Environmental Assessment of a Marine Geophysical Survey by the R/V *Melville* in the Santa Barbara Channel, November 2008

Prepared for

Scripps Institution of Oceanography
8602 La Jolla Shores Drive
La Jolla, CA. 92037

and

National Science Foundation
Division of Ocean Sciences
4201 Wilson Blvd., Suite 725
Arlington, VA 22230

by

LGL Ltd., environmental research associates
22 Fisher St., POB 280
King City, Ont. L7B 1A6

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ABSTRACT

The Scripps Institution of Oceanography (SIO), with research funding from the National Science Foundation (NSF), plans to conduct a seismic survey and test coring cruise in the Santa Barbara Channel for 12 days during November 2008. The seismic survey will occur in water depths ranging from <50 m to ~580 m during daylight hours. The seismic study will either use a 1.5-kJ (kiloJoule) electromechanical boomer or a 2-kJ sparker system for shallow water, and a small (25- to 45-in^3) GI airgun in deeper water. The survey will test the feasibility of extending the remarkable high-resolution paleoclimate record in the Santa Barbara Basin established in 1992 and 2005 from ~700,000 years ago back to ~1.2 million years ago. This will be done by conducting detailed 3D modeling of the structure and outcrop stratigraphy of the northern shelf to locate optimal core sites, and by conducting high-resolution seismic reflection site surveys, test coring, and core analyses of the northern shelf and an elevated portion of the mid-channel area called the Mid-Channel Trend. The seismic surveys will identify subsequent optimal and safe coring strategies suitable for recovering a continuous paleoclimate record from the shallow marine sediments in Santa Barbara Basin in the future as part of the Integrated Ocean Drilling Program (IODP).

SIO is requesting an Incidental Harassment Authorization (IHA) from the National Marine Fisheries Service (NMFS) to authorize the incidental, i.e., not intentional, harassment of small numbers of marine mammals should this occur during the seismic survey. The information in this Environmental Assessment (EA) supports the IHA application process and provides information on marine species that are not addressed by the IHA application, notably sea turtles, which are listed under the U.S. Endangered Species Act (ESA), and one mammal species (sea otter) that is managed by the U.S. Fish and Wildlife Service (USFWS) rather than by NMFS. The EA addresses the requirements of the National Environmental Policy Act (NEPA). 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 cetaceans and pinnipeds inhabit the Santa Barbara Channel. Several of these species are listed as ***endangered*** under the ESA, including the humpback, sei, fin, blue, North Pacific right, and sperm whales. Other species of special concern that could occur in the study area are the ***endangered*** leatherback turtle and ***threatened*** loggerhead, green, and olive ridley turtles.

Potential impacts of the seismic survey on the environment would be primarily a result of the operation of the GI airgun and the boomer or sparker. A multibeam echosounder, chirp echosounder, and sub-bottom profiler will also be operated. Impacts would be associated with increased underwater noise, which could result in avoidance behavior of 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. The planned monitoring and mitigation measures would minimize the possibility of such effects.

Protection measures designed to mitigate the potential environmental impacts to marine mammals and turtles will include the following: minimum of one dedicated observer maintaining a visual watch during all daytime seismic operations, two observers 30 min before and during start ups (and when possible at other times), shut downs when marine mammals or sea turtles are detected in or about to enter designated exclusion zones, and shut downs if North Pacific right whales are sighted at any distance from the source vessel (given their special status). SIO and its contractors are committed to apply these measures in order to minimize effects on marine mammals and other environmental impacts.

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, or the populations to which they belong, or on their habitats.

LIST OF ACRONYMS

~	approximately
CITES	Convention on International Trade in Endangered Species
CPA	Closest Point of Approach
CPUE	Catch per Unit Effort
CV	Coefficient of Variation
E	East
EA	Environmental Assessment
ESA	(U.S.) Endangered Species Act
GIS	Geographic Information System
h	hour
hp	horsepower
ha	hectares
IHA	Incidental Harassment Authorization (under MMPA)
in	inch
IUCN	International Union for the Conservation of Nature
IWC	International Whaling Commission
kJ	kiloJoule
kt	knot
m	meter
MBES	Multibeam echosounder
MCS	Multichannel Seismic
min	minute
MMVO	Marine Mammal Visual Observer
MMPA	(U.S.) Marine Mammal Protection Act
MONM	Marine Operations Noise Model
ms	millisecond
MTTS	Masked Temporary Threshold Shift
n.mi.	nautical mile
NATO	North Atlantic Treaty Organization
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	National Science Foundation
NVD	Night Vision Device
OBS	Ocean Bottom Seismometer
OBSIP	Ocean Bottom Seismometer Instrument Pool
PAM	Passive Acoustic Monitoring
PBR	Potential Biological Removal
pk	peak
PL	Propagation Loss
ppt	parts per thousand
psi	pounds per square inch
PTS	Permanent Threshold Shift
RDT	Rotational Directional Transmission
RAM	Range-dependent Acoustic Model
RL	Received Level
rms	root-mean-square
RP	reproductive patch

rpm	rotations per minute
s	second
SBP	Sub Bottom Profiler
SE	Southeast
SL	Source Level
SPL	sound pressure level
SOSUS	Sound Surveillance System
SWFSC	Southwest Fisheries Science Center
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
W	West

I. PURPOSE AND NEED

Scripps Institution of Oceanography (SIO), a part of the University of California, operates the oceanographic research vessel (R/V) *Melville* under a charter agreement with the U.S. Office of Naval Research (ONR). The title of the vessel is held by the U.S. Navy. SIO, in collaboration with other academic institutions and the U.S Geological Survey (USGS), plans to conduct a seismic survey and test coring program with the R/V *Melville* in the Santa Barbara Channel for 12 days in November 2008. The National Science Foundation (NSF) is the agency of the U.S. Government that is providing the funding to support the research to be undertaken on this research cruise. USGS will provide some scientific personnel and equipment in support of this project, because of the critical importance of this research for coastal hazard and environmental studies, as well as its contribution to understanding processes of global climate change. The marine seismic survey and test coring will take place in water depths ranging from <50 m to ~580 m.

The purpose of this project is to test the feasibility of extending the remarkable high-resolution paleoclimate record from Santa Barbara Basin from ~700,000 years ago back to ~1.2 million years ago. This would be accomplished by conducting detailed 3D modeling of the structure and outcrop stratigraphy of the northern shelf to locate optimal core sites, and by conducting high-resolution seismic reflection site surveys, test coring, and core analyses of both the northern shelf and mid-channel area. A similar seismic and coring expedition in 2005 verified the presence of this remarkable paleoclimate record back to ~700,000 years ago in the mid-channel region. An integrated seismic data acquisition and coring cruise will be conducted to (1) acquire piston core samples of older marine sediments that are now exposed at the seafloor to test the suitability of these older deep basin sediments to provide a high-quality paleoclimate record, and (2) conduct high-resolution multi-channel seismic (MCS) surveys of the coring sites to place the results from the core analyses in a wider basin context, and to identify subsequent optimal and safe coring strategies suitable for recovering a continuous paleoclimate record from the shallow marine sediments in Santa Barbara Basin in the future as part of the Integrated Ocean Drilling Program (IODP).

Numerous species of cetaceans and pinnipeds occur in the Santa Barbara Channel. Several of these species are listed as ***endangered*** under the U.S. Endangered Species Act (ESA), including the humpback, fin, blue, and sperm whale, as well as the Guadalupe fur seal, which is listed as ***threatened***. Other species of concern that could occur in the study area are the ***endangered*** leatherback turtle and ***threatened*** loggerhead, green, and olive ridley turtles.

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 GI airgun, boomer, and mini-sparker during the proposed study. The EA was prepared under the National Environmental Policy Act (NEPA). The EA addresses potential impacts of the proposed seismic survey on marine mammals, as well as other species of concern in the study area, notably sea turtles. The EA also provides useful information in support of an application for an Incidental Harassment Authorization (IHA) from the National Marine Fisheries Service (NMFS). The requested IHA would, if issued, allow the non-intentional, non-injurious "take by harassment" of small numbers of marine mammals during the proposed seismic survey by SIO in the Santa Barbara Channel during November 2008.

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

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

II. ALTERNATIVES INCLUDING PROPOSED ACTION

Three alternatives are 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 SIO's planned seismic survey are described in the following subsections.

(1) Project Objectives and Context

SIO plans to conduct a seismic survey in the Santa Barbara Channel as part of an integrated geologic and geophysical study. The study will test the feasibility of extending the remarkable high-resolution paleoclimate record from Santa Barbara Basin established in 1992 and 2005 from ~700,000 years ago back to ~1.2 million years ago by conducting detailed 3D modeling of the structure and outcrop stratigraphy of the northern shelf to locate optimal core sites, and by conducting high-resolution seismic reflection site surveys, test coring, and core analyses in the northern shelf and mid-channel areas. The seismic surveys will identify subsequent optimal and safe coring strategies suitable for recovering a continuous paleoclimate record from the shallow marine sediments in Santa Barbara Basin in the future as part of the Integrated Ocean Drilling Program (IODP).

(2) Proposed Activities

(a) Location of the Activities

The survey will encompass the small area ~34–34.5°N, ~119.5–120°W, north and northwest of Santa Cruz Island in the Santa Barbara Channel off southern California (Fig. 1). Water depths in the survey area range from <50 m to ~580 m. The seismic survey will be conducted in the territorial waters of the U.S., partly in California state waters, and is scheduled to occur for ~12 days during November 2008. Some minor deviation from these dates is possible, depending on logistics and weather.

(b) Description of the Activities

The survey will involve one source vessel, the R/V *Melville*. Seismic sources to be deployed by the R/V *Melville* will vary with water depth. At two shallow-water sites that cross into California state waters, a 1.5-kJ electromechanical boomer or a 2-kJ electric sparker system will be used, depending on water depth and seafloor conditions, and depending on which source provides the highest resolution and best sub-seafloor signal penetration. In general, the boomer source likely will be preferred. At three deeper-water sites outside state waters, a small (25- to 45-in^3) GI airgun will be used. The receiving system for the returning acoustic signals will consist of a 72-channel, 450-m-long towed hydrophone streamer. As the boomer, sparker, or GI airgun are towed along the survey lines, the hydrophone streamer will receive the returning acoustic signals and transfer the data to the on-board processing system.

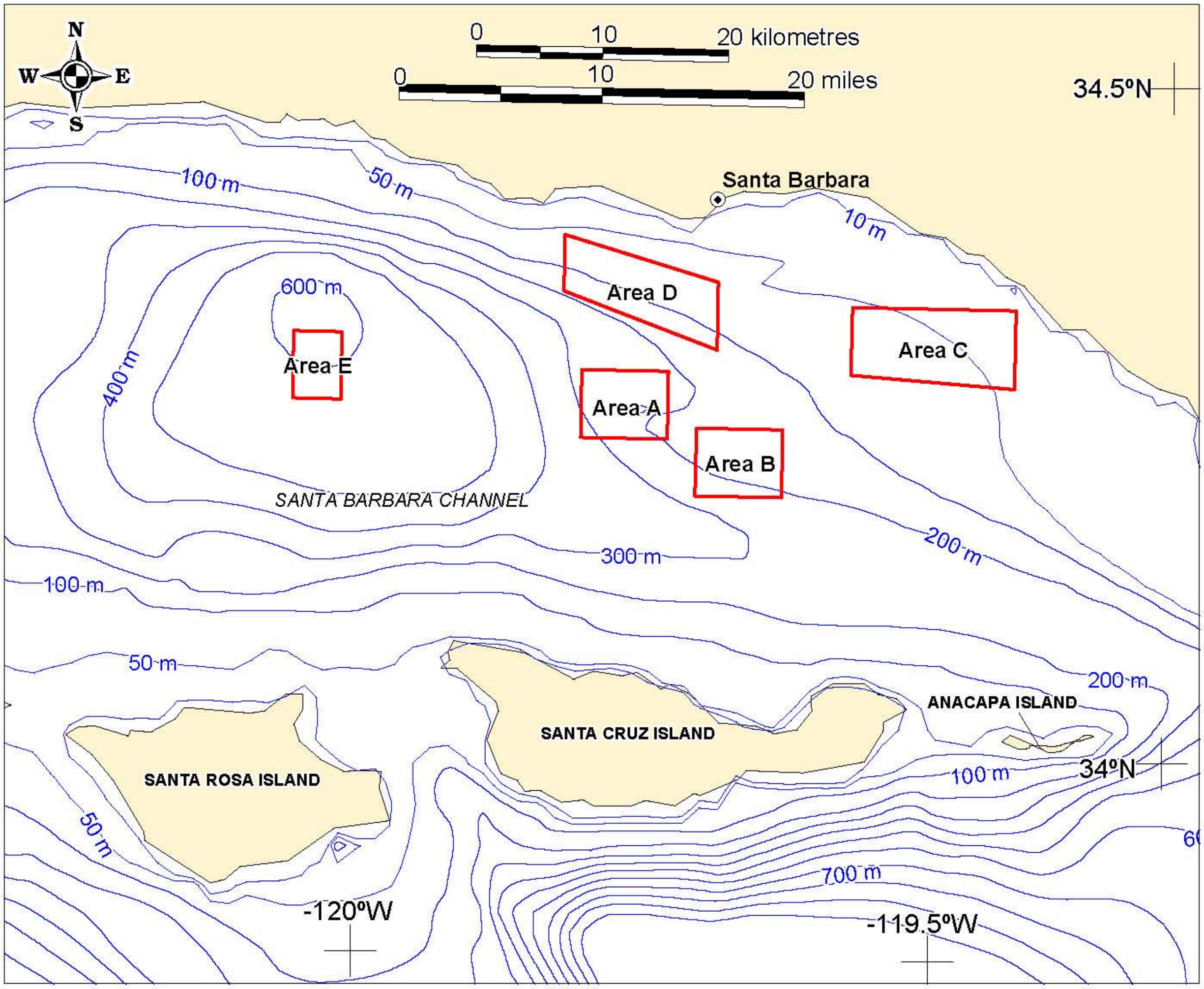

FIGURE 1. Proposed study areas for the survey in the Santa Barbara Channel, November 2008.

The seismic program will consist of grids of closely-spaced lines in each of 5 survey areas (Fig. 1). Line spacing will be 100–400 m. There will be additional operations associated with equipment testing, startup, line changes, and repeat coverage of any areas where initial data quality is sub-standard. Those additional operations are allowed for in the estimated total line km given below.

The planned seismic survey (including turns) will consist of ~600 km of survey lines using the GI airgun at Sites A, B, and E, and ~500 km of survey lines using the sparker or boomer at Sites C and D. At Sites A, B, and E, all of the lines will be in intermediate water depths of 100–1000 m, and at Sites C and D, the survey lines will be in water depths 100–1000 m and <100 m.

In addition to the boomer, minisparker, and GI airgun, a towed chirp system, a multibeam echosounder (MBES), and a sub-bottom profiler (SBP) will be used at various times during the cruise. The chirp system will be used in tandem with the seismic sources, or will be used separately to locate optimal piston core sites, up to 4 hours at a time to a maximum of 8–10 hours per day. A 3.5-kHz SBP will be used to help verify seafloor conditions at possible coring sites, and will also be used in tandem with a MBES during transit to and from the Santa Barbara Channel area to collect additional seafloor bathymetric data.

All planned geophysical data acquisition activities will be conducted by SIO and the U.S. Geological Survey (USGS) with on-board assistance by the scientists who have proposed the study. The Chief Scientist is Dr. Craig Nicholson of the University of California at Santa Barbara. The vessel will be self-contained, and the crew will live aboard the vessel for the entire cruise. Some crew changes may take place at mid-cruise if needed.

(c) Schedule

The R/V *Melville* is expected to depart San Diego and spend ~12 days conducting the survey and piston coring activities in November 2008. During daylight, seismic operations will be conducted at two shallow-water sites using a 1.5-kJ electromechanical boomer system or a 2-kJ electric sparker system, and at three deeper-water sites using a small (25- to 45-in^3) GI airgun. If the 2-kJ sparker is used, its output may be reduced to provide the best, most consistent output signal with this source. If the small GI airgun is used, its size will generally be limited to 25 in^3 to allow optimal shot spacing. Seismic operations will be conducted for 1–2 days at each site. At night, piston coring will be conducted. 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 *Melville* has a length of 85 m, a beam of 14.0 m, and a maximum draft of 5.0 m. The ship is powered by two 1385-hp Propulsion General Electric motors and a 900-hp retracting Azimuthing bow thruster. An operation speed of ~7.4–8 km/h (4–4.3 knots) will be used during seismic acquisition. When not towing seismic survey gear, the R/V *Melville* cruises at 21.7 km/h (11.7 knots) and has a maximum speed of 25.9 km/h (14 knots). It has a normal operating range of ~18,630 km.

The R/V *Melville* will also serve as the platform from which vessel-based marine mammal observers will watch for marine mammals and sea turtles before and during airgun operations, as described in § II(3), below.

Other details of the R/V *Melville* include the following:

Owner: U.S. Navy
Operator: Scripps Institution of Oceanography of the University of California
Flag: United States of America
Date Built: 1969
Gross Tonnage: 2516
Compressors for Air Guns: 1850 psi
Accommodation Capacity: 23 crew plus 38 scientists

The R/V *Melville* complies with International Maritime Organization (IMO) guidelines and United States Coast Guard (USCG) regulations for Ballast Water Management. The R/V *Melville*'s procedures are documented in the SIO Marine Facility's Safety Management Manual (SMM) in Section 256, "Ballast Water Management Plan." These procedures are in place and approved by the American Bureau of Shipping (ABS), which acts for USCG to approve and verify compliance with approved procedures. These procedures are audited internally annually and externally every 2.5 years. The loading and discharging of ballast water is recorded in the ship's Ballast Water Management Log and in the ship's official log located on the bridge. In short, the R/V *Melville* meets all international and US requirements for handling ballast water and U.S. requirements for reporting carriage and discharge of ballast water in US ports.

(e) Airgun Description

The airgun to be used in the proposed survey is a single GI airgun. SIO would try to reduce its standard 45-in^3 GI airgun to 25 or 35 in^3 for this cruise, but in case that is not possible, we are providing the specifications for a 45-in^3 GI airgun and using that at the basis for calculating exclusion zones [see § II(3)(e)]. Seismic pulses will be emitted at intervals of 3 seconds. At a speed of ~4 knots (7.4 km/h), the 3-s spacing corresponds to a shot interval of ~6 m.

If possible, the generator chamber of the GI airgun, the one responsible for introducing the sound pulse into the ocean, will be set to 25 in^3. The injector chamber also will be set to the same 25-in^3 size and will inject air into the previously-generated bubble to maintain its shape. This does not introduce more sound into the water. The 45-in^3, reduced to 25-in^3, GI airgun will be towed 21 m behind the R/V *Melville* at a depth of 2 m. The variation of the sound pressure field of that GI-gun set to its original 45-in^3 size and towed at a depth of 2.5 m has been modeled by L-DEO in relation to distance and direction from the GI airgun (see "Mitigation Measures" below). At its reduced chamber size of 25 in^3, these numbers will be further reduced. For comparison, the peak source sound level of the 45-in^3 gun is 225.3 dB re 1 µPa•m, whereas the peak source sound level of a USGS GI airgun with chamber sizes reduced to 24 in^3 is ~218 dB re 1 µPa•m.

As the GI airgun is towed along the survey line, the towed hydrophone array in the 450-m streamer receives the reflected signals and transfers the data to the on-board processing system. Given the relatively short streamer length behind the vessel, the turning rate of the vessel while the gear is deployed is much higher than the limit of five degrees per minute for a seismic vessel towing a streamer of more typical length (>>l km). Thus, the maneuverability of the vessel is not limited much during operations.

<u>GI-airgun Specifications</u>

Energy Source	GI airgun of 45 in^3 or GI airgun of 25 in^3
Source output (downward) (45 in^3)	0–pk is 1.8 bar-m (225.3 dB re 1 µPa•m$_p$); pk–pk is 3.4 bar-m (230.7 dB re 1 µPa•m$_{p-p}$)
Source output (downward) (25 in^3)	~218 dB re 1 µPa•m$_p$
Towing depth of energy source	2 m
Air discharge volume	~45 in^3 or ~25 in^3
Dominant frequency components	0–188 Hz (45 in^3) or <500 Hz (25 in^3)

The rms[1] (root mean square) received levels that are used as impact criteria for marine mammals are not directly comparable to the peak (p or 0–p) or peak to peak (p–p) values normally used to characterize source levels of airgun arrays. The measurement units used to describe airgun sources, peak or peak-to-peak decibels, are always higher than the "root mean square" (rms) decibels referred to in biological literature. A measured received level of 160 dB re 1 µPa$_{rms}$ in the far field would typically correspond to ~170 dB re 1 µPa$_p$, and to ~176–178 dB re 1 µPa$_{p-p}$, as measured for the same pulse received at the same location (Greene 1997; McCauley et al. 1998, 2000). The precise difference between rms and peak or peak-to-peak values 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 for an airgun-type source.

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[1] The rms (root mean square) pressure is an average over the pulse duration.

Additional discussion of the characteristics of airgun pulses is included in Appendix A (subpart 3).

(f) Electric Sparker Description

The sparker system is similar to the SQUID 2000™ minisparker system manufactured by Applied Acoustic Engineering, Inc. This minisparker includes electrodes mounted on a small pontoon sled that simultaneously discharge electric current through the seawater to an electrical ground, creating an electrical arc that momentarily vaporizes water between positive and negative leads. The collapsing bubbles produce an omnidirectional pulse. The pontoon sled that supports the minisparker is towed on the sea surface, ~5 m behind the ship.

Source characteristics of the SQUID 2000™ provided by the manufacturer show a source level of 209 dB re 1 μPa·m_{rms}. This is at the full power level of 2 kJ. The power level of this source may be reduced to provide more consistent, reliable output signals if necessary. The amplitude spectrum of this pulse indicates that most of the sound energy lies between 150 Hz and 1700 Hz, and the peak amplitude is at 900 Hz. The output sound pulse of the minisparker has a duration of about 0.8 ms. When operated at sea for the proposed MCS-reflection survey, the minisparker will be discharged every 0.5–3 seconds.

