Paper #2-9

OFFSHORE ENVIRONMENTAL MANAGEMENT OF SEISMIC AND OTHER GEOPHYSICAL EXPLORATION WORK

Prepared by the Offshore Operations Subgroup
of the
Operations & Environment Task Group

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Resource Development

Environmental Management of

Seismic and Other Geophysical Exploration Work

Findings of the

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EXECUTIVE SUMMARY

Geophysical exploration for offshore oil and gas resources relies heavily on seismic techniques in which sound waves penetrate through, and are reflected from, sub-surface geologic structures and rock units. For discovering, evaluating and producing offshore oil and gas, there are no realistic alternatives to seismic exploration although there are possibilities to further refine and improve specific seismic techniques.

Sound generated from offshore seismic exploration is acknowledged as a potential impact on marine mammals, including whales. The US is one of seven countries that have national laws or guidelines requiring mitigation measures be implemented during marine seismic surveys to reduce the potential impacts of seismic sources on marine life.

Mitigating impacts of seismic sound on marine life can involve attention to performance protocols as well as implementation of upgrades in specific equipment. In the US, the National Marine Fisheries Service (NMFS) and/or the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) require seismic operators to use ramp-up (or "soft start") and visual observation procedures when conducting seismic surveys. The "soft-start" procedure ramps up seismic activity slowly to warn marine animals of pending operations and to allow sufficient time for those animals to leave the immediate vicinity before auditory injury or physiological effects occur. Other requirements may be implemented by NMFS to place certain seasons and locations off-limits in recognition of vital marine animal activities such as breeding, calving, foraging or migration.

Considering the current state of seismic exploration technology, knowledge of marine mammal sensitivities and overlaps with regulatory purviews, it is found that:

- Scientific understanding of environmental conditions in sensitive environments in deep Gulf of Mexico waters, along the region's coastal habitats, and in areas proposed for more drilling, such as the Arctic, must be enhanced in order to meet the expectations of stakeholders.

- Seismic exploration methods will continue to be the key geophysical technologies required to discover, evaluate and enable production of offshore oil and gas resources. Non-seismic methods, although useful in complementary roles, will not supplant seismic methods.

- Seismic noise generated by offshore oil and gas exploration activities is recognized as a concern for whale populations and other marine life, including fish.

- The regulatory focus should be to set consistent, clear requirements for seismic permitting, based on best available science and acknowledging risk. E&P companies and regulators must work to ensure improvements are made with respect to risk mitigation and management.

- The US is one of at least seven nations that individually seek to minimize impacts on marine life through limits on seasons, locations and implementation procedures for performance of offshore seismic exploration. Those nations do not comprise a formal standards organization but ongoing dialogs and conferences could serve to encourage continuous improvements in sustainable offshore seismic practices.

- Additional technological refinements could supplement current mitigation methods during application of seismic exploration. Those additional considerations include design changes to reduce “unwanted noise” from airgun seismic sources and refining limited alternatives to airguns (e.g., marine vibrators or “vibroseis” seismic sources).

- Expanded use of joint industry programs is needed to advance sustainable seismic exploration technologies and to obtain regulatory recognition for the benefits of such efforts.

INTRODUCTION

A. Recognition of Sound as an Important Environmental Issue

There are increasing concerns about potential impacts from anthropogenic (human generated) sound on marine life. Sound is known to be important to marine mammals and fish for navigation, foraging, and social interactions and communications. Humans use sound in the oceans for a variety of reasons such as navigation, defense (sonar), scientific research and exploration for energy resources. Further, over the last three decades noise generated by offshore exploration and production activities, particularly seismic acquisition noise has been of increasing concern for marine life. This concern has resulted in research on the impacts of seismic on marine life and investigation of mitigation measures to minimize potential harm.

In the oceans, sound is generated by a variety of natural and anthropogenic sources. Examples of natural sources include vocalization by marine life, wind and wave action, ice movements, and meteorological and oceanographic conditions. Examples of anthropogenic sources include vessels, pile driving, dredging, geophysical surveys, and subsea equipment. Oceanographic variables such as the geologic characteristics of the seafloor, the water depth, temperature, salinity and density differences can influence the propagation of sound as it travels through water.

The oil and natural gas industry is committed to ensuring that any potential impacts from its geophysical operations on the marine environment are as low as reasonably practicable, and shares the belief that the marine environment should be used in a sustainable and environmentally considerate manner. By implementing risk-based mitigation measures grounded in the best available science, geophysical operations can continue to provide the important information necessary for oil and gas exploration while minimizing potential impacts on marine life.

B. Oil & Gas Industry Use of Sound-Active Exploration

Offshore exploration for oil and gas resources employs sound-active methods, including sonar and seismic techniques. The suite of techniques used depends on location, depth and the characteristics of the resources being sought. To more fully inform discussions of sound-active exploration methods in the marine environment, this paper will address the following topics:

- A summary of geophysical data and technologies employed in hydrocarbon exploration in offshore North American waters.
- A description of the role of geophysical data and technologies throughout the exploration and production (E&P) lifecycle, with an emphasis on the role of active sounding in risk identification, risk mitigation, and efficient production of resources.
- A discussion regarding the potential impacts of geophysical data acquisition on marine fauna and the environment.

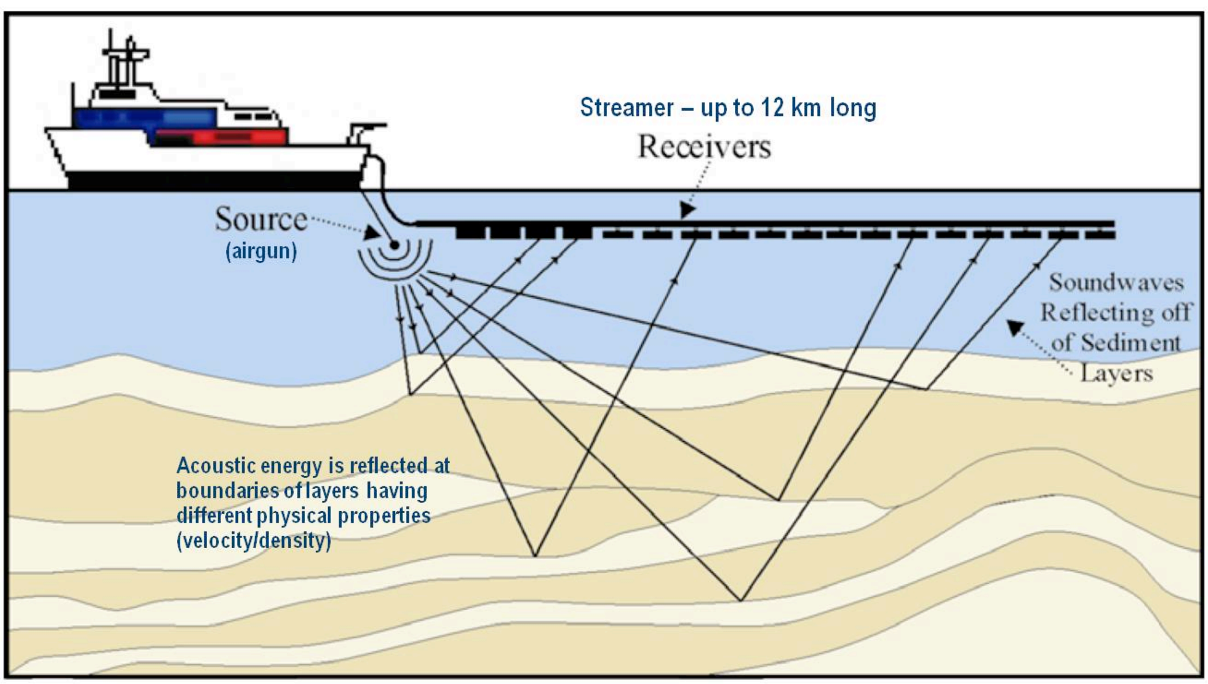
- A review of the current mitigation measures employed to minimize environmental impacts from geophysical data acquisition.
- Recommendations for future technology development in terms of focus, mitigation measures, research, and policy directions which have the potential to further reduce the environmental impact of geophysical data acquisition, while still allowing for responsible development of energy resources.

MARINE SEISMIC METHODS

A. Underlying Principles

The seismic reflection technique (commonly abbreviated as "seismic") used in most present-day geophysical data acquisition is analogous to ultra-sound used in hospital settings, and in much the same way the method is used to identify risks, monitor and manage activity. Seismic uses sound to generate images of the surface and subsurface. The sound wave is a short pulse of energy generated by a controlled source (typically an air-gun) towed behind a vessel. Sound waves propagate through the water and the solid earth encountering interfaces; these can be air-water, water-earth, boundaries between sub-surface strata, faults, and fluid contacts. At those interfaces the sound can be reflected, refracted, or partially transmitted to a deeper layer (Fig. 1). Reflected sound energy is detected by receivers, located either in a towed streamer or directly on the seafloor, and information is recorded for the elapsed travel time and strength of returning signals.

Figure 1. Schematic view of basic marine seismic acquisition principles (modified from Dellagiarino et al., 2005)



The solid earth acts like a filter for the propagating acoustic energy, and the goal of seismic processing and interpretation is to better understand those effects in order to generate an image of the subsurface and to predict the distribution of rock and fluid types. The raw seismic data are contaminated with noise (ocean swell, wind, mechanical noise from the vessel) and sophisticated signal-processing routines are applied to attenuate the interfering energy. The resultant data are further enhanced and repositioned in space and time to produce an image of the subsurface. The final product is delivered to geophysicists, geologists, and reservoir engineers who interpret the data to develop exploration strategies, make drilling decisions, or create field management plans.

