Environmental Assessment of a Marine Geophysical Survey by the R/V *Marcus G. Langseth* in the Southwest Pacific Ocean, January–February 2009

Prepared for

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ABSTRACT

Lamont-Doherty Earth Observatory (L-DEO) plans to conduct a marine seismic survey in the Lau Basin of the Southwest Pacific Ocean (SWPO) during January–February 2009 as part of the National Science Foundation's (NSF) RIDGE 2000 program. The survey will take place in the Exclusive Economic Zone (EEZ) of Tonga, in water depths >1000 m. L-DEO has requested clearance to work in these waters. The seismic study will use a towed array of 36 airguns with a total discharge volume of ~6600 in^3, firing at relatively long intervals—once every 400 m (180 s).

NSF, as the funding and action agency, has a mission to "promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…". The proposed seismic survey is part of a research proposal recommended for funding by an expert review panel. It will provide data integral to advancing scientific understanding of the Eastern Lau Spreading Center (ELSC) magma storage and thermal system. It will obtain information that will improve estimates of regional earthquake occurrence and distribution.

L-DEO is requesting an Incidental Harassment Authorization (IHA) from the U.S. 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 and provides information on marine species that are not addressed by the IHA application, including birds, sea turtles, invertebrates, and fish. The EA addresses the requirements of U.S. 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.

Numerous species of marine mammals inhabit Lau Basin and the waters of Tonga. Several of these species are listed as ***endangered*** under the U.S. Endangered Species Act (ESA), including the sperm, humpback, sei, fin, and blue whales. Other listed species that could occur in the study area include the ***endangered*** leatherback and hawksbill turtles, and the ***threatened*** green, olive ridley, and loggerhead turtles.

Potential impacts of the seismic survey on the environment would be primarily a result of the operation of the airgun array. 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 by marine mammals, sea turtles, and fish, and other forms of disturbance. An integral part of the planned survey is a monitoring and mitigation program designed to minimize impacts of the proposed activities on marine animals present during the proposed research, and to document as much as possible the nature and extent of any effects. Injurious impacts to marine mammals and sea turtles have not been proven to occur near airgun arrays, and also are not likely to be caused by the other types of sound sources to be used. However, given the high levels of sound emitted by a large array of airguns, a precautionary approach is warranted. The planned monitoring and mitigation measures would reduce the possibility of injurious effects.

Protection measures designed to mitigate the potential environmental impacts to marine mammals and turtles will include the following: ramp ups, minimum of one dedicated observer maintaining a visual watch during all daytime airgun operations, two observers 30 min before and during ramp ups during the day and at night (and when possible at other times), no start ups during poor visibility or at night unless at least one airgun has been operating, passive acoustic monitoring (PAM) via towed hydrophones during both day and night to complement visual monitoring (when practicable), and power downs (or if necessary shut downs) when marine mammals or sea turtles are detected in or about to enter designated exclusion zones. 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. The relatively wide spacing of the shots, in time and space, is an inherent mitigation measure relative to more typical seismic surveys with closer shotpoints.

With the planned monitoring and mitigation measures, unavoidable impacts to each species of marine mammal and turtle that could 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 U.S. Marine Mammal Protection Act (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, the populations to which they belong, or their habitats.

LIST OF ACRONYMS

~	approximately
3-D	Three Dimensional
AMC	Axial Magma Chamber
CITES	Convention on International Trade in Endangered Species
CPA	Closest Point of Approach
CPUE	Catch per Unit Effort
CV	Coefficient of Variation
DFO	(Canadian) Department of Fisheries and Oceans
EA	Environmental Assessment
EEZ	Exclusive Economic Zone
ELSC	Eastern Lau Spreading Center
ESA	(U.S.) Endangered Species Act
ETP	Eastern Tropical Pacific
ft	feet
$g\ C\ m^{-2}\ d^{-1}$	grams of Carbon per meter squared per day
GIS	Geographic Information System
h	hour
hp	horsepower
ha	hectares
IHA	Incidental Harassment Authorization (under U.S. MMPA)
in	inch
ISS	Integrated Studies Site
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
Langseth	R/V *Marcus G. Langseth*
m	meter
MBES	Multibeam echosounder
mi	mile
min	minute
MMO	Marine Mammal Observer
MMPA	(U.S.) Marine Mammal Protection Act
ms	millisecond
n.mi.	nautical mile
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
NVD	Night Vision Device
OBS	Ocean Bottom Seismometer
PAM	Passive Acoustic Monitoring
pk	peak
PL	Propagation Loss
psi	pounds per square inch
PTS	Permanent Threshold Shift

RIDGE	NSF program which was developed to facilitate the study of mid-ocean ridges and back-arc spreading centers
RL	Received Level
R/V	Research Vessel
rms	root-mean-square
rpm	rotations per minute
s	second
SBP	Sub-Bottom Profiler
SEL	Sound Exposure Level (a measure of acoustic energy)
SL	Source Level
SPL	sound pressure level
SPSG	South Pacific Subtropical Gyre
SPREP	Secretariat of the Pacific Regional Environment Programme
SPWRC	South Pacific Whale Research Consortium
TTS	Temporary Threshold Shift
UNEP	United Nations Environment Program
U.S.	United States of America
USFWS	U.S. Fish and Wildlife Service
USN	U.S. Navy
vs.	versus
WHOI	Woods Hole Oceanographic Institution

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 Southwest Pacific Ocean (SWPO) from ~14 January–21 February 2009, as part of the Lau Integrated Studies Site (Lau ISS) initiative of NSF's RIDGE 2000 program. The marine seismic survey will take place in the Exclusive Economic Zone (EEZ) of Tonga.

NSF, as the funding and action agency, has a mission to "promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…". The proposed seismic survey is part of a research proposal recommended for funding by an expert review panel. The proposed survey will provide data integral to advancing scientific understanding of the Eastern Lau Spreading Center (ELSC) magma storage and thermal system. More specifically, the survey will obtain information on the magma supply and volcanic processes along the ridge and the source of heat for the hydrothermal systems that support the biological communities. This information can in turn be used to understand how mid-ocean ridges influence global climatic conditions, and to obtain improved locations and source properties of regional earthquakes. The information is also vital to understanding plate tectonic processes and their effects on earthquake occurrence and distribution.

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 U.S. 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 "take by harassment" of small numbers of marine mammals during the proposed seismic survey by L-DEO in Lau Basin during January–February 2009.

To be eligible for an IHA under the U.S. Marine Mammal Protection Act (MMPA), 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 inhabit the Lau Basin and offshore waters of Tonga. Several of these species are listed as ***endangered*** under the ESA, including the sperm, humpback, sei, fin, and blue whales. Other listed species that occur in the study area include the ***endangered*** leatherback and hawksbill turtles, and the ***threatened*** green, olive ridley, and loggerhead turtles.

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. The proposed project would also have little impact on fish resources, and the only effect on fish habitat would be short-term disturbance that could lead to temporary relocation of pelagic fish species or their food. Impacts of seismic sounds on some pelagic seabirds are possible, although none are expected to be significant to individual birds or their populations.

II. ALTERNATIVES INCLUDING PROPOSED ACTION

Three alternatives are evaluated: (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 the seismic survey along the ELSC in the Lau Basin. This study is part of NSF's RIDGE 2000 program, which was developed to facilitate the study of mid-ocean ridges and back-arc spreading centers. These areas mark the boundaries where oceanic plates separate from one another. Around the mid-ocean ridges, heat from the mantle drives vast hydrothermal systems that influence ocean water chemistry and nourish enormous ecosystems. By affecting the chemical and thermal make-up of our oceans, mid-ocean ridges may influence global climatic conditions. Understanding cycles of mass and energy flux through the mid-ocean ridge systems helps us understand the history of the planet and predict its future.

Within the RIDGE 2000 program, the Lau ISS initiative is an interdisciplinary research program focused on understanding the combined mass, fluid, thermal, and biological processes interacting within the ELSC. The proposed survey in the Lau Basin is part of the Lau ISS initiative, and the survey's main purpose is to image the magmatic systems and thermal structure at the ELSC. These images will increase our understanding of the magma supply and volcanic processes along the ridge and the source of heat for the hydrothermal systems that support the biological communities. This information can in turn be used to understand how mid-ocean ridges influence global climatic conditions, and to obtain improved locations and source properties of regional earthquakes. The information is vital to understanding plate tectonic processes and their effects on earthquake occurrence and distribution.

(2) Proposed Activities

(a) Location of the Activities

The survey will encompass the area 19°40'–21°30'S, 175°30'–176°50'W (Fig. 1). Water depths in the survey area range from 1000 m to 2600 m. The seismic survey will be conducted in the EEZ of Tonga and will not approach land closer than 42 km. The project is scheduled to occur 14 January–21 February 2009. Some minor deviation from these dates is possible, depending on logistics and weather.

(b) Description of the Activities

The procedures to be used for the survey will be similar to those used during previous seismic surveys by L-DEO and will use conventional seismic methodology. The survey will involve one source vessel, the R/V *Marcus G. Langseth*. The *Langseth* will deploy an array of 36 airguns as an energy source and a receiving system consisting of ~55–64 Ocean Bottom Seismometers (OBSs). The OBSs

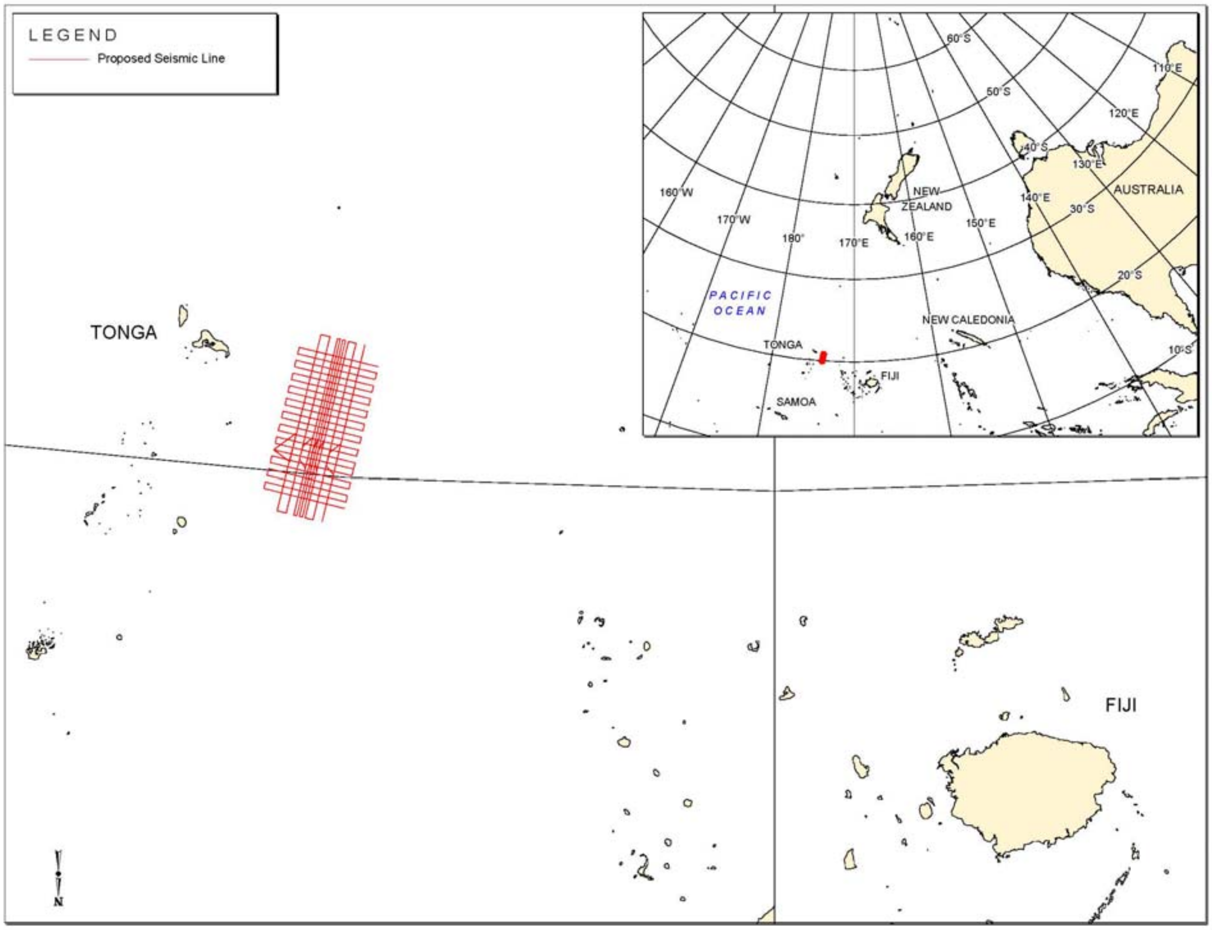

FIGURE 1. Study area and proposed seismic transect lines in the Lau Basin, Southwest Pacific Ocean.

record the returning acoustic signals internally for later analysis. A relatively short (up to 6-km) hydrophone streamer may also be used. As the airgun array is towed along the survey lines, the hydrophone streamer would receive the returning acoustic signals and transfer the data to the on-board processing system.

The planned seismic survey will consist of ~3650 km of survey lines. All survey effort will take place in deep (>1000 m) water. There will be additional operations associated with equipment testing, start up, line changes, and repeat coverage of any areas where initial data quality is sub-standard. In our calculations (see § IV(3)), 25% has been added to the total planned line-length to allow for those additional operations.

The survey will take place along the ELSC. To understand the ridge magma plumbing system and thermal structure of the ELSC, the delineation of lateral heterogeneity in physical properties at scales of several hundred meters to a few kilometers is needed. To achieve this, the proposed seismic transects (Fig. 2) will allow the tomographical imaging in three-dimensions of the physical properties of the crust and uppermost mantle of this area.

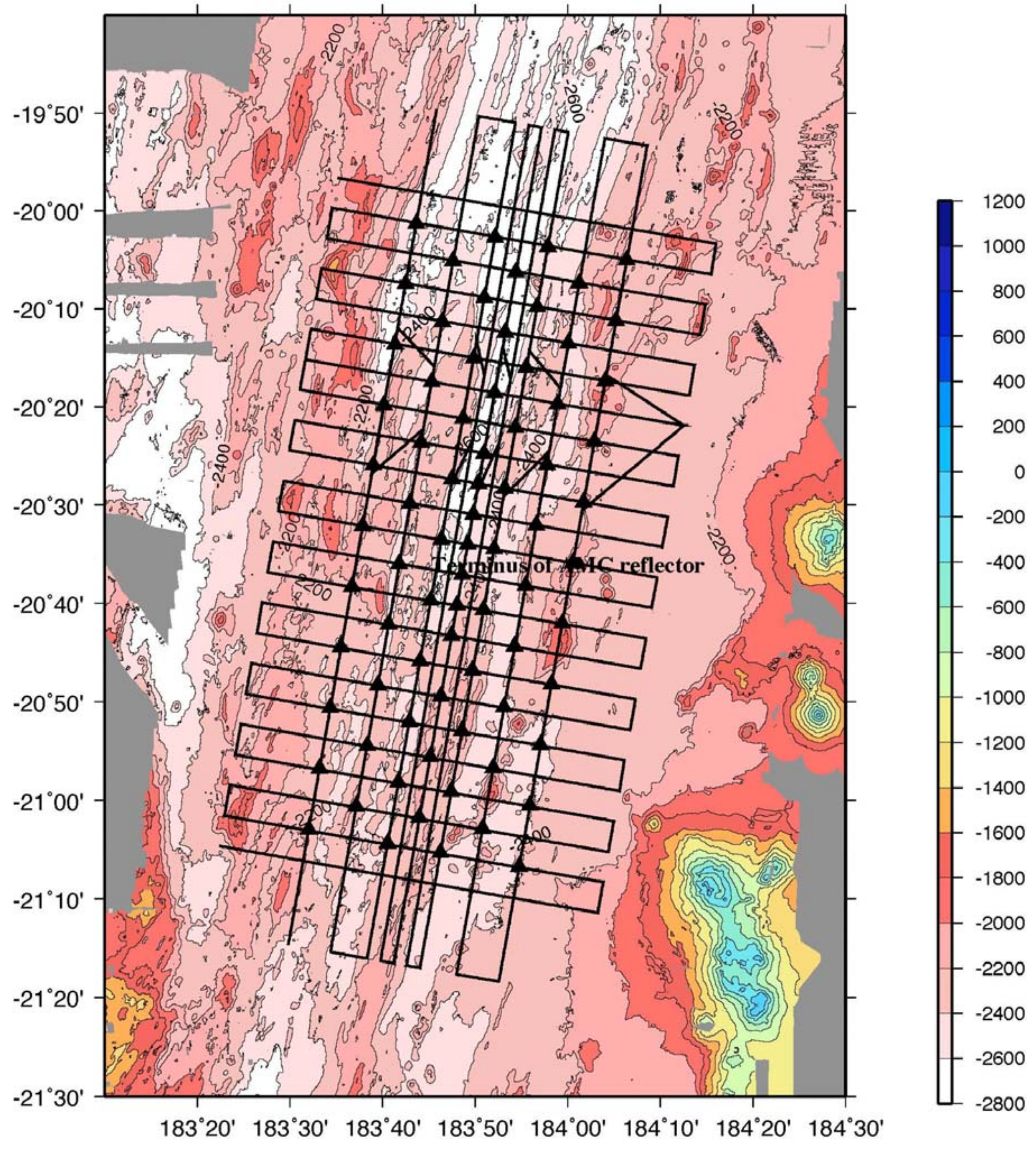

FIGURE 2. Study area and proposed seismic transect lines (solid black lines) in the Lau Basin, Southwest Pacific Ocean. Triangles represent OBS locations. The Axial Magma Chamber (AMC) reflector is a feature that sits ~2 km beneath the seafloor and is a sill filled with magma.

In addition to the operations of the airgun array, a multibeam echosounder (MBES) and a sub-bottom profiler (SBP) will also be operated from the *Langseth* continuously throughout the cruise. 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 scientific team consists of Dr. Doug Wiens (Washington University), Dr. Robert Dunn (University of Hawaii), Dr. Donna Blackman (Scripps Institution of Oceanography), and Dr. Spahr Webb (L-DEO). The vessel will be self-contained, and the crew will live aboard the vessel for the entire cruise.

(c) Schedule

The *Langseth* is expected to depart Nuku'alofa, Tonga, on ~14 January 2009 for a one-day transit to the study area in the Lau Basin (Fig. 1). Once at the study area, ~19 days of seismic operations will occur. Approximately 16.5 days will be spent deploying and recovering OBSs [see (f) below]. Once all of the equipment is recovered at the end of the study, the vessel will start on the two-day transit to Suva, Fiji, for arrival on ~21 February 2009. The exact dates of the activities depend on logistics, weather conditions, and 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 along predetermined lines (Fig. 2). The *Langseth* will also deploy and retrieve the OBSs and, if used, the hydrophone streamer. If the *Langseth* is towing the airgun array as well as the hydrophone streamer, 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 with the streamer.

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, and the shaft typically rotates at 750 revolutions per minute (rpm). The vessel also has an 800 hp bow-thruster, which is not used during seismic acquisition. The operation speed during seismic acquisition is typically 7.4–9.3 km/h. When not towing seismic survey gear, the *Langseth* can cruise at 20–24 km/h. 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 for animals before and during airgun operations, as described in § II(3), below.

Other details of the *Langseth* include the following:

Owner:	National Science Foundation
Operator:	Lamont-Doherty Earth Observatory of Columbia University
Flag:	United States of America
Date Built:	1991 (Refitted in 2006)
Gross Tonnage:	3834
Accommodation Capacity:	55 including ~35 scientists

(e) 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 airgun array will consist of a mixture of Bolt 1500LL and Bolt 1900LLX airguns. The airguns will be configured as four identical linear arrays or "strings" (Fig. 3). Each string will have ten

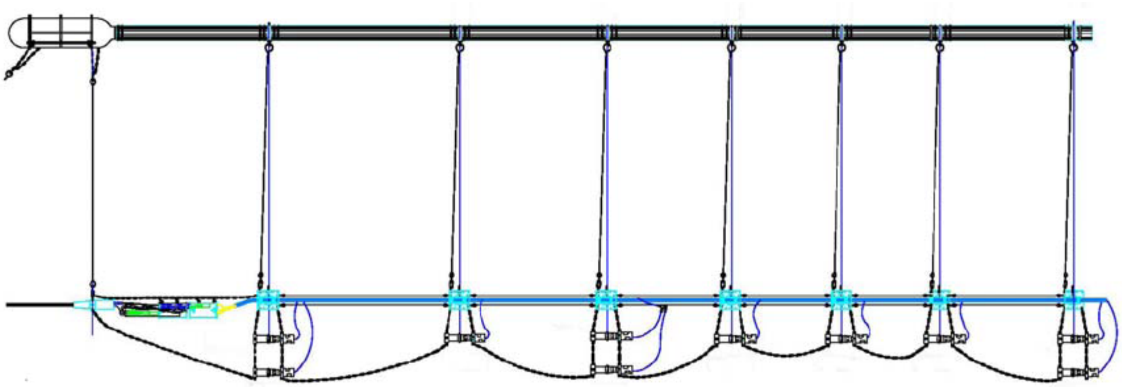

FIGURE 3. One linear airgun array or string with ten airguns, nine of which would be operating.

36-Airgun Array Specifications

Energy Source	Thirty-six 1900 psi Bolt airguns of 40–360 in^3, in four strings each containing nine operating airguns
Source output (downward)	0-pk is 84 bar-m (259 dB re 1 μPa·m); pk-pk is 177 bar·m (265 dB)
Air discharge volume	~6600 in^3
Dominant frequency components	2–188 Hz

airguns; the first and last airguns in the strings are spaced 16 m apart. Nine airguns in each string will be fired simultaneously, whereas 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 area of ~24×16 m behind the *Langseth* and will be towed ~50–100 m behind the vessel. The airgun array will fire every ~400 m (180 s) for OBS refraction data. The firing pressure of the array is 1900 psi. During firing, a brief (~0.1 s) pulse of sound is emitted. The airguns will be silent during the intervening periods.

The tow depth of the array will typically be 9 m, but the tow depth may, at times, be adjusted to 12 m. The depth at which the source is towed (particularly a large source) 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 shallow depths (see Fig. 4–6 and Table 1, later). However, the nominal 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. In our calculations, we have assumed a tow depth of 12 m at all times.

Because the actual source is a distributed sound source (36 airguns) rather than a single point source, the highest sound levels 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 nominal source level applicable to downward propagation because of the directional nature of the sound from the airgun array.

(f) OBS Description and Deployment

A total of ~55–64 OBSs will be deployed during the survey and will be spaced ~10–12 km apart (Fig. 2). An initial network of ~55 OBSs will be deployed over the southern part of the study area (south of ~20º15'S). This area will be surveyed first with the 36-airgun array. Some of the OBSs from the initial network will then be retrieved and redeployed over the northern part of the study area so that a second network of ~18 OBSs can be surveyed. All OBSs will be retrieved at the end of the study. Throughout the study, ~16.5 days will be spent deploying and retrieving OBSs.

Two different types of OBSs will be used. The Woods Hole Oceanographic Institution (WHOI) "D2" OBS has a height of ~1 m and a maximum diameter of 50 cm. The anchor is made of hot-rolled steel and weighs 23 kg. The anchor dimensions are 2.5 × 30.5 × 38.1 cm. The other OBS type is the LC4x4 from Scripps Institution of Oceanography. This OBS unit has a volume of ~1 m^3, with an anchor that consists of a large piece of steel grating (~1 m^2). Once the OBS is ready to be retrieved, an acoustic release transponder interrogates the OBS at a frequency of 9–11 kHz, and a response is received at a frequency of 9–13 kHz. The burn wire release assembly is then activated, and the instrument is released from the anchor to float to the surface.

(g) Multibeam Echosounder and Sub-bottom Profiler

Along with the airgun operations, two additional acoustical data acquisition systems will be operated during the survey. The ocean floor will be mapped with the 12-kHz Simrad EM120 MBES, and a 3.5-kHz SBP may also be used at times during the survey. These sound sources will be operated from the *Langseth* simultaneously with the airgun array.

The Simrad EM120 MBES 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 $\mu Pa \cdot m_{rms}$. 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 being mapped simultaneously 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·m; 800 watts
Normal source output (downward)	200 dB re 1 µPa·m; 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

(3) Monitoring and Mitigation Measures

Numerous species of marine mammals are known to occur in the proposed study area. However, the number of individual animals expected to be approached closely during the proposed activities will be small in relation to regional population sizes. With the proposed monitoring and mitigation provisions, effects on most if not all individuals are expected to be limited to minor behavioral disturbance. Those effects are expected to have negligible impacts both on individual marine mammals and on the associated species and stocks.

To minimize the likelihood that impacts will occur to the species and stocks, airgun operations will be conducted in accordance with all applicable U.S. federal regulations and IHA requirements. As the proposed activities will take place in the EEZ of Tonga, L-DEO will coordinate all activities with the Kingdom of Tonga and the relevant U.S. federal agencies, i.e., NMFS.

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

(a) Visual Monitoring

MMOs will watch for marine mammals and turtles near the seismic source vessel during all daytime airgun operations and during any start ups of the airguns at night. Airgun operations will be suspended when marine mammals or turtles are observed within, or about to enter, designated exclusion zones [see subsection (d) below] where there is concern about effects on hearing or other physical effects. MMOs 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, such as during transits.

During seismic operations in the Lau Basin, at least three visual observers will be based aboard the *Langseth*. MMOs will be appointed by L-DEO with NMFS concurrence. At least one MMO, and when practical two MMOs, will monitor marine mammals and turtles near the seismic vessel during ongoing daytime operations and nighttime start ups of the airguns. Use of two simultaneous observers will increase the proportion of the animals present near the source vessel that are detected. MMO(s) will be on duty in shifts of duration no longer than 4 h. Other crew will also be instructed to assist in detecting marine mammals and turtles and implementing mitigation requirements (if practical). Before the start of the seismic survey the crew will be given additional instruction regarding how to do so.

The *Langseth* is a suitable platform for marine mammal and turtle observations. When stationed on the observation platform, the eye level will be ~18 m above sea level, and the observer will have a good view around the entire vessel. During daytime, the MMO(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 (NVDs) will be available (ITT F500 Series Generation 3 binocular-image intensifier or equivalent), when required. Laser rangefinding binoculars (Leica LRF 1200 laser rangefinder or equivalent) will be available to assist with distance estimation. Those are useful in training observers to estimate distances visually, but are generally not useful in measuring distances to animals directly; that is done primarily with the reticles in the binoculars.

When mammals or turtles are detected within or about to enter the designated exclusion zone, the airguns will immediately be powered down or shut down if necessary. The MMO(s) will continue to maintain watch to determine when the animal(s) are outside the exclusion zone. Airgun operations will not resume until the animal has left the exclusion zone.

The vessel-based monitoring will provide data to estimate the numbers of marine mammals exposed to various received sound levels, to document any apparent disturbance reactions or lack thereof, and thus to estimate the numbers of mammals potentially "taken" by harassment. It will also provide the information needed in order to power down or shut down the airguns at times when mammals or turtles are present in or near the exclusion zone. 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 and power downs or shut downs will be recorded in a standardized format. Data will be entered into an electronic database. The accuracy of the data entry will be verified by computerized data validity checks as the data are entered and by subsequent manual checking of the database. These procedures will allow initial summaries of data to be prepared during and shortly after the field program, and will facilitate transfer of the data to statistical, graphical, and other programs for further processing and archiving.

Results from the vessel-based observations will provide

1. The basis for real-time mitigation (airgun power down or shut down).
2. Information needed to estimate the number of marine mammals potentially taken by harassment, which must be reported to NMFS.
3. Data on the occurrence, distribution, and activities of marine mammals and turtles in the area where the seismic study is conducted.
4. Information to compare the distance and distribution of marine mammals and turtles relative to the source vessel at times with and without seismic activity.
5. Data on the behavior and movement patterns of marine mammals and turtles seen at times with and without seismic activity.

(b) Passive Acoustic Monitoring

Passive acoustic monitoring (PAM) will take place to complement the visual monitoring program, when practicable. Visual monitoring typically is not effective during periods of poor visibility 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, and localization of cetaceans. The acoustic monitoring will serve to alert visual observers (if on duty) when vocalizing cetaceans are detected. It is only useful when marine mammals call, but it can be effect-tive either by day or by night, and does not depend on good visibility. 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).

The PAM system consists of hardware (i.e., hydrophones) and software. The "wet end" of the system consists of a 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.

The towed hydrophones will ideally be monitored 24 h per day while at the seismic survey area during air-gun operations, and during most periods when the *Langseth* is underway while the airguns are not operating. One MMO will monitor the acoustic detection system at any one time, by listening to the sig-nals 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 for 1–6 h at a time. Besides the visual MMOs, an additional MMO with primary responsibility for PAM will also be aboard. All MMOs are expected to rotate through the PAM position, although the most experien-ced with acoustics will be on PAM duty more frequently.

When a vocalization is detected while visual observations are in progress, the acoustic MMO will contact the visual MMO immediately, to alert him/her to the presence of cetaceans (if they have not already been seen), 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.

(c) Reporting

A report will be submitted to NMFS and NSF 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 provide 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 number and nature of exposures that could result in "takes" of marine mammals by harassment or in other ways.

(d) Proposed Exclusion Zones

Acoustic Measurement Units.—Received sound levels have been predicted by L-DEO, in relation to distance and direction from the airguns, for the 36-airgun array (Fig. 4 and 5) and for a single 1900LL 40-in^3 airgun, which will be used during power downs (Fig. 6). The maximum relevant depth shown on the Figures by the straight dashed line is the maximum assumed dive depth for deep-diving marine mammals and is relevant for predicting exclusion zones in deep water (see below). A detailed description of the modeling effort is provided in Appendix A.

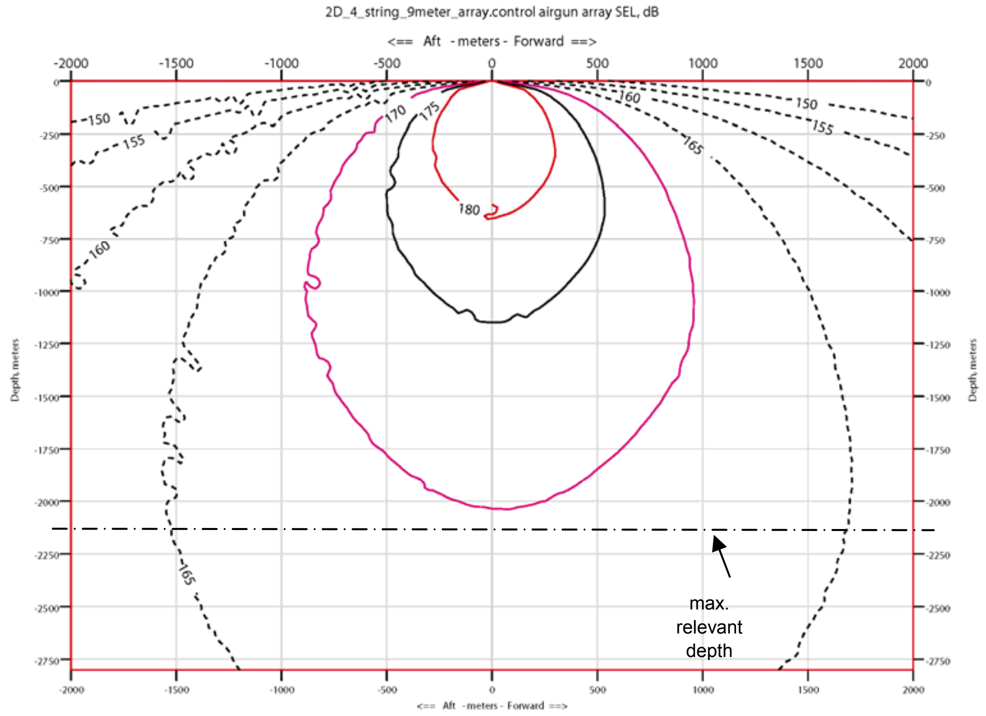

FIGURE 4. Modeled received sound levels (SELs) from the 36-airgun array operating in deep water at a ***9-m*** tow depth, planned for use during the ELSC survey, 14 January–21 February 2009. Received rms levels (SPLs) are expected to be ~10 dB higher. Maximum relevant depth is applicable to marine mammals.

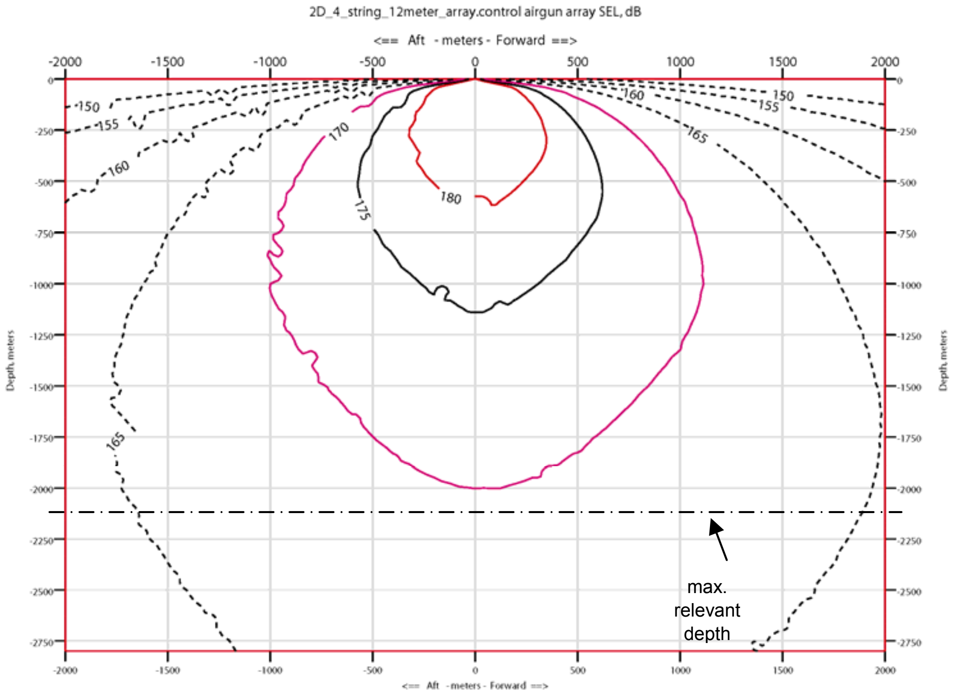

FIGURE 5. Modeled received sound levels (SELs) from the 36-airgun array operating in deep water at a ***12-m*** tow depth, planned for use during the ELSC survey, 14 January–21 February 2009. Otherwise as above.

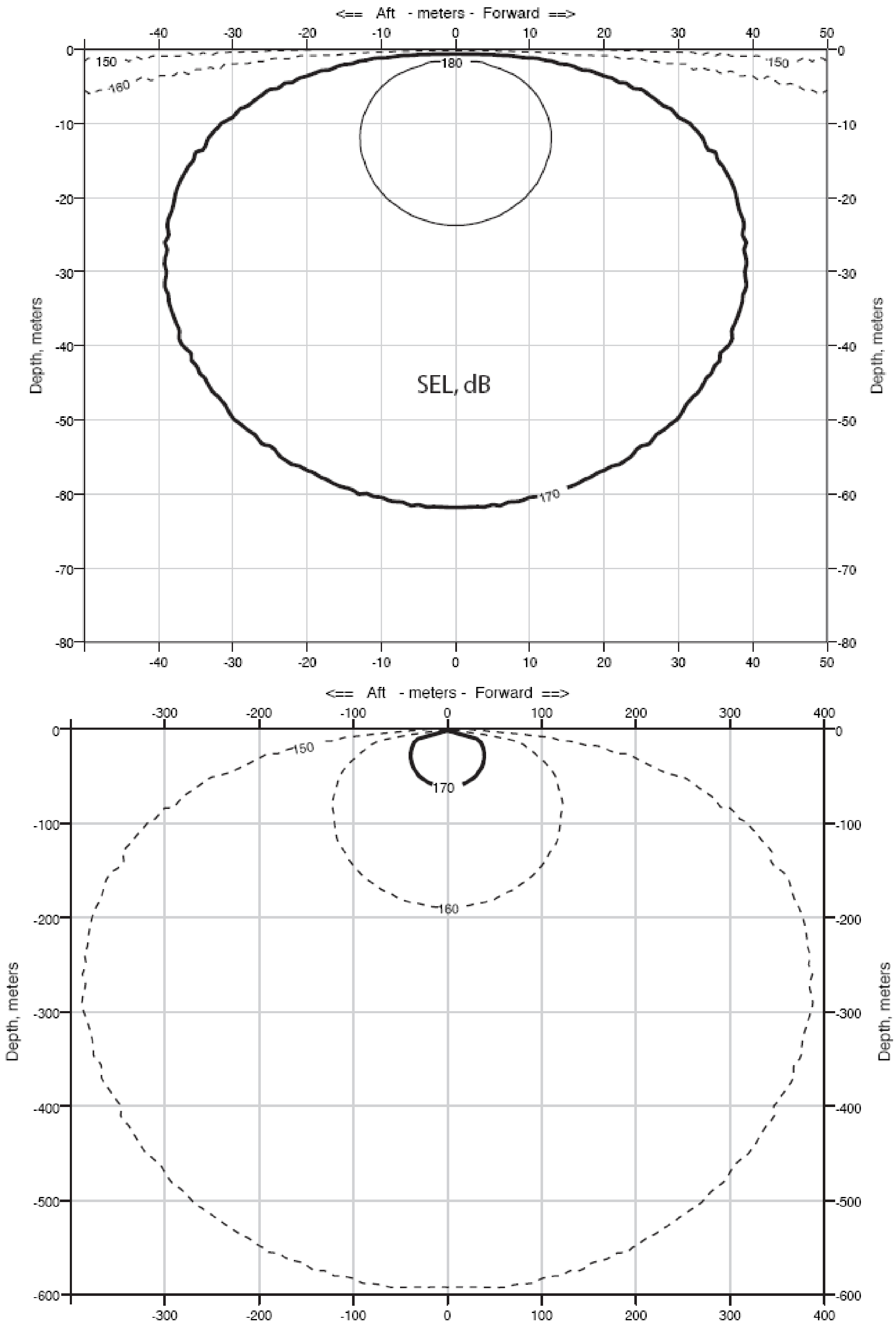

FIGURE 6. Modeled received sound levels (SELs) from a single 40-in^3 airgun operating in deep water, which is planned for use during the ELSC survey, 14 January–21 February 2009. Received rms levels (SPLs) are expected to be ~10 dB higher.

