebold et al. 2006; Frankel et al. 2006; Miller et al. 2006; Racca et al. 2006; Turner et al. 2006; Tyack et al. 2006a,b). These recent studies are affecting the way underwater sound is modeled. For example, DeRuiter et al. (2005) reported that on-axis source levels and spherical spreading assumptions alone insufficiently describe airgun pulse propagation and the extent of exposure zones.

Several important mitigating factors need to be kept in mind. *(1)* Airgun arrays produce intermittent sounds, involving emission of a strong sound pulse for a small fraction of a second followed by several seconds of near silence. In contrast, some other sources produce sounds with lower peak levels, but their sounds are continuous or discontinuous but continuing for much longer durations than seismic pulses. *(2)* Airgun arrays are designed to transmit strong sounds downward through the seafloor, and the amount of sound transmitted in near-horizontal directions is considerably reduced. Nonetheless, they also emit sounds that travel horizontally toward non-target areas. *(3)* An airgun array is a distributed source, not a point source. The nominal source level is an estimate of the sound that would be measured from a theoretical point source emitting the same total energy as the airgun array. That figure is useful in calculating the expected received levels in the far field, i.e., at moderate and long distances. Because the airgun array is not a single point source, there is no one location within the near field (or anywhere else) where the received level is as high as the nominal source level.

The strengths of airgun pulses can be measured in different ways, and it is important to know which method is being used when interpreting quoted source or received levels. Geophysicists usually quote peak-to-peak levels, in bar-meters or (less often) dB re 1 μPa · m. The peak (= zero-to-peak) level for the same pulse is typically ~6 dB less. In the biological literature, levels of received airgun pulses are often described based on the "average" or "root-mean-square" (rms) level, where the average is calculated over the duration of the pulse. The rms value for a given airgun pulse is typically ~10 dB lower than the peak level, and 16 dB lower than the peak-to-peak value (Greene 1997; McCauley et al. 1998, 2000a). A fourth measure that is sometimes used is the energy, or Sound Exposure Level (SEL), in dB re 1 $\mu Pa^2 \cdot s$. Because the pulses are <1 s in duration, the numerical value of the energy is lower than the rms pressure level, but the units are different. Because the level of a given pulse will differ substantially depending on which of these measures is being applied, it is important to be aware which measure is in use when interpreting any quoted pulse level. In the past, NMFS has commonly referred to rms levels when discussing levels of pulsed sounds that might "harass" marine mammals.

Seismic sound received at any given point will arrive via a direct path, indirect paths that include reflection from the sea surface and bottom, and often indirect paths including segments through the bottom sediments. Sounds propagating via indirect paths travel longer distances and often arrive later than sounds arriving via a direct path. (However, sound traveling in the bottom may travel faster than that in the water, and thus may, in some situations, arrive slightly earlier than the direct arrival despite traveling a greater distance.) These variations in travel time have the effect of lengthening the duration of the received pulse, or may cause two or more received pulses from a single emitted pulse. Near the source, the predominant part of a seismic pulse is ~10–20 ms in duration. In comparison, the pulse duration received at long horizontal distances can be much greater. For example, for one airgun array operating in the Beaufort Sea, pulse durations were ~300 ms at a distance of 8 km, 500 ms at 20 km, and 850 ms at 73 km (Greene and Richardson 1988).

Another important aspect of sound propagation is that received levels of low-frequency underwater sounds diminish close to the surface because of pressure-release and interference phenomena that occur at and near the surface (Urick 1983; Richardson et al. 1995). Paired measurements of received airgun sounds at depths of 3 vs. 9 or 18 m have shown that received levels are typically several decibels lower at 3 m (Greene and Richardson 1988). For a mammal whose auditory organs are within 0.5 or 1 m of the surface, the received level of the predominant low-frequency components of the airgun pulses would be further reduced. In deep water, the received levels at deep depths can be considerably higher than those at relatively shallow (e.g., 18 m) depths at the same horizontal distance from the airguns (Tolstoy et al. 2004a,b).

Pulses of underwater sound from open-water seismic exploration are often detected 50–100 km from the source location, even during operations in nearshore waters (Greene and Richardson 1988; Burgess and Greene 1999). At those distances, the received levels are low, <120 dB re 1 μPa on an approximate rms basis. However, faint seismic pulses are sometimes detectable Bt even greater ranges (e.g., Bowles et al. 1994; Fox et al. 2002). Considerably higher levels can occur at distances out to several kilometers from an operating airgun array. In fact, recent data show that low-frequency airgun signals can be detected thousands of kilometers from their source. For example, sound from seismic surveys conducted offshore of Nova Scotia, the coast of western Africa, and northeast of Brazil were reported as a dominant feature of the underwater noise field recorded along the mid-Atlantic ridge (Nieukirk et al. 2004).

(d) Masking Effects of Seismic Surveys

Masking effects of pulsed sounds on marine mammal calls and other natural sounds are expected to be limited, although there are few specific data on this. Some whales are known to continue calling in the presence of seismic pulses. Their calls can be heard between the seismic pulses (e.g., Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999; Nieukirk et al. 2004). Although there has been one report that sperm whales ceased calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994), more recent studies reported that sperm whales continued calling in the presence of seismic pulses (Madsen et al. 2002; Smultea et al. 2004; Holst et al. 2006; Tyack et al. 2006). Masking effects of seismic pulses are expected to be negligible in the case of the smaller odontocetes, given the intermittent nature of seismic pulses plus the fact that sounds important to them are predominantly at much higher frequencies than are airgun sounds.

Most of the energy in the sound pulses emitted by airgun arrays is at low frequencies, with strongest spectrum levels below 200 Hz, considerably lower spectrum levels above 1000 Hz, and smaller amounts of energy emitted up to ~150 kHz. These low frequencies are mainly used by mysticetes, but generally not by odontocetes, pinnipeds, or sirenians. An industrial sound source will reduce the effective communication or echolocation distance only if its frequency is close to that of the marine mammal signal. If little or no overlap occurs between the industrial noise and the frequencies used, as in the case of many marine mammals vs. airgun sounds, communication and echolocation are not expected to be disrupted. Furthermore, the discontinuous nature of seismic pulses makes significant masking effects unlikely even for mysticetes.

A few cetaceans are known to increase the source levels of their calls in the presence of elevated sound levels, or to shift their peak frequencies in response to strong sound signals (Dahlheim 1987; Au 1993; review in Richardson et al. 1995:233ff., 364ff.; Lesage et al. 1999; Terhune 1999; Nieukirk et al. 2005; Parks et al. 2005). These studies involved exposure to other types of anthropogenic sounds, not seismic pulses, and it is not known whether these types of responses ever occur upon exposure to seismic sounds. If so, these adaptations, along with directional hearing and preadaptation to tolerate some masking by natural sounds (Richardson et al. 1995), would all reduce the importance of masking.

(e) Disturbance by Seismic Surveys

Disturbance includes a variety of effects, including subtle changes in behavior, more conspicuous changes in activities, and displacement. In the terminology of the 1994 amendments to the MMPA, seismic noise could cause "Level B" harassment of certain marine mammals. Level B harassment is defined as "...disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering."

There has been debate regarding how substantial a change in behavior or mammal activity is required before the animal should be deemed to be "taken by Level B harassment". NMFS has stated that

> "…a simple change in a marine mammal's actions does not always rise to the level of disruption of its behavioral patterns. … If the only reaction to the [human] activity on the part of

> the marine mammal is within the normal repertoire of actions that are required to carry out that behavioral pattern, NMFS considers [the human] activity not to have caused a disruption of the behavioral pattern, provided the animal's reaction is not otherwise significant enough to be considered disruptive due to length or severity. Therefore, for example, a short-term change in breathing rates or a somewhat shortened or lengthened dive sequence that are within the animal's normal range and that do not have any biological significance (i.e., do no disrupt the animal's overall behavioral pattern of breathing under the circumstances), do not rise to a level requiring a small take authorization." (NMFS 2001, p. 9293).

Based on this guidance from NMFS (2001) and the National Research Council (NRC 2005), we assume that simple exposure to sound, or brief reactions that do not disrupt behavioral patterns in a potentially significant manner, do not constitute harassment or "taking". By potentially significant, we mean "in a manner that might have deleterious effects to the well-being of individual marine mammals or their populations".

Even with this guidance, there are difficulties in defining what marine mammals should be counted as "taken by harassment". For many species and situations, we do not have detailed information about their reactions to noise, including reactions to seismic and other sound pulses. Behavioral reactions of marine mammals to sound are difficult to predict. Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors. If a marine mammal does react to an underwater sound by changing its behavior or moving a small distance, the impacts of the change may not be significant to the individual, let alone the stock or the species as a whole. However, if a sound source displaces marine mammals from an important feeding or breeding area for a prolonged period, impacts on individuals and populations could be significant. Given the many uncertainties in predicting the quantity and types of impacts of noise on marine mammals, it is common practice to estimate how many mammals were present within a particular distance of industrial activities, or exposed to a particular level of industrial sound. This likely overestimates the numbers of marine mammals that are affected in some biologically important manner.

The definitions of "taking" in the U.S. MMPA, and its applicability to various activities, were altered slightly in November 2003 for military and federal scientific research activities. Also, NMFS is proposing to replace current Level A and B harassment criteria with guidelines based on exposure characteristics that are specific to species and sound types (NMFS 2005). In 2005, public meetings were conducted across the nation to consider the impact of implementing new criteria for what constitutes a "take" of marine mammals. Currently, a committee of specialists on noise impact issues is drafting recommendations for new impact criteria (Gentry et al. 2004; Hollingshead and Harrison 2005; Miller et al. 2005a); those recommendations are expected to be made public soon. Thus, for projects subject to U.S. jurisdiction, changes in procedures may be required in the near future.

The sound criteria used to estimate how many marine mammals might be disturbed to some biologically-important degree by a seismic program are based on behavioral observations during studies of several species. However, information is lacking for many species. Detailed studies have been done on humpback, gray, bowhead, and sperm whales, and on ringed seals. Less detailed data are available for some other species of baleen whales, sperm whales, and small toothed whales.

Baleen Whales

Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable. Whales are often reported to show no overt reactions to airgun pulses at distances beyond a few kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, baleen whales exposed to strong noise pulses from airguns often react by deviating from their normal migration route and/or interrupting their feeding and moving away. Some studies and reviews on this topic are Malme et al. (1984, 1985, 1988); Richardson et al. (1986, 1995, 1999); Ljungblad et al. (1988); Richardson and Malme (1993); McCauley et al. (1998, 2000a); Miller et al. (1999; 2005b); Gordon et al. (2004); Nowacek et al. (2007); and Moulton and Miller (in press). There is also evidence that baleen whales will often show avoidance of a small airgun source or upon onset of a ramp up when just one airgun is firing. Experiments with a single airgun showed that bowhead, humpback and gray whales all showed localized avoidance to a single airgun of 20–100 in^3 (Malme et al. 1984, 1985, 1986, 1987, 1988; Richardson et al. 1986; McCauley et al. 1998, 2000a,b). During a 2004 Caribbean seismic survey with a large airgun array, mean closest point of approach (CPA) of large whales during seismic was 1722 m compared to 1539 m during non-seismic, but sample sizes were small (Smultea et al. 2004; Holst et al. 2006).

Prior to the late 1990s, it was thought that bowhead, gray, and humpback whales all begin to show strong avoidance reactions to seismic pulses at received levels of ~160 to 170 dB re 1 μPa_{rms}, but that subtle behavioral changes sometimes become evident at somewhat lower received levels (Richardson et al. 1995). More recent studies have shown that some species of baleen whales (bowheads and humpbacks in particular) may show strong avoidance at received levels lower than 160–170 re 1 μPa_{rms}. The observed avoidance reactions involved movement away from feeding locations or statistically significant deviations in the whales' direction of swimming and/or migration corridor as they approached or passed the sound sources (e.g., Miller et al. 1999; McCauley et al. 2000a). In the case of the migrating whales, the observed changes in behavior appeared to be of little or no biological consequence to the animals—they simply avoided the sound source by displacing their migration route to varying degrees, but within the natural boundaries of the migration corridors (Malme et al. 1984; Malme and Miles 1985; Richardson et al. 1995).

Humpback Whales.—McCauley et al. (1998, 2000a) studied the responses of humpback whales off Western Australia to a full-scale seismic survey with a 16-airgun, 2678-in^3 array, and to a single 20 in^3 airgun with source level 227 dB re 1 μPa·m (p-p). They found that the overall distribution of humpbacks migrating through their study area was unaffected by the full-scale seismic program. McCauley et al. (1998) did, however, document localized avoidance of the array and of the single airgun. Observations were made from the seismic vessel, from which the maximum viewing distance was listed as 14 km. Avoidance reactions began at 5–8 km from the array, and those reactions kept most groups about 3–4 km from the operating seismic boat. McCauley et al. (2000a) noted localized displacement during migration of 4–5 km by traveling groups and 7–12 km by cow-calve pairs. Avoidance distances with respect to the single airgun were smaller but consistent with the results from the full array in terms of the received sound levels. Mean avoidance distance from the airgun corresponded to a received sound level of 140 dB re 1 μPa_{rms}; this was the level at which humpbacks started to show avoidance reactions to an approaching airgun. The standoff range, i.e., the closest point of approach (CPA) of the airgun to the whales, corresponded to a received level of 143 dB re 1 μPa_{rms}. The initial avoidance response generally occurred at distances of 5–8 km from the airgun array and 2 km from the single airgun. However, some individual humpback whales, especially males, approached within distances 100–400 m, where the maximum received level was 179 dB re 1 μPa_{rms}.

Humpback whales summering in southeast Alaska did not exhibit persistent avoidance when exposed to seismic pulses from a 1.64-L (100-in^3) airgun (Malme et al. 1985). Some humpbacks seemed "startled" at received levels of 150–169 dB re 1 µPa. Malme et al. (1985) concluded that there was no clear evidence of avoidance, despite the possibility of subtle effects, at received levels up to 172 re 1 µPa on an approximate rms basis.

It has been suggested that South Atlantic humpback whales wintering off Brazil may be displaced or even strand upon exposure to seismic surveys (Engel et al. 2004). The evidence for this was circumstantial, subject to alternative explanations (IAGC 2004), and not consistent with results from direct studies of humpbacks exposed to seismic surveys in other areas and seasons. After allowance for data from subsequent years, there was "no observable direct correlation" between strandings and seismic surveys (IWC 2007).

Bowhead Whales.—Bowhead whales on their summering grounds in the Canadian Beaufort Sea showed no obvious reactions to pulses from seismic vessels at distances of 6–99 km and received sound levels of 107–158 dB on an approximate rms basis (Richardson et al. 1986); their general activities were indistinguishable from those of a control group. However, subtle but statistically significant changes in surfacing–respiration–dive cycles were evident upon statistical analysis. Bowheads usually did show strong avoidance responses when seismic vessels approached within a few kilometers (~3–7 km) and when received levels of airgun sounds were 152–178 dB (Richardson et al. 1986, 1995; Ljungblad et al. 1988). In one case, bowheads engaged in near-bottom feeding began to turn away from a 30-airgun array with a source level of 248 dB re 1 µPa·m at a distance of 7.5 km, and swam away when it came within ~2 km. Some whales continued feeding until the vessel was 3 km away. This work and a more recent study by Miller et al. (2005b) show that feeding bowhead whales tend to tolerate higher sound levels than migrating bowhead whales before showing an overt change in behavior. The feeding whales may be affected by the sounds, but the need to feed may reduce the tendency to move away.

Migrating bowhead whales in the Alaskan Beaufort Sea seem more responsive to noise pulses from a distant seismic vessel than are summering bowheads. In 1996–1998, a partially-controlled study of the effect of Ocean Bottom Cable (OBC) seismic surveys on westward-migrating bowheads was conducted in late summer and autumn in the Alaskan Beaufort Sea (Miller et al. 1999; Richardson et al. 1999). Aerial surveys showed that some westward-migrating whales avoided an active seismic survey boat by 20–30 km, and that few bowheads approached within 20 km. Received sound levels at those distances were only 116–135 dB re 1 $\mu Pa_{rms.}$ At times when the airguns were not active, many bowheads moved into the area close to the inactive seismic vessel. Avoidance of the area of seismic operations did not persist beyond 12–24 h after seismic shooting stopped.

Gray Whales.—Malme et al. (1986, 1988) studied the responses of feeding eastern gray whales to pulses from a single 100-in^3 airgun off St. Lawrence Island in the northern Bering Sea. They estimated, based on small sample sizes, that 50% of feeding gray whales ceased feeding at an average received pressure level of 173 dB re 1 µPa on an (approximate) rms basis, and that 10% of feeding whales interrupted feeding at received levels of 163 dB. Malme at al. (1986) estimated that an average pressure level of 173 dB occurred at a range of 2.6–2.8 km from an airgun array with a source level of 250 dB (0-pk) in the northern Bering Sea. These findings were generally consistent with the results of experiments conducted on larger numbers of gray whales that were migrating along the California coast. Malme and Miles (1985) concluded that, during migration, changes in swimming pattern occurred for received levels of about 160 dB re 1 μPa and higher, on an approximate rms basis. The 50% probability of avoidance was estimated to occur at a CPA distance of 2.5 km from a 4000-in^3 array operating off central California. This would occur at an average received sound level of about 170 dB re 1 μPa_{rms}. Some slight behavioral changes were noted at received sound levels of 140 to 160 dB re 1 μPa_{rms}.

There was no indication that western gray whales exposed to seismic noise were displaced from their overall feeding grounds near Sakhalin Island during seismic programs in 1997 (Würsig et al. 1999) or in 2001. However, there were indications of subtle behavioral effects and (in 2001) localized avoidance by some individuals (Johnson et al. 2007; Weller et al. 2002, 2006a,b).

Gray whales in British Columbia exposed to seismic survey sound levels up to about 170 dB re 1 μPa did not appear to be disturbed (Bain and Williams 2006). The whales were moving away from the airguns but toward higher exposure levels (into deeper water where sound propagated more efficiently, so it was unclear whether their movements reflected a response to sounds associated with seismic surveys (Bain and Williams 2006).

Rorquals.—Blue, sei, fin, and minke whales have occasionally been reported in areas ensonified by airgun pulses. Sightings by observers on seismic vessels off the U.K. from 1997 to 2000 suggest that, at times of good sightability, numbers of rorquals seen are similar when airguns are shooting and not shooting (Stone 2003). Although individual species did not show any significant displacement in relation to seismic activity, all baleen whales combined were found to remain significantly further from the airguns during shooting compared with periods without shooting (Stone 2003). Baleen whale groups sighted from the ship were at a median distance of ~1.6 km from the array during shooting and 1.0 km during periods without shooting (Stone 2003). Baleen whales, as a group, made more frequent alterations of course (usually away from the vessel) during shooting compared with periods of no shooting. In addition, fin/sei whales were less likely to remain submerged during periods of seismic shooting (Stone 2003).

In a study off Nova Scotia, Moulton and Miller (in press) found little or no difference in sighting rates and initial sighting distances of balaenopterid whales when airguns were operating *vs*. silent, but there were indications that they were more likely to be moving away when seen during airgun operations.

Discussion and Conclusions.—Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable. Whales are often reported to show no overt reactions to airgun pulses at distances beyond a few kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, studies done since the late 1990s of humpback and especially migrating bowhead whales, show that reactions, including avoidance, sometimes extend to greater distances than documented earlier. Avoidance distances often exceed the distances at which boat-based observers can see whales, so observations from the source vessel are biased. Studies indicate monitoring over broader areas may be needed to determine the range of potential effects of some larger seismic surveys (Richardson et al. 1999; Bain and Williams 2006; Moore and Angliss 2006).

Some baleen whales show considerable tolerance of seismic pulses. However, when the pulses are strong enough, avoidance or other behavioral changes become evident. Because the responses become less obvious with diminishing received sound level, it has been difficult to determine the maximum distance (or minimum received sound level) at which reactions to seismic become evident and, hence, how many whales are affected.

Studies of gray, bowhead, and humpback whales have determined that received levels of pulses in the 160–170 dB re 1 μPa_{rms} range seem to cause obvious avoidance behavior in a substantial fraction of the animals exposed. In many areas, seismic pulses diminish to these levels at distances ranging from 4.5 to 14.5 km from the source. A substantial proportion of the baleen whales within this distance range may show avoidance or other strong disturbance reactions to the seismic array. In the case of migrating bowhead whales, avoidance extends to larger distances and lower received sound levels.

Data on short-term reactions (or lack of reactions) of cetaceans to impulsive noises do not necessarily provide information about long-term effects. It is not known whether impulsive noises affect reproductive rate or distribution and habitat use in subsequent days or years. Gray whales continued to migrate annually along the west coast of North America despite intermittent seismic exploration (and much ship traffic) in that area for decades (Appendix A in Malme et al. 1984; Richardson et al. 1995; Angliss and Outlaw 2005). The Western Pacific gray whale population did not seem affected by a seismic survey in its feeding ground during a prior year (Johnson et al. 2007). Bowhead whales continued to travel to the eastern Beaufort Sea each summer despite seismic exploration in their summer and autumn range for many years. Bowheads were often seen in summering areas where seismic exploration occurred in preceding summers (Richardson et al. 1987). They also have been observed over periods of days or weeks in areas repeatedly ensonified by seismic pulses. However, it is not known whether the same individual bowheads were involved in these repeated observations (within and between years) in strongly ensonified areas.

Toothed Whales

Little systematic information is available about reactions of toothed whales to noise pulses. Except for sperm whales, few studies similar to the more extensive baleen whale/seismic pulse work summarized above have been reported for toothed whales. Controlled exposure experiments on sperm whales took place in 2002 and 2003 (Miller et al. 2006; Tyack et al. 2006a,b), and there is an increasing amount of information about responses of various odontocetes to seismic surveys based on monitoring studies (e.g., Stone 2003; Smultea et al. 2004; Bain and Williams 2006; Holst et al. 2006; Moulton and Miller in press).

Delphinids (Dolphins).—Seismic operators sometimes see dolphins and other small toothed whales near operating airgun arrays, but in general there seems to be a tendency for most delphinids to show some limited avoidance of operating seismic vessels (e.g., Stone 2003; Holst et al. 2006; Moulton and Miller in press). Studies that have reported cases of small toothed whales close to the operating airguns include Duncan (1985), Arnold (1996), Stone (2003), and Holst et al. (2006). When a 3959-in^3, 18-airgun array was firing off California, toothed whales behaved in a manner similar to that observed when the airguns were silent (Arnold 1996). Most, but not all, dolphins often seemed to be attracted to the seismic vessel and floats, and some rode the bow wave of the seismic vessel regardless of whether the airguns were firing.

Goold (1996a,b,c) studied the effects on common dolphins of 2D seismic surveys in the Irish Sea. Passive acoustic surveys were conducted from the "guard ship" that towed a hydrophone 180-m aft. The results indicated that there was a local displacement of dolphins around the seismic operation. However, observations indicated that the animals were tolerant of the sounds at distances outside a 1-km radius from the airguns (Goold 1996a). Initial reports of larger-scale displacement were later shown to represent a normal autumn migration of dolphins through the area, and were not attributable to seismic surveys (Goold 1996a,b,c).

A monitoring study of summering belugas exposed to a seismic survey found that sighting rates, as determined by aerial surveys, were significantly lower at distances of 10–20 km compared with 20–30 km from the operating airgun array (Miller et al. 2005b). The low number of sightings from the vessel seemed to confirm a large avoidance response to the 2250-in^3 airgun array. The apparent displacement effect on belugas extended farther than has been shown for other small odontocetes exposed to airgun pulses.

Observers stationed on seismic vessels operating off the United Kingdom from 1997 to 2000 have provided data on the occurrence and behavior of various toothed whales exposed to seismic pulses (Stone 2003; Gordon et al. 2004). Dolphins of various species often showed more evidence of avoidance of operating airgun arrays than has been reported previously for small odontocetes. Sighting rates of white-sided dolphins, white-beaked dolphins, *Lagenorhynchus* spp., and all small odontocetes combined were significantly lower during periods of shooting. Except for pilot whales, all of the small odontocete species tested, including killer whales, were found to be significantly farther from large airgun arrays during periods of shooting compared with periods of no shooting. Pilot whales showed few reactions to seismic activity. The displacement of the median distance from the array was ~0.5 km or more for most species groups. Killer whales appeared to be more tolerant of seismic shooting in deeper waters.

For all small odontocete species, except pilot whales, that were sighted during seismic surveys off the U.K. in 1997–2000, the numbers of positive interactions with the survey vessel (e.g., bow-riding, approaching the vessel) were significantly fewer during periods of shooting. All small odontocetes combined showed more negative interactions (e.g., avoidance) during periods of shooting. Small odontocetes, including white-beaked dolphins, *Lagenorhynchus* spp., and other dolphin species, showed a tendency to swim faster during periods with seismic shooting; *Lagenorhynchus* spp. were also observed to swim more slowly during periods without shooting. Significantly fewer white-beaked dolphins, *Lagenorhynchus* spp. and pilot whales traveled towards the vessel and/or more were traveling away from the vessel during periods of shooting.

During two NSF-funded L-DEO seismic surveys using a large, 20-airgun array (~7000-in^3), sighting rates of delphinids were lower and initial sighting distances were farther away from the vessel during seismic than non-seismic periods (Smultea et al. 2004; Holst et al. 2005a, 2006). Monitoring results during a seismic survey in the Southeast Caribbean showed that the mean CPA of delphinids during seismic operations was 991 m compared with 172 m when the airguns were not operational (Smultea et al. 2004). Surprisingly, nearly all acoustic encounters (including delphinids and sperm whales) were made when the airguns were operating (Smultea et al. 2004). Although the number of sightings during monitoring of a seismic survey off the Yucatán Peninsula, Mexico, was small (n = 19), the results showed that the mean CPA of delphinids during seismic operations was 472 m compared with

178 m when the airguns were not operational (Holst et al. 2005b). The acoustic detection rates were nearly 5 times higher during non-seismic compared with seismic operations (Holst et al. 2005b).