Geophysical technologies have been a critical tool in hydrocarbon exploration since the early part of the 20th century. Prior to the mid-1980s, the majority of seismic data collected in offshore settings were two-dimensional (2D), meaning they defined a plane where the seismic-derived structure (depth of the plane) pertained to a single surface traverse (edge of the plane). Since that time, techniques to assemble three-dimensional (3D) seismic data were developed by integrating multiple 2D planes (as multiple surface traverses) into projection of a 3D volume. Currently, 3D seismic has become the standard tool for exploration and development, especially in the Gulf of Mexico. In an exploration context, seismic data are used to identify regions or geologic trends which have higher potential for commercial resources, with the ultimate goal being to reduce the amount of wildcat drilling necessary to successfully locate economic reserves. Once a prospect has been identified, seismic is a critical tool to identify potential drilling hazards. During the production phase, time-lapsed 3D seismic acquired over months or years (commonly called 4D seismic in recognition of the time dimension), can be a critical tool for understanding the effectiveness of the development strategy and allow for adjustments to maximize production from existing wellbores, potentially eliminating the need for additional drilling.

Geophysical technologies are also critical to the advance of Earth science. In the last several decades, efforts to understand the natural forces that shape and change our planet have accelerated rapidly, particularly in the field of marine geophysics, where researchers use advanced technology to probe deep beneath the oceans and observe Earth's interior. Here we have records of sea-level rise that are key to understanding global climate change, clues about fault behavior that lead to great tsunami-generating earthquakes, and structures that might contain new hydrocarbon resources (LDEO, 2006).

The following sections will briefly review the main types of seismic surveys currently used in both energy exploration and scientific research applications (summarized in Table 1). An additional review of current methods and principles is available from the International Association of Geophysical Contractors (IAGC, 2009) and the National Science Foundation (NSF) and US Geological Survey (USGS) Draft Programmatic Environmental Impact Statement (PEIS) for marine seismic research (NSF and USGS, 2010).

Table 1. Sound Characteristics of Seismic Surveys and Imaging Techniques (Weilgart, 2010). These values were developed during a workshop of industry representatives and biologists and may not represent actual, in situ seismic survey parameters. They should be considered only as estimated or indicative ranges.

Uses	Area Covered (typically)	Survey Time	Sound Intensity (dB re 1µpa)**	Power (Watts)*	Incidence (Shots / Day)	Peak Pressure (PSI)	Frequencies (Hz)
Shallow							
2D	100-5,000 miles	28 days-6 mos.	215-230 dB	150 - 270 KW	4,320 - 8,640	2,000	10-10,000 #
3D	9-1,000 sq. miles	2 mos.-1 year	240-255 dB	150 KW	4,320 - 8,640	2,000	10-10,000 #
4D	9 sq. miles	2 weeks-1 mo.	240-255 dB	150 KW	4,320 - 8,640	2,000	10-10,000 #
Deep							
Site Spec. Survey	60-600 miles	5 days-2 mos.	200-230 dB	1,500	17,280	2,000	10-10,000 #
2D	100-10,000 miles	28 days-1 year	215-230 dB	150-270 KW	4,320 - 8,640	2,000	10-10,000 #
3D (including WAZ)	9-25,000 sq. miles	2 mos.-3 years	240-255 dB	150 KW	4,320 - 8,640	2,000	10-10,000 #
4D	9-27 sq. miles	2 weeks-1 mo.	240-255 dB	150 KW	4,320 - 8,640	2,000	10-10,000 #
Shallow and Deep							
Refraction	Linear	1 day		270 KW	1,440	2,000	6 - 60
Bathymetry (@)	60-120 miles	varies	210 dB	100 - 2,000 KW	8,640 - 86,400	N/A	3,500 - 12,000
High Res		varies		500 KW	17,280	2,000	30 - 300
Sidescan Sonar	9-90 sq. miles	5 days- 2 weeks			1,440 - 7,200	N/A	50-600 kHz
Site Spec.Survey	60-120 miles	5 days- 2 weeks	200-230 dB	1,500 KW	17,280	2,000	10-10,000 #
Sub-Bottom Profile	60-120 miles	5 days- 2 weeks	200-230 dB		1,440 - 7,200	N/A	10-10,000 #
VSP	near well	1-2 days	200-230 dB		4,320 - 8,640	2,000	10-10,000 #

Note: several instruments are often used concurrently, such as bathymetry and high res for site surveys

* - note: actual units are total energy, Joule/square meter-Hz; one Joule = one Watt-second

** - note: an airgun signal is an energy signal (not power), therefore intensity @ 1 µPa makes more sense

- typically, the industry will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded, regardless of what is generated.

@ - time, area, and power values vary a lot for swath bathymetry surveys.

In deep water, power is high, pings are further spaced apart, swaths are wide, so more area is covered in a given time.

In shallow water, power is low, pings are frequent, swaths are narrow.

Table 1 is a broadly indicative set of estimates that generally summarize how seismic is used in its different applications. However, Table 1 does not capture the variations that are technique-, circumstance- and location-dependent. For example, the “Sound Intensity” values do not pertain to the entire “Area Covered” space. Sound intensity initially declines rapidly with distance from the acoustic source and the space between individual traverses largely is integrated through electronic signal processing of adjacent traverses. Therefore, actual distribution of acoustic energy in practice does not cover the entire area at the high source levels indicated in the “Sound Intensity” column. Appendix 2 provides a pictorial comparison of seismic airgun sounds with other anthropogenic and natural ocean sounds, including those made by marine mammals.

B. Towed Streamer Acquisition

Towed streamer acquisition consists of one or more marine vessels behind which are towed one or more streamers and seismic source arrays. The acquisition parameters (length, depth, separation, volume, data record length) depend on the objectives of each survey that, in turn, are functions of the geophysical requirements to correctly image the target.

2D Seismic. In 2D operations a single streamer is towed behind the survey vessel together with a single sound source. Typically, 2D surveys are conducted in frontier regions where no dataset exists and provide a sparsely sampled series of sub-surface images. Those images are used to identify play types and gross structural features, but are generally considered insufficient for detailed reservoir-scale evaluation. A 2D survey is almost exclusively used for exploration. Because of the 2D nature of the acquisition, energy from reflection interfaces outside the plane of the section cannot be properly processed and can interfere with the quality of resultant image.

3D Seismic. 3D seismic is acquired by towing a series of streamers behind a vessel with either one or two sound sources (Fig. 2). The streamers are separated in a pattern similar to prongs on a rake; the separation depends of the geophysical requirements of the survey but typically ranges from 50 to 150 meters. A survey area is defined that is large enough to image the area of interest, as well as halo of data around the target(s), which is necessary to properly process the data. The seismic vessel acquires the data in a lawn-mower pattern with adjacent lines, or in a race-track pattern that slowly works across the entire area until all the survey is complete (Fig. 3). A 3D survey can range in size from a few hundred square surface kilometers, taking a few weeks to acquire, up to ten thousand square surface kilometer surveys that can take many months. A completed 3D survey consists of a true three-dimensional volume of data which can be 'sliced' or viewed in whatever orientation is appropriate for the objectives of the interpreter.

Figure 2. Typical source and receiver geometry for a conventional towed streamer 3D survey (Shell, 2008). Although this configuration is specific to an Arctic Ocean application, it illustrates how towed arrays are used to generate three-dimensional analyses.

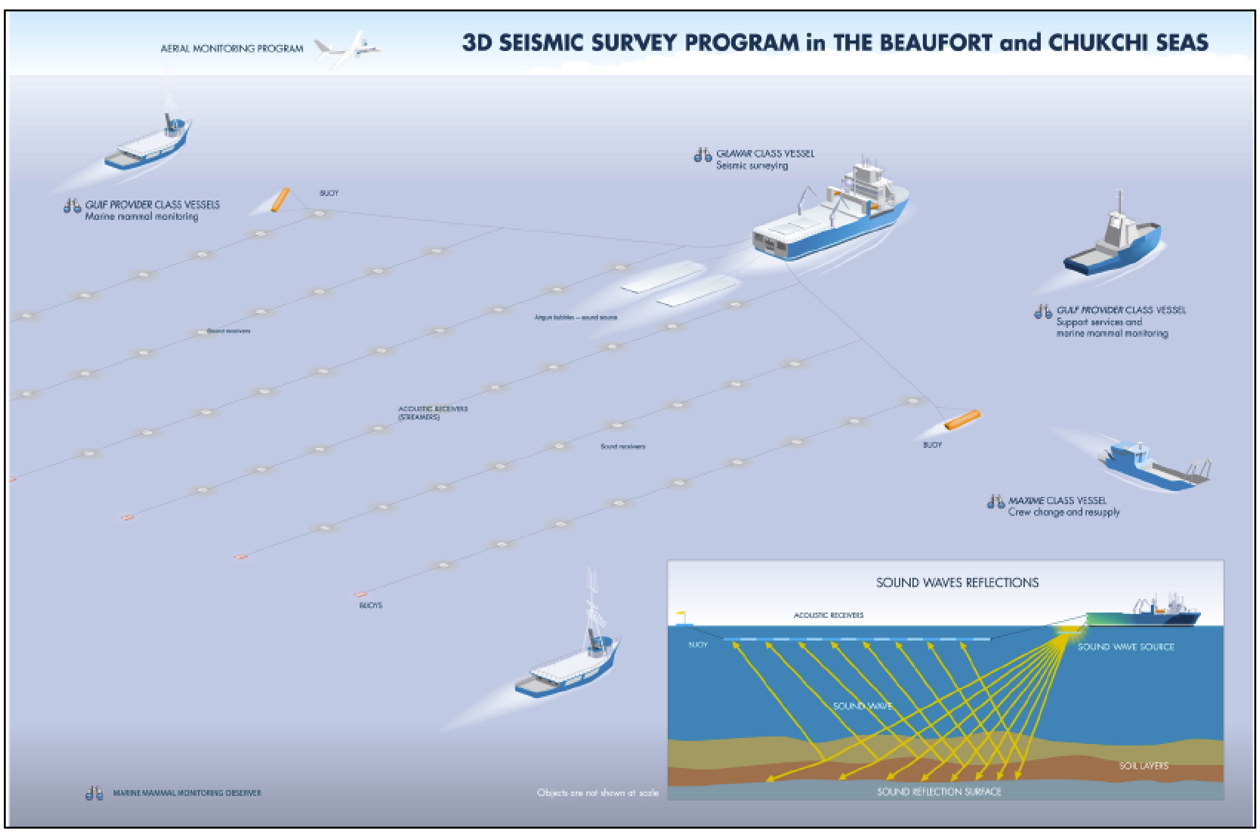
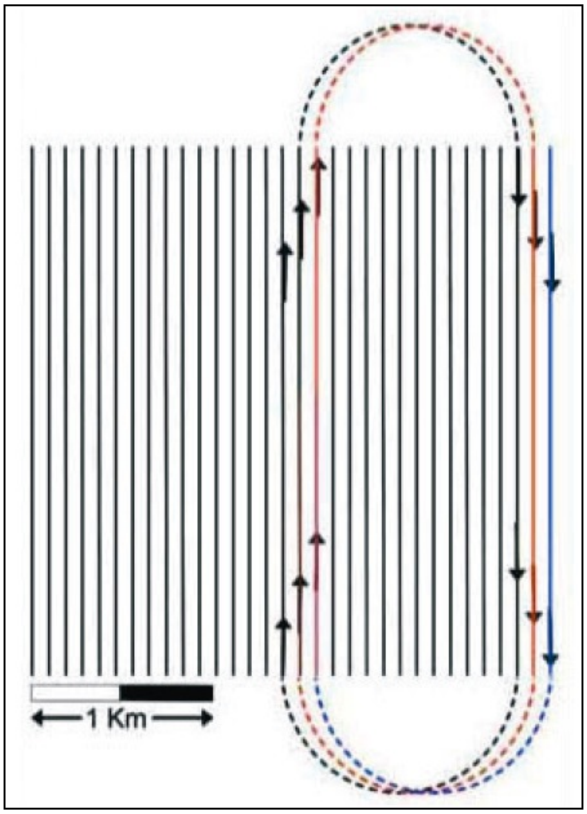