The predicted sound contours are shown as sound exposure levels (SEL) in decibels (dB) re 1 µPa$^2 \cdot$s. SEL is a measure of the received energy in the 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 in most situations, this means that the SEL value for a given pulse is usually lower than the SPL calculated for the actual duration of the pulse (see Appendix B). The advantage of working with SEL is that the SEL measure accounts for the total received energy in the pulse, and biological effects of pulsed sounds are believed to depend mainly on pulse energy (Southall et al. 2007). 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 is now believed to 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. SPL is often referred to as rms or "root mean square" pressure, averaged over the pulse duration. As noted above, the rms received levels that are used as impact criteria for marine mammals are not directly comparable to pulse energy (SEL). At the distances where rms levels are 160–190 dB re 1 µPa, the difference between the SEL and SPL values for the same pulse measured at the same location usually average ~10–15 dB, depending on the propagation characteristics of the location (Greene 1997; McCauley et al. 1998, 2000a; Appendix B). In this EA, we assume that rms pressure 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 dB 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 and peak-to-peak 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 dB re 1 µPa$_{rms}$ in the far field typically would correspond to a peak measurement of ~170–172 dB re 1 µPa, and to a peak-to-peak measurement of ~176–178 dB re 1 µPa, 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 145–150 dB re 1 µPa$^2 \cdot$s). The precise difference between rms and peak or peak-to-peak values for a given pulse depends on the 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 (for an airgun-type source at the ranges relevant here) higher than the SEL value.

Predicted Sound Levels vs. Distance and Depth.—Empirical data concerning 180-, 170-, and 160-dB re 1 µPa$_{rms}$ distances were acquired for various airgun configurations during the acoustic calibration study of the R/V *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 and 190-dB re 1 µPa$_{rms}$ safety criteria applied by NMFS (2000) to cetaceans and pinnipeds, respectively, although these were not measured. The empirical data indicated that the L-DEO model (as applied to the *Ewing*'s airgun configurations) overestimated the measured received sound levels at a given distance in deep water (>1000 m deep), and it underestimated the measured levels in shallow water (<100 m deep; Tolstoy et al. 2004a,b).

During the ELSC study, all survey effort will take place in deep (>1000 m) water. 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 modeled distances shown in Figures 4–6 for the planned *Langseth* airgun configuration operating in deep water are summarized in Table 1. As very few, if any, mammals are expected to occur below 2000 m, this depth was used as the maximum relevant depth in determining these distances. The tabulated distances are expected to overestimate the actual distances to the corresponding SPLs, given the deep-water results of Tolstoy et al. (2004a,b).

Table 1 shows the distances at which four rms sound levels are expected to be received from the 36-airgun array and a single airgun operating in water >1000 m deep. The 180- and 190-dB re 1 μPa_{rms} distances are the safety criteria as specified by NMFS (2000) and are applicable to cetaceans and pinnipeds, respectively. The 180-dB distance will also be used as the exclusion zone for sea turtles, as requireed by NMFS during most other recent L-DEO seismic projects (e.g., Smultea et al. 2004; Holst et al. 2005b; Holst and Beland 2008). If marine mammals or turtles are detected within or about to enter the appropriate exclusion zone, the airguns will be powered down (or shut down if necessary) immediately.

The conclusion that the model predictions in Table 1 are precautionary, relative to actual 180- and 190-dB (rms) radii, is based on empirical data from the acoustic calibration of different airgun configureations than those used on the *Langseth* (*cf.* Tolstoy et al. 2004a,b); that sound source verification study was done in the northern Gulf of Mexico. L-DEO has recently (late 2007/early 2008) conducted a more extensive acoustic calibration study of the *Langseth*'s 36-airgun (~6600-in^3) array, also in the northern Gulf of Mexico (LGL Ltd. 2006; Holst and Beland 2008). Distances where various sound levels (e.g., 190, 180, 170, and 160 dB re 1 μPa_{rms}) were received are being determined for various airgun configureations and water depths. Those results are not yet available. However, the empirical data from the 2007/2008 calibration study will be used to refine the exclusion zones proposed above for use during the cruise, if the data are appropriate and available at the time of the ELSC survey.

Southall et al. (2007) made detailed recommendations for new science-based noise exposure criteria. L-DEO will be prepared to revise its procedures for estimating numbers of mammals "taken", exclusion zones, etc., as may be required by any new guidelines that result. However, currently the procedures are based on best practices noted by Pierson et al. (1998), and Weir and Dolman (2007). As yet, NMFS has not specified a new procedure for determining exclusion zones.

(e) Mitigation During Operations

Mitigation measures that will be adopted during the survey include (1) power-down procedures, (2) shut-down procedures, and (3) ramp-up procedures.

***Power-down Procedures*.—**A power down involves decreasing the number of airguns in use such that the radius of the 180-dB (or 190-dB) zone is decreased to the extent that marine mammals or turtles are no longer in or about to enter the exclusion zone. A power down of the airgun array can also occur when the vessel is moving from one seismic line to another. During a power down for mitigation, one airgun will be operated. The continued operation of one airgun is intended to alert marine mammals and turtles to the presence of the seismic vessel in the area. In contrast, a shut down occurs when all airgun activity is suspended.

If a marine mammal or turtle is detected outside the exclusion zone but is likely to enter the exclusion zone, the airguns will be powered down before the animal is within the exclusion zone. Likewise, if a mammal or turtle is already within the safety zone when first detected, the airguns will be powered down immediately. During a power down of the airgun array, the 40-in^3 airgun will be operated. If a marine mammal or turtle is detected within or near the smaller exclusion zone around that single airgun (Table 1), it will be shut down (see next subsection).

TABLE 1. Predicted distances to which sound levels ≥190, 180, 170 and 160 dB re 1 µPa$_{rms}$ could be received in deep (>1000 m) water from the 36-airgun array, as well as a single airgun, planned for use during the Eastern Lau Spreading Centre survey, 14 January–21 February 2009 (based on L-DEO modeling). Predicted radii are based on Figures 4–6, assuming that received levels on an RMS basis are, numerically, 10 dB higher than the SEL values shown in Figures 4–6, and that mammals would not typically occur at depths >2000 m.

Source and Volume	**Tow Depth (m)**	**Predicted RMS Radii (m)**			
		190 dB	**180 dB**	**170 dB**	**160 dB**
Single Bolt airgun 40 in^3	9–12*	12	40	120	385
4 strings 36 airguns 6600 in^3	9	300	950	2900	6000
	12	340	1120	3300	6850

* The tow depth has minimal effect on the maximum near-field output and the shape of the frequency spectrum for the single 40 in^3 airgun; thus, the predicted safety radii are essentially the same at each tow depth. The most precautionary distances (i.e., for the deepest tow depth, 12 m) are shown.

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

- it is visually observed to have left the exclusion zone, or
- it has not been seen within the zone for 15 min in the case of small odontocetes or pinnipeds, or
- it has not been seen within the zone 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 exclusion zone for turtles, i.e., ~6 to 18 min, depending on the sighting distance, vessel speed, and tow depth [based on the length of time it will take the vessel to leave behind the turtle, so that it is outside the exclusion zone; e.g., if a turtle is sighted close to the vessel, the ship speed is 9.3 km/h, and the tow depth is 9 m, it would take the vessel ~6 min to leave the turtle behind].

During airgun operations following a power down (or shut down) whose duration has exceeded the limits specified above, the airgun array will be ramped up gradually. Ramp-up procedures are described below.

***Shut-down Procedures*.—**The operating airgun(s) will be shut down if a marine mammal or turtle is seen within or approaching the exclusion zone for a single airgun. Shut downs will be implemented (1) if an animal enters the exclusion zone of the single airgun after a power down has been initiated, or (2) if an animal is initially seen within the exclusion zone of a single airgun when more than one airgun (typically the full array) is operating. Airgun activity will not resume until the marine mammal or turtle has cleared the safety zone, or until the MMO is confident that the animal has left the vicinity of the vessel. Criteria for judging that the animal has cleared the safety zone 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 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 180-dB radius for the 36-airgun array (see Table 1) in relation to the planned speed of the *Langseth* while shooting (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 ~35 min. During ramp-up, the MMOs will monitor the exclusion zone, and if marine mammals or turtles are sighted, a power down or shut down will be implemented as though the full array were operational.

If the complete exclusion zone has not been visible for at least 30 min prior to the start of operations in either daylight or nighttime, ramp up will not commence unless at least one airgun (40 in^3 or similar) has been operating during the interruption of seismic survey operations. Given these provisions, it is likely that the airgun array will not be ramped up from a complete shut down at night or in thick fog, because the outer part of the safety zone for that array will not be visible during those conditions. If one airgun has operated during a power down period, ramp up to full power will be permissible at night or in poor visibility, 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 exclusion zones during the day or close to the vessel at night.

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 cruise (~14 January–21 February 2009) is the most suitable time logistically for the *Langseth* and the participating scientists. Given the limited weather window for the operations, and the fact that few baleen whales are expected to occur in Lau Basin in austral summer, altering the timing of the proposed project likely would result in no net benefits. If the IHA is issued for another period, it could result in significant delay and disruption not only of the proposed cruise, but of subsequent geophysical studies that are planned by L-DEO for 2009 and beyond. An evaluation of the effects of this alternative action is given in § IV.

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 research operations. If the research is not conducted, the “No Action” alternative would result in no disturbance to marine mammals due to the proposed activities.

The seismic data from the survey will be used to obtain information on the magma storage and thermal system of the ELSC. This in turn will improved information on locations and source properties of regional earthquakes. Such information is vital to understanding plate tectonic processes and their effects on earthquake occurrence and distribution. In addition, the RIDGE 2000 Lau ISS initiative aims to understand the sources of heat for the hydrothermal systems that support seafloor biological communities. Under the “No Action” alternative, this valuable scientific information would not become available.

In addition to forcing cancellation of the planned seismic survey in the Lau Basin, the "No Action" alternative could also, in some circumstances, result in significant delay of other geophysical studies that are planned by L-DEO for 2009 and beyond, depending on the timing of the decision. The entire proposal, based on the premise of collecting these data, would be compromised. Cancellation (no action) for this cruise would lessen available data and support for the academic institutions involved. Data collection is an essential first step for a much greater effort to analyze and report information concerning the scientifically significant topics indicated. The field effort will provide material for years of analyses involving multiple professors, students, and technicians. The lost opportunity to collect valuable scientific information would be compounded by lost opportunities for support of research infrastructure, training, and professional career growth.

III. AFFECTED ENVIRONMENT

Oceanography

Lau Basin is a back-arc spreading center, occurring between the Pacific and Australian tectonic plates (Zellmer and Taylor 2001). It is a young ocean basin bordered by Lau Ridge to the west (a ridge extending from Fiji toward New Zealand) and Tonga Ridge to the east (extending from Tonga toward New Zealand) (Zellmer and Taylor 2001). Just to the west of Tonga Ridge is the active Tofua Volcanic Arc and to the east of Tonga Ridge is the Tonga Trench.

The ELSC study area is within the western portion of the South Pacific Subtropical Gyre Province (SPSG) of the Pacific Trade Wind Biome, according to the pelagic biogeographical breakdown of Longhurst (2007). The SPSG, lying roughly between 5°S and 35°S, is the most uniform and seasonally stable region of the open oceans, but is also the region with the least data. The province occupies the central and southern portion of the gyre that occurs in the subtropical South Pacific Ocean. It is characterized by nitrate-depleted surface water and low primary productivity, with chlorophyll values reaching their maximum in August–September, during the austral winter. Typical chlorophyll values for the whole of the SPSG range from 0.06–0.13 $\mathrm{mg \cdot m^{-3}}$ (Longhurst 2007). Upwelling near coral reefs and atolls does not seem to increase primary productivity in the water column as the coral reefs quickly uptake any available nitrate. Sea surface temperatures in the SPSG are 19–23ºC (Longhurst 2007).

The western portion of the SPSG is composed of the South Equatorial Current which flows westward along the northern border, the East Australia Current which flows southward down the western border (with smaller currents flowing into the Coral Sea to the west), and the South Pacific Current which returns waters eastward along the southern border as part of the oceanic Subtropical Convergence Zone (Duxbury and Duxbury 1997; Longhurst 2007). There is also a South Subtropical Countercurrent that bisects the Subtropical Gyre at 20 to 25ºS, though it is quite weak, especially in the austral winter (Longhurst 2007).

Marine Mammals

Thirty species of cetacean, including 21 odontocete (dolphins and small- and large-toothed whales) species and nine mysticete (baleen whales) species may occur in the proposed ELSC study area in the SWPO. Table 2 summarizes the habitat, occurrence, and conservation status of the species. Several are listed under the ESA as ***endangered***: the sperm, humpback, fin, sei, and blue whales. In addition to those six species, the southern bottlenose, pygmy right, Antarctic minke, minke, and Bryde's whales are listed

TABLE 2. The habitat, occurrence, regional population sizes, and conservation status of marine mammals that could occur in or near the proposed seismic survey area in the Lau Basin, Southwest Pacific Ocean.

Species	Habitat	Occurrence in the South Pacific Ocean	Regional population size	U.S. ESA[1]	IUCN[2]	CITES[3]
Mysticetes						
Humpback whale (*Megaptera novaeangliae*)	Mainly nearshore waters and banks	Rare in Jan–Feb	~6200[4]	EN	VU	I
Pygmy right whale (*Caperea marginata*)	Coastal and oceanic	Common	N.A.	-	N.A.	I
Antarctic minke whale (*Balaenoptera bonaerensis*)	Coastal and oceanic	Rare in Jan–Feb	140,000–155,000[5]	-	LR-cd	I
Minke whale (*Balaenoptera acutorostrata*)	Pelagic and coastal	Rare in Jan–Feb	140,000–155,000[5]	-	LR-nt	I
Bryde's whale (*Balaenoptera edeni*)	Pelagic and coastal	Common	16,500[6]	-	DD	I
Sei whale (*Balaenoptera borealis*)	Primarily offshore, pelagic	Common	12,000[7]	EN	EN	I
Fin whale (*Balaenoptera physalus*)	Continental slope, mostly pelagic	Uncommon in Jan–Feb	3031[8]	EN	EN	I
Blue whale (*Balaenoptera musculus*)	Pelagic and coastal	Uncommon in Jan–Feb	756[9]	EN	EN	I
Odontocetes						
Sperm whale (*Physeter macrocephalus*)	Usually pelagic and deep seas	Common	22,700[10]	EN	VU	I
Pygmy sperm whale (*Kogia breviceps*)	Deep waters off the shelf	Common	N.A.	-	N.A.	II
Dwarf sperm whale (*Kogia sima*)	Deep waters off the shelf	Uncommon?	11,200[10]	-	N.A.	II
Cuvier's beaked whale (*Ziphius cavirostris*)	Pelagic	Common	20,000[10]	-	DD	II
Southern bottlenose whale (*Hyperoodon planifrons*)	Pelagic	Rare	N.A.	-	LR-cd	I
Longman's beaked whale (*Indopacetus pacificus*)	Pelagic	Uncommon	NA	-	DD	II
Blainville's beaked whale (*Mesoplodon densirostris*)	Pelagic	Common	25,300[10*]	-	DD	II
Ginkgo-toothed beaked whale (*Mesoplodon ginkgodens*)	Pelagic	Rare	25,300[10*]	-	DD	II
Rough-toothed dolphin (*Steno bredanensis*)	Deep water	Uncommon	145,900[10]	-	DD	II
Bottlenose dolphin (*Tursiops truncatus*)	Coastal and oceanic, shelf break	Common	243,500[10]	-	DD	II
Pantropical spotted dolphin (*Stenella attenuata*)	Coastal and pelagic	Uncommon	1,298,400[10]	-	LR-cd	II
Spinner dolphin (*Stenella longirostris*)	Coastal and pelagic	Rare south of 15ºS	1,019,300[10]	-	LR-cd	II
Striped dolphin (*Stenella coeruleoalba*)	Off continental shelf	Rare	1,918,000[10]	-	LR-cd	II
Fraser's dolphin (*Lagenodelphis hosei*)	Waters >1000 m	Rare south of 30°S	289,300[10]	-	DD	II
Short-beaked common dolphin (*Delphinus delphis*)	Shelf and pelagic, seamounts	Common	2,210,900[10]	-	N.A.	II
Risso's dolphin (*Grampus griseus*)	Waters >1000 m, seamounts	Common	175,800[10]	-	DD	II
Melon-headed whale (*Peponocephala electra*)	Oceanic	Uncommon south of 20ºS	45,400[10]	-	N.A.	II

Species	Habitat	Occurrence in the South Pacific Ocean	Regional population size	U.S. ESA[1]	IUCN[2]	CITES[3]
Pygmy killer whale (*Feresa attenuata*)	Deep, pantropical waters	Uncommon	38,900[10]	-	DD	II
False killer whale (*Pseudorca crassidens*)	Pelagic	Uncommon	39,800[10]	-	N.A.	II
Killer whale (*Orcinus orca*)	Widely distributed	Common	8,500[10]	-	LR-cd	II
Short-finned pilot whale (*Globicephala macrorhynchus*)	Mostly pelagic, high-relief topography	Common north of 40°S	160,200[10†]	-	LR-cd	II

N.A. - Data not available or species status was not assessed.
[1] EN = Endangered, - = Not listed
[2] EN = Endangered; VU = Vulnerable; LR = Lower Risk (-cd = Conservation Dependent; -nt = Near Threatened); DD = Data Deficient (IUCN 2007).
[3] UNEP-WCMC 2008.
[4] Humpback Group E, 2004 (Johnston and Butterworth 2005).
[5] Antarctic Area V, 1991/1992-2003/2004 (Branch 2006).
[6] Western South Pacific (IWC 1981 *in* Reeves et al. 1999).
[7] Antarctic Area V, 1973 (Horwood 1987:295).
[8] Antarctic Area V, 2003 (Murase et al. 2005).
[9] Antartctic Area V, 2001/2002-2003/2004 (Branch 2007)
[10] Eastern Tropical Pacific (Wade and Gerrodette 1993).
* Estimate is for all *Mesoplodon* species combined.
† Estimate includes long- and short-finned pilot whales.

in Appendix I (i.e., threatened with extinction) by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

There have been limited surveys for marine mammals in the proposed seismic survey area in Lau Basin. What information exists for the area is given in the species accounts below, in part derived from Reeves et al. (1999), who summarized information from the area served by the South Pacific Regional Environment Programme (SPREP). The SPREP region covers a vast area of the Pacific Ocean between the Tropic of Capricorn and the Equator from Papua New Guinea (140°E) to Pitcairn Island (130°W).

The survey area occurs in deep-water habitat (>1000 m) but is close to oceanic island habitats, so both coastal and oceanic species could be encountered. Abundance and density estimates of cetaceans noted below are provided for reference only, and are not necessarily the same as those that likely occur in the survey area.

(1) Mysticetes

Pygmy Right Whale

The pygmy right whale is the smallest of the baleen whales, with a maximum length of only 6.5 m (Kemper 2002a). Its distribution is circumpolar in the Southern Hemisphere and is believed to extend from 30°S to 55°S, where water temperatures are ~5–20°C (Kemper 2002a). Little is known regarding this species, as it has rarely been seen at sea, and has a short dive time of ~4 min (Kemper 2002a). Pygmy right whales have been seen in oceanic and coastal environments (Kemper 2002a). Most animals are seen in groups of one or two, but one group of 80 has been seen in oceanic waters (Kemper 2002a). They appear to be non-migratory, although there may be some movement inshore in spring and summer (Kemper 2002b). This species may occasionally occur in the survey area (Reeves et al. 1999), but is not listed by SPREP (2007) as occurring within the SPREP region.

Humpback Whale

The humpback whale is found throughout all of the oceans of the world (Clapham 2002). The species is listed as ***Endangered*** under the ESA, ***Vulnerable*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and it is listed in CITES Appendix I (UNEP-WCMC 2008) (Table 2). The worldwide population of humpback whales is divided into northern and southern ocean populations, but genetic analyses suggest some gene flow (either past or present) between the North and South Pacific oceans (e.g., Baker et al. 1993; Caballero et al. 2001). Although considered to be mainly a coastal species, humpback whales often traverse deep pelagic areas while migrating. Most migratory paths for southern humpback whales are unknown (Perry et al. 1999a). Humpback whales spend spring through fall on mid- or high-latitude feeding grounds, and winter on low-latitude breeding grounds, with limited interchange between regions (Clapham 2002; Baker et al. 1998; Garrigue et al. 2002). In summer feeding areas, humpbacks typically forage in the upper 120 m of the water column, with a maximum recorded dive depth of 500 m (Dolphin 1987; Dietz et al. 2002). On winter breeding grounds, humpback dives have been recorded at depths >100 m (Baird et al. 2000).

The Southern Hemisphere population that can be found south of 60°S in the austral summer feeding season is on the order of 42,000 individuals (IWC 2007a). Humpback whale populations in the Southwest Pacific were severely depleted by commercial whaling (see Robbins et al. 2008). Whereas some breeding stocks, including those off western and eastern Australia, appear to have recovered to numbers in the thousands, the humpback whales that winter off New Caledonia likely number only in the few hundreds (Baker et al. 1998; Noad et al. 2006). Some stocks that were formerly found around New Zealand and Fiji were extirpated through whaling activities and few humpbacks remain from those stocks (Gibbs et al. 2006 *in* Olavarría et al. 2007; Constantine et al. 2006). In Tonga, humpback whales were hunted until 1979 (Reeves 2002), but the population is now making some recovery (Robbins et al. 2008). Only 200–400 whales were estimated to occur off Tonga in 1979–1980 (Keller 1982 *in* Reeves et al. 1999), but based on data from 1991–2000, the population that winters around Tonga is estimated at 730–990 (IWC 2006).

Humpback whales are often sighted singly or in groups of two or three; however, while on their breeding and feeding ranges, they may occur in groups of up to 15 (Leatherwood and Reeves 1983; Donoghue 1996). Mean observed group size around the Cook Islands was 1.6 (Hauser and Clapham 2006). Humpback whales can be seen in Tongan waters from June to November, with a peak in August and September (Reeves et al. 1999). Tonga is considered an important breeding and calving ground, based on the presence of singing males, cow/calf pairs, and surface active groups (Donoghue 1996; Erikson et al. 2005). Humpbacks have been recorded from January to October around other nearby islands, including Fiji, Samoa, and Niue (Reeves et al. 1999). Peak numbers in American Samoa occur in September–October (Craig 1995 *in* Reeves et al. 1999).

Genetic evidence suggests several discrete breeding grounds in the South Pacific Ocean, including distinction between the Cook Islands, French Polynesia, Tonga, and New Caledonia (Olavarría et al. 2003, 2007; Garrigue et al. 2006a). However, photo-identification work suggests some movement between these breeding grounds, but at a relatively low level of interchange (Garrigue et al. 2002, 2006b; Hauser and Clapham 2006). Humpback whales that winter off East Australia and New Caledonia apparently belong to the Antarctic Area V stock, whereas humpback whales that winter off Tonga appear to be connected with Areas I, V, or VI (Garrigue and Gill 1994; Garrigue et al. 2002; Olavarría et al. 2003; Steel et al. 2008). However, such distinctions may be difficult to make since there is some evidence of stocks mixing on the summer feeding grounds between Antarctic areas IV (70º–130ºE), V

(130ºE–170ºW), and VI (170º–120º W) (Rock et al. 2006). Albertson-Gibb et al. (2008) noted that 78.9% of animals in the Antarctic Area VI originate from Tonga. Tonga is currently identified as a sub-stock of breeding stock E, distinct from the sub-stock in New Caledonia; no feeding ground is officially recognized for humpback whales over-wintering in Tonga (Garrigue et al. 2006a; IWC 2006) .

The available evidence suggests that humpback whales could be seasonally common in waters of the survey area. However, as the survey is currently scheduled to occur during January–February, they likely would not be present in high numbers in the area at that time, it at all, because they would be on higher-latitude summer feeding grounds.

Antarctic Minke Whale

The minke whale has a cosmopolitan distribution that spans ice-free latitudes (Stewart and Leatherwood 1985). The species of minke whale in the Southern Hemisphere, the Antarctic minke whale, is found between 55°S and the ice edge during the austral summer, between 55°S and the ice edge during the austral summer, and between 10°S and 30°S, 170°E and 100°W in the austral winter (Perrin and Brownell 2002). A smaller form (unnamed subspecies) of the common minke whale, known as the dwarf minke whale, occurs in the Southern Hemisphere where its distribution overlaps with that of the Antarctic minke whale (Perrin and Brownell 2002). Although not well known, the range of the dwarf minke whale extends as far north as 11°S off Australia, where it can be found year-round, and as far south as 65°S (Reeves et al. 2002). Based on data from 1992–1993 and 2003–2004, the most recent minimum estimate of minke whale abundance from 60ºS to the Antarctic ice edge during the austral summer was 338,000, and estimated abundance in Antarctic Area V, south of the study area, was 140,000–155,000 (Branch 2006).

The minke whale is relatively solitary, usually seen individually or in groups of two or three, but can occur in large aggregations of up to 100 at high latitudes where food resources are concentrated (Perrin and Brownell 2002). Little is known about the diving behavior of minke whales, but they are not known to make prolonged deep dives (Leatherwood and Reeves 1983).

Kasamatsu et al. (1990) used data from Japanese sightings surveys in October–December 1976–1987 to suggest a breeding area for minke whales between 10°S and 20°S and from 150°W to 170°W, i.e., just east to northeast of the proposed study area. Minke whale abundance there was highest in October, at the end of the estimated peak of the Southern Hemisphere breeding season (August–October). Within the study area, abundance was fairly consistent during October and November, at 0.003/n.mi. north of 20ºS and 0.001/n.mi. south of 20ºS (Kasamatsu et al. 1990). However, in December, the abundance of minke whales in the southern portion of the study area (south of 20ºS) increased to 0.002/n.mi., but there was no comparable effort during this month in the northern portion of the study area (north of 20ºS) (Kasamatsu et al. 1990). A possible Antarctic minke whale was seen in the waters of Tonga in August/September of 2002 (SPWRC 2002), and SPREP (2007) confirms the presence of minke whales in Tonga.

Kasamatsu et al. (1990) suggested that younger animals tend to migrate early and arrive in Antarctic waters in November, whereas mature minke whales, consisting mainly of pregnant females, migrate south beginning in November, and arrive in the Antarctic by January. Minke whales then leave the Antarctic for their northward migration by February and begin arriving in waters between 30°S and 40°S in March. Thus, minke whales likely would not be present in the survey area at the scheduled time of the proposed seismic survey (January–February), because most would still be feeding farther south at that time, or just starting their migration northward from Antarctic waters.

Bryde's Whale

Bryde's whale is found in tropical and subtropical waters throughout the world between 40ºN and 40ºS, generally in waters warmer than 20ºC, but at minimum 15ºC (Reeves et al. 1999; Kato 2002; Kanda et al. 2007). Populations in the western North Pacific, western South Pacific, eastern South Pacific, and eastern Indian Ocean currently show low levels of genetic interchange (Kanda et al. 2007). The western South Pacific stock (west of 120ºW) has been estimated at 52,700 (Ohsumi 1981 *in* Kanda et al. 2007). However, using the same data, the IWC arrived at an estimate of 16,500 for the western South Pacific population (IWC 1981 *in* Reeves et al. 1999).

Some populations show a general pattern of movement toward the equator in winter and toward higher latitudes in summer, though the locations of actual winter breeding grounds are unknown (Reeves et al. 1999; Kato 2002; Kanda et al. 2007). Bryde's whales are both pelagic and coastal (Reeves et al. 1999), and occur singly or in groups of up to five. Wade and Gerrodette (1993) reported a mean group size of 1.7 for the Eastern Tropical Pacific (ETP). The durations of Bryde's whale dives are 1–20 min (Cummings 1985).

Bryde's whale densities are thought to be relatively high in the SPREP region (see Fig. 3 *in* Kato 2002), and it is likely the most abundant mysticete in the area (Reeves et al. 1999). Although no sightings have been recorded for Tonga, confirmed sightings of "Bryde's-like" whales exist for Samoa, Fiji, and New Caledonia (SPREP 2007).

Sei Whale

The sei whale has a cosmopolitan distribution, with a marked preference for temperate oceanic waters (Gambell 1985a). It is listed as ***Endangered*** under the U.S. ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and it is listed in CITES Appendix I (UNEP-WCMC 2008) (Table 2). Sei whale populations were depleted by whaling, and their current status is generally uncertain (Horwood 1987). The global population is thought to be ~80,000 (Horwood 2002).

The sei whale is a mainly pelagic species and usually occurs in small groups of up to six. Sei whales generally do not dive deeply, and dive durations are 15 min or longer (Gambell 1985a). Sei whales migrate from temperate zones occupied in winter to higher latitudes in the summer, where most feeding takes place (Gambell 1985a). In the Southern Hemisphere, they migrate into and out of the Antarctic somewhat later than do blue and fin whales, and they do not migrate as far south. Their main summer concentrations appear to be between 40°S and 50°S (Gambell 1985a). They generally are not found north of 30ºS in the southern hemisphere, but can occasionally visit the southern portion of the SPREP region, which includes the study area, in the winter (Reeves et al. 1999). There have been no sightings in Tonga, but confirmed sighting records exist for Papua New Guinea and New Caledonia, with unconfirmed sightings in the Cook Islands (SPREP 2007). Sei whales likely would occur south of the seismic survey area, especially at the time that the survey is scheduled (January–February), because most sei whales feed at higher latitudes at that time.

Fin Whale

The fin whale is widely distributed in all the world's oceans (Gambell 1985b), but typically occurs in temperate and polar regions from 20° to 70° north and south of the equator (Perry et al. 1999b). It is listed as ***Endangered*** under the U.S. ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and it is listed in CITES Appendix I (UNEP-WCMC 2008) (Table 2). The fin whale is sometimes observed alone or in pairs, but on feeding grounds, groups of up to 20 are more common (Gambell 1985b). Croll et al. (2001) reported a mean dive depth and time of 98 m and 6.3 min for foraging fin whales, and a mean dive depth and time of 59 m and 4.2 min for non-foraging individuals. Dive depths of >150 m coinciding with the diel migration of krill were reported by Panigada et al. (1999).

Northern and southern fin whale populations are distinct, and are sometimes recognized as different subspecies (Aguilar 2002). In the Southern Hemisphere, the peak breeding season is April–August (Laws 1961). Whales from the Southern Hemisphere usually are distributed south of 50ºS in the austral summer, and in winter some migrate northward to breed (Gambell 1985b). There have been few sightings of fin whales in tropical waters, which may be related to the low level of survey effort at low latitudes (Reeves et al. 1999). The lack of records of large aggregations during the winter months suggests that they are more dispersed throughout their range during this time (Reeves et al. 1999). No sighting records exist for Tonga (SPREP 2007). They tend to enter and leave the Antarctic after the blue whales but before the sei whales (Gambell 1985b). Fin whales encountered in the seismic survey area likely would be from the New Zealand stock, which summers from 170°E to 145°W and winters in the Fiji Sea and adjacent waters (Gambell 1985b).

Fin whales likely would be uncommon in the survey area, especially during the time of the year that the survey is scheduled (January–February). Most fin whales would be south of the area on their summer feeding grounds, although some may have begun their migration from the Antarctic to wintering grounds in the Fiji Sea and adjacent waters.

Blue Whale

The blue whale is widely distributed throughout the world's oceans, occurring in pelagic, continental shelf, and inshore waters (Leatherwood and Reeves 1983). It is listed as ***Endangered*** under the U.S. ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and it is listed in CITES Appendix I (UNEP-WCMC 2008) (Table 2). Three subspecies of blue whale are generally recognized. *B. musculus musculus* is found in the Northern Hemisphere; *B. m. intermedia* (the true blue whale) is an Antarctic species; and *B. m. brevicauda* (the pygmy blue whale) inhabits the sub-Antarctic zone of the southern Indian Ocean and the SWPO (Perry et al. 1999a; Sears 2002). A fourth subspecies has been tentatively recognized; *B. m. indica* occurs in the northern Indian Ocean (Jefferson et al. 2008). All blue whale populations have been exploited commercially, and many have been severely depleted as a result. The Southern Hemisphere population, once the most numerous population, was estimated to contain 400–1400 individuals during the years 1980–2000 (IWC 2007a). Current population estimates range from 710 to 1255 (Sears 2002).

Blue whales usually occur alone or in small groups (Leatherwood and Reeves 1983; Palacios 1999). Wade and Gerrodette (1993) reported a mean group size of 1.5 for the ETP. Croll et al. (2001) reported mean dive depths and times of 140 m and 7.8 min for foraging blue whales, and 68 m and 4.9 min for non-foraging individuals. Dives of up to 300 m were recorded for tagged blue whales (Calambokidis et al. 2003).

Generally, blue whales are seasonal migrants between high latitudes in the summer, where they feed, and low latitudes in the winter, where they mate and give birth (Lockyer and Brown 1981). During the austral summer, true blue whales are located south of the Antarctic Convergence, whereas pygmy blue whales can be found north of the Antarctic Convergence (Perry et al. 1999a). Blue whales tend to enter and leave the Antarctic before the fin whales and the sei whales (Gambell 1985b). Little information is available on blue whale wintering areas (Perry et al. 1999a).

It is likely that the pygmy blue whale occurs more regularly in the SPREP region than the true blue whale (see Kato et al. 1995 *in* Reeves et al. 1999). There have been few confirmed sightings of blue whales outside of the Solomon Islands (Reeves et al. 1999). One sighting was made near the equator at 170ºE (Reeves et al. 1999), and confirmed sightings also exist for the Cook, Marshall, and Solomon islands, as well as New Caledonia (SPREP 2007). Unconfirmed sightings have been made in Fiji and Kiribati, but no sighting records exist for Tonga (SPREP 2007).

Blue whales could be encountered during the proposed survey, but are expected to be uncommon in the area, especially during the time of the year that the survey is scheduled (January–February), as they would be far south of the area on their summer feeding grounds.

(2) Odontocetes

Sperm Whale

Sperm whales are the largest of the toothed whales, with an extensive worldwide distribution (Rice 1989). The species is listed as ***Endangered*** under the U.S. ESA, but on a worldwide basis it is abundant and not biologically endangered. It is listed as ***Vulnerable*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and it is listed in CITES Appendix I (UNEP-WCMC 2008) (Table 2).

Sperm whale distribution is linked to social structure—mixed groups of adult females and juvenile animals of both sexes generally occur in tropical and subtropical waters, whereas adult males are commonly found alone or in same-sex aggregations, often occurring in higher latitudes outside the breeding season (Best 1979; Watkins and Moore 1982; Arnbom and Whitehead 1989; Whitehead and Waters 1990). In the South Pacific, males range into the Antarctic (65–70°S) in the summer, whereas females are rarely seen south of 40°S.

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 groups of 20–30 on average (Whitehead 1993, 2003). Wade and Gerrodette (1993) noted a mean group size of 7.9 for the ETP. In the Southern Hemisphere, mating occurs from July to March, with a peak from September to December, and most calves are born between November and March (Rice 1989).

Sperm whales generally are distributed over large areas that have high secondary productivity and steep underwater topography, in waters at least 1000 m deep (Jaquet and Whitehead 1996; Whitehead 2002a). They are often found far from shore, but can be found closer to oceanic islands that rise steeply from deep ocean waters (Whitehead 2002a). They can dive as deep as ~2 km and possibly deeper on rare occasions for periods of over 1 h; however, most of their foraging occurs at depths of ~300–800 m for 30–45 min (Whitehead 2003). During a foraging dive, sperm whales typically travel ~3 km horizontally and 0.5 km vertically (Whitehead 2003). Whales in the Galápagos Islands typically dove for ~40 min and then spent 10 min at the surface (Papastavrou et al. 1989).

There currently is no valid estimate for the size of any sperm whale population (Whitehead 2002a). Best estimates probably are those of Whitehead (2002b), who provided a sperm whale population size estimate of 12,069 for the Antarctic (south of 60°S) and a corresponding density estimate of 0.65/1000 km^2. The abundance of sperm whales in most of the remainder of the South Pacific Ocean is unknown. Sperm whale density in the proposed seismic survey area likely is substantially greater than that observed in the Antarctic, because female sperm whales generally do not occur south of 40°S, and the density of male sperm whales between 50°S and 70°S is probably <¼ of that between 30°S and 50°S (Gaskin 1973).

Sperm whales are the most common large cetacean (except perhaps for Bryde's whales) in the SPREP region (Reeves et al. 1999), and the most widespread cetacean species in the area (SPREP 2007). Sightings have been made throughout the SPREP region, including the waters of Tonga, Fiji, American

Samoa, Samoa, and Niue (SPREP 2007). In 1979, 30 sperm whales were sighted off Tonga's Tongatapu group, and both male and female sperm whales were detected acoustically in the vicinity of Tonga between 20 October and 7 November 1992 (see Reeves et al. 1999). Jaquet and Whitehead (1996) noted that high densities of sperm whales occurred along the Tonga archipelago in 1992/1993. In October–November 1977, Japanese whalers recorded sperm whales south of 21ºS between Fiji and Niue/Rarotonga (Reeves et al. 1999). Small groups of sperm whales were hunted off the Samoan islands in the late 1820s to late 1840s; they were not recorded in February–March (Reeves et al. 1999).

Mixed groups of sperm whales and some solitary males likely occur in the survey area. Young calves could also be present at the time of the year (January–February) during which the survey is scheduled.

Pygmy and Dwarf Sperm Whales

Pygmy sperm whales (*Kogia breviceps*) and dwarf sperm whales (*K. sima*) are distributed widely throughout tropical and temperate seas, but their precise distributions are unknown as most information on these species comes from strandings (McAlpine 2002). They are difficult to sight at sea, perhaps because of their avoidance reactions to ships and behavior changes in relation to survey aircraft (Würsig et al. 1998). The two species are difficult to distinguish from one another when sighted (McAlpine 2002). During sighting surveys and, hence, in population and density estimates, the two species are most often categorized together as *Kogia* spp. (Waring et al. 2008).

Barros et al. (1998) suggested that dwarf sperm whales could be more pelagic and dive deeper than pygmy sperm whales. Also, the dwarf sperm whale could prefer warmer waters than the pygmy sperm whale (McAlpine 2002). Pygmy sperm whales feed mainly on various species of squid in the deep zones of the continental shelf and slope (McAlpine et al. 1997). Pygmy sperm whales occur in small groups of up to six, and dwarf sperm whales can form groups of up to 10 (Caldwell and Caldwell 1989). Wade and Gerrodette (1993) noted a mean group size of 1.7 for the dwarf sperm whale in the ETP.

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. In the SPREP region, confirmed sightings have been recorded for Niue, New Caledonia, French Polynesia, Palau, Guam, and the Pitcairn Islands (SPREP 2007). Recent sighting data also confirm their presence in Tuvalu (SPWRC 2008). Unconfirmed sighting records exist for American Samoa and Fiji, but no sightings have been made in Tonga (SPREP 2007). There are stranding records for both *Kogia* species from New Caledonia (Reeves et al. 1999).

Cuvier's Beaked Whale

Cuvier's beaked whale is probably the most widespread of the beaked whales, although it is not found in polar waters (Heyning 1989). It is rarely observed at sea and is mostly known from strandings. It strands more commonly than any other beaked whale (Heyning 1989). Its inconspicuous blows, deep-diving behavior, and tendency to avoid vessels all help to explain the infrequent sightings (Barlow and Gisner 2006). 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). Wade and Gerrodette (1993) reported a mean group size of 2.2 for the ETP.

Cuvier's beaked whale is an offshore, deep-diving species that feeds on fish and squid (Heyning 2002). Its dives generally last 30–60 min, but dives of 85 min have been recorded (Tyack et al. 2006). Maximum dive depths have been reported as 1450 m (Baird et al. 2006) and 1888 m (Tyack et al. 2006).