(g) Electromechanical Boomer Description

A boomer is a broad-band sound source operating in the 100–2500 Hz range. By sending electrical energy from the power supply through wire coils, spring-loaded plates in the boomer transducer are electrically charged causing the plates to repel, thus generating an acoustic pulse. The boomer planned for this cruise has three plates with a power input of 500 J per plate. The source level is 219 dB re 1 μPa·m_p, and the boomer will be towed on the surface. When operated at sea for the proposed MCS-reflection survey, the boomer will be discharged every 0.5–2 seconds.

(h) Chirp Sub-bottom Profiler System Description

The Edgetech 512i Chirp sub-bottom profiler (SBP) is a high resolution system that provides full-spectrum ("chirp") imaging. The system is towed either at the water surface or slightly submerged, depending on the application and water depth. The 512i has a source level of 198 dB re 1 μPa·m_{rms}. It has a frequency range of 500 Hz–12 kHz with pulse widths from 5 ms to 50 ms depending on the application.

(i) Multibeam Echosounder and Sub-bottom Profiler Descriptions

Along with the seismic operations, two additional acoustical data acquisition systems will be operated during part of the R/V *Melville*'s cruise. The ocean floor will be mapped with the 12-kHz Simrad EM120 multi-beam echosounder (MBES) in transit to the survey area, and a 3.5-kHz sub-bottom profiler (SBP) will also be operated along with the MBES and also to help verify seafloor conditions at possible coring sites.

Kongsberg–Simrad EM120 Multi-beam Echo Sounder.—The Kongsberg-Simrad EM120 operates at 11.25–12.6 kHz, and is mounted in the hull of the R/V *Melville*. It operates in several modes, depending on water depth. In the proposed survey, it will be used in automatic mode, changing from "Shallow" to "Medium" mode at 450 m and from "Medium" to "Deep" mode at 1000 m. In "Shallow" mode, the beamwidth is 2° fore-aft and the estimated maximum source level is 232 dB re 1 μPa·m_{rms}. Each "ping" consists of three successive fan-shaped transmissions, each 2 ms in duration with a delay of 3 ms between pulses for successive sectors. In "Medium" mode, the beamwidth is 1° or 2° fore-aft and the estimated maximum source levels are 232 or 226 dB re 1 μPa·m_{rms}. Each "ping" consists of three successive fan-shaped transmissions, each 5 ms in duration with a delay of 6 ms between pulses for successive sectors. In "Deep" mode, the beamwidth is 1° or 2° fore-aft and the estimated maximum source levels are 239 or 233 dB re 1 μPa·m_{rms}. Each "ping" consists of nine successive fan-shaped transmissions, each 15 ms in duration with a delay of 16 ms between pulses for successive sectors.

Knudsen 320BR Sub-bottom Profiler.—The Knudsen Engineering Model 320BR sub-bottom profiler is a dual-frequency transceiver designed to operate at 3.5 and/or 12 kHz. It is used in conjunction with the MBES to provide data about the sedimentary features that occur below the sea floor. The energy from the sub-bottom profiler is directed downward via a 3.5-kHz transducer array mounted in the hull of the R/V *Melville*. The maximum power output of the 320BR is 10 kilowatts for the 3.5-kHz section and 2 kilowatts for the 12-kHz section. (The 12-kHz section is seldom used in survey mode on *R/V Melville* because of overlap with the operating frequency of the Kongsberg Simrad EM-120 multi-beam sonar.)

The pulse length for the 3.5 kHz section of the 320BR is 0.8–24 ms, controlled by the system operator in regards to water depth and reflectivity of the bottom sediments, and will usually be 1.5–6 ms at the water depths (<50–1000 m) at the study sites and in transit to and from San Diego. The system produces one sound pulse and then waits for its return before transmitting again. Thus, the pulse interval is directly dependent upon water depth, and in this survey is 0.8–1.5 sec. Using the Sonar Equations and assuming 100% efficiency in the system (impractical in real world applications), the source level for the 320BR is calculated to be 211 dB re 1μPa-m. In practice, the system is rarely operated above 80% power level.

Sub-bottom Profiler Specifications (this survey)

Maximum source output (downward)	211 dB re 1 μPa-m; 10 kilowatts
Dominant frequency components	3.5 kHz
Nominal beamwidth	80 degrees
Pulse interval	0.8–1.5 sec
Pulse duration	1.5–6 ms

(3) Monitoring and Mitigation Measures

Marine mammals and sea turtles are known to occur in the proposed study area. To minimize the likelihood that impacts will occur to the species and stocks, seismic operations will be conducted in accordance with regulations by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) under the Marine Mammal Protection Act (MMPA) and the Endangered Species Act (ESA), including obtaining permission for incidental harassment or incidental 'take' of marine mammals and other endangered species. The proposed seismic activities will take place in the territorial waters of the U.S.A., partly inside California state waters.

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 SIO seismic research cruises as approved by NMFS and USFWS, and on best practices recommended in Richardson et al (1995), Pierson et al. (1998), and Weir and Dolman (2007).

(a) Planning Phase

In designing this proposed seismic survey, SIO and NSF have considered potential environmental impacts including seasonal, biological, and weather factors; ship schedules; and equipment availability during a preliminary assessment carried out when ship schedules were still flexible. Included were using the smallest source possible to meet research objectives and designing the survey to minimize the time spent on seismic operations. The research cruise was also scheduled for November when seasonally migrating gray whales, as well as more tropical endangered species like sea turtles, are typically outside the immediate Santa Barbara Channel area.

(b) Visual Monitoring

Vessel-based marine mammal visual observers (MMVOs) will be based on board the seismic source vessel, and they will watch for marine mammals and turtles near the vessel during seismic operations. MMVOs will also watch for marine mammals and turtles near the seismic vessel for at least 30 minutes prior to the start of seismic operations after an extended shutdown. When feasible, MMVOs will also make observations during daytime periods when the seismic system is not operating for comparison of animal abundance and behavior. Based on MMVO observations, the seismic source will be shut down when marine mammals are observed within or about to enter a designated exclusion zone (EZ) [see section (e) below]. The EZ is a region in which a possibility exists of adverse effects on animal hearing or other physical effects.

MMVOs will be appointed by the academic institution conducting the research cruise, with NMFS Office of Protected Resources concurrence. At least one MMVO will monitor the EZ during seismic operations. MMVOs will normally work in shifts of 4-hour duration or less. The vessel crew will also be instructed to assist in detecting marine mammals and turtles.

Standard equipment for marine mammal observers will be 7 x 50 reticule binoculars and optical range finders. At night, night-vision equipment will be available, although seismic activity will be restricted to daylight hours. The observers will be in wireless communication with ship's officers on the bridge and scientists in the vessel's operations laboratory, so they can advise promptly of the need for avoidance maneuvers or seismic source shut down.

(c) MMVO Data and Documentation

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

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

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

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

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

1. The basis for decisions about shutting down the seismic source.

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

(d) Reporting

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

(e) Proposed Exclusion Zones

Received sound levels have been modeled by Lamont-Doherty Earth Observatory of Columbia University (L-DEO) for a number of airgun configurations, including one 45-in^3 GI airgun, in relation to distance and direction from the GI airgun (Fig. 2). The model does not allow for bottom interactions, and is most directly applicable to deep water. Based on the modeling, estimates of the maximum distances from the GI airgun where sound levels of 190, 180, 170, and 160 dB re 1 μPa_{rms} are predicted to be received in deep (>1000-m) water are shown in Table 1. Because the model results are for a 2.5-m tow depth, which is deeper than the proposed 2-m tow depth, the distances in Table 1 slightly overestimate the distances for the 45-in^3 GI airgun towed at 2-m depth.

Empirical data concerning the 180-, 170-, and 160-dB distances have been acquired based on measurements during the acoustic verification study conducted by L-DEO in the northern Gulf of Mexico from 27 May to 3 June 2003 (Tolstoy et al. 2004). Although the results are limited, the data showed that radii around the airguns where the received level would be 180 dB re 1 μPa_{rms}, the safety criterion applicable to cetaceans (NMFS 2000), vary with water depth. Similar depth-related variation is likely in the 190-dB distances applicable to pinnipeds. Correction factors were developed for water depths 100–1000 m and <100 m. The proposed survey using the GI airgun will occur only in depths ~150–580 m.

The empirical data indicate that, for ***deep water*** (>1000 m), the L-DEO model tends to overestimate the received sound levels at a given distance (Tolstoy et al. 2004). However, to be precautionary pending acquisition of additional empirical data, it is proposed that safety radii during GI-gun operations in deep water will be the values predicted by L-DEO's model (Table 1). Therefore, the assumed 180- and 190-dB radii are 23 m and 8 m, respectively.

Empirical measurements were not conducted for ***intermediate depths*** (100–1000 m). On the expectation that results will be intermediate between those from shallow and deep water, a 1.5x correction factor is applied to the estimates provided by the model for deep water situations. This is the same factor that was applied to the model estimates during L-DEO cruises in 2003. The assumed 180 and 190 dB radii in intermediate-depth water are 35 m and 12 m, respectively (Table 1).

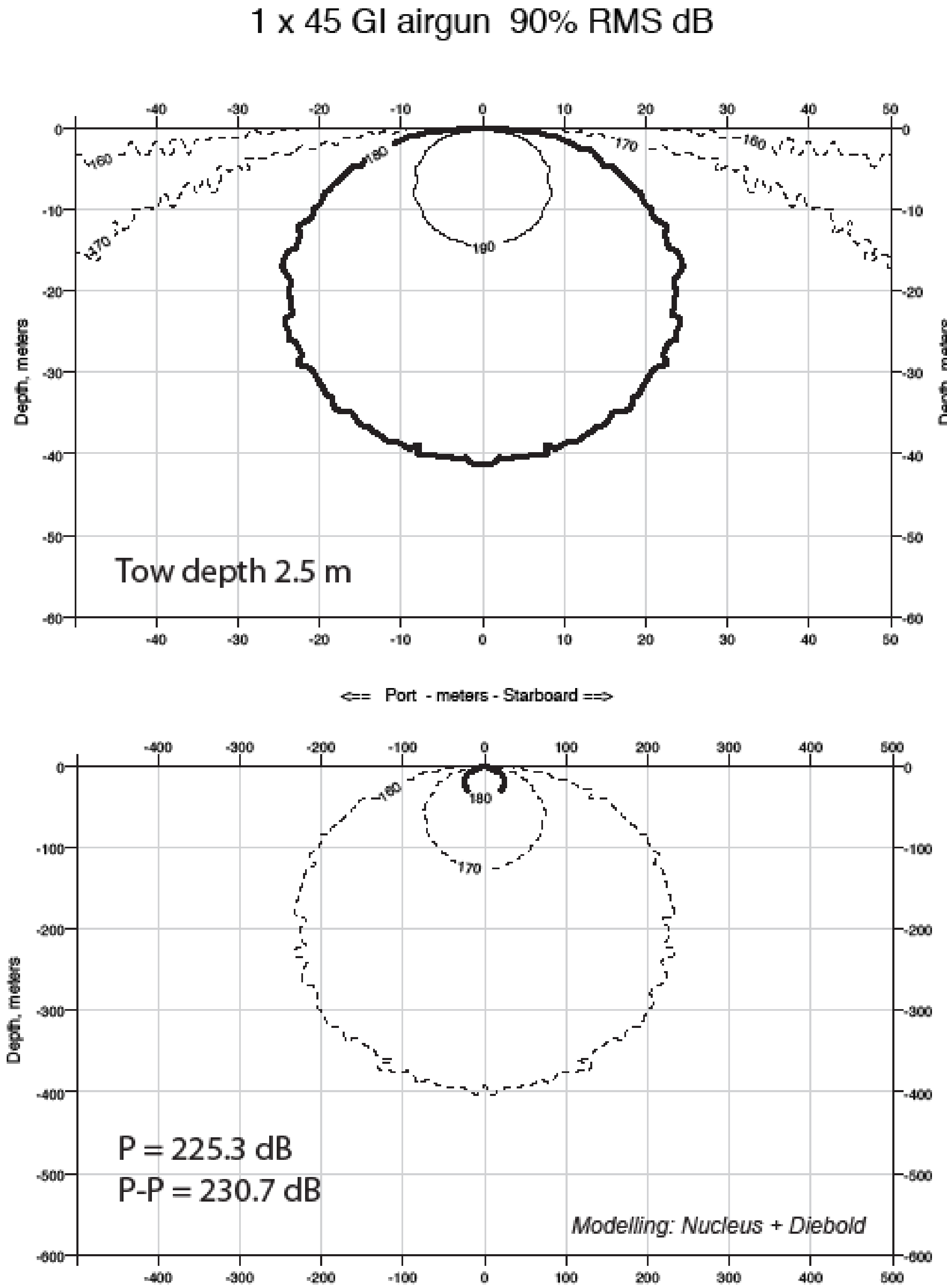

FIGURE 2. Modeled received sound levels from the 45-in^3 GI airgun that will be used during the SIO survey in the Santa Barbara Channel in November 2008. Model results provided by the Lamont-Doherty Earth Observatory of Columbia University.

TABLE 1. Distances to which sound levels ≥190, 180, 170, and 160 dB re 1 µPa$_{\mathrm{rms}}$ could be received from the 45-in^3 GI airgun that will be used during the seismic surveys in the Santa Barbara Channel in November 2008. Distances are based on model results provided by L-DEO.

Water depth	Estimated Distances (m) at Received Levels			
	190 dB	180 dB	170 dB	160 dB
>1000 m	8	23	70	220
100–1000 m	12	35	105	330

Received sound levels from the boomer proposed for use[2] in shallow water have not been modeled or measured. Burgess and Lawson (2001) measured received sound levels from a boomer with a source level of 203 dB re 1 µPa·m$_{\mathrm{rms}}$ in water depths 12–14 m, and Greene (2006) measured received sound levels from a boomer with a source level of 188.8 dB re 1 µPa·m$_{\mathrm{rms}}$ in water depths 37–48 m, both in the Alaskan Beaufort Sea. The distances at which sound levels 190-, 180-, and 160-dB re 1 µPa$_{\mathrm{rms}}$ were received are given in Table 2 together with the distances predicted using a spherical spreading model. In each case, more so for the larger source level, the modeled distance exceeded the measured distance. As a conservative (i.e., precautionary) measure, we will use modeled distances for our calculations. The source level of the boomer is 219 dB re 1 µPa·m$_{\mathrm{p}}$, corresponding roughly to 209 dB re 1 µPa·m$_{\mathrm{rms}}$[3]. Based on the spherical spreading model, distances to which sound levels ≥190, 180, 170, and 160 dB re 1 µPa$_{\mathrm{rms}}$ could be received from the boomer are 9, 28, 90, and 280, respectively (Table 2).

TABLE 2. Distances to which received sound levels ≥190, 180, and 160 dB re 1 µPa$_{\mathrm{rms}}$ were measured for two boomers in the Alaskan Beaufort Sea, and distances predicted by a spherical spreading model for those sources and for the boomer to be used in the proposed surveys..

Boomer source level (dB re 1 µPa·m$_{\mathrm{rms}}$) and distance	Estimated Distances (m) at			
	190 dB	180 dB	170 dB	160 dB
203, measured	<1	2	Not measured	22
203, modeled	4.5	16		140
188.8, measured	0.9	2.3	Not measured	14.6
188.8, modeled	1	2.7		27.5
209 (this study), modeled	9	28	90	280

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[2] Either the boomer or the mini sparker will be used in State waters. The boomer likely will be used (see text), and its source level is higher than that of the mini sparker, so our calculations are made for the boomer.

[3] The rms (root mean square) pressure is an average over the pulse duration. It is the measure commonly used in studies of marine mammal reactions to airgun sounds, and in NMFS guidelines concerning levels above which "taking" might occur. The rms level of a seismic pulse is typically about 10 dB less than its peak level (Greene 1997; McCauley et al. 1998, 2000a).

The seismic source will be shut down immediately when cetaceans or sea turtles are detected within or about to enter the 180-dB re 1 μPa_{rms} radius, or when pinnipeds are detected within or about to enter the 190-dB re 1 μPa_{rms} radius. The 180- and 190-dB shut-down criteria are consistent with guidelines listed for cetaceans and pinnipeds, respectively, by NMFS (2000) and other guidance by NMFS.

Detailed recommendations for new science-based noise exposure criteria were published recently (Southall et al. 2007). SIO 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. As yet, NMFS has not specified a new procedure for determining exclusion zones.

(e) Mitigation During Operations

Mitigation measures that will be adopted will include (1) vessel speed or course alteration, provided that doing so will not compromise operational safety requirements, (2) GI-gun or boomer shut down within calculated exclusion zones, (3) minimizing approach to slopes and submarine canyons, if possible, because of sensitivity of beaked whales, and (4) shut down at any range in the unlikely event that a North Pacific right whale or a concentration of sea otters is sighted. Two other standard mitigation measures—airgun array power down and airgun array ramp up—are not possible because only one, low-volume GI airgun, boomer, or sparker will be used for the surveys.

Speed or course alteration

If a marine mammal or sea turtle is detected outside the exclusion zone and, based on its position and the relative motion, is likely to enter the exclusion zone, the vessel's speed and/or direct course could be changed. This would be done if practicable while minimizing the effect on the planned science objectives. The activities and movements of the marine mammal or sea turtle (relative to the seismic vessel) will then be closely monitored to determine whether the animal is approaching the applicable exclusion zone. If the animal appears likely to enter the exclusion zone, further mitigative actions will be taken, i.e., either further course alterations or a shut down of the seismic source. Typically, during seismic operations, the source vessel is unable to change speed or course and one or more alternative mitigation measures (see below) will need to be implemented.

Shut-down procedures

If a marine mammal or turtle is detected outside the exclusion zone but is likely to enter the exclusion zone, and if the vessel's speed and/or course cannot be changed to avoid having the animal enter the exclusion zone, the seismic source will be shut 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 seismic source will be shut down immediately.

Following a shut down, seismic activity will not resume until the marine mammal or turtle has cleared the exclusion zone. The animal will be considered to have cleared the exclusion zone if it

- is visually observed to have left the exclusion zone, or
- has not been seen within the zone for 15 min in the case of small odontocetes and pinnipeds, or
- 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., ~1 min in intermediate-depth water to ~6 min in shallow water [based on the lengths of time it would take the vessel to leave the modeled exclusion zones of 35 m and 170 m, respectively, with a speed of 7.4 km/h].

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 November 2008 is the most suitable time logistically for the *Melville* and the participating scientists. If the IHA is issued for another period, it could result in significant delay and disruption not only of this cruise, but of additional geophysical studies that are planned by SIO for 2008 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 purpose of this project is to test the feasibility of extending the remarkable high-resolution paleoclimate record from Santa Barbara Basin from ~700,000 years ago back to ~1.2 million years ago by conducting detailed 3D modeling of the structure and outcrop stratigraphy of the northern shelf to locate optimal core sites, and by conducting high-resolution seismic reflection site surveys, test coring, and core analyses of the northern shelf and mid-channel areas. An integrated seismic data acquisition and coring cruise will be conducted to (1) acquire piston core samples of older marine sediments that are now exposed at the seafloor to test the suitability of these older deep basin sediments to provide a high-quality paleoclimate record, and (2) conduct high-resolution multi-channel seismic (MCS) surveys of the coring sites to place the results from the core analyses in a wider basin context, and to identify subsequent optimal and safe coring strategies suitable for recovering a continuous paleoclimate record from the shallow marine sediments in Santa Barbara Basin in the future as part of the Integrated Ocean Drilling Program (IODP). The acquisition of both seismic and coring data will also help tremendously in terms of providing critical sub-seafloor geologic and geophysical information needed to conduct additional coastal environmental and hazard studies in the Santa Barbara Channel area where a large and growing coastal population is currently at risk. In large part, it is because of this potential for these data to contribute to these other studies, as well as to a better understanding of the processes of global climate change, that the USGS is able and willing to participate as one of our principal research collaborators. Under the "No Action" alternative, this valuable scientific information would not become available.

In addition to forcing cancellation of the planned seismic survey, the "No Action" alternative could also, in some circumstances, result in significant delay of other geophysical studies that are planned by SIO for 2008 and beyond, depending on the timing of the decision, and would result in a cancellation of an important aspect of the IODP. 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 for the significant topics indicated. The ~12 days of field effort provides material for years of analyses involving multiple professors, students, and technicians. The lost opportunity to collect valuable scientific information is compounded by lost opportunities for support of research infrastructure, training, and professional career growth.

III. AFFECTED ENVIRONMENT

Marine Mammals

Thirty-two species of marine mammals, including 17 odontocetes, 8 mysticetes, 6 pinnipeds, and the southern sea otter (Table 3) could occur in the Santa Barbara Channel (SBC) area, based on many years of marine mammal surveys by ship and aircraft in the Southern California Bight (SCB) (e.g., Dohl et al., 1981, 1983; Barlow and Gerrodette 1996; Forney and Barlow 1998; Barlow and Taylor 2001; Calambokidis et al. 2003; Barlow 2003; Barlow and Forney 2007; Becker 2007; CINMS 2008). Eight of the cetacean and pinniped species and the southern sea otter are listed under the Endangered Species Act (ESA) as ***Endangered*** or ***Threatened***: the North Pacific right whale, humpback whale, sei whale, fin whale, blue whale, sperm whale, Guadalupe fur seal, and Steller sea lion. The Southern Resident Population of the killer whale is also listed as ***Endangered***. The California/Oregon/Washington stock of the short-finned pilot whale is considered "Strategic" under the MMPA, meaning that human impacts may influence the sustainability of these populations. No U.S.-designated critical habitat for any marine mammal species occurs in or near the project area. [The sea otter is the one marine mammal species mentioned in this document that, in the U.S.A., is managed by the USFWS; all others are managed by NMFS. Informal consultation from the USFWS is being sought for sea otters.]

Of the 32 species, 20 are considered residents or regular visitors to the Channel Islands National Marine Sanctuary (CINMS) waters, 14 of which are at least seasonally common to abundant in the SBC. The other 12 species are rare to extremely rare (Table 3).