Figure 3. "Racetrack" pattern of 3D acquisition (IAGC, 2009).



Wide azimuth (WAZ) acquisition is a type of 3D acquisition utilizing multiple vessels towing a combination of source arrays and streamer spreads. The use of multiple, spatially separated source arrays and receivers allows for acoustic energy to image the subsurface target from multiple angles (azimuths). The concept is analogous to using multiple light sources to illuminate an object. This increased azimuth coverage improves the seismic images in areas of complex structure (Barley and Summers, 2007; Corcoran et al., 2007). As such, wide-azimuth acquisition has become the preferred method to image complex structures beneath salt in areas such as the Gulf of Mexico.

<u>Time Lapse (4D) Seismic</u>. The time-lapse, or 4D, seismic method involves acquisition, processing, and interpretation of repeated seismic surveys over a producing hydrocarbon field. The objective is to determine the changes occurring in the reservoir as a result of hydrocarbon production or injection of water or gas into the reservoir by comparing the repeated datasets. A typical final processing product is a time-lapse difference dataset (i.e., the seismic data from Survey 1 is subtracted from the data from Survey 2). The difference should be close to zero, except where changes to the reservoir have occurred due to fluid movements or compaction due to fluid withdrawal. The 4D method is not restricted to towed-streamer techniques although 4D offshore datasets commonly are collected using towed streamer or seafloor acquisition geometries. Depending on project objectives, logistics, and economics, survey iterations may recur at intervals ranging from 6 months to several years.

Sonar. Sound detection and ranging (“sonar”) is a special case of seismic that more commonly is associated with underwater military applications than with oil and gas exploration activities. Indeed, E&P uses sonar less often and almost exclusively for detection of underwater hazards that might pose risks for other E&P activities, including seismic exploration or drilling. Seismic and sonar both employ underwater wave energy but at different frequencies and intensities (Table 1).

C. Seafloor Acquisition

Receivers can also be deployed directly on the seafloor, as opposed to being located within a towed streamer. Seafloor acquisition is typically more costly than towed streamer acquisition because the process of deploying and recovering receivers requires more complex efforts but is generally used in shallow water or areas with numerous surface obstructions (e.g., platforms) where towed-streamer acquisition is difficult or impossible. Additional benefits of seafloor acquisition which can favor the use of these technologies in some situations include (1) the ability to measure shear wave data, and (2) the ability to accurately replicate receiver locations for 4D surveys.

Two general types of seafloor acquisition are currently in use: ocean bottom cable (OBC) and seafloor node. For both types, the acoustic source is towed behind a surface vessel like in towed streamer acquisition. In OBC acquisition, receivers are located inside cables up to several kilometers long which are deployed and recovered from a surface vessel. OBC surveys can either be 2D (single cable), or more commonly 3D (multiple cables). Seafloor node acquisition uses receivers which are placed directly on the seafloor, generally by ROVs. The nodes are typically recovered after acquisition, although ‘permanent’ node installations have been tested. Unlike OBC surveys where the receiver spacing and acquisition geometry is controlled by cable deployment, seafloor nodes can be deployed in whatever spacing and geometry provides for optimal subsurface imaging characteristics. Node surveys are also practical in deep water settings, unlike OBC surveys.

D. Borehole Acquisition

Geophysical data acquired at a well location, either a vertical seismic profile (VSP) or checkshot survey, are used to provide a better tie between conventional seismic data and the well, and also to provide detailed information about the geology and reservoir characteristics in the vicinity of the borehole. Seismic receivers are lowered into the borehole as part of a wireline assembly and the acoustic source is located in the water column at or near the well location. There are five main classes of borehole geophysical data: (1) check-shot survey, (2) zero-offset VSP, (3) walkaway VSP, (4) 3D VSP, and (5) cross-well seismic (or electromagnetic) data. For check-shot and zero-offset VSP data, the source is located at the drill site, with the difference being greater vertical sampling for a zero-offset survey. For more detailed subsurface information, the source is towed away from the wellsite to provide greater offset between source and receiver. In a 3D VSP, the source is towed in a 3D grid around the well, while for a walkaway VSP the source is towed in one or more 2D traverses. In cross-well acquisition, the source and receivers are located in nearby wellbores, with the goal to produce an image of the subsurface between well locations.

E. Seismic Energy Sources

The goal of the seismic source is to create a sound wave that can travel through the water and sub-surface to reach the target with enough return energy to be recorded at the surface. Ideally the source should be repeatable, reliable, with a high signal to noise ratio and high resolution.

In the early years of offshore seismic exploration a single explosive charge (dynamite) was the most commonly used source of seismic energy. The use of explosives became intolerable as they risked worker safety and could obviously damage reefs and kill marine life. Subsequently many types of marine seismic sources were developed and used, some more successfully than others, including the airgun, sparker, boomer, maxi-pulse, gas-gun, water-gun, flexitor, detonating cord, steam-gun, flexichoc, and marine vibroseis (Evans, 1997).

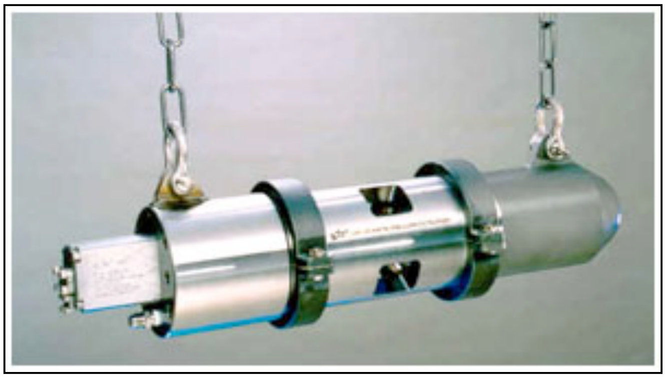
Presented here is a review of current technology and how it is deployed in the field. Seismic surveys typically target reservoirs many thousands of feet beneath the surface of the solid earth and it is important to deploy a source that can generate enough energy to fully image the target. Energy is lost as the sound wave propagates through the Earth. The high-frequency component of the signal attenuates more rapidly, leading to generally decreasing resolution with depth. The choice of seismic source(s) for a specific survey should be based on the objectives of the survey.

Airgun. The marine airgun (Figure 3) is the most widely used energy source for offshore seismic exploration. Airguns produce high levels of predominantly low frequency sound by releasing controlled volumes of high pressure air into the water creating an oscillating bubble which produces 90 per cent of its energy in the band 70 to 140 Hz (Wyatt, 2008).

To increase the power and focus the low frequencies downward, individual airguns are deployed as an array that is towed behind a vessel. The volume, spatial distribution, and tow depth of the air-gun array will define the energy / frequency distribution. The objective when designing an airgun array is to focus most of the energy downwards towards the target. The energy propagates in three dimensions as a series of lobes defined by the array geometry, tow depth, and interaction of each array element. The seismic source utilizes the air-water interface to reflect the wave-front downwards thus improving the overall efficiency.

Sparker. A seismic spark-gap source, or "sparker", generates an acoustic pulse by discharging an electrical current between electrodes, using the sparker body as ground and seawater as the conductor. Sparker acoustic pulses are more nearly continuous than are the intermittent-by-design airgun pulses. Sparker sources were adapted from onshore equivalents and have been used in marine applications since the 1970s before airguns became more widely established. Sparkers are most commonly used for shallow subsurface imaging, such as in shallow hazard surveys or scientific research studies (NSF and USGS, 2010).

Figure 3. Marine seismic-acoustic airgun suspended on tow chains (SeaSCAN, 2010). The gun uses pressurized air to drive a piston from right to left to generate sound waves that exit the left end of the device. The overall length of the gun is about three feet.