Reeves et al. (1999) reported that Cuvier's beaked whale "probably occurs in deep waters throughout much of the SPREP region". Recent sighting data confirm the presence of Cuvier's beaked whale in French Polynesia and the Cook Islands (SPWRC 2004; SPREP 2007). Sightings have also been reported for American Samoa, the Cook Islands, Niue, New Caledonia, French Polynesia, Palau, and the Pitcairn Islands (SPREP 2007). Two groups of two were sighted during >4600 km of inshore survey effort and >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). Those sightings occurred at depths 1100 m and 2100 m. No Cuvier's beaked whales were sighted during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 in the Marquesas Islands (Gannier 2002a).

Southern Bottlenose Whale

The southern bottlenose whale generally can be found throughout the Southern Hemisphere from 30°S to the ice edge, and there are no known areas of concentration (Gowans 2002). It is apparently migratory, found in Antarctic waters during the summer (Jefferson et al. 1993). The southern bottlenose whale is primarily a deep-water animal (Mead 1989a). Its main prey is deep-water oceanic squid from Antarctic, sub-Antarctic, and more temperate areas (Clarke and Goodall 1994; Slip et al. 1995).

Southern bottlenose whales can be found in groups of 1–20 (Gowans 2002). Mean group sizes in the Antarctic (south of 60°S) were estimated as 1.77 and 1.89 for two different sets of surveys (Branch and Butterworth 2001). The southern bottlenose whale is listed by CITES as an Appendix I species (Table 2).

Possible sightings have been made in the SPREP region and the North Pacific (Reeves et al. 1999). A sighting of 25 bottlenose whales was made northeast of the Phoenix Islands in 1966 (Reeves et al. 1999). Bottlenose whales have also been seen in the Philippines and the ETP (Wade and Gerrodette 1993; Reeves et al. 1999). It is possible that some sightings in these areas were of Longman's beaked whales. SPREP (2007) reported on confirmed sightings of southern bottlenose whales in Kiribati.

Longman's Beaked Whale

Until very recently, Longman's beaked whale was thought to be extremely rare, and 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*, but there now seems to be sufficient information to afford it status as a separate genus (Dalebout et al. 2003).

Pitman et al. (1999) suggested that several sightings of bottlenose whales in the tropical Pacific were misidentifications (e.g., Wade and Gerrodette 1993) and were, in fact, sightings of Longman's beaked whale. Sightings of Longman's beaked whale have occurred at many locations in tropical waters of the Indo-Pacific region (Jefferson et al. 2008). They have been sighted in waters with temperatures 21–31ºC, and have been seen in the tropics every month of the year except June, indicating year-round residency (Pitman et al. 1999; Jefferson et al. 2008). Longman's beaked whales have been seen alone, but more commonly in groups of at least ten and up to 100, with an average group size of 15–20 (Reeves et al. 2002; Jefferson et al. 2008). Pitman et al. (1999) reported a mean group size of 18.5 in the tropics. Dives are thought to last 18–33 min (Reeves et al. 2002; Jefferson et al. 2008).

Although widespread throughout the tropical Pacific, the species must still be considered rare because of a scarcity of sightings despite a great deal of survey effort (Pitman et al. 1999). No population estimates exist.

Mesoplodont Beaked Whales

Two species of mesoplodont whales likely occur in deep waters in the study area. They are Blainville's and the gingko-toothed beaked whales. No population estimates exist for either of these species in the South Pacific. Mesoplodont beaked whales that could occur but would be considered extralimital include Gray's and Andrew's beaked whales. These extralimital species will not be discussed further.

Almost everything that is known regarding most mesoplodont species has come from stranded animals (Pitman 2002). The different mesoplodont species are difficult to distinguish in the field, and are most often categorized during sighting surveys, and therefore in density and population estimates, as *Mesoplodon* spp. They are all thought to be deep-water animals, only rarely seen over the continental shelf. Typical group sizes range from one to six (Pitman 2002). Because of the scarcity of sightings, most are thought to be rare.

Blainville's beaked whale.—This species is found in tropical and temperate waters of all oceans (Jefferson et al. 2008). Blainville's beaked whale has the widest distribution throughout the world of all *Mesoplodon* species (Mead 1989b). There is no evidence that Blainville's beaked whales undergo seasonal migrations. Blainville's beaked whales are most often found in singles or pairs, but also in groups of 3–7 (Jefferson et al. 2008).

Like other beaked whales, Blainville's beaked whales are generally found in deep waters 200 m to 1400 m deep (Gannier 2000; Jefferson et al. 2008). Maximum dive depths have been reported as 1251 m (Tyack et al. 2006) and 1408 m (Baird et al. 2006), and dives have lasted as long as 54 min (Baird et al. 2006) to 57 min (Tyack et al. 2006). However, they also can occur in coastal areas and have been known to spend long periods of time at depths <50 m (Jefferson et al. 2008).

In the SPREP region, there are sighting records for the Cook Islands and French Polynesia (SPWRC 2004; SPREP 2007) and for Fiji and New Caledonia (SPREP 2007). Unconfirmed sightings have been reported for Samoa, Kiribati, and Palau, but there are no sighting records for Tonga (SPREP 2007).

Ginkgo-toothed beaked whale.—This species is only known from stranding records (Mead 1989b; Jeffer-son et al. 2008). In the South Pacific Ocean, it has stranded in New South Wales, Australia, and the North Island and Chatham Islands, New Zealand (Mead 1989b; Baker and van Helden 1999). The ginkgo-toothed whale is hypothesized to occupy tropical and warm temperate waters of the Indian and Pacific oceans (Pitman 2002). Although Reeves et al. (1999) reported that the ginkgo-toothed whale likely occurs in the SPREP region, SPREP (2007) did not include this species in the list of marine mammals occurring there.

Rough-toothed Dolphin

The rough-toothed dolphin is widely distributed around the world, but mainly occurs in tropical and warm temperate waters (Miyazaki and Perrin 1994), including the SPREP region (Reeves et al. 1999; SPREP 2007). Confirmed sightings in the SPREP region are known for Samoa, American Samoa, Solomon Islands, French Polynesia, Kiribati, New Caledonia, and the Northern Marianas Islands, with unconfirmed sightings in Fiji; no sighting have been made in Tonga (SPREP 2007).

Rough-toothed dolphins are deep divers and can dive for up to 15 min (Reeves et al. 2002). They usually form groups of 10–20 (Reeves et al. 2002), but aggregations of hundreds have been seen (Leatherwood and Reeves 1983). Wade and Gerrodette (1993) reported a mean group size of 14.7 for the ETP. Group sizes off the Society Islands were 1–40, and off the Marquesas, the average group size was 17.7 (Gannier 2002a). The rough-toothed dolphin has been seen in mixed-species associations with melon-headed whales and Fraser's dolphins off the Society Islands (Gannier 2000).

Off the Society Islands, it has been seen in waters ranging from <100 m to >3000 m deep (Gannier 2000). Off the Marquesas Islands, it was seen in coastal waters, over the continental slope, and in offshore waters (Gannier 2002a). Rough-toothed dolphins were sighted 30 times during >4600 km of inshore survey effort and twice during >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). They were sighted four times during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 in the Marquesas Islands (Gannier 2002a).

Bottlenose Dolphin

The bottlenose dolphin is distributed worldwide. There are two distinct bottlenose dolphin types: a shallow water type, mainly found in coastal waters, and a deep water 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). Bottlenose dolphins are known to occur throughout the SPREP region, including Tonga, Samoa, American Samoa, Fiji, Tuvatu, Vanuatu, New Caledonia, French Polynesia, Papua New Guinea, Solomon Islands, Micronesia, Kiribati, and the Marshall Islands (SPREP 2007). Possible sightings also exist for the Cook Islands (SPWRC 2004; SPREP 2007).

Although often seen in coastal areas, bottlenose dolphins have been 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). Off the Marquesas Islands, the species was most often sighted in coastal waters and occasionally close to the shelf break (Gannier 2002a). Mean group size in the ETP has been estimated at 24 (Smith and Whitehead 1999) and 22.7 (Wade and Gerrodette 1993). The average group size seen off the Marquesas Islands was 8.2 (Gannier 2002a).

Bottlenose dolphins were sighted only twice during >4600 km of inshore survey effort and >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). In contrast, they were sighted 17 times during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 in the Marquesas Islands, off almost every island (Gannier 2002a). Gannier (2002a) noted that bottlenose dolphins accounted for >17% of the delphinid sightings off the Galápagos Islands, whereas they made up ~6% of delphinid sightings off the Marquesas Islands, only 1% of sightings in the southwestern ETP, and a mere 0.2% of delphinid sightings in the Society Islands. Preliminary investigation of the species off Rangiroa (Tuamotu Islands, French Polynesia) suggests a local population of 20–30 off that island (Brasseur et al. 2002).

Pantropical Spotted Dolphin

The pantropical spotted dolphin can be found throughout tropical and some subtropical oceans of the world (Perrin and Hohn 1994). The southernmost limit of its range is ~40°S (Perrin 2002a). In the ETP, this dolphin is associated with warm (>25ºC) tropical surface water (Au and Perryman 1985; Reilly 1990; Reilly and Fiedler 1994; Reeves et al. 1999). There are two forms of pantropical spotted dolphin, coastal and offshore forms, although the coastal form occurs mainly in the ETP from Baha California to

South America (Jefferson et al. 2008). The offshore form inhabits tropical, equatorial, and southern subtropical water masses (Perrin 2002a). They are found primarily in deeper waters, and rarely over the continental shelf or continental shelf edge (Davis et al. 1998). Pantropical spotted dolphins are extremely gregarious, forming groups of hundreds or even thousands. Wade and Gerrodette (1993) reported a mean group size of 149.4 for the western/southern stock in the ETP. Pantropical spotted and spinner dolphins are commonly seen together in mixed-species groups, e.g., in the ETP (Au and Perryman 1985), off Hawaii (Psarakos et al. 2003), and off the Marquesas Archipelago (Gannier 2002a).

Within the SPREP region, confirmed sightings are known for Tonga, Cook Islands, Fiji, American Samoa, Vanuata, Papua New Guinea, Solomon Islands, French Polynesia, Kiribati, Marshall Islands, and New Caledonia (SPREP 2007), and a recent sighting was made in Tuvalu (SPWRC 2008). Pantropical spotted dolphins were not seen during >4600 km of inshore survey effort and >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). In contrast, they were the most commonly-sighted cetacean species off the Marquesas Islands, with 37 sightings during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 (Gannier 2002a). Off the Marquesas Islands, they were sighted more frequently in coastal and inshore waters, but were also seen in the deep ocean (Gannier 2002a). The mean group size was 17.6 off the Marquesas Islands (Gannier 2002a). Gannier (2002a) noted that pantropical spotted dolphins accounted for more than one quarter of the delphinid sightings off the Marquesas Islands and in the southwestern ETP, whereas they made up only 2% of delphinid sightings off the Society Islands and <1% of delphinid sightings off the Galápagos Islands.

Spinner Dolphin

The spinner dolphin is distributed in oceanic and coastal tropical waters, although its range is mostly oceanic in the ETP (Jefferson et al. 2008). In the ETP, it is associated with warm, tropical surface water, similar in distribution to the Pantropical spotted dolphin (Au and Perryman 1985; Reilly 1990; Reilly and Fiedler 1994; Reeves et al. 1999). In the South Pacific Ocean, it rarely occurs south of northern Australia (Evans 1987:113; see also Fig. 1 *in* Perrin and Gilpatrick 1994). Reeves et al. (1999) consider this species to be the dolphin most commonly sighted around oceanic islands in the SPREP region. Sightings are known for many areas within the SPREP region, including Tonga, Niue, Fiji, the Cook Islands, American Samoa, and Samoa (see SPREP 2007).

Spinner dolphins are extremely gregarious, and usually form large schools in the open sea and small ones in coastal waters (Perrin and Gilpatrick 1994). A mean group size of 33.5 was reported for the Society Islands (Gannier 2000), and a mean group size of 7.6 was reported off the Marquesas (Gannier 2002a). Group sizes of resting spinner dolphins in Baie des Pêcheurs, Tahiti, ranged from 15–30 to 100–150 (Gannier 2002b). Wade and Gerrodette (1993) reported a mean group size of 134.1 in the ETP. Spinner dolphins and pantropical spotted dolphins are commonly seen together in mixed-species groups, e.g., in the ETP (Au and Perryman 1985), off Hawaii (Psarakos et al. 2003), and off the Marquesas Archipelago (Gannier 2002a).

Spinner dolphins are seen year-round off the Society Islands in water depths 50–1000 m (Gannier 2000). Off the Marquesas Islands, they were most often observed in coastal or inshore waters, but were also seen offshore (Gannier 2002a). Spinner dolphins can be found resting in shallow sheltered sites in the Society Islands. They were seen resting in Baie des Pêcheurs, Tahiti West, with a higher occurrence from May to October than from February to April (Gannier 2002b).

Spinner dolphins were the most frequently seen cetacean species during >4600 km of inshore survey effort and >550 km of offshore survey effort in the Society Islands (Gannier 2000). The species was sighted 43 times during three years of fall and spring shipboard surveys. Off the Marquesas Archipelago, they were the second-most frequently-seen cetacean species, with 23 sightings during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 (Gannier 2002a). Gannier (2002a) noted that spinner dolphins accounted for more than half of the delphinid sightings off the Society Islands, whereas they made up <10% of delphinid sightings off the Marquesas Islands and in the southwestern ETP, and only 1% of delphinid sightings off the Galápagos Islands.

Striped Dolphin

The striped dolphin has a cosmopolitan distribution in tropical to warm temperate waters (Perrin et al. 1994a), and it generally seen below 43ºN (Archer 2002). It is typically found in waters outside the continental shelf and is often associated with convergence zones and areas of upwelling (Archer 2002). Striped dolphins are fairly gregarious (groups of 20 or more are common) and active at the surface (Whitehead et al. 1998). Wade and Gerrodette (1993) reported a mean group size of 60.9 in the ETP, and Smith and Whitehead (1999) reported a mean group size of 50 in the Galápagos Islands.

The distribution mapped by Perrin et al. (1994a) indicates that striped dolphins occur throughout the SPREP region (Reeves et al. 1999). In fact, there have been confirmed sightings of striped dolphins in Palau, Samoa, the Solomon Islands, Micronesia, and the Marshall Islands (SPREP 2007). There are no confirmed sightings for Tonga, but unconfirmed sighting records exist for Fiji (SPREP 2007). This species was not sighted during three years of fall and spring shipboard surveys off the Society Islands (Gannier 2000) or during November–January 1999 sighting surveys in the Marquesas Islands (Gannier 2002a).

Fraser's Dolphin

Fraser's dolphin is a tropical species found between 30°N and 30°S (Dolar 2002). It only occurs rarely in temperate regions, and then only in relation to temporary oceanographic anomalies such as El Niño events (Perrin et al. 1994b). The species typically occurs in deep, oceanic waters. In the ETP, most sightings were 45–100 km from shore in waters 1500–2500 m deep (Dolar 2002). Off Huahine and Tahiti (Society Islands), it was observed in waters 500–1500 m deep (Gannier 2000).

Fraser's dolphins travel in groups ranging from just a few animals to 100 or even 1000 (Perrin et al. 1994b). Wade and Gerrodette (1993) reported a mean group size of 394.9 for the ETP. Gannier (2000) reported school sizes ranging from 25 to 30 off the Society Islands. Fraser's dolphins were observed in association with melon-headed whales and rough-toothed dolphins in that study.

In the SPREP region, Fraser's dolphins are known to occur in the Cook Islands, Micronesia, French Polynesia, Kiribati, Nauru, Papua New Guinea, Samoa, and the Solomon Islands (SPREP 2007). Fraser's dolphins were sighted four times during >4600 km of inshore survey effort and >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys, but were not sighted in the Marquesas Islands during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 (Gannier 2002a). Gannier (2002a) noted that Fraser's dolphins accounted for almost one third of the delphinid sightings in the southwestern ETP, whereas they made up <10% of delphinid sightings off the Society Islands, <4% of sightings off the Galápagos Islands, and were not seen at all off the Marquesas Archipelago. Reeves et al. (1999) reported a historic sighting (from the 1930s) of Fraser's dolphin off the Fiji Islands, but this sighting appears to be unconfirmed (see SPREP 2007).

Short-beaked Common Dolphin

The common dolphin is found in tropical and warm temperate oceans around the world (Perrin 2002b). It ranges as far south as 40°S in the Pacific Ocean, is common in coastal waters 200–300 m deep, and is also associated with prominent underwater topography, such as seamounts (Evans 1994). Off northern New Zealand, it is generally seen at a mean distance <10 km from shore in the summer, and move further offshore in winter (Neumann 2001). Common dolphins often travel in fairly large groups; schools of hundreds or even thousands are common. Smith and Whitehead (1999) noted that common dolphins were frequently seen in waters near the Galápagos Islands, with a mean group size of 125. Wade and Gerrodette reported a mean group size of 472.8 in the southern portion of the ETP.

There are two species of common dolphins: the short-beaked common dolphin (*D. delphis*) and the long-beaked common dolphin (*D. capensis*). In the SPREP region, short-beaked common dolphins are known to occur in the waters of New Caledonia, but there have been no confirmed sightings of long-beaked common dolphins in the SPREP area (Reeves et al. 1999). Confirmed sightings of common dolphins in the SPREP region also exist for the Cook and Marshall islands, whereas unconfirmed sightings have been recorded for Fiji, Solomon Islands, and the Northern Mariana Islands (SPREP 2007). The species was not sighted during three years of fall and spring shipboard surveys off the Society Islands (Gannier 2000) or during November–January 1999 sighting surveys in the Marquesas Islands (Gannier 2002a). Similarly, no sighting records exist for the EEZ of Tonga, although 40 common dolphins were sighted southwest of Tonga (25º27'S, 177 º42'W) in November 1992 (see Reeves et al.1999).

Risso's Dolphin

Risso's dolphin is primarily a tropical and mid-temperate species distributed worldwide. It occurs between 60ºN and 60ºS, where surface water temperatures are at least 10ºC (Kruse et al. 1999). In the northern Gulf of Mexico, Risso's dolphin usually occurs over steeper sections of the upper continental slope (Baumgartner 1997) in waters 150–2000 m deep (Davis et al. 1998). In Monterey Bay, California, it is most numerous where there is steep bottom topography (Kruse et al. 1999). Risso's dolphins occur individually or in small to moderate-sized groups, normally ranging from 2 to <250. The majority of groups consist of <50 (Kruse et al. 1999). Wade and Gerrodette (1993) reported a mean group size of 11.8 in the ETP.

Risso's dolphin occurs throughout the SPREP region (Reeves et al. 1999; SPREP 2007), and its presence has been confirmed in Tonga (SPREP 2007). Off Moorea, it was sighted in groups of 10–20 in January–February 1994 (Reeves et al. 1999). Gannier (2000) reported a single sighting of Risso's dolphin in the Society Islands (~6 km south of Tahiti) during three years of fall and spring shipboard surveys. Risso's dolphin was also sighted only once in the Marquesas Islands during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 (Gannier 2002a). Gannier (2002a) noted that Risso's dolphins accounted for a mere 0.1% of delphinid sightings off the Marquesas and Society Islands, whereas they made up >4% of delphinid sightings off Galápagos Islands and 3.4% of delphinid sightings in the southwestern ETP. Risso's dolphins off the Marquesas Islands were sighted in water 800 m deep (Gannier 2002a).

Melon-headed Whale

The melon-headed whale is a pantropical and pelagic species that occurs mainly between 20ºN and 20ºS in offshore waters (Perryman et al. 1994). Melon head whales are known to occur throughout the SPREP region, with confirmed sightings in Tonga (SPREP 2007). Sightings off the Society Islands, French Polynesia, occurred in water depths 500–1500 m. Off the Marquesas Islands, on the other hand, melon-headed whales were commonly observed in coastal waters with depths as shallow as 300 m (Gannier 2002a).

Melon-headed whales tend to occur in groups of 100–500, but have also been seen in groups of up to 2000 (Jefferson et al. 2008). Wade and Gerrodette (1993) reported a mean group size of 199 for the ETP. Gannier (2000) reported group sizes ranging from 50 to 120 off the Society Islands. The average group size seen off the Marquesas Islands was 85 (Gannier 2002a). Melon-headed whales accounted for greater than half the delphinid sightings off the Marquesas Islands, whereas they made up <16% of delphinid sightings off the Society Islands (Gannier 2002a). Melon-head whales are commonly seen in mixed groups with other cetaceans (Jefferson and Barros 1997). Off the Society Islands of Huahine and Tahiti, they were sighted in association with Fraser's dolphins and rough-toothed dolphins (Gannier 2000). In January–February 1994, large groups (200–300) of melon-headed whales were sighted off Moorea (French Polynesia), often with Fraser's dolphins (Reeves et al. 1999).

Pygmy Killer Whale

The pygmy killer whale is distributed throughout tropical and subtropical oceans worldwide (Ross and Leatherwood 1994; Donahue and Perryman 2002). Little is known about the species in most of its range, but it is sighted frequently in the ETP, off Hawaii, and off Japan (Donahue and Perryman 2002). In warmer water, it is usually seen close to the coast (Wade and Gerrodette 1993), but it is also found in deep waters. In the Marquesas, it was sighted in water 100 m deep (Gannier 2002a). Pygmy killer whales tend to travel in groups of 15–50, although herds of a few hundred have been sighted (Ross and Leatherwood 1994). Wade and Gerrodette (1993) reported a mean group size of 27.9 in the ETP.

Recent sighting evidence confirms the presence of pygmy killer whales in Tonga, New Caledonia, and French Polynesia (SPWRC 2004; SPREP 2007). Gannier (2002a) reported one sighting of three pygmy killer whales in water 100 m deep during surveys in November–January 1999 in the Marquesas Islands. No sightings were made surveys in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000).

False Killer Whale

The false killer whale is found in all tropical and warmer temperate oceans, especially in deep, offshore waters (Odell and McClune 1999). It is also known to occur in nearshore areas (e.g., Stacey and Baird 1991). In the ETP, it is usually seen far offshore (Wade and Gerrodette 1993). False killer whales travel in pods of 20–100 (Baird 2002), although groups of several hundred are sometimes observed. Wade and Gerrodette (1993) reported a mean group size of 11.4 in the ETP.

False killer whales are thought to occur year-round in the SPREP region (Reeves et al. 1999). Recent sighting evidence confirms their presence in Tonga, American Samoa, Samoa, Fiji, New Caledonia, Niue, Solomon Islands, Papua New Guinea, and French Polynesia (SPWRC 2004; SPREP 2007). A group of 15 false killer whales was seen in the northern Tonga archipelago in October 1992 (Reeves et al. 1999). Gannier (2002a) reported a sighting of a group of three adults and one calf in water ~2000 m deep off the Marquesas Islands during November–January 1999. False killer whales were not sighted during >4600 km of inshore survey effort or during >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000).

Killer Whale

The killer whale is cosmopolitan and globally fairly abundant; it has been observed in all oceans of the world (Ford 2002). It is very common in temperate waters, and also frequents tropical waters, at least seasonally (Heyning and Dahlheim 1988; Reeves et al. 1999). High densities of the species occur in high latitudes, especially in areas where prey is abundant. Although resident in some parts of its range, the killer whale can also be transient. Killer whale movements generally appear to follow the distribution of their prey, which includes marine mammals, fish, and squid. Killer whales are large and conspicuous, often traveling in close-knit matrilineal groups of a few to tens of individuals (Dahlheim and Heyning 1999). Wade and Gerrodette (1993) reported a mean group size of 5.4 in the ETP.

Killer whales occur at least seasonally in many areas within the SPREP region (Reeves et al. 1999). Confirmed sightings exist for areas near the proposed study area, including Tonga, the Cook Islands, American Samoa, Samoa, and Niue (SPREP 2007). Unconfirmed sightings exist for Fiji (Reeves et al. 1999; SPREP 2007). Although killer whales are also known to occur in French Polynesia, they were not sighted during >4600 km of inshore survey effort or during >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). However, they were sighted only once during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 in the Marquesas Islands (Gannier 2002a). Japanese vessels observed a concen-tration of killer whales in November between the Phoenix and Tongan islands, in October near Samoa, and in March west of Samoa (Reeves et al. 1999).

Short-finned Pilot Whales

The short-finned pilot whale is found in tropical and warm temperate waters (Olson and Reilly 2002); it is seen as far south as ~40ºS, but is more common north of ~35ºS (Olson and Reilly 2002). Pilot whales occur on the shelf break, over the slope, and in areas with prominent topographic features, and are usually seen in groups of 20–90 (Olson and Reilly 2002). Wade and Gerrodette (1993) reported a mean group size of 18.3 in the ETP. Long-finned pilot whales outfitted with time-depth recorders dove to depths up to 828 m, although most of their time was spent above depths of 7 m (Heide-Jørgensen et al. 2002). The species' maximum recorded dive depth is 971 m (Baird pers. comm. *in* DoN 2005).

Short-finned pilot whales are thought to be widespread and common throughout the SPREP region (Reeves et al. 1999). Confirmed sightings exist for most islands in the SPREP area, including Tonga (SPREP 2007). Two large groups of 50–100 were sighted off Moorea, French Polynesia, in January–February 1994 (Reeves et al. 1999). Short-finned pilot whales were sighted five times during >4600 km of inshore survey effort but not during >550 km of offshore survey effort in the Society Islands during three years of fall and spring shipboard surveys (Gannier 2000). They were sighted once during >1000 km of inshore survey effort and >500 km of offshore survey effort during November–January 1999 in the Marquesas Islands (Gannier 2002a). Gannier (2002a) reported that short-finned pilot whales accounted for >5% of the delphinid sightings off the Society Islands, whereas they made up <2% of delphinid sightings off the Marquesas Islands.

Short-finned pilot whales sighted off the Marquesas were in water ~700 m deep (Gannier 2002a). Sightings of the species off Huahine, Tahiti, and Moorea (Society Islands) occurred in waters with depths ranging from 300 to 1400 m (Gannier 2000). In the Society Archipelago, sightings occurred between 0.5 and 7 km offshore (Gannier 2000). Group sizes off the Society Islands ranged from 10 to 35, and one group of 32 was seen off the Marquesas Archipelago (Gannier 2002a).

(3) Pinnipeds

There are no pinnipeds that have primary habitat within the SPREP region (Reeves et al. 1999). Two species of pinnipeds could occur in the proposed seismic survey area as extralimital sightings: the New Zealand fur seal (*Arctocephalus forsteri*) and the leopard seal (*Hydrurga leptonyx*) (Reeves et al. 1999; Rogers 2002). Because of the rare occurrence of these species in the area, they will not be discussed further.

Sea Turtles

Six species of sea turtle occur within the SPREP region: the leatherback (*Dermochelys coriacea*), green (*Chelonia mydas*), loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*), olive ridley (*Lepidochelys olivacea*), and flat back turtles (*Natator depressus*) (SPREP 2007). However, only five of these species could occur in the study area in the Lau Basin; the flat back turtle occurs only in Australia and Papua New Guinea, although unconfirmed sighting data exist for Vanuatu (SPREP 2007). The hawksbill and green turtles are the most widespread species in the SPREP region, and also nest in most countries and territories of this region (SPREP 2007).

(1) Leatherback Turtle

The leatherback turtle is listed as ***Endangered*** under the U.S. ESA and ***Critically Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The world leatherback turtle population is currently estimated at 35,860 females (Spotila 2004). A significant drop in the numbers of nesting leatherbacks in the Pacific has been reported (Dutton et al. 2007) with possible extirpation of some nesting groups in the eastern Pacific (Spotila et al. 2000).

The leatherback is the largest and most widely distributed sea turtle, ranging far from its tropical and subtropical breeding grounds (Plotkin 2003). Frair et al. (1972) and Greer et al. (1973) noted that leatherback turtles have evolved physiologically with anatomical adaptations to cold water, allowing them to use some habitats that other sea turtles species would not. They have been reported from 71°N to 42°S in the pelagic Pacific Ocean (NMFS and USFWS 1998a, 2007a). Leatherbacks are highly pelagic, spending the majority of their time in waters >1000 m deep and possibly swimming more than 10,000 km in a year (Eckert 1998 *in* NMFS 2002). Female leatherbacks approach coastal waters only during the reproductive season (EuroTurtle 2006), whereas males are rarely observed near nesting sites (NMFS 2002).

Leatherbacks are highly migratory, feeding in convergence zones and upwelling areas in the open ocean, along continental margins, and in archipelagic waters (Morreale et al. 1994; Eckert 1995a). Hatchling leatherbacks are pelagic, but nothing is known about their distribution for the first four years (Musick and Limpus 1997). Post-nesting adult leatherbacks appear to migrate along bathymetric contours from 200 to 3500 m (Morreale et al. 1994). 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).

The leatherback turtle is one of the deepest divers in the ocean, with dives deeper than 1000 m (Eckert et al. 1989). The leatherback dives continually and spends short periods of time on the surface between dives (Eckert et al. 1986; Southwood et al. 1998). Off Playa Grande, Costa Rica, six inter-nesting female leatherbacks spent 57–68% of their time underwater, diving to a mean depth of 19 m for 7.4 min (Southwood et al. 1999 *in* NMFS 2002). Off St. Croix, six inter-nesting females dove to a mean depth of

61.6 m for an average of 9.9 min, and post-dive surfacing intervals averaged 4.9 min (Eckert et al. 1989). During shallow-water diving in the South China Sea, typical dive durations averaged 6.9–14.5 min, with a maximum of 42 min (Eckert et al. 1996). Off central California, leatherbacks dove to 20–30 m with a maximum of 92 m, corresponding to the vertical distribution if their prey, and mean dive and surface durations were 2.9 and 2.2 min, respectively (Harvey et al. 2006).

In the eastern Pacific, leatherbacks nest along the west coast of Mexico and Central America from October to March (EuroTurtle 2006). In the western Pacific, they mainly nest in New Guinea, the Solomon Islands, and Vanuatu, with fewer nesting in Fiji, Malaysia, and Australia (EuroTurtle 2006; NMFS and USFWS 2007a). They are not known to nest in Tonga (SPREP 2007). In Papua New Guinea, nesting occurs from November through March, with peak activity during December to January (Benson et al. 2007). Satellite-tagged leatherback turtles traveled from nesting beaches in Papua New Guinea to foraging areas in the high latitudes of the South Pacific (Benson et al. 2007). One female tagged in Papua New Guinea crossed the New Hebrides Trench between New Caledonia and Vanuata, spent more than 5 weeks in the productive Southern Transition waters, and then traveled northward near the islands of Tonga (Benson et al. 2007). Thus, migrating or foraging leatherbacks could be encountered during the proposed survey.

(2) Green Turtle

The green turtle is listed as ***Threatened*** under the ESA throughout its Pacific range, except for the ***Endangered*** population nesting on the Pacific coast of Mexico. The green turtle is listed as ***Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007) and is listed in CITES Appendix I (UNEP-WCMC 2008). The worldwide green turtle population is estimated at 88,520 nesting females by Spotila (2004) and 110,000–150,000 by NMFS and USFWS (2007b). The worldwide population has declined 50–70% since 1900 (Spotila 2004).

The green turtle is widely distributed in tropical and subtropical waters near continental coasts and around islands. Some authorities treat the black turtle (*C. agassizii*) as a separate species, but most now recognize the black turtle as a subspecies of green turtle (Karl and Bowen 2001). Green turtles typically migrate along coastal routes from rookeries to feeding grounds, although some populations conduct trans-oceanic migrations (EuroTurtle 2006). Females typically show nest-site fidelity, and nest repeatedly in the same spot, or at least on the same beach from which they hatched. Hatchlings are epipelagic (surface dwelling in the open sea) for ~1–3 years. Subsequently, most green turtles live in bays and along protected shorelines, and feed during the day on seagrass and algae (Bjorndal 1982). Juvenile and sub-adult green turtles can travel thousands of kilometers before they return to breeding and nesting grounds (Carr et al. 1978). It has been suggested recently that some green turtles remain in oceanic habitats, foraging on jellyfish and other pelagic prey, and possibly never inhabit coastal foraging sites (NMFS and USFWS 2007b).

Green turtles typically make dives shallower than 30 m (Hochscheid et al. 1999; Hays et al. 2000), although they have been observed diving to 73–110 m in the eastern Pacific Ocean (Berkson 1967). The maximum dive time recorded for a juvenile green turtle off Hawaii was 66 min, and routine dive times were 9–23 min (Brill et al. 1995).

The largest nesting area of green turtles is Raine Island off eastern Australia; ~25,000 females nest there (NMFS and USFWS 2007b). Smaller numbers of green turtles are also known to nest on islands throughout the SPREP region (SPREP 2007). Green turtles occur in most countries and territories in the SPREP region, including Tonga, Fiji, American Samoa, Samoa, Niue, Cook Islands, French Polynesia, Vanuatu, and New Caledonia (SPREP 2007). In Tonga, green turtles nest from 1 November to 31 January (ESCAP 1990 *in* Zann 1994).

The green turtle is considered common in French Polynesian waters, although the numbers of nesting turtles have declined in recent years (Balazs et al. 1995). The atolls of Scilly, Motu-one, and Mopelia, located at the western limits of French Polynesia, ~250–300 km to the west of Bora Bora, were once the location of significant nesting colonies. Only Scilly continues to have substantial numbers of nesting turtles each year. Scilly Atoll is the only known nesting site of significance throughout the 130 islands of French Polynesia (Balazs et al. 1995). Nesting can occur throughout the year, but peaks between October and December.

Of seven post-nesting green turtles tagged at Rose Atoll (American Samoa), most migrated to Fiji (Craig et al. 2004). Long internesting intervals indicate that Rose Atoll turtles spend most of their adult life in Fiji, leaving only to nest on other islands (Craig et al. 2004). In fact, 96% of post-nesting sea turtles tagged in French Polynesia, American Samoa, and Cook Islands migrate westward with 58% going to Fiji (Craig et al. 2004). Turtles tagged in French Polynesia have also traveled to Tonga, Vanuatu, New Caledonia, and Wallis Island (Balazs et al. 1995). Fiji has considerable pastures of seagrass providing a rich foraging habitat for green sea turtles, which are not available east of Fiji where islands have limited areas for seagrass growth (Craig et al. 2004). Green sea turtles are important as a seasonal subsistence food for local indigenous Fijian and Indo-Fijian families (Morgan 2007).

(3) Loggerhead Turtle

The loggerhead turtle is listed as ***Threatened*** under the U.S. ESA throughout its range, primarily because of direct take, incidental capture in various fisheries, and the alteration and destruction of its habitat (NMFS 2002). The loggerhead is categorized as ***Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The global population of loggerhead turtles is estimated at 43,320–44,560 nesting females (Spotila 2004).

The loggerhead is a widely distributed species, occurring in coastal tropical and subtropical waters around the world. On average, loggerheads turtles spend over 90% of their time underwater (Byles 1988; Renaud and Carpenter 1994). In the North Pacific Ocean, two loggerheads tagged with satellite-linked depth recorders spent about 40% of their time in the top meter and virtually all their time shallower than 100 m; 70% of the dives were no deeper than 5 m (Polovina et al. 2003). Off Japan, virtually all the dives of two loggerheads between nesting were shallower than 30 m (Sakamoto et al. 1993). Routine dives can last 4–172 min (Byles 1988; Sakamoto et al. 1990; Renaud and Carpenter 1994). Small juvenile loggerheads live at or near the surface; for the 6–12 years spent at sea as juveniles, they spend 75% of their time in the top 5 m of water (Spotila 2004). Juveniles spend more time on the surface in deep, offshore areas than in shallow, nearshore waters (Lutcavage and Lutz 1997).

Loggerhead turtles undertake long migrations that take them far from their breeding grounds. Loggerheads may be seen in the open seas during migration. They 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 migration through the open sea, they eat jellyfish, pteropods, floating mollusks, floating egg clusters, flying fish, and squid, feeding mostly in the top 50 m (Polovina et al. 2003, 2004).

Nesting in the Pacific Ocean basin is restricted to the western region; the two main nesting stocks in Japan and Australia/New Caledonia have been identified as genetically distinct (NMFS and USFWS 2007c). In Australia, loggerheads nest from October through April (EuroTurtle 2006). The size structure of loggerheads in coastal and nearshore waters of the eastern and western Pacific Ocean suggest that hatchling loggerheads in the Pacific Ocean have a pelagic stage similar to that in the Atlantic (NMFS 2002), where they spend the first 2–6 years of their lives at sea. Telemetry studies, mark-recapture data, demographics, diet analysis, and oceanographic patterns suggest that North Pacific loggerhead turtles, mostly born in southern Japan, are transported as hatchlings and juveniles to the North Pacific by the Kuroshio Current, then spend the next 2–6 years moving from west to east, feeding along convergence and frontal zones. They arrive at the U.S. west coast as juveniles, and feed along the Baha California coast on pelagic red crabs, which are extremely abundant there in spring and early summer. When mature, they migrate back to natal beaches in Japan and remain in the western Pacific, migrating annually between nesting beaches and feeding grounds in the South and East China Seas (Nichols et al. 2000; Nichols 2005; Parker et al. 2005).

The closest nesting beaches to the project area are in eastern Australia and New Caledonia. Loggerhead turtles have been sighted throughout the SPREP region, including Fiji, Palau, Papua New Guinea, Solomon Islands, Tokelau, and Vanuatu; there are no sighting records for Tonga (SPREP 2007). Nonetheless, loggerhead turtles could be encountered during the proposed survey in the Lau Basin.

(4) Hawksbill Turtle

The hawksbill turtle is listed as ***Endangered*** under the U.S. ESA and ***Critically Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The hawksbill is a solitary nester, and population trends or estimates are difficult to determine. The worldwide hawksbill population is estimated at 20,000–26,000 nesting females, <10% of the population a century ago (Spotila 2004).

The hawksbill is the most tropical of all sea turtles. Nesting areas occur between ~30ºN and ~30ºS (Eckert 1995b), where water temperature is 25–35ºC, and include the Caribbean, islands off eastern Africa, Sri Lanka and the Maldives, Malaysia, and Papua New Guinea and the Solomon Islands (EuroTurtle 2006). 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. Post-hatchlings are believed to be pelagic, taking shelter in weed lines around convergence zones, and they re-enter coastal waters once attaining a length of ~25–35 cm (NMFS and USFWS 1998b). In the Pacific, the pelagic habitat of hawksbill juveniles is still unknown (NMFS 2008a).

Coral reefs are the foraging grounds for juveniles, subadults, and adults. Hawksbill turtles appear to be specialist sponge carnivores (e.g., Vicente 1994) that move from shallow to deeper (<200 m) water as they grow (NMFS and USFWS 1998b). They 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 (NMFS and USFWS 1998b, 2007d).

Hawksbills have very long routine dive times. For inter-nesting females in St. Croix, Starbird et al. (1999) reported dive times averaging 56 min, a maximum dive time of 73.5 min, and an average surface interval of ~2 min. Average day and night dive times were 34–65 and 42–74 min, respectively. Based on time-depth recorder studies in Puerto Rico, foraging dives of immature hawksbills were 8.6–14 min to a mean depth of 4.7 m (van Dam and Diez 1996).

Approximately 3000 turtles nest east of Australia (Witzell 1983). The hawksbill turtle is one of the most widespread turtle in the area SPREP region (SPREP 2007). They have been reported to forage around nearly all of the island groups of Oceana and Galapagos in the eastern Pacific to the Republic of

Palau in the Western Pacific. Hawksbill turtles are considered common in French Polynesian waters, but they are not known to breed on the islands. Confirmed sightings have also been made near the proposed study area off Tonga, Fiji, and Niue (SPREP 2007). In Tonga, hawksbill turtles nest from 1 November–31 January (ESCAP 1990 *in* Zann 1994).

