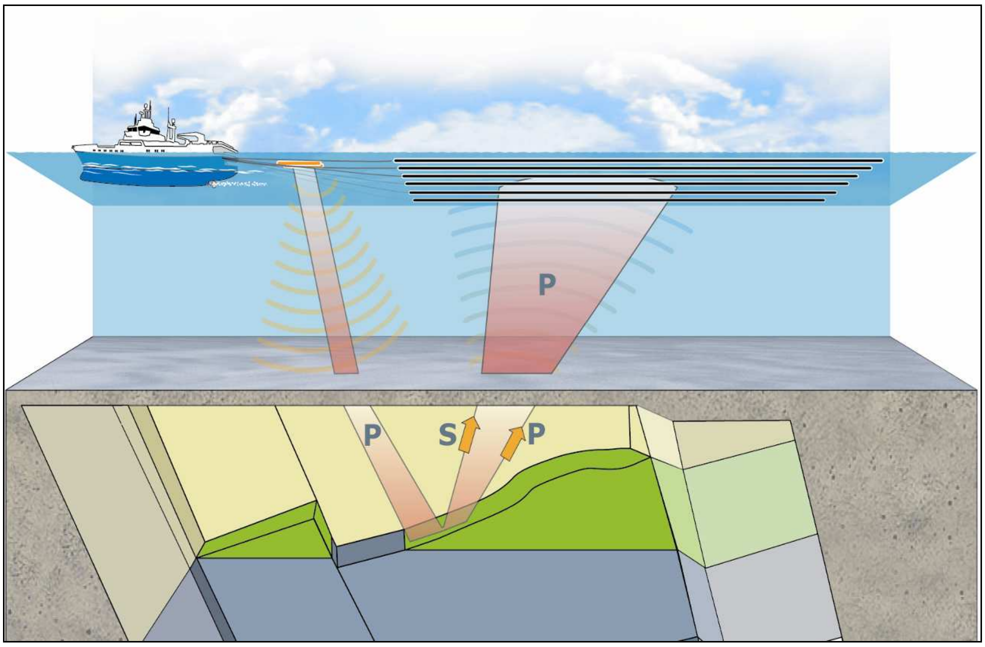
DNV ENERGY

Effects of seismic surveys on fish, fish catches and sea mammals

Report for the Cooperation group - Fishery Industry and Petroleum Industry
Report no.: 2007-0512



MANAGING RISK

Effects of seismic surveys on fish, fish catches and sea mammals

for

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Summary: Marine seismic surveys are the most important tool the authorities and the petroleum industry have for mapping potential deposits of oil and gas under the seabed and for following the development in the reservoirs.

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1.0 Summary

Marine seismic surveys are the most important tool the authorities and the petroleum industry have for mapping potential deposits of oil and gas under the seabed and for following the development in the reservoirs. These surveys are conducted by sending sound waves into the seabed. The time it takes for these waves to be reflected back from the formations, as well as the energy content in the reflected signals, provides a basis for evaluating the properties of the deposits.

Comprehensive studies have been performed by parties including the Institute of Marine Research to prove any potential effects of seismic surveys on marine organisms. The results of this research show that harm to individual fish and increased mortality from firing air guns can occur at distances less than five meters from the air guns. The most frequent and serious injuries occur at distances up to approx. 1.5 m. Fish in the early stages of life are most vulnerable. The extent of the seismic-induced mortality for commercial species in Norwegian waters is so low that it is considered not to have a significant negative impact on recruitment to the populations.

It has been documented that adult fish are frightened by the sound waves from seismic activity, and pelagic fish seem to be the most sensitive. The scare effect has been demonstrated in a radius of up to more than 30 kilometres from the sound source. If fish that are on their way to the spawning grounds are exposed to this type of noise, or if they are exposed to the noise during the actual spawning, the effects can have an impact on the fish's spawning success. Exposed fish may expend more energy on the spawning journey than fish that are not interrupted, and the spawning itself may be more or less deferred in time or displaced in space. Therefore, to avoid such effects, time restrictions have been introduced for seismic activity in spawning areas for important species, and in areas where concentrated spawning journeys take place.

The scare effects can entail catch reductions that will vary from species to species and between the various types of fishing gear. A Norwegian survey shows reduced trawl catches of e.g. cod out to approx. 33 km from the sound source, while another study shows reduced line catches out to approx. 8 km from the sound source. The results of a study in Australia during the period 1996-1999 show that there are scare effects out to distances of 1-2 km from the seismic vessel, but that they do not necessarily lead to negative effects for the fish or the fish population. There is not enough data to determine when fish that have been frightened by air canon firing return to an area they have abandoned, or in some other manner become just as abundant for catching as before the seismic shooting started. The effects are considered to be geographically limited, while local catch reductions have certainly been documented. This is significant for the individual fisherman.

There is no documented sea mammal mortality as a consequence of seismic surveys. Studies of individual incidents in which whales have stranded and seismic activity has occurred in the same area during the same time have been unable to document a cause and effect link. Nor are there any documented injuries to sea mammals in fields as a result of seismic surveys. The effects that have been found are typical changes in behavior, such as whales leaving areas where there is seismic activity.

In general, it can be confirmed that seismic surveys may have certain negative consequences for marine life in the nearby area. However, there are no results that indicate serious and long-lasting harm to populations of fish and sea mammals.

2.0 Introduction

Marine seismic surveys are the most important tool the authorities and the petroleum industry have for mapping potential deposits of oil and gas under the seabed. Sound waves are sent down into the seabed. The time it takes for these waves to be reflected back from the formations, as well as the energy content in the reflected signals, provides a basis for evaluating the properties of the rock. Such surveys have been conducted since the 1950s, in the beginning using explosives as the sound source (Jakosky and Jakosky 1956; Lovlia et al. 1966; Lavergne 1970). The explosions were considered to be very harmful to marine organisms and fishery activities because detonation of explosives and underwater blasting using e.g. dynamite have proven to have the potential of causing significant harm to marine life, including fish death (Coker and Hollis 1950; Hubbs and Rechnitzer 1952; Larsen et al. 1993). The air gun was developed as a signal source in the 1960s (Anon., 1974; 1981; 1989) with substantially fewer harmful effects than explosives (Falk and Lawrence 1973; Chelminski 1974). The water canon was developed and put to use in the 1970s. As a seismic source it did have its advantages, but it was considerably more harmful to marine life than air guns, and this type of source has not been used very extensively (Newman, 1978; Dalen and Knutsen, 1987).

Different types of seismic data are needed for the various stages of the activities, from the early exploration phase to development and production of potential reserves in a field. It may therefore be necessary to repeat seismic data collection several times in the same areas, but with different geographic coverage and time periods. The individual surveys can extend over many weeks, depending on the size of the sea area to be surveyed.

Marine researchers and the fishery industry have claimed that today's seismic surveys can also entail negative effects on marine organisms, although the extent of this is far less than with the methods used previously. The effects that are highlighted are, in particular, that the fish are frightened and move away from the areas they originally frequented and the original fishery areas, and that the fish are less active in seeking food - both of which result in reduced catches. Questions have also been raised regarding whether the effects of the sound from the air guns may have negative effects on marine mammals.

Increasing oil activity on the Norwegian Shelf brought more attention to these issues in the beginning of the 1990s (Figure 2-1).