Alternate Marine Seismic Sources. Two reports have been produced on acoustic and non-acoustic alternatives to existing seismic sources (Spence et al., 2007; Weilgart, 2010), with the aim of identifying technologies that can reduce environmental impacts. Much hope has been placed on the development of marine vibrator technology which the offshore industry developed from the land equivalent. Initial development started in the 1970s and continued into the 1980s. Those initial efforts were eventually abandoned due to engineering obstacles and cost constraints when compared to airguns. Early field tests noted reduced data quality at deep (> 3 seconds two-way travel time) target depths due to limitations in the low-frequency portion of the source spectrum (Haldorsen et al., 1985). In recent years several companies and an industry consortium have taken up the challenge once more in an attempt to produce an alternate marine seismic source that can be tuned to specific geophysical objectives and reduce unwanted noise. Initial results of those efforts have resulted in prototype marine vibrators capable of energy output down to 6 Hz (Weilgart, 2010).

The marine vibrator consists of an acoustic housing (analogous to a speaker) containing either a hydraulically or electrically driven oscillator. The oscillator is driven at various frequencies (sweep) causing expansion and contraction of the housing that generates sound waves. The advantage of this technology is two-fold: (1) controllable frequency range, and (2) coding of the sound waves (phase) that could allow for simultaneous acquisition (multiple sources). Target applications of marine vibrators currently in development include shallow water acquisition, seismic monitoring, and environmentally sensitive areas (Weilgart, 2010). Other technological alternatives discussed by the two reports (Spence et al., 2007; Weilgart, 2010) include deep-towed acoustic/geophysics system (DTAGS) and low-frequency acoustic source (LACS) and the non-acoustic systems surveyed below.

NON-SEISMIC METHODS

Non-active acoustic geophysical methods employed in hydrocarbon exploration include (1) controlled-source electromagnetic (CSEM), (2) marine magnetotelluric (MMT), (3) gravity, (4) magnetic, and (5) passive acoustic surveys. Each of these methods has specific exploration applications, but currently they are most often used as complementary technologies to seismic.

Controlled-Source Electromagnetics (CSEM). Reviews of the history, development, and applications of CSEM can be found in Constable (2010), Constable and Srnka (2007), and Edwards (2005). CSEM surveys measure resistivity contrasts in the subsurface in response to an induced electrical field. Electrical receivers, attached to standard or degradable concrete anchors, are deployed on the seafloor. The number of receivers employed will vary from one project to another, depending on imaging objectives and budgetary constraints. An electrical dipole transmitter, deployed from a surface vessel, is towed at a distance of between 10-100 meters above the seafloor. After data acquisition, the receivers are remotely released from their anchors and rise back to the surface where they are retrieved by the survey vessel.

Because hydrocarbon-charged sediments have higher electric resistivity than those filled with saline formation waters, CSEM surveys have the potential to aid in the identification of subsurface oil and gas accumulations. Resistivity measurements are used extensively in wireline logging applications for the identification of reservoir intervals in boreholes, but CSEM surveys allow for the collection of resistivity measurements on a much larger scale and thus can be appropriate in an exploration context. Several published examples in recent years have illustrated the potential of the technology, when combined with other types of data, to reduce uncertainty ahead of drilling (e.g., Lovatini et al., 2009; Hesthammer et al., 2008). The technique, however, does have several important limitations. The presence of other large, highly-resistive bodies, such as salt diapirs/sheets or volcanic layers, can mask the response from hydrocarbon-filled reservoirs. Additionally, CSEM surveys do not currently provide the degree of spatial resolution possible from modern seismic data (Constable, 2010). Finally, because of interference caused by the strong resistivity contrast at the air/water interface, CSEM surveys are generally more effective in water depths over 500 meters, although careful processing of the data can often mitigate this issue (Constable and Srnka, 2007; Hesthammer et al., 2010).

Marine Magnetotellurics (MMT). Like CSEM surveys, MMT surveys attempt to measure the resistivity structure of the subsurface, but use naturally occurring electrical currents induced by variations in the Earth's magnetic field instead of a towed source (Constable et al., 1998; Sandberg et al., 2008). MMT surveys employ the same type of receivers used for CSEM surveys, but because of the weaker (and variable) nature of the natural source, the receivers are typically left on the seafloor for up to several days (Hoversten et al., 2000). Because of the poor vertical and lateral resolution of the data (e.g., Hoversten, et al., 1998), MMT surveys are not used to directly identify potential hydrocarbon traps or accumulations, but have shown to be useful in delineating the extent of large resistive bodies such as salt sheets or diapirs. In areas of poor subsalt seismic data quality, MMT data have shown promise in helping (generally in conjunction with gravity data) to constrain the location of the base of salt which can result in improvement of the subsalt seismic image (Hoversten et al., 1998; Sandberg et al., 2008).

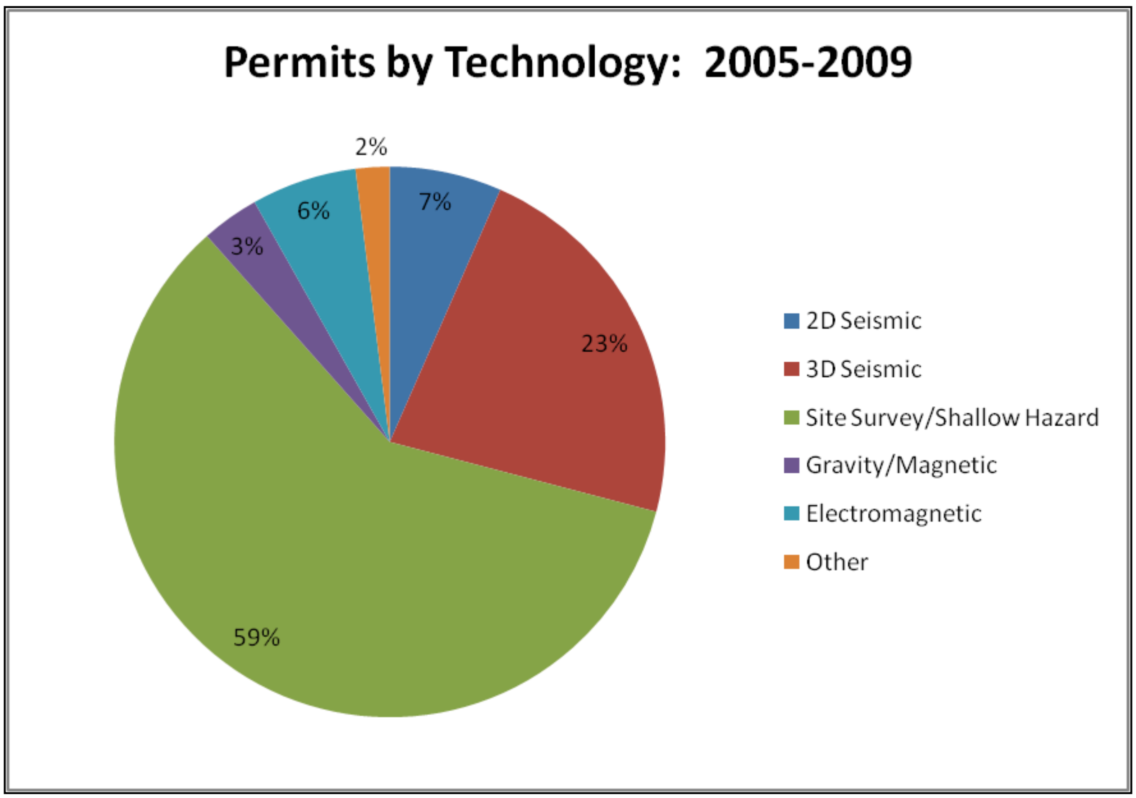
Gravity & Magnetic. Reviews of the history and use of gravity and magnetic surveys in petroleum exploration may be found in Nabighian et al. (2005a,b), respectively. Neither method provides the vertical or lateral resolution necessary to identify or map potential hydrocarbon accumulations directly, but both methods can provide valuable information regarding the distribution of salt and the configuration of deep basin structural elements. As such, they often times play an important role in developing regional-scale basin models which can help focus exploration efforts, particularly in frontier or under-explored basins. Gravity data, in conjunction with seismic data, also are used to help constrain resistivity models in MMT surveys in a process known as simultaneous joint inversion (Virgilio et al., 2010).

Passive Acoustic Seismic. Seismic exploration as discussed above is an active-acoustic approach in which seismic waves are artificially generated as the source of the sounding analysis. But the technologies used for active seismic exploration are relevant to passive monitoring, except there is no propagation of sound emanating from the Passive Acoustic Seismic devices. The Passive Acoustic Seismic approach consists of seismic-type detectors that listen for naturally occurring seismic or other acoustic energy (Nieukirk et al., 2004). Natural geologic processes that generate subsea seismic waves include volcanic eruptions, earthquakes and underwater landslides although the most typical context for Passive Acoustic Seismic pertains to listening for vocalizations of marine fauna, including whales. The latter application, which is used most often for detection of marine mammals (IAGC, 2009), normally is called Passive Acoustic Monitoring (PAM).

CURRENT APPLICATIONS OF TECHNOLOGY IN OCS PLANNING AREAS

Geologic objectives, operational conditions, infrastructure, accessibility, and the historical knowledge base vary considerably across offshore areas of the Gulf of Mexico or Arctic OCS. Because of those factors, the types of geophysical technologies applied in these areas vary as well. Conventional seismic, comprising deep-penetrating surveys (2D/3D/4D), comprise about one-fourth of the geophysical surveys permitted for OCS areas (Fig. 5). High-resolution, shallow-penetrating surveys, which can include a seismic component along with gravity, magnetic, electromagnetic and other techniques, comprise the remainder.