(5) Olive Ridley Turtle

The olive ridley turtle has a large range in tropical and subtropical regions in the Pacific, Indian, and South Atlantic oceans, and is generally found between 40ºN and 40ºS. The olive ridley is the most abundant sea turtle in the world, although its population is in serious decline worldwide (Spotila 2004). Olive ridley populations on the Pacific coast of Mexico are listed as ***Endangered*** under the U.S. ESA; all other populations are listed as ***Threatened***. The olive ridley is categorized as ***Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007) and is listed in CITES Appendix I (UNEP-WCMC 2008). The worldwide population of olive ridley turtles is estimated at ~2 million nesting females (Spotila 2004).

Olive ridley turtles lead a primarily pelagic existence (NMFS 2008b). The Pacific Ocean population migrates throughout the Pacific Ocean, from nesting grounds in Mexico and Central America to the North Pacific Ocean (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 the most abundant sea turtle in the open ocean waters of the ETP (Pitman 1990), where it forages, often in large groups, or flotillas (NMFS 2002).

Olive ridleys can dive and feed at considerable depths (80–300 m), although ~90% of their time is spent at depths <100 m (Eckert et al. 1986; Polovina et al. 2003). In the ETP, at least 25% of their total dive time is spent in the permanent thermocline, located at 20–100 m (Parker et al. 2003). Olive ridleys spend considerable time at the surface basking, presumably in an effort to speed their metabolism and digestion after a deep dive (Spotila 2004). In the open ocean of the ETP, olive ridley turtles are often seen near flotsam, possibly feeding on associated fish and invertebrates (Pitman 1992). In the North Pacific Ocean, two olive ridleys tagged with satellite-linked depth recorders spent about 20% of their time in the top meter and about 10% of their time deeper than 100 m; 70% of the dives were no deeper than 5 m (Polovina et al. 2003).

In the South Pacific, nesting colonies occur in the Philippines and northern Australia (EuroTurtle 2006), as well as Papua New Guinea (Spring 1982). Although most mating is generally assumed to occur near nesting beaches, Pitman (1990) observed olive ridleys mating at sea in the ETP, 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). As a significant proportion of mating is suspected to occur at sea, it is possible that some breeding groups do not migrate to the nearshore breeding grounds at all (Pitman 1991; Kopitsky et al. 2000).

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

In the eastern Pacific, the largest nesting concentrations occur in southern Mexico and northern Costa Rica, with stragglers nesting as far north as southern Baja California (Fritts et al. 1982) and as far south as Peru (Brown and Brown 1982). 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). Most females lay two clutches of eggs with an inter-nesting period of 1–2 months (Plotkin et al. 1994b). Radio-tracking studies showed 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). Olive ridleys nest throughout the year in the eastern Pacific with the highest numbers nesting during September–December (NMFS and USFWS 1998c). In the western Pacific, solitary nesting beaches occur in Australia, Brunei, Malaysia, Indonesia, and Vietnam, and arribadas are not known (Spotila 2004).

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 area in the 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 1998c, 2007e).

In the SPREP region, olive ridleys have been sighted in Fiji, Vanuatu, French Polynesia, the Solomon and Marshall islands, and Palau (SPREP 2007). The occurrence of olive ridleys in Tonga and Kiribati is suspected but unconfirmed (SPREP 2007).

IV. ENVIRONMENTAL CONSEQUENCES

Proposed Action

(1) Direct Effects 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 system to be used by L-DEO. A more detailed review of airgun effects on marine mammals appears in Appendix B. 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 2008. Appendix C contains a general review of the effects of seismic pulses on sea turtles. This section (along with Appendix B) 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 could be affected by the proposed activity during the seismic survey scheduled to occur from ~14 January to 21 February 2009. A description of the rationale for L-DEO's estimates of the numbers of exposures to various received sound levels that could occur during the planned seismic program is also provided.

(a) Summary of Potential Effects of Airgun Sounds

The effects of sounds from airguns could 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; Southall et al. 2007). Permanent hearing impairment, in the unlikely event that it occurred, would constitute injury, but temporary threshold shift (TTS) is not an injury (Southall et al. 2007). Although the possibility cannot be entirely excluded, it is unlikely that the project would result in any cases of temporary or especially permanent hearing impairment, or any significant non-auditory physical or physiological effects. Some behavioral disturbance is expected, but this would be localized and short-term.

***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 Appendix B (3). 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 B (5). 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 usually seem to be more tolerant of exposure to airgun pulses than are cetaceans, with the relative responsiveness of baleen and toothed whales being variable. During active seismic surveys, sea turtles typically do not show overt reactions to airgun pulses.

***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 on this. Because of the intermittent nature and low duty cycle of seismic pulses, animals can emit and receive sounds in the relatively quiet intervals between pulses. However, in exceptional situations, reverberation occurs for much or all of the interval between pulses (e.g., Simard et al. 2005; Clark and Gagnon 2006) which could mask calls. Some baleen and toothed whales are known to continue calling in the presence of seismic pulses, and their calls usually 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; Holst et al. 2005a,b, 2006). In the northeast Pacific Ocean, blue whale calls have been recorded during a seismic survey off Oregon (McDonald et al. 1995). Among odontocetes, there has been one report that sperm whales ceased calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994), but more recent studies found that they continued calling in the presence of seismic pulses (Madsen et al. 2002; Tyack et al. 2003; Smultea et al. 2004; Holst et al. 2006; Jochens et al. 2006). 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; Potter et al. 2007). The sounds important to small odontocetes are predominantly at much higher frequencies than are the dominant components of airgun sounds, thus limiting the potential for masking. In general, masking effects of seismic pulses are expected to be minor, given the normally intermittent nature of seismic pulses. Masking effects on marine mammals are discussed further in Appendix B (4). We are not aware of any information concerning masking of hearing in sea turtles.

***Disturbance Reactions*.—**Disturbance includes a variety of effects, including subtle to conspicuous changes in behavior, movement, and displacement. Based on NMFS (2001, p. 9293), NRC (2005), and Southall et al. (2007), 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 (Richardson et al. 1995; Wartzok et al. 2004; Southall et al. 2007). 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 population. 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 would be present within a particular distance of industrial activities and exposed to a particular level of industrial sound. In most cases, this approach likely overestimates the numbers of marine mammals that would be 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 primarily on behavioral observations of a few 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, small toothed whales, and sea otters, but for many species there are no data on responses to marine seismic surveys.

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 B (5), 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 cases 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 shown that seismic pulses with received levels of 160–170 dB re 1 μPa_{rms} seem to cause obvious avoidance behavior in a substantial fraction of the animals exposed (Richardson et al. 1995). In many areas, seismic pulses from large arrays of airguns diminish to those levels at distances ranging from 4 to 15 km from the source. A substantial proportion of the baleen whales within those distances may show avoidance or other strong behavioral reactions to the airgun array. Subtle behavioral changes sometimes become evident at somewhat lower received levels, and studies summarized in Appendix B (5) 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, on summer feeding grounds, and on Angolan winter breeding grounds; 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 $\mu Pa \cdot m_{p-p}$. McCauley et al. (1998) documented that avoidance reactions began at 5–8 km from the array, and that those reactions kept most pods ~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 more sensitive resting pods of cow-calf 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. The mean received level for initial avoidance of an approaching airgun was 140 dB re 1 μPa_{rms} for humpback pods containing females, and at the mean closest point of approach (CPA) distance the received level was 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 of 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 and subject to alternative explanations (IAGC 2004). Also, the evidence was not consistent with subsequent results from the same area of Brazil (Parente et al. 2006), or with 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 2007b:236).

There are no data on reactions of *right whales* to seismic surveys, but results from the closely-related *bowhead whale* show that their responsiveness can be quite variable depending on their activity (migrating vs. feeding). 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 at received sound levels of around 120–130 dB re 1 µPa$_{rms}$ [Miller et al. 1999; Richardson et al. 1999; see Appendix B (5)]. However, more recent research on bowhead whales (Miller et al. 2005; Harris et al. 2007) corroborates earlier evidence that, during the summer feeding season, bowheads are not as sensitive to seismic sources. Nonetheless, subtle but statistically significant changes in surfacing–respiration–dive cycles were evident upon statistical analysis (Richardson et al. 1986). In summer, bowheads typically begin to show avoidance reactions at received levels of about 152–178 dB re 1 µPa$_{rms}$ (Richardson et al. 1986, 1995; Ljungblad et al. 1988; Miller et al. 2005).

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 stopped 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 re 1 µPa$_{rms}$. Those findings were generally consistent with the results of experiments conducted on larger numbers of gray whales that were migrating along the California coast (Malme et al. 1984; Malme and Miles 1985), and western Pacific gray whales feeding off Sakhalin Island, Russia (Würsig et al. 1999; Gailey et al. 2007; Johnson et al. 2007; Yazvenko et al. 2007a,b), along with data on gray whales off British Columbia (Bain and Williams 2006).

Various species of *Balaenoptera* (blue, sei, fin, and minke whales) have occasionally been reported in areas ensonified by airgun pulses (Stone 2003; MacLean and Haley 2004; Stone and Tasker 2006). Sightings by observers on seismic vessels off the United Kingdom from 1997 to 2000 suggest that, during times of good sightability, sighting rates for mysticetes (mainly fin and sei whales) were similar when large arrays of airguns were shooting vs. silent (Stone 2003; Stone and Tasker 2006). However, these whales tended to exhibit localized avoidance, remaining significantly further (on average) from the airgun array during seismic operations compared with non-seismic periods (Stone and Tasker 2006). In a study off Nova Scotia, Moulton and Miller (2005) found little difference in sighting rates (after accounting for water depth) 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. Similarly, ship-based monitoring studies of blue, fin, sei and minke whales offshore of Newfoundland (Orphan Basin and Laurentian Sub-basin) found no more than small differences in sighting rates and swim directions during seismic vs. non-seismic periods (Moulton et al. 2005, 2006a,b).

Data on short-term reactions by cetaceans to impulsive noises are not necessarily indicative of long-term or biologically significant effects. It is not known whether impulsive sounds affect reproductive rate or distribution and habitat use in subsequent days or years. However, gray whales have continued to migrate annually along the west coast of North America with substantial increases in the population over recent years, 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 2008). The western Pacific gray whale population did not seem affected by a seismic survey in its feeding ground during a previous year (Johnson et al. 2007). Similarly, bowhead whales have continued to travel to the eastern Beaufort Sea each summer, and their numbers have increased notably, despite seismic exploration in their summer and autumn range for many years (Richardson et al. 1987; Angliss and Outlaw 2008).

Toothed Whales

Little systematic information is available about reactions of toothed whales to noise pulses. Few studies similar to the more extensive baleen whale/seismic pulse work summarized above and (in more detail) in Appendix B have been reported for toothed whales. However, there are recent systematic studies on sperm whales (Jochens et al. 2006; Miller 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; Moulton and Miller 2005; Bain and Williams 2006; Holst et al. 2006; Stone and Tasker 2006; Potter et al. 2007; Weir 2008).

Seismic operators and marine mammal observers on seismic vessels regularly see dolphins and other small toothed whales near operating airgun arrays, but in general there is a tendency for most delphinids to show some avoidance of operating seismic vessels (e.g., Goold 1996a,b,c; Calambokidis and Osmek 1998; Stone 2003; Moulton and Miller 2005; Holst et al. 2006; Stone and Tasker 2006; Weir 2008). Some dolphins 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 (e.g., Moulton and Miller 2005). Nonetheless, small toothed whales more often tend to head away, or to maintain a somewhat greater distance from the vessel, when a large array of airguns is operating than when it is silent (e.g., Stone and Tasker 2006; Weir 2008). In most cases the avoidance radii for delphinids appear to be small, on the order of 1 km less, and some individuals show no apparent avoidance. The beluga is a species that (at least at times) shows long-distance avoidance of seismic vessels. Aerial surveys conducted in the southeastern Beaufort Sea during summer found that sighting rates of beluga whales were significantly lower at distances 10–20 km compared with 20–30 km from an operating airgun array, and observers on seismic boats in that area rarely see belugas (Miller et al. 2005; Harris et al. 2007).

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). However, the animals tolerated high received levels of sound before exhibiting aversive behaviors.

Results for porpoises depend on species. The limited available data suggest that harbor porpoises show stronger avoidance of seismic operations than do Dall's porpoises (Stone 2003; MacLean and Koski 2005; Bain and Williams 2006; Stone and Tasker 2006). Dall's porpoises seem relatively tolerant of airgun operations (MacLean and Koski 2005; Bain and Williams 2006), although they too have been observed to avoid large arrays of operating airguns (Calambokidis and Osmek 1998; Bain and Williams 2006). This apparent difference in responsiveness of these two porpoise species is consistent with their relative responsiveness to boat traffic and some other acoustic sources (Richardson et al. 1995; Southall et al. 2007).

Most studies of sperm whales exposed to airgun sounds indicate that the sperm whale shows considerable tolerance of airgun pulses (e.g., Stone 2003; Moulton et al. 2005, 2006a; Stone and Tasker 2006; Weir 2008). In most cases the whales do not show strong avoidance, and they continue to call (see Appendix B for review). However, controlled exposure experiments in the Gulf of Mexico indicate that foraging behavior was altered upon exposure to airgun sound (Jochens et al. 2006).

There are almost no specific data on the behavioral reactions of beaked whales to seismic surveys. However, northern bottlenose whales continued to produce high-frequency clicks when exposed to sound pulses from distant seismic surveys (Laurinolli and Cochrane 2005; Simard et al. 2005). Most beaked whales tend to avoid approaching vessels of other types (e.g., Würsig et al. 1998). They may also dive for an extended period when approached by a vessel (e.g., Kasuya 1986). Thus, it is likely that beaked whales would also show strong avoidance of an approaching seismic vessel, although this has not been documented explicitly.

There are increasing indications that some beaked whales tend to strand when naval exercises involving mid-frequency sonar operation are ongoing nearby (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; NOAA and USN 2001; Jepson et al. 2003; Hildebrand 2005; 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 or other physiological effects may also be a involved. Whether beaked whales would ever react similarly to seismic surveys is unknown (see "Strandings and Mortality", below). Seismic survey sounds are quite different from those of the sonars in operation during the above-cited incidents.

Odontocete reactions to large arrays of airguns are variable and, at least for delphinids and Dall's porpoises, seem to be confined to a smaller radius than has been observed for the more responsive of the mysticetes, belugas, and harbor porpoises (Appendix B). A ≥170 dB re 1 μPa disturbance criterion (rather than ≥160 dB) is considered appropriate for delphinids (and pinnipeds), which tend to be less responsive than the more responsive cetaceans.

Pinnipeds

Pinnipeds are not likely to show a strong avoidance reaction to the airgun array. 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 B (5). In the Beaufort Sea, some ringed seals avoided an area of 100 m to (at most) a few hundred meters around seismic vessels, but many seals remained within 100–200 m of the trackline as the operating airgun array passed by (e.g., Harris et al. 2001; Moulton and Lawson 2002; Miller et al. 2005). Ringed seal sightings averaged somewhat farther away from the seismic vessel when the airguns were operating than when they were not, but the difference was small (Moulton and Lawson 2002). Similarly, in Puget Sound, sighting distances for harbor seals and California sea lions tended to be larger when airguns were operating (Calambokidis and Osmek 1998).

Previous telemetry work suggests that avoidance and other behavioral reactions may be stronger than evident to date from visual studies (Thompson et al. 1998). Nonetheless, 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.

Sea Turtles

The limited available data indicate that sea turtles will hear airgun sounds and sometimes exhibit localized avoidance (see Appendix C). Based on available data, it is likely that sea turtles will exhibit behavioral changes and/or avoidance within an area of unknown size near a seismic vessel (e.g., Holst et al. 2005a, 2006; Holst and Smultea 2008). Observed responses of sea turtles to airguns are reviewed in Appendix C. 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.

Additional details on the behavioral reactions (or the lack thereof) by all types of marine mammals to seismic vessels can be found in Appendix B (5). Corresponding details for sea turtles can be found in Appendix C.

Hearing Impairment and Other Physical Effects.—Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds, and TTS has been demonstrated and studied in certain captive odontocetes and pinnipeds exposed to strong sounds (reviewed in Southall et al. 2007). However, there has been no specific documentation of TTS let alone permanent hearing damage, i.e., permanent threshold shift (PTS), in free-ranging marine mammals exposed to sequences of airgun pulses during realistic field conditions. Current NMFS policy regarding exposure of marine mammals to high-level sounds is that cetaceans and pinnipeds should not be exposed to impulsive sounds with received levels ≥180 and 190 dB re 1 μPa_{rms}, respectively (NMFS 2000). Those criteria have been used in establishing the exclusion (=shut-down) zones planned for the proposed seismic survey. However, those criteria were established before there was any information about minimum received levels of sounds necessary to cause auditory impairment in marine mammals. As discussed in Appendix B (6) and summarized here,

- 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.
- TTS is not injury and does not constitute "Level A harassment" in U.S. 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. The actual PTS threshold is likely to be well above the level causing onset of TTS (Southall et al. 2007).

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. Preliminary information about this process, and about the possible structure of the new criteria, was given by Wieting (2004) and NMFS (2005). Detailed recommendations for new science-based noise exposure criteria for marine mammals, frequency-weighting procedures, and related matters were published recently (Southall et al. 2007).

Several aspects of the planned monitoring and mitigation measures for this project 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 (see § II, "Monitoring and Mitigation Measures"). In addition, many cetaceans and (to a limited degree) pinnipeds and sea turtles show some avoidance of the area where received levels of airgun sound are high enough such that hearing impairment could potentially occur. 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 might (in theory) 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 transient 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 unlikely that any effects of these types would occur during the present project given the brief duration of exposure of any given mammal, the deep water in the study area, and the planned monitoring and mitigation measures (see below). The following subsections discuss in somewhat more detail the possibilities of TTS, 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. Available data on TTS in marine mammals are summarized in Southall et al. (2007).

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 ~196–201 dB re 1 μPa_{rms}) in order to produce brief, mild TTS[2]. Exposure to several strong seismic pulses that each have received levels near 190 dB re 1 μPa_{rms} might result in cumulative exposure of ~186 dB SEL and thus 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, flat-weighted) would be expected to be ≥190 dB re 1 μPa_{rms} are estimated in Table 1. Levels ≥190 dB re 1 μPa_{rms} are

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[2] If the low frequency components of the watergun sound used in the experiments of Finneran et al. (2002) are downweighted as recommended by Miller et al. (2005) and Southall et al. (2007) using their M_{mf}-weighting curve, the effective exposure level for onset of mild TTS was 183 dB re 1 $\mu Pa^2 \cdot s$ (Southall et al. 2007).

expected to be restricted to radii no more than 340 m (Table 1). For an odontocete closer to the surface, the maximum radius with ≥190 dB re 1 μPa_{rms} would be smaller.

The above TTS information for odontocetes is derived from studies on the bottlenose dolphin and beluga. There is no published TTS information for other types of cetaceans. However, preliminary evidence from a harbor porpoise exposed to airgun sound suggests that its TTS threshold may have been lower (Lucke et al. 2007).

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 assumed to be 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 (Southall et al. 2007). In any event, no cases of TTS are expected given three considerations: (1) the low abundance of baleen whales in the planned study area at the time of the survey; (2) the strong likelihood that baleen whales would avoid the approaching airguns (or vessel) before being exposed to levels high enough for TTS to occur; 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. Initial evidence from more prolonged (non-pulse) exposures suggested that some pinnipeds (harbor seals in particular) incur TTS at somewhat lower received levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001). The TTS threshold for pulsed sounds has been indirectly estimated as being an SEL of ~171 dB re 1 $\mu Pa^2 \cdot s$ (Southall et al. 2007), which would be equivalent to a single pulse with received level ~181–186 dB re 1 $\mu Pa_{rms,}$ or a series of pulses for which the highest rms values are a few dB lower. Corresponding values for California sea lions and northern elephant seals are likely to be higher (Kastak et al. 2005).

NMFS (1995, 2000) concluded that cetaceans and pinnipeds should not be exposed to pulsed underwater noise at received levels exceeding 180 and 190 dB re 1 μPa_{rms}, respectively. Those sound levels are ***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 and in Southall et al. (2007), data that are now available imply that TTS is unlikely to occur in most odontocetes (and probably mysticetes as well) unless they are exposed to a sequence of several airgun pulses stronger than 190 dB re 1 μPa_{rms}. On the other hand, for the harbor seal and any species with similarly low TTS thresholds (possibly including the harbor porpoise), TTS may occur upon exposure to one or more airgun pulses whose received level equals the NMFS "do not exceed" value of 190 dB re 1 μPa_{rms}. That criterion corresponds to a single-pulse SEL of 175–180 dB re 1 $\mu Pa^2 \cdot s$ in typical conditions, whereas TTS is suspected to be possible (in harbor seals) with a cumulative SEL of ~171 dB re 1 $\mu Pa^2 \cdot s$.

Permanent Threshold Shift

When PTS occurs, there is physical damage to the sound receptors in the ear. In severe cases, there can be total or partial deafness, while in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges (Kryter 1985).

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 at least mild TTS, there has been further speculation about the possibility that some individuals occurring very close to airguns might incur PTS (Richardson et al. 1995, p. 372*ff*). Single or occasional occurrences of mild TTS are not indicative of permanent auditory damage.

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 B (6). 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 >6 dB (Southall et al. 2007). On an SEL basis, Southall et al. (2007:441-4) estimated that received levels would need to exceed the TTS threshold by at least 15 dB for there to be risk of PTS. Thus, for cetaceans they estimate that the PTS threshold might be an M-weighted SEL (for the sequence of received pulses) of ~198 dB re 1 $\mu Pa^2 \cdot s$ (15 dB higher than the TTS threshold for an impulse), where the SEL value is cumulated over the sequence of pulses. Additional assumptions had to be made to derive a corresponding estimate for pinnipeds, as the only available data on TTS-thresholds in pinnipeds pertain to non-impulse sound. Southall et al. (2007) estimate that the PTS threshold could be a cumulative M_{pw}-weighted SEL of ~186 dB re 1 $\mu Pa^2 \cdot s$ in the harbor seal exposed to impulse sound. The PTS threshold for the California sea lion and northern elephant seal the PTS threshold would probably be higher, given the higher TTS thresholds in those species.

Southall et al. (2007) also note that, regardless of the SEL, there is concern about the possibility of PTS if a cetacean or pinniped received one or more pulses with peak pressure exceeding 230 or 218 dB re 1 µPa (peak), respectively. A peak pressure of 230 dB re 1 µPa (3.2 bar·m, 0-pk) would only be found within a few meters of the largest (360-in^3) airguns in the planned airgun array (Caldwell and Dragoset 2000). A peak pressure of 218 dB re 1 µPa could be received somewhat farther away; to estimate that specific distance, one would need to apply a model that accurately calculates peak pressures in the near-field around an array of airguns.

Given the higher level of sound necessary to cause PTS as compared with TTS, it is considerably less likely that PTS would occur. 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 or approaching the "exclusion zones", will further reduce the probability of exposure of marine mammals to sounds strong enough to induce PTS.

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). However, explosives are no longer used for marine seismic research or commercial seismic surveys, and have been replaced entirely by airguns or related non-explosive pulse generators. Airgun pulses are less energetic and have slower rise times, and there is no specific evidence 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 and, in one case, an L-DEO seismic survey (Malakoff 2002; Cox et al. 2006), 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 (e.g., Hildebrand 2005; Southall et al. 2007). Appendix B (6) provides additional details.

Specific sound-related processes that lead to strandings and mortality are not well documented, but may include (1) swimming in avoidance of a sound into shallow water; (2) a change in behavior (such as a change in diving behavior) that might contribute to tissue damage, gas bubble formation, hypoxia, cardiac arrhythmia, hypertensive hemorrhage or other forms of trauma; (3) a physiological change such as a vestibular response leading to a behavioral change or stress-induced hemorrhagic diathesis, leading in turn to tissue damage; and (4) tissue damage directly from sound exposure, such as through acoustically mediated bubble formation and growth or acoustic resonance of tissues. There are increasing indications that gas-bubble disease (analogous to "the bends"), induced in supersaturated tissue by a behavioral response to acoustic exposure, could be a pathologic mechanism for the strandings and mortality of some deep-diving cetaceans exposed to sonar. However, the evidence for this remains circumstantial and associated with exposure to naval mid-frequency sonar, not seismic surveys (Cox et al. 2006; Southall et al. 2007).

Seismic pulses and mid-frequency sonar signals are quite different, and some mechanisms by which sonar sounds have been hypothesized to affect beaked whales are unlikely to apply to airgun pulses. Sounds produced by airgun arrays are broadband impulses with most of the energy below 1 kHz. Typical military mid-frequency sonars emit non-impulse sounds at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time. A further difference between seismic surveys and naval exercises is that naval exercises can involve sound sources on more than one vessel. 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 signals can, in special circumstances, lead (at least indirectly) to physical damage and mortality (e.g., Balcomb and Claridge 2001; NOAA and USN 2001; Jepson et al. 2003; Fernández et al. 2004, 2005; Hildebrand 2005; Cox et al. 2006) 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 or deaths at sea as a result of exposure to seismic surveys, but a few cases of strandings in the general area where a seismic survey was ongoing have led to speculation concerning a possible link between seismic surveys and strandings. • Suggestions that there was a link between seismic surveys and strandings of humpback whales in Brazil (Engel et al. 2004) were not well founded (IAGC 2004; IWC 2007b). • In Sept. 2002, there was a stranding of two Cuvier's beaked whales in the Gulf of California, Mexico, when the L-DEO vessel R/V *Maurice Ewing* was operating a 20-airgun, 8490-in^3 airgun array in the general area. The link between the stranding and the seismic surveys was inconclusive and not based on any physical evidence (Hogarth 2002; Yoder 2002). Nonetheless, the Gulf of California incident plus the beaked whale strandings near naval exercises involving use of mid-frequency sonar suggests a need for caution in conducting seismic surveys in areas occupied by beaked whales until more is known about effects of seismic surveys on those species (Hildebrand 2005). No injuries of beaked whales are anticipated during the proposed study because of (1) the high likelihood that any beaked whales nearby would avoid the approaching vessel before being exposed to high sound levels, (2) the proposed monitoring and mitigation measures, and (3) differences between the sound sources operated by L-DEO and those involved in the naval exercises associated with strandings.

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, resonance, and other types of organ or tissue damage (Cox et al. 2006; Southall et al. 2007). Studies examining such effects are limited. However, resonance (Gentry 2002) and direct noise-induced bubble formation (Crum et al. 2005) are not expected in the case of an impulsive source like an airgun array. If seismic surveys disrupt diving patterns of deep-diving species, this might perhaps result in bubble formation and a form of "the bends", as speculated to occur in beaked whales exposed to sonar. However, there is no specific evidence of this upon exposure to airgun pulses.

In general, very little is known about the potential for seismic survey sounds (or other types of strong underwater sounds) to cause non-auditory physical effects in marine mammals. Such effects, if they occur at all, would presumably be limited to short distances and to activities that extend over a prolonged period. The available data do not allow identification of a specific exposure level above which non-auditory effects can be expected (Southall et al. 2007), or any 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 non-auditory physical effects. Also, 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 by sea turtles extends from roughly 250–300 Hz to 500–700 Hz. Sensitivity deteriorates as one moves away from that 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. 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. TTS apparently occurred in loggerhead turtles exposed to many pulses from a single airgun ≤65 m away (see Moein et al. [1994] and Appendix C). 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; Holst and Smultea 2008). 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 MMOs stationed on the *Langseth* will also watch for sea turtles, and airgun operations will be shut down if a turtle enters the designated exclusion zone.

(b) Possible Effects of Multibeam Echosounder Signals

The Simrad EM120 12-kHz MBES will be operated from the source vessel during the planned study. Information about this equipment was provided in § II. Sounds from the MBES are very short pulses, occurring for 2–15 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 near 12 kHz, and the maximum source level is 242 dB re 1 $\mu Pa_{rms} \cdot m$ (rms). 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 2–15 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 receive the multiple pulses that might result in sufficient exposure to 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. more downward for the MBES. The area of possible influence of the MBES 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 naval sonar. 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. Possible effects of an MBES on marine mammals are outlined below.

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

Behavioral Responses.—Behavioral reactions of free-ranging marine mammals to sonars, echosounders, 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 reacted by orienting slightly away from the source and being deflected from their course by ~200 m (Frankel 2005). When a 38-kHz echosounder and a 150-kHz acoustic Doppler current profiler were transmitting during studies in the Eastern Tropical Pacific, baleen whales showed no significant responses, while spotted and spinner dolphins were detected slightly more often and beaked whales less often during visual surveys (Gerrodette and Pettis 2005).

Captive bottlenose dolphins and a white whale exhibited changes in behavior when exposed to 1-s tonal signals 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 duration as compared with those from an MBES.

Very few data are available on the reactions of pinnipeds to sonar sounds at frequencies similar to those used during seismic operations. Hastie and Janik (2007) conducted a series of behavioral response tests on two captive gray seals to determine their reactions to underwater operation of a 375-kHz multibeam imaging sonar that included significant signal components down to 6 kHz. Results indicated that the two seals reacted to the sonar signal by significantly increasing their dive durations. Because of 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.

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·m$_{rms}$ (see § II), the received level for an animal within the MBES beam 100 m below the ship would be ~202 dB re 1 μPa$_{rms}$, assuming 40 dB of spreading loss over 100 m (circular spreading). Given the narrow beam, only one pulse is likely to be received by a given animal as the ship passes overhead. The received energy level from a single pulse of duration 15 ms would be about 184 dB re 1 μPa^2·s, i.e., 202 dB + 10 log (0.015 s). That is below the TTS threshold for a cetacean receiving a single non-impulse sound (195 dB re 1 μPa^2·s) and even further below the anticipated PTS threshold (215 dB re 1 μPa^2·s) (Southall et al. 2007). In contrast, an animal that was only 10 m below the MBES when a ping is emitted would be expected to receive a level ~20 dB higher, i.e., 204 dB re 1 μPa^2·s in the case of the EM120. That animal might incur some TTS (which would be fully recoverable), but the exposure would still be below the anticipated PTS threshold for cetaceans. As noted by Burkhardt et al. (2007, 2008), cetaceans are very unlikely to incur PTS from operation of scientific sonars on a ship that is underway

In the harbor seal, the TTS threshold for non-impulse sounds is about 183 dB re 1 μPa^2·s, as compared with ~195 re 1 μPa^2·s in odontocetes (Kastak et al. 2005; Southall et al. 2007). TTS onset occurs at higher received energy levels in the California sea lion and northern elephant seal than in the harbor seal. A harbor seal as much as 100 m below the *Langseth* could receive a single MBES pulse with received energy level of ≥184 dB re 1 μPa^2·s (as calculated in the toothed whale subsection above) and thus could incur slight TTS. Species of pinnipeds with higher TTS thresholds would not incur TTS unless they were closer to the transducers when a sonar ping was emitted. However, the SEL criterion for PTS in pinnipeds (203 dB re 1 μPa^2·s) might be exceeded for a ping received within a few meters of the transducers, although the risk of PTS is higher for certain species (e.g., harbor seal). Given the intermittent nature of the signals and the narrow MBES beam, only a small fraction of the pinnipeds below (and close to) the ship would receive a pulse as the ship passed overhead.

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

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

An SBP will also be operated from the source vessel during the planned study. Details about this equipment were provided in § II. Sounds from the SBP are very short pulses, occurring for 1–4 ms once every second. Most of the energy in the sound pulses emitted by the SBP is at 3.5 kHz, and the beam is directed downward. The sub-bottom profiler on the *Langseth* has a maximum source level of 204 dB re 1 μPa·m (see § II). Kremser et al. (2005) noted that the probability of a cetacean swimming through the area of exposure when a bottom profiler emits a pulse is small—even for an SBP more powerful than that on the *Langseth*—if the animal was in the area, it would have to pass the transducer at close range and 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 the directionality of the signal and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of most baleen whales, the SBP 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 considerably weaker than those from the MBES. Therefore, behavioral responses are not expected unless marine mammals are very close to the source.

Hearing Impairment and Other Physical Effects.—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 survey 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. Also, the frequency of the SBP sounds is higher than the frequency range of best hearing by sea turtles.

(d) Possible Effects of Acoustic Release Signals

The acoustic release transponder used to communicate with the OBSs uses frequencies of 9–13 kHz. These signals will be used very intermittently. It is unlikely that the acoustic release signals would have a significant effect on marine mammals or sea turtles through masking, disturbance, or hearing impairment. Any effects likely would be negligible given the brief exposure at presumable low levels.

(2) Mitigation Measures

Several mitigation measures are built into the proposed seismic survey 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 to complement visual monitoring (when practicable), power downs (or if necessary shut downs) when mammals or turtles are detected in or about to enter designated exclusion zones. 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, as is the relatively wide spacing of the airgun shots during the planned project (400 m or 180 s).

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 Could 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 the number of potential exposures to various received sound levels and present estimates of the numbers of marine mammals that could be affected during the proposed ELSC seismic program. The estimates are based on a consideration of the number of marine mammals that could be disturbed appreciably by operations with the 36-airgun array to be used during ~3650 km of seismic surveys (plus an additional 25% contingency) in the Lau Basin. The sources of distributional and numerical data used in deriving the estimates are described in the next subsection.

It is assumed that, during simultaneous operations of the airgun array and the other sources, any marine mammals close enough to be affected by the MBES and SBP would already be affected by the airguns. However, whether or not the airguns are operating simultaneously with the other sources, marine mammals are expected to exhibit no more than short-term and inconsequential responses to the MBES and SBP given their characteristics (e.g., narrow downward-directed beam) and other considerations described in § II and IV(1)(b and c), 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"

Few systematic aircraft- or ship-based surveys have been conducted for marine mammals in offshore waters of the South Pacific Ocean, and the species of marine mammals that occur there are not well known. The density estimates used in this assessment are from one of Longhurst's (2007) biogeographic provinces north of the survey area that is oceanographically similar to the province in which the seismic activities will take place. Some of the surveys conducted by Ferguson and Barlow (2001) in the ETP during 1986–1996 are in Longhurst's (2007) North Pacific Tropical Gyre Province, which is similar to the SPSG, in which the proposed seismic survey will occur. The similarities are (1) they are both low-nitrate, low-chlorophyll regions of the oceans with numerous coral reefs, and (2) upwelled nutrients by islands are used by corals and do not increase pelagic productivity. Ferguson and Barlow (2001) calculated cetacean densities in 5º x 5º blocks in the ETP from the coast of North America to as far west as 155ºW. We used the data from Blocks 105, 106, 111, 112, and 124–131, which are bounded by 10ºN, 20ºN, 115ºW, and 155ºW, to compute the species group densities in Table 3.

The species assemblages that occur in the SWPO will be different than those sighted during the surveys in the ETP. However, the overall abundance of species groups with generally similar habitat requirements are expected to be roughly similar. Thus, we used the data from the appropriate part of the ETP to estimate the densities of beaked whales, delphinids, small whales, and mysticetes in the SWPO. Table 3 gives the average and maximum (see further, below) densities for those groups corrected for effort, based on the densities reported in Ferguson and Barlow (2001). Those densities had been corrected, by the original authors, for both detectability bias and availability bias. Detectability bias is associated with diminishing sightability with increasing lateral distance from the track line [$f(0)$]. Availability bias refers to the fact that there is less-than 100% probability of sighting an animal that is present along the survey track line, and it is measured by $g(0)$.

TABLE 3. Densities of cetacean species groups sighted during selected surveys in the ETP during 1986–1996, and estimated densities of species expected to occur in the SPSG Province of Longhurst (2007), during the L-DEO seismic survey in the Lau Basin during January–February 2009. Densities in bold are derived from data in Ferguson and Barlow (2001), as described in the text. Densities are corrected for *f*(0) and *g*(0). Species listed as *endangered* or *threatened* under the ESA are in italics.

				Estimated density in Lau Basin (#/1000 km^2)	
Suborder	**Family**	**Species**	**Relative abundance**	**Best Estimate**	**Maximum Estimate**
Mysticeti	Balaenidae	Pygmy right whale	1	0.05	0.16
	Balaenopteridae	*Humpback whale*	*1*	*0.05*	*0.16*
		Minke whale	1	0.05	0.16
		Dwarf minke whale	1	0.05	0.16
		Bryde's whale	5	0.23	0.79
		Sei whale	*1*	*0.05*	*0.16*
		Fin whale	*1*	*0.05*	*0.16*
		Blue whale	*1*	*0.05*	*0.16*
		All mysticetes		**0.55**	**1.90**
Odontoceti	Physeteridae	*Sperm whale*	*10*	***0.34***	***1.27***
		Pygmy sperm whale	2	5.45	20.15
		Dwarf sperm whale	2	5.45	20.15
		***Kogia* spp.**		**10.90**	**40.31**
	Ziphiidae	Cuvier's beaked whale	5	0.98	2.27
		Southern bottlenose whale	0	0.00	0.00
		Longman's beaked whale	2	0.39	0.91
		Blainville's beaked whale	5	0.98	2.27
		Ginkgo-toothed beaked whale	2	0.39	0.91
		All Beaked whales		**2.75**	**6.35**
	Delphinidae	Rough-toothed dolphin	5	48.91	94.11
		Bottlenose dolphin	1	9.78	18.82
		Pantropical spotted dolphin	5	48.91	94.11
		Spinner dolphin	10	97.82	188.21
		Striped dolphin	1	9.78	18.82
		Fraser's dolphin	3	29.35	56.46
		Common dolphin	1	9.78	18.82
		Risso's dolphin	1	9.78	18.82
		All Dolphins		**264.11**	**508.17**
		Melon-headed whale	5	2.48	8.65
		Pygmy killer whale	1	0.50	1.73
		False killer whale	3	1.49	5.19
		Killer whale	2	0.99	3.46
		Short-finned pilot whale	2	0.99	3.46
		All small whales		**6.45**	**22.50**

Table 3 also lists the species in each species group that are expected to occur in the offshore SWPO, and their estimated relative abundance within a group on a scale of 1 (rare) to 10 (abundant), based on information from near the proposed seismic survey area and general information on the species' distributions and habitat preferences. The status and relative abundance of each species are described in detail above in §III. We estimated the density of each species expected to occur in the survey area from the ETP densities for species groups in Table 3 by multiplying their relative abundance divided by the relative abundance for all species in the species group times the ETP density for the species group.

It should be noted that the following estimates of exposures to various sound levels assume that the surveys will be completed; in fact, the planned number of line-kilometers has been increased by 25% to accommodate lines that may need to be repeated, equipment testing, etc. As is typical during offshore ship surveys, inclement weather and equipment malfunctions are likely to cause delays and may limit the number of useful line-kilometers of seismic operations that can be undertaken. Furthermore, any marine mammal sightings within or near the designated exclusion zones will result in the power or shut down of seismic operations as a mitigation measure. Thus, the following estimates of the numbers of marine mammals potentially exposed to 160- or 170-dB re 1 μPa_{rms} sounds are precautionary, and probably overestimate the actual numbers of marine mammals that might be involved. These estimates assume that there will be no weather, equipment, or mitigation delays, which is highly unlikely.