Reactions of toothed whales to a single airgun or other small airgun source are not well documented, but do not seem to be very substantial (e.g., Stone 2003). Results from three NSF-funded L-DEO seismic surveys using small arrays (up to 3 GI guns and a 315-in^3 airgun) were inconclusive. During a survey in the Eastern Tropical Pacific (Holst et al. 2005a) and in the Northwest Atlantic (Haley and Koski 2004), detection rates were slightly lower during seismic compared to non-seismic periods. However, mean CPAs were closer during seismic operations during one cruise (Holst et al. 2005a), and greater during the other cruise (Haley and Koski 2004). Interpretation of the data was confounded by the fact that survey effort and/or number of sightings during non-seismic periods during both surveys was small. Results from another small-array survey in southeast Alaska were even more variable (MacLean and Koski 2005).

Captive bottlenose dolphins and beluga whales exhibited changes in behavior when exposed to strong pulsed sounds similar in duration to those typically used in seismic surveys (Finneran et al. 2000, 2002, 2005). Finneran et al. (2002) exposed a captive bottlenose dolphin and beluga to single impulses from a water gun (80 in^3). As compared with airgun pulses, water gun impulses were expected to contain proportionally more energy at higher frequencies because there is no significant gas-filled bubble, and thus little low-frequency bubble-pulse energy (Hutchinson and Detrick 1984). The captive animals sometimes vocalized after exposure and exhibited reluctance to station at the test site where subsequent exposure to impulses would be implemented (Finneran et al. 2002). Similar behaviors were exhibited by captive bottlenose dolphins and a beluga exposed to single underwater pulses designed to simulate those produced by distant underwater explosions (Finneran et al. 2000). It is uncertain what relevance these observed behaviors in captive, trained marine mammals exposed to single sound pulses may have to free-ranging animals exposed to multiple pulses. In any event, the animals tolerated rather high received levels of sound before exhibiting the aversive behaviors mentioned above; for pooled data at 3, 10, and 20 kHz sound exposure levels during sessions with 25, 50, and 75% altered behavior were 180, 190, and 199 dB re 1 µPa^2·s, respectively (Finneran and Schlundt 2004).

Observations of odontocete responses (or lack of responses) to noise pulses from underwater explosions (as opposed to airgun pulses) may be relevant as an indicator of odontocete responses to very strong noise pulses. During the 1950s, small explosive charges were dropped into an Alaskan river in attempts to scare belugas away from salmon. Success was limited (Fish and Vania 1971; Frost et al. 1984). Small explosive charges were "not always effective" in moving bottlenose dolphins away from sites in the Gulf of Mexico where larger demolition blasts were about to occur (Klima et al. 1988). Odontocetes may be attracted to fish killed by explosions, and thus attracted rather than repelled by "scare" charges. Captive false killer whales showed no obvious reaction to single noise pulses from small (10 g) charges; the received level was ~185 dB re 1 µPa (Akamatsu et al. 1993). Jefferson and Curry (1994) reviewed several additional studies that found limited or no effects of noise pulses from small explosive charges on killer whales and other odontocetes. Aside from the potential for temporary threshold shift (TTS), the tolerance to these charges may indicate a lack of effect or the failure to move away may simply indicate a stronger desire to eat, regardless of circumstances.

Phocinids (Porpoises).—Porpoises, like delphinids, show variable reactions to seismic operations. Calambokidis and Osmek (1998) noted that Dall's porpoises observed during a survey with a 6000-in^3, 12–16-airgun array tended to head away from the boat. Similarly, during seismic surveys off the U.K. in 1997–2000, significantly fewer harbor porpoises traveled towards the vessel and/or more were traveling away from the vessel during periods of shooting (Stone 2003). During both an experimental and a commercial seismic survey, Gordon et al. (1998 *in* Gordon et al. 2004) noted that acoustic contact rates for harbor porpoises were similar during seismic and non-seismic periods.

The limited available data suggest that harbor porpoises show stronger avoidance of seismic operations than Dall's porpoises (Stone 2003; Bain and Williams 2006). In Washington State waters, the harbor porpoise, a high-frequency specialist, appeared to be the species affected by the lowest level of sound (<145 dB re 1 μPa_{rms} at a distance >70 km) (Bain and Williams 2006). In contrast, Dall's porpoises seem relatively tolerant of airgun operations (MacLean and Koski 2005; Bain and Williams 2006). This apparent difference in responsiveness of the two species is consistent with their relative responsiveness to boat traffic in general (Richardson et al. 1995).

Beaked Whales.—There are no specific data on the behavioral reactions of beaked whales to seismic surveys. Most beaked whales tend to avoid approaching vessels of other types (e.g., Würsig et al. 1998). They commonly dive for an extended period when approached by a vessel (e.g., Kasuya 1986). It is likely that these beaked whales would normally show strong avoidance of an approaching seismic vessel, but this has not been documented explicitly. Northern bottlenose whales sometimes are quite tolerant of slow-moving vessels (Reeves et al. 1993; Hooker et al. 2001). However, those vessels were not emitting airgun pulses.

There are increasing indications that some beaked whales tend to strand when naval exercises, including sonar operation, are ongoing nearby (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; NOAA and USN 2001; Jepson et al. 2003; Barlow and Gisiner 2006; see also the "Strandings and Mortality" subsection, later). These strandings are apparently at least in part a disturbance response, although auditory or other injuries may also be a factor. Whether beaked whales would ever react similarly to seismic surveys is unknown. Seismic survey sounds are quite different from those of the sonars in operation during the above-cited incidents. There was a stranding of Cuvier's beaked whales in the Gulf of California (Mexico) in September 2002 when the R/V *Maurice Ewing* was conducting a seismic survey in the general area (e.g., Malakoff 2002). Another stranding of Cuvier's beaked whales in the Galapagos occurred during a seismic survey in April 2000; however "There is no obvious mechanism that bridges the distance between this source and the stranding site" (Gentry [ed.] 2002). The evidence with respect to seismic surveys and beaked whale strandings is inconclusive, and NMFS has not established a link between the Gulf of California stranding and the seismic activities (Hogarth 2002).

Sperm Whales.—All three species of sperm whales have been reported to show avoidance reactions to standard vessels not emitting airgun sounds (e.g., Richardson et al. 1995; Würsig et al. 1998; McAlpine 2002; Baird 2005). Thus, it is expected that they would tend to avoid an operating seismic survey vessel. There are some limited observations suggesting that sperm whales in the Southern Ocean ceased calling during some (but not all) times when exposed to weak noise pulses from extremely distant (>300 km) seismic exploration (Bowles et al. 1994). This "quieting" was suspected to represent a disturbance effect, in part because sperm whales exposed to pulsed man-made sounds at higher frequencies often cease calling (Watkins and Schevill 1975; Watkins et al. 1985). Also, there are several accounts of possible avoidance or other adverse effects of seismic vessels on sperm whales in the Gulf of Mexico (Mate et al. 1994; Johnson et al. 2004; Miller et al. 2006).

On the other hand, recent (and more extensive) data from vessel-based monitoring programs in U.K. waters suggest that sperm whales in that area show little evidence of avoidance or behavioral disruption in the presence of operating seismic vessels (Stone 2003). These types of observations are difficult to interpret because the observers are stationed on or near the seismic vessel, and may under-estimate reactions by some of the more responsive species or individuals, which may be beyond visual range. However, the U.K. results do seem to show considerable tolerance of seismic surveys by at least some sperm whales. Also, a recent study off northern Norway indicated that sperm whales continued to call when exposed to pulses from a distant seismic vessel. Received levels of the seismic pulses were up to 146 dB re 1 µPa pk-pk (Madsen et al. 2002). Similarly, a study conducted off Nova Scotia that analyzed recordings of sperm whale vocalizations at various distances from an active seismic program did not detect any obvious changes in the distribution or behavior of sperm whales (McCall Howard 1999).

An experimental study of sperm whale reactions to seismic surveys in the Gulf of Mexico took place in 2002 and 2003, along with a study of the movements of sperm whales with satellite-linked tags in relation to seismic surveys (Caldwell 2002; Tyack et al. 2006a,b). During controlled exposure experiments where sperm whales were exposed to seismic pulses at received levels of 131–167 dB re 1 µPa (peak-peak), neither gross diving behavior nor direction of movement changed for any of eight tagged sperm whales exposed to seismic airgun sounds at the onset of gradual ramp-up at ranges of 7 to 13 km or during full-power exposures ranging from 1.5 to 12.8 km (Miller 2006; Tyack et al. 2006a,b). However, some changes in foraging behavior were observed that suggested avoidance of deep dives near operating airguns.

Conclusions.—Dolphins and porpoises are often seen by observers on active seismic vessels, occasionally at close distances (e.g., bow riding). However, some studies, especially near the U.K., show localized avoidance. Belugas summering in the Beaufort Sea tended to avoid waters out to 10–20 km from an operating seismic vessel. In contrast, recent studies show little evidence of reactions by sperm whales to airgun pulses, contrary to earlier indications.

There are no specific data on responses of beaked whales to seismic surveys, but it is likely that most if not all species show strong avoidance. There is increasing evidence that some beaked whales may strand after exposure to strong noise from sonars. Whether they ever do so in response to seismic survey noise is unknown.

Pinnipeds

Few studies of the reactions of pinnipeds to noise from open-water seismic exploration have been published (for review, see Richardson et al. 1995). However, pinnipeds have been observed during a number of seismic monitoring studies. Monitoring in the Beaufort Sea during 1996–2002 provided a substantial amount of information on avoidance responses (or lack thereof) and associated behavior. Pinnipeds exposed to seismic surveys have also been observed during seismic surveys along the U.S. west coast. Some limited data are available on physiological responses of pinnipeds exposed to seismic sound, as studied with the aid of radio telemetry. Also, there are data on the reactions of pinnipeds to various other related types of impulsive sounds.

Early observations provided considerable evidence that pinnipeds are often quite tolerant of strong pulsed sounds. During seismic exploration off Nova Scotia, grey seals exposed to noise from airguns and linear explosive charges reportedly did not react strongly (J. Parsons *in* Greene et al. 1985). An airgun caused an initial startle reaction among South African fur seals but was ineffective in scaring them away from fishing gear (Anonymous 1975). Pinnipeds in both water and air sometimes tolerate strong noise pulses from non-explosive and explosive scaring devices, especially if attracted to the area for feeding or reproduction (Mate and Harvey 1987; Reeves et al. 1996). Thus, pinnipeds are expected to be rather tolerant of, or habituate to, repeated underwater sounds from distant seismic sources, at least when the animals are strongly attracted to the area.

In the U.K., a radio-telemetry study has demonstrated short-term changes in the behavior of harbor (=common) seals and grey seals exposed to airgun pulses (Thompson et al. 1998). In this study, harbor seals were exposed to seismic pulses from a 90-in^3 array (three 30-in^3 airguns), and behavioral responses differed among individuals. One harbor seal avoided the array at distances up to 2.5 km from the source and only resumed foraging dives after seismic stopped. Another harbor seal exposed to the same small airgun array showed no detectable behavioral response, even when the array was within 500 m. All grey seals exposed to a single 10-in^3 airgun showed an avoidance reaction: they moved away from the source, increased swim speed and/or dive duration, and switched from foraging dives to predominantly transit dives. These effects appeared to be short-term as all grey seals either remained in, or returned at least once to, the foraging area where they had been exposed to seismic pulses. These results suggest that there are interspecific as well as individual differences in seal responses to seismic sounds.

Off California, visual observations from a seismic vessel showed that California sea lions "typically ignored the vessel and array. When [they] displayed behavior modifications, they often appeared to be reacting visually to the sight of the towed array. At times, California sea lions were attracted to the array, even when it was on. At other times, these animals would appear to be actively avoiding the vessel and array" (Arnold 1996). In Puget Sound, sighting distances for harbor seals and California sea lions tended to be larger when airguns were operating; both species tended to orient away whether or not the airguns were firing (Calambokidis and Osmek 1998).

Monitoring work in the Alaskan Beaufort Sea during 1996–2001 provided considerable information regarding the behavior of seals exposed to seismic pulses (Harris et al. 2001; Moulton and Lawson 2002). Those seismic projects usually involved arrays of 6–16 airguns with total volumes 560–1500 in^3. The combined results suggest that some seals avoid the immediate area around seismic vessels. In most survey years, ringed seal sightings tended to be farther away from the seismic vessel when the airguns were operating then when they were not (Moulton and Lawson 2002). However, these avoidance movements were relatively small, on the order of 100 m to (at most) a few hundreds of meters, and many seals remained within 100–200 m of the trackline as the operating airgun array passed by. Seal sighting rates at the water surface were lower during airgun array operations than during no-airgun periods in each survey year except 1997.

The operation of the airgun array had minor and variable effects on the behavior of seals visible at the surface within a few hundred meters of the array (Moulton and Lawson 2002). The behavioral data indicated that some seals were more likely to swim away from the source vessel during periods of airgun operations and more likely to swim towards or parallel to the vessel during non-seismic periods. No consistent relationship was observed between exposure to airgun noise and proportions of seals engaged in other recognizable behaviors, e.g., "looked" and "dove". Such a relationship might have occurred if seals seek to reduce exposure to strong seismic pulses, given the reduced airgun noise levels close to the surface where "looking" occurs (Moulton and Lawson 2002).

Monitoring results from the Canadian Beaufort Sea during 2001–2002 were more variable (Miller et al. 2005b). During 2001, sighting rates of seals (mostly ringed seals) were similar during all seismic states, including periods without airgun operations. However, seals were seen closer to the vessel during non-seismic than seismic periods. In contrast, during 2002, sighting rates of seals were higher during non-seismic periods than seismic operations, and seals were seen farther from the vessel during non-seismic compared to seismic activity (a marginally significant result). The combined data for both years showed that sighting rates were higher during non-seismic periods compared to seismic periods, and that sighting distances were similar during both seismic states. Miller et al. (2005b) concluded that seals showed very limited avoidance to the operating airgun array.

In summary, visual monitoring from seismic vessels has shown only slight (if any) avoidance of airguns by pinnipeds, and only slight (if any) changes in behavior. These studies show that pinnipeds frequently do not avoid the area within a few hundred meters of an operating airgun array. However, initial telemetry work suggests that avoidance and other behavioral reactions may be stronger than evident to date from visual studies.

Fissipeds.—Behavior of sea otters along the California coast was monitored by Riedman (1983, 1984) while they were exposed to a single 100-in^3 airgun and a 4089-in^3 array. No disturbance reactions were evident when the airgun array was as close as 0.9 km. Otters also did not respond noticeably to the single airgun. The results suggest that sea otters may be less responsive to marine seismic pulses than other marine mammals. Also, sea otters spend a great deal of time at the surface feeding and grooming. While at the surface, the potential noise exposure of sea otters would be much reduced by the pressure release effect at the surface.

(f) Hearing Impairment and Other Physical Effects

Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds, but there has been no specific documentation of this in the case of exposure to sounds from seismic surveys. Current NMFS policy regarding exposure of marine mammals to high-level sounds has been that cetaceans and pinnipeds should not be exposed to impulsive sounds exceeding 180 and 190 dB re 1 μPa_{rms}, respectively (e.g., NMFS 2000). Those criteria have been used in establishing the safety zones planned for numerous seismic surveys. However, those criteria were established before there was any information about the minimum received levels of sounds necessary to cause auditory impairment in marine mammals. As discussed below,

- the 180 dB criterion for cetaceans is probably quite precautionary, i.e., lower than necessary to avoid temporary auditory impairment let alone permanent auditory injury, at least for delphinids.
- temporary threshold shift (TTS) is not injury and does not constitute “Level A harassment” in MMPA terminology.
- the minimum sound level necessary to cause permanent hearing impairment (“Level A harassment”) is higher, by a variable and generally unknown amount, than the level that induces barely-detectable TTS.
- the level associated with the onset of TTS is often considered to be a level below which there is no danger of permanent damage.

NMFS is presently developing new noise exposure criteria for marine mammals that account for the now-available scientific data on TTS, the expected offset between TTS and permanent threshold shift (PTS), differences in the acoustic frequencies to which different marine mammal groups are sensitive, and other relevant factors. For preliminary information about this process, and about the structure of the new criteria in marine and terrestrial mammals see Wieting (2004), Miller et al. (2005a), and NMFS (2005).

Several aspects of the monitoring and mitigation measures that are now often implemented during seismic survey projects are designed to detect marine mammals occurring near the airgun array, and to avoid exposing them to sound pulses that might, at least in theory, cause hearing impairment. In addition, many cetaceans show some avoidance of the area with ongoing seismic operations (see above). In these cases, the avoidance responses of the animals themselves will reduce or (most likely) avoid the possibility of hearing impairment.

Non-auditory physical effects may also occur in marine mammals exposed to strong underwater pulsed sound. Possible types of non-auditory physiological effects or injuries that might (in theory) occur include stress, neurological effects, bubble formation, and other types of organ or tissue damage. It is possible that some marine mammal species (i.e., beaked whales) may be especially susceptible to injury and/or stranding when exposed to strong pulsed sounds.

Temporary Threshold Shift (TTS)

TTS is the mildest form of hearing impairment that can occur during exposure to a strong sound (Kryter 1985). While experiencing TTS, the hearing threshold rises and a sound must be stronger in order to be heard. TTS can last from minutes or hours to (in cases of strong TTS) days. However, it is a temporary phenomenon, and (especially when mild) is not considered to represent physical damage or "injury". Rather, the onset of TTS is an indicator that, if the animals is exposed to higher levels of that sound, physical damage is ultimately a possibility.

The magnitude of TTS depends on the level and duration of noise exposure, among other considerations (Richardson et al. 1995). For sound exposures at or somewhat above the TTS threshold, hearing sensitivity recovers rapidly after exposure to the noise ends. Only a few data have been obtained on sound levels and durations necessary to elicit mild TTS in marine mammals, and none of the published data concern TTS elicited by exposure to multiple pulses of sound.

Baleen Whales*.—*There are no data, direct or indirect, on levels or properties of sound that are required to induce TTS in any baleen whale. The frequencies to which mysticetes are most sensitive are lower than those to which odontocetes are most sensitive, and natural background noise levels at those low frequencies tend to be higher. As a result, auditory thresholds of baleen whales within their frequency band of best hearing are believed to be higher (less sensitive) than are those of odontocetes at their best frequencies (Clark and Ellison 2004). From this, it is suspected that received levels causing TTS onset may also be higher in mysticetes.

In practice during seismic surveys, no cases of TTS are expected given the strong likelihood that baleen whales would avoid the approaching airguns (or vessel) before being exposed to levels high enough for there to be any possibility of TTS. (See above for evidence concerning avoidance responses by baleen whales.) This assumes that the ramp up (soft start) procedure is used when commencing airgun operations, to give whales near the vessel the opportunity to move away before they are exposed to sound levels that might be strong enough to elicit TTS. As discussed above, single-airgun experiments with bowhead, gray, and humpback whales show that those species do tend to move away when a single airgun starts firing nearby, which simulates the onset of a ramp up.

Toothed Whales.—Ridgway et al. (1997) and Schlundt et al. (2000) exposed bottlenose dolphins and beluga whales to single 1-s pulses of underwater sound. TTS generally became evident at received levels of 192 to 201 dB re 1 μPa_{rms} at 3, 10, 20, and 75 kHz, with no strong relationship between frequency and onset of TTS across this range of frequencies. At 75 kHz, one dolphin exhibited TTS at 182 dB re 1 μPa_{rms}, and at 0.4 kHz, no dolphin or beluga exhibited TTS after exposure to levels up to 193 dB re 1 μPa_{rms} (Schlundt et al. 2000). There was no evidence of permanent hearing loss; all hearing thresholds returned to baseline values at the end of the study.

Finneran et al. (2000) exposed bottlenose dolphins and a beluga whale to single underwater pulses designed to generate sounds with pressure waveforms similar to those produced by distant underwater explosions. Pulses were 5.1–13 ms in duration, and the measured frequency spectra showed a lack of energy below 1 kHz. Exposure to those impulses at a peak received SPL (sound pressure level) of up to 221 dB re 1 µPa did not produce temporary threshold shift, although disruption of the animals' trained behaviors occurred.

A similar study was conducted by Finneran et al. (2002) using an 80-in^3 water gun, which generated impulses with higher peak pressures and total energy fluxes than used in the aforementioned study. Water gun impulses were expected to contain proportionally more energy at higher frequencies than airgun pulses (Hutchinson and Detrick 1984). "Masked TTS" (MTTS refers to the fact that measurements were obtained under conditions with substantial, but controlled, background noise) was observed in a beluga after exposure to a single impulse with peak-to-peak pressure of 226 dB re 1 µPa, peak pressure of 160 kPa, and total energy flux of 186 dB re 1 $\mu Pa^2 \cdot s$. Thresholds returned to within 2 dB of pre-exposure value ~4 min after exposure. No MTTS was observed in a bottlenose dolphin exposed to one pulse with peak-to-peak pressure of 228 dB re 1 µPa, equivalent to peak pressure 207 kPa and total energy flux of 188 dB re 1 $\mu Pa^2 \cdot s$ (Finneran et al. 2002). In this study, TTS was defined as occurring when there was a 6 dB or larger increase in post-exposure thresholds. Pulse duration at the highest exposure levels, where MTTS became evident in the beluga, was typically 10–13 ms.

The data quoted above all concern exposure of small odontocetes to single pulses of duration 1 s or shorter, generally at frequencies higher than the predominant frequencies in airgun pulses. With single short pulses, the TTS threshold appears to be (to a first approximation) a function of the energy content of the pulse (Finneran et al. 2002). The degree to which this generalization holds for other types of signals is unclear (Nachtigall et al. 2003).

Finneran et al. (2005) examined the effects of tone duration on TTS in bottlenose dolphins. Bottlenose dolphins were exposed to 3 kHz tones for periods of 1, 2, 4 or 8 s, with hearing tested at 4.5 kHz. For 1-s exposures, TTS occurred with SELs of 197 dB, and for exposures >1 s, SEL ≥195 dB resulted in TTS. (SEL is equivalent to energy flux, in dB re 1 $\mu Pa^2 \cdot s$.) At SEL of 195 dB, the mean TTS (4 min after exposure) was 2.8 dB. Finneran et al. (2005) suggested that an SEL of 195 dB is the likely threshold for the onset of TTS in dolphins and white whales exposed to mid-frequency tones of durations 1-8 s, i.e., TTS onset occurs at a near-constant SEL, independent of exposure duration. That implies that a doubling of exposure time results in a 3 dB lower TTS threshold.

Mooney et al. (2005) exposed a bottlenose dolphin to octave-band noise ranging from 4 to 8 kHz at SPLs of 160–172 dB re 1 µPa for periods of 1.8–30 min. Recovery time depended on the shift and frequency, but full recovery always occurred within 40 min (Mooney et al. 2005). They reported that to induce TTS in a bottlenose dolphin, there is an inverse relationship of exposure time and SPL; as a first approximation, as exposure time was halved, an increase in noise SPL of 3 dB was required to induce the same amount of TTS.

Additional data are needed in order to determine the received sound levels at which small odontocetes would start to incur TTS upon exposure to repeated, low-frequency pulses of airgun sound with variable received levels. Given the results of the aforementioned studies and a seismic pulse duration (as received at close range) of ~20 ms, the received level of a single seismic pulse might need to be on the order of 210 dB re 1 μPa_{rms} (~221–226 dB pk-pk) in order to produce brief, mild TTS. Exposure to several seismic pulses at received levels near 200–205 dB re 1 μPa_{rms} might result in slight TTS in a small odontocete, assuming the TTS threshold is (to a first approximation) a function of the total received pulse energy. Seismic pulses with received levels of 200–205 dB or more are usually restricted to a radius of no more than 100 m around a seismic vessel.

To better characterize this radius, it would be necessary to determine the total energy that a mammal would receive as an airgun array approached, passed at various CPA distances, and moved away. At the present state of knowledge, it would also be necessary to assume that the effect is directly related to total energy even though that energy is received in multiple pulses separated by gaps. The lack of data on the exposure levels necessary to cause TTS in toothed whales when the signal is a series of pulsed sounds, separated by silent periods, is a data gap.

Pinnipeds.—TTS thresholds for pinnipeds exposed to brief pulses (either single or multiple) of underwater sound have not been measured. Two California sea lions did not incur TTS when exposed to single brief pulses with received levels of ~178 and 183 dB re 1 μPa_{rms} and total energy fluxes of 161 and 163 dB re 1 $\mu Pa^2 \cdot s$ (Finneran et al. 2003). However, initial evidence from prolonged exposures suggested that some pinnipeds may incur TTS at lower received levels than do small odontocetes exposed for similar durations, on the order of 171 dB SEL (Kastak et al. 1999, 2005; Ketten et al. 2001). For sounds of relatively long duration (20–22 min), Kastak et al. (1999) reported that they could induce mild TTS in California sea lions, harbor seals, and northern elephant seals by exposing them to underwater octave-band noise at frequencies in the 100–2000 Hz range. Mild TTS became evident when the received levels were 60–75 dB above the respective hearing thresholds, i.e., at received levels of about 135–150 dB. Three of the five subjects showed shifts of ~4.6–4.9 dB and all recovered to baseline hearing sensitivity within 24 hours of exposure.

Schusterman et al. (2000) showed that TTS thresholds of these pinnipeds were somewhat lower when the animals were exposed to the sound for 40 min than for 20–22 min, confirming that there is a duration effect in pinnipeds. Similarly, Kastak et al. (2005) reported that threshold shift magnitude increased with increasing SEL in a California sea lion and harbor seal. They noted that doubling the exposure duration from 25 to 50 min i.e., +3 dB change in SEL, had a greater effect on TTS than an increase of 15 dB (95 *vs*. 80 dB) in exposure level. Mean threshold shifts ranged from 2.9 to 12.2 dB, with full recovery within 24 h (Kastak et al. 2005). Kastak et al. (2005) suggested that sound exposure levels resulting in TTS onset in pinnipeds may range from 183 to 206 dB re 1 $\mu Pa^2 \cdot s$, depending on the absolute hearing sensitivity.

Likelihood of Incurring TTS.—A marine mammal within a radius of ≤100 m around a typical array of operating airguns might be exposed to a few seismic pulses with levels of ≥205 dB, and possibly more pulses if the mammal moved with the seismic vessel.

As shown above, most cetaceans show some degree of avoidance of seismic vessels operating an airgun array. It is unlikely that these cetaceans would be exposed to airgun pulses at a sufficiently high level for a sufficiently long period to cause more than mild TTS, given the relative movement of the vessel and the marine mammal. TTS would be more likely in any odontocetes that bow- or wake-ride or otherwise linger near the airguns. However, while bow- or wake-riding, odontocetes would be at or above the surface and thus not exposed to strong sound pulses given the pressure-release effect at the surface. But if bow-or wake-riding animals were to dive intermittently near airguns, they would be exposed to strong sound pulses, possibly repeatedly. If some cetaceans did incur mild or moderate TTS through exposure to airgun sounds in this manner, this would very likely be a temporary and reversible phenomenon.