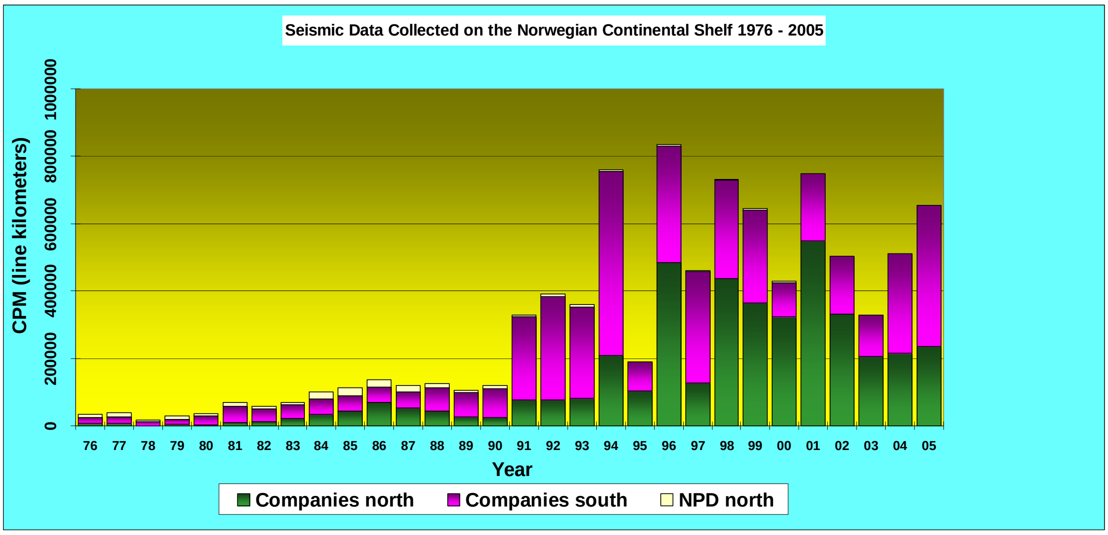


Figure 2-1. *Seismic survey activity on the Norwegian Shelf after 1976. Figure and data from the Norwegian Petroleum Directorate (NPD).*

In order to shed more light on these questions, the oil companies (through the Norwegian Oil Industry Association - OLF) and the authorities (through what was then the Ministry of Industry and Energy, the Norwegian Petroleum Directorate, the Ministry of Defense and the Ministry of Transport and Communication) allocated research funds via the Norwegian Fishery Research Council. The Ministry of Fisheries and the Institute of Marine Research also provided substantial funding.

The results, which were presented in a series of reports published in the 1990s, helped clarify a number of factors and documented the scope of potential effects. The results were also converted into actions in the form of regulation of seismic activity to limit the conflicts that could arise between the fishery and petroleum industries. Some of the issues raised subsequent to this, e.g. a certain type of effects on sandeels, have been studied by the Institute of Marine Research and financed by OLF and the Ministry of Fisheries.

Norwegian research activities have not shed much light on the effects of seismic activity on marine mammals. However, extensive material is available from studies conducted under the direction of both research and governmental institutions and oil companies in the United Kingdom, the USA, Canada and Australia, so that relevant experience and knowledge is also available in this area.

The purpose of this report is to prepare a comparison of updated results from scientific publications and expert technical reports dealing with the effects of shooting seismic on marine organisms. Other comparisons on this same topic are also used as a basis for this report and as a source to complete the overview of the research projects that have been carried out (including Kenchington, 2000; Østby, 2003; Anon., 2004; 2006).

The primary emphasis is placed on the effects on fish and fish catches, but the effects on marine mammals and plankton are also addressed. To the extent relevant, we have also obtained information regarding the effects of other types of sound waves in water, such as the ongoing evaluations of the military's new frigate sonars. The report has been prepared by DNV in cooperation with the Institute of Marine Research.

3.0 Seismic surveys

Today's surveys use large, specially constructed ships that tow air guns and cables with receivers. The air guns fire strong, compressed air-based sound pulses (sound waves) at regular intervals, typically each 25 meters the vessel moves. The sound wave is reflected from all transitions between the various geological layers in the subsurface. The reflected signals are registered by several groups of hydrophones mounted in special cables that are also towed behind the ship. The distance between the groups of hydrophones may be 25 m or less. The length of the cables and the distance between the groups of hydrophones varies depending on the purpose of the survey. The receiver cables can be from 3-8 km long. In three-dimensional seismic surveys, eight cables are usually drawn next to each other, 100 meters apart. The seismic vessel normally travels at a speed of about five knots (approx. 10 km/hour), along parallel lines.

3.1 Different types of surveys

Although the principles are largely the same, there are several methods used for seismic surveys in different phases of exploration for and production of petroleum.

The two-dimensional surveys (2D) are used in large regional surveys in early phases prior to extraction of resources in an area. The vessel follows lines or a grid where the lines are relatively far apart (1 km or more). One sound source is used, composed of several air guns to form an air gun array and one hydrophone cable. The air gun is normally fired every 25 meters or every 10 seconds at a speed of 5 knots.

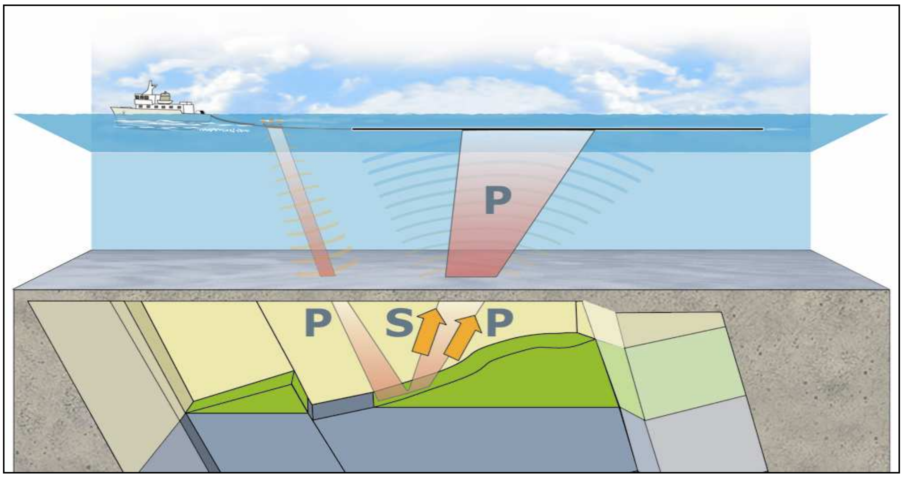


Figure 3-1. *Schematic diagram for 2D seismic. The vessel tows a sound source and a receiver cable with hydrophones.* P = pressure waves, S = shear waves (Figure © Statoil).

Today, three-dimensional (3D) surveys are increasingly used by the oil industry because they provide far more information about the seabed and the reservoirs. By using more hydrophone cables and, usually, two sound sources fired alternately, the surveys cover a far denser grid with grid meshes as small as 25 x 25 m. Double sound sources and more cables mean that the ship has to run fewer lines to cover the same area. This in turn leads to a reduction of potential disturbances to marine life compared with earlier methods using fewer cables.

For reservoir monitoring, so-called 4D seismic is used, which is equivalent to repeated 3D surveys over time (Time Lapse Surveys).