(1) Mysticetes

North Pacific Right Whale (*Eubalaena japonica*)

The North Pacific right whale is ***Endangered*** under the ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). NMFS designated Critical Habitat for this species on 8 May 2008 to include recently discovered summer feeding areas in the SE Bering Sea and Gulf of Alaska (NMFS 2008). A reliable estimate of abundance is currently not available for this species and there has been little indication of population recovery since whaling depleted the population (Caretta et al. 2007). It has been estimated that <1000 individuals inhabit the entire North Pacific, with <100 to possibly several hundred in the eastern North Pacific (NMFS 2006). A minimum of 17 different individuals were photo-identified off Alaska in 2004 (Angliss and Outlaw 2008).

Right whales are generally considered migratory, with at least a proportion of the population feeding during summer in temperate or high-latitude waters and breeding and calving in warmer, lower-latitude waters (Clapham et al. 2004; NMFS 2006). Historical whaling records indicate that North Pacific right whales once ranged across the entire North Pacific north of 35ºN, occasionally occurring as far south as 20ºN. However, sightings have been rare since the 1960s (e.g., Clapham et al. 2004; Sheldon et al. 2005; NMFS 2008). In the eastern North Pacific, south of 50ºN, only 29 reliable sightings were recorded from 1900 to 1994 (Scarff 1986, 1991; Carretta et al. 1994; Rowlett et al. 1994). NMFS (2008) identified the current occupied range of this species off the western U.S. from 60°N to 40°N, ~500 km north of the project area. There is no evidence that waters off the west coast of North America have ever been important for this species (Brownell et al. 2001; NMFS 2008). Since 1996, small aggregations of right whales have been detected annually on feeding grounds in the southeast Bering Sea from summer through November, including calves in some years (Goddard and Rugh 1998; LeDuc et al. 2001; Moore et al. 2000, 2002; Munger et al. 2005; Scarff 2006; Wade et al. 2006;

TABLE 3. The habitat, regional abundance, and conservation status of marine mammals that could occur in or near the proposed seismic survey area in the Santa Barbara Channel (SBC).

Species	Occurrence in SBC	Habitat	Abundance[1]	ESA[2]	IUCN[3]	CITES[4]
Mysticetes						
North Pacific right whale	Extremely rare; winter-spring vagrant	Offshore, occasionally inshore	100-200 [5]	EN	EN	I
Gray whale	Common when migrating; rare Oct-Nov	Coastal except near Channel Islands	18,813 [6]	NL	LR-cd	I
Humpback whale	All year, common May-Jun, Sep-Dec	Mainly nearshore waters and banks	>6000 [7]	EN	VU	I
Minke whale	All year, common spring-fall	Pelagic and coastal	9000 [8]	NL	LR-nt	I
Bryde's whale	Rare	Pelagic and coastal	13,000 [9]	NL	DD	I
Sei whale	Very rare	Mostly pelagic	7260–12,620 [7]	EN	EN	I
Fin whale	Uncommon all year	Slope, mostly pelagic	13,620–18,680[7]	EN	EN	I
Blue whale	All year, common Jun-Oct	Pelagic and coastal	1186 [10]	EN	EN	I
Odontocetes						
Sperm whale	Uncommon all year	Usually deep pelagic	24,000 [11]	EN	VU	I
Pygmy sperm whale	Uncommon all year	Deep waters off shelf	N.A. [10]	NL	LR-lc	II
Dwarf sperm whale	Very rare	Deep waters off shelf	11,200 [9]	NL	LR-lc	II
Cuvier's beaked whale	Rare all year	Slope and pelagic	20,000 [9]	NL	DD	II
Baird's beaked whale	Rare all year	Slope and pelagic	6000 [12]	NL	LR-cd	I
Mesoplodont beaked whale	Rare all year	Slope and pelagic	1024 [13]	NL	DD	II
Offshore bottlenose dolphin	Common all year	Offshore, slope, shelf	3257 [10]	NL	DD	II
Coastal bottlenose dolphin	Common all year	Within 1 km of shore	323 [14]	NL	DD	II
Striped dolphin	Rare	Off continental shelf	1,824,000 [9]	NL	LR-cd	II
Short-beaked common dolphin	Common all year	Shelf, pelagic, high relief	487,622 [10]	NL	LR-lc	II
Long-beaked common dolphin	Common all year	Coastal, high relief	1893 [10]	NL		II
Pacific white-sided dolphin	All year, common fall-winter	Offshore, slope	931,000 [15]	NL	LR-lc	II
Northern right whale dolphin	Common only winter, spring	Slope, offshore waters	15,305 [10]	NL	LR-lc	II
Risso's dolphin	Common all year	Shelf, slope, seamounts	12,093 [10]	NL	DD	II
Killer whale	Uncommon all year	Widely distributed	8500 [16]	NL	LR-cd*	II
Short-finned pilot whale	Rare all year	Mostly pelagic, high-relief	160,200 [9]	NL	LR-cd	II
Dall's porpoise	Uncommon all year	Shelf, slope, offshore	57,549 [10]	NL	LR-cd	II
Harbor porpoise	Rare	Coastal	202,988 [17]	NL	VU	II
Pinnipeds						
Guadalupe fur seal	Extremely rare	Coastal	7408 [10]	T	VU	I
Northern fur seal	Uncommon all year	Pelagic, offshore	721,935 [18]	NL	VU	NL
California sea lion	Common all year	Coastal, shelf	238,000 [19]	NL	LR/lc	NL
Steller sea lion	Rare all year	Coastal, shelf	44,584 [20]	T	EN	NL
Harbor seal	Common all year	Coastal	34,233 [21]	NL	LR-lc	NL
Northern elephant seal	All year, common Dec-Mar peak	Coastal, pelagic when migrating	124,000 [21]	NL	LR-lc	NL
Fissiped						
Southern sea otter	Common all year	Coastal	2825 [22]	T	EN	I

N.A. Not available or not assessed.

*Southern Resident stock is listed as endangered but is unlikely to occur in southern California.

[1] Abundance given for North Pacific, Eastern North Pacific, Eastern Tropical Pacific, or California/Oregon/Washington Stock, unless otherwise stated.

[2] U.S. Endangered Species Act: EN = Endangered, T = Threatened, NL = Not listed

[3] Codes for IUCN classifications: EN = Endangered; VU = Vulnerable; LR = Lower Risk (-cd = Conservation Dependent; -nt = Near Threatened; -lc = Least Concern); DD = Data Deficient. Classifications are from the 2007 IUCN *Red List of Threatened Species* (IUCN 2007), although the status of marine mammals has not been reassessed since 1996.

[4] Convention on International Trade in Endangered Species of Wild Fauna and Flora (UNEP-WCMC 2008); NL = Not listed.

[5] Eastern North Pacific (Wada 1973).

[6] Mean of 2000–2001 and 2001–2002 abundance estimates for eastern North Pacific (Angliss and Outlaw 2008)

[7] North Pacific Ocean (Carretta et al. 2007).

[8] North Pacific Ocean (Wada 1976).
[9] Eastern Tropical Pacific (Wade and Gerrodette 1993)
[10] California/Oregon/Washington (Carretta et al. 2007).
[11] Eastern temperate North Pacific (Whitehead 2002).
[12] Western North Pacific (Kasuya 2002).
[13] All mesoplodont whales; California/Oregon/Washington (Carretta et al. 2007).
[14] California (Carretta et al. 2007)
[15] North Pacific Ocean (Buckland et al. 1993).
[16] Eastern Tropical Pacific (Ford 2002).
[17] Eastern North Pacific Ocean (totals from Carretta et al. 2007 and Angliss and Outlaw 2008).
[18] Abundance for Eastern Pacific Stock (Angliss and Outlaw 2008)
[19] U.S. (Carretta et al. 2007)
[20] Minimum estimate for Eastern U.S. Stock (Angliss and Outlaw 2008)
[21] California (Carretta et al. 2007)
[22] California (Maender 2004)

Angliss and Outlaw 2008). The winter breeding and calving areas for the population are unknown (Scarff 1986; Clapham et al. 2004) but could be in offshore waters (NMFS 2008).

Based on a small number of recent sightings, North Pacific right whales tend to occur alone (Brownell et al. 2001), except in an area of the southeastern Bering Sea where small groups of up to 5–7 have been documented in several successive years (Tynan et al. 2001). While feeding, North Atlantic right whales typically dive to depths of 80–175 m for 5–14 min (Baumgartner and Mate 2003).

The North Pacific right whale is considered a rare winter or early spring vagrant off southern California (NMFS 2008). Over the last century, 13 right whale sightings have occurred off California including two sightings off Baja, all but one since 1955 (Scarff 2006). Most of the sightings were of single animals and most occurred in winter or early spring (March–May) and very close to shore (Scarff 1991, 2006). Three of these records were near the Santa Barbara project area: one sighting ~74 km southwest of the southeast tip of Santa Catalina Island on 24 March 1992 (Carretta et al. 1994), one whale ~15 km north of Santa Catalina Island on 9 May 1990 (Scarff 1991), and one near Santa Barbara on 17 April 1981 (Woodhouse and Strickley 1982).

Gray Whale (*Eschrichtius robustus*)

The eastern gray whale population ranges from the Chukchi and Beaufort seas to the Gulf of California (Rice 1998). Gray whales are found primarily in shallow water, and usually remain closer to shore than any other large cetacean. The current population estimate for this stock of 18,813 is based on the mean of the 2000–2001 and 2001–2002 abundance estimates (Angliss and Outlaw 2008). The population has increased overall from 1967/68 through 2001/02 at a rate of 1.86% (Rugh et al. 2005).

Gray whales make a well-defined seasonal north-south migration. Most of the population summers in shallow waters of the northern Bering Sea, the Chukchi Sea, and the western Beaufort Sea (Rice and Wolman 1971); some individuals also summer along the west coast from Canada to central California (Rice and Wolman 1971; Darling 1984; Nerini 1984). Nearly all feeding activity occurs between late spring and early fall, though some opportunistic feeding may occur in or near the breeding and calving grounds (Norris et al. 1977). In October and November, gray whales begin to migrate south, following the shoreline south to breeding grounds on the west coast of Baja California and the southeastern Gulf of California (Braham 1984; Rugh 1984). Some calves are born along the coast of California, but most are born in the shallow, protected waters on the west coast of Baja California from ~28°N to ~24°N (Urban et al. 2003).

Gray whales usually migrate alone, with the exception of cow/calf pairs, and groups of >6 whales are unusual (Rice and Wolman 1971; Leatherwood et al. 1988). A mean group size of 2.9 gray whales was reported for both coastal (16 groups) and non-coastal (15 groups) areas in the San Clemente Island Range Complex (SCIRC), ~250 km southeast of the study area (Carretta et al. 2000). The largest group reported was nine animals. Koski et al. (1998) reported a mean group size of 3.2 (n = 141) in the Point Mugu Sea Range, which extends roughly from Anacapa Island offshore for ~300 km and north to ~35.5ºN, a mean group size of 2.7 (n = 428) east of the range, close to shore in the SBC, and a maximum group size of 27. Foraging gray whales commonly dive to depths of 50–60 m, and the maximum known dive depth is 170 m (Jones and Swartz 2002). Migrating gray whales typically dive for 3–5 min and spend 1–2.5 min on the surface between dives (Jones and Swartz 2002).

The southward gray whale migration through the SCB extends from December through February, and the northward migration occurs from February through May, peaking in March (Leatherwood 1974; Bonnell and Dailey 1993). This migration generally follows the coastline closely, although south of Point Conception, most gray whales follow a more offshore route across the SCB and through the Channel Islands (Jones and Swartz 2002). Gray whales are usually absent from southern California waters during August–November (MMS 2005), although there have been a small number of sightings in the SBC during this period, including in early through late November (CINMS 2008). Approximately 2485 sightings of gray whales are recorded in the CINMS Sightings Database in and near the SBC from 2000 to 2008 during nearly every month of the year, but primarily from December to March (CINMS 2008).

Humpback Whale (*Megaptera novaeangliae*)

The humpback whale is listed as ***Endangered*** under the ESA and ***Vulnerable*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The North Pacific population numbers >6000, and the California/Oregon/Washington stock is estimated at 1396, based on 2002/2003 photographic mark-recapture data and 2001–2005 line transect data (Caretta et al. 2007). Recent population estimates indicate a 6–7% growth rate for this stock that is consistent with the recently observed growth rate for this species in the entire North Pacific Stock (Caretta et al. 2007).

Humpback whales occur worldwide, migrating from tropical breeding areas to polar or sub-polar feeding areas (Jefferson et al. 2008). The stock that occurs in and near the CINMS inhabits waters from Costa Rica (Steiger et al. 1991) to southern British Columbia (Calambokidis et al. 1993). This stock is most abundant in coastal waters off California during spring and summer and off Mexico during autumn and winter (Jefferson et al. 2008). Although the humpback whale is considered mainly a coastal species, it often traverses deep pelagic areas while migrating (Clapham and Mattila 1990; Norris et al. 1999; Calambokidis et al. 2001).

Humpback whales are often sighted singly or in groups of two or three, but while on breeding and feeding grounds, they may occur in groups of >20 (Leatherwood and Reeves 1983; Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 2.1 (n = 5) off southern California and 1.9 (n = 129) off California, Oregon, and Washington The diving behavior of humpback whales is related to time of year and whale activity (Clapham and Mead 1999). 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).

SBC waters are used by humpback whales as a migration corridor, and to a lesser degree for feeding, primarily in March–June and September–December; they are rarely seen there during other months (Bonnell and Dailey 1993; CINMS 2008). The deeper offshore waters of the western SBC are used by humpbacks feeding on krill during summer and fall (MMS 2005). Numbers of feeding humpbacks sighted in the SBC area vary from year to year (CINMS 2008). Approximately 1523 sightings of humpback whales are recorded in the CINMS Sightings Database in and near the SBC from 2002 to 2007 during every month of the year, but primarily during late spring through fall (CINMS 2008).

Minke Whale (*Balaenoptera acutorostrata*)

The minke whale inhabits all oceans of the world from the high latitudes to near the equator (Leatherwood et al. 1982). Wada (1976) estimated the North Pacific population at 9000. Two minke whale stocks are recognized in U.S. waters, the Alaskan stock and the California/Oregon/Washington stock (Angliss and Outlaw 2008). Current estimates of abundance are not for the Alaska stock (Angliss and Outlaw 2008). The estimated abundance for the California/Oregon/Washington stock is 898, based on 2001 and 2005 NMFS summer/fall vessel-based surveys (Carretta et al. 2007; Forney 2007).

In the northeast Pacific Ocean, minke whales range from the Chukchi Sea south to Baja California (Leatherwood et al. 1987; Jefferson et al. 2008). In the Northern Hemisphere, minke whales are usually seen in coastal areas but can be seen in pelagic waters during northward migrations in spring and summer and southward migration in autumn (Stewart and Leatherwood 1985).

Minke whales are relatively solitary, but may occur in aggregations of up to 100 when food resources are concentrated (Jefferson et al. 2008). Based on SWFSC vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 1.6 (n = 4) off southern California and 1.2 (n = 18) off California, Oregon, and Washington. The mean size of 89 groups in the Point Mugu Sea Range was 1.4 and the largest group was 17 (Koski et al 1998). Little is known about the diving behavior of minke whales, but they are not known to make prolonged deep dives (Leatherwood and Reeves 1983).

Minke whales occur year-round off California (Dohl et al. 1983; Barlow 1995; Forney et al. 1995; Koski et al. 1998; CINMS 2008). Minke whales off California, Oregon, and Washington appear to be resident in that area, and to have home ranges, whereas those farther north are migratory. Minke whale abundance in the SCB fluctuates dramatically through the year, with warm-water months being the period of greatest abundance (Dohl et al. 1981). Minke whales inhabit SBC and CINMS waters primarily from March through December, with dwindling numbers in October through December; they are rare in January and February (NOAA 2000; CINMS 2008). Although few minke whales are seen in the nearshore and continental slope parts of the SCB during winter, they appear to be present in offshore SCB waters at this time. The few sightings in winter sometimes include newborn or small calves, suggesting that the SCB is part of, or at least near, the calving grounds of this stock (Bonnell and Dailey 1993). Because of the apparent fluctuations in abundance, Bonnell and Dailey (1993) believed that some minke whales migrated northward through the SCB in spring and returned southward through the same area in autumn. Leatherwood et al. (1987) suggested that minke whales could remain in the area throughout the year, and that the scarcity of sightings during autumn and winter could be attributable to behavioral and environmental considerations. The lack of sightings in autumn and winter could also be attributable to movements into offshore areas where there has been less survey effort. During the summer in the SCB, minke whales are seen commonly along the shelves associated with the southern coasts of the Channel Islands, near offshore features south of there, and near the northern Channel Islands (Leatherwood et al. 1987; Bonnell and Dailey 1993). Approximately 163 sightings of minke whales are recorded in the CINMS Sightings Database in and near the SBC from 2002 to 2008 during every month of the year, but primarily during late spring through fall (CINMS 2008).

Bryde's Whale (*Balaenoptera edeni*)

Bryde's whale occurs in tropical and subtropical waters, generally between 40°N and 40°S (Jefferson et al. 2008). The North Pacific population was estimated at 20,000–30,000 (Best 1975 *in* Cummings 1985), and the Eastern Tropical Pacific population at 13,000 (Wade and Gerrodette 1993).

Bryde's whales are known to occur in both shallow coastal and deeper offshore waters (Jefferson et al. 2008). It does not undertake long migrations, although there is a general pattern of movement toward the equator in winter and toward higher latitudes in summer (Kato 2002). Bryde's whales are usually solitary or in pairs, although groups of 10–20 are known from the feeding grounds (Jefferson et al. 2008). Wade and Gerrodette (1993) reported a mean group size of 1.7 (n = 109) for the ETP. The durations of Bryde's whale dives are 1–20 min (Cummings 1985).

Bryde's whale is considered rare in the SCB. Only one Bryde's whale has ever been positively identified during extensive NMFS vessel and aerial surveys of California coastal waters from 1991 to 2005 (Barlow and Forney 2007), and that sighting was well offshore of central California, at ~36ºN, 125ºW (Hill and Barlow 1992). None have been recorded in the CINMS database from 2002 to 2007 (CINMS 2008).

Sei Whale (*Balaenoptera borealis*)

The sei whale is listed as ***Endangered*** under the ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2006), and is listed in CITES Appendix I (UNEP-WCMC 2008). The size of the North Pacific population in 1974 was estimated at 7260–12,620, depending on the method used (Tillman 1977). The estimated abundance for waters out to ~550 km off California, Oregon, and Washington is 43, based on 1996 and 2001 shipboard line-transect surveys (Caretta et al. 2007).

The sei whale has a nearly cosmopolitan distribution, with a marked preference for temperate pelagic waters, and is rarely seen in coastal waters (Gambell 1985a). In the open ocean, sei whales generally migrate from temperate zones occupied in winter to higher latitudes in the summer where most feeding takes place (Gambell 1985a). In the eastern Pacific, sei whales range in the summer from the Bering Sea and the northern Gulf of Alaska to the coast of southern California (Jefferson et al. 2008). Winter sightings have been made between southern Baja California and the Islas Revillagigedo (Rice 1998). Sei whales appear to prefer regions of steep bathymetric relief such as the continental shelf break, seamounts and canyons (Kenney and Winn 1987; Gregr and Trites 2001). On feeding grounds, they associate with oceanic frontal systems (Horwood 1987) such as the cold eastern currents in the North Pacific (Perry et al. 1999).

Sei whales are frequently seen in groups of 2–5 (Leatherwood et al. 1988; Jefferson et al. 2008), although larger groups sometimes form on feeding grounds (Gambell 1985a). Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 1.4 (n = 7) off central and northern California, Oregon, and Washington. Three groups sighted on the PMSR numbered 2, 2, and 8 (Koski et al. 1998). Sei whales generally do not dive deeply, and dive durations are 15 min or longer (Gambell 1985a).

The sei whale is rare in California waters (Carretta et al. 2007). Three sei whale sightings occurred in the PMSR, two north of Point Conception, and one south of the western tip of Santa Cruz Island (Koski et al. 1998). Only one confirmed sighting and five possible sightings (identified as either sei or Bryde's whales) were made in California waters during ship and aerial surveys in 1991–1993 (Mangels and Gerrodette 1994; Barlow 1995). The confirmed sighting was >370 km off northern California (Mangels and Gerrodette 1994). No sei whales were sighted during the NMFS/SWFSC surveys of the SCIRC in

1998–1999 (Carretta et al. 2000) or off southern California in 1991, 1993, 1996, 2001, and 2005 (Barlow and Forney 2007). No sei whale sightings are recorded for the SBC in the CINMS sighting database for 2002–2007 (CINMS 2008).

Fin Whale (*Balaenoptera physalus*)

The fin whale is listed as ***Endangered*** under the ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The size of the North Pacific population was estimated at 13,620–18,680 in 1973 (Ohsumi and Wada 1974). The estimated abundance for waters out to ~550 km off California, Oregon, and Washington is 3454, based on 2001 and 2005 shipboard line-transect surveys (Caretta et al. 2007).

Fin whales are widely distributed in all the world's oceans in coastal, shelf, and oceanic waters, but typically occur in temperate and polar regions (Gambell 1985b; Perry et al. 1999; Gregr and Trites 2001; Jefferson et al. 2008). The North Pacific population of fin whales summers from the Chukchi Sea to California, and winters from California southward (Gambell 1985b). The species appears to have complex seasonal movements, and is likely a seasonal migrant: mating and calving occurs in temperate waters during winter, followed by migration to northern latitudes to feed during the summer (Mackintosh 1965; Gambell 1985b; Jefferson et al. 2008). However, some evidence suggests that there is a resident population of fin whales in the Gulf of California (Tershy et al. 1993). Thus, some individuals or populations may not undertake the typical long-distance migrations that characterize this species. Sergeant (1977) suggested that fin whales tend to follow steep slope contours, either because they detect them readily or because biological productivity is high along steep contours because of tidal mixing and perhaps current mixing.

Fin whales are typically observed alone or in pairs, but also in groups of up to 7 or more, with the largest aggregations occurring on feeding grounds (Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 2.4 (n = 35) off southern California. 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).