Some pinnipeds show avoidance reactions to airguns, but their avoidance reactions are not as strong or consistent as those of cetaceans (see above). Pinnipeds occasionally seem to be attracted to operating seismic vessels. As previously noted, there are no specific data on TTS thresholds of pinnipeds exposed to single or multiple low-frequency pulses. It is not known whether pinnipeds near operating seismic vessels, and especially those individuals that linger nearby, would incur significant TTS.

NMFS (1995, 2000) concluded that cetaceans should not be exposed to pulsed underwater noise at received levels exceeding 180 dB re 1 μPa_{rms}. The corresponding limit for pinnipeds has been set at 190 dB, although the HESS Team (1999) recommended 180-dB limit for pinnipeds in California. The 180 and 190 dB re 1 μPa_{rms} levels are not considered to be the levels above which TTS might occur. Rather, they are the received levels above which, in the view of a panel of bioacoustics specialists convened by NMFS before any TTS measurements for marine mammals were available, one could not be certain that there would be no injurious effects, auditory or otherwise, to marine mammals. As discussed above, TTS data that have subsequently become available imply that, at least for dolphins, TTS is unlikely to occur unless the dolphins are exposed to airgun pulses stronger than 180 dB re 1 μPa_{rms}. Furthermore, it should be noted that mild TTS is not injury, and in fact is a natural phenomenon experienced by marine and terrestrial mammals (including humans).

It has been shown that most large whales tend to avoid ships and associated seismic operations. In addition, ramping up airgun arrays, which is standard operational protocol for many seismic operators, should allow cetaceans to move away from the seismic source and to avoid being exposed to the full acoustic output of the airgun array. [Three species of baleen whales that have been exposed to pulses from single airguns showed avoidance (Malme et al. 1984–1988; Richardson et al. 1986; McCauley et al. 1998, 2000a,b). This strongly suggests that baleen whales will begin to move away during the initial stages of a ramp up, when a single airgun is fired.] Thus, whales will likely not be exposed to high levels of airgun sounds. Likewise, any whales close to the trackline could move away before the sounds from the approaching seismic vessel become sufficiently strong for there to be any potential for TTS or other hearing impairment. Therefore, there is little potential for whales to be close enough to an airgun array to experience TTS. Furthermore, in the event that a few individual cetaceans did incur TTS through exposure to airgun sounds, this is a temporary and reversible phenomenon.

Permanent Threshold Shift (PTS)

When PTS occurs, there is physical damage to the sound receptors in the ear. In some cases, there can be total or partial deafness, whereas in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges. Physical damage to a mammal's hearing apparatus can occur if it is exposed to sound impulses that have very high peak pressures, especially if they have very short rise times (time required for sound pulse to reach peak pressure from the baseline pressure). Such damage can result in a permanent decrease in functional sensitivity of the hearing system at some or all frequencies.

There is no specific evidence that exposure to pulses of airgun sound can cause PTS in any marine mammal, even with large arrays of airguns. However, given the likelihood that some mammals close to an airgun array might incur at least mild TTS (see Finneran et al. 2002), there has been speculation about the possibility that some individuals occurring very close to airguns might incur TTS (Richardson et al. 1995, p. 372*ff*).

Single or occasional occurrences of mild TTS are not indicative of permanent auditory damage in terrestrial mammals. Relationships between TTS and PTS thresholds have not been studied in marine mammals but are assumed to be similar to those in humans and other terrestrial mammals. The low-to-moderate levels of TTS that have been induced in captive odontocetes and pinnipeds during recent controlled studies of TTS have been confirmed to be temporary, with no measurable residual PTS (Kastak et al. 1999; Schlundt et al. 2000; Finneran et al. 2002; Nachtigall et al. 2003, 2004). However, very prolonged exposure to sound strong enough to elicit TTS, or shorter-term exposure to sound levels well above the TTS threshold, can cause PTS, at least in terrestrial mammals (Kryter 1985). In terrestrial mammals, the received sound level from a single non-impulsive sound exposure must be far above the TTS threshold for any risk of permanent hearing damage (Kryter 1994; Richardson et al. 1995). However, there is special concern about strong sounds whose pulses have very rapid rise times. In terrestrial mammals, there are situations when pulses with rapid rise times can result in PTS even though their levels are only a few dB higher than the level causing slight TTS. The rise time of airgun pulses is fast, but not nearly as fast as that of explosions, which are the main concern in this regard.

Some factors that contribute to onset of PTS, at least in terrestrial mammals, are as follows:

- exposure to single very intense sound,
- repetitive exposure to intense sounds that individually cause TTS but not PTS, and
- recurrent ear infections or (in captive animals) exposure to certain drugs.

Cavanagh (2000) has reviewed the thresholds used to define TTS and PTS. Based on this review and SACLANT (1998), it is reasonable to assume that PTS might occur at a received sound level 20 dB or more above that inducing mild TTS. However, for PTS to occur at a received level only 20 dB above the TTS threshold, the animal probably would have to be exposed to a strong sound for an extended period, or to a strong sound with rather rapid rise time.

Sound impulse duration, peak amplitude, rise time, and number of pulses are the main factors thought to determine the onset and extent of PTS. Based on existing data, Ketten (1994) has noted that the criteria for differentiating the sound pressure levels that result in PTS (or TTS) are location and species-specific. PTS effects may also be influenced strongly by the health of the receiver's ear.

Given that marine mammals are unlikely to be exposed to received levels of seismic pulses that could cause TTS, it is highly unlikely that they would sustain permanent hearing impairment. If we assume that the TTS threshold for exposure to a series of seismic pulses may be on the order of 220 dB re 1 μPa (pk-pk) in odontocetes, then the PTS threshold might be as high as 240 dB re 1 μPa (pk-pk) or 10 bar-m. Such levels are found only in the immediate vicinity of the largest airguns (Richardson et al. 1995:137; Caldwell and Dragoset 2000). It is very unlikely that an odontocete would remain within a few meters of a large airgun for sufficiently long to incur PTS. The TTS (and thus PTS) thresholds of baleen whales and/or pinnipeds (e.g. harbor seal) may be lower, and thus may extend to a somewhat greater distance. However, baleen whales generally avoid the immediate area around operating seismic vessels, so it is unlikely that a baleen whale could incur PTS from exposure to airgun pulses. Pinnipeds, on the other hand, often do not show strong avoidance of operating airguns.

Although it is unlikely that airgun operations during most seismic surveys would cause PTS in marine mammals, caution is warranted given the limited knowledge about noise-induced hearing damage in marine mammals, particularly baleen whales. Commonly-applied monitoring and mitigation measures, including visual and passive acoustic monitoring, course alteration, ramp ups, and power downs or shut downs of the airguns when mammals are seen within the "safety zone", would minimize the already-low probability of exposure of marine mammals to sounds strong enough to induce PTS.

(g) Strandings and Mortality

Marine mammals close to underwater detonations of high explosive can be killed or severely injured, and the auditory organs are especially susceptible to injury (Ketten et al. 1993; Ketten 1995). Airgun pulses are less energetic and have slower rise times, and there is no proof that they can cause serious injury, death, or stranding. However, the spatiotemporal association of mass strandings of beaked whales with naval exercises and possibly an L-DEO seismic survey in 2002 has raised the possibility that beaked whales may be especially susceptible to injury and/or behavioral reactions that can lead to stranding when exposed to strong pulsed sounds.

In March 2000, several beaked whales that had been exposed to repeated pulses from high intensity, mid-frequency military sonars stranded and died in the Providence Channels of the Bahamas Islands, and were subsequently found to have incurred cranial and ear damage (NOAA and USN 2001). Based on post-mortem analyses, it was concluded that an acoustic event caused hemorrhages in and near the auditory region of some beaked whales. These hemorrhages occurred before death. They would not necessarily have caused death or permanent hearing damage, but could have compromised hearing and navigational ability (NOAA and USN 2001). The researchers concluded that acoustic exposure caused this damage and triggered stranding, which resulted in overheating, cardiovascular collapse, and physiological shock that ultimately led to the death of the stranded beaked whales. During the event, five naval vessels used their AN/SQS-53C or -56 hull-mounted active sonars for a period of 16 h. The sonars produced narrow (<100 Hz) bandwidth signals at center frequencies of 2.6 and 3.3 kHz (-53C), and 6.8–8.2 kHz (-56). The respective source levels were usually 235 and 223 dB re 1 μPa, but the -53C briefly operated at an unstated but substantially higher source level. The unusual bathymetry and constricted channel where the strandings occurred were conducive to channeling sound. That and the extended operations by multiple sonars apparently prevented escape of the animals to the open sea. In addition to the strandings, there are reports that beaked whales were no longer present in the Providence Channel region after the event, suggesting that other beaked whales either abandoned the area or perhaps died at sea (Balcomb and Claridge 2001).

Other strandings of beaked whales associated with operation of military sonars have also been reported (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; Hohn et al. 2006; Southall et al. 2006), although in most cases, the connection between the stranding and naval sonar activity was not conclusively established (Cox et al. 2006). In these cases, it was not determined whether there were noise-induced injuries to the ears or other organs. Another stranding of beaked whales (15 whales) happened on 24–25 September 2002 in the Canary Islands, where naval maneuvers were taking place, although the specifics of the naval activities are not readily available (D'Spain et al. 2006), and the sound levels received by the cetaceans prior to stranding are unknown.

Based on the strandings in the Canary Islands, Jepson et al. (2003) proposed that cetaceans might be subject to decompression injury in some situations. Fernández et al. (2005a) showed that those beaked whales did indeed have gas bubble-associated lesions and fat embolisms. Fernández et al. (2005b) also found evidence of fat embolism in three beaked whales that stranded 100 km north of the Canaries in 2004 during naval exercises. Examinations of several other stranded species have also revealed evidence of gas and fat embolisms (e.g., Arbelo et al. 2005; Jepson et al. 2005a; Méndez et al 2005; Dalton 2006). These effects were suspected to be induced by exposure to sonar sounds, but the mechanism of injury was not auditory. Most of the afflicted species were deep divers. Gas and fat embolisms could occur if cetaceans ascend unusually quickly when exposed to aversive sounds, or if sound in the environment causes the destabilization of existing bubble nuclei (Potter 2004; Moore and Early 2004; Arbelo et al. 2005; Fernández et al. 2005a; Jepson et al. 2005b). Rommel et al. (2006) suggested that the evolution of gas bubbles is driven by behaviorally altered dive profiles, e.g., extended surface intervals. Previously it was widely assumed that diving marine mammals are not subject to the bends or air embolism.

It is important to note that seismic pulses and mid-frequency sonar pulses are quite different. Sounds produced by the types of airgun arrays used to profile sub-sea geological structures are broadband with most of the energy below 1 kHz. Typical military mid-frequency sonars operate at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time (though the center frequency may change over time). Because seismic and sonar sounds have considerably different characteristics and duty cycles, it is not appropriate to assume that there is a direct connection between the effects of military sonar and seismic surveys on marine mammals. However, evidence that sonar pulses can, in special circumstances, lead to hearing damage and, indirectly, mortality suggests that caution is warranted when dealing with exposure of marine mammals to any high-intensity pulsed sound.

As noted earlier, in September 2002, there was a stranding of two Cuvier's beaked whales in the Gulf of California (Mexico) when a seismic survey by the R/V *Maurice Ewing* was underway in the general area. (Malakoff 2002). The airgun array in use during that project was the *Ewing*'s 20-airgun 8490-in^3 array. This might be a first indication that seismic surveys can have effects, at least on beaked whales, similar to the suspected effects of naval sonars. However, the evidence linking the Gulf of California strandings to the seismic surveys was inconclusive, and not based on any physical evidence (Hogarth 2002; Yoder 2002). The ship was also operating its multibeam echosounder at the same time but, as discussed elsewhere, this source had much less potential than the aforementioned naval sonars to affect beaked whales. Although the link between the Gulf of California strandings and the seismic (plus multibeam echosounder) survey is inconclusive, this plus the various incidents involving beaked whale strandings "associated with" naval exercises suggests a need for caution in conducting seismic surveys in areas occupied by beaked whales.

(h) Non-auditory Physiological Effects

Possible types of non-auditory physiological effects or injuries that might theoretically occur in marine mammals exposed to strong underwater sound might include stress, neurological effects, bubble formation, and other types of organ or tissue damage. However, studies examining such effects are limited. If any such effects do occur, they would probably be limited to unusual situations. Those could include cases when animals are exposed at close range for unusually long periods, when the sound is strongly channeled with less-than-normal propagation loss, or when dispersal of the animals is constrained by shorelines, shallows, etc.

Long-term exposure to anthropogenic noise may have the potential of causing physiological stress that could affect the health of individual animals or their reproductive potential, which in turn could (theoretically) cause effects at the population level (Gisiner [ed.] 1999). Romano et al. (2004) examined the effects of single underwater impulse sounds from a seismic water gun (up to 228 dB re 1 μPa peak-to peak pressure) and single pure tones (sound pressure level up to 201 dB re 1 μPa) on the nervous and immune systems of a beluga and a bottlenose dolphin. They found that neural-immune changes to noise exposure were minimal. Although levels of some stress-released substances (e.g., catecholamines) changed significantly with exposure to sound, levels returned to baseline after 24 h. Further information about the occurrence of noise-induced stress in marine mammals is not available at this time. However, it is doubtful that any single marine mammal would be exposed to strong seismic sounds for sufficiently long that significant physiological stress would develop. This is particularly so in the case of seismic surveys where the tracklines are long and/or not closely spaced.

High sound levels could potentially cause bubble formation of diving mammals that in turn could cause an air or fat embolism, tissue separation, and high, localized pressure in nervous tissue (Gisiner [ed.] 1999; Houser et al. 2001). Moore and Early (2004) suggested that sperm whales are subjected to natural bone damage caused by repeated decompression events during their lifetimes. Those authors hypothesized that sperm whales are neither anatomically nor physiologically immune to the effects of deep diving. The possibility that marine mammals may be subject to decompression sickness was explored at a workshop (Gentry [ed.] 2002) held to discuss whether the stranding of beaked whales in the Bahamas in 2000 (Balcomb and Claridge 2001; NOAA and USN 2001) might have been related to air cavity resonance or bubble formation in tissues caused by exposure to noise from naval sonar. A panel of experts concluded that resonance in air-filled structures was not likely to have caused this stranding. Among other reasons, the air spaces in marine mammals are too large to be susceptible to resonant frequencies emitted by mid- or low-frequency sonar; lung tissue damage has not been observed in any mass, multi-species stranding of beaked whales; and the duration of sonar pings is likely too short to induce vibrations that could damage tissues (Gentry [ed.] 2002). Opinions were less conclusive about the possible role of gas (nitrogen) bubble formation/growth in the Bahamas stranding of beaked whales. Workshop participants did not rule out the possibility that bubble formation/growth played a role in the stranding, and participants acknowledged that more research is needed in this area.

Jepson et al. (2003) first suggested a possible link between mid-frequency sonar activity and acute and chronic tissue damage that results from the formation *in vivo* of gas bubbles, based on 14 beaked whales that stranded in the Canary Islands close to the site of an international naval exercise in September 2002. The interpretation that the effect was related to decompression injury was initially unproven (Piantadosi and Thalmann 2004; Fernández et al. 2004). However, there is increasing evidence and suspicion that decompression illness can occur in beaked whales and perhaps some other odontocetes, and that there may, at times, be a connection to noise exposure (see preceding section).

Gas and fat embolisms may occur if cetaceans ascend unusually quickly when exposed to aversive sounds, or if sound in the environment causes the destabilization of existing bubble nuclei (Potter 2004; Moore and Early 2004; Arbelo et al. 2005; Fernández et al. 2005a; Jepson et al. 2005b). Thus, air and fat embolisms could be a mechanism by which exposure to strong sounds could, indirectly, result in non-auditory injuries and perhaps death. However, even if those effects can occur during exposure to mid-frequency sonar, there is no evidence that those types of effects could occur in response to airgun sounds.

The only available information on acoustically-mediated bubble growth in marine mammals is modeling assuming prolonged exposure to sound. Crum et al. (2005) tested *ex vivo* bovine liver, kidney, and blood to determine the potential role of short pulses of sound to induce bubble nucleation or decompression sickness. In their experiments, supersaturated bovine tissues and blood showed extensive bubble production when exposed to low-frequency sound. Exposure to 37 kHz at ~50 kPa caused bubble formation in blood and liver tissue, and exposure to three acoustic pulses of 10,000 cycles, each 1 min, also produced bubbles in kidney tissue. Crum et al. (2005) speculated that marine mammal tissue may be affected in similar ways under such conditions. However, these results may not be directly applicable to free-ranging marine mammals exposed to sonar.

Recent controlled exposure of head tissue from a neonate Cuvier's beaked whale to high-intensity sonar-like sounds (3.5 kHz at 180 dB re 1 μPa received level) and related computational modeling indicated no evidence of any significant injurious effects to the tissue at this sound level (Krysl et al. 2006). The authors concluded that within the range of parameters tested, such tissues are not likely to suffer direct mechanical or thermal damage. However, more animal tissues and parameters will need to be tested to extrapolate the results of this study and model to other situations.

In summary, very little is known about the potential for seismic survey sounds to cause either auditory impairment or other non-auditory physical effects in marine mammals. Available data suggest that direct physiological effects, if they occur at all, would be limited to short distances. However, the available data do not allow for meaningful quantitative predictions of the numbers (if any) of marine mammals that might be affected in these ways. Marine mammals that show behavioral avoidance of seismic vessels, including most baleen whales, some odontocetes, and some pinnipeds, are unlikely to incur auditory impairment or other physical effects. It is not known whether aversive behavioral responses to airgun pulses by deep-diving species could lead to indirect physiological problems as apparently can occur upon exposure of some beaked whales to mid-frequency sonar (Cox et al. 2006).

(i) Literature Cited

Akamatsu, T., Y. Hatakeyama and N. Takatsu. 1993. Effects of pulsed sounds on escape behavior of false killer whales. **Nippon Suisan Gakkaishi** 59(8):1297-1303.

Angliss, R.P. and R.B. Outlaw. 2005. Alaska marine mammal stock assessments, 2005. NOAA Tech. Memo. NMFS-AFSC-161. Alaska Fisheries Science Center, National Marine Fisheries Service, Seattle, WA. 250 p.

Anonymous. 1975. Phantom killer whales. **S. Afr. Ship. News Fish. Ind. Rev.** 30(7):50-53.

Arbelo, M., M. Méndez, E. Sierra, P. Castro, J. Jaber, P. Calabuig, M. Carrillo and A. Fernández. 2005. Novel "gas embolic syndrome" in beaked whales resembling decompression sickness. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Arnold, B.W. 1996. Visual monitoring of marine mammal activity during the Exxon 3-D seismic survey: Santa Ynez unit, offshore California 9 November to 12 December 1995. Rep. by Impact Sciences Inc., San Diego, CA, for Exxon Company, U.S.A., Thousand Oaks, CA. 20 p.

Au, W.W.L. 1993. The sonar of dolphins. Springer-Verlag, New York, NY. 277 p.

Au, W. W. L., A.N. Popper and R.R. Fay. 2000. Hearing by whales and dolphins. Springer-Verlag, New York, NY. 458 p.

Au, W., J. Darling and K. Andrews. 2001. High-frequency harmonics and source level of humpback whale songs. **J. Acoust. Soc. Am.** 110(5, Pt. 2):2770.

Bain, D.E. and R. Williams. 2006. Long-range effects of airgun noise on marine mammals: responses as a function of received sound level and distance. **Int. Whal. Comm. Working Pap.** SC/58/E35. 13 p.

Baird, R.W. 2005. Sightings of dwarf (*Kogia sima*) and pygmy (*K. breviceps*) sperm whales from the main Hawaiian Islands. **Pac. Sci.** 59:461-466.

Balcomb, K.C., III and D.E. Claridge. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. **Bahamas J. Sci.** 8(2):2-12.

Barlow, J. and R. Gisiner. 2006. Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. **J. Cetac. Res. Manage.** 7:239-249.

Barton, P., J. Diebold, and S. Gulick. 2006. Balancing mitigation against impact: a case study from the 2005 Chicxulub seismic survey. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS41A-04. 23–26 May, Baltimore, MD.

Bowles, A.E., M. Smultea, B. Würsig, D.P. DeMaster and D. Palka. 1994. Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island Feasibility Test. **J. Acoust. Soc. Am.** 96:2469-2484.

Breitzke, M., O. Boebel, S. El Naggar, W. Jokat, G. Kuhn, F. Niessen, H. Schenke, B. Werner, and J. Diebold. 2006. Broadband sound pressure field characteristics of marine seismic sources used by R/V Polarstern. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS41A-02. 23–26 May, Baltimore, MD.

Bullock, T.H., T.J. O'Shea and M.C. McClune. 1982. Auditory evoked potentials in the West Indian manatee (Sirenia: *Trichechus manatus*). **J. Comp. Physiol. A** 148(4):547-554.

Burgess, W.C. and C.R. Greene, Jr. 1999. Physical acoustics measurements. p. 3-1 to 3-63 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1998. LGL Rep. TA22303. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 390 p.

Burgess, W.C. and J.W. Lawson. 2000. Marine mammal and acoustic monitoring of Western Geophysical's shallow-hazards survey in the Alaskan Beaufort Sea, summer 2000. p. C-1 to C-28 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 2000: 90-day report. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Anchorage, AK, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 121 p.

Calambokidis, J. and S.D. Osmek. 1998. Marine mammal research and mitigation in conjunction with air gun operation for the USGS `SHIPS' seismic surveys in 1998. Draft Rep. from Cascadia Research, Olympia, WA, for U.S. Geol. Surv., Nat. Mar. Fish. Serv., and Minerals Manage. Serv.

Caldwell, J. 2002. Does air-gun noise harm marine mammals? **The Leading Edge** 2002(1, Jan.):75-78.

Caldwell, J. and W. Dragoset. 2000. A brief overview of seismic air-gun arrays. **The Leading Edge** 2000(8, Aug.): 898-902.

Cavanagh, R.C. 2000. Criteria and thresholds for adverse effects of underwater noise on marine animals. Rep by Science Applications Intern. Corp., McLean, VA, for Air Force Res. Lab., Wright-Patterson AFB, Ohio. AFRL-HE-WP-TR-2000-0092.

Clark, C.W. and W.T. Ellison. 2004. Potential use of low-frequency sounds by baleen whales for probing the environment: evidence from models and empirical measurements. p. 564-582 *In:* J.A. Thomas, C.F. Moss and M. Vater (eds.), Echolocation in bats and dolphins. Univ. Chicago Press, Chicago, IL.

Cook, M.L.H., R.A. Varela, J.D. Goldstein, S.D. McCulloch, G.D. Bossart, J.J. Finneran, D. Houser, and A. Mann. 2006. Beaked whale auditory evoked potential hearing measurements. **J. Comp. Phys. A** 192:489-495.

Cox T.M., T.J. Ragen, A.J. Read, E. Vos, R.W. Baird, K. Balcomb, J. Barlow, J. Caldwell, T. Cranford, L. Crum, A. D'amico, G. D'spain, A. Fernández, J. Finneran, R. Gentry, W. Gerth, F. Gulland, J. Hildebrand, D. Houser, T. Hullar, P.D. Jepson, D. Ketten, C.D. Macleod, P. Miller, S. Moore, D.C. Mountain, D. Palka, P. Ponganis, S. Rommel, T. Rowles, B. Taylor, P. Tyack, D.Wartzok, R. Gisiner, J. Meads, and L. Benner. 2006. Understanding the impacts of anthropogenic sound on beaked whales. **J. Cetac. Res. Manage.** 7(3):177-187.

Crum, L.A. M.R. Bailey, J. Guan, P.R. Hilmo, S.G. Kargl and T.J. Matula. 2005. Monitoring bubble growth in supersaturated blood and tissue ex vivo and the relevance to marine mammal bioeffects. **ARLO** 6(3):214-220.

Dahlheim, M.E 1987. Bio-acoustics of the gray whale (*Eschrichtius robustus*). Ph.D. Thesis, Univ. Brit. Columbia, Vancouver, B.C. 315 p.

Dalton, R. 2006. Panel quits in row over sonar damage. **Nature** 439:376-377.

DeRuiter, S.L., Y-T. Lin, A.E. Newhall, P.T. Madsen, P.J.O. Miller, J.F. Lynch, and P.L. Tyack. 2005. Quantification and acoustic propagation modeling of airgun noise recorded on DTAG-tagged sperm whales in the Gulf of Mexico. p. 73 *In*: Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12–16 December 2005, San Diego, CA.

Diebold, J.B., M. Tolstoy, P.J. Barton, and S.P. Gulick. 2006. Propagation of exploration seismic sources in shallow water. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS41A-03. 23–26 May, Baltimore, MD.

Duncan, P.M. 1985. Seismic sources in a marine environment. p. 56-88 *In*: Proc. Workshop on effects of explosives use in the marine environment, Jan. 1985, Halifax, N.S. Tech. Rep. 5. Can. Oil & Gas Lands Admin. Environ. Prot. Br., Ottawa, Ont. 398 p.

D'Spain, G.D., A. D'Amico, and D.M. Fromm. 2006. Properties of underwater sound fields during some well documented beaked whale mass stranding events. **J. Cetac. Res. Manage.** 7(3):223-238.

Engel, M.H., M.C.C. Marcondes, C.C.A. Martins, F.O. Luna, R.P. Lima, and A. Campos. 2004. Are seismic surveys responsible for cetacean strandings? An unusual mortality of adult humpback whales in Abrolhos Bank, northeastern coast of Brazil. Working Paper SC/56/E28. Int. Whal. Comm., Cambridge, U.K. 8 p.

Fernández, A., M. Arbelo, R. Deaville, I.A.P. Patterson, P. Castro, J.R. Baker, E. Degollada, H.M. Ross, P. Herráez, A.M. Pocknell, E. Rodríguez, F.E. Howie, A. Espinosa, R.J. Reid, J.R. Jaber, V. Martin, A.A. Cunningham and P.D. Jepson. 2004. Pathology: whales, sonar and decompression sickness (reply). **Nature** 428(6984).