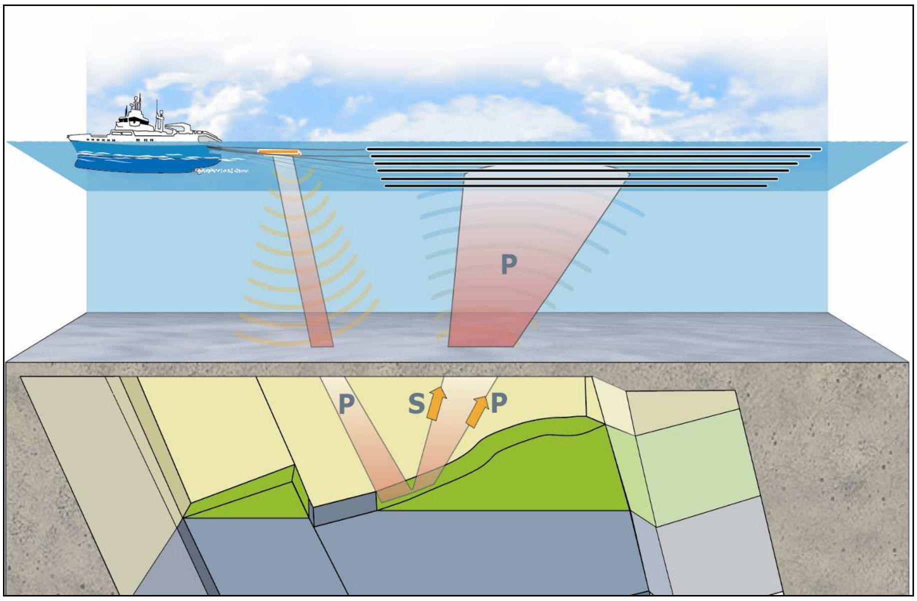


Figure 3-2. *Schematic diagram for 3D seismic. Multiple listening cables and at least one sound source are used. (Figure © Statoil).*

3.2 Sound source

Today, air guns are the predominant sound source (see Figure 3-3). Air at 140 atmospheres pressure (most commonly used supply pressure) is routed into a chamber in each air gun. A pressure wave is created in the water when the air is released quickly to the water through the gun portals.

Air gun volume is most often quoted in cubic inches (cu.in.) with comparable units in liters. The conversion factors are 1 cu.in. = 0.02 liters and 1 liter = 61.03 cu.in. The chamber volume per air gun is from 0.4 to 10 liters. By putting several air guns together into an extended air gun array, the overall chamber volume can be as much as 165 liters. Doing this increases the strength of the resulting seismic signal, thus achieving a focusing of the sound energy transmitted down into the ground.

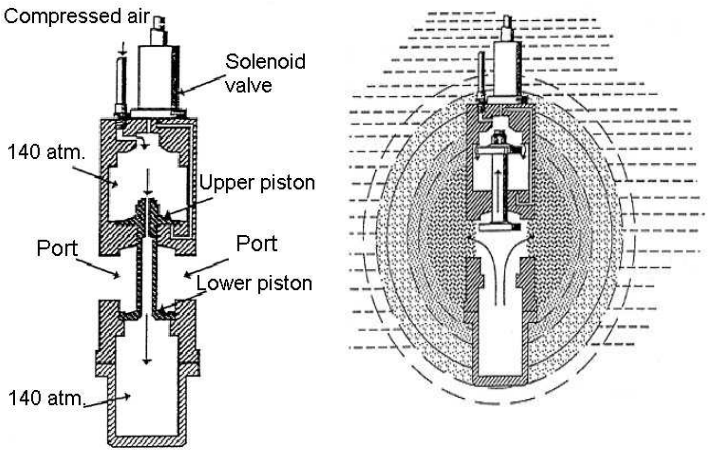


Figure 3-3. *Sketch of a Bolt-PAR air gun cross-section before firing and after firing. Figure obtained from http://www.bolt-technology.com*

3.3 The sound wave from air guns

Sound has a dualistic nature and may be described as fluctuations in pressure (pressure waves) or particle fluctuations in a medium. When regarding the perception of sound, there are significant differences from species to species both on land and at sea concerning the relevant stimulus parameter, pressure or particle movement, and what sound frequencies can be perceived. There are also substantial differences in the strength required at different frequencies in order to perceive the sound.

The frequency of a sound wave is the number of pressure or particle fluctuations per second, measured in hertz (Hz). The human ear is sensitive to sound pressure and can normally detect sounds between 30 and 20000 Hz. Seismic signals generally contain sound energy where most of the energy is at frequencies below 200 Hz. Single air guns generate a frequency range of 5-200 Hz, while the comparable range for multiple guns fired simultaneously is in the order of 5-150 Hz (Malme et al., 1986). The sound pressure for individual frequencies or bands varies, however the maximum level for most falls between 10-80 Hz.

Pressure changes are measured as force per unit of area (N/m2). This unit is called a Pascal (Pa), but it is more common to use the logarithmical ratio decibel (dB) to indicate sound strength. This is not a unit of measure, but a calculated size for measured pressure in relation to a reference value. An unambiguous expression of sound level in decibels should always include the reference value. This reference value is different in air and in water. In water, the sound pressure level is defined as 20 times the logarithm of the ratio between measured sound pressure in micro-Pascals (µPa) and the reference pressure, which is 1 µPa. A change of 6 dB is equivalent to a doubling or halving of the sound pressure, while a change of 20 dB indicates that the pressure changes by a factor of 10.

The kinetic component of sound, that is the particle movement, can be expressed as the particles' range of vibration (m), speed of vibration (m/s) or acceleration (m/s2). While marine mammals are sensitive to sound pressure, all marine invertebrates that can perceive sound are sensitive to particle movement. The inner ear in fish is also sensitive to particle movement, and the relevant stimulus parameter is the particle acceleration. Fish with swim bladders, e.g. herring and cod, can, however, also detect sound pressure since the swim bladder acts as a converter between pressure and movement. Fish without swim bladders, e.g. flounder and mackerel, are not sensitive to sound pressure (see Popper et al. 2003 for an overview of fish hearing).

Far from the sound source (in the acoustic far-field), there is a constant ratio between the pressure component and the kinetic component of the sound. Closer to the sound source than approx. 1/6 of the wave length (in the acoustic near-field), this ratio increases dramatically as distance decreases. For 10 Hz, which is within the frequency range where air guns provide maximum effect, the wavelength is e.g. approx. 150 m, and the near-field extends to approx. 25 m. It is likely that many of the harmful effects observed on organisms close to the sound source are due to particle acceleration, and not sound pressure. However, it is more difficult to measure particle acceleration than sound pressure, and nearly all of the reports on the effects of seismic signals on marine organisms listed the intensity of the sound as sound pressure. Therefore, it is important to be aware that sound with the same sound pressure may be far more harmful at short distances compared with longer distances.

There are different ways of expressing the sound pressure of these sound signals. Pulsed signals are often indicated with maximum sound pressure (peak level or peak-to-peak level) and the length of the pulse, while continuous sound is either described as a mean value (stated as the rms value: "root-mean-square", average amplitude over a time period) or as a spectral level where the strength is indicated per frequency band width, e.g. per Hz. It is important to know how the sound levels are indicated when evaluating the environmental aspects of sound.