Aggregations of fin whales occur year-round off southern California, including the SBC and CINMS, and are most common during the warm-water months from May to October (Dohl et al. 1983; Barlow 1997; Caretta et al. 2000; CINMS 2008). The fin whale was the second most commonly-encountered baleen whale (after the blue whale) off southern California during NMFS vessel surveys from 1991 to 2005 (Barlow and Forney 2007), and the second most commonly-encountered baleen whale (after the gray whale) during surveys conducted by NMFS in 1998–1999 in the SCIRC (Carretta et al. 2000). Fin whales occur in the SBC although they are more frequently seen somewhat farther offshore and south of the northern Channel Islands, particularly in winter (Leatherwood et al. 1987; Bonnell and Dailey 1993; CINMS 2008). Approximately 18 sightings of fin whales are recorded in the CINMS Sightings Database in and near the SBC from 2002 to 2007, 17 of which were in May–September (CINMS 2008).

Blue Whale (*Balaenoptera musculus*)

The blue whale is listed as ***Endangered*** under the ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). The worldwide population has been estimated at 15,000, with 10,000 in the Southern Hemisphere (Gambell 1976), 3,500 in the North Pacific Ocean, and up to 1,400 in the North Atlantic Ocean (NMFS 1998). Blue whale calls monitored from the U.S. Navy Sound Surveillance System (SOSUS) and other offshore hydrophones suggest that separate populations occur in the eastern and western North Pacific (Stafford et al. 1999, 2001, 2007; Watkins et al. 2000; Stafford 2003). Based on ship line-transect surveys in 2001 and 2005 and photographic mark-recapture methods in 2000–2002, the estimated population for the Eastern North Pacific Stock is 1186 (Caretta et al. 2007).

The blue whale is widely distributed throughout most of the world's oceans, occurring in coastal, shelf, and pelagic waters (Jefferson et al. 2008). Broad-scale acoustic monitoring indicates that blue whales of the Eastern North Pacific Stock may range from the eastern tropical Pacific Ocean along the coast of North America to Canada, and offshore at least 500 km (Stafford et al. 1999, 2001). In more recent studies, blue whales have been detected acoustically (Stafford 2003; Stafford and Moore 2005; Stafford et al. 2007) and sighted (Barlow 2004a,b) in the Gulf of Alaska. Generally, they are seasonal migrants between high latitudes in the summer, where they feed, and low latitudes in winter, where they mate and give birth (Lockyer and Brown 1981). Little is known about the movements and wintering grounds of the stocks (Mizroch et al. 1984). Some individuals may stay in low or high latitudes throughout the year (Reilly and Thayer 1990; Watkins et al. 2000). Moore et al. (2002) reported that blue whale calls are received in the North Pacific year-round, indicating that this area is suitable habitat for blue whales in all seasons. However, the number of whales producing the calls remains unknown.

Blue whales are typically found singly or in groups of two or three (Yochem and Leatherwood 1985; Jefferson et al. 2008). They commonly form scattered aggregations on feeding grounds (Jefferson et al. 2008) and apparent single whales are likely part of a large, dispersed group (Wade and Friedrichsen 1979). Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 1.8 (n = 106) off southern California. Four satellite-radio-tagged blue whales in the northeast Pacific Ocean spent 94% of their time underwater, 72% of dives were <1 min long, and "true" dives (>1 min) were 4.2–7.2 min long. Shallow (<16-m) dives were most common (75%), and the average depth of deep (>16-m) dives was 105 m (Lagerquist et al. 2000). 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).

The blue whale is the most abundant large whale off southern California (Smith et al. 1986). Migratory movements and feeding patterns off California likely are related to seasonal patterns and productivity (Croll et al. 2005), with feeding areas associated largely with coastal upwelling zones (Croll et al. 1998; Fiedler et al. 1998; Burtenshaw et al. 2004). Both feeding and migrating blue whales use the SBC mainly from spring through fall (MMS 2005; CINMS 2008), and photographic studies show that some blue whales remain in California waters throughout the summer, apparently to feed (Calambokidis 1995; Larkman and Veit 1998). During January through April, blue whales are rare off southern California (Barlow pers. comm. *in* DoN 2005). Feeding occurs most frequently at the western end of the SBC (Fiedler et al. 1998). In the CINMS and SBC, the number and timing of feeding blue whales appears to fluctuate from year to year. Numbers there are generally most abundant in July–September (Larkman and Veit 1998), although they are common during May and June as well (Barlow pers. comm. *in* DoN 2005; MMS 2005; CINMS 2008). Over 100 blue whales were present in the SBC in 1992 and 1994 (Calambokidis 1995). In 1995, blue whales were common in offshore waters near the southwestern Channel Islands as late as October (Spikes and Clark 1996; Clark and Fristrup 1997; Clark et al. 1998). In 2002 and 2007, blue whales were common in the SBC and CINMS during October-early November, whereas fewer sightings were recorded there at that time in 2003 and none were recorded during 1999–2001 or 2004–2006 (CINMS 2008). Approximately 1027 sightings of blue whales were recorded in SBC waters during 2002–2007 in nearly all months of the year, with most animals seen in July–August (CINMS 2008).

(2) Odontocetes

Sperm Whale (*Physeter macrocephalus*)

The sperm whale is listed as ***Endangered*** under the ESA and on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and is listed in CITES Appendix I (UNEP-WCMC 2008). Population estimates for the eastern North Pacific Ocean were 26,300 based on visual sightings during a survey in spring 1997, and 32,100 based on acoustic detections and visual group size estimates (Barlow and Taylor 2005). The most recent estimate of abundance for the California-Oregon-Washington stock is 2265, based on ship surveys conducted during summer/autumn in 2001 and 2005 (Caretta et al. 2007).

Sperm whales range between the northern and southern edges of the polar pack ice, although they are most abundant in tropical and temperate waters >1000 m deep over the continental shelf edge and slope, and in pelagic waters (e.g., Rice 1989; Gregr and Trites 2001; Waring et al. 2001). Adult females and juveniles generally occur year-round in tropical and subtropical waters, whereas males often move to higher latitudes outside the breeding season to forage (Best 1979; Watkins and Moore 1982; Arnbom and Whitehead 1989; Whitehead and Waters 1990). Sperm whales often associate with areas of high secondary productivity and steep underwater topography, such as volcanic islands (Jacquet and Whitehead 1996). In some areas, such as off Long Island, New York, and on the Scotian Shelf off Nova Scotia, adult males appear to consistently use waters with bottom depths <100 m and as shallow as 40 m (Whitehead et al. 1992; Scott and Sadove 1997). Females almost always occur in water depths >1000 m (Whitehead 2002).

Sperm whales occur singly (older males) or in groups, with mean group sizes of 20–30 but as many as 50 (Whitehead 2003; Jefferson et al. 2008). Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 8.1 (n = 19) off southern California. Sperm whales undertake some of the deepest-known dives for the longest durations among cetaceans. 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). A recent study of tagged male sperm whales feeding at high latitude (off Norway) found that foraging dives extended to highly variable maximum depths, ranging from 14 to 1860 m and with median 175 m (Teloni et al. 2008). During a foraging dive, sperm whales typically travel ~3 km horizontally and 0.5 km vertically (Whitehead 2003). The diet of sperm whales consists mainly of mesopelagic and benthic squids and fishes. Sperm whales are thought to forage for prey in a large part of the water column below the scattering layer (Wahlberg 2002).

Off southern California, sperm whales occur year-round in offshore waters, peaking in abundance from April to mid-June and again from late August to November (Dohl et al. 1981, 1983; Gosho et al. 1984; Barlow et al. 1997). They are rare in the SCB during spring and over the continental shelf (Bonnell and Dailey 1993; Koski et al. 1998; Carretta et al. 2007). During NMFS ship-based surveys off California in 1991–2005, sperm whales were sighted offshore and south of the SCB (Barlow and Forney 2007). No sperm whales were recorded in the SBC during aerial and shipboard surveys between 1991 and 2005 (Caretta et al. 2007). However, there are nine records of sperm whale sightings in the SBC and CINMS between 2002 and 2007, including four sightings during November (CINMS 2008).

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

Pygmy sperm whales (*Kogia breviceps*) and dwarf sperm whales (*Kogia sima*) are distributed widely throughout tropical and temperate seas, but their precise distributions are unknown because much of what we know of the species comes from strandings (McAlpine 2002). They are difficult to sight at sea, because of their dive behavior and 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 sightings surveys and, hence, in population and density estimates, the two species are most often categorized together as *Kogia* spp. (Waring et al. 2004). Wade and Gerrodette estimated that the population of dwarf sperm whales in the ETP was 11,200. There is currently insufficient information available to reliably estimate the best or minimum population size of the dwarf sperm whale off the Pacific U.S. coast given the rarity of sightings (Carretta et al. 2007). Barlow and Forney (2007) estimated that 1237 *Kogia* spp. occurred off California, Oregon, and Washington, based on five sightings using pooled survey data from 1991 to 2005. Based on stranding and sighting data, the pygmy sperm whale is more likely to occur off the California coast than the dwarf sperm whale, though records of both species are rare off California (Caretta et al. 2007).

Both *Kogia* species are sighted primarily along the continental shelf edge and slope and over deeper waters off the shelf (Hansen et al. 1994; Davis et al. 1998; Caretta et al. 2007; Jefferson et al. 2008). Several studies have suggested that pygmy sperm whales live mostly beyond the continental shelf edge, whereas dwarf sperm whales tend to occur closer to shore, often over the continental shelf (Rice 1998; Wang et al. 2002; MacLeod et al. 2004). Barros et al. (1998), on the other hand, suggested that dwarf sperm whales might be more pelagic and dive deeper than pygmy sperm whales. Another suggestion is that the pygmy sperm whale is more temperate, and the dwarf sperm whale more tropical, based at least partially on live sightings at sea from a large database from the ETP (Wade and Gerrodette 1993). This idea is also supported by the distribution of strandings in South American waters (Muñioz-Hincapié et al. 1998). Also, in the western tropical Indian Ocean, the dwarf sperm whale was much more common than the pygmy sperm whale, which is consistent with this hypothesis (Ballance and Pitman 1998).

Pygmy and dwarf sperm whales are usually found singly or in groups of less than six (Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 1.3 (n = 5) off California, Oregon, and Washington. Wade and Gerrodette (1993) reported a mean group size of 1.7 (n = 95) for dwarf sperm whales in the ETP. In the Gulf of California, median dive time for dwarf or unidentified sperm whales was 8.6 min and median surface time was 1.2 min, and dives of up to 25 min and surface times up to 3 min were common (J. Barlow, pers. comm. *in* Willis and Baird 1998). Little is known about dive depths of *Kogia* spp. A satellite-tagged pygmy sperm whale released off Florida made longer dives (> 8 min and up to ~18 min) at night and on overcast days, and shorter dives (usually 2–5 min) on clear days, probably because of the distribution of their prey, vertically-migrating squid (Scott et al. 2001).

Both species of *Kogia* are rare off southern California. No *Kogia* spp. was sighted off southern California during NMFS vessel-based surveys during 1991–2005 (Barlow and Forney 2007). One pygmy sperm whale was sighted off southern California during 1991–2005 aerial and shipboard surveys that included California waters, in deep offshore waters ~200 km south of the SBC (Carretta et al. 2007). No records of either species are reported from the SBC or CINMS in the 1999–2007 CINMS Sightings Database (CINMS 2008). The closest confirmed dwarf sperm whale sightings include 28 in the Gulf of California, one in nearshore waters west of Baja, and two in offshore waters between 20ºN and 25ºN (Mangels and Gerrodette 1994).

Cuvier's Beaked Whale (*Ziphius cavirostris*)

Cuvier’s beaked whale is probably the most widespread of the beaked whales, although it is not found in high-latitude polar waters (Heyning 1989). There are an estimated 20,000 Cuvier’s beaked whales in the ETP (Wade and Gerrodette 1993). The mean of the population estimates from 2001 and 2005 vessel-based surveys of the waters out to ~550 km off California, Oregon, and Washington is 2171 (Caretta et al. 2007).

Cuvier's beaked whale is found in deep water, but it appears to prefer steep continental slope waters (Jefferson et al. 2008), and is most common in water depths >1000 m (Heyning 1989). It is most commonly seen in groups of 2–7 but also up to 15, with a reported mean group size of 2.3 (MacLeod and D'Amico 2006; Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 2.7 (n = 3) off southern California and 2.6 (n = 17) off California/Oregon/Washington. The mean size of 27 groups in the Point Mugu Sea Range was 2.3 and the largest group size was 11 (Koski et al. 1998). Cuvier's beaked whales make long (30–60 min), deep dives with reported maximum depths of 1267 m (Johnson et al. 2004) and 1450 m (Baird et al. 2006).

Cuvier's beaked whales are relatively common in southern California waters, with an estimated abundance of 911 based on NMFS vessel-based surveys in 1991–2005, but they are rare in the SCB. They have been documented occasionally in deep waters generally offshore of the CINMS, with no known sightings within the SBC based on syntheses of aerial and vessel-based surveys and observations (Caretta et al. 2007; Barlow and Forney 2007; CINMS 2008).

Baird's Beaked Whale (*Berardius bairdii*)

Baird's beaked whale has a fairly extensive range across the North Pacific north of 30˚N, and strandings have occurred as far north as the Pribilof Islands and sightings have been made as far south as the southern Gulf of California (Rice 1998; Kasuya 2002; Jefferson et al. 2008). There is no population estimate for the eastern Pacific Ocean, but it is estimated that ~7000 Baird's beaked whales inhabit the western North Pacific (Kasuya 2002). The mean of the population estimates from 2001 and 2005 vessel-based surveys of the waters out to ~550 km off California, Oregon, and Washington is 313 (Forney 2007; Caretta et al. 2007).

Baird's beaked whales sometimes are seen close to shore, but their primary habitat is over or near the continental slope and oceanic seamounts in waters 1000–3000 m deep (Kasuya 1986; Jefferson et al. 1993). In the eastern North Pacific, Baird's beaked whales spend spring and summer in the Bering Sea (Jefferson et al. 2008). Off the U.S. west coast, they exhibit apparent seasonal shifts in distribution. From late spring through early fall they are seen mostly on the continental slope, and from November through April, they are seen less often and are presumed to move farther offshore (Caretta et al. 2007). However, their winter distribution is mostly unknown (Jefferson et al. 2008).

Baird's beaked whales usually travel in groups of a few to several dozen, although groups of up to 50 have been recorded (Balcomb 1989; Jefferson et al. 2008). Kasuya (1986) reported a mean group size of 7.2, based on shipboard sightings in 1984. Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 7.0 (n = 1) off southern California and 9.3 (n = 15) off California, Oregon, and Washington. Baird's beaked whales are deep, long divers; dives of 25–35 min are typical (Balcomb 1989). Most (66%) dives are <20 min long, and time at the surface is 1–14 min (Kasuya 2002). Whalers reported that when struck, they could dive to depths >1000 m and remain submerged for >1 hr (Balcomb 1989).

Off California, Baird's beaked whales are infrequently encountered along the continental slope and throughout deep waters (Carretta et al. 2007). Thirteen sightings of 42 individuals were made in the Point Mugu Sea Range (Koski et al. 1998). No sightings were made during the 1998–1999 NMFS surveys of the SCIRC (Carretta et al. 2000), and only two sightings, both well offshore, were reported off southern California during aerial and vessel-based surveys in 1991–2005 (Carretta et al. 2007). No Baird's beaked whales were recorded in the SBC by CINMS (2008).

Mesoplodont Beaked Whales (*Mesoplodon* spp.)

Mesoplodont beaked whales (*Mesoplodon* spp.) are difficult to distinguish in the field, and confirmed at-sea sightings are rare (Mead 1989; Caretta et al. 2007; Jefferson et al. 2008). Until better methods are developed for distinguishing the different *Mesoplodon* species from one another, the management unit is defined to include all *Mesoplodon* populations (Caretta et al. 2007). Wade and Gerrodette estimated a population size of 25,300 for the ETP, and the estimated abundance of mesoplodonts for the California/Oregon/Washington Stock is 1024 for waters out to ~550 km (Caretta et al. 2007).

Mesoplodonts are distributed primarily in deep waters (>2000 m) and along continental slopes at depths 200–2000 m, and are rarely found in continental shelf waters (Pitman 2002). Most mesoplodonts identified to species are known from strandings involving single individuals (Jefferson et al. 2008), thus it is not possible to identify spatial or seasonal patterns in their distribution (Caretta et al. 2007).

Mean group sizes are unknown for many of the *Mesoplodon* spp., particularly in the project region. Wade and Gerrodette (1993) reported a mean group size of 3.0 (n = 128) for the ETP. Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes for unidentified *Mesoplodon* of 2.3 (n = 1) off southern California and 2.0 (n = 11) off California/Oregon/Washington. Dive depths of most of these species are undocumented.

Six species of *Mesoplodon* could or are known to occur at least historically off the coast of southern California (Caretta et al. 2007). A few of these species have been sighted in deep waters near the CINMS offshore of the SBC (Caretta et al. 2007). Only one (unidentified) *Mesoplodon* spp. was observed during SWFCS vessel surveys conducted off southern California over the period 1991–2005, with none seen there since 1996 (Barlow and Forney 2007). None of the species is likely to occur in the SBC given its rarity and its presumed preference for deeper more pelagic waters, based on habits of other *Mesoplodon* spp.

Perrin's Beaked Whale (*M. perrini*)

Off central and southern California, all five documented occurrences of Perrin's beaked whale consist of strandings (Jefferson et al. 2008). Perrin's beaked whale was first discovered in 2002, when genetic analysis was carried out on four whales stranded between 1975 and 1979 along <80 km of beach just north of San Diego (Dalebout et al. 2002). The whales previously were identified by Mead (1981) as Hector's beaked whale (*Mesoplodon hectori*), which before then was known only from the Southern Hemisphere. A fifth Perrin's beaked whale was identified by genetic analysis of a stranded whale near Monterey in 1997 that previously had been identified as a neonate Cuvier's beaked whale. Dalebout et al. (2002) also suggested that two sightings off the coast of California in the 1970s that were tentatively identified as Hector's beaked whales were Perrin's beaked whale. Based on habitat preferences of other Mesoplodonts, and sightings believed to be of this species, Perrin's beaked whales presumably prefer pelagic waters >1000 m deep (Jefferson et al. 2008).

Because at-sea sightings of this species are unconfirmed, there is no information on group sizes. Presuming it behaves similarly to most other Mesoplodonts, it likely occurs in small groups. Dive depths are unknown but based on stomach contents consisting of mainly squid (Mead 1989), Perrin's beaked whale presumably feeds in deep water.

Pygmy Beaked Whale (M. peruvianus)

Information on the pygmy beaked whale is based on scattered sightings in the eastern tropical Pacific and a small number of strandings (Jefferson et al. 2008). The pygmy beaked whale is thought to occur between latitudes of ~28°N to 30°S from Baja California to Peru and Chile (Urbán-Ramírez and Aurioles-

Gamboa 1992; Pitman and Lynn 2001; Jefferson et al. 2008). This species is known to inhabit deep warm temperate waters beyond the continental shelf (Jefferson et al. 2008). Most sightings have consisted of two but as many as five animals with a mean group size of 2.3 (Jefferson et al. 2008). Carretta et al. (2007) reported that it is known to occur off the U.S. west coast, and Reeves et al. (2002) reported that it is also known to occur off southern California.

Hubb's Beaked Whale (M. carlhubbsi)

Hubb's beaked whale occurs in temperate waters of the North Pacific, and in the eastern North Pacific it is known from central British Columbia to southern California (Mead 1989; Jefferson et al. 2008). The distribution of this little-known species appears to be correlated with the deep subarctic current (Mead et al. 1982). Most (22 of 35) of the known records of this species are from California, including two records in Santa Barbara County (Mead 1989).

Because most information for this whale comes from strandings (Jefferson et al. 2008), data are insufficient to reliably describe group size information. The stomach contents of 5 stranded Hubb's beaked whales examined by Mead et al. (1982) consisted of beaks of pelagic squids and otoliths of deep-water fish, indicating that it is a deep diver (Mead 1989).

Hubb's beaked whale is considered rare off southern California, and only two recent occurrences are known based on syntheses of aerial and shipboard surveys and observations conducted there over the period 1991–2005: one "probable" live sighting was recorded in deep pelagic water off Monterey Bay (Caretta et al. 2007), and another sighting occurred ~20 km SSW of San Clemente Island (DoN 2005).

Ginkgo-toothed Beaked Whale (M. ginkgodens)

The ginkgo-toothed beaked whale is only known from stranding records (Mead 1989). Strandings have been reported for the western and eastern North Pacific, South Pacific, and Indian oceans, and from the Galápagos Islands (Palacios 1996). Two of the total 13 records reported by Mead (1989) were from the eastern North Pacific, one from Del Mar, California, and one from Baja California. The species is hypothesized to occupy relatively cool areas in the temperate and tropical Pacific, where upwelling is known to occur, such as in the California and Peru Currents and the equatorial front (Palacios 1996).

Blainville's Beaked Whale (*M. densirostris*)

Blainville's beaked whale is the most widely distributed *Mesoplodon* species (Mead 1989), although it is generally limited to pelagic tropical and warmer temperate waters (Leatherwood and Reeves 1983; Jefferson et al. 2008). Occasional occurrences in cooler higher-latitude waters are presumably related to warm-water incursions (Reeves et al. 2002). This species is generally found in slope waters ~500–1000 m deep (Davis et al. 1998; Reeves et al. 2002). However, long-term habitat studies in the northern Bahamas found that Blainville's beaked whales preferred continental slope waters 200–1000 m deep characterized by intermediate depth gradients (MacLeod and Zuur 2005), where they spent most of their time along a canyon wall in waters <800 m deep (Claridge 2003; MacLeod et al. 2004; MacLeod and Zuur 2005). Studies elsewhere indicate that Blainville's beaked whales most frequently occurred in waters 300–1400 m deep (Society Islands, Gannier 2000) and 100–500 m deep (Canary Islands, Ritter and Brederlau 1999). This species may also occur in coastal areas, particularly where deep water gullies come close to shore (Jefferson et al. 2008).

The most commonly observed group size for this species is 1–2 individuals, with a maximum of 9 off Hawaii (Baird et al. 2004; Jefferson et al. 2008). MacLeod and D'Amico (2006) reported a mean group size of 3.5 (n = 31), and Ritter and Brederlau (1999) reported a mean group size of 3.4. The maximum known dive depth of tagged Blainville's beaked whales is 1408 m off Hawaii (Baird et al. 2006).