Figure 5. Distribution of primary technology for all OCS geophysical permits approved 2005-2009. Other includes borehole (VSP) acquisition and permits for testing of equipment or acquisition technologies (data queried from the BOEMRE (2011) online database)



Gulf of Mexico. As reflected by trends in leasing, drilling, and production activities over the last 15-20 years, exploration in the Gulf of Mexico (GOM) has increasingly been focused on deepwater settings (water depth >1,000 ft) (Nixon et al., 2009). Much of the deepwater GOM is characterized by the presence of an extensive canopy of allochthonous salt up to 20,000 ft (6,100 meters) thick (e.g., Diegel et al., 1995). Over the past 5-10 years, a significant portion of the activity in deepwater has focused on exploration beneath this salt canopy, with drilling targets up to 35,000 feet (10,600 meters) below sea level. Exploration and development beneath the salt canopy presents a wide range of technical challenges (e.g., Barley and Summers, 2007), including seismic imaging through salt. Advances in seismic acquisition and processing technologies in recent years, most recently wide-azimuth (WAZ) 3D acquisition, have led to improved subsalt seismic imaging capability (e.g., Barley and Summers, 2007), but this remains a significant challenge and large parts of the subsurface beneath the canopy system have yet to be imaged adequately to address both exploration potential and risks. Although a number of potentially large discoveries have been made beneath salt in recent years (Nixon et al., 2009), a detailed understanding of reservoir distribution and characteristics is critical to the successful development of those fields.

Arctic. In contrast to the GOM where nearly 50,000 wells have been drilled in Federal waters, there has been relatively limited exploration activity in the offshore US and Canadian Arctic (Chukchi and Beaufort Seas). Drilling activity began in the 1970s and 1980s in shallow waters of the Canadian Beaufort Sea, followed by activity in the US Beaufort in the 1980s and 1990s. A small number of wells were drilled in the Chukchi Sea in the early 1990s. The majority of seismic data collected in Arctic waters has been 2D, although several 3D surveys have been acquired over individual prospect areas, with several somewhat larger 3D surveys acquired in deeper waters of the Canadian Beaufort Sea. Although the Arctic does not have the extensive salt canopy which complicates seismic imaging in the GOM, the harsh environmental conditions and limited open water season significantly complicate seismic acquisition activities.

ENVIRONMENTAL IMPACTS OF SEISMIC SURVEYS

To gain a better understanding of whether an anthropogenic sound source has an effect on a marine animal it is necessary, at minimum, to have a scientific understanding of the characteristics of the sound source, the propagation of the sound through the water, the auditory sensitivities of the animals, the biological significance of any impacts, and the cumulative effects. Certainly, this is a complex topic to address and requires a large amount of scientific and technical data.

The scientific understanding of the potential impacts of anthropogenic sound has expanded significantly in the last two decades as the issue has gained public attention and research prioritization, but important gaps in knowledge still exist. Potential impacts include behavioral changes, masking, auditory injury, physical injury, and stranding and other indirect effects. (For comprehensive reviews of the available scientific information on potential impacts of geophysical surveys on marine life refer to NRC (2003, 2005), Abgrall et al. (2008), DFO (2004), Southall et al. (2009), Marine Mammal Commission (2007), Weilgart (2007), and Richardson et al. (1995).

Masking. Simultaneous masking can occur when a sound of interest is made inaudible by noise or an unwanted sound. In general, low-frequency sounds travel more efficiently through seawater than they do through air (NRC, 2003). Although seismic arrays are oriented vertically towards the seafloor, seismic energy can propagate horizontally, also. A multi-year study of whale vocalizations and other low-frequency sounds off the Mid-Atlantic Ridge, using highly sensitive acoustic receivers, routinely detect sound from seismic exploration activities taking place more than 3000 kilometers away at levels above ambient (Nieukirk et al. 2004).

Seismic sources are classified as low-frequency (predominantly 10-200 Hz) "intermittent" sources of sound because they are activated once every 10-12 seconds in the course of a survey (Southall et al. 2007). Due to the intermittent nature of seismic pulses, significant effects from masking for filter-feeding whales is considered unlikely as a general condition (Abgrall et al. 2008). Sounds from airguns have a frequency bandwidth of about 10-25,000 Hz (when less than 50 meters from source) that changes at longer distances (500-3,000 meters) to very low frequencies of 10 Hz or less). In principle, because one airgun pulse might not fully decay before the next pulse, a near-continuous sound is possible at low frequencies in some seismic applications (Weilgart, 2010; IWC Scientific Committee, 2004; Clark et al. 2009a). That prolongation of the signal, especially when combined with other sound sources (e.g. shipping), has the potential to "mask" low-frequency animal vocalizations, such as feeding and breeding calls (Clark et al. 2009b), .Under unfavorable circumstances, it might be difficult for animals to detect biologically relevant sounds or to distinguish the contribution from each sound source at a particular location. Regardless, more research is needed to quantify the prevalence of that effect.

Behavioral Impacts. The low frequencies that dominate the acoustic energy produced by airguns coincide with frequencies used by baleen whales for foraging, breeding, and other biologically essential activities (Clark et al. 2009a; Weilgart, 2010), raising concerns about the potential for impacts on baleen whale perception and behavior (e.g., NRC, 2003).

Marine mammals' behavioral reactions to sound can depend on species, individual maturity, experience, the pertinent life function activity (feeding, breeding, etc.), time of day, and other factors. Bowhead whales are known to alter their migration paths through the Beaufort Sea, creating an avoidance zone that can run tens of kilometers from a seismic array, depending in part on when the survey occurs during the migration season (Richardson et al., 1999). Bowhead whales were also found to tolerate an increase of 40 dB in seismic survey noise when feeding in the summer (Richardson at al., 1995). Blue whales, for example, have been observed to alter their calling rate on exposure to relatively low levels of anthropogenic sound (e.g., sparker noise from shallow sub-bottom profiling); with a 131 dB re 1 μPa mean peak-to-peak pressure level and 114 dB re 1 μPa^2 mean sound exposure level within the relevant frequency band); but whether this behavior compensates to any meaningful degree for acoustic masking, and whether it exacts energetic and other costs of its own, remains unclear (Di Iorio and Clark, 2009).

Studies have demonstrated that seismic surveys can affect toothed whales, dolphins, and porpoises, which are generally thought to have greatest hearing sensitivity in the mid- and high frequencies (NRC, 2003; Richardson et al., 1995). Harbor porpoises, whose sensitivity to various types of sound is well documented (e.g., Olesiuk et al. 2002; Kastelein et al., 2005, 2006), have appeared to exhibit the strongest displacement, with avoidance seen over seventy kilometers from an array (Bain and Williams, 2006). No direct data are available for beaked whales, a large family of species for which concerns have been raised in connection with naval mid-frequency sonar sources (Cox et al. 2006; Fernandez et al., 2005); but they have been shown to respond behaviorally to predominantly low-frequency broadband noise at relatively low levels (Soto et al., 2006). Numerous other studies have found that marine mammals at distances more than a few kilometers from operating seismic vessels often show no apparent response (refer to literature cited in Haley et al., 2010). Although various baleen whales, toothed whales, and (less frequently) pinnipeds have been shown to react behaviorally to airgun pulses under some conditions, at other times mammals of all three types have shown no overt reactions. In general, pinnipeds and sea otters seem to be more tolerant of exposure to airgun pulses than are baleen whales (Haley et al., 2010).

In the Gulf of Mexico, sperm whales have been a topic of concern, due to the small size of the Gulf population, exposure to seismic surveys and other industrial noise, and their primary use of deep-water habitat off Louisiana that is targeted for further oil and gas development. Results from studies of northern Gulf of Mexico sperm whale responses to seismic exploration indicate that sperm whales do not appear to exhibit horizontal avoidance of seismic survey activities, but that there may be a decrease in foraging effort during exposure to seismic sources at the study's target levels approaching and above 140 decibels (dB). The researchers concluded that the study's sample size (8 focal follows) was insufficient to generate statistically definitive results; but they interpreted the data as indicating that the foraging behavior of sperm whales might be affected at exposure levels well below those currently used by the National Marine Fisheries Service to predict disruption of behavior (Miller et al., 2009; Jochens et al., 2008).

Auditory and Physical Impacts. In close proximity to the source, seismic pulses have the potential to cause temporary and permanent hearing loss or "threshold shift" – long considered a serious impact given the importance of hearing to marine mammal ecology (NRC, 2003) – and other forms of injury given their sharp rise times and high peak pressures. Initial criteria for temporary and permanent threshold shift have been identified for pulsed sounds based primarily on tests on bottlenose dolphins and beluga whales (Southall et al., 2007). Using those criteria, immediate permanent hearing damage (i.e., acute permanent threshold shift) is unlikely to occur because of exposure to seismic operations. A recent study indicates that pulses from a seismic source induces temporary hearing loss in harbor porpoises at significantly lower levels than in the species previously tested (Lucke et al., 2009) but it remains uncertain how to extrapolate those results into general avoidance criteria. Additional uncertainties persist about the degree of temporary threshold shift necessary to cause permanent loss of hearing (e.g., Kastak et al., 2008; Kujawa and Liberman, 2009).

Strandings, whether induced by injury or behavioral responses to the sound source, constitute another potential source of injury and mortality. Although some researchers have hypothesized that seismic can cause strandings (Hildebrand, 2005; IWC Scientific Committee, 2009), to date no conclusive pathological evidence, such as has been seen in beaked whales stranded after exposure to mid-frequency active sonar (Cox et al., 2006; Fernandez et al., 2005), has been found with respect to seismic. In the case of a mass stranding off Madagascar, results are still awaiting scientific review by an independent panel (IWC Scientific Committee, 2009).