The strength of the seismic signal in a certain position will largely depend on the distance from the source. Sound pressure levels with peak values of over 230 dB rel. 1 µPa only occur in the immediate vicinity of the air guns, at distances of just a few meters. In comparison, modern container ships emit noise of up to 190-200 dB rel. 1 µPa referred to 1 m at full speed (Peterson, 2004). A sound pressure level of 230 dB rel. 1 µPa is 100 times greater than a sound pressure of 190 db rel. 1 µPa.

Generally speaking, one can assume that the sound pressure level of the signal in a given position is in inverse ratio with the distance from the sound source at constant sound velocity over the sound dispersion area. At greater distances, the signals may be somewhat more reduced than this, depending entirely on the depth conditions, the local sound propagation conditions in the sea and the geological conditions in the seabed. Sound from seismic surveys is normally transmitted from a source near the surface, which entails significantly greater horizontal attenuation than if the sound source were deeper down in the water. In various reports regarding the effect of seismic signals, the intensity of the sound is stated either as sound pressure (dB rel. 1 µPa) or, less precisely, as the total volume of the air guns. In both cases, it is important that the distance to the source is known.

Sound can occur either as continuous signals, for example from a ship's propellers, or as pulses. Signals used in today's seismic surveys are short pulses that are repeated every 8-10 seconds during the operations, and may in relation to their nature and effect on marine life be classified as pulsed sound.

Sound stress on the part of living organisms generally occurs as a consequence of either sudden, loud noises that can result in immediate reactions on the part of the individual or as a consequence of long-lasting exposure to relatively high levels of sound. Peak pressure is presumed to be the most relevant parameter for stating the likelihood of acute damage occurring as a result of pulsed sound, while the mean value level (rms level) is considered to be a better parameter for evaluating the effects of continuous sound.

3.4 New seismic methods

Electromagnetic surveys are a relatively new method used to collect geophysical data for evaluation of oil and gas deposits. The surveys take place after a number of receivers are placed along a line on the seabed, with a distance of approx. 1 km. A low-frequency electromagnetic source is then towed over the receivers. The receivers record signals that are transmitted several kilometres into the subsurface.

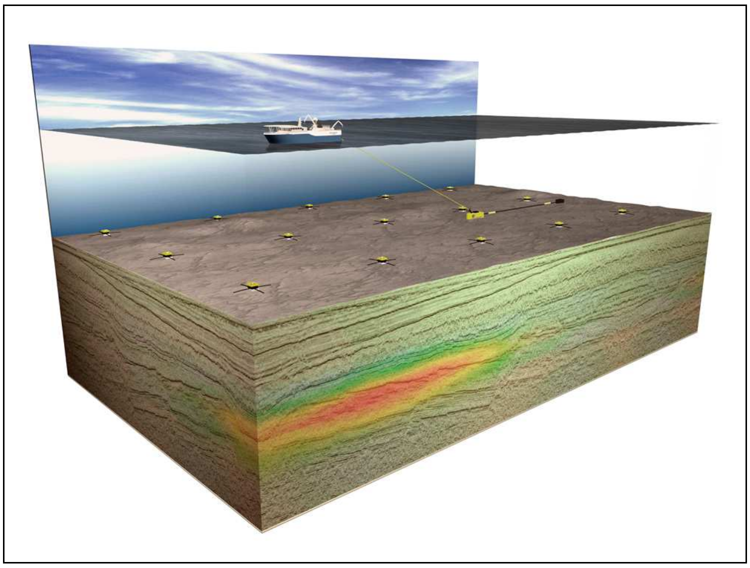


Figure 3-4. *Schematic diagram for electromagnetic surveys. The vessel tows a low-frequency electromagnetic source in deep water. Reflected signals are captured by a number of receivers placed on the seabed.*

All geological media have electrical conductivity. The differences in electrical conductivity between slate, sandstone and chalk, which are the most common rocks in sedimentary basins, are relatively small. When the sandstone or chalk is filled with oil, the electrical conductivity is radically reduced. The frequencies used are less than 1 Hz to achieve sufficient penetration depth into the bedrock.

The most important limitation today is that the method requires sea depths of at least 500-1000 m. Moreover, the reservoir cannot be located too deep in the subsurface, preferably no deeper than 2000 m below the seabed. Therefore, the method has some limitations. An operative advantage of the method is that it is possible to collect data within a broad weather window.

So far, there are no studies of the biological effects of these types of surveys. However, it is worth noting that cartilaginous fish (sharks and sting rays) are extremely sensitive to electrical fields, and spiked dogfish may in particular be an important commercial species in the relevant areas. The potential effects of weak electrical and magnetic fields on marine organisms have previously been studied in a report financed by Statkraft, in connection with planned underwater power cables between Norway and the Continent (Poleo et al., 2005).

3.5 Last year's seismic surveys

According to the Norwegian Petroleum Directorate (NPD), a total of 719,844 km of seismic were shot on the Norwegian Shelf in 2006, divided between 45,646 km 2D seismic and 674,198 km 3D seismic. For purposes of comparison, approximately 836,000 km were collected in 1996 (see Figure 2-1).

The total area surveyed amounted to 16,850 square kilometers. As in previous years, most of the surveys were conducted in the North Sea and the Norwegian Sea, with considerably less activity in the Barents Sea.

The activity is greatest in the three summer months - June, July and August (Figure 3-5).

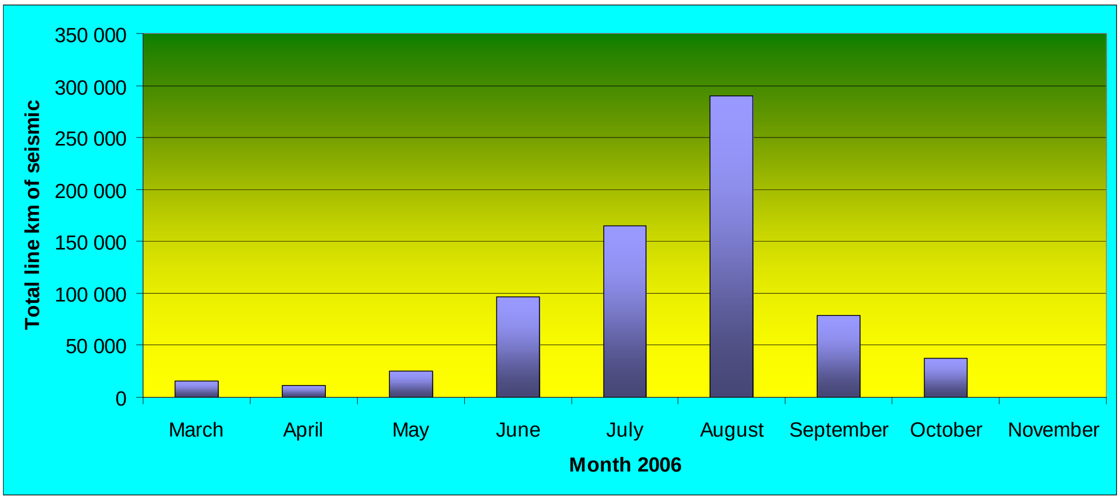


Figure 3-5. *Distribution of seismic survey activity by month in 2006. Data from the Norwegian Petroleum Directorate.*

4.0 Effects on fish

4.1 Introduction

Seismic surveys can have an impact on individual fish, fish populations and fisheries, either directly through harmful physiological effects or behavioral effects. We often classify the effects as "harmful effects" and "behavioral effects". Harmful effects can cover everything from "immediate death" to "nearly fatal effects", or expressed as various types of inflicted internal injury that can cause results ranging from "directly lethal" via "indirectly lethal" to temporarily reduced viability ending with full restitution.