Fernández, A., J.F. Edwards, F. Rodriquez, A.E. de los Monteros, P. Herráez, P. Castro, J.R. Jaber, V. Martin and M. Arbelo. 2005a. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (Family Ziphiidae) exposed to anthropogenic sonar signals. **Vet. Pathol.** 42(4):446-457.

Fernández, A., M. Méndez, E. Sierra, A. Godinho, P. Herráez, A.E. De los Monteros, F. Rodrigues and M. Arbelo. 2005b. New gas and fat embolic pathology in beaked whales stranded in the Canary Islands. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Finneran, J.J. and C.E. Schlundt. 2004. Effects of intense pure tones on the behavior of trained odontocetes. Tech. Rep. 1913. Space and Naval Warfare (SPAWAR) Systems Center, San Diego, CA.

Finneran, J.J., C.E. Schlundt, D.A. Carder, J.A. Clark, J.A. Young, J.B. Gaspin and S.H. Ridgway. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. **J. Acoust. Soc. Am.** 108(1):417-431.

Finneran, J.J., C.E. Schlundt, R. Dear, D.A. Carder and S.H. Ridgway. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. **J. Acoust. Soc. Am.** 111(6):2929-2940.

Finneran, J.J., R. Dear, D.A. Carder and S.H. Ridgway. 2003. Auditory and behavioral responses of California sea lions (*Zalophus californianus*) to single underwater impulses from an arc-gap transducer. **J. Acoust. Soc. Am.** 114(3):1667-1677.

Finneran, J.J., D.A. Carder, C.E. Schlundt and S.H. Ridgway. 2005. Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. **J. Acoust. Soc. Am.** 118(4):2696-2705.

Fish, J.F. and J.S. Vania. 1971. Killer whale, *Orcinus orca*, sounds repel white whales, *Delphinapterus leucas*. **Fish. Bull.** 69(3):531-535.

Fox, C.G., R.P. Dziak and H. Matsumoto. 2002. NOAA efforts in monitoring of low-frequency sound in the global ocean. **J. Acoust. Soc. Am.** 112(5, Pt. 2):2260.

Frankel, A.S. 2005. Gray whales hear and respond to a 21–25 kHz high-frequency whale-finding sonar. p. 97 *In*: Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12–16 December 2005, San Diego, CA.

Frankel, A., W.J. Richardson, S. Carr, R. Spaulding, and W. Ellison. 2006. Estimating the acoustic exposure of marine mammals to seismic sources of the R/V *Maurice Langseth*. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS42A-05. 23–26 May, Baltimore, MD.

Frantzis, A. 1998. Does acoustic testing strand whales? **Nature** 392(6671):29.

Frost, K.J., L.F. Lowry and R.R. Nelson. 1984. Belukha whale studies in Bristol Bay, Alaska. pp. 187-200 *In*: B.R. Melteff and D.H. Rosenberg (eds.), Proc. workshop on biological interactions among marine mammals and commercial fisheries in the southeastern Bering Sea, Oct. 1983, Anchorage, AK. Univ. Alaska Sea Grant Rep. 84-1. Univ. Alaska, Fairbanks, AK.

Gentry, R. (ed.). 2002. Report of the workshop on acoustic resonance as a source of tissue trauma in cetaceans, Silver Spring, MD, April 2002. Nat. Mar. Fish. Serv. 19 p. Available at http://www.nmfs.noaa.gov/prot_res/PR2/Acoustics_Program/acoustics.html

Gentry, R., A. Bowles, W. Ellison, J. Finneran, C. Greene, D. Kastak, D. Ketten, J. Miller, P. Nachtigall, W.J. Richardson, B. Southall, J. Thomas and P. Tyack. 2004. Noise exposure criteria. Presentation to U.S. Mar. Mamm. Commis. Advis. Commit. on Acoustic Impacts on Marine Mammals, Plenary Meeting 2, Arlington, VA, April 2004. Available at http://mmc.gov/sound/plenary2/pdf/gentryetal.pdf

Gerstein, E.R., L.A. Gerstein, S.E. Forsythe and J.E. Blue. 1999. The underwater audiogram of a West Indian manatee (*Trichechus manatus*). **J. Acoust. Soc. Am.** 105(6):3575-3583.

Gisiner, R.C. (ed.). 1999. Proceedings/Workshop on the effects of anthropogenic noise in the marine environment, Bethesda, MD, Feb. 1998. Office of Naval Research, Arlington, VA. 141 p. Available at www.onr.navy.mil/sci%5Ftech/personnel/cnb%5Fsci/proceed.pdf.

Goold, J.C. 1996a. Acoustic assessment of common dolphins off the west Wales coast, in conjunction with 16th round seismic surveying. Rep. from School of Ocean Sciences, Univ. Wales, Bangor, Wales, for Chevron UK Ltd, Repsol Explor. (UK) Ltd., and Aran Energy Explor. Ltd. 22 p.

Goold, J.C. 1996b. Acoustic assessment of populations of common dolphin *Delphinus delphis* in conjunction with seismic surveying. **J. Mar. Biol. Assoc. U.K.** 76:811-820.

Goold, J.C. 1996c. Acoustic cetacean monitoring off the west Wales coast. Rep. from School of Ocean Sciences, Univ. Wales, Bangor, Wales, for Chevron UK Ltd, Repsol Explor. (UK) Ltd, and Aran Energy Explor. Ltd. 20 p.

Goold, J.C. and R.F.W. Coates. 2006. Near source, high frequency air-gun signatures. Working Paper SC/58/E30. Int. Whal. Comm., Cambridge, U.K.

Goold, J.C. and P.J. Fish. 1998. Broadband spectra of seismic survey air-gun emissions, with reference to dolphin auditory thresholds. **J. Acoust. Soc. Am.** 103(4):2177-2184.

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M.P. Simmonds, R. Swift and D. Thompson. 2004. A review of the effects of seismic surveys on marine mammals. **Mar. Technol. Soc. J.** 37(4):16-34.

Greene, C.R. 1997. An autonomous acoustic recorder for shallow arctic waters**. J. Acoust. Soc. Am.** 102(5, Pt. 2):3197.

Greene, C.R., Jr. and W.J. Richardson. 1988. Characteristics of marine seismic survey sounds in the Beaufort Sea. **J. Acoust. Soc. Am.** 83(6):2246-2254.

Greene, G.D., F.R. Engelhardt and R.J. Paterson (eds.). 1985. Proceedings of the workshop on effects of explosives use in the marine environment. Canadian Oil and Gas Lands Admin. and Environ. Prot. Branch, Ottawa, Ont. 398 p.

Greene, C.R., Jr., N.S. Altman and W.J. Richardson. 1999. Bowhead whale calls. p. 6-1 to 6-23 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1998. LGL Rep. TA2230-3. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 390 p.

Haley, B. and W.R. Koski. 2004. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic program in the Northwest Atlantic Ocean, July–August 2004. LGL Rep. TA2822-27. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Service, Silver Spring, MD. 80 p.

Harris, R.E., G.W. Miller and W.J. Richardson. 2001. Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. **Mar. Mamm. Sci.** 17(4):795-812.

HESS. 1999. High Energy Seismic Survey review process and interim operational guidelines for marine surveys offshore Southern California. Report from High Energy Seismic Survey Team for California State Lands Commission and U.S. Minerals Management Service [Camarillo, CA]. 39 p. + App. Available at www.mms.gov/omm/pacific/lease/fullhessrept.pdf

Hildebrand, J. 2004. Sources of anthropogenic noise in the marine environment. Paper presented at the International Policy Workshop on Sound and Marine Mammals, Mar. Mamm. Comm. and Joint Nature Conserv. Comm., 28–30 September,London,.U.K.

Hogarth, W.T. 2002. Declaration of William T. Hogarth in opposition to plaintiff's motion for temporary restraining order, 23 October 2002. Civ. No. 02-05065-JL. U.S. District Court, Northern District of California, San Francisco Div.

Hohn, A.A., D.S. Rotstein, C.A. Harms, and B.L. Southall. 2006. Report on marine mammal unusual mortality event UMESE0501Sp: multi-species stranding of short-finned pilot whales (*Globicephala macrorhnchus*), minke whale (*Balaenoptera acuturostrata*), and dwarf sperm whales (*Kogia sima*) in North Carolina, 15–16

January 2005. NOAA Tech. Memo. NMFS-SEFSC 537. Southeast Fisheries Science Center, Nat. Mar. Fish. Service, Miami, FL. 222 p.

Hollingshead, K R. and J. Harrison. 2005. Taking marine mammals incidental to maritime activities: an "insurance policy" for scientific, industrial and military maritime activities? p. 129 *In*: Abstr. 16th Bienn. Conf. Biol. Mar. Mamm., 12–16 December 2005, San Diego, CA.

Holst, M., M.A. Smultea, W.R. Koski and B. Haley. 2005a. Marine mammal and sea turtle monitoring during Lamont-Doherty Earth Observatory's marine seismic program off the Northern Yucatán Peninsula in the Southern Gulf of Mexico, January–February 2005. LGL Rep. TA2822-31. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 96 p.

Holst, M., M.A. Smultea, W.R. Koski and B. Haley. 2005b. Marine mammal and sea turtle monitoring during Lamont-Doherty Earth Observatory's marine seismic program in the Eastern Tropical Pacific Ocean off Central America, November–December 2004. LGL Rep. TA2822-30. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 125 p.

Holst, M., W.J. Richardson, W.R. Koski, M.A. Smultea, B. Haley, M.W. Fitzgerald, and M. Rawson. 2006. Effects of large and small-source seismic surveys on marine mammals and sea turtles. Abstract. Presented at Am. Geophys. Union - Soc. Explor. Geophys. Joint Assembly on Environ. Impacts from Marine Geophys. & Geological Studies - Recent Advances from Academic & Industry Res. Progr., May 2006, Baltimore, MD.

Hooker, S.K., R.W. Baird, S. Al-Omari, S. Gowans and H. Whitehead. 2001. Behavioural reactions of northern bottlenose whales (*Hyperoodon ampullatus*) to biopsy darting and tag attachment procedures. **Fish. Bull.** 99(2):303-308.

Houser, D.S., R. Howard and S. Ridgway. 2001. Can diving-induced tissue nitrogen supersaturation increase the chance of acoustically driven bubble growth in marine mammals? **J. Theor. Biol.** 213(2):183-195.

Hutchinson, D.R. and R.S. Detrick. 1984. Water gun vs. air gun: a comparison. **Mar. Geophys. Res.** 6(3):295-310.

IAGC. 2004. Further analysis of 2002 Abrolhos Bank, Brazil humpback whale strandings coincident with seismic surveys. Intern. Assoc. Geophys. Contr., Houston, TX.

IWC. 2007. Report of the standing working group on environmental concerns. Annex K to Report of the Scientific Committee. **J. Cetacean Res. Manage.** 9(Suppl.):227-260.

Jefferson, T.A. and B.E. Curry. 1994. Review and evaluation of potential acoustic methods of reducing or eliminating marine mammal-fishery interactions. Rep. from Mar. Mamm. Res. Prog., Texas A & M Univ., College Station, TX, for U.S. Mar. Mamm. Comm., Washington, DC. 59 p. NTIS PB95-100384.

Jepson, P.D., M. Arbelo, R. Deaville, I.A.P. Patterson, P. Castro, J.R. Baker, E. Degollada, H.M. Ross, P. Herráez, A.M. Pocknell, F. Rodríguez, F.E. Howie, A. Espinosa, R.J. Reid, J.R. Jaber, V. Martin, A.A. Cunningham and A. Fernández. 2003. Gas-bubble lesions in stranded cetaceans. **Nature** 425(6958):575-576.

Jepson, P.D., D.S. Houser, L.A. Crum, P.L. Tyack and A. Fernández. 2005a. Beaked whales, sonar and the "bubble hypothesis". Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Jepson, P.D. R. Deaville, I.A.P. Patterson, A.M. Pocknell, H.M. Ross, J.R. Baker, F.E. Howie, R.J. Reid, A. Colloff and A.A. Cunningham. 2005b. Acute and chronic gas bubble lesions in cetaceans stranded in the United Kingdom. **Vet. Pahol.** 42(3):291-305.

Johnson, M., P. Tyack, and P. Miller. 2004. Studies report on SWSS records with the digital sound recording tag. p. 87-90 *In*: A.E. Jochens and D.C. Biggs (eds.), Sperm whale seismic study in the Gulf of Mexico; Annual

Report: Year 2. . U.S. Dept. of the Int., Min. Manage. Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2004-067.

Johnson, S.R., W.J. Richardson, S.B. Yazvenko, S.A. Blokhin, G. Gailye, M.R. Jenkerson, S.K. Meier, H.R. Melton, M.W. Newcomer, A.S. Perlov, S.A. Rutenko, B. Würsig, C.R. Martin, and D.E. Egging. 2007. A western gray whale mitigation and monitoring program for a 3-D seismic survey, Sakhalin Island, Russia. **Environ. Monit. Assess.** DOI 10.1007/s10661-007-9813-0.

Kastak, D. and R.J. Schusterman. 1998. Low-frequency amphibious hearing in pinnipeds: methods, measurements, noise and ecology. **J. Acoust. Soc. Am.** 103(4): 2216-2228.

Kastak, D. and R.J. Schusterman. 1999. In-air and underwater hearing sensitivity of a northern elephant seal (*Mirounga angustirostris*). **Can. J. Zool.** 77(11):1751-1758.

Kastak, D., R.L. Schusterman, B.L. Southall and C.J. Reichmuth. 1999. Underwater temporary threshold shift induced by octave-band noise in three species of pinnipeds. **J. Acoust. Soc. Am.** 106:1142-1148.

Kastak, D., B.L. Southall, R.J. Schusterman and C.R. Kastak. 2005. Underwater temporary threshold shift in pinnipeds: effects of noise level and duration. **J. Acoust. Soc. Am.** 118(5):3154-3163.

Kastelein, R.A., P. Mosterd, B. van Santen, M. Hagedoorn and D. de Haan. 2002. Underwater audiogram of a Pacific walrus (*Odobenus rosmarus divergens*) measured with narrow-band frequency-modulated signals. **J. Acoust. Soc. Am.** 112(5):2173-2182.

Kasuya, T. 1986. Distribution and behavior of Baird's beaked whales off the Pacific coast of Japan. **Sci. Rep. Whales Res. Inst.** 37:61-83.

Kenyon, K.W. 1975. The sea otter in the eastern Pacific Ocean. Dover Publications, Inc., New York, NY.

Ketten, D.R. 1991. The marine mammal ear: specializations for aquatic audition and echolocation. p. 717-750 *In*: D. Webster, R. Fay and A. Popper (eds.), The Biology of Hearing. Springer-Verlag, Berlin.

Ketten, D.R. 1992. The cetacean ear: form, frequency, and evolution. p. 53-75 *In*: J. A. Thomas, R. A. Kastelein and A. Ya Supin (eds.), Marine Mammal Sensory Systems. Plenum, New York. 773 p.

Ketten, D.R. 1994. Functional analysis of whale ears: adaptations for underwater hearing. **IEEE Proc. Underwat. Acoust.** 1:264-270.

Ketten, D.R. 1995. Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. p. 391-407 *In:* R.A. Kastelein, J.A. Thomas, and P.E. Nachtigall (eds.), Sensory systems of aquatic mammals. De Spil Publ., Woerden, Netherlands. 588 p.

Ketten, D.R. 1998. Marine mammal auditory systems: a summary of audiometric and anatomical data and its implications for underwater acoustic impacts. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-256. Southwest Fisheries Science Center, Nat. Mar. Fish. Service, La Jolla, CA.

Ketten, D.R. 2000. Cetacean ears. p. 43-108 *In*: W.W.L. Au, A.N. Popper and R.R. Fay (eds.), Hearing by Whales and Dolphins. Springer-Verlag, New York, NY. 485 p.

Ketten, D.R., J. Lien and S. Todd. 1993. Blast injury in humpback whale ears: evidence and implications. **J. Acoust. Soc. Am.** 94(3, Pt. 2):1849-1850.

Ketten, D.R., J. O'Malley, P.W.B. Moore, S. Ridgway and C. Merigo. 2001. Aging, injury, disease, and noise in marine mammal ears. **J. Acoust. Soc. Am.** 110(5, Pt. 2):2721.

Klima, E.F., G.R. Gitschlag and M.L. Renaud. 1988. Impacts of the explosive removal of offshore petroleum platforms on sea turtles and dolphins. **Mar. Fish. Rev.** 50(3):33-42.

Krysl, P., T.W. Cranford, S.M. Wiggins, and J.A. Hildebrand. 2006. Simulating the effect of high-intensity sound on cetaceans: modeling approach and a case study for Cuvier's beaked whale (*Ziphius cavirostris*). **J. Acoust. Soc. Amer.** 120:2328-2339.

Kryter, K.D. 1985. The effects of noise on man, 2nd ed. Academic Press, Orlando, FL. 688 p.

Kryter, K.D. 1994. The handbook of hearing and the effects of noise. Academic Press, Orlando, FL. 673 p.

Lesage, V., C. Barrette, M.C.S. Kingsley and B. Sjare. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. **Mar. Mamm. Sci.** 15(1):65-84.

Ljungblad, D.K., B. Würsig, S.L. Swartz and J.M. Keene. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. **Arctic** 41(3):183-194.

MacLean, S.A. and W.R. Koski. 2005. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic program in the Gulf of Alaska, August–September 2004. LGL Rep. TA2822-28. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Service, Silver Spring, MD. 102 p.

Madsen, P.T., B. Mohl, B.K. Nielsen and M. Wahlberg. 2002. Male sperm whale behavior during exposures to distant seismic survey pulses. **Aquat. Mamm.** 28(3):231-240.

Malakoff, D. 2002. Suit ties whale deaths to research cruise. **Science** 298(5594):722-723.

Malme, C.I. and P.R. Miles. 1985. Behavioral responses of marine mammals (gray whales) to seismic discharges. p. 253-280 *In*: G.D. Greene, F.R. Engelhard and R.J. Paterson (eds.), Proc. Workshop on effects of explosives use in the marine environment, Jan. 1985, Halifax, N.S. Tech. Rep. 5. Can. Oil & Gas Lands Admin., Environ. Prot. Br., Ottawa, Ont. 398 p.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration. BBN Rep. 5586. Rep. from Bolt Beranek & Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. NTIS PB86-218377.

Malme, C.I., P.R. Miles, P. Tyack, C.W. Clark and J.E. Bird. 1985. Investigation of the potential effects of underwater noise from petroleum industry activities on feeding humpback whale behavior. BBN Rep. 5851; OCS Study MMS 85-0019. Rep. from BBN Labs Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Var. pag. NTIS PB86-218385.

Malme, C.I., B. Würsig, J.E. Bird and P. Tyack. 1986. Behavioral responses of gray whales to industrial noise: feeding observations and predictive modeling. Outer Cont. Shelf Environ. Assess. Progr., Final Rep. Princ. Invest., NOAA, Anchorage, AK 56(1988):393-600. BBN Rep. 6265. 600 p. OCS Study MMS 88-0048; NTIS PB88-249008.

Malme, C.I., B. Würsig, B., J.E. Bird and P. Tyack. 1987. Observations of feeding gray whale responses to controlled industrial noise exposure. p 55-73 *In:* W.M. Sackinger, M.O. Jeffries, J.L. Imm and S.D. Treacy (eds.), Port and Ocean Engineering Under Arctic Conditions. Vol. II. Symposium on noise and marine mammals. Published 1988. University of Alaska Fairbanks, Fairbanks AK.

Malme, C.I., B. Würsig, J.E. Bird and P. Tyack. 1988. Observations of feeding gray whale responses to controlled industrial noise exposure. p. 55-73 *In*: W.M. Sackinger, M.O. Jeffries, J.L. Imm and S.D. Treacy (eds.), Port and ocean engineering under arctic conditions, vol. II. Geophysical Inst., Univ. Alaska, Fairbanks, AK. 111 p.

Mann, D.A., R.A. Varela, J.D. Goldstein, S.D. McCulloch, G.D. Bossart, J.J. Finneran, D. Houser and M.L.H. Cook. 2005. Gervais' beaked whale auditory evoked potential hearing measurements. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Marine Technological Society. 2004. Human-generated ocean sound and the effects on marine life. **Mar. Tech. Soc. J.** 7:1-82.

Mate, B.R. and J.T. Harvey. 1987. Acoustical deterrents in marine mammal conflicts with fisheries. ORESU-W-86-001. Oregon State Univ., Sea Grant Coll. Progr., Corvallis, OR. 116 p.

Mate, B.R., K.M. Stafford and D.K. Ljungblad. 1994. A change in sperm whale (*Physeter macrocephalus*) distribution correlated to seismic surveys in the Gulf of Mexico. **J. Acoust. Soc. Am.** 96(2):3268-3269.

McAlpine, D.F. 2002. Pygmy and dwarf sperm whales *Kogia breviceps* and *K. sima*. p. 1007-1009 *In*: W.F. Perrin, B. Würsig, and J.G.M. Thewissen (eds.), Encyclopedia of marine mammals. Academic Press, San Diego, CA. 1414 p.

McCall Howard, M.P. 1999. Sperm whales *Physeter macrocephalus* in the Gully, Nova Scotia: Population, distribution, and response to seismic surveying. B.Sc. (Honors) Thesis. Dalhousie Univ., Halifax, N.S.

McCauley, R.D., M.-N. Jenner, C. Jenner, K.A. McCabe and J. Murdoch. 1998. The response of humpback whales (*Megaptera novaeangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. **APPEA J.** 38:692-707.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch and K. McCabe. 2000a. Marine seismic surveys: Analysis of airgun signals; and effects of air gun exposure on humpback whales, sea turtles, fishes and squid. Rep. from Centre for Marine Science and Technology, Curtin Univ., Perth, W.A., for Austral. Petrol. Prod. Assoc., Sydney, N.S.W. 188 p.

McCauley, R.D., J. Fewtrell, A.J. Duncan, M.-N. Jenner, M-N., C. Jenner, R.I.T. Prince, A. Adhitya, K. McCabe and J. Murdoch. 2000b. Marine seismic surveys - a study of environmental implications. **APPEA J.** 40:692-708.

McDonald, M.A., J.A. Hildebrand and S.C. Webb. 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. **J. Acoust. Soc. Am.** 98(2 Pt.1):712-721.

McShane, L.J., J.A. Estes, M.L. Riedman, and M.M. Staedler. 1995. Repertoire, structure, and individual variation of vocalizations in the sea otter. **J. Mammal.** 76:414-427.

Méndez, M., M. Arbelo, E. Sierra, A. Godinho, M.J. Caballero, J. Jaber, P. Herráez and A. Fernández. 2005. Lung fat embolism in cetaceans stranded in Canary Islands. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Miller, G.W., R.E. Elliott, W.R. Koski, V.D. Moulton and W.J. Richardson. 1999. Whales. p. 5-1 to 5-109 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1998. LGL Rep. TA2230-3. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 390 p.

Miller, J.H., A.E. Bowles, B.L. Southall, R.L. Gentry, W.T. Ellison, J.J. Finneran, C.R. Greene Jr., D. Kastak, D.R. Ketten, P.L. Tyack, P.E. Nachtigall, W.J. Richardson, and J.A. Thomas. 2005a. Strategies for weighting exposure in the development of acoustic criteria for marine mammals. **J. Acoust. Soc. Am.** 118:2019 (Abstract). Presentation accessed on 21 March 2007 at http://www.oce.uri.edu/faculty_pages/miller/Noise_Weighting_10_18_2005.ppt.

Miller, G.W., V.D. Moulton, R.A. Davis, M. Holst, P. Millman, A. MacGillivray, and D. Hannay. 2005b. Monitoring seismic effects on marine mammals—southeastern Beaufort Sea, 2001-2002. *In*: S.L. Armsworthy, P.J. Cranford, and K. Lee (eds.), Offshore oil and gas environmental effects monitoring/ Approaches and technologies. Battelle Press, Columbus, OH.

Miller, P.J., P.L. Tyack, M.P. Johnson, P.T. Madsen, and R. King. 2006. Techniques to assess and mitigate the environmental risk posed by use of airguns: recent advances from academic research program. Abstract. Presented at Am. Geophys. Union - Soc. Explor. Geophys. Joint Assembly on Environ. Impacts from Marine Geophys. & Geological Studies - Recent Advances from Academic & Industry Res. Progr., May 2006, Baltimore, MD. 125p.

Mooney, T.A., P.E. Nachtigall, W.W.L. Au, M. Breese and S. Vlachos. 2005. Bottlenose dolphins: effects of noise duration, intensity, and frequency. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Moore, M.J. and G.A. Early. 2004. Cumulative sperm whale bone damage and the bends. **Science** 306:2215.

Moore, S.E. and R.P. Angliss. 2006. Overview of planned seismic surveys offshore northern Alaska, July-October 2006. Working Paper SC/58/E6, Int. Whal. Comm., Cambridge, U.K.

Moulton, V.D. and J.W. Lawson. 2002. Seals, 2001. p. 3-1 to 3-48 *In*: W.J. Richardson (ed.), Marine mammal and acoustical monitoring of WesternGeco's open water seismic program in the Alaskan Beaufort Sea, 2001. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for WesternGeco, Houston, TX, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. LGL Rep. TA2564-4.

Moulton, V.D. and G.W. Miller. In press. Marine mammal monitoring of a seismic survey on the Scotian Slope, 2003. **Can. Tech. Rep Fish. Aquat. Sci.** 2003.

Nachtigall, P.E., J.L. Pawloski and W.W.L. Au. 2003. Temporary threshold shifts and recovery following noise exposure in the Atlantic bottlenosed dolphin (*Tursiops truncatus*). **J. Acoust. Soc. Am.** 113(6):3425-3429.

Nachtigall, P.E., A.Y. Supin, J. Pawloski and W.W.L. Au. 2004. Temporary threshold shifts after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using evoked auditory potentials. **Mar. Mamm. Sci.** 20 (4):673-687

Nachtigall, P.E., A.Y. Supin, M. Amundin, B. Röken,,T. Møller, A. Mooney, K.A. Taylor, and M. Yuen. 2007. Polar bear *Ursus maritimus* hearing measured with auditory evoked potentials. **J. Exp. Biol.** 210:1116-1122.