Stress. The study of noise-related stress and marine mammals is in its infancy although a number of studies have expressed concern over long-term stress effects from noise exposure (e.g., NRC 2003; Slabbekoorn et al., 2010; Wright and Highfill, 2007). Initial research on beluga whales and dolphins indicated possible biological stress markers (changes in two blood-borne enzymes) after noise exposure (Romano et al., 2004). Other research suggested an interaction between noise and lipophilic contaminants (chemicals that tend to concentrate in body fat) as an additional source of stress on cetaceans (Martineau, 2007). It is possible that anthropogenic noise, by itself or in combination with other factors, can adversely affect the vital rates of individual marine mammals and decrease the viability of some marine mammal populations (Wright et al., 2007) but additional research is needed to determine the biological significance of noise with respect to stress.

Cumulative and Population-Level Impacts. It is always difficult to assess the cumulative, long-term impacts of any particular stressor on wild populations of marine animals (NRC, 2003; Wright, 2009). Currently, there is no single mechanism agreed among scientists for addressing cumulative effects. For noise, the recent literature has devised alternative bottom-up and top-down approaches. The bottom-up model translates acute, short-term behavioral responses into effects on life functions which if large enough could lead to impacts on vital rates, survival and reproduction of marine mammal stocks in individuals and ultimately to impacts on the population, referred to as the Population Consequences of Acoustic Disturbance framework (NRC, 2005). The top-down, ecosystem-based model, considers the distribution and intensity of exposures, the density of species, and a score representing the relative vulnerability of animals to “map” cumulative stress on marine habitat (Wright, 2009; see also Halpern et al., 2008). Some researchers have, in the case of one or two small, coastal (and thus more easily studied) populations with limited ranges, linked disturbance from whale-watching with population-level outcomes (e.g., Bejder et al., 2006; Lusseau, 2004, 2005; Lusseau et al., 2006) based on the bottom-up model approach. One study has suggested seismic surveys off the Brazilian coast may have resulted in population impacts, i.e., a loss in marine mammal biodiversity (Parente et al., 2007); however, most studies to date have not included a thorough investigation of other/all ecological factors that could have been attributed to the same findings. Recent work on baleen whales focused on masking as a mechanism for potential population-level impacts.

Effects on individual and population vital rates have not been modeled, but the researchers noted the potential for population impacts given the scale and degree of the modeled effect and the conservation status of the whales (Clark et al., 2009a,b; see also Clark and Gagnon, 2006). Of the three species considered, right whales, which are critically endangered in the North Atlantic and North Pacific, appear most susceptible to the masking impacts from shipping and airgun noise, due to their acoustic ecology and the particular sound characteristics of their calls (Clark et al., 2009a,b). Additionally, the Clark et al. (2009b) study is premised on the assumption that these animals use only a signal-to-noise ratio (engineering approach) to communicate. However, the communication process could be more complex and therefore additional research is needed.

Effects on Fish. Like marine mammals, fish use sound for communication, homing, and other important purposes, and, like marine mammals, they can experience temporary or permanent hearing loss on exposure to intense sound (Popper, 2003). There are two primary but distinct issues with regard to fish and seismic surveys. One is the potential for a seismic source to affect fish physically, auditorily, or behaviorally, which in turn could create a significant biological impact. The other issue is commercial in nature, meaning the potential for seismic surveys to impact the catch rate for fishermen.

Fish species tend to divide into two classes of auditory ability, the "specialists," which have acute sensitivity in the low frequencies, and the "generalists," which have lower acoustic sensitivity overall. Specialists appear from several studies to be appreciably more susceptible to hearing loss (Popper et al., 2005; Scholik and Yan 2002a,b). The loss proved permanent and irrecoverable in one airgun study (McCauley et al., 2003), though not in others (Popper et al., 2005), indicating significant variability among fish species. Some laboratory-scale experiments have shown that airguns can cause significant injury and mortality of fish eggs and larvae, at distances ranging up to five meters (Booman et al., 1996; Kostyuchenko, 1973). A Norwegian study found that, when put into a volumetric context, seismic operations would have an effect on the studied fish populations due to damage to eggs and larvae, but not a lingering one (Booman et al. 1996). However, an unresolved question is whether and how the caged-fish conditions used in some of the experiments can be generalized to ocean conditions. Also, the experiments conducted on "specialist" species have not been demonstrated equally on "generalist" species and have not been controlled for consistent sound fields across experiments (Edds-Walton and Finneran, 2006).

Commercial fishermen have complained about declining catch rates during some seismic survey operations (McCauley et al., 2000a,b), spurring a number of experiments that compare fishing success at various distances from the source. Airguns have been demonstrated in Norwegian studies to dramatically depress catch rates of cod and haddock by 40 to 80 percent (depending on catch method) over thousands of square kilometers around a single array (Engås et al., 1996; Løkkeborg, 1991); and a subsequent study indicates both horizontal (spatial range) and vertical (depth) displacement of two other commercial species, blue whiting and Norwegian spring spawning herring, on a similar spatial scale (Slotte et al., 2004). Those impacts were found to last for some time beyond the survey period (Engås et al., 1996) but their exact durations are not clear. Airguns also have been shown to substantially reduce catch rates of rockfish, at least to the distances (less than 5 km) observed in the experiment (Skalski et al., 1992). The Norwegian Institute of Marine Research (Løkkeborg et al., 2010) noted that gillnet catches of Greenland halibut and redfish were higher during and after seismic than before, that line catches of Greenland halibut declined during the survey but rebounded within 25 days afterwards, and that pollock catches showed a declining trend during and after the seismic, although the variations were statistically significant only in near-shore areas where the fish was most abundant. In summary, seismic-associated reductions in catch rates seem to depend on species and fishing methods.

Summary of Current Knowledge. Based on the best available scientific information, the risk of a marine animal experiencing direct, immediate, and permanent physical or auditory injury from a seismic survey is extremely low (Hannay et al., 2010, Southall et al., 2007). An animal would need to be in extreme close proximity to the seismic source array in order to experience such injury (DFO, 2004). Because both the source and animals are moving, and because many animals naturally avoid the source to begin with, the risk is relatively low for an animal being close enough to the source to experience a physical injury or permanent auditory impact.

Therefore, scientists are primarily concerned with potential impacts from seismic sources which might result in a behavioral change that has a biologically significant impact on a marine animal or animal population. As noted in National Research Council reports (NRC, 2000, 2005), "It does not make sense to regulate minor changes in behavior having no adverse impact; rather, regulations must focus on significant disruption of behaviors critical to survival and reproduction." For example, an impact from an activity might be biologically significant if it results in the displacement of breeding, feeding or nursing marine mammals or dispersion of spawning aggregations of fish in their spawning areas. As recently as 2005, the NRC concluded "no scientific studies have conclusively demonstrated a link between exposure to sound and adverse effects on a marine mammal population" (NRC, 2005). Scientific research is underway to investigate if there are links between observed short-term responses of individuals to sound and ultimately impacts to survival and reproduction of a marine animal population.

MITIGATING POTENTIAL IMPACTS OF SEISMIC SURVEYS

A. Mitigation and Monitoring Methods

Current Practice. Seven countries[1] (including the US) have national laws or guidelines which require mitigation measures to be implemented during marine seismic surveys to reduce the potential impacts of seismic sources on marine life (Tsoflias and Gill, 2008; Weir and Dolman, 2007). The seven nations do not comprise a formal organization and do not issue international standards. Instead, some nations maintain awareness of the activities and practices of their peers and experiences are sometimes shared informally through dialogs and conferences. With further dialogue, the overall effect could be to encourage continuous improvements in environmentally-sustainable offshore seismic practices among the nations as a whole.

In the US, mitigation measures for the Gulf of Mexico are described in the *Implementation of Seismic Survey Mitigation Measures and Protected Species Observer Program* Notice to Lessees and Operators (MMS, 2007). Mitigation measures for seismic surveys conducted offshore Alaska are determined on a survey-by-survey basis and are contained in the Incidental Harassment Authorizations (IHA) issued to operators by the National Marine Fisheries Service (NMFS) under the MMPA.

During seismic operations, a primary mitigation is the animals' natural avoidance of the fully operational sound source. In the US and in most of the other countries[1] which have laws or

[1] Australia (DEWHA, 2008), Brazil (IBAMA, 2005), Canada (DFO, 2004), Ireland (DEHLG, 2007), New Zealand (DOC, 2006), United Kingdom (JNCC, 2010), United States Gulf of Mexico (MMS, 2007)

guidelines, the two most commonly used mitigation measures involve (1) visually observing a "monitoring zone" around the array and temporarily suspending seismic activities when a protected species is detected within the zone; and (2) gradually increasing the emitted sound level from the seismic array (called soft-start or ramp-up) before a survey begins or resumes after a period of silence. The intent of a soft-start procedure is to warn marine animals of pending seismic operations and to allow sufficient time for those animals to leave the immediate vicinity. Under normal conditions, it is assumed that cetaceans will find the source sound aversive and will move away before auditory injury or physiological effects occur (Richardson et al., 1995).

Although the effectiveness of the current US mitigation measures have not yet been tested, the US regulatory agencies, BOEMRE and NMFS, have determined that to date those measures are appropriate based on environmental assessments and risk assessments and are minimizing potential impacts as intended; however, the agencies are in the course of considering alternatives as part of several programmatic regional reviews (see below). In 2009, Canada convened a workshop to examine the effectiveness of measures used to mitigate potential impacts of seismic sound on marine mammals; the 2010 Science Advisory Report produced by the workshop recommended that additional research was needed to determine the effectiveness of current mitigation measures (DFO, 2010). The BOEMRE, together with the International Association of Oil & Gas Producers (OGP) E&P Sound & Marine Life Joint Industry Project (JIP), is currently funding a large research study, the Australian Humpback Whale Behavioral Response Study (OGP, 2010) that includes testing the efficacy of the soft-start procedure. Also, BOEMRE has attempted to encourage the development and use of technologies like PAM in conditions where line-of-sight visibility is low. The goal of PAM systems is to detect and locate vocalizing animals even if they are not visible. If the necessary research is continued, future PAM techniques might also make possible classification or identification of vocalizing animals.