The physiological effects will mainly affect younger life stages of fish such as eggs, larvae and fry (Kostyuchenko 1973; Dalen and Knutsen, 1987; Holliday et al., 1987; Booman et al., 1992; Kosheleva, 1992; Popper et al., 2005). These are stages in fish development where the organisms have limited ability to escape from their original areas in the event of various influences. The effects are often classified as immediate mortality (short-term effects), mortality over time (long-term effects) and non-lethal injuries. Although some injuries do not as such lead to directly lethal conditions for the organisms, such effects can indirectly lead to the same fatal conditions via reduced ability to assimilate food, or a change in swimming capacity which makes them more vulnerable in relation to predatory fish. Based on actual energy and behavioral data from fish, this has been demonstrated by Holmstrøm (1993) for typical seismic 3D surveys. In a fish resource/biological context, this can be summarized as increased mortality of eggs, larvae and fry, which can thus contribute to a certain diminished net production in fish populations.

For later life stages and for adult fish, the behavioral effects are considered most important. This can mean that fish are scared away from fishing banks and areas. It can thus be of indirect but significant importance for the fisheries due to reduced abundance of fish to catch and thus smaller catches. Some findings by McCauley et al. (2003) also indicated harmful effects on the part of adult fish. Serious injuries were proven in hearing sensor cells. The fish were kept in cages and the seismic vessel passed the cages along course lines running from 400-800 m distant at the beginning and up to 5-15 m from the cages. Since the experimental fish were so close to the air guns, one could discuss whether these types of injuries are representative for adult, free-swimming fish. These findings are otherwise of the same type as Booman et al. (1996) found for fish larvae of some species.

Another issue is potential disturbances that spawning fish may be exposed to in spawning areas and during concentrated spawning journeys to the spawning grounds. This can change the areas that are used for spawning, and possibly the timing of the spawning, so that spawning conditions become less favorable. This could at worst reduce the total annual reproduction. It must also be emphasized that any and all effects must be interpreted in the light of the fact that they will be unique for each species, and that the vulnerability and effect of external stimuli depend on the life stage.

4.2 Sound from air guns and behavioural responses in large-scale experiments

When fish receive a strong sound stimulus, an alarm reaction or an escape reaction is triggered (Blaxter et al., 1981; Blaxter and Hoss, 1981; Popper and Carlson, 1998; Karlsen et al., 2004). The reaction is often characterized by a typical so-called "C-start" response, as the body of the fish forms a "C" and the body points away from the sound source. The C-start response can therefore trigger an evasive reaction away from a harmful or frightening source of stimulus. Field experiments have demonstrated that sound energy transmitted from air guns initiates this type of response on the part of cod (Wardle et al., 2001), redfish species (Pearson et al., 1987; 1992), European sea bass (Santulli et al., 1999) and sandeel (Hassel et al., 2004).

Knudsen et al. (1992) conducted a systematic study of which sound frequencies are most frightening for salmon smolt. It proved that infrasound with frequencies lower than 20 Hz triggered fear and evasive reactions far more effectively than higher frequencies. These experiments were followed up by field tests on Atlantic salmon (Knudsen et al., 1994), several species of Pacific salmon (Knudsen et al., 1997), silver eel (Sand et al., 2000) and several species of cyprinids (Sonny et al., 2006). In all of these studies, intense infrasound resulted in escape reactions. Fish generally have very good infrasound hearing (Sand and Karlsen, 1986, 2000) and infrasound has a substantial potential in acoustic fish barriers (Sand et al., 2001; Sonny et al., 2006). In this context, it is interesting to note that a significant portion of the emitted sound energy from air guns is in the infrasound area.

Chapman and Hawkins (1969) observed that the depth distribution of whiting changed during shooting with an air gun. The fish avoided loud levels of noise by immediately moving deeper into the water. Similar behavioral changes during shooting with one air gun (0.6 liter) were observed in herring by Dalen (1973) in Imsterfjorden and Verrafjorden in Sør-Trøndelag county.

Changes in behavior have been observed during special studies in fishery areas (Pearson et al., 1992) on the part of redfish species exposed to air gun shooting. Fish of these species that were held in net cages exhibited changes in swimming patterns and depth distribution during the course of ten minutes' sound exposure from a single air gun with a chamber volume of 1.6 liters. These observations showed that relatively minor behavioral changes, such as changes in depth distribution and changes towards more active behavior such as going in circles, were observed even at low sound levels, and that alarm responses such as increased activity and changes in school behavior and placement in the water column, become more and more obvious as the sound level increased. Rapid responses similar to C-start responses have also been observed on the part of European sea bass and sandeel in relation to air gun shooting at distances of up to 2.5 and 5.0 km respectively (Santulli et al., 1999; Hassel et al., 2004). The fish were kept in cages while the seismic vessel towed the seismic sound source at varying distances from the cages. Although these three experiments were conducted using fish under large-scale field conditions, major escape reactions cannot be detected using confined fish.

Wardle et al. (2001) made observations of cod, pollock, coalfish and whiting on a bank in sheltered, shallow waters, while shooting took place with an array of air guns consisting of three guns with a total chamber volume of 2.5 liters. The behavioral patterns of the fish did change to some extent, but there was no systematic migration away from the air gun or away from the bank. We interpret this such that every sound exposure with its surface and bottom echo contribution was either too complex or too variable to provide directional information to the fish, so that it could possibly swim directly away from the air gun. As mentioned, this study was conducted in a shallow, sheltered area and constitutes an example of conditions where there may be many surface and bottom reflections of the sound together with the direct sound pulse. This will result in a complex sound field which has reduced directional information.

Dalen and Raknes (1985) observed in 1984 on the Gullfaks field in the North Sea that the distribution of fish at 100-300 meters depth changed along the course lines of a seismic vessel towing an air gun array of 40 guns with a total chamber volume of 78 liters during a three-dimensional seismic survey. The average measured echo volume (acoustic measurement of fish quantity) which represented the common quantity of fish, bottom fish - mainly cod and pollock - was reduced by 36% after the shooting compared with the measured values prior to shooting. The reason for this was that the fish migrated out of the seismic area, or that they went down so close to the bottom that they could not be observed using echo sounders. For blue whiting, the comparable reduction in fish quantity was 54%, while the reduction for small pelagic species was 13%. Slotte et al., (2004) also observed that fish (herring and blue whiting) in an area where 3D seismic is being shot, move to greater depths.

Engås et al. (1993, 1996) conducted a large-scale study in 1992 on the North Cape bank in the Barents Sea to map the extent and duration of effects from seismic survey activities on fish quantities in the area and on the catch rates for commercial species. The seismic shooting took place for five days within an area of 3 x 10 nautical miles, where an air gun array of 18 guns with a total chamber volume of 82 liters was used. In addition to trawling, catches were made using lines before, during and after the shooting and the fish quantities were measured using acoustic mapping in the same periods. The catch rates during the shooting were found to decrease over an area of 18 nautical miles out of the seismic area. The acoustic measurements that showed changes in the quantity of fish were found to decline in the same ratio as the reductions in catches.