Nieukirk, S.L., K.M. Stafford, D.K. Mellinger, R.P. Dziak and C.G. Fox. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. **J. Acoust. Soc. Am.** 115(4):1832-1843.

Nieukirk, S.L., D.K. Mellinger, J.A. Hildebrand, M.A. McDonald and R.P. Dziak. 2005. Downward shift in the frequency of blue whale vocalizations. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

NMFS. 1995. Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. **Fed. Regist.** 60(200, 17 Oct.):53753-53760.

NMFS. 2000. Small takes of marine mammals incidental to specified activities; marine seismic-reflection data collection in southern California/Notice of receipt of application. **Fed. Regist.** 65(60, 28 Mar.):16374-16379.

NMFS. 2001. Small takes of marine mammals incidental to specified activities; oil and gas exploration drilling activities in the Beaufort Sea/Notice of issuance of an incidental harassment authorization. **Fed. Regist**. 66(26, 7 Feb.):9291-9298.

NMFS. 2005. Endangered fish and wildlife; Notice of intent to prepare an Environmental Impact Statement. **Fed. Regist.** 70(7, 11 Jan.):1871-1875.

NOAA and USN. 2001. Joint interim report: Bahamas marine mammal stranding event of 14-16 March 2000. U.S. Dep. Commer., Nat. Oceanic Atmos. Admin., Nat. Mar. Fish. Serv., Sec. Navy, Assis. Sec. Navy, Installations and Envir. 61 p.

Nowacek, D.P., L.H. Thorne, D.W. Johnston, and P.L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. **Mammal Rev.** 37(2):81-115.

NRC. 2005. Marine mammal populations and ocean noise: determining when noise causes biologically significant effects. U.S. Nat. Res. Counc., Ocean Studies Board, Committee on Characterizing Biologically Significant Marine Mammal Behavior (D.W. Wartzok, J. Altmann, W. Au, K. Ralls, A. Starfield, and P.L. Tyack). Nat. Acad. Press, Washington, DC. 126 p.

Parks, S.E., C.W. Clark and P.L. Tyack. 2005. North Atlantic right whales shift their frequency of calling in response to vessel noise. Abstracts of the 16th biennial conference on the biology of marine mammals, San Diego, CA, 12-16 December 2005.

Piantadosi, C.A. and E.D. Thalmann. 2004. Pathology: whales, sonar and decompression sickness. **Nature** 428(6984).

Potter, J.R. 2004. A possible mechanism for acoustic triggering of decompression sickness symptoms in deep-diving marine mammals. Paper presented to the 2004 IEEE International Symposium on Underwater Technology, Taipei, Taiwan, 19-23 April 2004.

Potter, J.R., M. Thillet, C. Douglas, M. Chitre, Z. Doborzynski, and P. Seekings. 2006. Visual and passive acoustic marine mammal observations and high-frequency seismic source characteristics recorded during a seismic survey. Working Paper SC/58/Info15. Int. Whal. Comm., Cambridge, U.K.

Racca, R., D. Hannay, and S. Carr. 2006. Current state of acoustic wave propagation modeling and its use in the estimation of impact on marine mammals. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS42A-04. 23–26 May, Baltimore, MD.

Reeves, R.R., E. Mitchell and H. Whitehead. 1993. Status of the northern bottlenose whale, *Hyperoodon ampullatus*. **Can. Field-Nat.** 107(4):490-508.

Reeves, R.R., R.J. Hofman, G.K. Silber and D. Wilkinson. 1996. Acoustic deterrence of harmful marine mammal-fishery interactions: proceedings of a workshop held in Seattle, Washington, 20-22 March 1996. NOAA Tech. Memo NMFS-OPR-10. U.S. Dep. Commerce, Nat. Mar. Fish. Serv. 70 p.

Richardson, W.J. and C.I. Malme. 1993. Man-made noise and behavioral responses. p. 631-700 *In*: J.J. Burns, J.J. Montague and C.J. Cowles (eds.), The bowhead whale. Spec. Publ. 2, Soc. Mar. Mammal., Lawrence, KS. 787 p.

Richardson, W.J. and B. Würsig. 1997. Influences of man-made noise and other human actions on cetacean behaviour. **Mar. Freshwat. Behav. Physiol.** 29(1-4):183-209.

Richardson, W.J., B. Würsig and C.R. Greene. 1986. Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. **J. Acoust. Soc. Am.** 79(4):1117-1128.

Richardson, W.J., R.A. Davis, C.R. Evans, D.K. Ljungblad and P. Norton. 1987. Summer distribution of bowhead whales, *Balaena mysticetus*, relative to oil industry activities in the Canadian Beaufort Sea, 1980-84. **Arctic** 40(2):93-104.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme and D.H. Thomson. 1995. Marine mammals and noise. Academic Press, San Diego. 576 p.

Richardson, W.J., G.W. Miller and C.R. Greene Jr. 1999. Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. **J. Acoust. Soc. Am.** 106(4, Pt. 2):2281.

Ridgway, S.H., D.A. Carder, R.R. Smith, T. Kamolnick, C.E. Schlundt and W.R. Elsberry. 1997. Behavioral responses and temporary shift in masked hearing threshold of bottlenose dolphins, *Tursiops truncatus*, to 1-second tones of 141 to 201 dB re 1 µPa. Tech. Rep. 1751. NRAD, RDT&E Div., Naval Command, Control & Ocean Surveillance Center, San Diego, CA. 27 p.

Riedman, M.L. 1983. Studies of the effects of experimentally produced noise associated with oil and gas exploration and development on sea otters in California. Rep. from Cent. Coastal Mar. Stud., Univ. Calif. Santa Cruz, CA, for U.S. Minerals Manage. Serv., Anchorage, AK. 92 p. NTIS PB86-218575

Riedman, M.L. 1984. Effects of sounds associated with petroleum industry activities on the behavior of sea otters in California. P. D-1 to D-12 *In*: C.I. Malme, P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird, Investigations of the potential effects of underwater noise form petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration. BBN Rep. 5586. Rep. from Bolt Beranek & Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Var. pag. NTIA PB86-218377.

Romano, T.A., M.J. Keogh, C.Kelly, P. Feng, L. Berk, C.E. Schlundt, D.A. Carder and J.J. Finneran. 2004. Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. **Can. J. Fish. Aquat. Sci.** 61:1124-1134.

Rommel, S.A., A.M. Costidis, A. Fernandez, P.D. Jepson, D.A. Pabst, W.A. McLellan, D.S. Houser, T.W. Cranford, A.L. van Helden, D.M. Allen, and N.B. Barros. 2006. Elements of beaked whale anatomy and diving physiology, and some hypothetical causes of sonar-related stranding. **J. Cetac. Res. Manage.** 7(3):189-209.

SACLANT. 1998. Estimation of cetacean hearing criteria levels. Section II, Chapter 7 *In*: SACLANTCEN Bioacoustics Panel Summary Record and Report. Report by NATO SACLANT Undersea Research Center. 60 p. Available at http://enterprise.spawar.navy.mil/spawarpublicsite/

Schlundt, C.E., J.J. Finneran, D.A. Carder and S.H. Ridgway. 2000. Temporary shift in masking hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. **J. Acoust. Soc. Am.** 107(6):3496-3508.

Schusterman, R., D. Kastak, B. Southall and C. Kastak. 2000. Underwater temporary threshold shifts in pinnipeds: tradeoffs between noise intensity and duration. **J. Acoust. Soc. Am.** 108(5, Pt. 2):2515-2516.

Simmonds, M. P. and L.F. Lopez-Jurado. 1991. Whales and the military. **Nature** 351(6326):448.

Simmonds, M.P., S.J. Dolman, and L. Weilgart (eds.). 2006. Oceans of noise 2004: A WDCS science report. Whale and Dolphin Conservation Society, Chippenham, UK. 168 p. Accessed on 21 March 2007 at http://www.wdcs.org/dan/publishing.nsf/allweb/48A0C8D9C559FA0680256D2B004027D4.

Smultea, M.A., M. Holst, W.R. Koski and S. Stoltz. 2004. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic program in the Southeast Caribbean Sea and adjacent Atlantic Ocean, April–June 2004. LGL Rep. TA2822-26. Rep. From LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. 106 p.

Sodal, A. 1999. Measured underwater acoustic wave propagation from a seismic source. Proc. Airgun Environ. Workshop, 6 July, London, UK.

Southall, B.L., R. Braun, F.M.D. Gulland, A.D. Heard, R.W. Baird, S.M. Wilkin, and T.K. Rowles. 2006. Hawaiian melon-headed whale (*Peponacephala electra*) mass stranding event of July 3–4, 2004. NOAA Tech. Memo. NMFS-OPR-31. Nat. Mar. Fish. Service, Silver Spring, MD. 73 p.

Stone, C.J. 2003. The effects of seismic activity on marine mammals in UK waters 1998-2000. JNCC Report 323. Joint Nature Conservancy, Aberdeen, Scotland. 43 p.

Terhune, J.M. 1999. Pitch separation as a possible jamming-avoidance mechanism in underwater calls of bearded seals (*Erignathus barbatus*). **Can. J. Zool.** 77(7):1025-1034.

Thompson, D., M. Sjöberg, E.B. Bryant, P. Lovell and A. Bjørge. 1998. Behavioural and physiological responses of harbour (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals to seismic surveys. p. 134 *In:* World Marine Mammal Science Conf. Abstract volume, Monaco. 160 p.

Thomson, D.H. and W.J. Richardson. 1995. Marine mammal sounds. p. 159-204 *In:* W.J. Richardson, C.R. Greene, Jr., C.I. Malme, and D.H. Thomson, Marine mammals and noise. Academic Press, San Diego, CA. 576 p.

Tolstoy, M., J. Diebold, S. Webb, D. Bohnenstiehl and E. Chapp. 2004a. Acoustic calibration measurements. Chapter 3 *In:* W.J. Richardson (ed.), Marine mammal and acoustic monitoring during Lamont-Doherty Earth Observatory's acoustic calibration study in the northern Gulf of Mexico, 2003. Revised ed. Rep. from LGL Ltd., King City, Ont., for Lamont-Doherty Earth Observ., Palisades, NY, and Nat. Mar. Fish. Serv., Silver Spring, MD. [Advance copy of updated Chapter 3.]

Tolstoy, M., J.B. Diebold, S.C. Webb, D.R. Bohenstiehl, E. Chapp, R.C. Holmes and M. Rawson. 2004b. Broadband calibration of R/V *Ewing* seismic sources. **Geophys. Res. Lett.** 31:L14310.

Turner, S., M. Zykov, and A. MacGillivray. 2006. Preliminary acoustic level measurements of airgun sources from ConocoPhillips' 2006 seismic survey in Alaskan Chukchi Sea. Rep. from JASCO Research Ltd., Victoria, BC.

Tyack, P., M. Johnson and P. Miller. 2003. Tracking responses of sperm whales to experimental exposures of airguns. p. 115-120 *In:* A.E. Jochens and D.C. Biggs (eds.), Sperm whale seismic study in the Gulf of Mexico/Annual Report: Year 1. OCS Study MMS 2003-069. Rep. from Texas A&M Univ., College Station, TX, for U.S. Minerals Manage. Serv., Gulf of Mexico OCS Reg., New Orleans, LA.

Tyack, P., M. Johnson, and P. Miller. 2006a. Response of sperm whales to airgun sounds in the Gulf of Mexico. Pages 215-168 *In:* A.E. Jochens et al., Sperm whale seismic study in the Gulf of Mexico. Summary Report, 2002-2004. OCS Study MMS 2006-034. Rep. from Texas A&M Univ., College Station, TX, for U.S. Minerals Manage. Serv., Gulf of Mexico OCS Reg., New Orleans, LA.

Tyack, P.L., M.P. Johnson, P.T. Madsen, P.J. Miller, and J. Lynch. 2006b. Biological significance of acoustic impacts on marine mammals: examples using an acoustic recording tag to define acoustic exposure of sperm whales, *Physeter catodon*, exposed to airgun sounds in controlled exposure experiments. Eos Trans. Amer. Geophys. Union 87(36), Joint Assembly Suppl., Abstr. OS42A-02. 23–26 May, Baltimore, MD.

Urick, R.J. 1983. Principles of underwater sound, 3rd ed. McGraw-Hill, New York, NY. 423 p.

Watkins, W.A. 1986. Whale reactions to human activities in Cape Cod waters. **Mar. Mamm. Sci.** 2(4):251-262.

Watkins, W.A. and W.E. Schevill. 1975. Sperm whales (*Physeter catodon*) react to pingers. **Deep-Sea Res.** 22(3):123-129.

Watkins, W.A., K.E. Moore and P. Tyack. 1985. Sperm whale acoustic behaviors in the southeast Caribbean. **Cetology** 49:1-15.

Weller, D.W., Y.V. Ivashchenko, G.A. Tsidulko, A.M. Burdin and R.L. Brownell, Jr. 2002. Influence of seismic surveys on western gray whales off Sakhalin Island, Russia in 2001. Working Paper SC/54/BRG14, Int. Whal. Comm., Western Gray Whale Working Group Meeting, Ulsan, South Korea, 22-25 October 2002. 12 p.

Weller, D.W., S.H. Rickards, A.L. Bradford, A.M. Burdin, and R.L. Brownell, Jr. 2006a. The influence of 1997 seismic surveys on the behavior of western gray whales off Sakhalin Island, Russia. Working Paper SC/58/E4, Int. Whal. Comm., Cambridge, U.K.

Weller, D.W., G.A. Tsidulko, Y.V. Ivashchenko, A.M. Burdin, and R.L. Brownell Jr. 2006b. A re-evaluation of the influence of 2001 seismic surveys on western gray whales off Sakhalin Island, Russia. Working Paper SC/58/E5, Int. Whal. Comm., Cambridge, U.K.

Wieting, D. 2004. Background on development and intended use of criteria. p. 20 *In*: S. Orenstein, L. Langstaff, L. Manning, and R. Maund (eds.), Advisory Committee on Acoustic Impacts on Marine Mammals, final meeting summary. Second meeting, Mar. Mamm. Comm., April 28–30, 2004, Arlington, VA.

Würsig, B., S.K. Lynn, T.A. Jefferson and K.D. Mullin. 1998. Behaviour of cetaceans in the northern Gulf of Mexico relative to survey ships and aircraft. **Aquat. Mamm.** 24(1):41-50.

Würsig, B.G., D.W. Weller, A.M. Burdin, S.H. Reeve, A.L Bradford, S.A. Blokhin and R.L Brownell (Jr.). 1999. Gray whales summering off Sakhalin Island, Far East Russia: July-October 1997. A joint U.S.-Russian scientific investigation. Final Report by Texas A&M Univ., College Station, TX, and Kamchatka Inst. Ecol. and Nature Manage., Russian Acad. Sci., Kamchatka, Russia, for Sakhalin Energy Investment Co. Ltd and Exxon Neftegaz Ltd, Yuzhno-Sakhalinsk, Russia. 101 p.

Yoder, J.A. 2002. Declaration of James A. Yoder in opposition to plaintiff's motion for temporary restraining order, 28 October 2002. Civ. No. 02-05065-JL. U.S. District Court, Northern District of California, San Francisco Division.

APPENDIX D:
REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON SEA TURTLES[7]

The following subsections review relevant information concerning the potential effects of airgun sounds on sea turtles. This information is included here as background for the briefer summary of this topic included in § IV of the EA. This background material is little changed from corresponding subsections included in IHA applications and EAs submitted to NMFS for previous L-DEO seismic surveys. Those documents concerned L-DEO projects in the following areas: northern Gulf of Mexico, Hess Deep (Eastern Tropical Pacific), Norwegian Sea, Mid-Atlantic Ocean, Southeast Caribbean, Southeast Alaska, Blanco Fracture Zone (northeast Pacific), Eastern Tropical Pacific off Central America, southern Gulf of Mexico (Yucatán Peninsula), and Aleutian Islands, Alaska. Much of this information has also been included in varying formats in other reviews, assessments, and regulatory applications prepared by LGL Ltd., environmental research associates.

(a) Sea Turtle Hearing

Although there have been a limited number of studies on sea turtle hearing, the available data are not very comprehensive. However, the available data show that sea turtles can hear moderately low-frequency sounds, including some of the frequencies that are prominent in airgun pulses.

Ridgway et al. (1969) and Lenhardt et al. (1985) provide detailed descriptions of the sea turtle ear structure; the reader is referred to those documents for further detail. Sea turtles do not have external ears. However, the sea turtle middle ear is well designed as a peripheral component of a bone conduction system. The thick tympanum, which is unique to sea turtles, is disadvantageous as an aerial receptor, but likely enhances low-frequency bone conduction hearing (Lenhardt et al. 1985). The tympanum acts as additional mass loading to the middle ear, which in mammals increases low-frequency bone conduction sensitivity (Tonndorf 1966 *in* Lenhardt et al. 1985). Sea turtles may be able to localize the direction from which an underwater sound is being received (Lenhardt et al. 1983). There is also the possibility that the middle ear functions as a "traditional aerial" receptor underwater. Any air behind the tympanum could vibrate, similar to the air in a fish swim bladder, and result in columellar motion (Lenhardt et al. 1985). (The columella of turtles takes the place of the three middle-ear ossicles in mammals.) Turtle hearing may involve both bone conduction and air conduction. However, it is likely that the path of sound energy to the sea turtle ear involves water/bone conduction and not air conduction, as sea turtles spend the majority of their time underwater (Musick and Limpus 1997).

Ridgway et al. (1969) obtained the first direct measurements of hearing sensitivity in any sea turtle. They used an electrophysiological technique (cochlear potentials) to determine the response of green sea turtle ears to aerial and vibrational stimuli that produced tones from 30 to 700 Hz. They found that green

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[7] By **Valerie D. Moulton and W. John Richardson**, LGL Ltd., environmental research associates. November 2000.

turtles exhibit maximum hearing sensitivity between 300 and 500 Hz, and speculated that the turtles had a useful hearing span of 60–1000 Hz. (However, there was some response to strong vibrational signals at frequencies down to the lowest one tested—30 Hz.) Electrophysiological measures of hearing in other types of animals have shown that those methods provide good information about relative sensitivity to different frequencies, but may underestimate the frequency range to which the animal is sensitive, and may not determine the absolute hearing thresholds very precisely.

Moein Bartol et al. (1999) tested the hearing of juvenile loggerhead turtles. The authors used a standard electrophysiological method (auditory brainstem response, ABR) to determine the response of the sea turtle ear to two types of vibrational stimuli: (1) brief, low-frequency broadband clicks, and (2) brief tone bursts at four frequencies from 250 to 1000 Hz. They demonstrated that loggerhead sea turtles hear well between 250 and 1000 Hz; within that frequency range, the turtles were most sensitive at 250 Hz. The authors did not measure hearing sensitivity below 250 Hz or above 1000 Hz. There was an extreme decrease in response to stimuli above 1000 Hz, and the vibrational intensities required to elicit a response may have damaged the turtle's ear. The signals used in this study were very brief—0.6 ms for the clicks, and 0.8–5.5 ms for the tone bursts. In other animals, auditory thresholds decrease with increasing signal duration up to about 100–200 ms. Thus, sea turtles probably could hear weaker signals than demonstrated in the study if the signal duration were longer.

Moein et al. (1994) used a related evoked potential method to test the hearing of loggerhead sea turtles exposed to a few hundred pulses from a single airgun. Turtle hearing was tested before, within 24 h after, and two weeks after exposure to pulses of airgun sound. Levels of airgun sound to which the turtles were exposed were not specifically reported. (The exposures to airgun sound are described in more detail in the next section, on behavioral reactions.) The authors concluded that five turtles (of ~11 tested?) exhibited some change in their hearing when tested within 24 h after exposure relative to pre-exposure hearing, and that hearing had reverted to normal when tested two weeks after exposure. The results are consistent with the occurrence of Temporary Threshold Shift (TTS), i.e. temporary hearing impairment, upon exposure of the turtles to airgun pulses. Unfortunately, the report did not state the size of the airgun used, or the received sound levels at various distances. The distances of the turtles from the airgun were also variable during the tests; the turtle was about 30 m from the airgun at the start of each trial, but it could then either approach the airgun or move away to a maximum of about 65 m during subsequent airgun pulses. Thus, the levels of airgun sounds that apparently elicited TTS are not known. Nonetheless, it is noteworthy that there was evidence of TTS from exposure to pulses from a single airgun. However, it may be relevant that the turtles were confined and unable to move more than about 65 m away. Turtles in the open sea might move away, resulting in less exposure than occurred during the experiment.

In summary, the limited available data indicate that the frequency range of best hearing sensitivity by sea turtles extends from roughly 250–300 Hz to 500–700 Hz. Sensitivity deteriorates as one moves away from this range to either lower or higher frequencies. However, there is some sensitivity to frequencies as low as 60 Hz, and probably as low as 30 Hz. Thus, there is substantial overlap in the frequencies that sea turtles detect *vs*. the frequencies in airgun pulses. Given that, plus the high levels of airgun pulses, sea turtles undoubtedly hear airgun sounds. We are not aware of measurements of the absolute hearing thresholds of any sea turtle to waterborne sounds similar to airgun pulses. Given the high source levels of airgun pulses and the substantial levels even at distances many km away from the source, sea turtles probably can hear distant seismic vessels. However, in the absence of relevant absolute threshold data, we cannot estimate how far away an airgun array might be audible. The apparent occurrence of TTS in loggerhead turtles exposed to pulses from a single airgun ≤65 m away suggests that sounds from an airgun array could cause at least temporary hearing impairment in sea turtles if they do not avoid the (unknown) radius where TTS occurs.

(b) Effects of Airgun Pulses on Behavior and Movements

Effects of exposure to airgun pulses on the behavior and distribution of various marine animals have been studied during the past two decades. Most of these studies have concerned marine mammals and fish, as reviewed by Richardson et al. (1995) and Gordon et al. (2004) for marine mammals, and Thomson et al. (2001) for fish. There have been far fewer studies of the effects of airgun noise (or indeed any type of noise) on sea turtles. We are aware of three such studies, each of which focused on short-term behavioral responses of sea turtles in enclosures to single airguns. Comparisons of results among studies are difficult because experimental designs and reporting procedures have varied greatly, and only one of the studies provided specific information about the levels of the airgun pulses received by the turtles. We are not aware of any studies on responses of free-ranging sea turtles to seismic sounds or on the long-term effects of seismic or other sounds on sea turtles.

The most recent of the studies of caged sea turtles exposed to airgun pulses was a study by McCauley et al. (2000) off Western Australia. This is apparently the only such study in which received sound levels were estimated carefully. McCauley et al. exposed caged green and loggerhead sea turtles (one of each) to pulses from an approaching and then receding 20-in^3 airgun operating at 1500 psi and 5 m airgun-depth. The single airgun fired every 10 s. There were two trials separated by two days; the first trial involved ~2 h of airgun exposure and the second ~1 h. The results from the two trials showed that, above a received level of 166 dB re 1 μPa_{rms} [8], the turtles noticeably increased their speed of swimming relative to periods when no airguns were operating. The behavior of the sea turtles became more erratic when received levels exceeded 175 dB re 1 μPa_{rms}. The authors suggested that the erratic behavior exhibited by the caged sea turtles would likely, in unrestrained turtles, be expressed as an avoidance response (McCauley et al. 2000).

O'Hara and Wilcox (1990) tested the reactions to airguns of loggerhead sea turtles held in a 300 x 45 m area of a canal 10 m deep in Florida. Nine turtles were tested at different times. The sound source consisted of one 10 in^3 airgun plus two 0.8 in^3 "poppers" operating at 2000 psi [9] and airgun-depth 2 m for prolonged periods: 20-36 hours in duration. The turtles maintained a standoff range of about 30 m when

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[8] rms = root mean square. This measure represents the average received sound pressure over the duration of the pulse, with duration being defined in a specific way (from the time when 5% of the pulse energy has been received to the time when 95% of the energy has been received). The rms received level of a seismic pulse is typically about 10 dB less than its peak level, and about 16 dB less than its peak-to-peak level (Greene et al. 1997, 2000; McCauley et al. 1998, 2000).

[9] There was no significant reaction by five turtles during an initial series of tests with the airguns operating at the unusually low pressure of 1000 psi. The source and received levels of airgun sounds would have been substantially lower when the air pressure was only 1000 psi than when it was at the more typical operating pressure of 2000 psi.

exposed to airgun pulses every 15 s or every 7.5 s. It was also possible that some turtles remained on the bottom of the enclosure when exposed to airgun pulses. O'Hara and Wilcox (1990) did not measure the received airgun sound levels. McCauley et al. (2000) estimated that "the level at which O'Hara saw avoidance was around 175–176 re 1 μPa_{rms}". The levels received by the turtles in the Florida study probably were actually a few dB less than 175–176 dB re 1 μPa_{rms} because the calculations by McCauley et al. apparently did not allow for the shallow 2-m airgun depth in the Florida study. The effective source level of airguns is less when they are near 2 m depth than at 5 m (Greene et al. 2000).

Moein et al. (1994) investigated the avoidance behavior and physiological responses of loggerhead turtles exposed to an operating airgun, as well as the effects on their hearing as summarised earlier. The turtles were held in a netted enclosure about 18 m by 61 m by 3.6 m deep, with an airgun of unspecified size at each end. Only one airgun was operated at any one time; firing rate was one shot every 5-6 s. Ten turtles were tested individually, and seven of these were retested several days later. The airgun was initially discharged when the turtles were near the centre of the enclosure and the subsequent movements of the turtles were documented. The turtles exhibited avoidance during the first presentation of airgun sounds at a mean range of 24 m, but the avoidance response waned quickly. Additional trials conducted on the same turtles several days later did not show statistically significant avoidance reactions, although there was an indication of slight initial avoidance followed by rapid waning of the avoidance response. The authors described the rapid waning of the avoidance response as "habituation". Their auditory study indicated that exposure to the airgun pulses may have resulted in temporary hearing impairment (TTS, see earlier). Reduced hearing sensitivity may also have contributed to the waning response upon continued exposure. There was some evidence from the physiological measurements of increased stress in the sea turtles, but this stress could also have been a result of handling of the turtles.