As noted above, there is some uncertainty about the representativeness of the data and the assumptions used in the calculations below. However, the approach used here is believed to be the best available approach. Also, to provide some allowance for these uncertainties "maximum estimates" as well as "best estimates" of the densities present and numbers potentially affected have been derived. Best estimates are based on average densities from all survey blocks weighted by effort, whereas maximum estimates are based on the highest densities in any one block [based on data from Ferguson and Barlow (2001)]. The estimated numbers of individuals potentially exposed are presented in Table 4 based on the 160-dB re 1 μPa_{rms} criterion for all cetaceans and pinnipeds, and the 170-dB re 1 μPa_{rms} criterion for delphinids. It is assumed that marine mammals exposed to airgun sounds that strong might change their behavior sufficiently to be considered "taken by harassment".

(b) Potential Number of Marine Mammals Exposed to Airgun Sounds

Number of Cetaceans that could be Exposed to ≥160 dB.—The number of different individuals that could 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 along with the expected density of animals in the area. The proposed seismic lines run parallel to each other in relatively close proximity; thus, an individual mammal could be exposed numerous times during the survey. The number of possible exposures to airgun sounds with received levels ≥160 dB re 1 μPa_{rms} (including repeated exposures of the same individuals) can be estimated by considering the total marine area that would be within the 160-dB radius around the operating airguns, including areas of overlap. However, it is unlikely that a particular animal would stay in the area during the entire survey. The best estimates in this section are based on the averages of the densities from the appropriate blocks in the 1986–1996 NMFS surveys (as described above), and maximum estimates are based on the highest density among those blocks.

The number of potential exposures and the number of different individuals potentially exposed to ≥160 dB re 1 μPa_{rms} were calculated by multiplying

TABLE 4. Estimates of the possible numbers of marine mammal exposures to the different sound levels, and the numbers of different individuals that might be exposed, during L-DEO's proposed seismic survey in the Lau Basin, SWPO, during January–February 2009. Received levels of airgun sounds are expressed in dB re 1 µPa (rms, averaged over pulse duration), consistent with NMFS' practice. Not all marine mammals will change their behavior when exposed to these sound levels, but some may alter their behavior when levels are lower (see text). Delphinids are unlikely to react to levels below 170 dB. Species in italics are listed under the ESA as *endangered* or *threatened*. The column of numbers in boldface shows the numbers of "takes" for which authorization is requested.

	# Exposures to sound levels ≥160 dB (≥170 dB, Delphinids)		**# Individuals exposed to sound levels ≥160 dB (≥170 dB, Delphinids)**			
Species	**Best Estimate**	**Maximum Estimate**	**Best Estimate**	**% Reg'l Pop'n**	**Maximum Estimate**	**Requested Take Authorization**
Mysticetes						
Balaenidae						
Pygmy right whale	3	10	1	NA	3	**3**
Balaenopteridae						
Humpback whale	*3*	*10*	*1*	*0.01*	*3*	**3**
Minke whale	3	10	1	0	3	**3**
Dwarf minke whale	3	10	1	0	3	**3**
Bryde's whale	15	52	4	0.02	14	**14**
Sei whale	*3*	*10*	*1*	*0.01*	*3*	**3**
Fin whale	*3*	*10*	*1*	*0.03*	*3*	**3**
Blue whale	*3*	*10*	*1*	*0.11*	*3*	**3**
Odontocetes						
Physeteridae						
Sperm whale	*22*	*83*	*6*	*0.03*	*22*	**22**
Pygmy sperm whale	358	1324	96	NA	353	**353**
Dwarf sperm whale	358	1324	96	0.85	353	**353**
Ziphiidae						
Cuvier's beaked whale	65	149	17	0.09	40	**40**
Southern bottlenose whale	0	0	0	0	0	**0**
Longman's beaked whale	26	60	7	NA	16	**16**
Blaineville's beaked whale	65	149	17	NA	40	**40**
Ginkgo-toothed beaked whale	26	60	7	NA	16	**16**
Delphinidae						
Rough-toothed dolphin	3214 (1448)	6184 (2786)	857 (726)	0.59	1649 (1397)	**1649**
Bottlenose dolphin	643 (290)	1237 (557)	171 (145)	0.07	330 (279)	**330**
Pantropical spotted dolphin	3214 (1448)	6184 (2786)	857 (726)	0.07	1649 (1397)	**1649**
Spinner dolphin	6428 (2896)	12367 (5571)	1714 (1452)	0.17	3298 (2794)	**3298**
Striped dolphin	643 (290)	1237 (557)	171 (145)	0.01	330 (279)	**330**
Fraser's dolphin	1928 (869)	3710 (1671)	514 (436)	0.18	990 (838)	**990**
Common dolphin	643 (290)	1237 (557)	171 (145)	0.01	330 (279)	**330**
Risso's dolphin	643 (290)	1237 (557)	171 (145)	0.10	330 (279)	**330**
Melon-headed whale	163 (73)	569 (256)	43 (37)	0.10	152 (128)	**152**
Pygmy killer whale	33 (15)	114 (51)	9 (7)	0.02	30 (26)	**30**
False killer whale	98 (44)	341 (154)	26 (22)	0.07	91 (77)	**91**
Killer whale	65 (29)	227 (102)	17 (15)	0.20	61 (51)	**61**
Short-finned pilot whale	65 (29)	227 (102)	17 (15)	0.01	61 (51)	**61**

[1] Best estimate and maximum estimates of density are from Tables 3 and 4.

[2] Regional population size estimates are from Table 2. NA indicates that regional population estimates are not available.

- the expected species density, either "mean" (i.e., best estimate) or "maximum", times
- the anticipated minimum area to be ensonified to that level during airgun operations including overlap (exposures), or
- the anticipated area to be ensonified to that level during airgun operations excluding overlap (individuals).

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 (or, in the next subsection, 170-dB) buffer (see Table 1) around each seismic line, and then calculating the total area within the buffers. Areas where overlap occurred (because of closely-spaced lines) were included when estimating the number of exposures; areas of overlap were included only once when estimating the number of individuals exposed.

Applying the approach described above, ~17,525 km^2 (including 25% contingency) would be within the 160-dB isopleth on one or more occasions during the survey, whereas 65,710 km^2 is the area ensonified to ≥160 dB when overlap is included. Thus, it is possible that an average individual marine mammal could be exposed up to four times during the survey. Because this approach does not allow for turnover in the mammal populations in the study area during the course of the survey, the actual number of individuals exposed could be underestimated, although the conservative (i.e., probably overestimated) line-kilometer distances used to calculate the area could offset this. Also, 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.

Table 4 shows the best and maximum estimates of the number of exposures and the number of different individual marine mammals that could potentially be exposed to ≥160 dB re 1 μPa_{rms} during the seismic survey if no animals moved away from the survey vessel. The ***Requested Take Authorization***, given in the far right column of Table 4, is based on the maximum estimates rather than the best estimates of the numbers of individuals exposed, because of uncertainties associated with applying density data from one area to another.

The 'best estimate' of the number of individual cetaceans that could be exposed to seismic sounds with received levels ≥160 dB re 1 μPa_{rms} during the proposed survey is 4996 (Table 4). That total includes 11 baleen whales, four of which are considered ***endangered*** under the ESA: one humpback whale (0.01% of the regional population), one blue whale (0.11%), one sei whale (0.01%), and one fin whale (0.03%) (Table 4).

In addition, six sperm whales (also listed as ***endangered under*** the ESA) or 0.03% of the regional population could be exposed during the survey, as well as 48 beaked whales (Table 4). The spinner dolphin is estimated to be the most common species in the area, with a best estimate of 1714 or 0.17% of the regional population exposed to ≥160 dB re 1 μPa_{rms}. However, a more meaningful estimate is the one for sound levels ≥170 dB (see below). The 'Maximum Estimate' column in Table 4 shows an estimated total of 10,173 cetaceans. Again, most of these consist of spinner dolphins. The best estimate of the number of exposures of cetaceans to seismic sounds with received levels ≥160 dB re 1 μPa_{rms} during the survey is 18,734 (Table 4).

Number of Delphinids that could 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 many baleen whales. As summarized in Appendix B (5), 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, the estimates in this subsection 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, but others would not do so even upon exposure to levels somewhat >170 dB.)

The area ensonified by levels ≥170 dB was estimated to be 14,848 km^2 (as described above for levels ≥160 dB), and the estimated area, including overlap, is 29,601 km^2. Thus, an average individual delphinid could be exposed to ≥170 dB twice during the survey. The best and maximum estimates of the numbers of individual delphinids that could be exposed to ≥170 dB during the survey are 4017 and 7879, respectively (Table 4). These values are based on the predicted 170-dB radius around the airgun array to be used during the study, and are considered to be more realistic estimates of the number of individual delphinids that could be affected.

(4) Conclusions re Marine Mammals and Sea Turtles

The proposed seismic survey will involve towing an airgun array that introduces pulsed sounds into the ocean, along with simultaneous operation of an MBES and a SBP. The survey will employ 36-airgun array similar to the airgun arrays used for typical high-energy seismic surveys, but shot intervals will be long (~180 s). The total airgun discharge volume is ~6600 in^3. 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 and c), i.e., sounds are beamed downward, the beam is narrow, and the pulses are extremely short.

(a) Cetaceans

Several species of mysticetes show strong avoidance reactions to seismic vessels at ranges up to 6–8 km and occasionally as far as 20–30 km from the source vessel when medium-large airgun arrays have been used. However, reactions at the longer distances appear to be atypical of most species and situations. If mysticetes are encountered, the numbers estimated to occur within the 160-dB isopleth in the survey area are expected to be low. In addition, the estimated numbers presented in Table 4 are considered overestimates of actual numbers because the predicted 160- and 170-dB radii used here are probably overestimates of the actual 160- and 170-dB radii at deep-water locations such as the present study area (Tolstoy et al. 2004a,b).

Odontocete reactions 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 dolphins are often seen from seismic vessels. In fact, there are documented instances of dolphins approaching active seismic vessels. However, delphinids (along with other cetaceans) sometimes show avoidance responses and/or other changes in behavior when 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 regional population sizes. The best estimate of the number of individuals that would be exposed to sounds ≥160 dB re 1 μPa_{rms} represent, for all species, <1% of the regional population (Table 4).

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 or ≥170 dB) and density criterion used (best or maximum). The requested "take authorization" for each species is based on the estimated maximum number of individuals that could be exposed to ≥160 dB re 1 μPa_{rms}. That figure likely overestimates (in most cases by a large margin) the actual number of animals that will be exposed to and will react to the seismic sounds. The reasons for that conclusion are outlined above. The 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 look outs, ramp ups, and power downs or shut downs when marine mammals are seen within defined ranges, should further reduce short-term reactions, and avoid or 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 occur in the survey area.

(c) Sea Turtles

The proposed activity will occur near some sea turtle nesting beaches, although the closest beaches in Tonga are 42 km away. Green and hawksbill turtles could nest in Tonga as well as Fiji, and leatherbacks are known to nest in Fiji. Thus, these turtles, as well as olive ridley and loggerhead turtles, could be encountered during the proposed survey in the Lau Basin. However, it is anticipated that the proposed seismic survey will have, at most, a short-term effect on behavior and no long-term impacts on individual sea turtles or their populations.

(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 D). 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 they occur) 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. The studies of individual fish have often been on caged fish that were exposed to airgun pulses in situations not representative of an actual seismic survey. 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 issues concern effects on marine fish populations, their viability, and 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.

(a) 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 D). For a given sound to result in hearing loss, the sound must exceed, by some substantial amount, the hearing threshold of the fish for that sound (Popper 2005). The consequences of temporary or permanent hearing loss in individual fish on a fish population are unknown; however, they likely depend 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 papers with proper experimental methods, controls, and careful pathological investigation implicating sounds produced by actual seismic survey airguns in causing 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 fish species from the Mackenzie River Delta. This study found that broad whitefish (*Coregonus nasus*) that received a sound exposure level of 177 dB re 1 $\mu Pa^2 \cdot s$ 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 airguns [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).

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.

(b) 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 D).

(c) 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

(a) Seismic operations

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 E).

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. Benthic invertebrates in the study area are not expected to be affected by seismic operations, as sound levels from the airguns will diminish dramatically by the time the sound reaches the ocean floor more than 1000 m below.

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 E.

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 (J. Payne, DFO research scientist, St. John's, NL, Canada, pers. comm.). 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). 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).

(b) OBS deployment

A total of ~55–64 OBSs will be used during the study (Fig. 2). Two different types of OBSs will be used. The WHOI "D2" OBS has an anchor made of hot-rolled steel with dimensions 2.5 × 30.5 × 38.1 cm. The anchor of the Scripps' LC4x4 OBS consists of a 1-m^2 piece of steel grating. OBS anchors will be left behind upon equipment recovery. Although OBS placement will disrupt a very small area of seafloor habitat and could disturb benthic invertebrates, the impacts are expected to be localized and transitory.

(7) 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 would 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 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.

(8) Cumulative Effects

Cumulative effects refer to the impacts on the environment that result from a combination of past, existing, and reasonably foreseeable 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, when conducted separately or in combination with other activities, could affect marine mammals and sea turtles in the study area.

(a) Shipping, Tourism, and Vessel Noise

Within the waters of Tonga, vessel traffic consists of commercial, sport, and subsistence fishing vessels, other commercial (cargo) vessels, whale watching vessels, and ferries. Only commercial vessels are expected to occur within the offshore study area; subsistence fishing and whale watching generally take place close to shore. Tonga has a narrow export base in agricultural goods including squash, vanilla beans, copra, bananas, coffee, cocoa, ginger, yams, and fish. Tonga imports more commodities than it exports. Imports include fossil fuels, food, machinery, and equipment (CIA 2008). Tonga's merchant marine fleet is comprised of 14 ships (1000 tonnes or over) consisting of one bulk carrier, nine cargo vessels, one liquefied gas vessel, one livestock carrier, one passenger/cargo vessel, and one refrigerated cargo vessel. An inter-island ferry system is also operated by the government. Major ports are located at

Nuku'alofa on the island of Tongatapu and Neiafu on Vava'u in northern Tonga. Smaller ports are located at Pangai and Niuatopuapu.

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 survey area.

Reactions of gray and humpback whales to vessels have been studied, and there is limited information available about the reactions of right whales and rorquals (fin, blue and minke whales). Reactions of humpback whales to boats are variable, ranging from approach to avoidance (Payne 1978; Salden 1993). Baker et al. (1982, 1983) and Baker and Herman (1989) found that humpbacks often move away when vessels are within several kilometers. Humpbacks seem less likely to react overtly when actively feeding than when resting or engaged in other activities (Krieger and Wing 1984, 1986).

Many odontocetes show considerable tolerance of vessel traffic, although they sometimes react at long distances if confined by ice or shallow water, or if previously harassed by vessels, or have had little or no recent exposure to ships (Richardson et al. 1995). Dolphins of many species tolerate or even approach vessels. Some dolphin species approach moving vessels to ride the bow or stern waves (Williams et al. 1992). Killer whales rarely showed avoidance to boats within 400 m (Duffus and Dearden 1993), but when more than one boat was nearby, the whales swam faster, and moved toward less confined waters (Kruse 1991; Williams et al. 2002a,b). Sperm whales can often be approached with small motorized or sailing vessels (Papastavrou et al. 1989), but sometimes avoid outboard-powered whale watching vessels up to 2 km away (J. McGibbon *in* Cawthorn 1992). Resident sperm whales that are repeatedly exposed to small vessels show subtle changes in various measures of behaviour, and transient individuals (which presumably had less exposure to vessels) reacted more strongly (Richter et al. 2003, 2006).

(b) Oil and Gas Industry

The South Pacific region including the proposed study area has not seen large-scale oil and gas activity. Tonga is listed as having zero production of crude oil, natural gas liquids, and refinery processing abilities (EIA 2008). Tonga is a consumer of fossil fuels and imported ~880 barrels/day during 2005 and 2006 (CIA 2008; EIA 2008), but did not import natural gas during those years.

(c) Fisheries

Several fisheries are important components of the Tongan economy. These include commercial fishing for tuna, snapper (and grouper), and harvesting of seaweed (*Cladosiphon* sp.). Tuna are harvested primarily by longliners, and snapper and grouper are harvested using dropline techniques. The commercial fishery occurs on offshore slopes and seamounts (ESCAP 1990 *in* Zann 1994). Subsistence fishing for invertebrates and fish is based on inshore coral reefs and slopes (see Zann 1994). Zann (1994) reported that the annual catch for subsistence is ~3100 tonnes of which most (1920 tonnes) comes from shallow reefs.

The snapper fishery began in 1980 and is significant to the Tongan economy. Much of the snapper harvest is exported by air freight, mainly to Hawaii. Between 1986 to 2006, the number of vessels fishing annually has ranged from 10 in 2000 to 44 in 1988 (Fig. 7; Halafihi 2007). Vessels and recorded catch peaked in the late 1980s and declined through the 1990s, then began to increase again in the 2000s (Fig. 7). Vessels are constructed primarily of wood and range in length from ~8 to 12 m. No current manage-

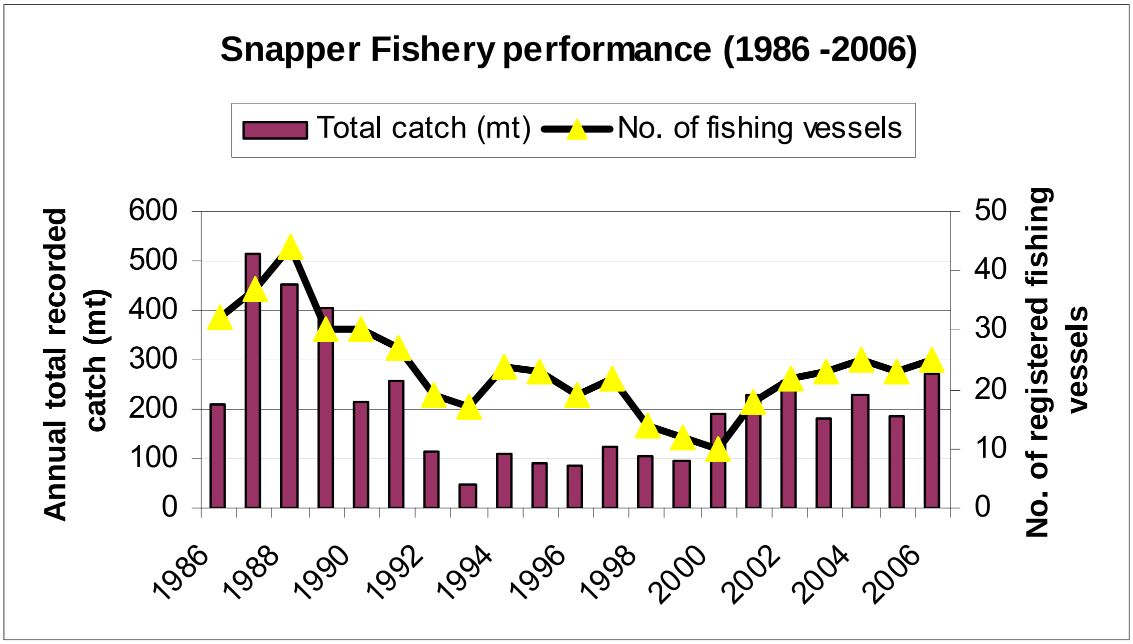

Figure 7. Annual total recorded catch and number of registered fishing vessels involved in the Tongan snapper fishery, 1986–2006 (Halafihi 2007).

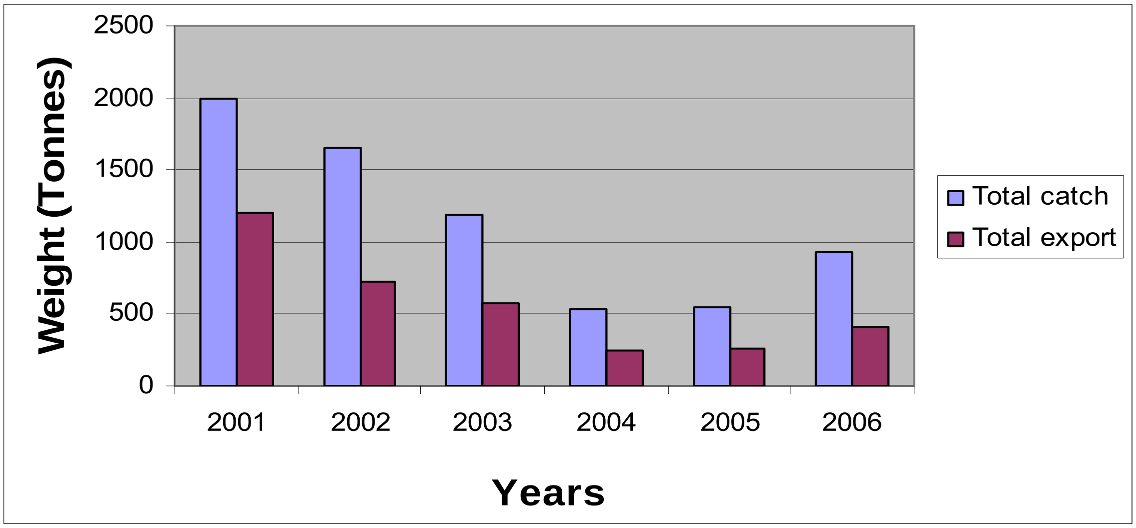

Figure 8. Total annual Tongan tuna catch and the amount of the catch exported to other countries, 2001–2006 (Fa'anunu 2007).

ment plan exists for the snapper fishery although a framework for a future plan was discussed at the Tonga Commercial Fisheries Conference in 2007 (see Halafihi 2007).

Longline tuna fishing in Tonga began in the 1970s with the number of vessels increasing over the years. Much of the longline fishing effort has been run or backed by the government, although the government is attempting to make the business environment more favorable for growth of the industry.

The number of vessels peaked in 2002 and declined to 12 in 2006 and 9 in 2007 (Fa'anunu 2007). The total annual tuna catch in Tonga gradually declined from 2001 through 2005, and then increased in 2006 (Fig. 8). Albacore, yellow fin, and bigeye tuna are the primary species in the fishery. Swordfish and marlin are also taken along with numerous other species. Much of the fish harvest is exported; the percentage of the total catch that was exported ranged from 44 to 61% from 2001 to 2006 (Fig. 8). Most fish were exported to Hawaii, Japan, and the west coast of the U.S. A significant number of albacore and skipjack tuna were also exported to Pago Pago.

Sport fishing is becoming a popular tourist attraction in many parts of Tonga where daily fishing charters are available year-round although the peak season runs from July–December. Black, blue and striped marlin, sailfish, barracuda, and wahoo, as well as tuna and giant trevally, are target species for sport fisheries. Commercial sport fishing vessels are required to be licensed. There were no commercial sport fishing vessels licensed in Tongatapu from 1995 through 2006; five to six commercial sport fishing vessel were licensed in Vava'u during this period. In 2007, there was one commercial sport fishing vessel licensed in Tongatapu and six in Vava'u (Matoto 2007). Commercial sport fishing is not a major contributor the Tongan economy.

(d) Hunting

Tonga is not a member of the International Whaling Commission. Historically the people of Tonga hunted humpback whales, continuing to as recently as the 1970s; 11 whaling operations were active in Tonga in the 1970s (Reeves 2002). A royal ban on Tongan whale hunting has been in effect since 1979 (see Reeves 2002), and marine mammals are also afforded protection under the Tongan Fisheries Management Act of 2002. Japan currently hunts whales in the Antarctic, although humpback whales are not taken at this time. Possible future hunting of humpback whales by Japan could have the potential to impact the Tongan humpback population.

(e) Whale Watching

In recent years whale watching has become an important tourist attraction adding significantly to the Tongan economy (Orams 2002). Whales can be observed from shore in some locations, and numerous vessels are available for offshore whale watching trips, particularly in the Vava'u island group in the northern part of the Kingdom. Tonga is one of the few places in the world where swimming with humpback whales occurs although scuba gear is not allowed. In addition to humpback whales, killer whales, and spinner and bottlenose dolphins are frequently observed during whale-watching tours.

(f) Summary of Cumulative Impacts to Marine Mammals

Because human activities in the area of the proposed seismic survey are limited, cumulative impacts on marine mammals are expected to be no more than minor and short–term. Although the airgun sounds from the seismic survey will have higher source levels than do the sounds from most other human activities in the area, the program will only last for ~34 days, and airgun operations will be intermittent during the program. In contrast, sounds from shipping have lower peak pressures but occur continuously over extended periods.

(g) Cumulative Impacts to Sea Turtles

Major threats to sea turtles in the Pacific region include unsustainable harvesting (direct take for meat and handicraft and egg harvesting); feral animal predation on turtle nests (eggs); incidental capture in commercial fishing; degradation of habitat (e.g., coastal development); pollution, marine debris (e.g., plastic bags and fishing gear), and pathogens; boat strikes; and climate change (SPREP 2007). Kaplan (2005) noted that in western and central Pacific, coastal sources lead to a 13% annual mortality rate of leatherback turtles, and longlining accounts for 12%. In the western Pacific, the three primary longline fishing countries are Japan, Taiwan, and Korea (Kaplan 2005). SPREP (2001) reported 27% mortality for sea turtles in longline sets in the western tropical Pacific, and 18% mortality in the western sub-tropical Pacific. Lewison and Crowder (2007) also report that the cumulative bycatch of sea turtles by longline vessels is a major source of mortality. In Tonga, sea turtles are fished seasonally from November to February (Tonga Department of Environment 2006).

According to SPREP (2007), "The main challenges to effective conservation of marine turtles in the region include the lack of data on populations, harvesting, and interactions with fishing activities due to limited research and monitoring. A major constraint is limited resources, both financially and in terms of manpower (including skills) available for implementing management actions in the region."

Impacts of L-DEO's proposed seismic survey in the Lau Basin are expected to be no more than a minor (and short-term) increment when viewed in light of other human activities that affect sea turtles in the area.

(9) Unavoidable Impacts

Unavoidable impacts to the species of marine mammals and turtles occurring in the proposed study area will be limited to short-term, localized changes in behavior of individuals and possibly a few occurrences of TTS in marine mammals that approach close to the operating airgun array. 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). TTS, if it occurs, will be limited to a few individuals, is a temporary phenomenon that does not involve injury, and is unlikely to have long term consequences for the few individuals involved. 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.

(10) Coordination with Other Agencies and Processes

This EA has been adopted by NSF primarily to address issues relating to the request that an IHA be issued by NMFS to authorize, under the U.S. MMPA, "taking by harassment" (disturbance) of small numbers of cetaceans during L-DEO's planned activities during the proposed seismic project. L-DEO and NSF will coordinate the planned marine mammal monitoring program associated with the seismic survey in the Lau Basin with other parties that may have interest in this area. L-DEO and NSF will coordinate with Tonga and will comply with the Kingdom's requirements.

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 dates for the cruise (~14 January–21 February 2009) are the dates when the personnel and equipment essential to meet the overall project objectives are available.

Marine mammals are expected to be found throughout the proposed study area. However, baleen whales are migratory in this area. During the proposed period of January–February, most of the baleen whales will be on summer feeding grounds in or near the Antarctic. Thus, the seismic survey is proposed for a period when marine mammal numbers (especially baleen whales) in the area are expected to be reduced (see § III, above).

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 were not conducted, the "No Action" alternative would result in no disturbance to marine mammals or sea turtles attributable to the proposed activities, but geological data of considerable scientific value and relevance in understanding earthquake potential and global climate (see § I) would not be acquired.

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APPENDIX A:

L-DEO MODELING FOR MARINE SEISMIC SOURCE ARRAYS FOR SPECIES MITIGATION[3]

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 exclusion 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.

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.

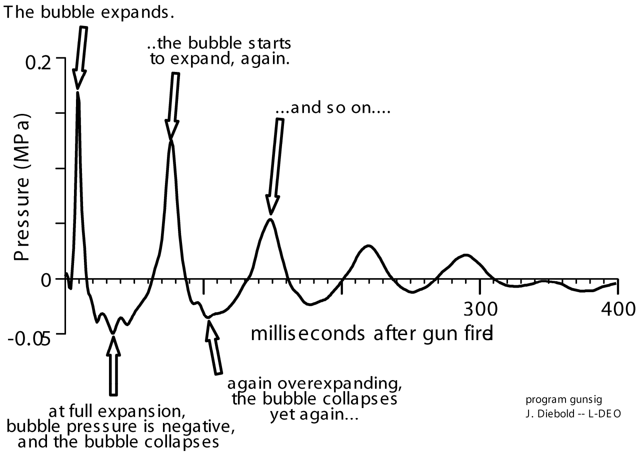

FIGURE A-1. Recording of a single airgun pulse made during R/V *EWING* tests, 1990.

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[3] 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.

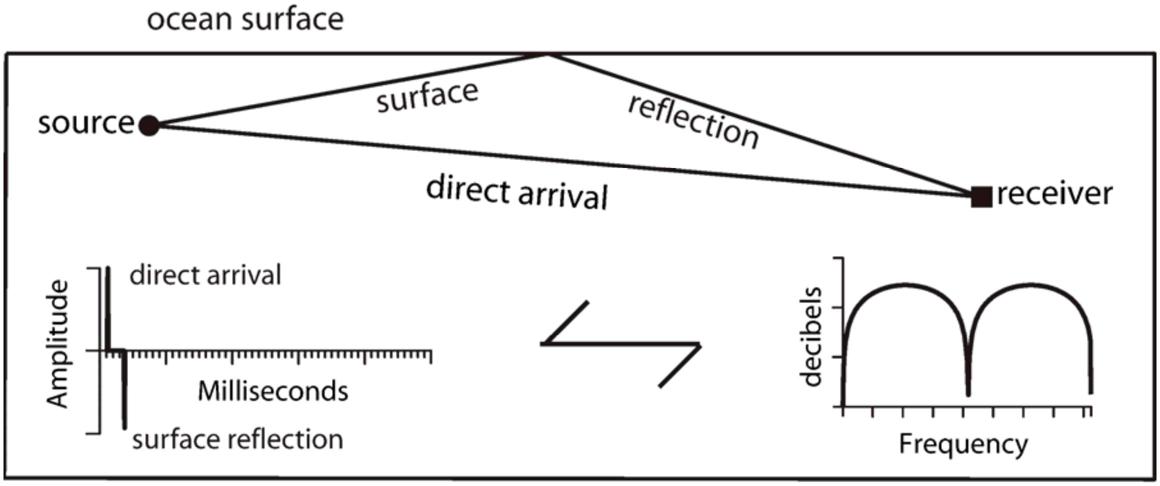


FIGURE A-2. Top: pathways for direct and surface-reflected arrivals used in modeling. Bottom: direct and ghosted arrival amplitudes in the time domain can be considered an operator whose spectrum is predictable, and which acts as a filter on the spectrum of the intrinsic near field source, whatever that 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.

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 ***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.

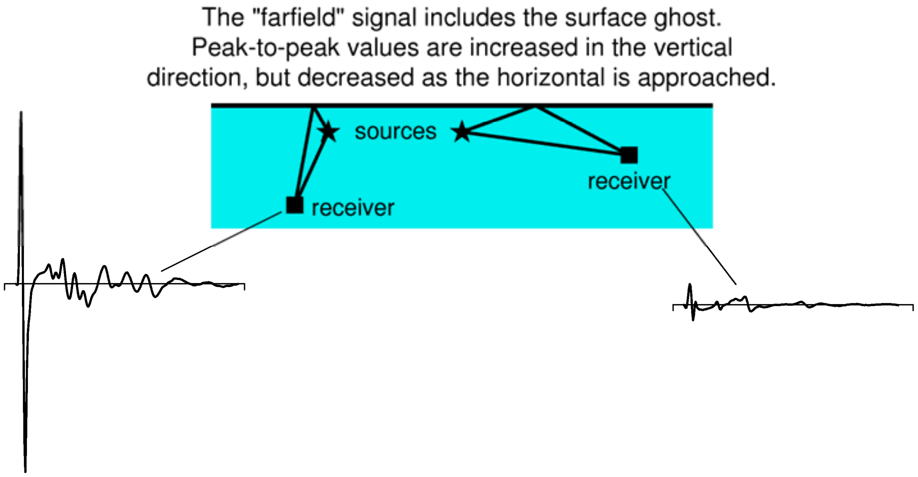


Figure A-3. The far field signature of a 20-airgun array modeled at two receiver positions equidistant from the center of the array. Differences are due to array directivity and surface ghosting effects.

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).

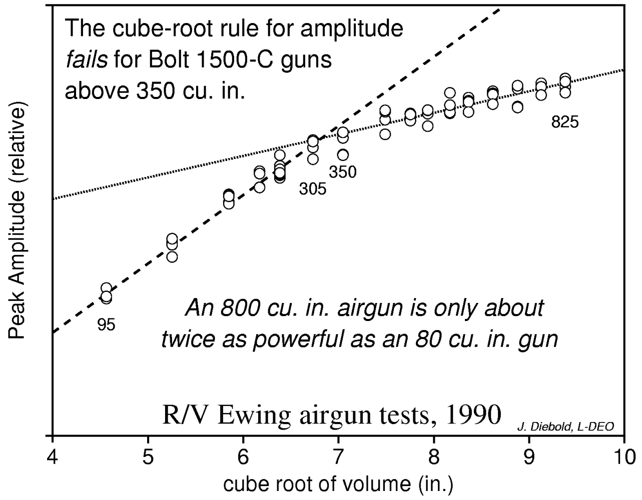


Figure A-4. R/V ***Ewing*** test results, 1990.

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:

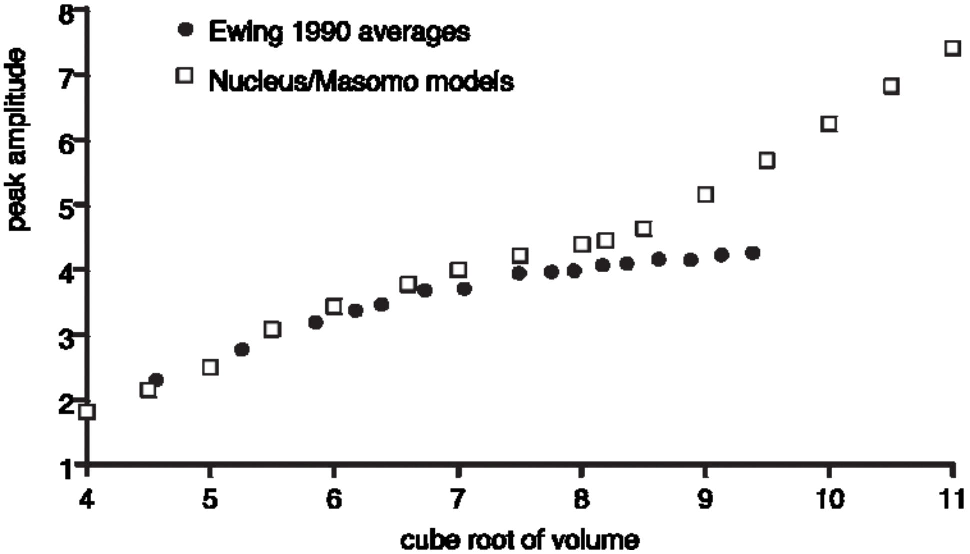


FIGURE A-5. Nucleus/Masomo overestimates peak values for large Bolt airguns.

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.

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:

$$\text{dB [wrt } \mu\text{Pascal –m]} = 220 * 20 \log^{10}(\text{B-m})$$

RMS dB and the exclusion zone

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.

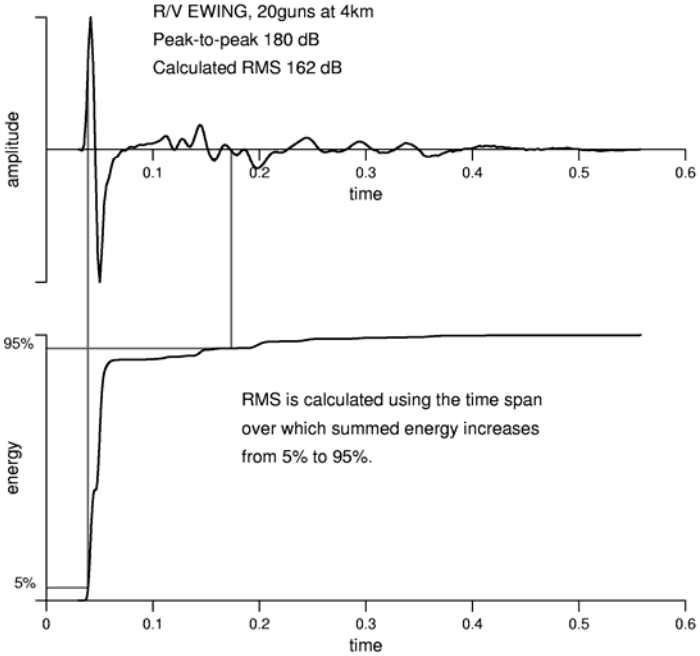


FIGURE A-6. The "standard" 90% RMS calculation. Energy is summed as a function of time for the entire signal. From this result, the times at which 5% and 95% of the total energy are attained define the RMS integration window.

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).

Calculating the exclusion 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.

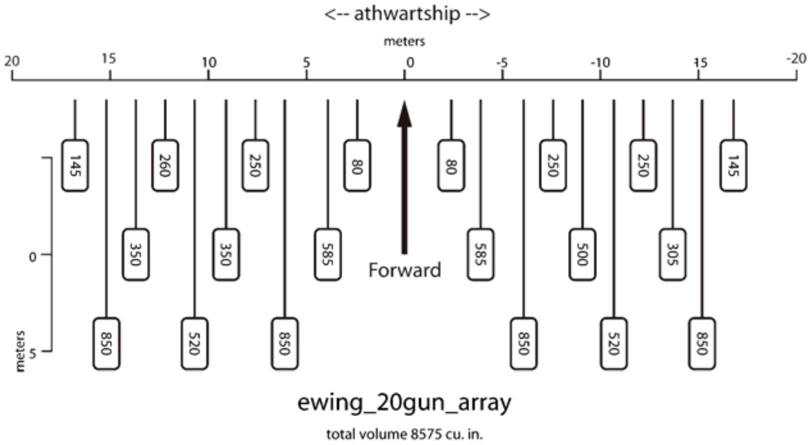


FIGURE A-7. Plan view of the 20-airgun array used to calculate Fig. 3, 4, and 6. Tow depth is 7.5 m.

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).