Blainville's beaked whale is considered rare off southern California and is likely limited to more offshore waters of the CINMS; no sightings are known from the SBC based on syntheses of recent aerial and vessel-based surveys and observations (Caretta et al. 2007; Barlow and Forney 2007; CINMS 2008).

Stejneger's beaked whale (M. stejnegeri)

Stejneger's beaked whale occurs in subarctic and cool temperate waters of the North Pacific (Mead 1989). In the NPO, it is distributed from Alaska to southern California (Mead et al. 1982; Mead 1989). However, most records are from Alaskan waters, and the Aleutian Islands appear to be its center of distribution (Mead 1989). Small groups have been known to strand at the Aleutian Islands (Mead 1989). This species occurs in groups of 3–4, ranging to ~15 (Reeves et al. 2002).

Bottlenose Dolphin (*Tursiops truncatus*)

Bottlenose dolphins occur throughout the world's tropical, subtropical, and temperate waters, most commonly in coastal and continental shelf waters (Jefferson et al. 2008). Wade and Gerrodette estimated that the population in the ETP numbered 243,500. In many regions, including southern California, separate populations occur in coastal and offshore waters (Carretta et al. 2007). The population estimate for the California Coastal Stock is 450–500, based on photographic mark-recapture surveys along the San Diego coast in 2004 and 2005 and accounting for dolphins that do not have identifiable dorsal fin marks, and the mean population estimate for the California Offshore Stock from vessel-based surveys in 2001 and 2005 is 3257 (Carretta et al. 2007).

Based on 12 months of cliff-based observations, 99% of the coastal population occurred <500 m from shore and 90% occurred <0.25 km from shore, in water depths 1–6 m (Hanson and Defran 1993). Hansen (1990) reported that they occurred primarily just outside the surf zone (Hansen 1990), and Defran and Weller (1999) reported that all dolphins encountered in their photo-identification studies were within 1 km of shore, corresponding to water depths 10–30 m. The offshore population off California is thought to have a continuous distribution encompassing both inshore and offshore waters (Mangels and Gerrodette 1994; Caretta et al. 2007; Jefferson et al. 2008).

Bottlenose dolphins usually occur in groups of 2–20, although groups of >100 are occasionally seen in offshore areas (Shane et al. 1986; Jefferson et al. 2008). Wade and Gerrodette (1993) reported a mean group size of 22.7 (n = 298) for the ETP. Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 13.4 (n = 31) for bottlenose dolphins off southern California, including inshore and offshore areas. Reeves et al. (2002) suggested that bottlenose dolphins dive to depths of >500 m based on the consumption of deep-sea fish by some offshore bottlenose dolphins, although typical dives are more shallow.

In the SCB, coastal bottlenose dolphins appear to be highly mobile within a relatively narrow, continuous coastal zone (Defran et al. 1999). Based on photo-identification studies off San Diego, they exhibit no year-round or seasonal site fidelity to the region (Defran and Weller 1999). Offshore bottlenose dolphins occur year-round throughout the SCB, although they appear to stay at least a few km from the mainland (Caretta et al. 2007). During most of the year, relatively large numbers center on Santa Catalina Island and, to a lesser degree, the eastern coast of San Clemente Island (Bonnell and Dailey 1993; DeDecker et al. 1999); the summer population is greater and more widely dispersed (Bonnell and Dailey 1993). Both the coastal and offshore populations commonly occur in the SBC (Caretta et al. 2007). Approximately 650 bottlenose dolphin sightings were recorded for SBC waters in all months of the year during 2002–2007 in the CINMS Sightings Database (CINMS 2008).

Striped Dolphin (*Stenella coeruleoalba*)

Striped dolphins have a cosmopolitan distribution in tropical to warm temperate waters from ~50°N to 40°S (Perrin et al. 1994; Jefferson et al. 2008). Wade and Gerrodette (1993) estimated that the population in the ETP numbered 1.9 million. The mean population estimate from ship surveys conducted in 2001 and 2005 is 23,883 for California/Oregon/Washington (Caretta et al. 2007).

The striped dolphin's preferred habitat seems to be cool, deep oceanic waters (Davis et al. 1998) along the edge and seaward of the continental shelf, particularly convergence zones and upwelling areas (Au and Perryman 1985). Striped dolphin group sizes are typically several dozen to 500 animals, though groups of thousands sometimes form (Jefferson et al. 2008). Wade and Gerrodette (1993) noted a mean group size of 61 in the ETP, and Smith and Whitehead (1999) reported a mean group size of 50 in the Galápagos. Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 67.2 (n = 37) off southern California. Striped dolphins are believed to be capable of diving to depths of 200–700 m based on stomach content analyses (Archer and Perrin 1999).

In and near the CINMS, striped dolphins are found mostly in deep and/or offshore waters (Barlow and Forney 2007; Caretta et al. 2007). Based on NMFS vessel-based surveys over 1991–2005, all striped dolphins were seen well offshore of the Channel Islands (Barlow and Forney 2007). None are recorded for the SBC in the CINMS Sightings Database (CINMS 2008). Based on available information, the striped dolphin is considered rare and unlikely to occur in the SBC.

Short- and Long-beaked Common Dolphin (*Delphinus delphis and D. capensis*)

Two species of common dolphin occur off California: the more coastal long-beaked dolphin (*Delphinus capensis*) and the more offshore short-beaked dolphin (*D. delphis*). The long-beaked common dolphin is less abundant, and only recently has been recognized as a separate species (Heyning and Perrin 1994). Thus, much of the historically available information has not differentiated between the two species. The mean population estimates for California/Oregon/Washington from ship-based surveys conducted in 2001 and 2005 are 487,622 and 1893 short-beaked and long-beaked common dolphins, respectively (Carretta et al. 2007).

Common dolphins occur in the warm temperate and subtropical Atlantic and Pacific oceans (Jefferson et al. 2008). Their distributions are associated with prominent underwater topography, such as sea mounts (Evans 1994). Short-beaked common dolphins are widely distributed from the coast to at least 550 km from shore, whereas long-beaked common dolphins are usually found <90 km from shore (Carretta et al. 2007).

Common dolphins travel in group of ~10 to >10,000 individuals (Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 168 (n = 239) for the short-beaked common dolphin and a mean group size of 286.6 (n = 16) for the long-beaked form off southern California. Available data show a mean group size of 353.6 animals (n=61 groups) in the SCIRC with a maximum observed group size of 2700 (Carretta et al. 2000). Mean group sizes of 141 (n = 417) and 306 (n = 110) were found in the Point Mugu Sea Range and in areas east of the range, respectively, with a maximum group size of 2000 (Koski et al. 1998). Most dives of a radio-tagged common dolphin off southern California were to depths 9–50 m, and maximum depth was ~200 m (Evans 1994).

Off southern California, both species of common dolphin are common throughout the year, although abundance appears to change both seasonally and inter-annually with oceanographic conditions (Dohl et al. 1986; Barlow 1995; Forney et al. 1995; Forney and Barlow 1998). Abundance has increased markedly since the late 1970s, coincident with a decreased abundance in the ETP, suggesting a shift in distribution in the eastern North Pacific (Forney et al. 1995; Forney and Barlow 1998). In the SCB, common dolphins were restricted to the warm, southeastern parts of the SCB in winter-spring 1975–1978, whereas they were more widely distributed throughout the SCB, including the northern Channel Islands in summer-autumn (Dohl et al. 1986). Approximately 2300 common dolphin sightings were recorded in SBC waters in all months of the year during 2002–2008 in the CINMS Sightings Database (CINMS 2008). Short-beaked common dolphins were sighted throughout the SBC during NMFS vessel-based surveys conducted during 1991–2005 (Barlow and Forney 2007).

Pacific White-sided Dolphin (*Lagenorhynchus obliquidens*)

The Pacific white-sided dolphin is found in cool temperate waters of the North Pacific from the southern Gulf of California to Alaska. Across the North Pacific, it appears to have a relatively narrow distribution between 38°N and 47°N (Brownell et al. 1999). The North Pacific population was estimated by Buckland et al. (1993) at 931,000. The mean population estimate from ship surveys conducted in 2001 and 2005 is 25,233 for California/Oregon/Washington (Caretta et al. 2007).

In the eastern North Pacific, Pacific white–sided dolphins inhabit primarily temperate shelf and slope waters from the Aleutian Islands and Gulf of Alaska south to near the mouth of the Gulf of California; they are also occasionally sighted in offshore and coastal waters (Jefferson et al. 2008). Group size of Pacific white-sided dolphins varies from 1 to ~6,000, and groups of hundreds to thousands of individuals are common (Leatherwood et al. 1984; Jefferson et al. 2008). Based on NMFS vessel surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 33.7 (n = 15) off southern California and 78.5 (n = 71) off California/Oregon/Washington. The mean size of 26 groups recorded in and near the SCIRC was 24.2 (Carretta et al. 2000). The mean size of 348 groups recorded in and near the Point Mugu Sea Range was 80, and the largest group size was 2,500 (Koski et al. 1998). Pacific white-sided dolphins from coastal and offshore waters apparently dive to different depths; the former feed on epipelagic (0–200 m) fish and cephalopods, and the latter feed on mesopelagic (200–1000 m) fish and cephalopods (Brownell et al. 1999). Mean dive times for three individuals tracked in Monterey Bay were 22.0–25.7 sec, and maximum dive times were 3.3–6.2 min (Black 1994 *in* Brownell et al. 1999).

The Pacific white-sided dolphin is seasonally abundant off southern California, and is a year-round resident in the SCB (Bonnell and Dailey 1993). Animals found primarily off California during the colder-water months move northward into Oregon and Washington with increasing water temperatures during late spring and summer (Carretta et al. 2007). Approximately 233 sightings of Pacific white-sided dolphins were reported in the SBC throughout the year during 2002–2007 in the CINMS sightings database, with most sightings reported during late winter through spring (CINMS 2008).

Northern Right Whale Dolphin (*Lissodelphis borealis*)

The northern right whale dolphin is found in cool temperate and sub-arctic waters of the North Pacific, from the Gulf of Alaska to near northern Baja California, ranging from 30°N to 50°N (Reeves et al. 2002). The mean population estimate from ship surveys conducted in 2001 and 2005 is 15,305 for California/Oregon/Washington (Caretta et al. 2007).

The northern right whale dolphin occurs primarily in shelf and slope waters ~100 m to >2000 m deep (Green et al. 1993; Carretta et al. 2007; Barlow 2003), but comes closer to shore where there is deep water, such as over submarine canyons (Carwardine 1995; Reeves et al. 2002). Animals found primarily off California during the colder-water months move northward into Oregon and Washington with increasing water temperatures during late spring and summer (Carretta et al. 2007).

Northern right whale dolphins are gregarious, and groups of several hundred to over a thousand are not uncommon (Reeves et al. 2002). They are often seen in mixed-species schools with Pacific white-sided dolphins. Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 13.9 (n = 12) off southern California and 29.1 (n = 60) off California, Oregon, and Washington. The mean size of 11 groups in the SCIRC was 12.4 (Carretta et al. 2000). The mean size of 214 groups sighted in the Point Mugu Sea Range was 89, and the largest group seen there was 2500 (Koski et al. 1998). Northern right whale dolphins feed primarily on mesopelagic squid and fish at depths >300 m (Jefferson et al. 1994).

In 1991–1992, northern right whale dolphins were widespread throughout the SCB, but were absent in summer (Forney and Barlow 1998). Numbers decline during late spring and summer when most animals move offshore and northward into Oregon and Washington as waters warm up (Caretta et al. 2007). Nine sightings of Pacific white-sided dolphins were reported in the SBC during 2002–2007 in the CINMS sightings database, all during November–June (CINMS 2008). Available data suggest that this species is uncommon in the SBC and is most likely to occur there during the cold-water months.

Risso's Dolphin (*Grampus griseus*)

Risso's dolphin is primarily a tropical and mid-temperate species distributed worldwide between 60ºN and 60ºS, where surface water temperatures are ~10ºC (Kruse et al. 1999). The mean population estimate from ship surveys conducted in 2001 and 2005 is 12,093 for waters off California, Oregon, and Washington (Caretta et al. 2007).

Risso's dolphin usually occurs over steeper sections of the upper continental slope in waters 400–1000 m deep (Baumgartner 1997; Davis et al. 1998), and is known to frequent seamounts and escarpments (Kruse et al. 1999). Risso's dolphins occur individually or in small- to moderate-sized groups, normally ranging in numbers from 10 to 100 but up to as many as 4000 (Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported a mean group size of 15.1 (n = 50) off southern California. The mean size of 320 groups sighted in the Point Mugu Sea Range was 42, although when the five largest groups are excluded, the mean group size was 25 (Koski et al. 1998). Risso's dolphin can remain underwater up to 30 min (Kruse et al. 1999).

In SCB waters, Risso's dolphins occur year-round, with peak numbers occurring during September–November (Bonnell and Dailey 1993). Animals found primarily off California during the colder-water months move northward into Oregon and Washington with increasing water temperatures during late spring and summer (Carretta et al. 2007). The distribution of Risso's dolphin off the U.S. west coast is highly variable, both within and among years (Forney and Barlow 1998). Approximately 250 sightings of Risso's dolphins were reported in the SBC throughout the year during 2002–2007 in the CINMS sightings database (CINMS 2008).

Killer Whale (*Orcinus orca*)

The Eastern North Pacific Offshore Stock of killer whales is not listed as Endangered under the ESA, but the Eastern North Pacific Southern Resident Stock of killer whales is listed as ***Endangered***. There is currently no way to reliably distinguish the different stocks of killer whales from sightings at sea (Caretta et al. 2007). Killer whales are segregated socially, genetically, and ecologically into three distinct groups: resident, transient, and offshore animals. Offshore whales do not appear to mix with the other types of killer whales (Black et al. 1997; Dahlheim et al. 1997). The number of killer whales in the ETP was estimated at 8500 (Ford 2002). The number of all killer whales within ~550 km of the coasts of California, Oregon, and Washington is estimated at 1214 (Caretta et al. 2007).

Killer whales inhabit all oceans from pole to pole in deep pelagic to shallow estuarine waters, although they are seen more frequently in higher latitudes and coastal areas (Dahlheim and Heyning 1999; Jefferson et al. 2008). The greatest abundance is thought to occur <800 km from major continents

(Mitchell 1975). Groups sizes of killer whales range from 1–75, though offshore transient groups generally contain <10 (Dahlheim et al. 1982; Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 4.1 (n = 2) off southern California and 6.6 (n = 23) off California, Oregon, and Washington. The maximum depth to which free-ranging killer whales dove off British Columbia was 264 m, whereas ~99% of all dives made by seven tagged whales were <30 m (DoN 2005).

Most of the killer whales off southern California are transient and offshore whales belonging to the Eastern North Pacific Offshore Stock. However, resident whales from the Eastern North Pacific Southern Resident Stock could also occur there, as they have been documented recently off central California, and little is known of their winter distribution (Caretta et al. 2007). Off California, killer whales are frequently seen in pelagic waters but also in coastal kelp beds, bays, and inlets (Leatherwood et al. 1987). During 1974–1984, 35 confirmed sightings were reported in the SCB (Leatherwood et al. 1987). Barlow and Forney (2007) reported two groups of killer whales off southern California during NMFS vessel-based surveys conducted during 1991–2005. The CINMS Sightings Database contains 48 records of killer whale sightings in the SBC during all four seasons over the years 2002–2007 (CINMS 2008).

Short-finned Pilot Whale (*Globicephala macrorhynchus*)

The short-finned pilot whale is not listed under the ESA, nor is it listed as "depleted" under the MMPA, but the California/Oregon/Washington Stock is considered strategic under the MMPA (Carretta et al. 2007). Wade and Gerrodette (1993) estimated that there were 160,000 short-finned pilot whales in the ETP. The mean population estimate from NMFS vessel-based surveys conducted in 2001 and 2005 is 245 for California, Oregon, and Washington (Caretta et al. 2007).

The short-finned pilot whale typically inhabits pelagic tropical and warm temperate waters of ~1000 m depth near the continental shelf edge but also slope waters (Davis et al. 1998; Jefferson et al. 2008). It is generally nomadic but resident populations have been reported in certain locations, including Hawaii and California (Olson and Reilly 2002). Pilot whales are usually seen in groups of 20–90, although groups of several hundred are also seen (Olson and Reilly 2002; Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 31.6 (n = 1) off southern California and 18 (n = 5) off California, Oregon, and Washington. Mean group sizes of 22 (n = 41) and 18 (n = 57) were found in the Point Mugu Sea Range and in coastal and nearshore areas east of the range, respectively, with a maximum group size of 200 (Koski et al. 1998). Pilot whales outfitted with time-depth recorders dove to depths of 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* US Navy 2005).

The range of the short-finned pilot whale in the eastern North Pacific Ocean extends from the tropics north to the Gulf of Alaska, although sightings north of Point Conception are uncommon (Forney 1994). Off southern California, prior to the 1982–1983 El Niño event, short-finned pilot whales were common with an apparently resident population around Santa Catalina Island (Dohl et al. 1981). After this El Niño event, they virtually disappeared from the region and few sightings were made from 1984 to 1992 (Caretta et al. 2007). Small numbers of short-finned pilot whales appear to have recently returned to California waters based on increased sighting records as well as incidental fishery bycatch (Caretta et al. 2007). However, this species is still considered rare off southern California, where its occurrence appears to vary from year to year, although it has been seen there during all seasons of the year (Bonnell and Dailey 1993; Carretta et al. 2007). No short-finned pilot whales were sighted during the 1998–1999 NMFS surveys of the SCIRC (Carretta et al. 2000), and only one was sighted during NMFS vessel-based surveys conducted during 1991–

2005. Two pilot whale sightings were recorded in the SBC in January and July of 2006 in the 1999–2007 CINMS Sightings Database (CINMS 2008).

Dall's Porpoise (*Phocoenoides dalli*)

Dall's porpoise is only found in the North Pacific and adjacent seas. The mean population estimate from NMFS vessel-based surveys conducted in 2001 and 2005 is 57,549 for California, Oregon, and Washington (Caretta et al. 2007).

Dall's porpoise is widely distributed across the North Pacific over the continental shelf and slope waters, and over deep (>2500 m) oceanic waters (Hall 1979). Its distribution extends from southern California and southern Japan to ~65°N (Buckland et al. 1993). It is probably the most abundant small cetacean in the North Pacific Ocean, and its abundance changes seasonally, likely in relation to water temperature (Becker 2007; Jefferson et al. 2008). Animals found primarily off California during the colder-water months move northward into Oregon and Washington with increasing water temperatures during late spring and summer (Carretta et al. 2007).

Dall's porpoises are typically seen in groups of 2–12, and groups of >20–30 are uncommon (Jefferson et al. 2008). Based on NMFS vessel-based surveys from 1991 to 2005, Barlow and Forney (2007) reported mean group sizes of 2.5 (n = 5) off southern California and 3.6 (n = 214) off California, Oregon, and Washington. The average size of 401 groups seen in the Point Mugu Sea Range was 4.2, and the largest group contained 40 (Koski et al. 1998). During the 1998–1999 NMFS surveys of the SCIRC, the mean size of 8 groups was 3.4 (Carretta et al. 2000). Data from one tagged Dall's porpoise showed a mean dive depth of 33.4 m for a mean duration 0f 1.3 min (Hanson and Baird 1998).

Off southern California, during the warm-water period, Dall's porpoises occur most commonly north of Point Conception; in the cold-water periods, they occur primarily along the coast from Point Conception south to approximately the U.S./Mexico border (DoN 2005). Approximately 270 Dall's porpoise sightings were recorded in SBC waters in all months of the year during 2002–2007 in the CINMS Sightings Database (CINMS 2008). Based on available data, this species occurs year-round in the SBC where it appears to be relatively common, particularly during cool-water periods.

Harbor Porpoise (*Phocoena phocoena*)

The harbor porpoise is not listed under the ESA but it is listed as *Vulnerable* on the 2007 IUCN Red List of Threatened Species (IUCN 2007) and is listed in CITES Appendix II (UNEP-WCMC 2008). There are an estimated 202,988 harbor porpoises in the Northeast Pacific Ocean (Carretta et al. 2007; Angliss and Outlaw 2008). There are five stocks off harbor porpoise from California to Washington, and three in Alaska. The mean population estimate of the nearest stock to the study area, the Morro Bay Stock, is 1656 (Caretta et al. 2007). There has been a significantly increasing abundance trend in this stock since 1988 (Caretta et al. 2007)

In the eastern North Pacific, the harbor porpoise's usual range extends from Point Barrow, Alaska, to Point Conception, California. The Morro Bay Stock of harbor porpoises occurs from just south of Monterey Bay to just south of Point Conception (Caretta et al. 2007). The harbor porpoise inhabits temperate, subarctic, and arctic waters, primarily in shallow coastal areas (Caretta et al. 2007; Jefferson et al. 2008). However, sightings also occur over deeper waters between land masses (Bjørge and Tolley 2002).

Harbor porpoises are normally found in small groups of up to 5 or 6, although loose aggregations of ~50 to several hundred porpoises occur sometimes (Jefferson et al. 2008). The dives of harbor porpoises are short, usually <5 min (Read 1999). Tagged harbor porpoises in the Bay of Fundy dove to mean depths of 14–41 min for mean durations of 44–103 s, and to a maximum depth of 226 m (Westgate et al. 1995).

In the SBC, sightings of harbor porpoises are uncommon. The southernmost extent of the distribution of the Morro Bay Stock of harbor porpoises around Point Conception appears to be fairly abrupt and borders the northwestern SBC (Caretta et al. 2007). Harbor porpoises occurring south of Point Conception are considered strays (Leatherwood et al. 1988). Seven sightings of this species were recorded for the SBC in the CINMS Sightings Database during winter and spring of 2004–2006 (CINMS 2008).

(3) Pinnipeds

Guadalupe Fur Seal (*Arctocephalus townsendi*)

The Guadalupe fur seal is listed as ***Threatened*** under the ESA and ***Vulnerable*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007) and is listed in CITES Appendix I (UNEP-WCMC 2008). The most recent minimum population estimate of 6443 is based on 1993 data (Carretta et al. 2007). This population increased at an average annual rate of 13.7% from 1954 to 1993 (Carretta et al. 2007), and the species may be expanding its range (Le Boeuf and Bonnell 1980; Maravilla-Chavez and Lowry 1999).