Seasonal and geographical restrictions have been implemented in some jurisdictions including Australia, Brazil, Canada, UK and US. Those types of closures can be associated with areas which are critical for marine animals breeding, calving, foraging or migrating. Other restrictions are used to limit potential impacts to sensitive areas such as marine national parks. As one example, Brazil created a 95,000 square kilometer exclusion area and buffer zone to minimize impacts on the Abrolhos Bank and its marine national park (Agardy et al., 2007). Another potentially effective measure involves limiting the amount of exploration activity that may occur over the course of a season within a biologically relevant area (Parsons et al., 2009). As a number of papers have observed, protected areas should ordinarily be identified during the planning stage based on biological and oceanographic factors, although surveys can be used in some cases to confirm marine mammal presence (Agardy et al., 2007; Dolman et al., 2009; Parsons et al., 2009). Avoiding important habitat and seasonal concentrations of marine mammals is widely considered the most effective currently available means of reducing impacts from a variety of sound sources (e.g., Agardy et al., 2007; NOAA, 2010; OSPAR, 2009; Parsons et al. 2009). Obviously avoidance as a mitigation tool cannot be utilized in certain circumstances so other mitigation measures are required.

Other mitigation measures include reduction of sound emitted from the sound source itself. To date, only the UK has attempted to include noise-reduction measures in its guideline, recommending that operators "seek methods to reduce and/or baffle unnecessary high-frequency noise produced by airguns" (JNCC, 2010).

Another form of sound-source reduction involves eliminating redundant surveys, particularly for off-lease surveys where large areas may be shot on exploratory speculation. Industry representatives have asserted that in some instances, multi-client surveys reduce the need for repeat surveys by licensing the data to several different companies, and that a certain number of repeat surveys may be necessary as technology improves and to meet the different demands of different clients.

<u>Future Mitigation and Monitoring Practice</u>. In the US and other jurisdictions, research is underway to develop additional mitigation and monitoring tools and to investigate the effectiveness of current mitigation measures. For example, in November 2009, the MMS (since replaced by BOEMRE) convened a workshop on "Status and Applications of Acoustic Mitigation and Monitoring Systems for Marine Mammals". The workshop topics included Passive Acoustic Monitoring, Active Acoustic Monitoring, Operational Considerations, Signal Processing and Metrics. Information from the workshop will be used to assist BOEMRE and NMFS in determining which mitigation and monitoring methods are most appropriate for different activities. The 2010 Canadian Science Advisory Report from the workshop on efficacy of mitigation measures during marine seismic operations recommended that additional research should be conducted to develop active acoustic monitoring technologies, passive acoustic monitoring technologies, and. standardization of data reporting formats. As mentioned previously, BOEMRE and the OGP Sound & Marine Life JIP are co-funding a large, multi-disciplinary research project which is investigating the behavioral responses of humpback whales to seismic sources and evaluating the effectiveness of soft-start procedure. Furthermore, extensive research is being conducted on Passive and Active Acoustic Monitoring for the detection of marine mammals in low-visibility conditions. Examples of research efforts include the 2010 National Oceanographic Partnership Program (NOPP) Marine Mammal Monitoring & Detection BAA (NOPP, 2010) and the OGP E&P Sound & Marine Life JIP (OGP, 2010). Therefore, in the near future, there will be available additional monitoring tools and scientific information for use in further reducing the potential environmental effects of seismic surveys.

Currently, NMFS is in the process of preparing a Draft Programmatic Environmental Impact Statement (PEIS) for geological and geophysical (G&G) activities in the Gulf of Mexico and announced it would start developing a Draft PEIS on the effects of oil and gas activities in the Arctic Ocean. In 2010, BOEMRE announced that it would begin developing a Draft PEIS for G&G exploration on the Mid- and South Atlantic OCS In the Federal Register notices announcing the development of those NEPA documents, BOEMRE and NMFS indicated that they will evaluate the available scientific information and consider a wider range of alternatives and mitigation measures than currently apply, citing as possibilities, "Exclusion zones based on received levels of sounds; Exclusion zones based on presence of specific biological factors in combination with received levels of sound; and Limitations on certain combinations of activities in specific temporal/spatial circumstances" (MMS, 2010). In developing the PEISs, associated rulemaking, and mitigation measures, BOEMRE and NMFS will need to review and assess the available scientific information on mitigation and monitoring techniques and determine which are appropriate for different activities.

B. Alternative Technologies and Engineering Modifications

Two technical reports, one released in 2007 and the other in 2010, highlight the potential in new or improved technologies that could reduce the environmental footprint of seismic imaging (Spence et al., 2007; Weilgart, 2010). The 2010 report, which was based on a workshop of industry experts and biologists, concluded that:

- Airguns produce "waste sound" that is not used by the industry, yet has the potential to impact marine life.
- That this sound (mainly high frequencies and lateral propagation) could be eliminated without sacrificing any data quality for the hydrocarbon industry.
- That reducing peak sound levels is a worthwhile goal even at the expense of requiring a slightly longer signal.
- That technologies are available or emerging that do not introduce any anthropogenic sound, or introduce substantially less sound, into the environment.
- That less sound may be required to gather the same quality of data due to more sensitive receivers.
- That regulatory pressure/incentives and more funding to develop these technologies will expedite their availability and broaden their applications.

Spence et al. (2007) does not include policy recommendations, but makes similar findings about the potential environmental benefits and availability of quieter exploration technologies.

The two subject reports considered acoustic and non-acoustic techniques for resource target imaging. Acoustic technologies include engineering modifications to airguns, both to reduce unnecessary vibration and to minimize emissions at unneeded frequencies; controlled sources such as marine vibrators, which can alter biologically relevant characteristics of the sound signature, such as frequency, peak pressure, and duration; and fiber-optic receivers, which have potential to reduce the sound pressure levels needed for imaging the subsurface geology.

Non-acoustic sources (alternatives to seismic) include electromagnetic surveys, which can image the subsurface by relying on differences in electrical resistance among different types of rock; and passive seismic devices, originally developed for land-based exploration, which can measure the Earth's natural seismic signals. Those technologies have different applications within the exploration and production cycle and different time horizons for commercial use. In general, the non-acoustic technologies, while promising, are less mature than the acoustic ones and either are emerging or in an early stage of development; they are not ready to supplant seismic techniques as the principal techniques for hydrocarbon resource exploration.

Both reports (Spence et al., 2007; Weilgart, 2010) cite marine vibrators ("marine vibroseis") as a potentially significant technology that could be made available within a few years. The technology could address several factors in current seismic imaging that are associated with greater environmental risk: it could reduce peak sound pressure levels by 30-50 decibels dB below those presently generated by airguns, could eliminate much of the broadband output beyond the low frequencies actually needed by oil and gas operators, and could further limit horizontal propagation. Conversely, marine vibrators would also spread acoustic energy over time, which may be several seconds long or continuous, increasing the chance of masking; but, as the 2010 report notes, airgun noise itself tends to spread over time, and the expected reductions in peak pressures alone could be of considerable environmental benefit.

Hydraulic marine vibrators have been around for several decades, but their poor mechanical reliability, size, unfavorable low-frequency output, and commercialization costs of initial models quickly limited their use. Even in light of historically unfavorable commercial performance, there continues to be limited field-testing of new and reportedly more reliable electric marine vibrators with commercial applications possible in less than 3 years.

In Canada, Offshore Energy Environmental Research (OEER) is funding a team from Defence Research Development Canada (DRDC), as well as several consulting firms, to investigate the feasibility of using a marine vibroseis system to conduct seismic testing, and to reduce potential impacts of seismic acoustic energy on the marine environment. The study will focus on forming a hypothesis and designing experiments to determine whether the impact of seismic energy is reduced by using a marine vibroseis system with a lower peak intensity and longer pulse duration. The team will develop specifications for a system that could replace conventional airguns, and investigate the feasibility of using the Modular Projector System (MPS) as a marine vibroseis source. The project is scheduled to be completed in May 2011 (OEER, 2010).

A Joint Industry Program (JIP) for next generation marine vibroseis development was initiated by ExxonMobil in 2007. Not to be confused with the Sound and Marine Life Joint Industry Programme, the marine vibroseis JIP consists of three phases for which Phase I (Project Scoping) has been completed. Currently three major oil companies (ExxonMobil, Shell, Total) have agreed to begin work on Phase II (Evaluation of transducer designs and proposals for constructing a prototype). Based upon results from Phase II, Phase III (Build and Test a prototype) will begin. The length of time taken to develop the transducer would depend on the current development stage of the transducer. If a currently available transducer needs modification, it could be developed much faster than if the transducer is solely an engineering design. It is expected that a full scale prototype could be constructed and field tested within 3 to 5 years. The general consensus in both the oil and seismic industries is that marine vibrators will not replace airguns in all situations, at least not as they are currently conceived. Marine vibrators do have potential in biologically sensitive areas where the target depths (deep targets attenuate the signal more) allow sufficient dynamic range to record the returning seismic signals. Marine vibrators have certain geophysical advantages over airguns and have the potential to improve seismic data quality in certain geological settings.

FINDINGS

A review of exploration technologies currently applied in offshore environments confirms that seismic methods are key techniques and comprise a significant proportion of all permits issued for OCS exploration activities. Although several non-seismic methods are available for limited purposes, no significant prospects exist for replacing the functionality of seismic exploration methods with non-seismic methods. Therefore, managing the potential environmental impacts of seismic exploration will require ongoing refinements to techniques as well as updates to baseline knowledge of the marine environment. Potential impacts of seismic sound on marine life are recognized and research topics have been identified where more knowledge is needed.

Specific findings include:

- Scientific understanding of environmental conditions in sensitive environments in deep Gulf of Mexico waters, along the region's coastal habitats, and in areas proposed for more drilling, such as the Arctic, must be enhanced in order to meet the expectations of stakeholders.