Once again, inconsistencies in reporting procedures and experimental design prevent direct comparison of this study with either McCauley et al. (2000) or O'Hara and Wilcox (1990). Moein et al. stated, without further details, that "three different decibel levels (175, 177, 179) were utilised" during each test. These figures probably are received levels in dB re 1 µPa, and probably relate to the initial exposure distance (mean 24 m), but these details were not specified. Also, it was not specified whether these values were measured or estimated, or whether they are expressed in peak-peak, peak, rms, SEL, or some other units. Given the shallow water in the enclosure (3.6 m), any estimates based on simple assumptions about propagation would be suspect.

Despite the problems in comparing these three studies, there is a consistent trend showing that, at some received level, sea turtles show avoidance of an operating airgun. McCauley et al. (2000) found evidence of behavioral responses when the received level from a single small airgun was 166 dB re 1 $\mu Pa_{rms,}$ and avoidance responses at 175 dB re 1 μPa_{rms}. Based on these data, McCauley et al. estimated that, for a typical airgun array (2678 in^3, 12-elements) operating in 100-120 m water depth, sea turtles may exhibit behavioral changes at approximately 2 km and avoidance around 1 km. These estimates are subject to great variation, depending on the seismic source and local propagation conditions.

A further potential complication is that sea turtles on or near the bottom may receive sediment-borne "headwave" signals from the airguns (McCauley et al. 2000). As previously discussed, it is believed that sea turtles use bone conduction to hear. It is unknown how sea turtles might respond to the headwave component of an airgun impulse, or to bottom vibrations.

A pair of related studies involving stimuli other than airguns may also be relevant. ***(1)*** Two loggerhead turtles resting on the bottom of shallow tanks responded repeatedly to low frequency (20-80 Hz) tones by becoming active and swimming to the surface. They remained at the surface or only slightly submerged for the remainder of the 1-min trial (Lenhardt 1994). Although no detailed data on sound levels at the bottom vs. surface were reported, the surfacing response probably reduced the levels of underwater sound to which the turtles were exposed. ***(2)*** In a separate study, a loggerhead and an Atlantic ridley sea turtle responded similarly when 1-s vibratory stimuli at 250 or 500 Hz were applied to the head for 1 s (Lenhardt et al. 1983). There appeared to be rapid habituation to these vibratory stimuli. The tones and vibratory stimuli used in these two studies were quite different from airgun pulses. However, it is possible that resting sea turtles may exhibit a similar "alarm" response, possibly including surfacing, when exposed to any audible noise, regardless of whether it is a pulsed sound or tone.

(c) Possible Impacts of Airgun Sounds

The limited available data indicate that sea turtles will hear airgun sounds, and that exposure to a series of shots from a single airgun at close range may reduce sea turtle hearing sensitivity for a short period of time (temporary threshold shift or TTS). It is not known whether received sounds from a full-scale array could ever be strong enough to cause permanent hearing damage. Regarding behavioral and distributional effects, resting turtles are likely to become active, and avoidance reactions are likely to occur. Little is known about the sound levels that will or will not elicit various types of behavioral reactions. Although limited information is available about short-term effects of exposure to sounds from a single airgun, the long term effects (if any) of a marine seismic operation on sea turtles are unknown.

Hearing Loss

Noise-induced hearing damage can be either temporary or permanent. In general, the received sound must be strong for either to occur, and must be especially strong and/or prolonged for permanent impairment to occur.

There have been few studies that have directly investigated hearing or noise-induced hearing loss in sea turtles. In a study on the effect of sound pulses from a single airgun of unspecified size on loggerhead sea turtles, Moein et al. (1994) observed apparent TTS after exposure to a few hundred airgun pulses at distances no more than 65 m. The hearing capabilities had returned to "normal" when the turtles were re-tested two weeks later. Studies with terrestrial reptiles have also demonstrated that exposure to impulse noise can cause hearing loss. Desert tortoises (*Gopherus agassizii*) exhibit TTS after exposure to repeated high intensity sonic booms (Bowles et al. 1999). Recovery from these temporary hearing losses was usually rapid (<1 h), which suggested that tortoises can tolerate these exposures without permanent injury (Bowles et al. 1999). However, there are no data to indicate whether or not there are any plausible situations in which exposure to repeated airgun pulses at close range could cause permanent hearing impairment in sea turtles.

Behavioral avoidance and hearing damage are related. If sea turtles exhibit little or no behavioral avoidance, or if they acclimate to seismic noise to the extent that avoidance reactions cease, sea turtles might sustain hearing loss if they are close enough to seismic sources.

Turtles in the area of seismic operations prior to start-up may not have time to move out of the area even if standard ramp-up (=soft-start) procedures are in effect. It has been proposed that sea turtles require a longer ramp-up period because of their relatively slow swimming speeds (Eckert 2000). However, it is unclear at what distance from a seismic source sea turtles will sustain hearing impairment, and whether there would ever be a possibility of exposure to sufficiently high levels for a sufficiently long period to cause irreversible hearing damage.

In theory, a reduction in hearing sensitivity, either temporary or permanent, may be harmful for sea turtles. However, very little is known about the role of sound perception in the sea turtle's normal activities. Hence, it is not possible to estimate how much of a problem it would be for a turtle to have either temporary or permanent hearing impairment. ***(1)*** It has been suggested (Eckert 2000) that sea turtles may use passive reception of acoustic signals to detect the hunting sonar of killer whales (*Orcinus orca*), a known predator of leatherback sea turtles (Caldwell and Caldwell 1969). Further investigation is needed before this hypothesis can be accepted. Some communication calls of killer whales include components at frequencies low enough to overlap the frequency range where sea turtles hear. However, the echolocation signals of killer whales are at considerably higher frequencies and may be inaudible to sea turtles (see review of odontocete sounds in Chapter 7 of Richardson et al. 1995). ***(2)*** Hearing impairment, either temporary or permanent, might inhibit a turtle's ability to avoid injury from vessels. ***(3)*** Hearing may play a role in navigation. For example, it has been proposed that sea turtles may identify their breeding beaches by their acoustic signature (Lenhardt et al. 1983). However, recent evidence suggests that visual, wave, and magnetic cues are the main navigational cues used by sea turtles, at least in the case of hatchlings and juveniles (Lohmann et al. 1997, 2001; Lohmann and Lohmann 1998).

Behavioral and Distributional Effects

In captive enclosures, sea turtles generally respond to seismic noise by increasing swimming speed and swimming away from the noise source. Animals resting on the bottom often become active and move toward the surface where received sound levels normally will be reduced. Unfortunately, data for free-ranging sea turtles exposed to seismic pulses are unavailable, and potential long-term behavioral effects of seismic exposure have not been investigated. The paucity of data precludes predictions of sea turtle responses to seismic noise. The possible responses of free-ranging sea turtles to seismic pulses could include

- avoiding the entire seismic survey area to the extent that they move to less preferred habitat;
- avoiding only the immediate area around the active seismic vessel, i.e., local avoidance of the source vessel but remain in the general area; and
- exhibiting no appreciable avoidance, although short-term behavioral reactions are likely.

Holst et al. (2006) noted that sea turtles were seen significantly farther (at least 100 m farther) from an operating seismic vessel compared to when airguns were not firing. Complete avoidance of an area, if it occurred, could exclude sea turtles from their preferred foraging or breeding area and could displace them to areas where foraging or breeding conditions are sub-optimal. However, we are not aware of any information that would indicate that sea turtles show more than localized avoidance of airguns.

The potential alteration of a migration route might have negative impacts. However, it is not known whether the alteration would ever be on a sufficient geographic scale, or be sufficiently prolonged, to prevent turtles from reaching an important destination.

Avoidance of a preferred foraging area because of seismic noise may prevent sea turtles from obtaining preferred prey species and hence could impact their nutritional status. However, it is highly unlikely that sea turtles would completely avoid a large area along a migration route. Available evidence suggests that the zone of avoidance around seismic sources is not likely to exceed a few kilometres (McCauley et al. 2000). Avoidance reactions on that scale could prevent sea turtles from using an important coastal area or bay if there was a prolonged seismic operation in the area. Sea turtles might be excluded from the area for the duration of the seismic operation, or they might remain but exhibit abnormal behavioral patterns (e.g., lingering at the surface where received sound levels are lower). Whether those that were displaced would return quickly after the seismic operation ended is generally unknown.

It is unclear whether exclusion from a particular nesting beach by seismic operations, if it occurred, would prevent or decrease reproductive success. It is believed that females migrate to the region of their birth and select a nesting beach (Miller 1997). However, the degree of site fidelity varies between species and also intra-seasonally by individuals. If a sea turtle is excluded from a particular beach, it may select a more distant, undisturbed nesting site in the general area (Miller 1997). For instance, Bjorndal et al. (1983 *in* Miller [1997]) reported a maximal intra-seasonal distance between nesting sites of 290 km. Also, it is uncertain whether a turtle that failed to go ashore because of seismic survey activity would abandon the area for that full breeding cycle, or would simply delay going ashore until the seismic vessel had moved to a different area.

The results of experiments and monitoring studies on responses of marine mammals and fish to seismic surveys show that any kind of response is possible, depending on species, time of year, activity of the animal, and other unknown factors. The same species may show different kinds of responses at different times of year or even on different days (Richardson et al. 1995; Thomson et al. 2001). It is reasonable to expect similar variability in the case of sea turtles exposed to airgun sounds. For example, sea turtles of different ages have very different sizes, behavior, feeding habits, and preferred water depths. Nothing specific is known about the ways in which these factors may be related to airgun sound effects. However, it is reasonable to expect lesser effects in young turtles concentrated near the surface (where levels of airgun sounds are attenuated) as compared with older turtles that spend more time at depth where airgun sounds are generally stronger.

(d) Conclusions

Based on available data concerning sea turtles and other marine animals, it is likely that sea turtles will exhibit behavioral changes and/or avoidance within an area of unknown size in the vicinity of a seismic vessel. There is also the possibility of temporary hearing impairment or perhaps even permanent hearing damage to turtles close to the airguns. However, there are few data on temporary hearing loss and no data on permanent hearing loss in sea turtles exposed to airgun pulses. Seismic operations in or near areas where turtles concentrate are likely to have the greatest impact. There are no specific data that demonstrate the consequences to sea turtles if seismic operations do occur in important areas at important times of year. Until there are sufficient new data to allow a reassessment, it would be prudent to avoid seismic operations near important nesting beaches or in any areas of known concentrated feeding during the times of year when those areas are in use by many sea turtles.

(e) Literature Cited

Bowles, A.E., S. Eckert, L. Starke, E. Berg, L. Wolski and J. Matesic Jr. 1999. Effects of flight noise from jet aircraft and sonic booms on hearing, behavior, heart rate, and oxygen consumption of desert tortoises (*Gopherus agassizii*). U.S. Air Force Res. Lab., Wright-Patterson AFB, Ohio. 131 p.

Caldwell, D.K. and M.C. Caldwell. 1969. Addition of the leatherback sea turtle to the known prey of the killer whale, *Orcinus orca*. **J. Mammal.** 50(3):636.

Eckert, S.A. 2000. Letter to M. James, Nova Scotia Leatherback Turtle Working Group, re possible impacts of seismic exploration off Nova Scotia on sea turtles. Hubbs-Sea World Res. Inst., San Diego, CA. 4 p.

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M.P. Simmonds, R. Swift and D. Thompson. 2004. A review of the effects of seismic surveys on marine mammals. **Mar. Technol. Soc. J.** 37(4):16-34.

Greene, C.R., Jr., with J.S. Hanna and R.W. Blaylock. 1997. Physical acoustics measurements. p. 3-1 to 3-63 *In:* W.J. Richardson (ed.), Northstar marine mammal monitoring program, 1996: marine mammal and acoustical monitoring of a seismic program in the Alaskan Beaufort Sea. LGL Rep. 2121-2. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 245 p.

Greene, C.R., Jr. and W.C. Burgess, with R. Norman and R.W. Blaylock. 2000. Physical acoustics measurements, 1999. p. 3-1 to 3-45 *In:* W.J. Richardson (ed.), Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 1999. LGL Rep. TA2313-4. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and U.S. Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 155 p.

Holst, M., W.J. Richardson, W.R. Koski, M.A. Smultea, B. Haley, M.W. Fitzgerald, and M. Rawson. 2006. Effects of large and small-source seismic surveys on marine mammals and sea turtles. Abstract + oral presentation presented at Am. Geophys. Union - Soc. Explor. Geophys. Joint Assembly on Environ. Impacts from Marine Geophys. & Geological Studies - Recent Advances from Academic & Industry Res. Progr., May 2006, Baltimore, MD.

Lenhardt, M.L. 1994. Seismic and very low frequency sound induced behaviors in captive loggerhead marine turtles (*Caretta caretta*). p. 238-241 *In*: K.A. Bjorndal, A.B. Bolten, D.A. Johnson and P.J. Eliazar (eds.), Proc. 14th Symp. on Sea Turtle Biology and Conservation. NOAA Tech. Memorandum NMFS-SEFSC-351. 323 p.

Lenhardt, M.L., S. Bellmund, R.A. Byles, S.W. Harkins and J.A. Musick. 1983. Marine turtle reception of bone-conducted sound. **J. Aud. Res**. 23:119-125.

Lenhardt, M.L., R.C. Klinger and J.A. Musick. 1985. Marine turtle middle-ear anatomy. **J. Aud. Res**. 25:66-72.

Lohmann, K.J. and C.M.F. Lohmann. 1998. Migratory guidance mechanisms in marine turtles. **J. Avian Biol.** 29(4):585-596.

Lohmann, K.J., B.E. Witherington, C.M.F. Lohmann and M. Salmon. 1997. Orientation, navigation, and natal beach homing in sea turtles. p. 107-135 *In*: P.L. Lutz and J.A. Musick (eds.), The biology of Sea Turtles. CRC Press, Boca Raton, FL. 432 p.

Lohmann, K.J., S.D. Cain, S.A. Dodge and C.M.F. Lohmann. 2001. Regional magnetic fields as navigational markers for sea turtles. **Science** 294(5541):364-366.

McCauley, R.D., M.-N. Jenner, C. Jenner, K.A. McCabe and J. Murdoch. 1998. The response of humpback whales (*Megaptera novaeangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. **APPEA J.** 38:692-707.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch and K. McCabe. 2000. Marine seismic surveys – a study of environmental implications. **APPEA J.** 40:692-708.

Miller, J.D. 1997. Reproduction in sea turtles. p. 51-81 *In*: P.L. Lutz and J.A. Musick (eds.), The Biology of Sea Turtles. CRC Press, Boca Raton, FL. 432 p.

Moein, S.E., J.A. Musick, J.A. Keinath, D.E. Barnard, M. Lenhardt and R. George. 1994. Evaluation of seismic sources for repelling sea turtles from hopper dredges. Rep. from Virginia Inst. Mar. Sci., [Gloucester Point], VA, for U.S. Army Corps of Engineers. 33 p.

Moein Bartol, S., J.A. Musick and M.L. Lenhardt. 1999. Auditory evoked potentials of the loggerhead sea turtle (*Caretta caretta*). **Copeia** 1999(3):836-840.

Musick, J.A. and C.J. Limpus. 1997. Habitat utilization and migration in juvenile sea turtles. p. 137-163 *In*: P.L. Lutz and J.A. Musick (eds.), The Biology of Sea Turtles. CRC Press, Boca Raton, FL. 432 p.

O'Hara, J. and J.R. Wilcox. 1990. Avoidance responses of loggerhead turtles, *Caretta caretta*, to low frequency sound. **Copeia** 1990(2):564-567.

Richardson, W.J., C.R. Greene Jr., C.I. Malme and D.H. Thomson. 1995. Marine mammals and noise. Academic Press, San Diego, CA. 576 p.

Ridgway, S.H., E.G. Wever, J.G. McCormick, J. Palin and J.H. Anderson. 1969. Hearing in the giant sea turtle, *Chelonia mydas*. **Proc. Nat. Acad. Sci. U.S.** 64:884-890.

Thomson, D.H., J.W. Lawson and A. Muecke. 2001. Proceedings of a workshop to develop methodologies for conducting research on the effects of seismic exploration on the Canadian east coast fishery, Halifax, Nova Scotia, 7-8 September 2000. ESRF Rep. 139. Environ. Stud. Res. Funds, Calgary, AB. 75 p.

APPENDIX E:
REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON FISH

Relevant literature on the effects of seismic survey sound on fish is reviewed in this section as a condensation and summary of a larger review conducted for the American Petroleum Institute (Buchanan et al. 2004). Research on fish has been conducted on individuals of species from a number of different orders. Material is presented here for freshwater, anadromous, and marine species. Hastings and Popper (2005) provide a comprehensive critical review of the known effects of sound received by fish.

It is often difficult to interpret studies on the effects of noise on marine animals because authors often do not provide received sound levels or they do not provide the sound measurement type including the physical phenomenon being measured, the range from the sound source, the water depth, and the appropriate units and references. Underwater sound levels are typically reported as a number of decibels referenced to a common level, usually 1 micro-Pascal (µPa) at a distance of 1 m (e.g., 180 dB µPa-1 m). However, the dB number can differ because of what we have called the “measurement type” as “zero to peak,” “peak to peak,” or averaged (“rms”). Unless measurement types are provided, it is difficult to provide direct comparisons between studies. It is essential to be aware of all units, references, ranges, what is being measured and how. With transient sounds, the time over which a measurement’s data are collected becomes important (Madsen 2005). Treatments in Richardson et al. (1995) are helpful.

(a) Acoustic Capabilities

Animal sensory systems function to provide their bearers pertinent information about the physical, biotic, and social environments in which they find themselves. This is no less true in water than in air. Extensive work has been done to understand the structures, mechanisms, and functions of animal sensory systems in aquatic environments (Atema et al. 1988; Kapoor and Hara 2001; Collin and Marshall 2003). All fish species have hearing and skin-based mechanosensory systems (inner ear and lateral line systems, respectively). These systems inform them about their surroundings (Fay and Popper 2000). Any anthropogenic sound that affects fish hearing or other sensory systems may have important negative consequences for fish survival and reproduction. Potential negative effects include masking of important environmental sounds or social signals, displacing fish from their habitat, or interfering with sensory orientation and navigation.

Although there have been few or no studies on the audiology of most fish species, there is a growing body of work on representative species of a number of diverse fish taxa. For the most part, as compared to mammals, fish hearing is restricted to rather low frequencies. In order for any vertebrate animal to hear a sound there must be a mechanism by which the beds of hair cells (Howard et al. 1988; Hudspeth and Markin 1994) of the inner ear are disturbed in such a way as to bend them and thereby cause a neural discharge (Popper and Fay 1999).

At least two major pathways have been identified for sound transmittance between source and ear. The first and most primitive are the otoliths, calcium carbonate masses of the inner ear of fish, which are denser than the rest of the fish and the surrounding water. The bodies of fish have approximately the same density as water; therefore, when a fish swims though a sound field, the sound waves cause the entire fish to move with the water. The denser otoliths move more slowly in response to sound waves than does the rest of the fish. The difference between the motion of the fish and the otoliths stimulates the hair cells in the inner ear. The hair cells then send signals down the sensory nerve fibres, which are interpreted by the brain as sound.

The swim bladder is the second sound pathway in a fish and it involves a structure that is much lower in density than the fish as a whole because it is filled with gas. Any such gas pocket, being more compressible and expandable than either water or fish tissue, will both contract and expand differentially and substantially more than the rest of the fish in a sound field. The bladder expands and contracts in the sound field, which is an alternating series of high and low pressure zones. Such a pulsating structure can become a secondary source of mechanical disturbance and re-radiate the sound's signal within the animal. Such a secondary source may be more or less effective at stimulating the inner ears depending on the amplitude and frequency of the pulsation and the distance and mechanical coupling between the gas bladder and the inner ears (Popper and Fay 1993).

The herrings and allies (Clupeiformes), some cods and allies (Gadiformes in part), some squirrelfishes (Perciform family Holocentridae, in part), and a number of other fish have specialized swim bladders which extend more or less close to the inner ear. These fish have been found to have more sensitive hearing than fish lacking such specialization and are called '*hearing specialists*'. For these animals, the upper limit of the hearing frequency range can be from 1 to a few kHz.

Some species may only have a direct pathway to the inner ear (i.e., without swim bladders, with reduced swim bladders, or with swim bladders that are not connected or otherwise couples to the inner ear) and tend to have relatively poor auditory sensitivity. These species are known as '*hearing generalists*' (Popper and Fay 1999). It is important to recognize that the bladder itself is not a sensory end organ, but that the sound pathway involves sound energy re-radiation from the swim bladder to the ear. The ear in both hearing specialists and non-specialists is the ultimate sound detecting structure, and that detection involves relative motion between the otolith and the sensory hair cells.

A third mechanosensory pathway, the lateral line system found in most bony fishes and elasmobranchs (i.e., sharks), is sensitive to water motions. The basic sensory unit of the lateral line system is the neuromast, which is a bundle of sensory and supporting cells whose projecting cilia, similar to those in the ears, are encased in a gelatinous cap. For example, as a fish approaches an object, such as a rock or the glass wall of an aquarium, the pressure waves around its body are distorted, and these changes are quickly detected by the lateral line system, enabling the fish to swerve or to take other suitable Bction. Generally, fish use the neuromasts to detect low frequency acoustic signals (160–200 Hz) over a distance of one to two body lengths. Typically, the lateral line is used in conjunction with other sensory information, including hearing (Sand 1981; Coombs and Montgomery 1999). Reviews of fish-hearing mechanisms and capabilities can be found in Fay and Popper (2000) and Ladich and Popper (2004).

Hearing Generalists <1 kHz

Currently most fishes, including cartilaginous fishes (the sharks, skates, rays, and chimeras of the Class Chondrichthys), are classified as hearing generalists. This is more the case in marine systems than in fresh water, where many hearing specialists are found. The generalists either do not have large gas pockets in their bodies (the gas bladder having been reduced or lost through evolution), or those pockets do not have close proximity or mechanical connections to the ear structures; thus, they are not very involved in sound transduction and perception (see next section). Salmon are hearing generalists (Hawkins and Johnstone 1978), as are flatfishes (Chapman and Sand 1974), and well as many other fish species.

Hearing Specialists 1 – 4 kHz

Hearing specialists are found in a diverse assortment of fish groups, and rather than being limited to a kHz or less in hearing, can hear up to several kHz. Most bony fish have some sort of gas-filled structure in their bodies that is thought to function in buoyancy regulation. Although some bottom-dwelling bony fish have secondarily lost the trapped gas pocket, the swim bladder (sometimes called a gas bladder) is the norm across most bony fish taxa. Swim bladders do not occur in all fish species and fish species without gas bladders include flatfishes and sculpins and some other very actively swimming fish such as some tunas.

In hearing specialists, this gas-filled structure or an extension thereof, is located very near to or mechanically coupled to the sensory structures of the inner ear. In some fish, the swim bladder is either very close to the inner ear or it is in direct physical contact to the inner ear by a system of small bones called Weberian ossicles. In cods, the connection is much less direct. Other examples of connections between the swim bladder and the inner ear include elongated gas ducts or extensions of the swim bladder. The swim bladder located near the inner ear expands and contracts in response to fluctuating sound pressure. The swim bladder serves to convert the changes in pressure to motions that are transmitted to the otoliths in the inner ear and then interpreted as sound. This increases both the sensitivity and sound frequency range that is accessible to the fish (Blaxter 1981).

Extreme Hearing Specialists >5 kHz

All members of the anadromous herring subfamily Alosinae (the anadromous shads and near-shore menhadens) that have thus far been studied respond to sounds over 100 kHz (Mann et al. 1997, 1998, 2001). Those sound frequencies are far higher than the acoustic sources used in seismic surveys, although it may be that fish of alosine species could hear some components of the sounds produced by the vessel echosounders.

Fish ears respond to changes in pressure and particle motions (van Bergeijk 1967; Schuijf 1981; Kalmijn 1988, 1989; Schellert and Popper 1992; Hawkins 1993; Fay 2005). In general, underwater sound levels considered likely to stimulate the skin-borne lateral line system of fish are relatively low in frequency, less than about 150 Hz (Coombs et al. 1988, 1989; Coombs and Montgomery 1999). In addition, sound amplitude generally attenuates (decreases) with increasing distance from the sound source (exceptions can occur in water that is shallow relative to the sound's wavelength, see Hastings and Popper [2005]). Thus, even very powerful and low-frequency sound sources are unlikely to have profound effects at anything but rather short ranges (Kalmijn 1988, 1989). On the other hand, sound propagation is more efficient at lower frequencies, assuming boundary conditions, especially water depth, are adequate for sound propagation (Rogers and Cox 1988). As a result, low-frequency sound may be propagated over a considerable distance. Because seismic surveys are characterized by low-frequency sounds, this aspect needs to be considered with respect to potential impacts on fish and their auditory functions, the acoustic environments they inhabit, and their associated ecology.

(b) Potential Effects on Fish

Effects on Freshwater Fish

Popper et al. (2005) tested three fish species after stimulation with five blasts of a seismic airgun with a received mean peak sound level of ~205 dB re 1 µPa (a received mean SEL of ~175 dB re 1 $\mu Pa^{2\cdot}s$). The broad whitefish showed no TTS to this signal; in contrast, adult northern pike (a hearing generalist) and lake chub (a hearing specialist) showed 10–15 dB of hearing loss with complete recovery within 24 hr after exposure. Mann et al. (2007) speculated that seismic airguns would have the most impact on freshwater fish species with the most sensitive hearing (e.g., lake chub and longnose sucker).

Effects on Marine Fish

The often-cited examples of evidence for damage to fish ears attributable to exposure to seismic airgun energy were provided by McCauley et al. (2000 a,b; 2003) with pink snapper (a porgie of the family Sparidae). The fish were caged and exposed to a seismic airgun energy pulse every 10 s for a total of 1 hr and 41 min. The moving peak-to-peak source SPL was just below 223 dB re 1 µPa at the source and the approximate peak-to-peak received SPLs ranged between 165 and 209 dB re 1 µPa. The energy was highest over the 20–70 Hz frequency range. Over 600 seismic pulses were emitted during exposure. The sensory epithelium of the inner ear sustained extensive damage as indicated by ablated hair cells. Damage was more extensive in the ears of fish sacrificed 58 days after exposure than in fish examined 18 hr after exposure. There was no evidence of repair or replacement of damaged sensory cells up to 58 days after exposure to the sound. The authors provided the following caveats: (1) fish were caged and unable to swim away from the seismic source, (2) only one species of fish was examined, (3) the impact on the ultimate survival of the fish is unclear, and (4) precise airgun exposure specifics required to cause the observed damage were not obtained (i.e., a few high SPL signals or the cumulative effect of many low to moderate SPL signals).