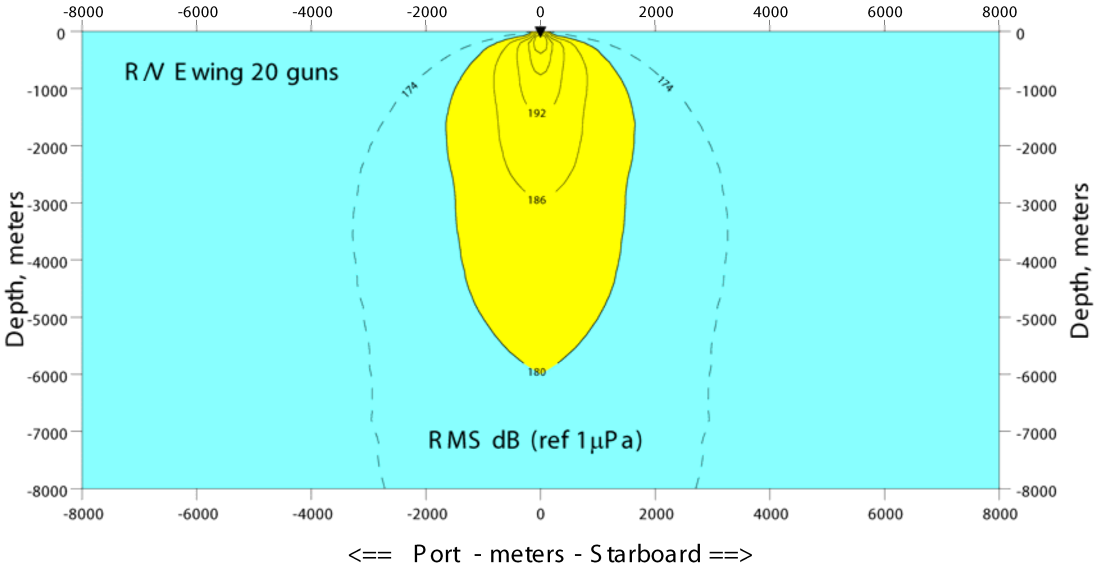


FIGURE A-8a. 90% RMS isopleths calculated in the crosstrack direction for a 20-airun array. Yellow denotes RMS values >180 dB.

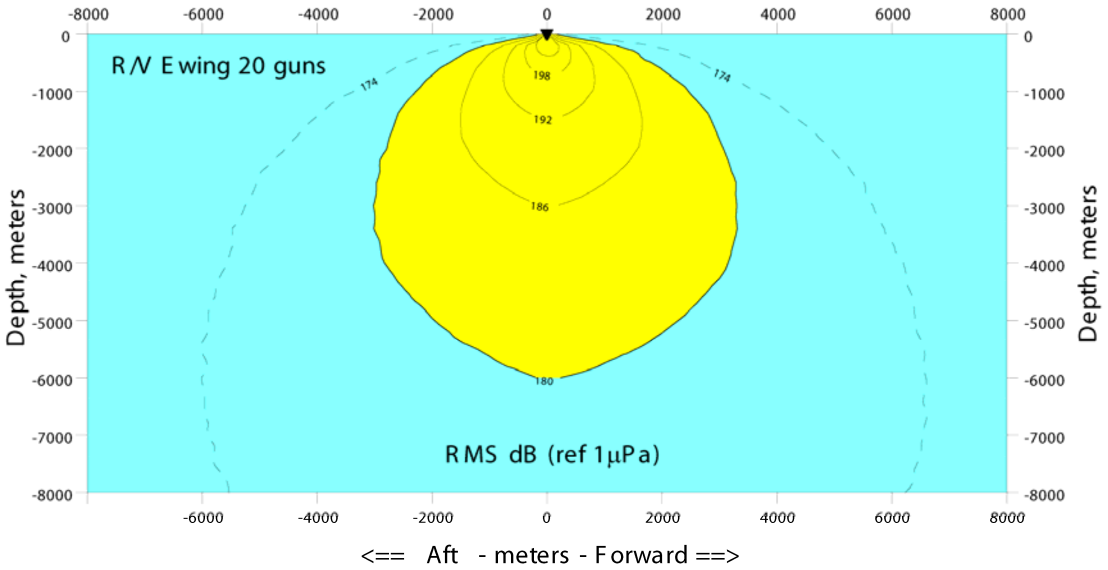


Figure A-8b. 90% RMS isopleths calculated in the along track direction for a 20-airun array. Yellow denotes RMS values >180 dB.

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 exclusion zones.

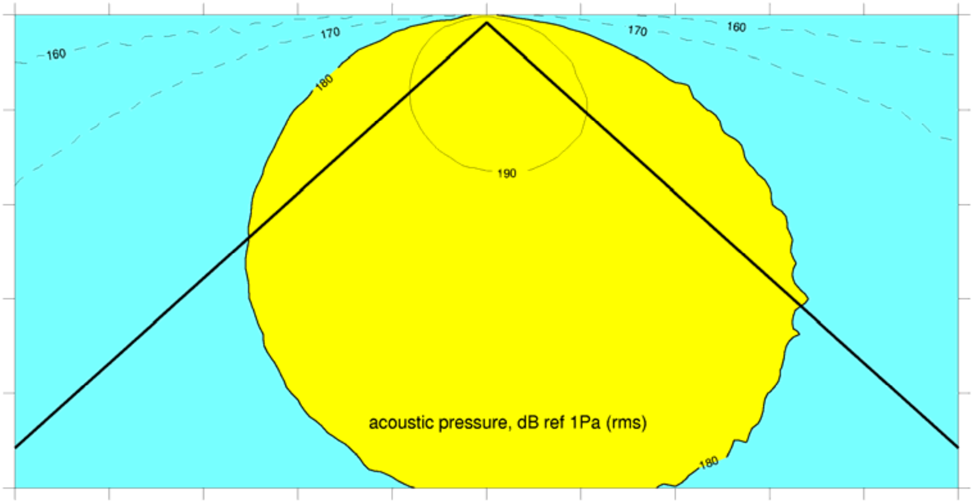


Figure A-9. The pathways in offset and depth which intersect maximum-radius isopleths. These are used to calculate radii for various 90% RMS levels.

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 exclusion zones 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 gun 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).

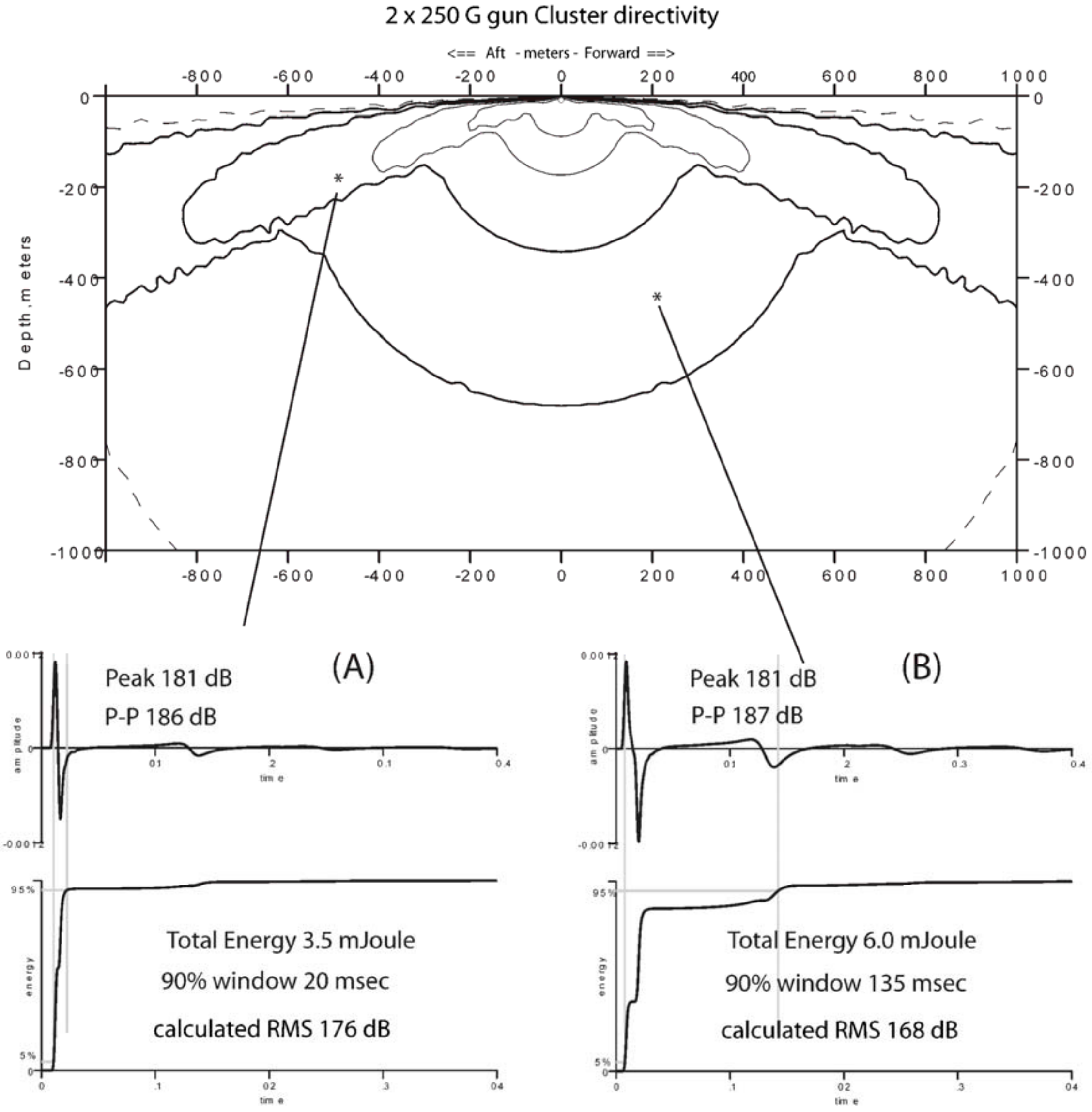


FIGURE A-10. Modeled results from a simple 2-airgun cluster source.

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% RMS window length. A contour plot of 90% RMS window length shows that for this source, they vary between 5 and 137 milliseconds (Fig. 11).

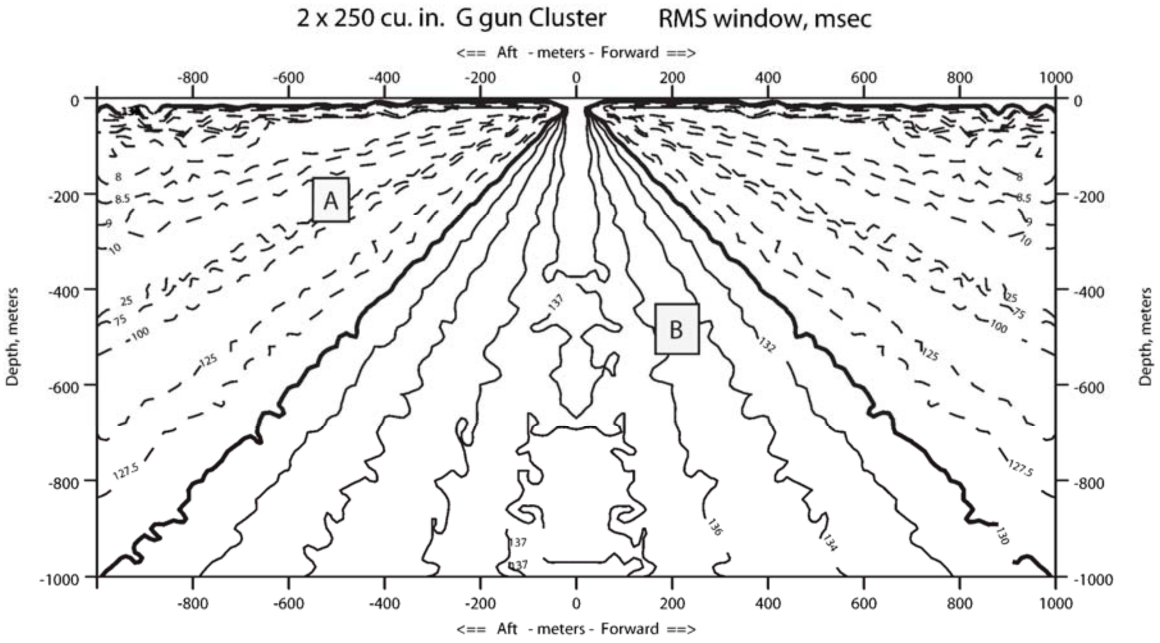


Figure A-11. The locations from which signals (A) and (B) were extracted are shown for reference.

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:

$$DB_{SEL} = dB_{RMS} + 10 * \text{Log}_{10} \text{ (window), where the window has units of seconds.}$$

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.

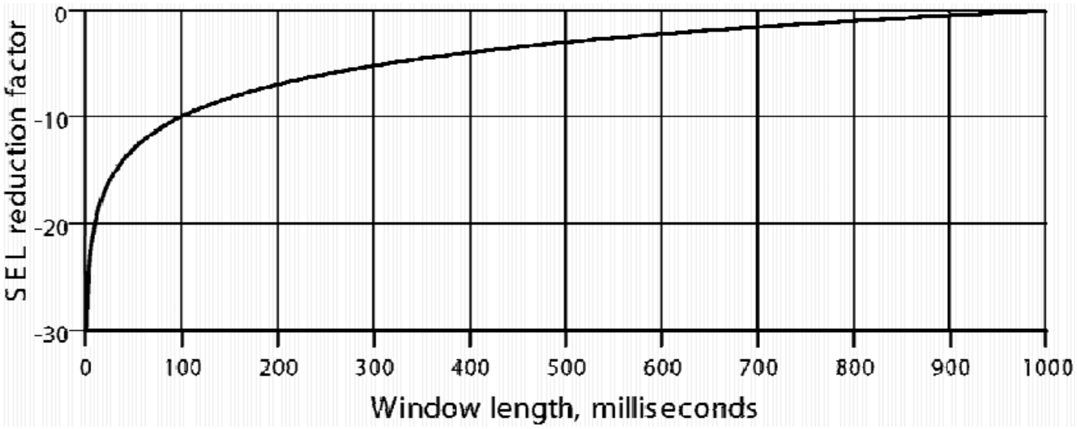


Figure A-12.

Calculation of SEL for the two cluster signatures shown above shows the effect of the calculation's window length correction factor:

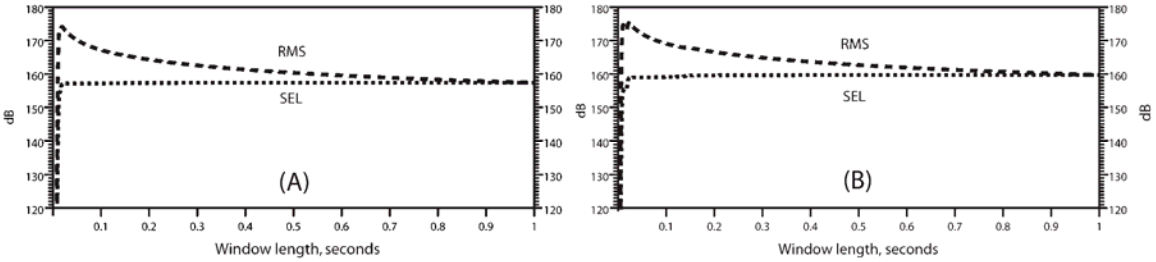
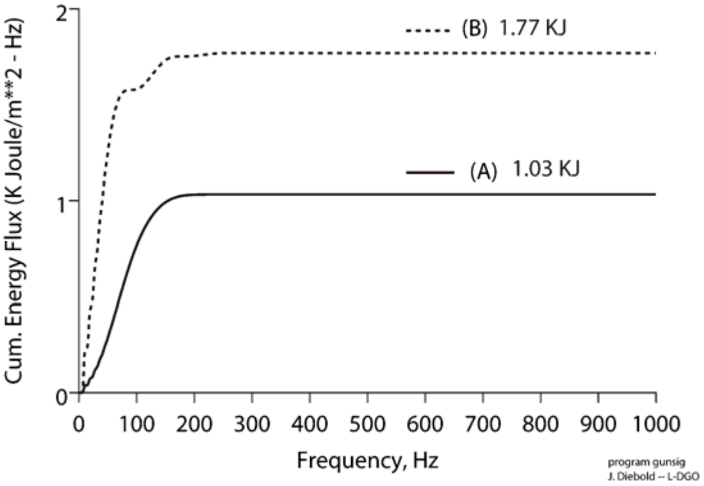


Figure A-13.

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).



program gunsig
J. Diebold -- L-DGO

FIGURE A-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 A-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?

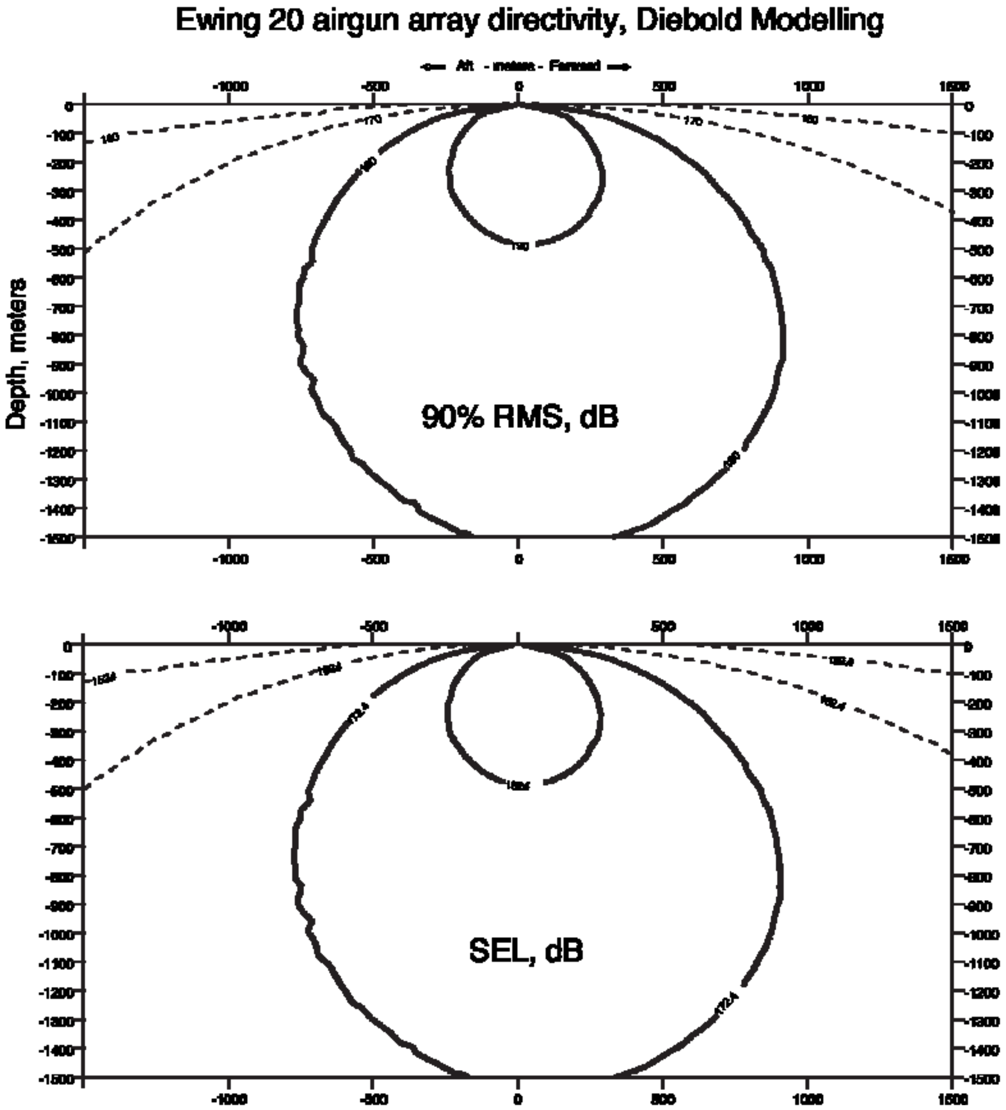


FIGURE A-15. Here we have matched the RMS and SEL contours nearly perfectly by using an SEL value equal to RMS – 7.6 dB, an offset corresponding to the normal 90% energy window length of about 174 msec. Current IHA applications have used an SEL "discount" of 15 dB, which is equivalent to an RMS window 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):

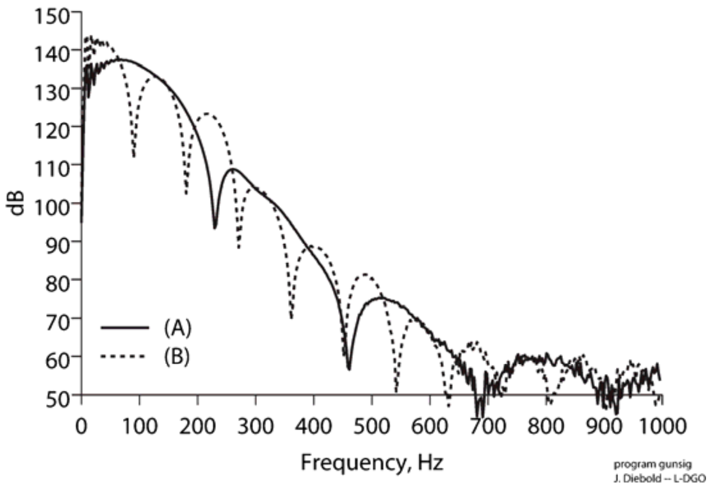


FIGURE A-16.

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.

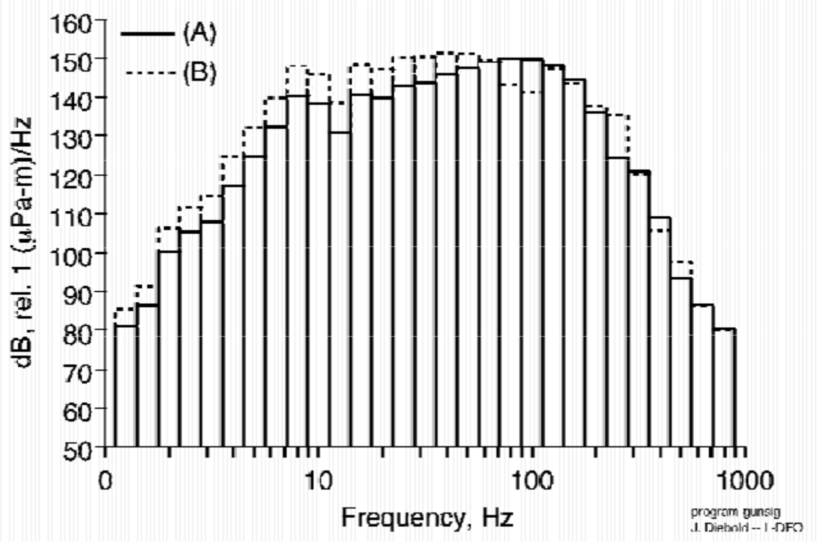


FIGURE A-17.

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.

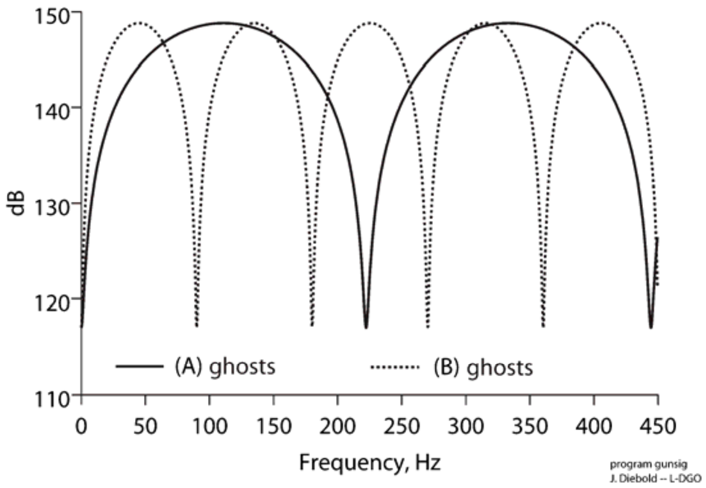


Figure A-18.

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:

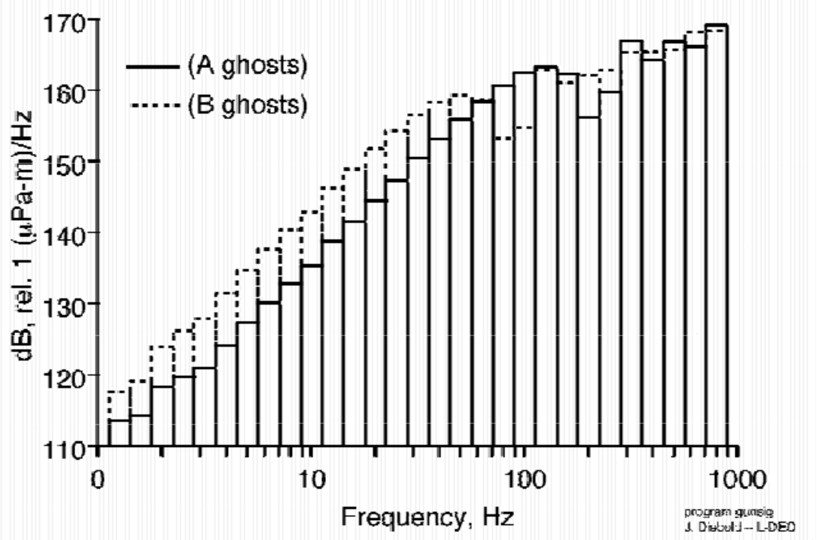


Figure A-19.

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APPENDIX B:

REVIEW OF THE EFFECTS OF AIRGUN AND SONAR SOUNDS ON MARINE MAMMALS [4]

The following subsections review relevant information concerning the potential effects of airgun and sonar sounds on marine mammals, with the sonar section being focused on systems similar to those operated during marine seismic operations including multibeam bathymetric echosounders (MBES), sub-bottom profilers (SBP), and pingers. 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.

1. 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 mammal 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 sonar pulses could cause strong 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.

2. Hearing Abilities of Marine Mammals

The hearing abilities of marine mammals are functions of the following (Richardson et al. 1995; Au et al. 2000):

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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 and monitoring studies also show that they hear and may react to many man-made sounds including sounds made during seismic exploration (Richardson et al. 1995; Gordon et al. 2004).

2.1 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, Cook et al. (2006) found that a Gervais' beaked whale showed evoked potentials from 5 kHz up to 80 kHz (the entire frequency range that was tested), with the best sensitivity at 40–80 kHz.

Most of the odontocete species have been classified as belonging to the "mid-frequency" (MF) hearing group, and the MF odontocetes (collectively) have functional hearing from about 150 Hz to 160 kHz (Southall et al. 2007). However, individual species may not have quite so broad a functional frequency range. Very strong sounds at frequencies slightly outside the functional range may also be detectable. The remaining odontocetes—the porpoises, river dolphins, and members of the genera *Cephalorhynchus* and *Kogia*—are distinguished as the "high frequency" (HF) hearing group. They have functional hearing from about 200 Hz to 180 kHz (Southall et al. 2007).

Airguns produce a small proportion of their sound at mid- and high-frequencies, although at progressively lower levels with increasing frequency. In general, most of the energy in the sound pulses emitted by airgun arrays is at low frequencies; strongest spectrum levels are below 200 Hz, with considerably lower spectrum levels above 1000 Hz, and smaller amounts of energy emitted up to ~150 kHz (Goold and Fish 1998; Sodal 1999; Goold and Coates 2006; Potter et al. 2007).

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, airgun sounds are sufficiently strong, and contain sufficient mid- and high-frequency energy, that their received levels sometimes remain above the hearing thresholds of odontocetes at distances out to several tens of kilometers (Richardson and Würsig 1997). There is no evidence that most small odontocetes react to airgun pulses at such long distances. However, beluga whales do seem quite responsive at intermediate distances (10–20 km) where sound levels are well above the ambient noise level (see below).

In summary, even though odontocete hearing is relatively insensitive to the predominant low frequencies produced by airguns, sounds from airgun arrays are audible to odontocetes, sometimes to distances of 10s of kilometers.

2.2 Baleen Whales (Mysticetes)

The hearing abilities of baleen whales (mysticetes) 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). 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, with components to >24 kHz (Au et al. 2006). The anatomy of the baleen whale inner ear seems to be well adapted for detection of low-frequency sounds (Ketten 1991, 1992, 1994, 2000). For baleen whales as a group, the functional hearing range is thought to be about 7 Hz to 22 kHz and they constitute the "low-frequency" (LF) hearing group (Southall et al. 2007). The absolute sound levels that they can detect below 1 kHz are probably limited by increasing levels of natural ambient noise at decreasing frequencies (Clark and Ellison 2004). Ambient noise levels are 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 source) sounds would be detectable and 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 levels that the whales are assumed to detect (see below).

2.3 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: 211ff; Kastak and Schusterman 1998, 1999; Kastelein et al. 2002). The functional hearing range for pinnipeds in water is considered to extend from 75 Hz to 75 kHz (Southall et al. 2007), although some individual species—especially the eared seals—do not have that broad an auditory range (Richardson et al. 1995). 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 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 ~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).

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 seals (harbor seal).

2.4 Manatees and Dugong (Sirenians)

The West Indian manatee can apparently detect sounds from 15 Hz to 46 kHz, based on a study involving 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).

2.5 Sea Otter and Polar Bear

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). Sea otter vocalizations are considered to be most suitable for short-range communication among individuals (McShane et al. 1995). In-air audiograms for two river otters indicate that this related species has its best hearing sensitivity at the relatively high frequency of 16 kHz, with some sensitivity from about 460 Hz to 33 kHz (Gunn 1988). However, these data apply to a different species of otter, and to in-air rather than underwater hearing.

Data on the specific hearing capabilities of polar bears are limited. A recent study of the in-air hearing of polar bears applied the auditory evoked potential method 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. Although low-frequency hearing was not studied, the data suggested that medium- and some 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 underwater sounds.

3. Characteristics of Airgun Sounds

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 significant energy up to 500–1000 Hz and some energy at higher frequencies (Goold and Fish 1998; Potter et al. 2007). Studies in the Gulf of Mexico have shown that the horizontally-propagating sound can contain significant energy above the frequencies that airgun arrays are designed to emit (DeRuiter et al. 2006; Madsen et al. 2006; Tyack et al. 2006). Energy at frequencies up to 150 kHz was found in tests of single 60-in^3 and 250-in^3 airguns (Goold and Coates 2006). Nonetheless, the predominant energy is at low frequencies.

The pulsed sounds associated with seismic exploration have higher peak levels than other industrial sounds (except those from explosions) to which whales and other marine mammals are routinely exposed.

The nominal 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_{p-p}, considering the frequency band up to ~250 Hz. The source level for the largest airgun array deployed from the R/V *Marcus G. Langseth* (36 airguns) is 265 dB re 1 μPa_{p-p}. 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 the source consists of numerous airguns spaced apart from one another. 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.

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 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, but not in the near field. 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 (p-p) levels, in bar-meters or (less often) dB re 1 μPa · m. The peak (= zero-to-peak, or 0-p) 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 increasingly used is the energy, or Sound Exposure Level (SEL), in dB re 1 $\mu Pa^2 \cdot s$. Because the pulses, even when stretched by propagation effects (see below), are usually <1 s in duration, the numerical value of the energy is usually lower than the rms pressure level. However, the units are different.[5] 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, the U.S. National Marine Fisheries Service (NMFS) has commonly referred to rms levels when discussing levels of pulsed sounds that might “harass” marine mammals.

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[5] The rms value for a given airgun array pulse, as measured at a horizontal distance on the order of 0.1 km to 1–10 km in the units dB re 1 μPa, usually averages 10–15 dB higher than the SEL value for the same pulse measured in dB re 1 $\mu Pa^2 \cdot s$ (e.g., Greene 1997). However, there is considerable variation, and the difference tends to be larger close to the airgun array, and less at long distances (Blackwell et al. 2007; MacGillivray and Hannay 2007a,b). In some cases, generally at longer distances, pulses are “stretched” by propagation effects to the extent that the rms and SEL values (in the respective units mentioned above) become very similar (MacGillivray and Hannay 2007a,b).

Seismic sound pulses 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 as received at long horizontal distances can be much greater. For example, for one airgun array operating in the Beaufort Sea, pulse duration was ~300 ms at a distance of 8 km, 500 ms at 20 km, and 850 ms at 73 km (Greene and Richardson 1988).

The rms level for a given pulse (when measured over the duration of that pulse) depends on the extent to which propagation effects have "stretched" the duration of the pulse by the time it reaches the receiver (e.g., Madsen 2005). As a result, the rms values for various received pulses are not perfectly correlated with the SEL (energy) values for the same pulses. There is increasing evidence that biological effects are more directly related to the received energy (e.g., to SEL) than to the rms values averaged over pulse duration (Southall et al. 2007).

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; Potter et al. 2007). 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 and 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 usually low, <120 dB re 1 μPa on an approximate rms basis. However, faint seismic pulses are sometimes detectable at even greater ranges (e.g., Bowles et al. 1994; Fox et al. 2002). In fact, low-frequency airgun signals sometimes 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).

4. Masking Effects of Airgun Sounds

Masking is the obscuring of sounds of interest by interfering sounds, generally at similar frequencies (Richardson et al. 1995). Introduced underwater sound will, through masking, reduce the effective communication distance of a marine mammal species if the frequency of the source is close to that used as a signal by the marine mammal, and if the anthropogenic sound is present for a significant fraction of the time (Richardson et al. 1995). If little or no overlap occurs between the introduced sound and the frequencies used by the species, communication is not expected to be disrupted. Also, if the introduced sound is present only infrequently, communication is not expected to be disrupted much if at all. The duty cycle of airguns is low; the airgun sounds are pulsed, with relatively quiet periods between pulses. In most situations, strong airgun sound will only be received for a brief period (<1 s), with these sound pulses being separated by at least several seconds of relative silence, and longer in the case of deep-penetration surveys or refraction surveys. A single airgun array might cause appreciable masking in only one situation: When propagation conditions are such that sound from each airgun pulse reverberates strongly and persists for much or all of the interval up to the next airgun pulse (e.g., Simard et al. 2005). Situations with prolonged strong reverberation are infrequent, in our experience.

Although masking effects of pulsed sounds on marine mammal calls and other natural sounds are expected to be limited, there are few specific studies on this. Some whales continue calling in the presence of seismic 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; Holst et al. 2005a,b, 2006). However, there is one recent summary report indicating that calling fin whales distributed in one part of the North Atlantic went silent for an extended period starting soon after the onset of a seismic survey in the area (Clark and Gagnon 2006). It is not clear from that preliminary paper whether the whales ceased calling because of masking, or whether this was a behavioral response not directly involving masking.

Among the odontocetes, there has been one report that sperm whales ceased calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994), but more recent studies of sperm whales found that they continued calling in the presence of seismic pulses (Madsen et al. 2002; Tyack et al. 2003; Smultea et al. 2004; Holst et al. 2006; Jochens et al. 2006). Madsen et al. (2006) noted that airgun sounds would not be expected to mask sperm whale calls given the intermittent nature of airgun pulses. Dolphins and porpoises are also commonly heard calling while airguns are operating (Gordon et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b; Potter et al. 2007). 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 the dominant components of airgun sounds.

Pinnipeds, sirenians and sea otters have best hearing sensitivity and/or produce most of their sounds at frequencies higher than the dominant components of airgun sound, but there is some overlap in the frequencies of the airgun pulses and the calls. However, the intermittent nature of airgun pulses presumably reduces the potential for masking.

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; reviewed in Richardson et al. 1995:233*ff*, 364*ff*; Lesage et al. 1999; Terhune 1999; Nieukirk et al. 2005; Scheifele et al. 2005; Parks et al. 2007). These studies involved exposure to other types of anthropogenic sounds, generally of a more continuous nature than seismic pulses. 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.

5. Disturbance by Seismic Surveys

Disturbance includes a variety of effects, including subtle to conspicuous changes in behavior, movement, and displacement. In the terminology of the 1994 amendments to the U.S. Marine Mammal Protection Act (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, and on NRC (2005), simple exposure to sound, or brief reactions that do not disrupt behavioral patterns in a potentially significant manner, do not constitute harassment or "taking". In this analysis, we interpret "potentially significant" to mean in a manner th*at might have deleterious effects on 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". Available detailed data on reactions of marine mammals to airgun sounds (and other anthropogenic sounds) are limited to relatively few species and situations (see Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Southall et al. 2007). Behavioral reactions of marine mammals to sound are difficult to predict in the absence of site- and context-specific data. Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors (Richardson et al. 1995; Wartzok et al. 2004; Southall et al. 2007). If a marine mammal reacts 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 population. 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 sound on marine mammals, it is common practice to estimate how many mammals would be present within a particular distance of industrial activities and exposed to a particular level of industrial sound. In most cases, this approach likely overestimates the numbers of marine mammals that would be affected in some biologically important manner. One of the reasons for this is that the selected distances/isopleths are based on limited studies indicating that some animals exhibited short-term reactions at this distance or sound level, whereas the calculation assumes that all animals exposed to this level would react in a biologically significant manner.

The definitions of "taking" in the U.S. MMPA, and its applicability to various activities, were slightly altered 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 particular groups of mammal species and to particular sound types (NMFS 2005). Recently, a committee of specialists on noise impact issues has proposed new science-based impact criteria (Southall et al. 2007). 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 significant degree by seismic survey activities are primarily based on behavioral observations of a few 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 and small toothed whales, but for many species there are no data on responses to marine seismic surveys.

5.1 Baleen Whales

Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable among species, locations, whale activities, oceanographic conditions affecting sound propagation, etc. (reviewed in Richardson et al. 1995; Gordon et al. 2004). 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, baleen whales exposed to strong sound pulses from airguns often react by deviating from their normal migration route and/or interrupting their feeding and moving away. Some of the major 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,b); Miller et al. (1999, 2005); Gordon et al. (2004); Moulton and Miller (2005); Stone and Tasker (2006); Johnson et al. (2007); Nowacek et al. (2007) and Weir (2008). Although baleen whales often show only slight overt responses to operating airgun arrays (Stone and Tasker 2006; Weir 2008), strong avoidance reactions by several species of mysticetes have been observed at ranges up to 6–8 km and occasionally as far as 20–30 km from the source vessel when large arrays of airguns were used. 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, 1988; Richardson et al. 1986; McCauley et al. 1998, 2000a,b).

Studies of gray, bowhead, and humpback whales have shown that seismic pulses with received levels of 160–170 dB re 1 μPa_{rms} seem to cause obvious avoidance behavior in a substantial portion of the animals exposed (Richardson et al. 1995). In many areas, seismic pulses from large arrays of airguns diminish to those levels at distances ranging from 4–15 km from the source. More recent studies have shown that some species of baleen whales (bowheads and humpbacks in particular) at times show strong avoidance at received levels lower than 160–170 dB re 1 μPa_{rms}. The largest avoidance radii involved migrating bowhead whales, which avoided an operating seismic vessel by 20–30 km (Miller et al. 1999; Richardson et al. 1999). In the cases of migrating bowhead (and gray) 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). Feeding bowhead whales, in contrast to migrating whales, show much smaller avoidance distances (Miller et al. 2005; Harris et al. 2007), presumably because moving away from a food concentration has greater cost to the whales than does a course deviation during migration.

The following subsections provide more details on the documented responses of particular species and groups of baleen whales to marine seismic operations.