In 2002, the Institute of Marine Research conducted a field experiment in the North Sea to find out whether seismic surveys under certain conditions caused special behavior on the part of sandeel (Hassel et al., 2003; 2004). Sandeel is a species that, in part, buries itself in the bottom sediments at night and swims in the water column during the day. The experiments comprised bottom samples to find buried sandeel in order to determine their spread within the test area and to obtain fish for the experiments. The main objective of the project was to carry out experiments where the sandeel were confined in large cages placed on the seabed, to observe whether and to what extent the sandeel buried themselves or exhibited other changes in behavior in connection with shooting seismic. It was not proven that the sandeel buried themselves in connection with seismic influences, however, marked reactions were observed, C-start reactions, which constitute the beginning of escape reactions. The behavioral studies were supported by acoustic monitoring of the sandeel populations in and around the test areas and the fishery activities in the area were also monitored. The observed acoustic quantity of sandeel varied greatly during the duration of the experiment, but this could not be linked to seismic activity, since the observation design and methodology were not adapted to determine whether the sandeel remained within the seismic area or migrated out of it, or if its abundance for catching was altered during the seismic period. Analysis of data for the amount of sandeel landed by Norwegian trawlers exhibited a temporary drop in the amount of landed fish for a brief period after the experiments.

4.3 Effects on fish eggs, larvae and fry

Up to 1990, some research had been done to illuminate the scope and type of harm to fish that were exposed to air gun and water canon shooting in the former Soviet Union (Kostyuchenko, 1973; Kosheleva, 1992), in Norway (Dalen and Knutsen, 1987) and in the USA (Weinhold and Weaver, 1972; Holliday et al., 1987). In order to supplement earlier results and illuminate the type of internal damage that fish eggs, larvae and fry might sustain, a major project was implemented under the direction of the Institute of Marine Research in 1991-1992 regarding the influence of air gun shooting on the early life stages of five species of fish (Booman et al., 1996). The air gun setups used were equivalent to parts of the commonly used air gun arrays in 3D surveys where the effective stimulus source had a total chamber volume equal to 9.6 liters. Similar studies have since been followed up by McCauley et al. (2003) and Popper et al. (2005).

In order to increase the understanding and precision of the results from the many studies, the results were, insofar as possible, grouped and presented in relation to the development stage of the relevant species, in which the stage also indicates age. The development stage and effective age (degree-day) for the fish are based on examples for cod (spawn in free water masses) and herring (spawn at the bottom) during normal temperature conditions on the spawning fields and in typical operations areas in Norwegian waters, i.e. from the temperate and sub-artic zone. Results from other waters and zones may deviate from this as regards effective age. The following stages of development were used:

- egg,
- yolk sac larvae - age-wise; cod from 1 to approx. 35 degree-days and herring from 0 to approx. 50 degree-days
- larvae - correspondingly; cod from approx. 35 to approx. 335 degree-days and herring from approx. 50 to approx. 650 degree-days
- post-larvae - correspondingly, cod from approx. 335 to approx. 575 degree-days and herring from approx. 650 to approx. 890 degree-days,
- fry - approximately corresponding to what was used for the 0 group stage at the Institute of Marine Research, i.e. the fish are approx. one-half year old.

The results of the Norwegian studies in 1991-1992 confirmed and expanded previous knowledge gained from surveys of mortality resulting from air gun shooting.

- Increased mortality rates for fish eggs were proven out to approx. 5 meters distance from the air guns.
- For yolk sac larvae, particularly for turbot (consistently representative for flounder species), the mortality rates were high, 40-50% at a distance of 2-3 m. Lower mortality figures have been shown for yolk sac larvae of anchovies at the same distances (Holliday et al., 1987) from a single air gun of 5 liters. Matishov (1992) proved significant eye injuries (retinal stratification) on the part of yolk sac larvae of cod at a distance of 1 m from an air gun array of approx. 8 liters.
- In later stages, such as for larvae, post-larvae and fry, the highest mortality rates found for plaice were 10-20% at a distance of 2 m. Clearly higher mortality was also proven for cod at a distance of 5 m, in the larvae stage.
- Increased mortality rates at the post-larvae stage were proven for several species at distances of 1-2 m.
- Increased mortality was proven for cod at the fry stage at distances of 1-2 m.
- Changes were also observed in the buoyancy of the organisms, changes in the ability to avoid predators and effects that had an impact on the general condition of larvae, and thus their ability to survive.

When researchers looked for potential pathological effects on fish, i.e. damage at the cellular level, Booman et al. (1996) found that yolk sac larvae of turbot that were exposed to sound energy from air guns suffered effects and damage to brain cells when the larvae were approx. 1.6 m from an air gun cluster.

The sideline system of fish can be vulnerable to damage caused by sound energy, particularly on the part of larvae, where the so-called free neuromasts represent in many respects the sideline system until this is fully developed. The neuromasts are regarded as being an important organ in escape reactions on the part of many fish larvae, and thus their ability to avoid predators (Blaxter and Hoss, 1981; Eaton and Hackett, 1984). Booman et al. (1996)

proved injury to the free neuromasts on the part of turbot yolk sac larvae, with complete cutting of all cilia (flagellum). Similar findings were made for post-larvae of cod.

Similar effects on the hearing organs of adult fish were proven by McCauley et al. (2003) when caged pink snapper were subjected to the firing of several air guns. Signs of damage to the sensor hair cells in the inner ear were observed as early as 18 hours after the air guns were fired. Significant injuries of the same type were observed in fish that were examined 58 days after the exposure and there were no signs that the damaged sensor cells repaired themselves. This study did not prove the impact of these injuries on the fish's hearing.

In summary, we can say that research has shown that injuries and increased mortality from air gun shooting can occur at distances less than 5 m from the air guns. The most frequent and serious injuries occur at distances out to approx. 1.5 m and fish in the early stages of life are most vulnerable.

4.4 Seismic mortality and effects on population levels

One can thus pose the question of what impact seismic mortality may have on recruitment to populations. An important study, although limited in scope, has been performed to shed light on the consequences seismic-created mortality may have on the population level (Sætre and Ona, 1996). The work was based on the observed mortality figures for larvae and fry at given distances in Holliday et al. (1987) and Booman et al. (1996). Typical versions of air gun arrays and course line densities used in 3D surveys were used as a basis, together with observed depth distributions for larvae and fry (Bjørke et al., 1991; Holmstrøm, 1993). As a "worst case" situation, it was estimated that the number of larvae killed during a typical seismic survey was 0.45% of the total larvae population. When more realistic "expected values" were applied to each parameter of the calculation model, the estimated value for killed larvae during one run was equal to 0.03% of the larvae population. If the same larvae population was exposed to multiple seismic runs, the effect would add up for each run.

If we look at the seismic mortality in relation to natural mortality for these life stages, we get the following connections: For species such as cod, herring and capelin, the natural mortality is estimated at 5-15% per day of the total population for eggs and larvae. The daily natural mortality is reduced to 1-3% until the 0 group stage is achieved, i.e. when the fish has reached approx. one-half year in age (Sætre and Ona, 1996). Consequently, the seismic-created mortality for these species and other commercial species in Norwegian waters is so low that it is not considered to have any (significant) negative impact on recruitment to the populations (Dalen et al., 1996).