- Seismic exploration methods will continue to be the key geophysical technologies required to discover, evaluate and enable production of offshore oil and gas resources. Non-seismic methods, although useful in complementary roles, will not supplant seismic methods as the leading exploration technology.

- Seismic noise generated by offshore oil and gas exploration activities is recognized as a concern for whale populations and other marine life, including fish. Research has documented some correlations of biological responses with seismic sources even though the experiments have not always consistently included active and control populations. It is important to recognize, refine and consistently apply mitigation approaches based on high-quality science.

- The US is one of at least seven nations that seek to minimize impacts on marine life through limits on seasons, locations and implementation procedures for performance of offshore seismic exploration. Those nations do not comprise a formal standards organization but ongoing dialogs and conferences could serve to encourage continuous improvements in sustainable offshore seismic practices.

- There is a need for additional technological refinements to supplement current mitigation methods during application of seismic exploration. Those additional considerations include: (1) Design changes to reduce "unwanted noise" from airgun seismic sources; (2) Refinement of vibroseis devices as limited alternatives to airguns.

- There is a need for expanded use of joint industry programs to advance sustainable seismic exploration technologies and to obtain regulatory recognition for the general benefits of such efforts.

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APPENDICES

A. Appendix 1: Glossary

2D Seismic. Two-dimensional seismic sounding.

3D Seismic. Three-dimensional seismic sounding.

4D Seismic. Four-dimensional seismic sounding comprising 3D Seismic taken over an extended time period to accomplish time-lapsed results.

BOEMRE. US Bureau of Ocean Energy Management, Regulation and Enforcement. As of June 2010, BOEMRE (sometimes shortened to BOEM) is the successor to the former Minerals Management Service (MMS).

Cetacean. Biological order of marine mammals commonly known as whales, dolphins and porpoises.

CSEM. Controlled-Source Electromagnetics. A non-seismic exploration method that uses variations in electrical resistivity of solid-earth layers as a way to differentiate relative concentrations of hydrocarbons on those layers. The CSEM method requires physical contact with the ocean bottom and a series of electrodes that induce artificial electrical currents.

dB. Decibel. A unit of measurement used for sound intensity. For most practical applications, 1 dB is 10 times the base-10 logarithm of a sound-generating device output power as measured in watts. Ranges of dB values that comprise threats to marine mammals comprise ongoing research topics.

E&P. Exploration and production activities involving discovery, evaluation and recovery of oil and gas resources.

G&G. Geological and geophysical. An abbreviation favored in some MMS or BOEMRE documents with reference to offshore oil and gas exploration otherwise abbreviated as E&P.

GOM. Gulf of Mexico.

Hz. Hertz. A unit of measurement used for wave energy (include seismic wave energy) expressed as frequency of wave occurrences per second of time. In terms of sound, the larger the Hz number, the higher is the "pitch" of the sound. Frequency (Hz) is complementary to wavelength (meters) in that wavelength decreases as frequency increases. Some simple mathematical relationships are 1 Hz = 1 wave cycle per second or 1000 Hz is equivalent to a sound wave of 0.343 meters in air or 1.5 meters in water.

MMS. US Minerals Management Service (MMS). As of June 2010, it was replaced by the BOEMRE.

MMT. Marine Magnetotellurics. A non-seismic exploration method that uses naturally occurring electrical currents in the solid-earth layers, which are induced by Earth's magnetic field, to differentiate resistive from non-resistive geologic bodies as a way to narrow the search for hydrocarbons.

NEPA. National Environmental Policy Act (NEPA). US federal legislation, dating from 1970, that provides for an environmental impact statement (EIS) as a core requirement of federal regulatory agencies that are responsible for permitting infrastructure projects, including oil and gas exploration and development.

NMFS. US National Marine Fisheries Service.

Node. A seismic receiver placed at a fixed location on the ocean bottom either as a temporary or permanent listening device.

OBC. Ocean bottom cable. A seismic receiver array temporarily laid on the ocean bottom during seismic exploration. OBC techniques offer some advantages, such as shear-wave data acquisition, that are not possible using only towed streamers.

Odontocete. Biological sub-order of Cetaceans denoting "toothed whales".

PEIS. Programmatic Environmental Impact Statement.

Pinneped. Biological sub-order of marine mammals denoting "fin-footed" creatures, including seals, sea lions and walrus.

ROV. Remotely-operated vehicle. An underwater vehicle equipped with cameras and other sensors, as well as some external manipulators, which is operated from shipboard work stations in order to accomplish observations, inspections and limited interventions with subsea equipment.

Seismic. Physical analyses involving transmission and reflection of sound waves ("sounding") to decipher sub-surface geologic structures. Natural seismic waves are generated by geologic phenomena that include earthquakes, landslides and volcanic eruptions. Anthropogenic (human-generated) seismic waves, as used in subsea exploration, include those generated by airguns, sparkers or vibrators operated from ships.

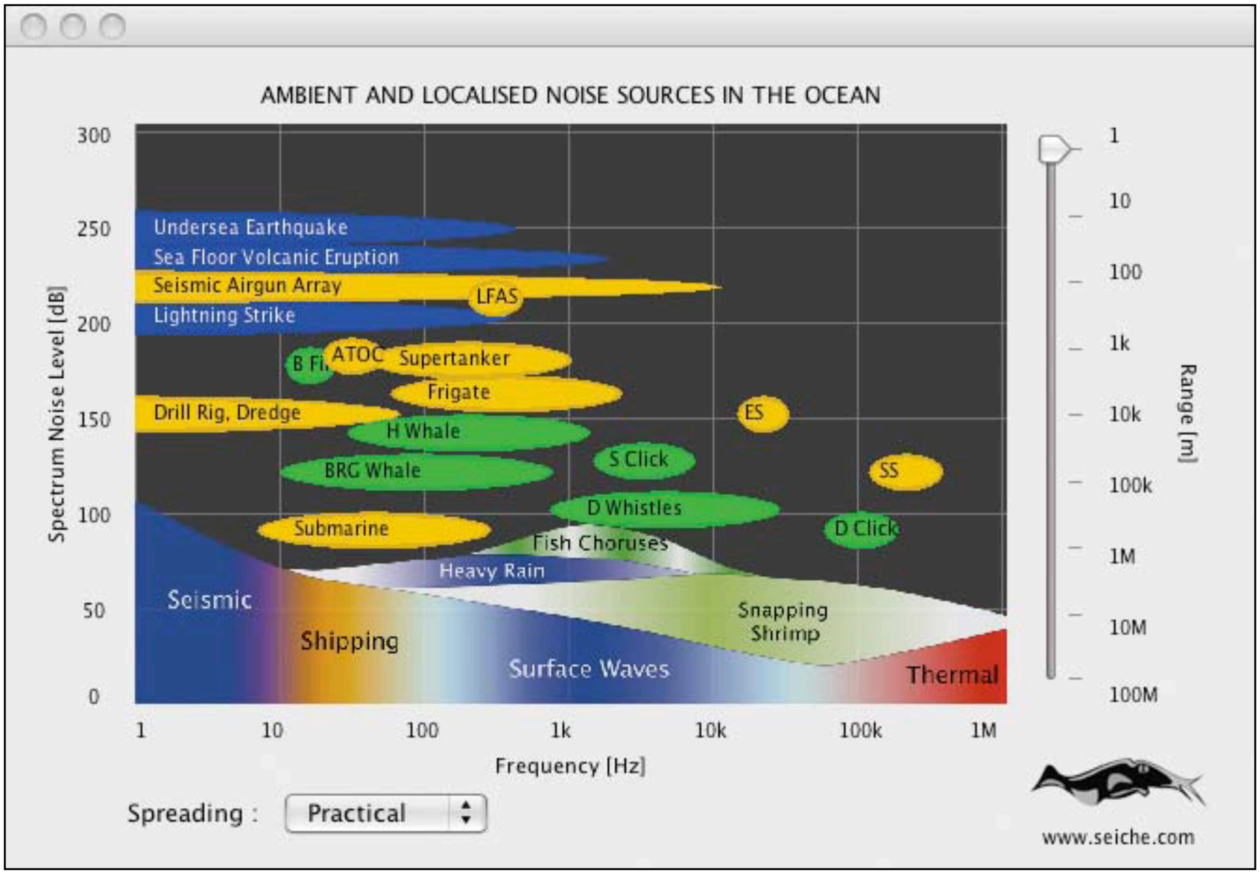
Shear wave. A variety of seismic wave that moves through the solid Earth in a sideways (whip- or snake-like) motion. Shear waves are useful for differentiating strengths of rock materials. But shear waves cannot move through liquids such as water so shear-wave data acquisition cannot be accomplished with towed streamers and therefore requires ocean-bottom data acquisition.

Sonar. Physical analysis involving transmission and reflection of sound waves to determine ocean bottom depths and sub-sea topography. Sonar waves are distinguished from other seismic waves by frequency and intensity.

VSP. Vertical seismic profile. Seismic data acquired from a seafloor borehole using instrumented cables lowered vertically down the borehole as listening devices for a seismic source located above the borehole.

WAZ. Wide-azimuth seismic survey.

B. Appendix 2: Seismic exploration in the context of other ocean sounds



Explanation.

This chart (© Seiche Ltd. 2006) compares sound spectra used by marine mammals and fish with sound spectra produced by natural geologic or metocean phenomena as well as by various anthropogenic sources, including seismic airguns.

The horizontal axis (Frequency) shows increasing sound "pitch" from low (left side) to high (right side). The lefthand vertical axis (Spectrum Noise Level) is a measure of intensity (decibels, dB) while the righthand vertical axis (Range) is an adjustable scale (in the associated software application) of distance (meters) from a selected source of noise and an observer who might be affected by the noise. The snapshot of the chart as shown here is scaled for a distance of one meter from noise source to observer. (In the live software application, the distance is adjustable as a sliding control, from 1 to 100 meters, which causes the colorized zones of the chart to self-adjust as the distance is changed.)