Humpback Whales.—Responses of humpback whales to seismic surveys have been studied during migration, on the summer feeding grounds, and on Angolan winter breeding grounds; there has also been discussion of effects on the Brazilian wintering grounds. McCauley et al. (1998, 2000a) studied the responses of migrating 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 a (horizontal) source level of 227 dB re 1 $\mu Pa \cdot m_{p\text{-}p}$. They found that the overall distribution of humpbacks migrating through their study area was unaffected by the full-scale seismic program, although localized displacement varied with pod composition, behavior, and received sound levels. Observations were made from the seismic vessel, from which the maximum viewing distance was listed as 14 km. Avoidance reactions (course and speed changes) began at 4–5 km for traveling pods, with the closest point of approach (CPA) being 3–4 km at an estimated received level of 157–164 dB re 1 μPa_{rms} (McCauley et al. 1998, 2000a). A greater stand-off range of 7–12 km was observed for more sensitive resting pods (cow-calf pairs; McCauley et al. 1998, 2000a). The mean received level for initial avoidance of an approaching airgun was 140 dB re 1 μPa_{rms} for humpback pods containing females, and at the mean CPA distance the received level was 143 dB re 1 μPa_{rms}. One startle response was reported at 112 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 of 100–400 m, where the maximum received level was 179 dB re 1 μPa_{rms}. The McCauley et al. (1998, 2000a,b) studies show evidence of greater avoidance of seismic airgun sounds by pods with females than by other pods during humpback migration off Western Australia.

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.

Among wintering humpback whales off Angola (*n* = 52 useable groups), there were no significant differences in encounter rates (sightings/hr) when a 24-airgun array (3147 in^3 or 5085 in^3) was operating vs. silent (Weir 2008). There was also no significant difference in the mean CPA (closest observed point of approach) distance of the humpback sightings when airguns were on vs. off (3050 m vs. 2700 m, respectively).

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 and subject to alternative explanations (IAGC 2004). Also, the evidence was not consistent with subsequent results from the same area of Brazil (Parente et al. 2006), or with direct studies of humpbacks exposed to seismic surveys in other areas and seasons (see above). After allowance for data from subsequent years, there was “no observable direct correlation” between strandings and seismic surveys (IWC 2007b:236).

Bowhead Whales.—Responsiveness of bowhead whales to seismic surveys can be quite variable depending on their activity (feeding vs. migrating). Bowhead whales on their summer feeding 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; Miller et al. 2005). 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 (Richardson et al. 1986). This work and subsequent studies in the same region by Miller et al. (2005) and Harris et al. (2007) showed that many feeding bowhead whales tend to tolerate higher sound levels than migrating bowhead whales before showing an overt change in behavior. They found that, on the feeding grounds, bowhead whales are often seen from the operating seismic ship, though average sighting distances tend to be larger when the airguns are operating. However, some individual bowheads apparently begin to react at distances a few kilometers away, beyond the distance at which observers on the ship can sight bowheads (Richardson et al. 1986; Citta et al. 2007). The feeding whales may be affected by the sounds, but the need to feed may reduce the tendency to move away until the airguns are within a few kilometers.

Migrating bowhead whales in the Alaskan Beaufort Sea seem more responsive to noise pulses from a distant seismic vessel than are summering bowheads. Bowhead whales migrating west across the Alaskan Beaufort Sea in autumn are unusually responsive, with substantial avoidance occurring out to distances of 20–30 km from a medium-sized airgun source at received sound levels of around 120–130 dB re 1 μPa_{rms} (Miller et al. 1999; Richardson et al. 1999). Those results came from 1996–98, when 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. 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.

There are no data on reactions of bowhead whales to seismic surveys in winter or spring.

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 stopped 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 re 1 μPa_{rms}. 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 re 1 μPa_{peak} in the northern Bering Sea. These findings were generally consistent with the results of studies conducted on larger numbers of gray whales migrating off California (Malme et al. 1984; Malme and Miles 1985) and western Pacific gray whales feeding off Sakhalin, Russia (Würsig et al. 1999; Gailey et al. 2007; Johnson et al. 2007; Yazvenko et al. 2007a,b), along with a few data on gray whales off British Columbia (Bain and Williams 2006).

Malme and Miles (1985) concluded that, during migration off California, gray whales showed changes in swimming pattern with received levels of ~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 airgun array operating off central California. This would occur at an average received sound level of ~170 dB re 1 μPa_{rms}. Some slight behavioral changes were noted when approaching gray whales reached the distances where received sound levels were 140 to 160 dB re 1 μPa_{rms}, but these whales generally continued to approach (at a slight angle) until they passed the sound source at distances where received levels averaged ~170 dB re 1 μPa_{rms} (Malme et al. 1984; Malme and Miles 1985).

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) and in 2001 (Johnson et al. 2007; Meier et al. 2007; Yazvenko et al. 2007a). However, there were indications of subtle behavioral effects among whales that remained in the areas exposed to airgun sounds (Würsig et al. 1999; Gailey et al. 2007; Weller et al. 2006a). Also, there was evidence of localized redistribution of some individuals within the nearshore feeding ground so as to avoid close approaches by the seismic vessel (Weller et al. 2002, 2006b; Yazvenko et al. 2007a). Despite the evidence of subtle changes in some quantitative measures of behavior and local redistribution of some individuals, there was no apparent change in the frequency of feeding, as evident from mud plumes visible at the surface

(Yazvenko et al. 2007b). It should be noted that the 2001 seismic program involved an unusually comprehensive combination of real-time monitoring and mitigation measures designed to avoid exposing western gray whales to received levels of sound above about 163 dB re 1 µPa_{rms} (Johnson et al. 2007). The lack of strong avoidance or other strong responses was presumably in part a result of the mitigation measures. Effects probably would have been more significant without such intensive mitigation efforts.

Gray whales in British Columbia exposed to seismic survey sound levels up to ~170 dB re 1 µPa did not appear to be strongly disturbed (Bain and Williams 2006). The few whales that were observed moved away from the airguns but toward deeper water where sound levels were said to be higher due to propagation effects (Bain and Williams 2006).

Rorquals.—Blue, sei, fin, and minke whales (all of which are members of the genus *Balaenoptera*) have often been reported in areas ensonified by airgun pulses (Stone 2003; MacLean and Haley 2004; Stone and Tasker 2006). Sightings by observers on seismic vessels during 110 large-source seismic surveys off the U.K. from 1997 to 2000 suggest that, during times of good sightability, sighting rates for mysticetes (mainly fin and sei whales) were similar when large arrays of airguns were shooting vs. silent (Stone 2003; Stone and Tasker 2006). However, these whales tended to exhibit localized avoidance, remaining significantly further (on average) from the airgun array during seismic operations compared with non-seismic periods ($P = 0.0057$; Stone and Tasker 2006). The average CPA distances for baleen whales sighted when large airgun arrays were operating vs. silent were about 1.6 vs. 1.0 km. Baleen whales, as a group, were more often oriented away from the vessel while a large airgun array was shooting compared with periods of no shooting ($P < 0.05$; Stone and Tasker 2006). 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 (2005) found little difference in sighting rates (after accounting for water depth) and initial average sighting distances of balaenopterid whales when airguns were operating (mean = 1324 m) vs. silent (mean = 1303 m). However, there were indications that these whales were more likely to be moving away when seen during airgun operations. Baleen whales at the average sighting distance during airgun operations would have been exposed to sound levels (via direct path) of about 169 dB re 1 µPa_{rms} (Moulton and Miller 2005). Similarly, ship-based monitoring studies of blue, fin, sei and minke whales offshore of Newfoundland (Orphan Basin and Laurentian Sub-basin) found no more than small differences in sighting rates and swim directions during seismic vs. non-seismic periods (Moulton et al. 2005, 2006a,b). Analyses of CPA data yielded variable results.[6] The authors of the Newfoundland reports concluded that, based on observations from the seismic vessel, some mysticetes exhibited localized avoidance of seismic operations (Moulton et al. 2005, 2006a).

Minke whales have occasionally been observed to approach active airgun arrays where received sound levels were estimated to be near 170–180 dB re 1 µPa (McLean and Haley 2004).

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

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[6] The CPA of baleen whales sighted from the seismic vessels was, on average, significantly closer during non-seismic periods vs. seismic periods in 2004 in the Orphan Basin (means 1526 m vs. 2316 m, respectively; Moulton et al. 2005). In contrast, mean distances without vs. with seismic did not differ significantly in 2005 in either the Orphan Basin (means 973 m vs. 832 m, respectively; Moulton et al. 2006a) or in the Laurentian Sub-basin (means 1928 m vs. 1650 m, respectively; Moulton et al. 2006b). In both 2005 studies, mean distances were greater (though not significantly so) *without* seismic.

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 migrating humpback and migrating bowhead whales show reactions, including avoidance, that 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 can be biased. Observations over broader areas may be needed to determine the range of potential effects of some large-source seismic surveys where effects on cetaceans may extend to considerable distances (Richardson et al. 1999; Bain and Williams 2006; Moore and Angliss 2006). Longer-range observations, when required, can sometimes be obtained via systematic aerial surveys or aircraft-based observations of behavior (e.g., Richardson et al. 1986, 1999; Miller et al. 1999, 2005; Yazvenko et al. 2007a,b) or by use of observers on one or more scout boats operating in coordination with the seismic vessel (e.g., Smultea et al. 2004; Johnson et al. 2007).

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 to 15 km from the source. A substantial proportion of the baleen whales within such distances may show avoidance or other strong disturbance reactions to the operating airgun array. However, in other situations, various mysticetes tolerate exposure to full-scale airgun arrays operating at even closer distances, with only localized avoidance and minor changes in activities. At the other extreme, in migrating bowhead whales, avoidance often extends to considerably larger distances (20–30 km) and lower received sound levels (120–130 dB re 1 μPa_{rms}). Also, even in cases where there is no conspicuous avoidance or change in activity upon exposure to sound pulses from distant seismic operations, there are sometimes subtle changes in behavior (e.g., surfacing–respiration–dive cycles) that are only evident through detailed statistical analysis (e.g., Richardson et al. 1986; Gailey et al. 2007).

Data on short-term reactions by cetaceans to impulsive noises are not necessarily indicative of long-term or biologically significant effects. It is not known whether impulsive sounds affect reproductive rate or distribution and habitat use in subsequent days or years. However, gray whales have 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), and there has been a substantial increase in the population over recent decades (Angliss and Outlaw 2008). 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). Similarly, bowhead whales have 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), and their numbers have increased notably (Angliss and Outlaw 2008). Bowheads also have been observed over periods of days or weeks in areas ensonified repeatedly by seismic pulses (Richardson et al. 1987; Harris et al. 2007). However, it is generally not known whether the same individual bowheads were involved in these repeated observations (within and between years) in strongly ensonified areas. In any event, in the absence of some unusual circumstances, the history of coexistence between seismic surveys and baleen whales suggests that brief exposures to sound pulses from any single seismic survey are unlikely to result in prolonged effects.

5.2 Toothed Whales

Little systematic information is available about reactions of toothed whales to noise pulses. Few studies similar to the more extensive baleen whale/seismic pulse work summarized above have been reported for toothed whales. However, there are recent systematic data on sperm whales (Jochens et al. 2006; Miller 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; Moulton and Miller 2005; Bain and Williams 2006; Holst et al. 2006; Stone and Tasker 2006; Potter et al. 2007; Weir 2008).

Delphinids (Dolphins and similar) and Monodontids (Beluga).—Seismic operators and marine mammal observers on seismic vessels regularly see dolphins and other small toothed whales near operating airgun arrays, but in general there is a tendency for most delphinids to show some avoidance of operating seismic vessels (e.g., Goold 1996a,b,c; Calambokidis and Osmek 1998; Stone 2003; Moulton and Miller 2005; Holst et al. 2006; Stone and Tasker 2006; Weir 2008). In most cases, the avoidance radii for delphinids appear to be small, on the order of 1 km or less, and some individuals show no apparent avoidance. 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). Some dolphins seem to be attracted to the seismic vessel and floats, and some ride the bow wave of the seismic vessel even when a large array of airguns is firing (e.g., Moulton and Miller 2005). Nonetheless, small toothed whales more often tend to head away, or to maintain a somewhat greater distance from the vessel, when a large array of airguns is operating than when it is silent (e.g., Stone and Tasker 2006; Weir 2008).

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. 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).

The beluga is a species that (at least at times) shows long-distance avoidance of seismic vessels. Aerial surveys conducted in the southeastern Beaufort Sea in summer found that sighting rates of belugas were significantly lower at distances 10–20 km compared with 20–30 km from an operating airgun array (Miller et al. 2005). The low number of beluga sightings by marine mammal observers on the vessel seemed to confirm there was a strong avoidance response to the 2250 in^3 airgun array. More recent seismic monitoring studies in the same area have confirmed that the apparent displacement effect on belugas extended farther than has been shown for other small odontocetes exposed to airgun pulses (e.g., Harris et al. 2007).

Observers stationed on seismic vessels operating off the U.K. 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; Stone and Tasker 2006). 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 when large-volume[7] airgun arrays were shooting. Except for the pilot whale and bottlenose dolphin, CPA distances for all of the small odontocete species tested, including killer whales, were significantly farther from large airgun arrays during periods of shooting compared with periods of no shooting. Pilot whales were less responsive than other small odontocetes in the presence of seismic surveys (Stone and Tasker 2006). For small odontocetes as a group, and most individual species, orientations differed between times when large airgun arrays were operating vs. silent, with significantly fewer animals traveling towards and/or more traveling away from the vessel during shooting (Stone and Tasker 2006). Observers' records suggested that fewer cetaceans were feeding and fewer were interacting with the survey vessel (e.g., bow-riding) during periods with airguns operating, and small odontocetes tended to swim faster during periods of shooting (Stone and Tasker 2006). For most types of small odontocetes sighted by observers on seismic vessels, the median CPA distance was ≥0.5 km larger during airgun operations (Stone and Tasker 2006). Killer whales appeared to be more tolerant of seismic shooting in deeper waters.

During two NSF-funded L-DEO seismic surveys that used 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 detections via a towed passive acoustic monitoring (PAM) array, including both 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 distance of delphinids during seismic operations there was 472 m compared with 178 m when the airguns were not operational (Holst et al. 2005a). The acoustic detection rates were nearly 5 times higher during non-seismic compared with seismic operations (Holst et al. 2005a).

During two seismic surveys off Newfoundland and Labrador in 2004–05, dolphin sighting rates were higher during non-seismic periods than during seismic periods after taking temporal factors into account, although the difference was statistically significant only in 2004 (Moulton et al. 2005, 2006a). In 2005, the mean CPA distance of dolphins was significantly closer during non-seismic periods (652 m vs. 807 m); in 2004, the corresponding difference was not significant.

Among Atlantic spotted dolphins off Angola (n = 16 useable groups), marked short-term and localized displacement was found in response to seismic operations conducted with a 24-airgun array (3147 in^3 or 5085 in^3) (Weir 2008). Sample sizes were low, but CPA distances of dolphin groups were significantly larger when airguns were on (mean 1080 m) vs. off (mean 209 m). No Atlantic spotted dolphins were seen within 500 m of the airguns when they were operating, whereas all sightings when airguns were silent occurred within 500 m, including the only recorded "positive approach" behaviors.

Reactions of toothed whales to a single airgun or other small airgun source are not well documented, but tend to be less substantial than reactions to large airgun arrays (e.g., Stone 2003; Stone and Tasker 2006). Effects on orientation were evident for all species tested (Stone and Tasker 2006). Results from three NSF-funded L-DEO seismic surveys using small arrays (up to 3 GI guns and 315 in^3) were inconclusive. During a survey in the Eastern Tropical Pacific (Holst et al. 2005b) and in the

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[7] Large volume means at least 1300 in^3, with most (79%) at least 3000 in^3.

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. 2005b), 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 transient sounds 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.

Odontocete responses (or lack of responses) to noise pulses from underwater explosions (as opposed to airgun pulses) may be indicative 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 causing auditory impairment (see below), 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.

Phocoenids (Porpoises).—Porpoises, like delphinids, show variable reactions to seismic operations, and reactions apparently depend on species. The limited available data suggest that harbor porpoises show stronger avoidance of seismic operations than Dall's porpoises (Stone 2003; MacLean and Koski 2005; Bain and Williams 2006). In Washington State waters, the harbor porpoise—despite being considered a high-frequency specialist—appeared to be the species affected by the lowest received level of airgun sound (<145 dB re 1 μPa_{rms} at a distance >70 km; Bain and Williams 2006). Similarly, during seismic surveys with large airgun arrays off the U.K. in 1997–2000, there were significant differences in directions of travel by harbor porpoises during periods when the airguns were shooting vs. silent (Stone 2003; Stone and Tasker 2006). In contrast, Dall's porpoises seem relatively tolerant of airgun operations (MacLean and Koski 2005; Bain and Williams 2006), although they too have been observed to avoid large arrays of operating airguns (Calambokidis and Osmek 1998; Bain and Williams 2006). The apparent tendency for greater responsiveness in the harbor porpoise is consistent with their relative responsiveness to boat traffic and some other acoustic sources (Richardson et al. 1995; Southall et al. 2007).

Beaked Whales.—There are almost 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 may also dive for an extended period when approached by a vessel (e.g., Kasuya 1986). Thus, it is likely that these beaked whales would also show strong avoidance of an approaching seismic vessel, regardless of whether or not the airguns are operating. However, this has not been documented explicitly. Northern bottlenose whales sometimes are quite tolerant of slow-moving vessels not emitting airgun pulses (Reeves et al. 1993; Hooker et al. 2001). The few detections (acoustic or visual) of northern bottlenose whales from seismic vessels during recent seismic surveys off Nova Scotia have been during times when the airguns were shut down; no detections were reported when the airguns were operating (Moulton and Miller 2005; Potter et al. 2007). However, separate acoustic studies indicated that northern bottlenose whales continued to produce high-frequency clicks when exposed to sound pulses from distant seismic surveys (Laurinolli and Cochrane 2005; Simard et al. 2005).

There are increasing indications that some beaked whales tend to strand when military exercises involving mid-frequency 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 or other physiological effects 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. No conclusive link has been established between seismic surveys and beaked whale strandings. There was a stranding of two 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; Hildebrand 2005). However, NMFS did not establish a cause and effect relationship between this stranding and the seismic survey activities (Hogarth 2002). Cox et al. (2006) noted the "lack of knowledge regarding the temporal and spatial correlation between the [stranding] and the sound source". Hildebrand (2005) illustrated the approximate temporal-spatial relationships between the stranding and the *Ewing*'s tracks, but the time of the stranding was not known with sufficient precision for accurate determination of the CPA distance of the whales to the *Ewing*. Another stranding of Cuvier's beaked whales in the Galápagos 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).

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). However, most studies of the sperm whale *Physeter macrocephalus* exposed to airgun sounds indicate that this species shows considerable tolerance of airgun pulses. The whales usually do not show strong avoidance (i.e., they do not leave the area) and they continue to call.

There were some early and 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. However, other operations in the area could also have been a factor (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 was an early preliminary account of possible long-range avoidance of seismic vessels by sperm whales in the Gulf of Mexico (Mate et al.

1994). However, this has not been substantiated by subsequent more detailed work in that area (Gordon et al. 2006; Jochens et al. 2006; Winsor and Mate 2006).

Recent and more extensive data from vessel-based monitoring programs in U.K. waters and off Newfoundland and Angola suggest that sperm whales in those areas show little evidence of avoidance or behavioral disruption in the presence of operating seismic vessels (Stone 2003; Stone and Tasker 2006; Moulton et al. 2005, 2006a; Weir 2008). Among sperm whales off Angola (n = 96 useable groups), there were no significant differences in encounter rates (sightings/hr) when a 24-airgun array (3147 in^3 or 5085 in^3) was operating vs. silent (Weir 2008). There was also no significant difference in the CPA distances of the sperm whale sightings when airguns were on vs. off (means 3039 m vs. 2594 m, respectively). Encounter rate tended to increase over the 10-month duration of the seismic survey. These types of observations are difficult to interpret because the observers are stationed on or near the seismic vessel, and may underestimate reactions by some of the more responsive animals, which may be beyond visual range. However, these results do seem to show considerable tolerance of seismic surveys by at least some sperm whales. Also, a 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_{p-p} (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).

A detailed study of sperm whale reactions to seismic surveys has been done recently in the Gulf of Mexico (Jochens et al. 2006; Gordon et al. 2006; Madsen et al. 2006; Winsor and Mate 2006). Controlled exposure experiments indicated that "neither gross diving behavior nor direction of movement changed for any of the eight exposed whales at the onset of gradual ramp up at ranges of 7.3–12.5 km, nor during full power exposures at distances 1.5–12.8 km. Acoustic exposure ranged from <130 to 162 dB re 1 μPa_{p-p}" (Jochens et al. 2006:14). However, there was evidence that foraging behavior was altered upon exposure to airgun sound at levels ranging from <130 to 162 dB re 1 μPa_{p-p} at distances of roughly 1–12 km from the sound source (Jochens et al. 2006:14).

Discussion and Conclusions.—Dolphins and porpoises are often seen by observers on active seismic vessels, occasionally at close distances (e.g., bow riding). However, some studies near the U.K., Newfoundland and Angola have shown localized avoidance. Also, belugas summering in the Canadian Beaufort Sea showed larger-scale avoidance, tending to avoid waters out to 10–20 km from operating seismic vessels. In contrast, recent studies show little evidence of conspicuous reactions by sperm whales to airgun pulses, contrary to earlier indications.

There are almost 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. Northern bottlenose whales seem to continue to call when exposed to pulses from distant seismic vessels.

Overall, 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 some mysticetes. However, other data suggest that some odontocetes species, including belugas and harbor porpoises, may be more responsive than might be expected given their poor low-frequency hearing. Reactions at longer distances may be particularly likely when sound propagation conditions are conducive to transmission of the higher-frequency components of airgun sound to the animals' location (DeRuiter et al. 2006; Goold and Coates 2006; Tyack et al. 2006; Potter et al. 2007).

For delphinids, and possibly the Dall's porpoise, the available data suggest that a ≥170 dB re 1 μPa_{rms} disturbance criterion (rather than ≥160 dB) would be appropriate. The 160 dB (rms) criterion currently applied by NMFS was developed based primarily on data from gray and bowhead whales. Avoidance distances for delphinids and Dall's porpoises tend to be shorter than for those two mysticete species. For delphinids and Dall's porpoises, there is no indication of strong avoidance or other disruption of behavior at distances beyond those where received levels would be ~170 dB re 1 μPa_{rms} (on the order of 2 or 3 km for a large airgun array).

5.3 Pinnipeds

Few studies of the reactions of pinnipeds to noise from open-water seismic exploration have been published (for review of the early literature, 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, gray 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 demonstrated short-term changes in the behavior of harbor (=common) and gray seals exposed to airgun pulses (Thompson et al. 1998). Harbor seals were exposed to seismic pulses from a 90 in^3 array (3 × 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. Gray 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 gray 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). Bain and Williams (2006) also stated that their small sample of harbor seals and sea lions tended to orient and/or move away upon exposure to sounds from a large airgun array.

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. Subsequent monitoring work in the Canadian Beaufort Sea in 2001–2002, with a somewhat larger airgun system (24 airguns, 2250 in^3), provided similar results (Miller et al. 2005).

The combined results suggest that some seals avoid the immediate area around seismic vessels. In most survey years, ringed seal sightings averaged somewhat farther away from the seismic vessel when the airguns were operating than when they were not (Moulton and Lawson 2002). Also, seal sighting rates at the water surface were lower during airgun array operations than during no-airgun periods in each survey year except 1997. However, the 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.

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 airguns (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. 2005). During 2001, sighting rates of seals (mostly ringed seals) were similar during all seismic states, including periods without airgun operations. However, seals tended to be 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. (2005) 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. This minimal tendency for avoidance is a concern. It suggests that one cannot rely on pinnipeds to move away before received levels of sound from an approaching seismic survey vessel approach those that may cause hearing impairment (see below). However, previous telemetry work suggests that avoidance and other behavioral reactions may be stronger than evident to date from visual studies.

5.4 Sirenians, Sea Otter and Polar Bear

We are not aware of any information on the reactions of sirenians to airgun sounds.

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 airgun array. No disturbance reactions were evident when the airgun array was as close as 0.9 km. Sea otters also did not respond noticeably to the single airgun. These results suggest that sea otters may be less responsive to marine seismic pulses than some other marine mammals, such as mysticetes and odontocetes (summarized above). Also, sea otters spend a great deal of time at the surface feeding and grooming (Riedman 1983, 1984). While at the surface, the potential noise exposure of sea otters would be much reduced by pressure-release and interference (Lloyd's mirror) effects at the surface (Greene and Richardson 1988; Richardson et al. 1995).

Airgun effects on polar bears have not been studied. However, polar bears on the ice would be largely unaffected by underwater sound. Sound levels received by polar bears in the water would be attenuated because polar bears generally do not dive much below the surface and received levels of airgun sounds are reduced near the surface because of the aforementioned pressure release and interference effects at the water's surface.

6. Hearing Impairment and Other Physical Effects of Seismic Surveys

Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds, and temporary threshold shift (TTS) has been demonstrated and studied in certain captive odontocetes and pinnipeds exposed to strong sounds (reviewed in Southall et al. 2007). However, there has been no specific documentation of TTS let alone permanent hearing damage, i.e. permanent threshold shift (PTS), in free-ranging marine mammals exposed to sequences of airgun pulses during realistic field conditions. 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 (NMFS 2000). Those criteria have been used in establishing the safety (=shut-down) radii planned for numerous seismic surveys conducted under U.S. jurisdiction. 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.
- TTS is not injury and does not constitute "Level A harassment" in U.S. 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. The actual PTS threshold is likely to be well above the level causing onset of TTS (Southall et al. 2007).

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 PTS thresholds, differences in the acoustic frequencies to which different marine mammal groups are sensitive, and other relevant factors. Preliminary information about this process, and about the anticipated structure of the new criteria, was given by Wieting (2004) and NMFS (2005). Detailed recommendations for new science-based noise exposure criteria for marine mammals, frequency-weighting procedures, and related matters were published recently (Southall et al. 2007).

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 and (to a limited degree) pinnipeds show some avoidance of the area where received levels of airgun sound are high enough such that hearing impairment could potentially occur. In those 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. The following subsections summarize available data on noise-induced hearing impairment and non-auditory physical effects.

6.1 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. It is a temporary phenomenon, and (especially when mild) is not considered to represent physical damage or “injury” (Southall et al. 2007). Rather, the onset of TTS is an indicator that, if the animal 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 (Kryter 1985; Richardson et al. 1995; Southall et al. 2007). For sound exposures at or somewhat above the TTS threshold, hearing sensitivity recovers rapidly after exposure to the noise ends. In terrestrial mammals, TTS can last from minutes or hours to (in cases of strong TTS) days. Only a few data have been obtained on sound levels and durations necessary to elicit mild TTS in marine mammals (none in mysticetes), and none of the published data concern TTS elicited by exposure to multiple pulses of sound during operational seismic surveys (Southall et al. 2007).

Toothed Whales.—There are empirical data on the sound exposures that elicit onset of TTS in captive bottlenose dolphins and belugas. The majority of these data concern non-impulse sound, but there are some limited published data concerning TTS onset upon exposure to a single pulse of sound from a watergun (Finneran et al. 2002). A detailed review of all TTS data from marine mammals can be found in Southall et al. (2007). The following summarizes some of the key results from odontocetes, emphasizing data on TTS in response to impulse noise.

Recent information corroborates earlier expectations that the effect of exposure to strong transient sounds is closely related to the total amount of acoustic energy that is received. Finneran et al. (2005) examined the effects of tone duration on TTS in bottlenose dolphins. Bottlenose dolphins were exposed to 3 kHz tones (non-impulsive) 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 an 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 belugas exposed to tones of durations 1–8 s (i.e., TTS onset occurs at a near-constant SEL, independent of exposure duration). That implies that, at least for non-impulsive tones, 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 to 172 dB re 1 μPa for periods of 1.8 to 30 min. Recovery time depended on the shift and frequency, but full recovery always occurred within 40 min. Consistent with the results of Finneran et al. (2005) based on shorter exposures, Mooney et al. 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. In other words, for toothed whales receiving single short exposures to non-impulse sound, the TTS threshold appears to be, to a first approximation, a function of the total energy received (Finneran et al. 2002, 2005).

The TTS threshold for odontocetes exposed to a single impulse from a watergun (Finneran et al. 2002) appeared to be somewhat lower than for exposure to non-impulse sound. This was expected, based on evidence from terrestrial mammals showing that broadband pulsed sounds with rapid rise times have greater auditory effect than do non-impulse sounds (Southall et al. 2007). The received energy level of a single seismic pulse that caused the onset of mild TTS in the beluga, as measured without frequency weighting, was ~186 dB re 1 $\mu Pa^2 \cdot s$ or 186 dB SEL (Finneran et al. 2002).[8] The rms level of an airgun pulse (in dB re 1 μPa measured over the duration of the pulse) is typically 10–15 dB higher than the SEL for the same pulse when a few kilometers of the airguns. Thus, a single airgun pulse might need to have a received level of ~196–201 dB re 1 μPa_{rms} in order to produce brief, mild TTS. Exposure to several strong seismic pulses that each have flat-weighted received levels near 190 dB_{rms} (175–180 dB SEL) could result in cumulative exposure of ~186 dB SEL (flat-weighted) or ~183 dB SEL (M_{mf}-weighted), and thus slight TTS in a small odontocete. That assumes that the TTS threshold upon exposure to multiple pulses is (to a first approximation) a function of the total received pulse energy, without allowance for any recovery between pulses.

Insofar as we are aware, there are no published data confirming that the auditory effect of a sequence of airgun pulses received by an odontocete is a function of their cumulative energy. Southall et al. (2007) consider that to be a reasonable, but probably somewhat precautionary, assumption. It is precautionary because, based on data from terrestrial mammals, one would expect that a given energy exposure would have somewhat less effect if separated into discrete pulses, with potential opportunity for partial auditory recovery between pulses. However, as yet there has been little study of the rate of recovery from TTS in marine mammals, and in humans and other terrestrial mammals the available data on recovery are quite variable. Southall et al. (2007) conclude that—until relevant data on recovery are available from marine mammals—it is appropriate not to allow for any assumed recovery during the intervals between pulses within a pulse sequence.

The above TTS information for odontocetes is derived from studies on the bottlenose dolphin and beluga. There is no published TTS information for other types of cetaceans. However, preliminary evidence from a harbor porpoise exposed to airgun sound suggests that its TTS threshold may have been lower (Lucke et al. 2007).

Additional data are needed 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. To determine how close an airgun array would need to approach in order to elicit TTS, it is necessary to determine the total energy that a mammal would receive as an airgun array approaches, passes at various CPA distances, and moves away. At the present state of knowledge, it is also necessary to assume that the effect is directly related to total received 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

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[8] If the low-frequency components of the watergun sound used in the experiments of Finneran et al. (2002) are downweighted as recommended by Miller et al. (2005a) and Southall et al. (2007) using their M_{mf}-weighting curve, the effective exposure level for onset of mild TTS was 183 dB re 1 $\mu Pa^2 \cdot s$ (Southall et al. 2007).

toothed whales when the signal is a series of pulsed sounds, separated by silent periods, remains a data gap, as is the lack of published data on TTS in odontocetes other than the beluga and bottlenose dolphin.

***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 assumed to be 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 (Southall et al. 2007).

In practice during seismic surveys, few if any 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.[9]

***Pinnipeds*.**—In pinnipeds, TTS thresholds associated with exposure to brief pulses (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 more prolonged (non-pulse) exposures suggested that some pinnipeds (harbor seals in particular) incur TTS at somewhat lower received levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001). Kastak et al. (2005) reported that the amount of threshold shift increased with increasing SEL in a California sea lion and harbor seal. They noted that, for non-impulse sound, doubling the exposure duration from 25 to 50 min (i.e., a +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 2.9–12.2 dB, with full recovery within 24 hr (Kastak et al. 2005). Kastak et al. (2005) suggested that, for non-impulse sound, SELs resulting in TTS onset in three species of pinnipeds may range from 183 to 206 dB re 1 $\mu Pa^2 \cdot s$, depending on the absolute hearing sensitivity.

As noted above for odontocetes, it is expected that—for impulse as opposed to non-impulse sound—the onset of TTS would occur at a lower cumulative SEL given the assumed greater auditory effect of broadband impulses with rapid rise times. The threshold for onset of mild TTS upon exposure of a harbor seal to impulse sounds has been estimated indirectly as being an SEL of ~171 dB re 1 $\mu Pa^2 \cdot s$ (Southall et al. 2007). That would be approximately equivalent to a single pulse with received level ~181–186 dB re 1 μPa_{rms}, or a series of pulses for which the highest rms values are a few dB lower.

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[9] Three species of baleen whales that have been exposed to the onset of pulses from single airguns showed avoidance, specifically *gray whales* [Malme et al. 1984, 1986, 1988]; *bowhead whales* [Richardson et al. 1986, Ljungblad et al. 1988] and *humpback whales* [Malme et al. 1985, McCauley et al. 1998, 2000a, b]. Since startup of a single airgun is equivalent to the start of a ramp-up (=soft start), this strongly suggests that many baleen whales will begin to move away during the initial stages of a ramp-up.

At least for non-impulse sounds, TTS onset occurs at appreciably higher received levels in California sea lions and northern elephant seals than in harbor seals (Kastak et al. 2005). Thus, the former two species would presumably need to be closer to an airgun array than would a harbor seal before TTS is a possibility. Insofar as we are aware, there are no data to indicate whether the TTS thresholds of other pinniped species are more similar to those of the harbor seal or to those of the two less-sensitive species.

***Sirenians, Sea Otter and Polar Bear*.—**There are no available data on TTS in sea otters and polar bears. However, TTS is considered unlikely to occur in sea otters or polar bears if they are on the water surface, given the pressure release and Lloyd's mirror effects at the water's surface. Furthermore, sea otters tend to inhabit shallow coastal habitats where large seismic survey vessels towing large spreads of streamers may be unable to operate. TTS is also considered unlikely to occur in sirenians as a result of exposure to sounds from a seismic survey. They, like sea otters, tend to inhabit shallow coastal habitats and rarely range far from shore, whereas seismic survey vessels towing large arrays of airguns and (usually) even larger arrays of streamers normally must remain farther offshore due to equipment clearance and maneuverability limitations. Exposures of sea otters and sirenians to seismic surveys are more likely to involve smaller seismic sources that can be used in shallow and confined waters. The impacts of these are inherently less than would occur from a larger source of the types often used farther offshore.

Likelihood of Incurring TTS.—Most cetaceans show some degree of avoidance of seismic vessels operating an airgun array (see above). 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 the surface and thus not exposed to strong sound pulses given the pressure-release and Lloyd Mirror effects 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. However, even a temporary reduction in hearing sensitivity could be deleterious in the event that, during that period of reduced sensitivity, a marine mammal needed its full hearing sensitivity to detect approaching predators, or for some other reason.

Some pinnipeds show avoidance reactions to airguns, but their avoidance reactions are not as strong or consistent as those of cetaceans. Pinnipeds occasionally seem to be attracted to operating seismic vessels. There are no specific data on TTS thresholds of pinnipeds exposed to single or multiple low-frequency pulses. However, given the indirect indications of a lower TTS threshold for the harbor seal than for odontocetes exposed to impulse sound (see above), it is possible that some pinnipeds close to a large airgun array could incur TTS.

NMFS (1995, 2000) concluded that cetaceans should not be exposed to pulsed underwater noise at received levels >180 dB re 1 μPa_{rms}. The corresponding limit for pinnipeds has been set by NMFS at 190 dB, although the HESS Team (HESS 1999) recommended a 180-dB limit for pinnipeds in California. The 180 and 190 dB re 1 μPa_{rms} levels have not been 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 in various odontocetes (and probably mysticetes as well) unless they are exposed to a sequence of several airgun pulses stronger than 190 dB re 1 μPa_{rms}. On the other hand, for the harbor seal and any species with similarly low TTS thresholds (possibly including the harbor porpoise—Lucke et al. 2007), TTS may occur upon exposure to one or more airgun pulses whose received level equals the NMFS "do not exceed" value of 190 dB re 1 μPa_{rms}. That criterion corresponds to a single-pulse SEL of 175–180 dB re 1 $\mu Pa^2 \cdot s$ in typical conditions, whereas TTS is suspected to be possible (in harbor seals) with a cumulative SEL of ~171 dB re 1 $\mu Pa^2 \cdot s$.

It has been shown that most large whales and many smaller odontocetes show at least localized avoidance of ships and associated seismic operations (see above). Even when avoidance is limited to the area within a few hundred meters of an airgun array, that should usually be sufficient to avoid the possibility of TTS based on what is currently known about thresholds for TTS onset in cetaceans. In addition, ramping up airgun arrays, which is standard operational protocol for many seismic operators, should allow cetaceans near the airguns at the time of startup to move away from the seismic source and to avoid being exposed to the full acoustic output of the airgun array (see above). Thus, most baleen whales likely will not be exposed to high levels of airgun sounds provided the ramp-up procedure is applied. Likewise, many whales close to the trackline are likely to move away before the sounds from an approaching seismic vessel become sufficiently strong for there to be any potential for TTS or other hearing impairment. Therefore, there is little potential for baleen whales or odontocetes that show avoidance of ships or airguns to be close enough to an airgun array to experience TTS. In the event that a few individual cetaceans did incur TTS through exposure to strong airgun sounds, this is a temporary and reversible phenomenon unless the exposure exceeds the TTS-onset threshold by a sufficient amount such that PTS is also incurred (see below). If TTS but not PTS were incurred, it would most likely be mild, in which case recovery is expected to be quick (probably within minutes).

6.2 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, while in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges (Kryter 1985). 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 increase from the baseline pressure to peak pressure).

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 above), there has been further speculation about the possibility that some individuals occurring very close to airguns might incur PTS (Richardson et al. 1995, p. 372*ff*).

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 (Southall et al. 2007). 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 >6 dB higher (Southall et al. 2007). The low-to-moderate levels of TTS that have been induced in captive odontocetes and pinnipeds during 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, 2005; 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 (e.g., from explosions) can result in PTS even though their peak levels are only a few dB higher than the level causing slight TTS. The rise time of airgun pulses is fast, but not as fast as that of an explosion.

Some factors that contribute to onset of PTS, at least in terrestrial mammals, are as follows:

- exposure to single very intense sound,
- fast rise time from baseline to peak pressure,
- 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) 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.

More recently, Southall et al. (2007) estimated that received levels would need to exceed the TTS threshold by at least 15 dB, on an SEL basis, for there to be risk of PTS. Thus, for cetaceans exposed to a sequence of sound pulses, they estimate that the PTS threshold might be an M-weighted SEL of ~198 dB re 1 $\mu Pa^2 \cdot s$ (15 dB higher than the TTS threshold for an impulse), where the SEL value is cumulated over the sequence of pulses. Additional assumptions had to be made to derive a corresponding estimate for pinnipeds, as the only available data on TTS-thresholds in pinnipeds pertain to non-impulse sound (see above). Southall et al. (2007) estimated that the PTS threshold could be a cumulative M_{pw}-weighted SEL of ~186 dB re 1 $\mu Pa^2 \cdot s$ in the case of a harbor seal exposed to impulse sound. The PTS threshold for the California sea lion and northern elephant seal would probably be higher given the higher TTS thesholds in those species. Southall et al. (2007) also note that, regardless of the SEL, there is concern about the possibility of PTS if a cetacean or pinniped received one or more pulses with peak pressure exceeding 230 or 218 dB re 1 µPa, respectively.

Sound impulse duration, peak amplitude, rise time, number of pulses, and inter-pulse interval are the main factors thought to determine the onset and extent of PTS. 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.