4.5 Effects on farmed fish

Thomsen (2002) reported a study on the effects of seismic surveys on salmon fish in fish farms. There was mainly rainbow trout in the fish cages (a total of 140 tonnes with an average weight of 3.5 kg), but in connection with the experiment a cage of salmon smolt was also set out (200 fish, weight 50 grams). Two 0.4-liter and two 0.7-liter air guns were used, fired simultaneously. The supply pressure was 110 bar. The sound pressure level was approx. 229 dB rel. 1 µPa referred to 1 m from the air guns. The sound waves were measured at two locations using hydrophones at 142 dB rel. 1 µPa at a distance of 4000 m (at the fish farm) and to 186 dB rel. 1 µPa at a distance of 150 m from the air guns. The fish in the fish farm were monitored using video cameras, and appeared to remain calm throughout the experiment. Individual fish exhibited sudden movements, but these could not with certainty be differentiated from normal behavior. The fish consumed normal amounts of food during the entire experiment.

Turnpenny and Nedwell (1994) quote experiments with Coho salmon in cages that were exposed to sound waves from air guns up to 214-216 dB rel. 1 µPa without lethal effects, while at 226-234 dB rel. 1 µPa, there were injuries to the swim bladder. At 192-198 dB rel. 1 µPa, the salmon were paralyzed, but were restored after about 30 minutes.

4.6 Effects on zooplankton and other small organisms

During 2006, there have been discussions in the fishery press regarding potential effects on plankton organisms from the extensive seismic activity in the North Sea. So far, little research has been conducted in this field. From available literature, we are only aware of one experiment with air guns on zooplankton (copepods) and mussels (Kosheleva, 1992). The bottom species used were gammaridae, (Gammarus locusta), snails, (flat periwinkle and edible periwinkle) and one shellfish species (mussels). For zooplankton, one higher and one lower order of crustaceans were used, primarily copepods. Only the experiments with Gammarus locusta and shellfish were successful. For these, no significant harmful effects were observed at distances of 0.5 m and greater from a single air gun with a chamber volume of 3 liters.

In the USA, Pearson et al. (1994) conducted experiments with air guns on early life stages of Dungeness crabs. From an air gun array consisting of seven guns with a total chamber volume of 13.8 liters, they observed a reduction in survival of less than 10% for the larvae at a specific stage, i.e. at the stage for the second ecdysis. There were no other effects. Christian et al. (2003) conducted similar experiments on snow crabs. Their egg development stages exhibited definite developmental differences between the control groups and the test groups for eggs exposed at a distance of 2 m from a single, small air gun of 0.7 liter. Both the test and control groups were examined over a 12-week incubation period in the laboratory. Other than this, there was no indication of immediate or delayed mortality or other effects.

5.0 Effects on fish catches

For a long time, fishers have expressed concern that certain types of geophysical surveys conducted in fishery areas led to smaller catches. Scientific studies have been conducted to examine and quantify such effects from firing air guns (Dalen and Raknes, 1985; Malme et al., 1986a; Pearson et al., 1987; Skalski et al., 1992; Løkkeborg and Soldal, 1993; Engås et al., 1996; i Jakupsstovu et al., 2001). All of these studies demonstrated catch reductions during the course of the air gun shooting, compared with catches before the shooting began.

Malme et al. (1986a); Pearson et al. (1987) and Skalski et al. (1992) examined how the sound energy from a single air gun affected the catches of redfish species in a fishery using floats along the California coast. A seismic vessel sailed over the fish stocks along mountain peaks on the seabed in water depths of 82-183 m. The sound transmissions caused an average catch reduction in total catch rates of 52%. The reduced catches were explained by behavioral changes proved using echo sounders which showed that the fish went deeper, but still stayed close by the steep seabed formations. This unique observation concurs with the findings of Wardle et al. (2001) and Boeger et al. (2005) which indicated that fish that are drawn to seabed structures appear to be more stationary than free-swimming fish. Another conclusion was that such fish with an affinity for the seabed were less likely to spread through the water masses in the event of exposure to air guns as compared with fish located in less unique bank areas.

Løkkeborg (1991) and Løkkeborg and Soldal (1993) analyzed catch data from logs on line vessels and trawlers that had fished in areas where seismic surveys were carried out. The catch rates from the line vessels increased with increasing distance from the seismic area. The catches on lines set within the seismic area were 55-80% lower than those set 1-8 nautical miles from this area. In two fishing areas where shrimp trawlers fished during seismic surveys, the by-catch of cod was reduced by 79% and 83% respectively when the shooting started. The observed reductions in catch rates were explained by the fish moving away from the seismic areas. During two brief air gun firing sequences of 3 and 9 hours, it was found that the by-catch of cod tripled for some pollock trawlers in the area. This catch increase was assumed to be an effect of the relatively brief shooting sessions which could give rise to a temporary increase in fish density close to the seabed. Similar effects were observed by Dalen and Raknes (1985) for some bottom fish in the North Sea.

Engås et al. (1996) refined and expanded the approach used by Dalen and Raknes (1985) into a large-scale experimental setup to investigate spatial extents and duration of the effects of seismic activities on local quantities of fish and on catch rates for commercial species. Continuous seismic shooting was conducted over a five-day period within a seismic area of 3 x 10 nautical miles, in which an air gun array of 18 guns was used and operated in accordance with normal procedures for 3D surveys. The trawl catches of cod and haddock and the line catches of haddock declined by about 50% in an area of 40 x 40 nautical miles, centered around the seismic area during the course of the shooting period, as compared with a seven-day fishing period before the shooting started. The catch reduction was most pronounced within the seismic area, where the trawl catches of both species and the line catches of haddock declined by about 70% and the line catches of cod declined by about 45%. Apart from the line catches of cod, the catch rates declined over an area of 18 nautical miles out from the seismic area. Nor was there any sign of increases in the catch rates during a five-day period after the shooting was over. The quantity of cod and haddock within the test areas was measured using acoustic mapping, and was found to decline at the same ratio as the catch reductions. As a conclusion, this extensive study demonstrated that seismic surveys caused substantial reductions in local quantities of fish. It also showed that catch rates for cod and haddock were greatly reduced within an area of at least 18 nautical miles out from the shooting area, and that these effects lasted for at least five days after the shooting stopped.

On the Faroe Islands, a comprehensive study was carried out in 2000-2001 to illuminate the effect seismic surveys might have on the fisheries (i Jakupstovu et al., 2001). The surveys included trawlers, paired trawlers, line vessels, net vessels and jig boats. The analyses were based on questionnaires and interviews with 186 fishers. It covered longer fishing periods in connection with seismic activities near to or far away from the fishing vessels. A special study was also conducted based on log books from 23 fishing vessels, together with information on seismic activities in 1997. Some special factors must be noted as only 2D seismic was shot in 1997 (long distance between course lines), and also that the log book information from the seismic vessels was either inadequate or missing altogether. This made it difficult to map the seismic activities in time and position, i.e. where the seismic activities had taken place throughout the year. In summary, there were similar results as those found in Norway (Løkkeberg and Soldal, 1993) for catch changes in relation to seismic activities from the questionnaire and interview survey, but with greater variation in the results. The analysis of the log books from the fishing vessels in relation to the 2D surveys did not show any significant connection between fish catches and seismic.