Pearson et al. (1992) investigated the effects of seismic airgun energy on the behaviors of captive rockfish. The single airgun had a source 0-to-peak SPL of 223 dB re 1 µPa-1 m and measured received 0-to-peak SPLs ranged from 137–206 dB re 1 µPa. The authors reported that rockfish reacted to the airgun sounds by exhibiting varying degrees of startle and alarm responses, depending on the species and the received sound level. Startle responses were observed when the received 0-to-peak SPL was at least 200 dB re 1 µPa; alarm responses occurred at a minimum received 0-to-peak SPL of 177 dB re 1 µPa. Other observed behavioral changes included the tightening of schools, downward distributional shift, and random movement and orientation. Some fish rose in the water column and commenced to mill (i.e. “eddy”) at increased speed while others moved to the bottom of the enclosure and remained motionless. Pre-exposure behavior was reestablished within 20–60 min. of the cessation of seismic firing. The authors concluded that reasonable received 0-to-peak SPL thresholds for obvious rockfish behavioral response and more subtle rockfish behavioral response are 180 dB re 1 µPa and 161 dB re 1 µPa, respectively.

Skalski et al. (1992) studied the potential effects of seismic airgun energy on the distribution and level of catch of “rockfish” (in this case scorpaenids) through an experimental hook-and-line fishery. The source 0-to-peak SPL of the single airgun was 223 dB re 1 µPa-1 m and the received 0-to-peak SPLs at the base of the rockfish aggregation ranged from 186–191 re 1 µPa. Characteristics of the fish aggregations were assessed using echosounders. During long-term seismic airgun firing from a stationary source, there was an overall increase in depth of fish aggregation indicating a downward shift in distribution. The authors also observed a significant decline in total catch of rockfish during seismic firing. It should be understood that this approach was quite different from an actual seismic survey as the duration of exposure was much longer (i.e., more repetitious) than likely to occur in an actual survey; thus, these results should be interpreted as a "worst case".

Caged European sea bass were exposed to multiple sound pressure waves from a moving seismic airgun array with a source SPL of ~210 dB re 1 µPa (unspecified measure type) (Santulli et al. 1999). The pulses were emitted every 25 s over a 2-hr period. The minimum distance between fish and seismic source was 180 m. The authors did not indicate any observed pathological injury to the sea bass. Blood was collected from both exposed fish (6 hr after exposure) and control fish (6 hr before exposure). The sera were subsequently analyzed for cortisol, glucose, and lactate levels. Levels of cortisol, glucose and lactate were significantly higher in the sera from exposed fish compared to that from the control fish. The levels of all three chemicals returned to pre-exposure state within 72 hr of exposure (Santulli et al. 1999).

Santulli et al. (1999) also installed underwater video cameras in the cage positioned closest to the seismic transect in order to monitor the fish responses to seismic shooting. There were indications of a slight startle response in some of the sea bass when the seismic array was as far as 1.5 mi. (2.5 km) from the cage. The proportion of fish displaying "startle" responses increased as the seismic source approached the cage. At 180 m, the sea bass were densely packed at the middle of the enclosure in random orientation, appearing more active than they had been under pre-exposure conditions. Normal behavior resumed about 2 hr after occurrence of airgun firing nearest the fish (Santulli et al. 1999).

Chapman and Hawkins (1969) tested the reactions of whiting (hake) in the wild to an airgun emitting low-frequency, high-amplitude pulses (0-to-peak 220 dB re 1 µPa-1 m). Received 0-to-peak SPLs were estimated at 178 dB re 1 µPa. The research vessel was anchored and the school of whiting was monitored with an echosounder. The airgun fired intermittently. Before the airgun was fired, the fish were at a depth of 25–55 m. In response to the sound pulses, the fish dove and formed a compact layer below a depth of 55 m. By the end of an hour of exposure to the sound pulses, the fish had habituated: they rose in the water despite the continued presence of the sound pulses. The airgun was switched off and, when it resumed firing, the fish began to descend again. The habituation seems to have been of short duration. Assuming spherical spreading from the single airgun, received levels would have been 192 dB re 1 µPa at 25 m and 185 dB re 1 µPa at 55 m.

Hassel et al. (2003, 2004) studied the potential effects of exposure to airgun pulses on the behavior of captive lesser sandeel. Depth of the enclosure used to hold the sandeel was ~55 m. The airgun array had an estimated source SPL of 256 dB re 1 µPa-1 m (unspecified measure type) but received SPLs were not measured. Exposures were conducted over a 3-day period. No mortality attributable to exposure to the airgun sounds was noted. Behavior of the fish was monitored using underwater video cameras, echosounders, and commercial fishery data from regions closest to the survey area. The approach of the seismic vessel appeared to cause an increase in tail-beat frequency although the sandeels still appeared to swim calmly. During seismic shooting, many fish exhibited startle responses, followed by flight from the immediate area. The frequency of occurrence of startle response seemed to increase as the operating seismic array moved closer to the fish. The sandeels stopped exhibiting the startle response once the seismic firing ceased. The sandeel tended to remain higher in the water column during the seismic firing and none of them were observed burying themselves in the soft substrate. The commercial fishery catch data from areas nearby the experimentation site were inconclusive.

Kostyvchenko (1973), in uncontrolled experiments, exposed the eggs of numerous fish species (anchovy, red mullet, crucian carp, blue runner) to various seismic sources, including seismic airguns. Even as close as 0.5 m from the source, over 75% of the eggs survived exposure to the airgun shots. Survival rate increased to over 90% at a distance of 33 10 m from the airgun source. The received 0-to-peak SPLs of the airguns ranged from ~215–233 dB re 1 µPa. Handling of larvae and adult fish with eggs can be an important component of stress and mortality. Kostyvchenko (1973) does not address that but does report high rates of survival.

Various species of demersal fishes, blue whiting and some small pelagics, were exposed to a seismic array with a source SPL of about 250 dB re 1 µPa-1 m (unspecified measure type) (Dalen and Knutsen 1986). Received SPLs estimated using the assumption of spherical spreading ranged from 200 to 210 dB re 1 µPa (unspecified measure type). Exposure to the seismic survey sound pulses occurred once every 10 s for a 1-week period. The authors assessed the pre- and post-exposure fish distributions by acoustic mapping with echosounders and sonars. The acoustic mapping results indicated a significant decrease in abundance of demersal fish (36%) after seismic firing; however, comparative trawl catches did not support this. There were also non-significant reductions in the abundances of blue whiting and small pelagics indicated by post-exposure acoustic mapping.

Eggs, yolk sac larvae, post-yolk sac larvae, post-larvae, and fry of various commercially important fish species (cod, saithe, herring, turbot, and plaice) were exposed to received SPLs ranging from 220–242 dB re 1 µPa (unspecified measure type) (Booman et al. 1996). These received levels corresponded to exposure distances ranging from 0.75 to 6 m. The authors reported some cases of injury and mortality but most of these occurred after exposures at very close range (i.e., <15 m). Rigor of anatomy and pathology were questionable.

La Bella et al. (1996) studied the effects of exposure to seismic survey sound energy on fish distributional behavior using echosounder monitoring and changes in catch rate of hake by trawl, and clupeoids by gill netting. The seismic source was a 16-airgun array with a source SPL of 210 dB re 1 µPa-1 m (unspecified measure type). The shot interval was 25 sec and exposure durations ranged from 4.6–12 h. Horizontal distributions did not appear to change as a result of exposure to seismic firing; however, there was some indication of a downward shift in the vertical distribution. The experimental fishing catch rates did not differ significantly between pre- and post-seismic fishing periods.

McCauley et al. (2000 a,b) exposed various caged fish species to 600+ seismic airgun pressure waves. They conducted 10 trials that involved the exposure of live caged specimens of 10 assorted marine fish species to firing airguns and simultaneous monitoring of changes in fish behavior using underwater video. Fixed seismic sources were used in five of the trials (10–30 m from the cage) and mobile seismic sources were used in the remaining five trials (as close as 5–15 m from the cage, and as far as 350–450 m from the cage). The received SPLs ranged from 146–195 dB re 1 µPa mean squared pressure. Fish exhibited startle responses to short range start-up firing and longer-range full energy firing (i.e., received SPLs of 182–195 dB re 1 µPa mean squared pressure). Smaller fish showed a tendency to display startle response more often. “Responses” were observed above received SPLs of 156–161 dB re 1 µPa mean squared pressure. The occurrence of both startle response and alarm response decreased over time. Other behavioral observations included downward distributional shift that was restricted by the 10 m x 6 m x 3 m cages, increase in swimming speed, and the formation of denser aggregations. Fish behavior appeared to return to pre-exposure state 15–30 min. after cessation of seismic firing.

Wardle et al. (2001) made behavioral observations of marine fish (primarily juvenile saithe, adult pollock, juvenile cod, and adult mackerel) inhabiting an inshore reef off Scotland using video and telemetry before, during, and after exposure to firing of a stationary airgun. The approximate received peak SPLs ranged from 195–218 dB re 1 µPa. Pollock tagged in Scotland and the U.S. did not move away from the reef in response to the seismic firing and their diurnal rhythm did not appear to be affected. However, there was an indication of a slight and relatively minor effect on the long-term day-to-night movements of the pollock. Video camera observations indicated that fish exhibited startle responses (“C-starts”) to all received levels. If the seismic source was visually obvious to the fish, they fled from it, but if the source was not visible to the fish, they often continued to move toward it. Therefore, there was indication of fish response to visual stimuli rather than only to acoustic stimuli.

The potential effect on fish abundance and distribution of exposure to seismic survey sound was investigated by Slotte et al. (2004). The 12 days of seismic survey operations spread over a period of 1 month involved an array with a source peak-to-peak SPL of 222.6 dB re 1 µPa-1 m. The SPLs received by the fish were not measured. Acoustic surveys of the local distributions of various kinds of pelagic fish, including herring, blue whiting, and mesopelagic species, were conducted during the seismic surveys. There was no strong evidence of short-term scaring effects in terms of horizontal distribution. With respect to vertical distribution, blue whiting and mesopelagics were distributed deeper (20–50 m) during the seismic survey compared to pre-exposure). The average densities of fish aggregations were lower within the seismic survey area and fish abundances appeared to increase in accordance with increasing distance from the seismic survey area.

Saetre and Ona (1996) applied a “worst-case scenario” mathematical model to investigate the effects of seismic energy on fish eggs and larvae. They concluded that mortality rates caused by exposure to seismic are so low compared to the natural mortality that the impact of seismic surveying on recruitment to a fish stock must be regarded as insignificant.

Effects on Anadromous Fish

In uncontrolled experiments on a very small sample of different groups of young salmonids, including Arctic cisco, fish were caged and exposed to various types of sound. One sound type was either a single firing or a series of four firings 10–15 s apart of a 300-in^3 seismic airgun at 2000–2200 psi (Falk and Lawrence 1973). Swim bladder damage was reported but no mortality observed when fish were exposed within 1 to 2 m of a source SPL of ~230 dB re 1 µPa (unspecified measure), although the method of determination is unclear and the small sample size makes drawing statistically valid conclusions impossible.

Thomsen (2002) exposed rainbow trout and Atlantic salmon held in aquaculture enclosures to the sounds from a small airgun array. Received peak-to-peak SPLs ranged from 142–186 dB re 1 µPa. The fish were exposed to 124 pulses over a 3-day period. In addition to monitoring fish behavior with underwater video cameras, the authors also analyzed cod and haddock catch data from a longline fishing vessel operating in the immediate area. Eight of the 124 shots seemed to evoke only subtle behavioral reactions by the salmonids but overall behavioral impacts were minimal. No fish mortality was observed during and immediately after exposure. The author reported no significant effects on cod and haddock catch rates and the behavioral effects were hard to differentiate from normal behavior.

Weinhold and Weaver (1972, cited in Turnpenny et al. 1994) exposed caged coho salmon smolts to impulses from 330 and 660 in^3 airguns, resulting in received levels estimated at ~214–216 dB (units not given). No lethal effects were observed.

It should be noted that, in a recent and comprehensive review, Hastings and Popper (2005) take issue with many of the authors cited herein for problems with experimental design and execution, measurements, and interpretation. Hastings and Popper (2005) deal primarily with the possible effects of pile-driving sounds on fish, but they provide an excellent and critical review of the impacts to fish from other underwater anthropogenic sounds.

Effects on Fisheries (Indirect)

The most comprehensive experiments on the effects of seismic shooting on abundance and catch of fish were conducted in the Barents Sea by Engås et al. (1993, 1996). They investigated the effects of seismic airgun sounds on distributions, abundances, and catch rates of cod and haddock using acoustic mapping and experimental fishing with trawls and longlines. The maximum measured source 0-to-peak SPL was ~248 dB re 1 µPa-1 m but no measurements of the received SPLs were made. Davis et al. (1998) estimated the received 0-to-peak SPL at the bottom below the array as 205 dB re 1 µPa, and as 178 dB re 1 µPa at 11 mi. (18 km) from the array. Engås et al. (1993, 1996) concluded that there were indications of distributional change during and immediately following the seismic survey (45-64% decrease in acoustic density in their sonar data). The lowest densities were within 9.3 km of the shooting area. They indicated that trawl catches of both cod and haddock were less after the seismic operations as compared to before. Longline catches of haddock and cod declined and increased, respectively, after the seismic firing.

Løkkeborg (1991), Løkkeborg and Soldal (1993), and Dalen and Knutsen (1986) examined effects of seismic shooting on catch of demersal fish such as cod and haddock. Løkkeborg (1991) examined the effect of seismic airgun discharges on the catch rate of cod. The source SPL of the airgun array was 239 dB re 1 µPa-1 m (unspecified measure type) but received SPLs were not measured. Approximately 43 hr of seismic shooting occurred during an 11-day period. There was an interval of 5 s between pulses. Catch rates decreased 55 to 80% within the seismic survey area; this apparent effect persisted for at least 24 hr within 5 nm (9.3 km) of the survey area.

Turnpenny et al. (1994) examined results of these studies and the results of other studies on rockfish. They roughly estimated received sound levels at catch locations and estimated that catchability is reduced when received sound levels exceed 160–180 dB re 1 µPa (0-to-peak). They also estimated that reaction thresholds of fish without swim bladders, such as flatfish, would be about 20 dB higher. Given the variability in transmission loss in different areas, the sound levels that were actually received by the fish observed in these studies are not known.

Turnpenny and Nedwell (1994) also reported on the effects of seismic shooting on inshore bass fisheries in shallow U.K. waters (5–30 m deep). They used tagged fish and catch records. There was no reduction in bass catch on days when shooting took place. Results of the tagging study showed no migration out of the area. The airgun array had a peak output of 250 dB re 1 µPa-1 m. Received levels in the fishing areas were estimated to have been 163–191 dB re 1 µPa (0-to-peak). Turnpenny and Nedwell

(1994) concluded that effects on fisheries would be smaller in shallow nearshore waters than in deep water because attenuation of sound is more rapid in shallow water than in deep water. See Hastings and Popper (2005) for criticism of many of these reports.

Skalski et al. (1992) used a 100 in^3 airgun with a 0-to-peak source level of 223 dB re 1 µPa-1 m to examine effects on catch per unit effort (CPUE) of rockfish. The ship with the airgun traversed the trial fishing area and then stood off while the fishing vessel deployed a set line, did three echosounder transects, and then deployed two more set lines, each for 20 min. Each fishing experiment lasted 1 hr 25 min. Received levels at the base of the rockfish aggregations were 186–191 dB re 1 µPa (0-to-peak). The CPUE of rockfish declined by an average of 52.4% when the airguns were operating. Skalski et al. (1992) believed that the reduction in catch resulted from a change in behavior of the fish. The fish schools descended to near the bottom when the airgun was firing, and the fish changed their swimming and schooling behavior. The fish did not disperse, but the authors hypothesized that dispersal could have occurred at a different location with a different bottom type. Skalski et al. (1992) did not continue fishing after airgun firing ceased. They speculated that CPUE would return to normal quickly in their experimental area because fish behavior returned to normal within minutes after the sounds ceased. However, in an area where sound had caused the fish to disperse, they suggested that a lowered CPUE might persist.

European sea bass were exposed to sounds from seismic airgun arrays with a 0-to-peak source SPL of 262 dB re 1 µPa-1 m and a maximum SPL at some unspecified frequency of 202 dB re 1 µPa-1 m (Pickett et al. 1994). The seismic survey was conducted over a period of 4–5 months. The study was intended to investigate the effects of seismic shooting on inshore bass fisheries. Information was collected through a tag and release program, and from the logbooks of commercial fishermen. Most of the 152 recovered fish from the tagging program were caught within 6 mi. (10 km) of the release site, and it was suggested that most of these bass did not leave the area for any long-term period. With respect to the commercial fishery, no significant changes in catch rate were observed (Pickett et al. 1994).

Only the study conducted by Chapman and Hawkins (1969) addressed habituation. They found that fish quickly habituated to seismic survey sounds over the short term. The other studies did not address long-term habituation. Only Chapman and Hawkins (1969) and Skalski et al. (1992) followed the behavior of individual schools of fish. With the exception of the California studies of rockfish (Skalski et al. 1992), investigators did not measure received noise levels. Thus, it is not possible to say, with any certainty, what sound levels could cause reduction in catchability of cod and haddock.

(c) Literature Cited

Atema, J., R.R. Fay, A.N. Popper, and W.N. Tavolga. 1988. The Sensory Biology of Aquatic Animals. Springer-Verlag, New York, NY.

Blaxter, J.H.S. 1981. The swim bladder and hearing. Pages 61-69 *in* W.N. Tavolga, A.N. Popper, and R.R. Fay, eds. Hearing and Sound Communication in Fishes. Springer-Verlag, New York, NY.

Booman, C., J. Dalen, H. Leivestad, A. Levsen, T. van der Meeren, and K. Toklum. 1996. Effecter av luftkanonskyting på egg, larver og yngel. **Fisken Og Havet** 1996(3):1-83 (Norwegian with English summary).

Buchanan, R.A., J.R. Christian, S. Dufault, and V.D. Moulton. 2004. Impacts of underwater noise on threatened or endangered species in United States waters. Report No. SA791. Report prepared by LGL Ltd. for American Petroleum Institute, Washington, DC.

Chapman, C.J. and A.D. Hawkins. 1969. The importance of sound in fish behaviour in relation to capture by trawls. **FAO Fisheries Report** 62:717-729.

Chapman, C.J. and O. Sand. 1974. Field studies of hearing in two species of flatfish, *Pleuronectes platessa* and *Limanda limanda*. **Comp. Biochem. Physiol. A.** 47: 371-385.

Collin, S.P. and N.J. Marshall, eds. 2003. Sensory Processing in Aquatic Environments. Springer-Verlag, New York, NY.

Coombs, S. and J.C. Montgomery. 1999. The enigmatic lateral line system. Pages 319-362 *in* R.R. Fay and A.N. Popper, eds. Comparative Hearing: Fish and Amphibians. Springer Handbook of Auditory Research 11. Springer-Verlag, New York, NY.

Coombs S., J. Jansen, and J.F. Webb. 1988. Diversity of lateral line systems: evolutionary and functional considerations. Pages 267-288 *in* J. Atema., R.R. Fay, A.N. Popper, and W.N. Tavolga, eds. The Sensory Biology of Aquatic Animals. Springer-Verlag, New York.

Coombs, S, P. Görner, and H. Münz, eds. 1989. The Mechanosensory Lateral Line: Neurobiology and Evolution. Springer-Verlag, New York, NY.

Dalen, J. and G.M. Knutsen. 1986. Scaring effects in fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. Symposium on Underwater Acoustics, Halifax.

Davis, R.A., D. Thomson, and C.I. Malme. 1998. Environmental assessment of seismic exploration of the Scotian Shelf. Unpublished Report by LGL Ltd., environmental research associates, King City, ON and Charles I. Malme, Engineering and Science Services, Hingham, MA for Mobil Oil Canada Properties Ltd, Shell Canada Ltd., and Imperial Oil Ltd.

Engås, A., S. Løkkeborg, A.V. Soldal, and E. Ona. 1993. Comparative trials for cod and haddock using commercial trawl and longline at two different stock levels. **J. Northw. Atl. Fish. Sci.** 19:83-90.

Engås, A, S. Løkkeborg, E. Ona, and A.V. Soldal. 1996. Effects of seismic shooting on local abundance and catch rates of cod (*G. morhua*) and haddock (*M. aeglefinus*). **Can. J. Fish. Aquat. Sci.** 53:2238-2249.

Falk, M.R. and M.J. Lawrence. 1973. Seismic exploration: its nature and effects on fish. Canada Technical Report Series No. CEN/T-73-9. Department of the Environment, Fisheries and Marine Service, Resource Management Branch, Fisheries Operations Directorate, Central Region (Environment), Winnipeg, MB.

Fay, R.R. 2005. Sound source localization by fishes. Pages 36-66 *in* A.N. Popper and R.R. Fay, eds. Sound Source Localization. Springer-Verlag, New York, NY.

Fay, R.R. and A.N. Popper. 2000. Evolution of hearing in vertebrates: The inner ears and processing. **Hearing Research** 149: 1-10.

Hassel, A., T. Knutsen, J. Dalen, S. Løkkeborg, K. Skaar, Ø. Østensen, E.K. Haugland, M. Fonn, Å. Høines, and O.A. Misund. 2003. Reaction of sandeel to seismic shooting: A field experiment and fishery statistics study. Institute of Marine Research, Bergen, Norway.

Hassel, A., T. Knutsen, J. Dalen, K. Skaar, S. Løkkeborg, O.A. Misund, O. Ostensen, M. Fonn, and E.K. Haugland. 2004. Influence of seismic shooting on the lesser sandeel (*Ammodytes marinus*). **ICES J. Mar. Sci.** 61:1165-1173.

Hastings, M.C. and A.N. Popper. 2005. Effects of Sound on Fish. Prepared for Jones & Stokes, Sacramento, CA, for California Department of Transportation, Sacramento, CA. 28 January.

Hawkins, A.D. 1993 Underwater sound and fish behaviour. Pages 129-169 *in* T.J Pitcher, ed. Behaviour of Teleost Fishes. Second Edition. Chapman and Hall, London, UK.

Hawkins, A.D. and A.D.F. Johnstone. 1978. The hearing of the Atlantic salmon, Salmo salar. **J. Fish Biol.** 13:655-673.

Howard J, W.M. Roberts, and A.J. Hudspeth. 1988. Mechanoelectrical transduction by hair cells. **Ann. Rev. Biophys. Chem.** 17:99-124.

Hudspeth, A.J. and V.S. Markin. 1994. The ear's gears: mechanical transduction by hair cells. **Physics Today** February:22-28.

Kalmijn, A.J. 1988. Hydrodynamic and acoustic field detection. Pages 83-130 in J. Atema, R.R. Fay, A.N. Popper, and W.N. Tavolga, eds. The Sensory Biology of Aquatic Animals. Springer-Verlag, New York, NY.

Kalmijn, A.J. 1989. Functional evolution of lateral line and inner ear systems. Pages 187-216 in S. Coombs P. Görner, and H. Münz, eds. The Mechanosensory Lateral Line: Neurobiology and Evolution. Springer-Verlag, New York, NY.

Kapoor, B.G. and T.J. Hara, eds. 2001. Sensory Biology of Jawed Fishes: New Insights. Science Publishers, Inc., Enfield, NH.

Kostyvchenko, L.P. 1973. Effects of elastic waves generated in marine seismic prospecting on fish eggs in the Black Sea. **Hydrobiol. J.** 9:45-48.

La Bella, G., S. Cannata, C. Froglia, A. Modica, S. Ratti, and G. Rivas. 1996. First assessment of effects of air-gun seismic shooting on marine resources in the Central Adriatic Sea. Pages 227-238 *in* Society of Petroleum Engineers, International Conference on Health, Safety and Environment, New Orleans, Louisiana, 9-12 June.

Ladich, F. and A.N. Popper. 2004. Parallel evolution in fish hearing organs. Pages 95-127 *in* G.A. Manley, A.N. Popper, and R.R. Fay, eds. Evolution of the Vertebrate Auditory System. Springer-Verlag, New York, NY.

Løkkeborg, S. 1991. Effects of geophysical survey on catching success in longline fishing. Paper presented at the International Council for the Exploration of the Sea (ICES) Annual Science Conference. **ICES CM B** 40:1-9.

Løkkeborg, S. and A.V. Soldal. 1993. The influence of seismic explorations on cod (*Gadus morhua*) behaviour and catch rates. **ICES Mar. Sci. Symp.** 196:62-67.

Madsen, P.T. 2005. Marine mammals and noise: Problems with root mean square sound pressure levels for transients. **J. Acoust. Soc. Am.** 117:3952-3957.

Mann, D.A., Z. Lu, and A.N. Popper. 1997. A clupeid fish can detect ultrasound. **Nature** 389:341.

Mann, D.A., Z. Lu, M.C. Hastings, and A.N. Popper. 1998. Detection of ultrasonic tones and simulated dolphin echolocation clicks by a teleost fish, the American shad (*Alosa sapidissima*). **J. Acoust. Soc. Am.** 104:562-568.

Mann, D.A., D.M. Higgs, W.N. Tavolga, M.J. Souza, and A.N. Popper. 2001. Ultrasound detection by clupeiforme fishes. **J. Acoust. Soc. Am.** 109:3048-3054.

Mann, D.A., P.A. Cott, B.W. Hanna, and A.N. Popper. 2007. Hearing in eight species of northern Canadian freshwater fishes. **J. Fish Biol.** 70:109-120.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, and K. McCabe. 2000a. Marine seismic surveys: Analysis of airgun signals; and effects of air gun exposure on humpback whales, sea turtles, fishes and squid. Report from Centre for Marine Science and Technology, Curtin University, Perth, Western Australia, for Australian Petroleum Production Association, Sydney, NSW.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, and K. McCabe. 2000b. Marine seismic surveys – a study of environmental implications. **APPEA J.** 40:692-706.

McCauley, R.D., J. Fewtrell, and A.N. Popper. 2003. High intensity anthropogenic sound damages fish ears. **J. Acoust. Soc. Am.** 113:638-642.

Pearson, W.H., J.R. Skalski, and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on behavior of captive rockfish (*Sebastes* spp.). **Can. J. Fish. Aquat. Sci.** 49:1343-1356.