Guadalupe fur seals prefer rocky habitat for breeding and hauling out. They generally haul out at the base of towering cliffs on shores characterized by solid rock and large lava blocks (Peterson et al. 1968), although they can also inhabit caves and recesses (Belcher and Lee 2002). While at sea, this species usually is solitary but typically gathers in the hundreds to thousands at breeding sites. Females have been observed feeding south of Guadalupe Island, making an average round trip of 2375 km (Ronald and Gots 2003).

Most breeding and births occur at Isla Guadalupe, Mexico; a secondary rookery exists at Isla Benito del Este (Maravilla-Chavez and Lowry 1999). A few Guadalupe fur seals are known to inhabit California sea lion rookeries in the Channel Islands, primarily San Nicolas and San Miguel islands, and sightings have also been made at Santa Barbara and San Clemente islands (Stewart et al. 1987). One birth was recorded at San Miguel Island, California (Caretta et al. 2007). There is one record of this species in the CINMS database: in March 2005 ~20 km west-southwest of Santa Barbara in the SBC (CINMS 2008).

Northern Fur Seal (*Callorhinus ursinus*)

Two stocks of northern fur seals inhabit the eastern Pacific Ocean, both of which occur off southern California at least seasonally. The San Miguel Island Stock is not considered depleted under the MMPA, whereas the Eastern Pacific Stock is (Carretta et al. 2007). The current estimate of the size of the San Miguel Island Stock is 9424 (Caretta et al. 2007). The abundance of this stock has steadily increased with the exception of substantive declines in the 1983 and 1988 El Niño years (Carretta et al. 2007). The estimate for the Eastern Pacific Stock is 721,935 (Angliss and Outlaw 2008).

In the eastern North Pacific Ocean, northern fur seals range from southern California north to the Bering Sea (Caretta et al. 2007; Jefferson et al. 2008; Angliss and Outlaw 2008). All northern fur seals except those belonging to the San Miguel Island Stock migrate along continental margins from northern summer breeding islands to southern winter foraging areas (Gentry 2002). This species spends ~90% of its time at sea, typically in areas of upwelling along the continental slopes and over seamounts (Gentry 1981, 2002a; Jefferson et al. 2008). The remaining ~10% of its life is spent on or near rookery islands or haulouts on rocky shorelines, primarily on the Pribilof and Bogoslof islands (Caretta et al. 2007).

While at sea, northern fur seals usually occur singly or in pairs, although larger groups can form in waters rich with prey (Antonelis and Fiscus 1980; Gentry 1981). Thousands to tens of thousands of seals typically aggregate on terrestrial rookeries (Jefferson et al. 2008). Northern fur seals dive to relatively shallow depths to feed: 100–200 m for females, and <400 m for males (Gentry 2002).

In the SCB, northern fur seals of the San Miguel Island Stock occur year-round and breed and pup primarily on San Miguel Island; members of the Eastern North Pacific Stock occur in the SCB primarily during fall and winter while foraging (e.g., Koski et al. 1998). In the SCB, northern fur seal colonies occur on San Miguel Island and on Castle Rock, an offshore island 2.2 km north of San Miguel Island (Le Boeuf and Bonnell 1980). Individual seals are also occasionally sighted in offshore waters (DoN 2005). Fur seal numbers decline near San Miguel Island from late November to May, when most are feeding offshore; numbers begin to increase again in late May when the breeding season begins (Bonnell et al. 1978). No northern fur seal sightings are recorded in the CINMS Sightings Database (CINMS 2008).

California Sea Lion (*Zalophus californianus*)

The current population estimate for the U.S. Stock of California sea lions is 238,000, based on pup counts during the 2005 breeding season (Caretta et al. 2007). The U.S. stock has increased from the early 1900s to the present; pup counts increased at an annual rate of 5.6% between 1975 and 2001, excluding pup counts during El Niño years when numbers decreased as a result of related oceanographic and temperature changes (Carretta et al. 2007).

In the eastern North Pacific Ocean, California sea lions occur from Mexico northward to the Gulf of Alaska, typically in waters over the continental shelf and slope (Jefferson et al. 2008). Breeding rookeries are located predominantly south of Point Conception, where >95% of the stock breeds and gives birth in the Channel Islands in large breeding colonies on San Miguel and San Nicolas islands, and in smaller breeding colonies on Santa Barbara and San Clemente islands (Bonnell and Dailey 1993). Smaller numbers of pups are born on the Farallon Islands and Año Nuevo Island (Lowry et al. 1992). Most adult and subadult males are seasonal migrants that occupy southern breeding areas from mid-to-late May until late July and then migrate north to feed, whereas females and presumably most juveniles remain year-round near the breeding area (Lowry et al. 1992; Jefferson et al. 2008). California sea lions commonly occur in bays, harbors, and river mouths (Jefferson et al. 1993, 2007), and frequently haul out on rocky shores as well as piers, jetties, offshore buoys, and oil platforms (Riedman 1990). Occasionally, they have been sighted several hundred kilometers from shore (Jefferson et al. 1993, 2007).

While at sea, most sea lions are solitary although they sometimes form into large groups near food-rich areas (Antonelis and Fiscus 1980). In Santa Monica Bay, Bearzi et al. (2008) reported a mean at-sea group size of 1.97 with a range of 1–50 based on 1,393 sightings. For ten tagged female California sea lions during the summer breeding seasons of 1982 and 1983 on San Miguel Island, dive depths and times averaged 31–98 m and 1.0–1.9 min, and the maximum depth and time were 274 m and 9.9 min (Feldkamp et al. 1989).

In the SCB, the California sea lion is by far the most commonly-sighted pinniped species at sea or on land; it occurs there during all months of the year from near shore to offshore areas, except after the breeding season, when most males and many juveniles move and spend the fall and winter in waters farther north (Bonnell and Dailey 1993). During vessel-based surveys of Santa Monica Bay, Bearzi et al. (2008) regularly found California sea lions in waters <500 from shore, although animals were also seen throughout the bay, particularly near underwater canyons. Peak densities in the SCB occur during the summer breeding season (Bonnell and Dailey 1993). In the SBC, females spend more time ashore (mean of 41%) during the mid May–mid August pupping/breeding season (Antonelis et al. 1990) than during the non-breeding season

(24–28%; Melin et al. 2000). Only seven records of California sea lions occur in the CINMS Sightings Database, and all occurred during winter–spring 2002–2007 (CINMS 2008). Based on available data, California sea lions occur in small numbers throughout the year in the SBC, many of which are likely associated with the breeding rookery on San Miguel Island at least during the breeding season. However, much of the population appears to occur farther off the mainland and further south on and around the main breeding rookeries and haulouts of the southern Channel Islands.

Steller Sea Lion (*Eumetopias jubatus*)

The Steller sea lion is listed under the ESA as ***Threatened*** in the eastern portion of its range (including California), and as ***Endangered*** in the western portion, and is listed as ***Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007). Federally Designated Critical Habitat for Steller sea lions includes all rookeries and major haulouts, none of which occurs in California (50 CFR 226.202). The minimum population estimate for the Eastern U.S. Stock of Steller sea lions is 44,584, including animals off California, Oregon, Washington, and Alaska (Angliss and Outlaw 2008). The overall size of this stock has increased in recent years, but counts of non-pups off southern and central California have declined by >50% since 1947 (Angliss and Outlaw 2008). The size of the closest breeding colony to the study area, on Año Nuevo Island off central California, declined by 85% between 1970 and 1987 (Angliss and Outlaw 2008).

In the eastern North Pacific Ocean, Steller sea lions are currently distributed from the Bering Strait along the coast of North America south to central California, although they formerly inhabited the Channel Islands (Rice 1998; Jefferson et al. 2008). They typically inhabit waters from the coast to the outer continental shelf and slope throughout their range; they are not considered migratory although foraging animals travel long distances (Loughlin 2002; Angliss and Outlaw 2008; Jefferson et al. 2008). Steller sea lions haul out on beaches and rocky shorelines of remote islands, often in areas exposed to wind and waves (NMFS 1992). During the breeding season, some haulouts are used as rookeries, but haulouts are also used at other times. Rookeries typically occur on gently sloping beaches that are protected from waves (NMFS 1992). Steller sea lions spend more time at sea in the winter than during the breeding season; during the non-breeding season from late May-early July, they disperse to sea (Sease and York 2003).

While at sea, Steller sea lions usually occur in groups of 1–12 (Jefferson et al. 2008). At rookeries and haulouts they typically occur in the hundreds to thousands. Steller sea lions make relatively shallow dives, generally <250 m, and the maximum known dive depth is 328 m (Loughlin 2002).

Currently, the nearest Steller sea lion breeding colony to the SBC occurs on Año Nuevo Island near Santa Cruz to the north off Central California. Steller sea lions were once the most abundant pinniped in the SCB; breeding animals formerly occurred in the CINMS on San Miguel Island, but none have been documented there since 1980 (Bonnell and Dailey 1993). Three sightings of Steller sea lions in the SBC are recorded in the CINMS Sightings Database: one in August 2002, one in July 2005, and one in February 2008 (CINMS 2008). Based on available data, Steller sea lions are considered rare in the SBC.

Harbor Seal (*Phoca vitulina richardsi*)

In the northeast Pacific Ocean, the harbor seal ranges from Baja California, north along the western coasts of the United States, British Columbia, and SE Alaska, and north in the Bering Sea to the Pribilof Islands. The combined U.S. population is estimated at 253,594 (Carretta et al. 2007; Angliss and Outlaw 2008). The most recent population estimate for the California Stock, based on counts in 2004, is 34,233

(Carretta et al. 2007). The California population has increased from the mid-1960s to the mid-1990s, although the rate of increase appears to have slowed since then (Caretta et al. 2007).

The harbor seal ranges from the Bering Sea south along the coast to Baja California, although the SCB is near the southern limit of its range (Bonnell and Dailey 1993). Harbor seals inhabit estuarine and coastal waters, hauling out on rocks, reefs, beaches, and glacial ice flows. They are generally non-migratory, but move locally with the tides, weather, season, food availability, and reproduction (Scheffer and Slipp 1944; Fisher 1952; Bigg 1969, 1981). Juvenile harbor seals can travel significant distances (525 km) to forage or disperse, whereas tagged adults were generally found within 190 km of the tagging location (Lowry et al. 2001). At sea, harbor seals are usually alone or in small groups (Jefferson et al. 2008), although they often gather in groups of up to several thousand on land (Bigg 1981). In Santa Monica Bay, Bearzi et al. (2008) reported a mean at-sea group size of 1.4 with a range of 1–12 based on 131 sightings. Hastings et al. (2004) studied the diving behavior of harbor seals in the Gulf of Alaska and found that most dives (40–80%) were to depths <20 m and < 4 min long. Dives of 50–150 m were also recorded, as well as dives as deep as ~500 m (Hastings et al. 2004). Most diving activity occurs at night (Hastings et al. 2004).

In the SCB, small numbers of harbor seals occur year-round on coasts and in nearshore waters of the mainland and all the Channel Islands (Koski et al. 1998; Lowry and Carretta 2003; Bearzi et al. 2008). Most harbor seals in the SCB breed on San Nicolas and San Miguel Islands, while the main haulout sites are on the mainland coast north of the Channel Islands and on Santa Cruz Island (Stewart and Yochem 1985; Lowry and Carretta 2003). Pupping, nursing and/or breeding in the SCB occurs in spring, and peak numbers of hauled-out seals occur during the molt in late May–early June (Bonnell and Dailey 1993). Afterwards, harbor seals remain near haul-out sites and forage close to shore in relatively shallow waters (Bonnell and Dailey 1993). During the 1998–1999 NMFS survey of the SCIRC, all 9 sightings of harbor seals were in territorial waters, mostly on the west side of San Clemente Island where haul-out sites occur. Two sightings of harbor seals in the SBC are recorded in the CINMS Sightings Database: one during October 2002 and the other during February 2007 (CINMS 2008). In summary, available data indicate that the harbor seal is relatively common year-round in the SBC.

Northern Elephant Seal (*Mirounga angustirostris*)

The range of the northern elephant seal encompasses the eastern and central North Pacific from near the eastern Aleutian Islands south to Baja California (Caretta et al. 2007). Populations off Mexico and California are considered separate stocks (Caretta et al. 2007). The California Breeding Stock has recovered from near extinction in the early 1900s to an estimated population size of estimate of 124,000 in 2005 seals (Carretta et al. 2007). Off California, the northern elephant seal population appeared to increase through 2005 based on pup count trends, although it appears to be stable or slowly decreasing off Mexico (Stewart et al. 1994; Caretta et al. 2007).

Northern elephant seals breed and give birth mostly on offshore islands in California and Baja California from December to March. Males remain for the entire period (McGinnis and Schusterman 1981), whereas females remain for an average of 34 days (Bonnell and Dailey 1993). Females return to land to molt in May, whereas males do so during July (Stewart and DeLong 1995). When not on land, males migrate north to feed in the Gulf of Alaska, whereas females feed south of 45ºN (Carretta et al. 2007). Feeding habitat consists primarily of deep, offshore waters in the central North Pacific up to thousands of kilometers from the coast (Stewart and DeLong 1993, 1995; Stewart 1997; Le Boeuf et al. 2000).

At sea, northern elephant seals are mostly solitary but gather on land in the hundreds to thousands in breeding and molting areas (Jefferson et al. 2008). In Santa Monica Bay, Bearzi et al. (2008) reported that all 12 at-sea sightings of northern elephant seals consisted of solitary animals. Both sexes routinely dive 150–800 m deep (Le Boeuf et al. 2000); dives average 15–25 min, depending on time of year, and surface intervals between dives are 2–3 min. The deepest dives recorded for both sexes are over 1500 m (e.g., Le Boeuf et al. 2000; Williams et al. 2000; Schreer et al. 2001). Females remain submerged ~86–92% of the time and males ~88–90% (Le Boeuf et al. 1988; Stewart and DeLong 1993, 1995). Feeding juvenile northern elephant seals dive for slightly shorter periods (13–18 min), but they dive to similar depths (300–450 m) and spend a similar proportion (86–92%) of their time submerged (Le Boeuf et al. 1996).

In the SCB, northern elephant seals can be seen throughout the year, primarily in the Channel Islands and offshore waters, with the highest breeding and haul-out concentrations on San Miguel (~67% of seals on land) and San Nicolas Islands (32%), and smaller colonies on Santa Rosa, Santa Cruz, Anacapa, San Clemente, and Santa Barbara islands (Koski et al. 1998). Peak numbers in the SCB occur during December–March when animals gather at the Channel Islands to breed (Bonnell and Dailey 1993), and lowest numbers occur in the SCB during June–November, between molting and breeding, when most northern elephant seals are farther north feeding. During vessel-based surveys of Santa Monica Bay, Bearzi et al. (2008) sighted only 12 northern elephant seals during 1291 hr of year-round vessel surveys from 1997 to 2007, and only in offshore waters, near underwater canyons. Thirteen sightings of northern elephant seals in the SBC during 2002–2007 are recorded in the CINMS Sightings Database, primarily during March and August–September (CINMS 2008). Based on available data, the elephant seal is common year-round near the northern Channel Islands, although numbers are highest during late winter and early spring.

(4) Marine Fissiped

Southern Sea Otter (*Enhydra lutris nereis*)

The southern subspecies of sea otter is listed as ***Threatened*** under the ESA, the species is listed as ***Endangered*** on the 2007 IUCN Red List of Threatened Species (IUCN 2007), and the southern subspecies is listed in CITES Appendix I (UNEP-WCMC 2008). Based on a 1994 count, the minimum population estimate for the California Stock of the southern sea otter was 2359 (USFWS 1995 *in* Carretta et al. 2005). During the 2004 spring survey, 2825 California sea otters were counted, representing an increase of 12.8% from 2003 to 2004 (Maender 2004). Following an EIS prepared by USFWS (1987), an attempt was made from 1987 to 1990 to establish an "experimental population" of sea otters at San Nicolas Island by translocating 139 individuals there. That population was designated as Experimental Population, Non-Essential, in 1987. The population diminished to about 17 in 1994, including pups (USFWS 1995 *in* Carretta et al. 2005), and as of June 2002 was ~27 (USFWS 2003).

Currently, the southern sea otter's primary range is restricted to the coastal area of central California from Point Año Nuevo to Purisima Point, just north of Point Conception (USFWS 1995 *in* Carretta et al. 2005), not including the experimental population on San Nicolas Island. Since 1998, sea otters have been documented south and east of Point Conception in the Cojo Anchorage area during winter and spring, most of which return to more northern water by mid-summer (USFWS 2003; Hatfield 2004 *in* MMS 2005). Between 2002 and 2004, spring surveys counted <50 sea otters south of Point Conception (Hatfield 2004 in MMS 2005). Numbers may be higher based on aerial survey data during January–February 1999, when 100–152 sea otters were counted in this area (unpublished Otter Project data *in* MMS 2005

They often inhabit rocky shoreline with kelp and forage in soft- and hard-sediment marine habitats from the intertidal zone to ~100 m water depth, although most sea otters occur between shore and the 20-

m isobath (Riedman and Estes 1990; USFWS 2003). At sea, sea otters usually occur alone or in rafting groups of 2–12 (Jefferson et al. 2008). They generally dive to depths of <10 m (Kenyon 1981), but are known to dive to depths of ~100 m (Jefferson et al. 2008).

In the SBC, sea otters are commonly sighted in nearshore waters between Point Conception and near Santa Barbara during winter, although this appears to represent a fairly recent expansion of their current range (USFWS 2000, 2003; Hatfield 2004 *in* MMS 2005; CINMS 2008). Three sea otter sightings were made ~5 km from San Clemente Island during the NMFS 1998–1999 surveys of the SCIRC (Carretta et al. 2000). Approximately 178 sea otter sightings are recorded in the CINMS Sightings Database, close to the mainland coast of the SBC near Santa Barbara from 2002 to 2007, all but one during February–August, and mostly during February–April (CINMS 2008). Available data indicate this species is common in the SBC close to shore, primarily during late winter–early spring, along the entire SBC coast to as far east as ~119.00°W (CINMS 2008).

Sea Turtles

(1) Leatherback Turtle (*Dermochelys coriacea*)

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 estimated at 35,860 females (Spotila 2004).

The leatherback is the largest and most widely distributed sea turtle, ranging far from its tropical and subtropical breeding grounds. It has the most extensive range of any adult, 71ºN to 47ºS (Eckert 1995; NMFS and USFWS 1998a). Leatherbacks are highly pelagic and approach coastal waters only during the reproductive season (EuroTurtle 2001). This species is one of the deepest divers in the ocean, with dives deeper than 4000 m (Spotila 2004). The leatherback dives continually and spends short periods of time on the surface between dives (Eckert et al. 1986; Southwood et al. 1998). Off St. Croix, 6 inter-nesting females dove to a mean depth of 61.6 m for an average of 9.9 min/dive, 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). During migrations or long distance movements, leatherbacks maximize swimming efficiency by traveling within 5 m of the surface (Eckert 2002).

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). 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 1995). 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).

In the Pacific Ocean, leatherbacks nest along the west coast of Mexico, south of Puerto Vallarta, and in Central America. All of the northernmost nesting sites have been showing notable declines in numbers. Leatherbacks nest along the west coast of Mexico from November to February, with some females arriving in August (NMFS and USFWS 1998a). Females may lay up to nine clutches in a season (although six is more likely), and the incubation period is 58–65 days. There are no nesting sites near the study area.

Based on 363 sea turtle records sighted off the west coast of North America, Stinson (1984) reported that the leatherback was the most common sea turtle in U.S. waters north of Mexico. Of 274 sea turtles stranded in California during 1982–2004, 36% were leatherbacks (Fahy 2006). Leatherbacks are found from California to Alaska as far north as 60°N, 145°W, near Prince William Sound (NMFS and USFWS 1998a). Leatherbacks forage off central California, where strong coastal upwelling occurs and leatherback prey are retained and concentrated during upwelling relaxation (Benson et al. 2003, 2006). Based on aerial surveys off central California during 1990–2001, an average of 170 leatherbacks were present in nearshore waters off central California in late summer and fall (Benson et al. 2003). Telemetry and genetic studies indicate that these leatherbacks are from western Pacific populations (Dutton et al. 1998, 2006; Dutton and Eckert 2005). Telemetry studies also suggest that post-nesting females from eastern Pacific populations in Mexico and Central America migrated southward to equatorial and Southern Hemisphere waters (Dutton et al. 2006).

(2) Loggerhead Turtle (*Caretta caretta*)

The loggerhead turtle is listed as ***Threatened*** under the U.S. ESA throughout its range and ***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).

Nesting in the Pacific Ocean basin is restricted to the western region, primarily Japan and Australia (NMFS and USFWS 1998b). The nesting season is typically from May to August. 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).

Most records of loggerheads off the U.S. west coat are from southern California (Stinson 1984; Guess 1981a,b), but there are a few sightings from Washington (Hodge 1982) and Alaska (Bane 1992). Of 274 sea turtles stranded in California during 1982–2004, 12% were loggerheads (Fahy 2006). Most of the sightings in northern U.S. waters are of juveniles; of 43 records summarized by Stinson (1984), only a few may have been adults or near adults e.g., in the Channel Islands and in Encinitas, California. Sightings are typically confined to the summer months in the eastern Pacific, peaking in July–September off southern California and southwestern Baja California (Stinson 1984; NMFS and USFWS 1998b).

(3) Green Turtle (*Chelonia mydas*)

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. It 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 (Spotila 2004). 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. Green turtles typically migrate along coastal routes from rookeries to feeding grounds, although some populations conduct trans-oceanic migrations (e.g., Ascension Island–Brazil; Carr 1975). 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, they live in bays and along protected shorelines, and feed during the day on seagrass and algae (Bjorndal 1982). Juvenile and sub-adult green turtles may travel thousands of kilometers before they return to breeding and nesting grounds (Carr et al. 1978). Juveniles have been observed by research vessels operating thousands of miles from land in the southeastern Pacific Ocean (NMFS and USFWS 1998c).

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).