As described above for TTS, in estimating the amount of sound energy required to elicit the onset of TTS (and PTS), it is assumed that the auditory effect of a given cumulative SEL from a series of pulses is the same as if that amount of sound energy were received as a single strong sound. There are no data from marine mammals concerning the occurrence or magnitude of a potential partial recovery effect between pulses. In deriving the estimates of PTS (and TTS) thresholds quoted here, Southall et al. (2007) made the precautionary assumption that no recovery would occur between pulses.

The TTS section (above) concludes that exposure to several strong seismic pulses that each have flat-weighted received levels near 190 dB re 1 μPa_{rms} (175–180 dB re 1 $\mu Pa^2 \cdot s$ SEL) could result in cumulative exposure of ~186 dB SEL (flat-weighted) or ~183 dB SEL (M_{mf}-weighted), and thus slight

TTS in a small odontocete. Allowing for the assumed 15 dB offset between PTS and TTS thresholds, exposure to several strong seismic pulses that each have flat-weighted received levels near 205 dB_{rms} (190–195 dB SEL) could result in cumulative exposure of ~198 dB SEL (M_{mf}-weighted), and thus slight PTS in a small odontocete. However, the levels of successive pulses that will be received by a marine mammal that is below the surface as a seismic vessel approaches, passes and moves away will tend to increase gradually and then decrease gradually, with periodic decreases superimposed on this pattern when the animal comes to the surface to breathe. To estimate how close an odontocete's CPA distance would have to be for the cumulative SEL to exceed 198 dB SEL (M_{mf}-weighted), one would (as a minimum) need to allow for the sequence of distances at which airgun shots would occur, and for the dependence of received SEL on distance in the region of the seismic operation.

It is unlikely that an odontocete would remain close enough to a large airgun for sufficiently long to incur PTS. There is some concern about bowriding odontocetes, but for animals at or near the surface, auditory effects are reduced by Lloyd's mirror and surface release effects. The TTS (and thus PTS) thresholds of baleen whales are unknown but, as an interim measure, assumed to be no lower than those of odontocetes. Also, 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. The TTS (and thus PTS) thresholds of some pinnipeds (e.g., harbor seal) and perhaps also the harbor porpoise may be lower (Lucke et al. 2007; Southall et al. 2007). If so, TTS and potentially PTS may extend to a somewhat greater distance for those animals. Again, Lloyd's mirror and surface release effects will ameliorate the effects for animals at or near the surface.

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, pinnipeds, and sea otters. The avoidance reactions of many marine mammals, along with commonly-applied monitoring and mitigation measures (visual and passive acoustic monitoring, ramp ups, and power downs or shut downs when mammals are detected within or approaching the "safety radii"), would reduce the already-low probability of exposure of marine mammals to sounds strong enough to induce PTS.

6.3 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). However, explosives are no longer used either for seismic research or for commercial seismic surveys in marine areas; they have been replaced by airguns and other non-explosive sources. Airgun pulses are less energetic and have slower rise times, and there is no specific evidence 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 and, in one case, a seismic survey (Malakoff 2002; Cox et al. 2006), 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 (e.g., Hildebrand 2005; Southall et al. 2007). Hildebrand (2005) reviewed the association of cetacean strandings with high-intensity sound events and found that deep-diving odontocetes, primarily beaked whales, were by far the predominant (95%) cetaceans associated with these events, with 2% mysticete whales (minke). However, as summarized below, there is no definitive evidence that airguns can lead to injury, strandings, or mortality even for marine mammals in close proximity to large airgun arrays.

Specific sound-related processes that lead to strandings and mortality are not well documented, but may include (1) swimming in avoidance of a sound into shallow water; (2) a change in behavior (such as a change in diving behavior that might contribute to tissue damage, gas bubble formation, hypoxia, cardiac arrhythmia, hypertensive hemorrhage or other forms of trauma; (3) a physiological change such as a vestibular response leading to a behavioral change or stress-induced hemorrhagic diathesis, leading in turn to tissue damage; and (4) tissue damage directly from sound exposure, such as through acoustically mediated bubble formation and growth or acoustic resonance of tissues. There are increasing indications that gas-bubble disease (analogous to "the bends"), induced in supersaturated tissue by a behavioral response to acoustic exposure, could be a pathologic mechanism for the strandings and mortality of some deep-diving cetaceans exposed to sonar. However, the evidence for this remains circumstantial and associated with exposure to naval mid-frequency sonar, not seismic surveys (Cox et al. 2006; Southall et al. 2007).

Seismic pulses and mid-frequency sonar signals are quite different, and some mechanisms by which sonar sounds have been hypothesized to affect beaked whales are unlikely to apply to airgun pulses. Sounds produced by airgun arrays are broadband impulses with most of the energy below 1 kHz. Typical military mid-frequency sonars emit non-impulse sounds at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time (though the frequency may change over time). Thus, it is not appropriate to assume that the effects of seismic surveys on beaked whales or other species would be the same as the apparent effects of military sonar. For example, resonance effects and acoustically-mediated bubble-growth are implausible in the case of exposure to broadband airgun pulses. Nonetheless, evidence that sonar signals can, in special circumstances, lead (at least indirectly) to physical damage and mortality (e.g., Balcomb and Claridge 2001; NOAA and USN 2001; Jepson et al. 2003; Fernández et al. 2004, 2005; Hildebrand 2005; Cox et al. 2006) suggests that caution is warranted when dealing with exposure of marine mammals to any high-intensity pulsed sound. One of the hypothesized mechanisms by which naval sonars lead to strandings might, in theory, also apply to seismic surveys: If the strong sounds sometimes cause deep-diving species to alter their surfacing–dive cycles in a way that causes bubble formation in tissue, that hypothesized mechanism might apply to seismic surveys as well as mid-frequency naval sonars.

There is no conclusive evidence of cetacean strandings or deaths at sea as a result of exposure to seismic surveys, but a few cases of strandings in the general area where a seismic survey was ongoing have led to speculation concerning a possible link between seismic surveys and strandings. • Suggestions that there was a link between seismic surveys and strandings of humpback whales in Brazil (Engel et al. 2004) were not well founded (IAGC 2004; IWC 2007b). • In Sept. 2002, there was a stranding of two Cuvier's beaked whales in the Gulf of California, Mexico, when the L-DEO seismic vessel R/V *Maurice Ewing* was operating a 20-airgun, 8490-in^3 airgun array in the general area. The evidence linking the stranding to the seismic survey 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 this had much less potential than the aforementioned naval sonars to affect beaked whales (see below). Nonetheless, the Gulf of California incident plus the beaked whale strandings near naval exercises involving use of mid-frequency sonar suggest a need for caution in conducting seismic surveys in areas occupied by beaked whales until more is known about effects of seismic surveys on those species (Hildebrand 2005).

6.4 Non-Auditory Physiological Effects

Based on evidence from terrestrial mammals and humans, sound is a potential source of stress. However, almost no information is available on sound-induced stress in marine mammals, or on its potential to affect the long-term well-being or reproductive success of odontocetes (Fair and Becker 2000; Hildebrand 2005). Such effects, if they occur at all, would be mainly associated with chronic noise exposure, which is not characteristic of most seismic surveys.

Romano et al. (2004) examined the effects of single underwater impulse sounds from a seismic water gun (up to 228 dB re 1 μPa · $m_{p\text{–}p}$) 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 hr. Further information about the occurrence of noise-induced stress in marine mammals is not available at this time.

Other types of physiological effects that have been mentioned as perhaps being involved in beaked whale strandings upon exposure to naval sonar (Cox et al. 2006), such as resonance and gas bubble formation, have not been demonstrated to occur upon exposure to airgun pulses. Resonance (Gentry 2002) and direct noise-induced bubble formation (Crum et al. 2005) are not expected in the case of an impulsive source like an airgun array. If seismic surveys disrupt diving patterns of deep-diving species, this might perhaps result in bubble formation and a form of "the bends", as speculated to occur in beaked whales exposed to sonar. However, there is no specific evidence of this upon exposure to airgun pulses.

In summary, very little is known about the potential for seismic survey sounds (or other types of strong underwater sounds) to cause non-auditory physiological effects in marine mammals. Such effects, if they occur at all, would presumably be limited to short distances and to activities that extend over a prolonged period. The available data do not allow identification of a specific exposure level above which non-auditory effects can be expected (Southall et al. 2007), or any meaningful quantitative predictions of the numbers (if any) of marine mammals that might be affected in these ways.

7. Characteristics and Effects of Sonar Sounds

The following subsections review relevant information on the potential effects of sonar sounds on marine mammals. Discussion focuses on the types of systems operated during some marine seismic surveys, including multibeam echosounders (MBESs), sub-bottom profilers (SBPs), acoustic current profilers (ACP), fathometers, and pingers. These systems are used to obtain information on (and map) water depths, bottom topography, and sub-bottom composition and stratigraphy; to monitor ocean currents; to track fish and concentrations of invertebrates; to locate and track hydrophone streamers and coring gear; and for other purposes. Relatively few studies have been conducted on the effects of these and other types of sonar systems on marine mammals. Given this, the present section also summarizes relevant data on the effects of other types of sonars similar to those used during some seismic surveys.

7.1 Characteristics of Sonar Pulses

Sonar is an acronym for sound navigation and ranging. Sonar is a technique that uses sound to determine water depth below a vessel and/or to detect and determine the position of underwater objects such as fish, geological features on the seafloor, mines, or underwater vessels.

Two broad categories of sonar are in use: passive and active sonar. Passive sonar involves listening to sounds created by other sources, but does not include the purposeful emission of sound. Active sonar involves emission of sounds with characteristics optimized for the specific purpose of that sonar. This section focuses on the available information concerning effects of active sonar on marine mammals.

Active sonar systems emit sound, some of which is reflected back if it strikes an object. Because the speed of sound in water is relatively constant, the distance to the object can be calculated by measuring the time between the transmission of the signal and the receipt of the reflected echo. Experienced sonar technicians often can tell the difference between echoes produced by a submarine, rocky outcrop, school of fish, or whale. Active sonars are in use throughout the world on private, commercial, research, and military vessels.

Because active sonars produce sound, they have the potential to impact the marine environment. This potential is a function of the output power, beamwidth, duty cycle of the device, the frequency of the sound, and the sound transmission characteristics of the marine environment. (Duty cycle refers to the percentage of the time when the source is emitting sound.) The potential for impact on an animal also depends on the animal's distance, position relative to the sonar beam, and the received sound level as well as the animal's auditory and behavioral sensitivity.

The auditory effects of sonar depend on whether the emitted sounds are impulsive or non-impulsive. Impulsive sounds involve very rapid increases in pressure (rapid rise time) and are broadband. Most sonar pulses are considered non-impulsive, in part because they are often narrowband (reviewed in Southall et al. 2007). In general, any sound that is a tone (rather than broadband), even it if it called a "tone pulse", is in the non-impulse category (see Southall et al. 2007). Examples of non-impulse sounds include military low-frequency active (LFA) sonar and tactical mid-frequency sonar, many acoustic harassment/deterrent devices, acoustic tomography sources (ATOC), and some signals from depth sounders. Examples of single or multiple impulse sounds include those from seismic airguns, some depth sounders and pingers, pile strikes, and explosions (Southall et al. 2007).

The characteristics of an active sonar system depend on the purpose of the system. A system that is required to detect objects at great distances necessitates a higher output strength (and lower frequency) than sonar systems designed to detect nearby objects. One way of classifying active sonars is by frequency (i.e., high, medium, and low frequency). Herein, high frequency is >10 kHz, medium frequency is 1 kHz up to 10 kHz, and low frequency is <1 kHz. .

***High-frequency (HF) Sonar (>10 kHz)*.—**These sonars typically operate at frequencies >10 kHz and provide excellent resolution for locating small objects such as fish, zooplankton, and mines, and for mapping the sea-bed. Higher frequency sounds attenuate more rapidly in seawater than do lower frequency sounds. Hence, HF sonar systems are most practical for use in shallow water or over short distances. Side-scan sonars are among the most commonly used HF sonars available; they are used for object detection and sea-bed mapping. Side-scan sonars typically operate with a narrow along-track beamwidth (0.75–1.5º), a moderately broad vertical beamwidth (5–10º), and an operating frequency of ≥100 kHz. The range over which targets can be resolved is usually <1.6 km at the higher frequencies, and as much as 10 km at the lower-frequency end of the HF band. Forward-looking sonars are used for obstacle detection and avoidance, and are useful for fish-finding and area surveillance. These sonars may be pulsed or use continuous-transmission frequency modulation. Downward-looking HF sonars (consisting either of a single beam or a multibeam array) may also be used for bottom mapping, fish-finding, estimation of zooplankton biomass, or depth-sounding in shallow to intermediate water depths. MBES systems, in which downward-pointing beams are directed vertically below and to the side of a ship, are commonly used to map the bottom contours. MBES systems have beams that are narrow in the fore-aft direction and broader in directions perpendicular to the trackline. MBES systems designed for use in deep water operate in the lower-frequency portion of the HF band (e.g., 10–15.5 kHz) whereas MBESs designed for shallower areas may operate at higher frequencies.

***Mid-frequency (MF) Sonar (1–10 kHz)*.—**Mid- or medium-frequency sonars emit sounds at frequencies of 1–10 kHz. MF tactical sonars are used on naval vessels around the world and typically have a relatively narrow bandwidth at any one time (though the center frequency may change over time). Compared to HF systems, MF sonars have an extended detection range because of the decreased absorption of MF sound in seawater. However, they require a larger transducer array to achieve the same beamwidth. These systems may have a range of 10 to >100 km.

***Low-frequency (LF) Sonar (<1 kHz)*.—**Low-frequency sonars emit sounds at frequencies <1 kHz. The negligible attenuation of LF sound in seawater permits detection of objects at very long ranges (hundreds of kilometers), but this requires a high source level and a large array of transmitter elements. The U.S. Navy's Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) sonar is an example of a LF sonar system (100–500 Hz).

The "marine vibrator" is a seismic source that has been tested as a possible substitute for airguns. It can generate modulated low frequency sound at approximately 10–250 Hz. As a modulated source, the signal is emitted over several seconds, thereby decreasing instantaneous peak pressure but increasing the duty cycle compared to airguns. Through use of an array of sources, much of the energy is directed downward toward the seafloor.

7.2 Sonars Used during Marine Seismic Surveys

During marine seismic surveys with airguns as the primary acoustic source, one or more echosounders usually operate simultaneously with the airguns, and sometimes while the airguns are not operating.

An MBES is commonly used during academic seismic surveys (and other oceanographic projects) to map characteristics of the ocean bottom. The MBES emits brief pulses of MF or HF sound in a fan-shaped beam that extends downward and to the sides of the ship, with a narrow beamwidth in the forward and aft directions. During seismic operations in deep water (>1000 m), an MBES usually operates at a frequency of 10–15 kHz, but for projects limited to shallow water (<100 m), a higher frequency MBES is often used. For example, the MBES used during seismic surveys from the R/V *Langseth* is the Simrad EM120. It operates at a frequency of 11.25–12.6 kHz and a maximum source level of 242 dB re 1 µPa · m (rms). The beam is fan-shaped, narrow (1º) in the fore-aft extent, and wide (150º) in the cross-track direction. In deep water, each ping consists of nine successive transmissions, each 15 ms in duration with 16 ms gaps between pulses. In shallow water, the pulse duration is reduced to 2 ms, and the number of beams is reduced.

An SBP operates at mid- to high frequencies and is generally used simultaneously with an MBES to provide information about the sedimentary features and bottom topography. SBP pulses are directed downward at typical frequencies of ~3–18 kHz. For example, the SBP used aboard the *Langseth* uses seven beams simultaneously, with a beam spacing of ≤15° and a fan width of ≤30°. Pulse duration is 0.4–100 ms at intervals of 1 s; a common mode of operation is to broadcast five pulses at 1-s intervals followed by a 5-s pause. The source level of the *Langseth*'s SBP is 204 dB re 1 µPa · m. Other vessels use alternative SBP systems that may have a single downward-directed beam and pulsed signals differing in details from those described above, but generally within the 3–18 kHz band.

Some seismic research vessels also use an acoustic Doppler current profiler (ADCP) to determine the speed, direction, depth, and dimension of water currents. The ACP transmits HF pings of sound into the water, generally at frequencies of 150–1200 kHz.

Pingers are typically used on airgun arrays, hydrophone streamers, coring equipment, ocean bottom seismometers or hydrophones, and other instruments such as cameras to locate and track positions of these devices. Pingers typically operate at high frequencies. For example, pingers deployed from the *Langseth* operate at 55–110 kHz and have a peak output of 183 dB re 1 μPa · m, with a maximum rate of 3 pings per 10 s per pinger; the transducers are powered by NiCad batteries. In addition, a 12-kHz pinger may be used during seismic survey cruises if ancillary bottom coring operations are done. The pinger is used to monitor the depth of the corer relative to the sea floor. It is a battery-powered acoustic beacon that is attached to the coring mechanism. This pinger has a source output of ~192 dB re 1 μPa · m with one pulse of 0.5, 2, or 10 ms duration per second.

7.3 Masking by Sonar

Specific information is lacking on masking of sounds relevant to marine mammals by the types of sonars operated during marine seismic surveys. However, little masking is expected given the pulsed nature and low duty cycles of these sonar sounds and (for the MBES and SBP) the fact that the emitted sounds are limited to certain directions (beams).

7.4 Disturbance by Sonar

Most studies on the disturbance of marine mammals during seismic surveys have focused on the effects of sound from airguns and similar low-frequency sources, and have not been designed to address effects of sound from simultaneously-operating sonar systems. During a recent NSF-funded low-energy seismic survey from the R/V *Thompson*, the 30 kHz EM300 MBES operated most of the time, and many cetaceans and a small number of pinnipeds were seen by marine mammal observers aboard the ship (Ireland et al. 2005). Similarly, during most seismic operations by L-DEO’s previous seismic research ship, the R/V *Ewing*, a 15.5 kHz MBES (and frequently also a 3.5-kHz SBP) were operated simultaneously, and numerous mysticetes, odontocetes, and pinnipeds were seen (and/or detected acoustically) from the ship at various times. Although the potential effects of these sonars could not be assessed given the simultaneous operation of one or more sonars plus airguns during most periods, results suggest that marine mammals often appear to tolerate the presence of these sources when they were operating within several kilometers, and sometimes within a few hundred meters. Given the directional nature of the sounds from these sonars, only a fraction of the marine mammals seen by observers were likely to have been within the beams before or during the time of the sightings. Many of these mammals probably were not exposed to the sonar sounds despite the proximity of the ship.

A small number of studies have more specifically assessed the behavioral effects of sonar sounds somewhat similar to those used during marine seismic survey on some marine mammal species. The limited available information indicates that reactions vary by species and circumstance, as described below.

***Baleen Whales*.—**Humpback whales wintering in Hawaii moved away upon exposure to 3.3 kHz sonar pulses, and increased their swimming speeds and track linearity in response to 3.1- to 3.6-kHz sonar sweeps (Maybaum 1990, 1993). Humpbacks in Hawaii showed some changes in their songs and swimming patterns upon exposure to LFA sonar transmissions (Miller et al. 2000; Clark et al. 2001), but those prolonged low-frequency sounds are quite unlike the sonar signals emitted during seismic surveys. Frankel (2005) reported that migrating gray whales reacted to a 21–25 kHz “whale-finding” sonar (source level of 215 dB re 1 μPa · m) by orienting slightly away from the source and being deflected from their course by ~200 m. These responses were not obvious in the field and were only determined later during data analysis. In 1998–2000, a study in the Eastern Tropical Pacific assessed the reactions of marine mammals to a 38-kHz echosounder and a 150-kHz ADCP. Results indicated that mysticetes showed no significant responses when the echosounder and ADCP were transmitting (Gerrodette and Pettis 2005).

Whaling catcher boats reported that baleen whales showed strong avoidance of echosounders that were sometimes used to track baleen whales underwater (Ash 1962; Richardson et al. 1995). "Ultrasonic" pulses emitted by "whale scarers" during whaling operations tended to scare baleen whales to the surface (Reeves 1992; Richardson et al. 1995). No reactions were noted by right, humpback, and fin whales to pingers and sonars at and above 36 kHz, although these species often reacted to sounds at frequencies of 15 Hz to 28 kHz (Watkins 1986).

Toothed Whales.—Little is known about reactions of odontocetes to underwater noise pulses, including sonar. Available data on responses to sonar are limited to a small number of species and conditions, including studies of captive animals. Most available data on odontocete responses to sonar are associated with beaked whales and high-intensity MF military sonars that are not comparable to the smaller and generally down- and/or laterally-directed echosounders, or the much weaker pingers, used during some marine seismic surveys.

Behavioral reactions of free-ranging odontocetes to echosounders such as MBES and SBP, and to ACP and pingers, appear to vary by species and circumstance. Various dolphin and porpoise species have been seen bowriding while the MBES, SBP, and airguns were operating during NSF-sponsored L-DEO seismic surveys (Smultea et al. 2004; Holst et al. 2004a,b; MacLean and Koski 2005). Gerrodette and Pettis (2005) assessed odontocete reactions to an echosounder and an ADCP operated from oceanographic vessels in the ETP. Results indicated that when the echosounder and ADCP were on, spotted and spinner dolphins were detected slightly more often and beaked whales less often during visual surveys (Gerrodette and Pettis 2005). Commercial whalers were judicious in their use of sonar when following sperm whales because it tended to make them scatter (Richardson et al. 1995). In response to 6–13 kHz pingers, some sperm whales stopped emitting pulses (Watkins and Schevill 1975). In contrast, sperm whales usually continued calling and did not appear to otherwise react to continual pulsing from echosounders, e.g., at 12 kHz (Backus and Schevill 1966; Watkins 1977).

Behavior of captive bottlenose dolphins in an open-sea enclosure appeared to change in response to sounds from a close and/or approaching marine geophysical survey vessel that was conducting seismic and bathymetric studies in the Red Sea (van der Woude 2007). The sonar sounds included a 1-kHz sparker, 375-kHz sidescan sonar, 95-kHz MBES, and two 20–50 kHz singlebeam echosounders. It was not clear which specific source(s) may have induced the behavioral changes. Captive bottlenose dolphins and a beluga exhibited changes in behavior when exposed to 1-s to 8-s tonal signals at high received levels and frequencies similar to those emitted by the MBES, 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, 2005; 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 duration as compared with those from an MBES.

There are increasing indications that beaked whales, particularly Cuvier's beaked whales, sometimes strand when naval exercises, including operation of mid-frequency tactical sonars, are ongoing nearby (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; NOAA and USN 2001). It has been hypothesized that these strandings may be related to behavioral reactions (e.g., changes in dive behavior) that indirectly result in physiological damage leading to stranding (Jepson et al. 2003; Cox et al. 2006; D'Spain et al. 2006). Mid-frequency tactical sonars used by naval vessels differ in important ways from the sonar systems used on research vessels. For example, the sonars on research vessels emit very brief pulses that are beamed downward, and individual mammals are unlikely to be in the beam for more than a brief period. Navy tactical sonars emit more prolonged signals that are often directed close to horizontal, and animals can be exposed repeatedly to these signals over an extended period. Also, cases of beaked whale strandings associated with navy operations usually involve more than one naval vessel operating in the same area. Research-vessel sonars are not expected to elicit the same types of reactions as navy tactical sonars.

Studies of reactions of odontocetes to underwater sounds other than sonar and seismic airguns have also been conducted and some of these may be of some relevance. Several studies indicate that underwater sounds from acoustic harassment devices and alarms displace some odontocetes. During a 15-year study of killer whales in Johnstone Strait and Broughton Archipelago, British Columbia, the occurrence of killer whales was significantly lower during a 7-year period when acoustic harassment devices (10 kHz at 194 dB re 1 µPa · m) were installed in the area; whales returned to baseline numbers when these sound sources were removed (Morton and Symonds 2002). Kraus et al. (1997) found acoustic alarms operating at 10 kHz with a source level of 132 dB re 1 µPa · m were an effective deterrent for harbor porpoises. Kastelein et al. (2008) subjected one harbor porpoise in a large floating pen to a continuous 50 kHz pure tone with a source level of 122 ± 3 dB re 1 µPa · m rms. The porpoise moved away from the sound at an estimated avoidance threshold of 108 ± 3 dB re 1 µPa rms and did not habituate to it despite 66 exposures (Kastelein et al. 2008). Other related studies, mainly on harbor porpoises, are summarized in Southall et al. (2007).

***Pinnipeds*.—**Very few data are available on the reactions of pinnipeds to sonar sounds at frequencies similar to those used during marine seismic operations. Hastie and Janik (2007) conducted a series of behavioral response tests on two captive gray seals to determine their reactions to underwater operation of a HF (375 kHz) multibeam imaging sonar that included significant signal components down to 6 kHz. Results indicated that the two seals reacted to the sonar signal by significantly increasing their dive duration; no significant differences were found in swimming direction relative to the operating sonar.

***Sirenians, Sea Otter and Polar Bear*.—**We are not aware of any data on the reactions of these types of marine mammals to sonar sounds at frequencies similar to the MF and HF sounds produced during marine seismic operations.

7.5 TTS and Sonar Pulses

A general introduction to TTS is provided in the seismic section of this Appendix (above), and Southall et al. (2007) review all available data on TTS in marine mammals. There has been no specific documentation of TTS in free-ranging marine mammals exposed to sonar pulses of the types used during marine seismic surveys. However, data on TTS in captive marine mammals exposed to various related sounds provide some basis for estimating the circumstances in which TTS might occur in free-ranging cetaceans and pinnipeds. In general, studies indicate that TTS thresholds are higher for non-impulse sounds (such as most sonars) than for impulsive sounds (Southall et al. 2007). The following sections summarize the limited relevant information available on this topic.

***Toothed Whales*.—**The TTS threshold for the beluga whale and bottlenose dolphin has been measured in captivity to be ~195 dB re 1 $\mu Pa^2 \cdot s$ for exposure to a single non-impulsive tonal sound (Schlundt et al. 2000; Finneran et al. 2005; reviewed in Southall et al. 2007).

Kremser et al. (2005) and other authors have 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 a speed and direction similar to the vessel in order to be subjected to repeated pulses and cumulative sound energy levels that could cause TTS (Kremser et al. 2005). For example, given the maximum source level of 242 dB re 1 µPa·m (rms) for the *Langseth*'s MBES, the received level for an animal within the sonar beam 100 m below the ship would be about 202 dB re 1 µPa (rms), assuming 40 dB of spreading loss. Given the MBES' narrow beam, only one pulse is likely to be received by a given animal as the ship passes overhead. The received energy level at 100 m range 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 is below the TTS threshold for cetaceans receiving a non-impulse sound (195 dB re 1 $\mu Pa^2 \cdot s$). The corresponding received energy level at 10 m range would be <204 dB re 1 $\mu Pa^2 \cdot s$, given that a location 10 m below the MBES transducers would be in the near field of this distributed source. An odontocete in the beam at that distance might incur some TTS (which would be fully recoverable).

***Baleen Whales*.—**For mysticetes, there are no data, direct or indirect, on levels or properties of sound that are required to induce TTS from active sonar of any type. In general, auditory thresholds of mysticetes 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). If so, their TTS thresholds may also be higher (Southall et al. 2007).

***Pinnipeds*.—**TTS thresholds for sounds of the types produced by MBES, SBP, ADCP, and pingers have not been measured in pinnipeds. However, studies of TTS onset upon exposure to prolonged non-impulse sounds have been done with the harbor seal, California sea lion, and northern elephant seal (Kastak et al. 2005; Southall et al. 2007). Those studies suggest that some pinnipeds, e.g., the harbor seal, may incur TTS at somewhat lower received energy levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001; Southall et al. 2007). In the harbor seal, the TTS threshold for non-impulse sounds is about 183 dB re 1 $\mu Pa^2 \cdot s$, as compared with ~195 dB re 1 $\mu Pa^2 \cdot s$ in odontocetes (Kastak et al. 2005; Southall et al. 2007). TTS onset occurs at higher received energy levels in the California sea lion and northern elephant seal than in the harbor seal.

A harbor seal as much as 100 m below the *Langseth* could receive a single MBES pulse with received energy level of ≥184 dB re 1 $\mu Pa^2 \cdot s$ (as calculated in the toothed whale subsection above) and thus could incur slight TTS. Species of pinnipeds with higher TTS thresholds would not incur TTS unless they were closer to the transducers when a sonar ping was emitted. Given the intermittent nature of the sonar signals and the narrow MBES beam, only a small fraction of the pinnipeds below (and close to) the ship would receive a pulse as the ship passed overhead.

***Sirenians, Sea Otter and Polar Bear*.—**There are no published data on TTS in these types of marine mammals.

7.6 PTS and Sonar Pulses

There are no direct measurements of the sound exposure necessary to cause PTS in any marine mammal exposed to any type of sound. However, the general principles are assumed to be similar to those in humans and other terrestrial mammals (see Southall et al. 2007 and the seismic section above). The low-to-moderate levels of TTS that have been induced in captive odontocetes during controlled studies have shown no measurable residual PTS (Schlundt et al. 2000; Finneran et al. 2002; Nachtigall et al. 2003, 2004).

For non-impulsive sonar sounds, the PTS threshold is expected to be at least 20 dB higher, on a received energy basis, than is the TTS threshold (Southall et al. 2007). The PTS thresholds in cetaceans and pinnipeds are estimated to be ≥215 and ≥203 dB re 1 $\mu Pa^2 \cdot s$, respectively (Southall et al. 2007).

Burkhardt et al. (2007, 2008) performed a theoretical risk assessment that included evaluating the likelihood of PTS in cetaceans upon exposure to sounds from an MBES (i.e., Hydrosweep), a parametric echosounder, and a multi-frequency Simrad EK60 echosounder (i.e., "fish finder"). Source levels were 230–245 dB re 1 µPa·m (rms). Burkhardt et al. based their analysis on the SEL and peak pressure criteria proposed by Southall et al. (2007) for impulsive sources, i.e., ≥198 dB re 1 $\mu Pa^2 \cdot s$ and ≥230 dB re 1 μPa_{peak}. According to Southall et al. (2007), it would be appropriate to apply the criteria that they proposed for non-impulse sounds, i.e., 215 dB re 1 $\mu Pa^2 \cdot s$ and ≥230 dB re 1 μPa_{peak}. Thus, Burkhardt et al.'s SEL-based conclusions are precautionary, but their conclusions based on peak pressure are consistent with Southall et al.'s recommendations.

- ***SEL***: The maximum energy levels of the three sonars that they considered, at any point in the near field, were 200–210 dB re 1 $\mu Pa^2 \cdot s$ (Burkhardt et al. 2007). For cetaceans, the non-impulse SEL criterion for PTS (215 dB SEL) would not be exceeded even for a cetacean immediately adjacent to the transducers unless it remained there long enough to receive multiple pings. Burkhardt et al. did not address pinnipeds, but the non-impulse SEL criterion for PTS in pinnipeds (203 dB re 1 $\mu Pa^2 \cdot s$) could be exceeded for a single ping received within a few meters of the transducers of the stronger sonars.
- ***Peak pressure***: Southall et al. (2007) note that, regardless of the SEL that might elicit onset of PTS, there is also concern about the possibility of PTS if a cetacean or pinniped received sound signals containing an instantaneous peak pressure exceeding, respectively, 230 or 218 dB re 1 µPa (peak). Burkhardt et al. (2007) reported that the maximum peak pressures in the water near the three sonars that they considered were 223–233 dB re 1 μPa_{peak}. Thus, a peak pressure ≥230 dB re 1 µPa would not occur beyond a few meters from their strongest source. However, a peak pressure of ≥218 dB re 1 µPa as relevant for pinnipeds could occur out to ~20 m from the strongest source.

Some caution is recommended in drawing conclusions about PTS effects given the limited knowledge of TTS, PTS and their relationships, but available information suggests that scientific sonars could only cause direct auditory injury if a marine mammal were very near the source and in the beam when one or more pings were emitted. As noted by Burkhardt et al. (2007, 2008), cetaceans are very unlikely to incur PTS from operation of scientific sonars on a ship that is underway. The risk of PTS could be somewhat higher for certain pinnipeds if they were close to the transducers. PTS might be possible if a cetacean or (more likely) pinniped dove under the ship near the operating transducers while the vessel was on station and remained there long enough to receive multiple pings.

7.7 Strandings and Mortality

There is no evidence that the operation of MBES, SBP, ACP, or pingers associated with seismic surveys induces strandings or mortality among marine mammals. However, there is evidence that MF tactical sonars on naval vessels can, directly or indirectly, result in strandings and mortality of some marine mammals, especially beaked whales. Detailed reviews of associations between MF navy sonar and cetacean strandings include Balcomb and Claridge (2001), NOAA and USN (2001), Jepson et al. (2003), Fernández et al. (2004, 2005), Hildebrand (2005), Cox et al. (2006), and D'Spain et al. (2006).

The MBES and SBP used during typical seismic surveys are quite different from the high-intensity, MF tactical navy sonars associated primarily with beaked whales strandings. For example, pulse durations of the MBES (0.2 to 20 ms) and SBP (0.4–100 ms) used on the *Langseth* are very short relative to naval sonars (at least a few hundred milliseconds, and sometimes longer). Thus, the sound energy received from an MBES and SBP would be substantially less than that received at a similar distance from a military tactical sonar. In addition, at any given location, an individual marine mammal would be in the beam of an MBES or SBP for much less time given the intermittent nature, narrow beamwidth, and generally downward orientation of the beam. (In contrast, Navy sonars often use near-horizontally-directed sound.) Animals close to the ship (where the beam is narrowest and has relatively high received levels) are especially unlikely to be ensonified for more than one or two pulses from the moving vessel. Those factors would all reduce the sound energy received from an MBES or SBP rather drastically relative to that from the sonars used by the Navy. The source levels of an ACP and pingers often used during seismic surveys are weaker than those of an MBES or SBP.

Burkhardt et al.'s (2007, 2008) theoretical risk assessment included assessing the likelihood of behaviorally-induced damage to beaked whales through use of sonars associated with marine scientific research. Results indicated that such immediate indirect injury is unlikely to occur during scientific applications based on available information used as input to the model. This assessment was based on the aforementioned fundamental hydroacoustic differences between the scientific echosounders versus the naval MF sonars associated with beaked whale strandings.

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 evidence linking these strandings to the seismic surveys was inconclusive (see seismic section above). The ship was also operating its MBES at the same time but, as discussed elsewhere, this sonar had much less potential than the aforementioned naval sonars to affect beaked whales.

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APPENDIX C:

REVIEW OF EFFECTS OF AIRGUN SOUNDS ON SEA TURTLES[10]

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 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

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[10] By **Valerie D. Moulton and W. John Richardson**, LGL Ltd., environmental research associates. November 2000.

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) [11], 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 [12] and airgun-depth 2 m for prolonged periods: 20-36 hours in duration. The turtles maintained a standoff range of about 30 m when 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 dB 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 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).

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[11] 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).

[12] 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.

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 μPa 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.

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.

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APPENDIX D:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON FISH[13]

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•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. 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. When the fish, which is on the whole similar in

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density to water, moves in a sound field the denser otoliths lag slightly behind because of their inertia and the differential movement of fish and otolith comes to bear on the beds of sensory hair cells that underly the calcareous otolith masses in the inner ear. This motion is interpreted by the central nervous system 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 action. 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 sonar systems.

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, including broad whitefish, 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.

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. (2000a,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 source SPL was just below 223 dB re 1 $\mu Pa_{p\text{-}p}$ at the source and the approximate received SPLs ranged between 165 and 209 dB re 1 $\mu Pa_{p\text{-}p}$. 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 SPL of 223 dB re 1 $\mu Pa \cdot m_{0\text{-}p}$ and measured received SPLs were 137–206 dB re 1 $\mu Pa_{0\text{-}p}$. 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 SPL was at least 200 dB re 1 $\mu Pa_{0\text{-}p}$; alarm responses occurred at a minimum received SPL of 177 dB re 1 $\mu Pa_{0\text{-}p}$. 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 SPL thresholds for obvious rockfish behavioral response and more subtle rockfish behavioral response are 180 dB re 1 $\mu Pa_{0\text{-}p}$ and 161 dB re 1 $\mu Pa_{0\text{-}p}$, 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 SPL of the single airgun was 223 dB re 1 $\mu Pa \cdot m_{0\text{-}p}$ and the received SPLs at the base of the rockfish aggregation ranged from 186–191 re 1 $\mu Pa_{0\text{-}p}$. 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 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 (220 dB re 1 $\mu\text{Pa}\cdot\text{m}_{0\text{-p}}$). Received SPLs were estimated at 178 dB re 1 $\mu\text{Pa}_{0\text{-p}}$. 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 depths 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·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 10 m from the airgun source. The received SPLs of the airguns were ~215–233 dB re 1 μ$\text{Pa}_{0\text{-p}}$. 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·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 to 242 dB re 1 μPa (unspecified measure type) (Booman et al. 1996). These received levels corresponded to exposure distances ranging from 0.75–6 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·m (unspecified measure type). The shot interval was 25 s and exposure durations ranged from 4.6 to 12 hr. 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_{rms}. 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_{rms}. Smaller fish showed a tendency to display startle response more often. "Responses" were observed above received SPLs of 156–161 dB re 1 μPa_{rms}. 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 SPLs ranged from 195–218 dB re 1 μ$\text{Pa}_{0\text{-p}}$. 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 SPL of 222.6 dB re 1 μPa•m$_{p\text{-}p}$. 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 was observed when fish were exposed within 1–2 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 SPLs were 142–186 dB re 1 µPa$_{p\text{-}p}$. 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 SPL was ~248 dB re 1 µPa·$m_{0\text{-}p}$ but no measurements of the received SPLs were made. Davis et al. (1998) estimated the received SPL at the bottom below the array as 205 dB re 1 µ$Pa_{0\text{-}p}$, and at 178 dB re 1 µ$Pa_{0\text{-}p}$ at 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·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 from 55% to 80% within the seismic survey area; this apparent effect persisted for at least 24 hr within 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 µ$Pa_{0\text{-}p}$. 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 source level of 250 dB re 1 µPa·$m_{0\text{-}p}$. Received levels in the fishing areas were estimated to have been 163–191 dB re 1 µ$Pa_{0\text{-}p}$. 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 source level of 223 dB re 1 µPa·$m_{0\text{-}p}$ to examine effects on 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 µ$Pa_{0\text{-}p}$. 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 source SPL of 262 dB re 1 µPa·$m_{0\text{-}p}$ and a maximum SPL at some unspecified frequency of 202 dB re 1 µPa·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 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.

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APPENDIX E:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES[14]

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.

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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 source SPLs for snapping ship were 183–189 dB re 1 μPa·$m_{p\text{-}p}$ 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_{0-p}) 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_{0-p}. 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 $\mu Pa_{0\text{-}p}$. 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 $\mu Pa_{0\text{-}p}$. 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 (J. Payne, Research Scientist, DFO, St. John's, Newfoundland, personal communication). 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, personal communication). 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 $\mu Pa_{0\text{-}p}$ 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 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 $\mu Pa_{0\text{-}p}$ 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 catch-per-unit-effort 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, personal communication). '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 (J. Payne, Research Scientist, DFO, St. John's, Newfoundland, personal communication). However, the lack of peer review of this study limits its validity.

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, personal communication). 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·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 to 119 min. at a firing rate of once every 10–15 s. The maximum SPL was >200 dB re 1 $\mu Pa_{0\text{-}p}$. 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.

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