Pickett, G.D., D.R. Eaton, R.M.H. Seaby, and G.P. Arnold. 1994. Results of bass tagging in Poole Bay during 1992. Laboratory Leaflet Number 74. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research, Lowestoft, UK.

Popper, A.N. and R.R. Fay. 1993. Sound detection and processing by fish: critical review and major research questions. **Brain Behav. Evol.** 41:14-38.

Popper, A.N. and R.R. Fay. 1999. The auditory periphery in fishes. Pages 43-100 *in* R.R. Fay and A.N. Popper, eds. Comparative Hearing: Fish and Amphibians. Springer-Verlag, New York, NY.

Popper, A.N., M.E. Smith, P.A. Cott, B.W. Hanna, A.O. MacGillivray, M.E. Austin, and D.A. Mann. 2005. Effects of exposure to seismic airgun use on hearing of three fish species. **J. Acoust. Soc. Am.** 117:3958-3971.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego, CA.

Rogers, P. and M. Cox. 1988. Underwater sound as a biological stimulus. Pages 131-149 in J. Atema., R.R. Fay, A.N. Popper, and W.N. Tavolga, eds. The Sensory Biology of Aquatic Animals. Springer-Verlag, New York, NY.

Saetre, R. and E. Ona. 1996. Seismiske undersøkelser og skader på fiskeegg og -larver en vurdering av mulige effekter pa bestandsniv0. [Seismic investigations and damages on fish eggs and larvae; an evaluation of possible effects on stock level] **Fisken og Havet** 1996:1-17, 1-8. (in Norwegian with English summary).

Sand, O. 1981. The lateral line and sound reception. Pages 459-478 *in* W.N. Tavolga, A.N. Popper, and R.R. Fay, eds. Hearing and Sound Communication in Fishes. Springer-Verlag, New York, NY.

Santulli, A., C. Messina, L. Ceffa, A. Curatolo, G. Rivas, G. Fabi, and V. Damelio. 1999. Biochemical responses of European sea bass (*Dicentrachus labrax*) to the stress induced by offshore experimental seismic prospecting. **Mar. Poll. Bull.** 38:1105-1114.

Schellert, A.M. and A.N. Popper. 1992. Functional aspects of the evolution of the auditory system of actinoperygian fish. Pages 295-323 *in* B.D. Webster, R.R. Fay, and A.N. Popper, eds. Evolutionary Biology of Hearing. Springer-Verlag, New York.

Schuijf, A. 1981. Models of acoustic localization. Pages 267-310 *in* W.N. Tavolga, A.N. Popper, and R.R. Fay, R.R., eds. Hearing and Sound Communication in Fishes. Springer-Verlag New York, NY.

Skalski, J.R., W.H. Pearson, and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (*Sebastes* spp.). **Can. J. Fish. Aquat. Sci.** 49:1357-1365.

Slotte, A., K. Hansen, J. Dalen, and E. Ona. 2004. Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. **Fish. Res.** 67:143-150.

Thomsen, B. 2002. An experiment on how seismic shooting affects caged fish. Thesis, Faroese Fisheries Laboratory, University of Aberdeen, Aberdeen, Scotland. 16 August.

Turnpenny, A.W.H. and J.R. Nedwell. 1994. Consultancy Report: The Effects on Marine Fish, Diving Mammals and Birds of Underwater Sound Generated by Seismic Surveys. FCR 089/94. Prepared by Fawley aquatic research laboratories, Ltd. for the UK Offshore Operators Association (UKOOA).

Turnpenny, A.W.H., K.P. Thatcher, J.R. Nedwell. 1994. Research Report: The Effects on Fish and Other Marine Animals of High-level Underwater Sound. FRR 127/94. Prepared by Fawley aquatic research laboratories, Ltd. for the Defence Research Agency.

Van Bergeijk, W.A. 1967. The evolution of vertebrate hearing. Pages 1-49 *in* W.D. Neff, ed. Contributions to Sensory Physiology. Academic Press, New York, NY.

Wardle, C.S., T.J. Carter, G.G. Urquhart, A.D.F. Johnstone, A.M. Ziolkowski, G. Hampson, and D. Mackie. 2001. Effects of seismic airguns on marine fish. **Cont. Shelf Res.** 21:1005-1027.

APPENDIX F:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES

This appendix is intended to provide a more detailed summary of the limited data and literature available on what is known about the potential effects of underwater sound on marine invertebrates. Specific conditions and results of the studies including sound exposure levels and sound thresholds of responses are discussed as available.

The large amounts of energy released by underwater seismic survey equipment results in energy pulses with very high peak pressures (Richardson et al. 1995). This was especially true when chemical explosives were used for underwater surveys. Virtually all underwater seismic surveying is now done with airguns with comparatively lower peak pressures. However, the shock waves that result from underwater gas discharges are still high enough to have the potential to injure or kill animals close to the source. Less overt than those effects are the disturbances to normal behaviors that animals in the vicinity of such discharges may experience.

The following sections provide an overview of sound production and detection in invertebrates, and available information on the effects of exposure to sound on marine invertebrates, with an emphasis on seismic survey sound. The information includes results of studies of varying degrees of scientific veracity as well as anecdotal information.

(a) Sound Production

Most available information on acoustic abilities as they relate to marine invertebrates pertains to crustaceans, specifically lobsters, crabs, and shrimps. Fewer acoustic-related studies have been conducted on cephalopods. Many invertebrates are capable of producing sound; this includes barnacles, amphipods, shrimp, crabs, and lobsters (Au and Banks 1998; Tolstoganova 2002). Invertebrates typically produce sound by scraping or rubbing various parts of their bodies, although they also produce sound in other ways. Sounds made by marine invertebrates may be associated with territorial behavior, mating, courtship, and aggression. On the other hand, some of these sounds may be incidental and not have any biological relevance. Sounds produced by invertebrates can range from 87 Hz to 200 kHz, depending on the species.

Both male and female American lobsters produce a buzzing vibration with their carapace when grasped (Pye and Watson III 2004; Henninger and Watson III 2005). Larger lobsters vibrate more consistently than smaller lobsters, suggesting that sound production is involved with mating behavior. Sound production by other species of lobsters has also been studied. Among deep-sea lobsters, sound level was more variable at night than during the day, with the highest levels occurring at the lowest frequencies.

While feeding, king crab produce pulsed sounds that appear to stimulate movement by other crabs receiving the sounds, including approach behavior (Tolstoganova 2002). King crab also appeared to produce ‘discomfort’ sounds when environmental conditions were manipulated. These discomfort sounds differ from the feeding sounds in terms of frequency range and pulse duration.

Snapping shrimp (*Synalpheus parneomeris*) are among the major sources of biological sound in temperate and tropical shallow-water areas (Au and Banks 1998). By rapidly closing one of its frontal chela (claws), a snapping shrimp generates a forward jet of water and the cavitation of fast moving water produces a sound. Both the sound and the jet of water appear to function as weapons in the territorial behavior of alpheidae shrimp. Measured peak-to-peak source SPLs for snapping ship were 183–189 dB re 1 µPa @ 1 m and extended over a frequency range of 2–200 kHz.

(b) Sound Detection

There is considerable debate about the hearing capabilities of aquatic invertebrates. Whether they are able to hear or not depends on how underwater sound and underwater hearing are defined. In contrast to fish and aquatic mammals, no physical structures have been discovered in aquatic invertebrates that are stimulated by the pressure component of sound. However, vibrations (i.e., mechanical disturbances of the water) characterize sound waves as well. Rather than being pressure-sensitive, invertebrates appear to be most sensitive to the vibrational component of sound (Breithaupt 2002). Statocyst organs may provide one means of vibration detection for aquatic invertebrates.

More is known about the acoustic detection capabilities in decapod crustaceans than in any other marine invertebrate group. Crustaceans appear to be most sensitive to sounds of low frequencies, i.e., <1000 Hz (Budelmann 1992; Popper et al. 2001). A study by Lovell et al. (2005) suggests greater sensitivity of the prawn (*Palaemon serratus*) to low-frequency sound than previously thought. Studies involving American lobster suggest that these crustaceans are more sensitive to higher frequency sounds than previously realized (Pye and Watson III 2004).

It is possible that statocyst hair cells of cephalopods are directionally sensitive in a way that is similar to the responses of hair cells of the vertebrate vestibular and lateral line systems (Budelmann and Williamson 1994). Studies by Packard et al. (1990), Rawizza (1995) and Komak et al. (2005) have tested the sensitivities of various cephalopods to water-borne vibrations, some of which were generated by low-frequency sound.

In summary, only a few studies have been conducted on the sensitivity of certain species to sound. Available data suggest that they are capable of detecting vibrations but they do not appear to be capable of detecting pressure fluctuations.

(c) Potential Seismic Effects

There are three categories of potential effects of exposure to sound on marine invertebrates: pathological, physiological, and behavioral. Pathological effects include lethal and sub-lethal injury to the animals, physiological effects include temporary primary and secondary stress responses, and behavioral effects refer to changes in exhibited behaviors (i.e., disturbance). The three categories should not be considered as independent of one another and are interrelated in complex ways. For example, it is possible that certain physiological and behavioral changes could potentially lead to an ultimate pathological effect on individual animals (i.e., mortality).

Pathological Effects

In water, acute injury or death of organisms as a result of exposure to sound might depend on two features of the sound source: the received peak pressure and the time required for the pressure to rise and decay. Generally, the higher the received pressure and the less time it takes for the pressure to rise and decay, the greater the chance of acute pathological effects. Considering the peak pressure and rise/decay time characteristics of seismic airgun arrays used today, the associated pathological zone for invertebrates would be expected to be small (i.e., within a few meters of the seismic source). Few studies have assessed the potential for pathological effects on invertebrates from exposure to seismic sound, and some of these results are questionable as summarized below.

The pathological impacts of seismic survey sound on marine invertebrates were investigated on a limited scale in a pilot study on snow crabs (Christian et al. 2003, 2004). Because this study has not been peer reviewed, results must be interpreted cautiously. Under controlled field experimental conditions captive adult male snow crabs, egg-carrying female snow crabs, and fertilized snow crab eggs were exposed to variable SPLs (191–221 dB re 1 μPa_{peak}) and SELs (<130–187 dB re 1 $\mu Pa^2 \cdot s$). Neither acute nor chronic (12 weeks after exposure) mortality was observed for the adult crabs. There was a significant difference in development rate noted between the exposed and unexposed fertilized eggs/embryos. The egg mass exposed to seismic energy had a higher proportion of less-developed eggs than the unexposed mass. It should be noted that both egg masses came from a single female and any measure of natural variability was unattainable (Christian et al. 2003, 2004).

Another limited study of the effects of seismic survey sound on invertebrates had serious design problems that impacted the interpretation of some of the results (Chadwick 2004). In 2003, a collaborative study was conducted in the southern Gulf of St. Lawrence, Canada, to investigate the effects of exposure to sound from a commercial seismic survey on egg-bearing female snow crabs (DFO 2004). Caged animals were placed on the ocean bottom at a location within the survey area and at a location outside of the survey area. The maximum received SPL was ~195 dB re 1 μPa_{peak}. The crabs were exposed for 132 hr of the survey, equivalent to many thousands of seismic shots of varying received SPLs. The animals were retrieved and transferred to laboratories for analyses. Neither acute nor chronic lethal or sub-lethal injury to the female crabs or crab embryos was indicated. DFO (2004) reported that some exposed individuals had short-term soiling of gills, antennules, and statocysts; bruising of the hepatopancreas and ovary; and detached outer membranes of oocytes. However, these differences could not be conclusively linked to exposure to seismic survey sound.

In a field study, Pearson et al. (1994) exposed Stage II larvae of the dungeness crab to single discharges from a seven-airgun array and compared their mortality and development rates with those of unexposed larvae. For immediate and long-term survival and time to molt, this study did not reveal any statistically significant differences between the exposed and unexposed larvae, even those exposed within 1 m of the seismic source.

In 2001 and 2003, there were two incidents of multiple strandings of the giant squid on the north coast of Spain, and there was speculation that they were caused by exposure to geophysical seismic survey sounds occurring at about the same time in the Bay of Biscay (Guerra et al. 2004). A total of nine giant squid, either stranded or moribund surface-floating, were collected at these times. However, Guerra et al. (2004) did not present any evidence that conclusively links the giant squid strandings and floaters to seismic activity in the area. Based on necropsies of seven (six females and one male) specimens, there was evidence of acute tissue damage. The authors speculated that one female with extensive tissue damage was affected by the impact of acoustic waves. However, little is known about the impact of marine acoustic technology on cephalopods and the authors did not describe the seismic sources, locations, and durations of the Bay of Biscay surveys. In addition, there were no controls, the presence of seismic activity was entirely circumstantial, and the examined animals had been dead long enough for commencement of tissue degradation.

McCauley et al. (2000a,b) exposed caged cephalopods to noise from a single 20-in^3 airgun with maximum SPLs of >200 dB re 1 μPa_{peak}. Statocysts were removed and preserved, but at the time of publication, results of the statocyst analyses were not available. However, behavioral reactions were observed (see below). No squid or cuttlefish mortalities were reported as a result of these exposures.

Physiological Effects

Biochemical responses by marine invertebrates to acoustic stress have also been studied, albeit in a very limited way in studies that were not peer reviewed. The study of the biochemical parameters influenced by acoustic stress could possibly provide some indication of the acute extent of the stress and perhaps any subsequent chronic detrimental effects. Stress could potentially affect animal populations by reducing reproductive capacity and adult abundance.

Stress indicators in the haemolymph of adult male snow crabs were monitored immediately after exposure of the animals to seismic survey sound (Christian et al. 2003, 2004) and at various intervals after exposure. No significant acute or chronic differences between exposed and unexposed animals in terms of the stress indicators (e.g., proteins, enzymes, cell type count) were indicated. Again, this pilot study was not peer reviewed.

Pilot studies on the effects of exposure to seismic survey sound on American lobsters have recently been conducted by DFO, St. John's, Newfoundland. The received SPL during these studies was ~197 dB re 1 μPa_{peak}. Each exposure session consisted of 200 shots over a 33-min period. Preliminary results suggest that haemolymph parameters such as serum protein, enzyme, and calcium ion levels were depressed for days to weeks in lobsters exposed to seismic survey sound compared to control animals. These results might suggest disturbance to the osmoregulatory system (Payne et al. 2007). However, the lack of peer review of this study limits its validity.

Behavioral Effects

The very limited study of the effects of exposure to sound on marine invertebrates has not indicated any serious pathological and physiological effects. However, some recent studies have focused on potential behavioral effects on marine invertebrates.

Anecdotal information from Newfoundland, Canada, indicated that catch rates of snow crabs showed a significant reduction immediately following a pass by a seismic survey vessel (G. Chidley, Newfoundland fisherman, pers. comm.). Christian et al. (2003) investigated the behavioral effects of exposure to seismic survey sound on snow crabs. Eight animals were equipped with ultrasonic tags, released and monitored for multiple days prior to exposure and after exposure. Received SPL and SEL were ~191 dB re 1 μPa_{peak} and <130 dB re 1 $\mu Pa^2 \cdot s$, respectively. The crabs were exposed to 200 discharges over a 33-min period. None of the tagged animals left the immediate area after exposure to the seismic survey sound. Five animals were captured in the snow crab commercial fishery the following year, one at the release location, one 22 mi (35 km) from the release location, and three at intermediate distances from the release location.

Another approach used by Christian et al. (2003) involved exposure of caged snow crabs to seismic survey sound while monitoring the crabs with a remote video camera. The caged animals were placed on the ocean bottom at a depth of 50 m. Received SPL and SEL were ~202 dB re 1 μPa_{peak} and 150 dB re 1 $\mu Pa^2 \cdot s$, respectively. The crabs were exposed to 200 discharges over a 33-min period. The snow crabs did not exhibit any overt startle response during the exposure period.

Christian et al. (2003) also investigated the pre- and post-exposure catchability of snow crabs during a commercial fishery. Received SPLs and SELs were not measured directly and likely ranged widely considering the area fished. Maximum SPL and SEL were likely similar to those measured during the telemetry study. There were seven pre-exposure and six post-exposure trap sets. Unfortunately, there was considerable variability in set duration because of poor weather. Results indicated that the CPUE did not decrease after the crabs were exposed to seismic survey sound.

Caged female snow crabs exposed to sound associated with a recent commercial seismic survey conducted in the southern Gulf of St. Lawrence, Canada, exhibited a higher rate of ‘righting’ than those crabs not exposed to seismic survey sound (J. Payne, Research Scientist, DFO, St. John’s, Newfoundland, pers. comm.). Righting refers to a crab’s ability to return itself to an upright position after being placed on its back. Christian et al. (2003) made the same observation in their study.

The preliminary results from the previously discussed studies on the effects of exposure to seismic survey sound on American lobsters suggest that feeding behavior of exposed lobsters was reduced for several days following exposure (Payne et al. 2007). However, Parry and Gason (2006) reported no changes in rock lobster CPUE during or after seismic surveys off western Victoria, Australia, from 1978–2004.

More anecdotal information from Newfoundland, Canada, indicates that a school of shrimp observed on a fishing vessel sounder shifted downwards and away from a nearby seismic sound source (H. Thorne, Newfoundland fisherman, pers. comm.). This observed effect was temporary. Andriguetto-Filho et al. (2005) attempted to evaluate the impact of seismic survey sound on artisanal shrimp fisheries off Brazil. Bottom trawl yields were measured before and after multiple-day shooting of an airgun array with a source SPL of 196 dB re 1 µPa-1 m. Water depth in the experimental area ranged between 2 and 15 m. Results of the study did not indicate any significant deleterious impact on shrimp catches.

Caged brown shrimp reared under different acoustical conditions exhibited differences in aggressive behavior and feeding rate (Lagardère 1982). Those exposed to a continuous sound source showed more aggression and less feeding behavior. It should be noted that behavior and response to stress in a cage may be vastly different from behavior of animals in the wild.

McCauley et al. (2000a,b) provided the first evidence of the behavioral response of southern calamari squid exposed to seismic survey sound. McCauley et al. reported on the exposure of caged cephalopods (50 squid and two cuttlefish) to noise from a single 20-in^3 airgun. The cephalopods were exposed to both stationary and mobile sound sources. The two-run total exposure times of the three trials ranged from 69–119 min. at a firing rate of once every 10–15 s. The maximum SPL was >200 dB re 1 μPa_{peak}. Some of the squid fired their ink sacs apparently in response to the first shot of one of the trials and then moved quickly away from the airgun. In addition to the above-described startle responses, some squid also moved towards the water surface as the airgun approached. McCauley et al. (2000a,b) reported that the startle and avoidance responses occurred at a received SPL of 174 dB re 1 μPa_{rms}. They also exposed squid to a ramped approach-depart airgun signal whereby the received SPL was gradually increased over time. No strong startle response was observed (i.e., ink discharge) but alarm responses were observed once the received SPL reached a level in the 156–161 dB re 1 μPa_{rms} range.

Komak et al. (2005) also reported the results of a study of cephalopod behavioral responses to local water movements. In this case, juvenile cuttlefish exhibited various behavioral responses to local sinusoidal water movements of different frequencies between 0.01 and 1000 Hz. These responses included body pattern changing, movement, burrowing, reorientation, and swimming.

Low-frequency sound (<200 Hz) has also been used as a means of preventing settling/fouling by aquatic invertebrates such as zebra mussels (Donskoy and Ludyanskiy 1995) and balanoid barnacles (Branscomb and Rittschof 1984). There are no organs in mussels or barnacles to suggest any likelihood of sound detection. It is most likely that effects of the low-frequency sound on these invertebrates are mechanical in nature.

Although not demonstrated in the literature, masking can be considered a potential effect of anthropogenic underwater sound on marine invertebrates. Some invertebrates are known to produce sounds (Au and Banks 1998; Tolstoganova 2002; Latha et al. 2005) and the detection capabilities of others are partially known (Packard et al. 1990; Budelmann 1996; Jeffs et al. 2003; Lovell et al. 2005). The functionality of these sounds is not understood and it is not known whether they have any biological relevance or not. Masking of produced sounds and received sounds (e.g., conspecifics and predators), at least the particle displacement component, could potentially have adverse effects on marine invertebrates.

(d) Literature Cited

Andriguetto-Filho, J.M., A. Ostrensky, M.R. Pie, U.A. Silva, and W.A. Boeger. 2005. Evaluating the impact of seismic prospecting on artisanal shrimp fisheries. **Cont. Shelf Res.** 25:1720-1727.

Au, W.W.L. and K. Banks. 1998. The acoustics of snapping shrimp *Synalpheus parneomeris* in Kaneohe Bay. **J. Acoust. Soc. Am.** 103:41-47.

Branscomb, E.S. and D. Rittschof. 1984. An investigation of low frequency sound waves as a means of inhibiting barnacle settlement. **J. Exp. Mar. Biol. Ecol.** 79:149-154.

Breithaupt, T. 2002. Sound perception in aquatic crustaceans. Pages 548-558 *in* K. Wiese, ed. Crustacean Nervous System. Springer-Verlag, Berlin-Heidelberg, Germany.

Budelmann, B.U. 1992. Hearing in crustacea. Pages 131-139 *in* D.B. Webster, R.R. Fay, and A.N. Popper, eds. Evolutionary Biology of Hearing. Springer-Verlag, New York, NY.

Budelmann, B.U. 1996. Active marine predators: the sensory world of cephalopods. **Mar. Freshwater Behav. Physiol.** 27:59-75.

Budelmann, B.U. and R. Williamson. 1994. Directional sensitivity of hair cell afferents in the Octopus statocyst**. J. Exp. Biol.** 187:245-259.

Chadwick, M. 2004. Proceedings of the Peer Review on Potential Impacts of Seismic Energy on Snow Crab. Gulf Region, Department of Fisheries and Oceans Canada, Science Advisory Secretariat Proceedings Series 2004/045.

Christian, J.R., A. Mathieu, D.H. Thomson, D. White, and R.A. Buchanan. 2003. Effect of seismic energy on snow crab (*Chionoecetes opilio*). Environmental Studies Research Funds Report No. 144. Calgary, AB, Canada. November.

Christian, J.R., A. Mathieu, and R.A. Buchanan. 2004. Chronic effects of seismic energy on snow crab (*Chionoecetes opilio*). Environmental Studies Research Funds Report No. 158, Calgary, AB. March.

DFO. 2004. Potential impacts of seismic energy on snow crab. Canadian Science Advisory Secretariat Habitat Status Report 2004/003.

Donskoy, D.M. and M.L. Ludyanskiy. 1995. Low frequency sound as a control measure for zebra mussel fouling. Proceedings of the Fifth International Zebra Mussel and Other Aquatic Nuisance Organisms Conference, February 1995, Toronto, Canada.

Guerra, A., A.F. González, and F. Rocha. 2004. A review of the records of giant squid in the north-eastern Atlantic and severe injuries in *Architeuthis dux* stranded after acoustic explorations. Paper presented at the International Council for the Exploration of the Sea (ICES) Annual Science Conference, 22–25 September 2004, Vigo, Spain. ICES CM 2004/CC:29.

Henninger, H.P. and W.H. Watson, III. 2005. Mechanisms underlying the production of carapace vibrations and associated waterborne sounds in the American lobster, *Homarus americanus*. **J. Exp. Biol.** 208:3421-3429.

Jeffs, A., N. Tolimieri, and J.C. Montgomery. 2003. Crabs on cue for the coast: the use of underwater sound for orientation by pelagic crab stages. **Mar. Freshwater Res.** 54:841-845.

Komak, S., J.G. Boal, L. Dickel, and B.U. Budelmann. 2005. Behavioural responses of juvenile cuttlefish (*Sepia officinalis*) to local water movements. **Mar. Freshwater Behav. Physiol.** 38:117-125.

Lagardère, J.P. 1982. Effects of noise on growth and reproduction of *Crangon crangon* in rearing tanks. **Mar. Biol.** 71:177-186.

Latha, G., S. Senthilvadivu, R. Venkatesan, and V. Rajendran. 2005. Sound of shallow and deep water lobsters: Measurements, analysis, and characterization (L). **J. Acoust. Soc. Am.** 117: 2720-2723.

Lovell, J.M., M.M. Findley, R.M. Moate, and H.Y. Yan. 2005. The hearing abilities of the prawn *Palaemon serratus*. **Comp. Biochem. Physiol. Part A** 140:89-100.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, and K. McCabe. 2000a. Marine seismic surveys: Analysis of airgun signals; and effects of air gun exposure on humpback whales, sea turtles, fishes and squid. Report from Centre for Marine Science and Technology, Curtin University, Perth, Western Australia, for Australian Petroleum Production Association, Sydney, NSW.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch and K. McCabe. 2000b. Marine seismic surveys – a study of environmental implications. **APPEA J.** 40:692-706.

Packard, A., H.E. Karlsen, and O. Sand. 1990. Low frequency hearing in cephalopods. **J. Comp. Physiol. A** 166: 501-505.

Parry, G.D. and A. Gason. 2006. The effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia. **Fish. Res.** 79:272-284.

Payne, J.F., C.A. Andrews, L.L. Fancey, A.L. Cook, and J.R. Christian. 2007. Pilot study on the effects of seismic air gun noise on lobster (*Homarus americanus*). Canadian Technical Report of Fisheries and Aquatic Sciences No. 2712:v + 46 p.

Pearson, W., J. Skalski, S. Sulkin, and C. Malme. 1994. Effects of seismic energy releases on the survival and development of zoeal larvae of Dungeness crab (*Cancer magister*). **Mar. Environ. Res.** 38:93-113.

Popper, A.N., M. Salmon, and K.W. Horch. 2001. Acoustic detection and communication by decapod crustaceans. **J. Comp. Physiol. A** 187:83-89.

Pye, H.J., and W.H. Watson, III. 2004. Sound detection and production in the American lobster, *Homarus americanus*: Sensitivity range and behavioural implications. **J. Acoust. Soc. Am.** 115 (Part 2):2486.

Rawizza, H.E. 1995. Hearing and associative learning in cuttlefish, *Sepia officinalis*. Hopkins Marine Station Student Paper. Stanford University, Palo Alto, CA.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego, CA.

Tolstoganova, L.K. 2002. Acoustical behaviour in king crab (*Paralithodes camtschaticus*). Pages 247-254 *in* A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby, eds. Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01. Fairbanks, AK.