In the eastern Pacific, green turtles nest at several locations on the Mexican mainland, Central America, and off the coast of Colombia and Ecuador. The primary nesting grounds are located in Michoacán, Mexico, with an estimated 850 nesting females, and the Galápagos Islands, Ecuador, with an estimated 1400 nesting females (Spotila 2004). Nesting occurs in Michoacán between August and January, with a peak in October–November, and on the Galápagos Islands between December and May with a peak in February (Alvarado and Figueroa 1995). In Central America, small numbers of green turtles nest at major nesting sites of other species, primarily olive ridleys, in Nicaragua (Ocean Resources Foundation 1998) and in Costa Rica (NMFS and USFWS 1998c). Green turtles also nest in very small numbers in El Salvador (Hasbún and Vásquez 1999). There are no known nesting sites on the U.S. west coast (NMFS and USFWS 1998c).

In the North Pacific, the species has been documented as far north as southern Alaska (NMFS 2004). Of 274 sea turtles stranded in California during 1982–2004, 34% were green turtles (Fahy 2006). Based on 363 sea turtle records sighted off the west coast of North America, Stinson (1984) reported that the green turtle was the most common hard-shelled sea turtle on the U.S. Pacific coast. Most of the sightings (62%) were reported from northern Baja California and southern California. The northernmost reported resident population occurs in San Diego Bay (Stinson 1984; Dutton and McDonald 1990a,b, 1992; Dutton et al. 1994). Green turtles are sighted year-round in the waters of southern California, with the highest frequency of sightings occurring during the warm summer months of July–October (Stinson 1984). In waters south of Point Conception, Stinson (1984) found this seasonal sighting pattern to be independent of inter-year temperature fluctuations. North of Point Conception, more sightings occurred during warmer years.

(4) Olive Ridley Turtle (Lepidochelys olivacea)

The olive ridley is the most abundant sea turtle in the world, but 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). Worldwide, olive ridleys are in serious decline (Spotila 2004).

The olive ridley 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. Most olive ridley turtles lead a primarily pelagic existence. 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 kilometers out into the central Pacific Ocean (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 eastern Pacific Ocean, 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).

Females and males begin to aggregate near their nesting beaches two months before the nesting season, and most mating likely occurs near the nesting beaches (NMFS 2002). However, Pitman (1990) observed olive ridleys mating at sea, as far as 1850 km from the nearest mainland, during every month of the year except March and December. 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).

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 peak months, including major arribadas, occurring from September through December (NMFS and USFWS 1998d). There is no known nesting on the U.S. west coast.

Outside of the breeding season, the turtles disperse, but little is known of their behavior. Neither males nor females migrate to one specific foraging area, but exhibit a nomadic movement pattern and occupy a series of feeding areas in oceanic waters (Plotkin et al. 1994a,b). Aggregations of turtles[4], sometimes >100 individuals, have been observed as far offshore as 120°W, ~3000 km from shore (Arenas and Hall 1991), however movements of turtles tagged in Central America were highly dissociated from each other, indicating that olive ridleys are "nomadic epipelagic foragers that prey on patchily distributed food" (Morreale et al. 2007:220).

Olive ridley turtles occasionally venture into cold waters, some as far as the Gulf of Alaska (Hodge and Wing 2000). At-sea occurrences in the United States and waters under U.S. jurisdiction are limited to the west coast of the continental United States (Stinson 1984) and Hawaii. Many published records located north of southern California are of dead, stranded turtles. Known records from Alaska (n=3) were all dead stranded turtles (Hodge & Wing 2000), and a ridley stranded on the ocean side of Point Reyes Peninsula was also dead (Evens 1993). Of 274 sea turtles stranded in California during 1982–2004, 13.5% were olive ridley turtles (Fahy 2006). However, there are also a number of California sightings of live olive ridleys. Hubs (1977) reported a pair mating off the La Jolla coast, and an adult was hooked by a fisherman in Los Angeles Harbor in 1983 (NMFS and USFWS 1998d). In October 2001, a live adult male was found entangled in fishing line ~1 km west of Muir Point off Marin County, and on 28 November 2002, an olive ridley was observed swimming up to and hauling out on Shell Beach in Tomales Bay State Park (Steiner and Walder 2005).

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 SIO. A more detailed review of airgun effects on marine mammals appears in Appendix A. That Appendix is similar to corresponding parts of previous EAs and associated IHA applications concerning other SIO and L-DEO seismic surveys since 2003, but was updated in 2008. Appendix B contains a general review of the effects of seismic pulses on sea turtles. This section (along with Appendix A) also includes a discussion of the potential impacts of operations by SIO's multi-beam echosounder (MBES) and sub-bottom profiler (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 during November 2008. A description of the rationale for SIO'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,

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

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). With the possible exception of some cases of temporary threshold shift in harbor seals and perhaps some other seals, 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 A (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 A (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.

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. Some baleen and toothed whales are known to continue calling in the presence of seismic pulses, and their calls can usually 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). 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. 2002c; 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 A (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 A (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 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 (Richardson et al. 1995). In many areas, seismic pulses from large arrays of airguns diminish to those levels at distances ranging from 4.5 to 14.5 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 A (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 2007:236).

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 A (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 A 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 A 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 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 A). A ≥170 dB re 1 μPa_{rms} 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 A (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). Even if reactions of any pinnipeds that might be encountered in the present study area are as strong as those evident in the telemetry study, reactions are expected to be confined to relatively small distances and durations, with no long-term effects on pinniped individuals or populations. As for delphinids, a ≥170 dB disturbance criterion is considered appropriate for pinnipeds, which tend to be less responsive than many cetaceans.

***Fissipeds*.**—Behavior of sea otters along the California coast was monitored by Riedman (1983, 1984) while they were exposed to a single 100-in^3 airgun and a 4089-in^3 airgun array. No disturbance reactions were evident when the airgun array was as close as 0.9 km. Otters also did not respond noticeably to the single airgun. The results suggest that sea otters are less responsive to marine seismic pulses than are baleen whales. Also, sea otters spend a great deal of time at the surface feeding and grooming. While at the surface, the potential noise exposure of sea otters would be much reduced by the pressure release effect at the surface.

***Sea Turtles*.**—The limited available data indicate that sea turtles will hear airgun sounds and sometimes exhibit localized avoidance (see Appendix B). 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). Observed responses of sea turtles to airguns are reviewed in Appendix B. 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 A (5). Corresponding details for sea turtles can be found in Appendix B.

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 A (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 could (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, and the planned monitoring and mitigation measures (see below). The following subsections discuss in somewhat more detail the possibilities of TTS, permanent threshold shift (PTS), and non-auditory physical effects.

Temporary Threshold Shift (TTS).—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[5]. 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

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[5] If the low frequency components of the watergun sound used in the experiments of Finneran et al. (2002) are downweighted as recommended by J. Miller et al. (2005) and Southall et al. (2007) using their Mmf-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).

TTS threshold is (to a first approximation) a function of the total received pulse energy. The distances from the R/V *Melville*'s GI airgun and boomer at which the received energy level (per pulse, flat-weighted) would be expected to be ≥190 dB re 1 μPa_{rms} are estimated in Tables 1 and 2. Levels ≥190 dB re 1 μPa_{rms} are expected to be restricted to radii no more than 12 m from the GI airgun in intermediate-depth areas, where the GI airgun will be used, or 9 m from the boomer (Tables 1 and 2). 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 most parts of the planned study area; (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 (PTS).—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 or human 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 A (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 A (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 2007). • 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 2002b) 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 B). This suggests that sounds from an airgun array might cause temporary hearing impairment in sea turtles if they do not avoid the (unknown) radius where TTS occurs. However, exposure duration during the planned surveys would be much less than during the study by Moein et al. (1994). Also, recent monitoring studies show that some sea turtles do show localized movement away from approaching airguns (Holst et al. 2005a, 2006). At short distances from the source, received sound level diminishes rapidly with increasing distance. In that situation, even a small-scale avoidance response could result in a significant reduction in sound exposure.

As noted above, the MMOs stationed on the R/V *Melville* 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 Multi-beam Echosounder Signals

The Simrad EM120 12-kHz MBES will be operated from the source vessel at some times 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 μPa_{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 Navy sonar. During SIO'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 echosounder 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 SIO, 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 SIO 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 $\mu Pa^2 \cdot s$, 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 $\mu Pa^2 \cdot s$) and even further below the anticipated PTS threshold (215 dB re 1 $\mu Pa^2 \cdot s$) (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 $\mu Pa^2 \cdot s$ 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 $\mu Pa^2 \cdot s$, 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 R/V *Melville* 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. However, the SEL criterion for PTS in pinnipeds (203 dB re 1 $\mu Pa^2 \cdot s$) 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 surveys would significantly affect sea turtles through masking, disturbance, or hearing impairment. Any effects likely would be negligible given the brief exposure and the fact that the multibeam frequency is far above the range of optimal hearing by sea turtles (see Appendix B).

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

A sub-bottom profiler will be operated from the source vessel during the planned study. Details about this equipment were provided in § II. Sounds from the sub-bottom profiler are very short pulses, occurring for 1.5–6 ms once every second or so. Most of the energy in the sound pulses emitted by the sub-bottom profiler is at 3.5 kHz, and the beam is directed downward. The sub-bottom profiler on the R/V *Melville* has a maximum source level of 211 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, and—even for an SBP more powerful than that on the R/V *Melville*—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 sub-bottom profiler signals given their directionality and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of most baleen whales, the sub-bottom profiler 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 sub-bottom profiler are likely to be similar to those for other pulsed sources if received at the same levels. However, the pulsed signals from the sub-bottom profiler 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 sub-bottom profiler 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 sub-bottom profiler 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 sub-bottom profiler. 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 sub-bottom profiler.

Sea Turtles

It is very unlikely that sub-bottom profiler 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.

(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: minimum of one dedicated observer maintaining a visual watch during all daytime airgun operations (and when possible at other times) and 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 GI airgun, as a result of its design, directs the majority of the energy downward, and less energy laterally, is also an inherent mitigation measure.

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

(3) Numbers of Marine Mammals that could be Exposed to Various Received Sound Levels

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 seismic program. The estimates are based on consideration of the number of marine mammals that could be disturbed appreciably by ~1100 km of seismic surveys in the Santa Barbara Channel. The main 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 seismic sources and the other sources, any marine mammals close enough to be affected by the MBES or SBP would already be affected by the seismic sources. However, whether or not the seismic sources 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 Exposure to Various Received Sound Levels

Extensive systematic aircraft- and ship-based surveys have been conducted for marine mammals off the U.S. west coast; the most comprehensive and recent density data available for cetacean species in shelf, slope, and offshore waters of California are from the 1991, 1993, 1996, 2001, and 2005 NMFS/SWFSC shipboard surveys as synthesized by Barlow and Forney (2007). The surveys were conducted up to ~550 km offshore from June or July to November or December. Densities are available for all of California in each of the five years, and for southern California (south of the latitude of Point Conception) for all years combined (Barlow and Forney 2007), but not for southern California in each year except 2005 (Forney 2007). Another set of surveys that included southern California was conducted by NMFS in the ETP during summer and fall 1986–1996, as summarized by Ferguson and Barlow (2001). Densities were calculated for 5° x 5° blocks; the partial block that includes the waters off southern California (Block 58) has its northern boundary at 35ºN, just north of Point Conception. It extends off the coast as a wedge with a maximum distance of ~375 km offshore, and included 2925 km of survey effort in Beaufort sea states 0–5 and 600 km of survey effort in Beaufort sea states 0–2. We decided to use those density estimates because a smaller proportion of the waters surveyed were offshore. For two species expected to be common in the SBC but for which there were no sightings in Ferguson and Barlow (2001)—humpback whales and Dall's porpoise—we used the 2005 densities for southern California in Forney (2007).

Systematic at-sea survey data for pinnipeds are more limited. The only densities to our knowledge are for California sea lions, and are based on ~31,000 km of aerial surveys of the SCB during 1975–1978, as summarized by Bonnell and Ford (1987). There are no density data, to our knowledge, for sea otters in the study area.

Oceanographic conditions, including occasional El Niño and La Niña events, influence the distribution and numbers of marine mammals present in the NEPO, including California, resulting in considerable year-to-year variation in the distribution and abundance of many marine mammal species (Forney and Barlow 1998; Buchanan et al. 2001; Escorza-Treviño 2002; Ferrero et al. 2002; Philbrick et al. 2003;

Becker 2007). Thus, for some species the densities derived from recent surveys may not be representative of the densities that will be encountered during the proposed seismic survey.

Table 4 gives the estimated densities for each cetacean and pinniped species that are likely to occur in the Santa Barbara Channel. The densities have been corrected for both detectability and availability bias by the authors. Detectability bias is associated with diminishing sightability with increasing lateral distance from the trackline [*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 trackline, and it is measured by *g*(0).

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 of density for cetaceans are those in Barlow and Ferguson (2001) or Forney (2007), whereas maximum estimates of density for cetaceans are the observed (best) densities multiplied by 1.5. Best and maximum estimates of California sea lion densities are from Figure 4 of Bonnell and Ford (1987).

The estimated numbers of individuals potentially exposed are presented below 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, Dall's porpoise, and pinnipeds. It is assumed that marine mammals exposed to airgun sounds this strong might change their behavior sufficiently to be considered "taken by harassment".

It should be noted that the following estimates of exposures to various sound levels assume that the surveys will be fully 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 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 zone will result in the shut down of seismic operations as a mitigation measure. Thus, the following estimates of the numbers of marine mammals potentially expose 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.

(b) Potential Number of Marine Mammals Exposed to ≥160 and ≥170 dB

Number of Cetaceans that could be Exposed to ≥160 dB

The number of different individuals that could be exposed to GI-gun or boomer 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 seismic sources 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 close proximity; thus, an individual mammal may be exposed numerous times during the survey. The number of possible exposures to GI-gun and boomer 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 seismic sources, including areas of overlap. However, it is unlikely that a particular animal would stay in the area during the entire survey. 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. Densities of marine mammals sighted during surveys off southern California, with their approximate coefficients of variation (CV). Cetacean densities are from Ferguson and Barlow (2001) and are based on ship transect surveys conducted up to 375 km offshore in 1986–1996. The pinniped density is from at-sea surveys conducted by Bonnell and Ford (1987). Densities are corrected for *f*(0) and *g*(0). Species listed as "Endangered" under the ESA are in italics.

	Best Density (#/1000 km^2)		**Maximum Density (#/1000 km^2)**
Species	**Density**	**CV [1]**	**Density**
Mysticetes			
North Pacific right whale	*0*	-1	*0*
Gray whale	0	-1	0
Humpback whale	*0.22*	0.94	*0.33*
Minke whale	0.36	0.94	0.54
Bryde's whale	0	-1	0
Sei whale	*0*	*-1*	*0*
Fin whale	*0.55*	*0.76*	*0.82*
Blue whale	*5.45*	0.36	*8.15*
Odontocetes			
Sperm whale	*0.31*	*0.83*	*0.47*
Pygmy sperm whale	21.78	0.68	32.68
Dwarf sperm whale	0	-1	0
Cuvier's beaked whale	1.44	0.94	2.16
Baird's beaked whale	0	-1	0
Mesoplodon spp.	0	-1	0
Bottlenose dolphin	6.12	0.55	9.18
Striped dolphin	3.37	0.83	5.05
Short-beaked common dolphin	1364.41	0.25	2046.61
Long-beaked common dolphin	174.69	0.55	262.04
Pacific white-sided dolphin	33.00	0.65	49.50
Northern right-whale dolphin	16.80	0.68	25.20
Risso's dolphin	18.35	0.50	27.53
Killer whale	0	-1	0
Short-finned pilot whale	0	-1	0
Phocoenidae			
Harbor porpoise	0	-1	0
Dall's porpoise	9.17	0.68	13.76
Pinnipeds[2]			
Guadalupe fur seal	N/A	N/A	N/A
Northern fur seal	N/A	N/A	N/A
California sea lion	100	N.A.	300
Steller sea lion	N/A	N/A	N/A
Harbor seal	N/A	N/A	N/A
Elephant seal	N/A	N/A	N/A

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

[2] Densities are not available for most pinnipeds in SBC; only the California sea lion and harbor seal are expected to occur there during the proposed survey.

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

- the anticipated area to be ensonified to that level during seismic 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 Tables 1 and 2) 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, whereas the areas of overlap were included only once when estimating the number of individuals exposed.

Applying the approach described above, ~289 km^2 would be within the 160-dB isopleth on one or more occasions during the survey, whereas ~690 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 two or three 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 may be underestimated, although the conservative (i.e., probably overestimated) line-kilometer distances used to calculate the area may offset this. Also, the approach assumes that no cetaceans will move away or toward the trackline as the R/V *Melville* approaches in response to increasing sound levels prior to the time the levels reach 160 dB.

Table 5 shows the best and maximum estimates of the number of exposures and the number of different individual marine mammals that potentially could 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 5, is based on the maximum estimates of the numbers of individuals exposed. For ***endangered*** species, the maximum estimate and ***Requested Take Authorization*** have been increased to the mean group size for the particular species (from Barlow and Forney 2007) in cases where the calculated maximum number of individuals exposed was between 0.05 and the mean group size (i.e., for humpback, fin, and sperm whales).

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 survey is 478 (Table 5). That total includes two ***endangered*** whales (blue whales), which would represent 0.13% of the regional population (Table 5). The short-beaked common dolphin is estimated to be the most common species exposed, with a best estimate of 394 (Table 5) or 0.08% 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 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 1144, including 4 blue whale exposures, and 1 Cuvier's beaked whale exposure. The short-beaked common dolphin is estimated to be exposed most frequently, with a best estimate of 942 exposures.

The 'Maximum Estimate' column in Table 5 shows an estimated total of 717 cetaceans exposed to seismic sounds ≥160 dB during the surveys. The ***Requested Take Authorizations*** are based on the maximum estimates of the number of individuals that could be exposed to seismic sounds with received levels ≥160 dB re 1 μPa_{rms} during the survey.

TABLE 5. 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 SIO's proposed seismic survey in the Santa Barbara Channel in November 2008. The proposed sound source consists of one GI airgun in deeper water and a mini-sparker or boomer in state waters. Received levels of seismic 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 and Dall's porpoise 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.

Species	Number of Exposures to Sound Levels ≥160 dB (≥170 dB)				Number of Individuals Exposed to Sound Levels ≥160 dB (≥170 dB)					Requested Take Authori-zation
	Best Estimate[1]		Maximum Estimate[1]		Best Estimate[1]			Maximum Estimate[1]		
					Number		% of Regional Pop'n[2]			
Balaenopteridae										
North Pacific right whale	*0*		*0*		*0*		*0*	*0*		***0***
Gray whale	0		0		0		0	0		**0**
Humpback whale	*0*		*0*		*0*		*<0.01*	*2*		***2***
Minke whale	0		0		0		<0.01	0		**0**
Bryde's whale	0		0		0		0	0		**0**
Sei whale	*0*		*0*		*0*		*0*	*0*		***0***
Fin whale	*0*		*1*		*0*		*<0.01*	*2*		***2***
Blue whale	*4*		*6*		*2*		*0.13*	*2*		***2***
Physeteridae										
Sperm whale	*0*		*0*		*0*		*<0.01*	*8*		***8***
Pygmy sperm whale	15		23		6		N.A.	9		**9**
Dwarf sperm whale	0		0		0		0	0		**0**
Ziphiidae										
Cuvier's beaked whale	1		1		1		<0.01	1		**1**
Baird's beaked whale	0		0		0		0	0		**0**
Mesoplodon spp.	0		0		0		0	0		0
Delphinidae										
Bottlenose dolphin	4	(1)	6	(2)	2	(1)	0.05	3	(2)	**3**
Striped dolphin	2	(1)	3	(1)	1	(1)	>0.01	1	(1)	**1**
Short-beaked common dolphin	942	(311)	1413	(466)	394	(273)	0.08	591	(409)	**591**
Long-beaked common dolphin	121	(40)	181	(60)	50	(35)	2.66	76	(52)	**76**
Pacific white-sided dolphin	23	(8)	34	(11)	10	(7)	<0.01	14	(10)	**14**
Northern right-whale dolphin	12	(4)	17	(6)	5	(3)	0.03	7	(5)	**7**
Risso's dolphin	13	(4)	19	(6)	5	(4)	0.04	8	(5)	**8**
Killer whale	0		0		0		0	0		**0**
Short-finned pilot whale	0		0		0		0	0		**0**
Phocoenidae										
Harbor porpoise	0		0		0		0	0		**0**
Dall's porpoise	6	(2)	10	(3)	3	(2)	<0.01	4	(3)	**4**
Pinnipeds[3]										
California sea lion	69	(23)	207	(68)	29	(20)	0.01	87	(60)	**87**
Harbor seal	0		0		0		0	20		**20**

[1] Best and maximum estimates are based on densities from Table 4, except maximum estimates for endangered species (see text).

[2] Regional population size estimates are from Table 3; NA means not available.

[3] Guadalupe fur seals, northern fur seals, Steller sea lions, and northern elephant seals are not included because they are rare in the SBC or are not expected to occur there during the study period.

Number of Delphinids and Dall's Porpoises 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 A (5), delphinids and Dall's porpoises 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 and Dall's porpoises exposed to airgun sounds. However, the estimates in this subsection assume that only those individuals 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 determined (as described above for levels ≥160 dB) and was multiplied by the marine mammal density in order to obtain best and maximum estimates.

The area ensonified by levels ≥170 dB was estimated to be 200 km^2 (as described above for levels ≥160 dB), and the estimated area, including overlap, is 228 km^2. Thus, an average individual marine mammal could be exposed to ≥170 dB slightly more than once during the survey. The best and maximum estimates of the numbers of delphinids that could be exposed to ≥170 dB during the surveys are 325 and 717, respectively (Table 5), and the corresponding estimates for the short-beaked common dolphin are 273 and 409 (Table 5). The estimates are based on the predicted 170-dB radii around the seismic sources to be used during the study and are considered to be more realistic estimates of the number of individual delphinids and Dall's porpoises that could be affected.

Number of Pinnipeds that could be Exposed to ≥160 dB and ≥170 dB

Two of the six pinniped species discussed in § III—the Guadalupe fur seal and the Steller sea lion—are rare in the SBC, and another two—the northern fur seal and the northern elephant seal—are not expected to occur there at the time of the proposed survey (November) because they are feeding offshore at that time. Densities are available for the California sea lion, the most abundant pinniped in the Channel Islands, but not for the harbor seal, which could be encountered during the survey. Therefore, we have made allowance in Table 5 for the exposure of a small number of harbor seals to received sound levels ≥160 dB re 1 μPa_{rms}.

As summarized in § IV(1)(a) and Appendix A, most pinnipeds seem to be less sensitive to airgun sounds than are mysticetes. Thus, the numbers of pinnipeds likely to be exposed to received levels ≥170 dB re 1 μPa_{rms} were also calculated, based on the estimated 170-dB radii (Tables 1 and 2).

The methods described previously for cetaceans were also used to calculate exposure numbers for the two pinniped species likely to be in the survey area and whose densities were estimated. Based on the "best" density, 36 California sea lions are considered likely to be exposed to seismic sounds ≥160 dB re 1 μPa_{rms}. The 'Maximum Estimate' column in Table 5 shows an estimated 87 or 60 California sea lions that could be exposed to GI airgun sounds ≥160 dB or ≥170 dB re 1 μPa_{rms}, respectively, during the survey. We have also included a low maximum estimate for the harbor seal, a species that likely would be present but whose density in the SBC has not been estimated, to our knowledge. The numbers for which "take authorization" is requested, given in the far right column of Table 5, are based on the maximum 160-dB estimates.

Best and Maximum Estimates of the Number of Fissipeds that could be Exposed to ≥160 dB and ≥170 dB.— Sea otters occur primarily off central California, north of Point Conception, although there have been reports of sea otters just south of Point Conception in winter and spring (see § III). Sea otters generally occur in waters <40 m deep (Riedman and Estes 1990), and very few (75 km) of the proposed seismic lines are in waters <40 m deep. Furthermore, sea otters spend a great deal of time at the surface feeding and grooming. While at the surface, the potential noise exposure of sea otters would be much reduced by the pressure release effect at the surface. Considering all the factors presented above, it is clear that only small numbers of otters, if any, would be exposed to strong seismic sounds. Furthermore, a study in California showed that sea otters show little or no reaction to exposure to sound pulses from either a small airgun source or from a large array of airguns (Riedman 1983, 1984).

(4) Conclusions re Marine Mammals and Sea Turtles

The proposed seismic project will involve towing a GI airgun and a boomer that introduce pulsed sounds into the ocean, along with, at times, simultaneous operation of an MBES and a SBP. Routine vessel operations, other than the proposed seismic 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.

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

Taking into account the mitigation measures that are planned (see § II), effects on cetaceans are generally expected to be limited to avoidance of the area around the seismic operation and short-term changes in behavior, falling within the MMPA definition of "Level B harassment". Furthermore, the estimated numbers of animals potentially exposed to sound levels sufficient to cause appreciable disturbance are generally low percentages of the 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 most species, <0.1% of the regional populations. For only one species (the long-beaked common dolphin), >1% of the regional populations were estimated to be exposed (Table 5).

Varying estimates of the numbers of marine mammals that could 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 controlled speed, course alternation, look outs, non-pursuit, shut downs when marine mammals are seen within defined ranges, and special measures for species of particular concern should further reduce short-term reactions, and avoid or minimize any auditory effects. In all cases, the effects are expected to be short-term, with no lasting biological consequence.

(b) Pinnipeds

Only two pinniped species—the California sea lion and the harbor seal—are likely to occur in the study area. A best estimate of 29 California sea lions and fewer harbor seals could be exposed to seismic sounds with received levels ≥160 dB re 1 $\mu\mathrm{Pa}_{\mathrm{rms}}$. These estimates represent <0.1% of their regional populations. The numbers for which "take authorization" is requested are given in the far right column of Table 5. As for cetaceans, the estimated numbers of pinnipeds that could be exposed to received levels ≥160 dB are probably overestimates of the actual numbers that will be affected.

(c) Sea Otters

It is unlikely that any sea otters would be exposed during seismic operations because proposed survey lines in shallow water are in locations where sea otters are not expected to occur. Furthermore, sea otters spend a great deal of time at the surface feeding and grooming, and while at the surface, the potential noise exposure would be much reduced by the pressure release effect at the surface. If concentrations of sea otters are sighted, the seismic source will be shut down and operations will cease in the area until the concentrations move away or disperse. As for cetaceans and pinnipeds, the short-term exposures to airgun sounds are not expected to result in any long-term negative consequences for the individuals or their populations.

(d) Sea Turtles

The proposed activity will occur one thousand or more kilometers from areas where sea turtles nest. Four species—the leatherback, loggerhead, green, and olive ridley turtles—could be encountered in the study area, and then only foraging or migrating individuals would occur. Although it is possible that some turtles will be encountered during the survey, 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 C). 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. Thus, available information provides limited insight on possible real-world effects at the ocean or population scale. This makes drawing conclusions about impacts on fish problematic because ultimately, the most important aspect of potential impacts relates to how exposure to seismic survey sound affects marine fish populations and their viability, including their availability to fisheries.

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

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

Little is known about the mechanisms and characteristics of damage to fish that may be inflicted by exposure to seismic survey sounds. Few data have been presented in the peer-reviewed scientific literature. As far as we know, there are only two valid papers with proper experimental methods, controls, and careful pathological investigation implicating sounds produced by actual seismic survey airguns with adverse anatomical effects. One such study indicated anatomical damage and the second indicated TTS in fish hearing. The anatomical case is McCauley et al. (2003), who found that exposure to airgun sound caused observable anatomical damage to the auditory maculae of "pink snapper" (*Pagrus auratus*). This damage in the ears had not been repaired in fish sacrificed and examined almost two months after exposure. On the other hand, Popper et al. (2005) documented only TTS (as determined by auditory brainstem response) in two of three fishes from the Mackenzie River Delta. This study found that broad whitefish (*Coreogonus 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 airgun arrays [less than ~400 Hz in the study by McCauley et al. (2003) and less than ~200 Hz in Popper et al. (2005)] likely did not propagate to the fish because the water in the study areas was very shallow (~9 m in the former case and <2 m in the latter). Water depth sets a lower limit on the lowest sound frequency that will propagate (the "cutoff frequency") at about one-quarter wavelength (Urick 1983; Rogers and Cox 1988).

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

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

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

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

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 D).

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

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

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 seismic source 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, Department of Fisheries and Oceans [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).

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

The proposed seismic 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 in the region of the proposed seismic survey in and near the Santa Barbara Channel include commercial and recreational vessel traffic and fishing, and oil and gas production.

(a) Collisions with Vessels and Vessel Noise

Vessel traffic in the proposed study area will consist of fishing vessels, as well as other commercial (cargo), cruise, and pleasure vessels. 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. On infrequent occasions, whales and ships collide, resulting in injury or death to the animal (Laist et al. 2001; Moore and Clarke 2002).

Large Vessel Traffic

The Santa Barbara Channel is a major thoroughfare for oceangoing ships traveling between domestic and international ports along the Pacific coast of North America, and for large vessels traveling between ports in North America and Asia. Nearly 40% of vessels calling at California ports are from a

Far Eastern port such as Japan, China, or Korea; 20% are from a North American port such as Canada or Mexico; and 13% are from a South American port (California State Lands Commission 2001 *in* NOAA 2008). Containerized trade at the Port of Los Angeles/Long Beach, which is the busiest container port in North America, grew 150% percent from 1995 to 2006 (Port of Long Beach 2007), and the Santa Barbara Channel is a main thoroughfare for this trade. Approximately 75% of the departing vessel traffic from LA/Long Beach leaves northbound and 65% of arriving vessel traffic comes southbound, passing through the Santa Barbara Channel. For the year 2006, an estimated 6980 vessels (including container ships and other large vessels) going to or coming from the ports of LA/Long Beach transited the Santa Barbara Channel (McKenna 2007 *in* NOAA 2008).

Recreational vessels

The Channel Islands are popular diving destinations. Dive charters based in Santa Barbara and Ventura usually take divers to the Northern Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa), whereas those based in San Pedro, Long Beach, and San Diego most often visit the Southern Channel Islands of San Nicolas, Santa Barbara, Santa Catalina, and San Clemente (Krival 2001). In 2007, there were 8 vessels based in Santa Barbara, Ventura, and Oxnard that bring visitors to the CINMS, primarily for whale watching (CINMS 2007).

The total transit distance by SIO's vessel (a maximum of ~3090 line km) will be minimal relative to total transit length for all cargo, cruise, and recreational vessels operating in the Santa Barbara Channel. As previously discussed, SIO's seismic operations will not cause any large-scale or prolonged effects. Thus, the combination of SIO's operations with the existing shipping and marine tourism operations is expected to produce only a negligible increase in overall ship disturbance effects on marine mammals.

(b) Fisheries

The fishing industry impacts marine mammals and sea turtles. For example, the average annual mortality of dolphins as bycatch in the eastern Pacific Ocean during 2000–2005 was ~1550 (IATTC 2007). Incidental catch in fisheries is also widely recognized as a major mortality factor for sea turtles. Also, commercial fisheries may accidentally entangle and drown or injure cetaceans during fishing operations or by lost and discarded fishing gear (e.g., Northridge and Hofman 1999). Humpback whales, perhaps because of their abundance in coastal waters where nets are commonly used or because of the many barnacles they carry seem to be extremely vulnerable to entanglement in fishing gear (Lien 2002). Trites et al. (1997) suggested that fisheries might indirectly compete with cetaceans by reducing the amount of primary production accessible to cetaceans, thereby negatively affecting their numbers.

Historically, the area where the survey would occur has been fished using several gear types targeting multiple species: 1) purse seines for coastal pelagic fish such as sardine, northern anchovy, mackerel, and squid; 2) trawls for shrimp, sole, flounder, and halibut; 3) hook and line or longline for rockfish; 4) traps for crab and lobster; 5) drift/set gillnets for shark and swordfish; and 6) trolls for albacore and salmon. Commercial fishing occurs within the survey area on a seasonal, quota, and trip limit basis and in response to market forces throughout the year (MMS 2005). Total landings in the Santa Barbara area in 2006 were ~23,000 tonnes (CDFG 2008).

The commercial catch has varied over the long term because of decadal-scale changes in environmental conditions (coastal pelagics), warming from El Niño events (tunas, herring, and squid), the depletion and regulation of many stocks (including several rockfish), and domestic and international market conditions (Mason 2004). The fishery likely will continue, although it likely will not increase in intensity in the future. In her analysis of historical patterns from 74 years of commercial landings from California waters, Mason (2004) noted that the declining trend in the total value of landings, despite increased total landings, raises concern for the future of the fishing economy. Thus, future growth in the commercial fishing industry is not likely.

The commercial passenger fishing vessel (CPFV, also known as "partyboat") fleet is a valuable recreational and economic unit in California (Young 1969). Dotson and Charter (2003), in an analysis of the 1959–1998 database for the Southern California CPFV fleet, reported that angler effort has been consistent throughout the time series at about 620,000 passengers per year. The annual fish catch averaged 4.25 million fish from 1963 to 1991 but has declined since 1992 to 2.5 million fish in 1998. The increasing popularity and availability of private boats may be the major area of growth in coastal fishing (Dotson and Charter 2003). In southern California, private boats in 1998 accounted for 45% of the recreational fishing effort as opposed to 23% for the CPFV fleet (NMFS 2000 *in* Dotson and Charter 2003).

SIO's seismic operations in the study area are expected to have a negligible impact on marine mammals in the study area when compared to that of commercial fisheries activities.

(c) Oil and Gas Activities

Offshore oil and gas development has occurred in leased tracts in California waters from the mean high tide line to 3 miles offshore, and in federal waters from 3 to 11 miles offshore. Twenty platforms, one island (Rincon Island), and ~290 km of associated pipelines are located off Santa Barbara County; 16 of the platforms and ~250 km of pipelines are in the SBC (MMS 2000). Federal OCS leases within the yield ~93,200 barrels of oil per day and ~112,300 million cubic feet of gas per day (County of Santa Barbara Energy Division 2001 *in* NOAA 2006). To date, seven relatively small offshore oil structures have been removed from state waters of the Santa Barbara Channel. The most recent project occurred in 1996 when Chevron removed Platforms Hope, Heidi, Hilda, and Hazel from water depths ranging from 100 to 140 feet. No new platforms have been erected off California since 1989 (Love et al. 2003 *in* DoN), and it is unlikely that any leasing will occur in the future (McCrary et al. 2003).

(d) Summary of Cumulative Impacts to Marine Mammals

Impacts of SIO's proposed seismic survey in the Santa Barbara Channel are expected to be no more than a very minor (and short-term) increment when viewed in light of other human activities within the study area. Unlike some other ongoing and routine activities, SIO's activities are not expected to result in injuries or deaths of marine mammals. Although the sounds from the seismic survey will have higher source levels than those of some other human activities in the area, GI airgun and boomer operations will take place only for a 12-d period, in contrast to other noise-producing activities that occur continuously over extended periods.

(e) Cumulative Impacts to Sea Turtles

Major threats to sea turtles include hunting and poaching, the collection of eggs, coastal development, increased tourism including beaches obstructed with lights and chairs, beach sand mining, pedestrian traffic, oil spills, ship strikes, entanglement in fishing gear, ingestion of plastic and marine garbage, and destruction of feeding habitat in coral reefs and seagrass beds (Horrocks 1992; Marcovaldi et al. 2003). Because the proposed study area does not have any sea turtle nesting sites and only small numbers of non-breeding turtles, potential impacts will be minimal.

(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. For cetaceans, some of the changes in behavior may be sufficient to fall within the MMPA definition of "Level B Harassment" (behavioral disturbance; no serious injury or mortality). No long-term or significant impacts are expected on any of these individual marine mammals or turtles, or on the populations to which they belong. Effects on recruitment or survival are expected to be (at most) negligible.

(10) Coordination with Other Agencies and Processes

This EA has been adopted by the NSF primarily to address issues relating to the request that an IHA be issued by NMFS to authorize "taking by harassment" (disturbance) of small numbers of cetaceans and pinnipeds during SIO's planned activities during the seismic survey. Another important component has been to address potential impacts on sea otters, which are managed by USFWS.

SIO and NSF will coordinate the planned marine mammal monitoring program associated with the seismic survey in the Santa Barbara Channel area with other parties that may have interest in this area. SIO and NSF will coordinate with other applicable Federal and State agencies as required, and will comply with their 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 (12 Days in November 2008) 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 and throughout the time period during which the project may occur. A number of marine mammal species (see Table 3) are year-round residents in the SCB, so altering the timing of the proposed project likely would result in no net benefits for those species (see § III, above). Other marine mammal species (e.g., the gray whale and northern elephant seal) are migratory, and are absent from the SBC at the time of the proposed survey (see § III, above). Postponing the proposed project to a later time in the year could result in higher numbers of migratory species in the SBC during the proposed survey.

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.

V. LIST OF PREPARERS

LGL Ltd., environmental research associates

William E. Cross, M.Sc., King City, Ont.*
Mari Smultea, M.Sc., King City, Ont.*
Beth Haley, B.A., Anchorage, AK
Meike Holst, M.Sc., Sidney, B.C.
John Christian, M.Sc., St. John's, Nfld.
Mark Fitzgerald, B.A.A., King City, Ont.
Michelle Gilders, B.A., M.A., Calgary, Alb.
William R. Koski, M.Sc., King City, Ont.
W. John Richardson, Ph.D., King City, Ont.

Lamont Doherty Earth Observatory

John Diebold, Ph.D., Palisades, NY

National Science Foundation

William Lang, Ph.D., Arlington, VA
Holly E. Smith, M.A., Arlington, VA

* Principal preparers of this specific document. Others listed above contributed to a lesser extent, or contributed substantially to previous related documents from which material has been excerpted.

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APPENDIX A:

REVIEW OF THE EFFECTS OF AIRGUN AND SONAR SOUNDS ON MARINE MAMMALS[6]

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 or physiological 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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[6] By **W. John Richardson** and **Valerie D. Moulton**, with subsequent updates (to June 2008) by WJR and VDM plus **Patrick Abgrall**, **William E. Cross**, **Meike Holst**, **Andrea Hunter**, and **Mari A. Smultea**, all of LGL Ltd., environmental research associates

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 determine 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.[7] 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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[7] 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 by seismic pulses.

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 that 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 human activities and exposed to a particular level of anthropogenic 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 2007, p. 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*) often have 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.[8] 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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[8] 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[9] 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). During 91 site surveys off the U.K. in 1997–2000, sighting rates of all small odontocetes combined were significantly lower during periods the low-volume[10] airgun sources were operating, and

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

[10] For low volume arrays, maximum volume was 820 in^3, with most (87%) ≤180 in^3.

effects on orientation were evident for all species and groups 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 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 feed, 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 $\mu Pa_{p–p}$ 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 to 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 and to some degree on frequency, 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.

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).[11] 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 received within 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 has a flat-weighted received level 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) concluded 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,

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[11] 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).

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 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.[12]

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 $\mu Pa^2 \cdot s$

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[12] 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.

(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.

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 because of 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 2007). • 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 Oceanographic 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 230 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 Audibility of Sonar Pulses

General information on hearing abilities of the various groups of marine mammals is summarized in §2 of this Appendix. *Baleen whales* are expected to hear sonar signals at frequencies within their functional hearing range (7 Hz to 22 kHz for mysticetes as a group) if the whales are within the sonar beam. Some types of echosounders, side-scan sonars, etc., operate well above 20–30 kHz, and would not be audible to baleen whales even if the whales were in the beams of these devices. *Odontocetes* are expected to hear sonar signals from most types of oceanographic sonars (with the exception of the highest frequency units operating above 160–180 kHz) if the animals are within the sonar beam. Pinnipeds are also expected to hear sonar signals at frequencies within their functional hearing range if the animals are within the sonar beam. Phocids and otariids would hear sonars operating at frequencies up to about 75 kHz and 35 kHz, respectively. Likewise, sirenians might hear sonars operating at frequencies up to ~45 kHz (if in the beam).

7.4 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).

7.5 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.

7.6 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 μPa^2·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 μPa^2·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 μPa^2· s). The corresponding received energy level at 10 m range would be <204 dB re 1 μPa^2·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 μPa^2·s, as compared with ~195 dB 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. 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.

7.7 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.

7.8 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 B:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON SEA TURTLES[13]

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 SIO and L-DEO seismic surveys. Those documents concern SIO and L-DEO projects in the following areas: northern Gulf of Mexico, Eastern Tropical Pacific, Norwegian Sea, mid-Atlantic Ocean, southeast Caribbean, southeast Alaska, northeast Pacific Ocean, Eastern Tropical Pacific off Central America, southern Gulf of Mexico (Yucatán Peninsula), Aleutian Islands, Arctic Ocean, southwest Pacific Ocean, and Indian Ocean. 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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[13] 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) [14], 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 [15] 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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[14] 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).

[15] 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 C:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON FISH[16]

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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[16] By **John Christian, Bob Bocking, and Carl Schilt**, LGL Ltd., environmental research associates.

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 µPa·m$_{0-p}$). Received SPLs were estimated at 178 dB re 1 µPa$_{0-p}$. 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 μPa$_{0\text{-p}}$. 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$_{\text{rms}}$. 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$_{\text{rms}}$. Smaller fish showed a tendency to display startle response more often. “Responses” were observed above received SPLs of 156–161 dB re 1 μPa$_{\text{rms}}$. 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 μPa$_{0\text{-p}}$. 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-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-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 µPa$_{0\text{-}p}$, and at 178 dB re 1 µPa$_{0\text{-}p}$ 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 µPa$_{0\text{-}p}$. 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 µPa$_{0\text{-}p}$. 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 µPa$_{0\text{-}p}$. 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 D:

REVIEW OF POTENTIAL IMPACTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES[17]

This appendix is intended to provide a more detailed summary of the limited data and literature available on what is known about the potential effects of underwater sound on marine invertebrates. Specific conditions and results of the studies including sound exposure levels and sound thresholds of responses are discussed as available.

The large amounts of energy released by underwater seismic survey equipment results in energy pulses with very high peak pressures (Richardson et al. 1995). This was especially true when chemical explosives were used for underwater surveys. Virtually all underwater seismic surveying is now done with airguns with comparatively lower peak pressures. However, the shock waves that result from underwater gas discharges are still high enough to have the potential to injure or kill animals close to the source. Less overt than those effects are the disturbances to normal behaviors that animals in the vicinity of such discharges may experience.

The following sections provide an overview of sound production and detection in invertebrates, and available information on the effects of exposure to sound on marine invertebrates, with an emphasis on seismic survey sound. The information includes results of studies of varying degrees of scientific veracity as well as anecdotal information.

(a) Sound Production

Most available information on acoustic abilities as they relate to marine invertebrates pertains to crustaceans, specifically lobsters, crabs and shrimps. Fewer acoustic-related studies have been conducted on cephalopods. Many invertebrates are capable of producing sound; this includes barnacles, amphipods, shrimp, crabs, and lobsters (Au and Banks 1998; Tolstoganova 2002). Invertebrates typically produce sound by scraping or rubbing various parts of their bodies, although they also produce sound in other ways. Sounds made by marine invertebrates may be associated with territorial behavior, mating, courtship, and aggression. On the other hand, some of these sounds may be incidental and not have any biological relevance. Sounds produced by invertebrates can range from 87 Hz to 200 kHz, depending on the species.

Both male and female American lobsters produce a buzzing vibration with their carapace when grasped (Pye and Watson III 2004; Henninger and Watson III 2005). Larger lobsters vibrate more consistently than smaller lobsters, suggesting that sound production is involved with mating behavior. Sound production by other species of lobsters has also been studied. Among deep-sea lobsters, sound level was more variable at night than during the day, with the highest levels occurring at the lowest frequencies.

While feeding, king crab produce pulsed sounds that appear to stimulate movement by other crabs receiving the sounds, including approach behavior (Tolstoganova 2002). King crab also appeared to produce ‘discomfort’ sounds when environmental conditions were manipulated. These discomfort sounds differ from the feeding sounds in terms of frequency range and pulse duration.

Snapping shrimp (*Synalpheus parneomeris*) are among the major sources of biological sound in temperate and tropical shallow-water areas (Au and Banks 1998). By rapidly closing one of its frontal

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[17] By **John Christian, Bob Bocking, and Carl Schilt**, LGL Ltd., environmental research associates.

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 $\mu Pa_{0\text{-}p}$) 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 $\mu Pa_{0\text{-}p}$. 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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