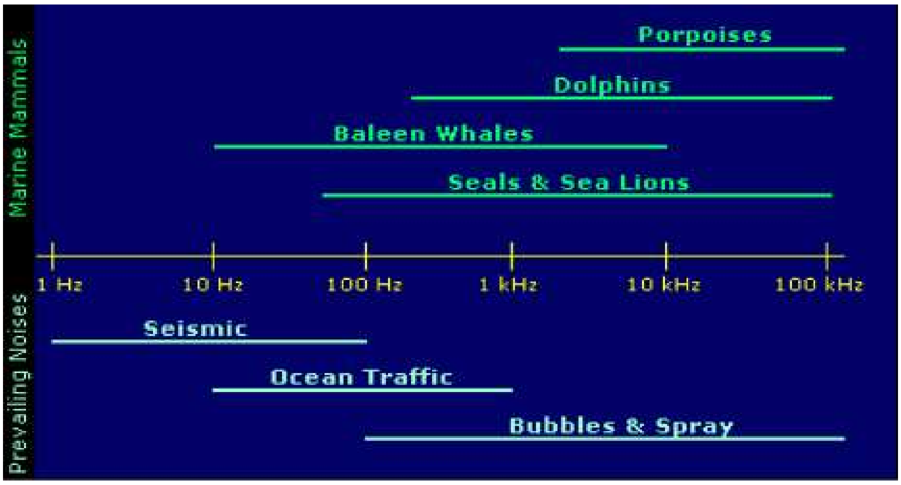
In some contexts, one should be cautious in transferring observations and findings from one species to another, however, physiologists argue that fish within the same "class" (the same hearing physiology, hearing classes/same trophic level) often have similar responses to similar types of sound stimuli. The quoted studies of cod, haddock and redfish species (all hearing generalists) should in this context be representative for a broad spectrum of other fish species.

6.0 Effects on marine mammals

6.1 Hearing and echo localization in marine mammals

Potential effects of human-made sound on marine mammals may be categorized as directly harmful physiological effects on individuals, behavioral effects or masking. However, the effects depend partly on which frequency range they can hear in (Richardson et al., 1995). Beluga whales have relatively poor hearing at the low frequencies used in seismic surveys (see Table 6-1). Among others, sperm whales, dolphins and porpoises appear to be most sensitive to sounds above 10 kHz, and are capable of detecting frequencies as high as 200 kHz. Moderate high frequency sounds are used in communication between individuals or groups, while the highest frequencies are used for echo localization (Harwood and Wilson 2001).

Table 6-1. *Approximate frequency range for communication on the part of marine mammals - the upper part of the figure, and common background noise in the sea ("prevailing noises") - lower part of the figure.*



The Baleen whale species blue whales and fin whales are known for their ability to communicate across large sea areas using low frequency sounds (Evans, 1987, Würsig and Evans, 2001). However, there is little available literature on the hearing of this group, but the sounds they produce are typically low frequency, in the range below 1 kHz, with some actually as low as 20 Hz. It is assumed, therefore, that they are sensitive to low to medium frequency sounds.

Seals also produce sounds under water, but these are restricted to clicking and barking sounds in the frequency range from somewhat lower than 1 to 4 kHz. Harbor seals, which are found along the entire coast of Norway, can perceive sounds at frequencies as high as 180 kHz, while their sensitivity is low for sounds above 60 kHz (Harwood and Wilson, 2001).

6.2 Harmful effects

Harmful effects on hearing resulting from sound energy can be divided into temporary and permanent hearing damage. The extent depends on the intensity of the sound, the frequency and the duration of the specific sound. Studies of certain dolphin species in captivity have shown that they may suffer temporary hearing damage if they are exposed to sound at a level between 193-196 dB rel. 1 µPa for one-second intervals in the frequency range around 20 kHz (Ridgway et al., 1997). A similar study refers to the same effect on beluga whales (Finneran et al., 2002). One assumption made is that these species are most vulnerable to temporary hearing damage in the same frequency range used by the species itself (Hildebrand, 2004). For baleen whales, this assumption would mean that they are most vulnerable to low frequency sound, while smaller species of beluga whales are most vulnerable to medium to high frequency sound. Erbe (2002) found that orcas could suffer permanent hearing damage if they were exposed to noise above a critical level over a longer time period, based on acoustic modeling.

There has been little study of the harmful effects of seismic survey activity and sonar on marine mammals; however, there have been discussions as to whether the phenomenon of mass stranding of whales can be connected with the use of military sonar. On three occasions, these incidents coincided with military exercises.

In 1996, there was a mass stranding of beaked whales along the Greek coast in the Mediterranean. This incident occurred during the same time period as a major NATO drill took place in the same area. Examinations were subsequently conducted on eight of the dead individual whales, but there were no abnormal findings (Frantzis, A.; afratzis@atlas.uoa.gr).

After a stranding of beaked whales in the Bahamas in 2000, severe internal hemorrhaging was found in the cavities inside their skulls (Balcomb and Claridge 2001). They suggested that these hemorrhages could have been caused by resonance in soft tissues and inside the skull due to strong sound within certain frequencies which coincided with the resonance frequencies for the above-mentioned organs. However, it was also proposed that this could just as easily have been an effect of illness.

A mass stranding of whales on the Canary Islands in 2002 took place during the same period as a major marine exercise using low frequency sonar. Subsequent pathological examinations of the dead whales indicated that the whales may have died due to decompression sickness (Jepson et al., 2003). Two theories were subsequently presented:

1) The animals were frightened by the sonar during diving, and rose too quickly to the surface.

2) The sound waves from the sonar caused an expansion of microscopic gas bubbles in the blood and damaged the organs.

The theories proposed by Jepson et. al (2003) are not well documented. A study by Falke et al. (1985) on Weddle seal shows, in fact, that rapid ascent does not increase the danger of decompression sickness. The study showed that since the lungs are compressed at a depth of approx. 30 meters, the nitrogen content in the blood will be limited, and in fact less after a rapid ascent than after a slow ascent. The other theory (2) has not been documented.

With regard to seals, a controlled study was conducted under the direction of the Norwegian Defence Research Establishment (FFI) (Sevaldsen and Kvadsheim, 2006). Four harbor seals were placed in an aquaculture cage and equipped with sensors to monitor diving activity, swimming activity and heart rate. A sound source was placed at a depth of 5 m, close to the cage. Pairs of the animals were subjected to noise in the frequency range from 1.3 to 7.0 kHz in repeated sequences. The seals reacted to the sound signals in the form of increased swimming activity, by staying as far away from the sound source as possible and by jumping up on to a raft placed in the cage. Neurological examinations were subsequently performed on the animals, and no injuries or other abnormal findings were identified on the animals after the experiment.

6.3 Behavioral effects

Behavioral studies of marine mammals are generally difficult to perform, and there may be great uncertainty associated with the results of these studies. Marine mammals, and whales in particular, spend as much as 60% of their lives under water, which poses a significant restriction in the ability to observe them.

The frequencies used by baleen whales overlap to a greater degree than those used by beluga whales with the frequencies used to shoot seismic surveys. For example, fin whales use calling signals that lie in the frequency range between 20 and 40 Hz (Evans and Nice, 1996), while seismic exploration activity utilizes the entire frequency spectrum up to 220 Hz. Therefore, these species are considered to be more vulnerable to seismic disturbances (Evans and Nice, 1996), and for that reason more behavioral studies have been performed on this group.

During the period 1998-2000, a study was conducted in British waters where the behavioral patterns of various baleen whales and beluga whales were observed in connection with seismic surveys (Stone 2003). The species consisted of dolphin, pilot whales, orcas, sperm whales, fin whales and minke whales. The observation rate for all of the whale species as a whole declined during seismic shooting, but there were also annual fluctuations during this three-year period. It was also observed that the whales had a tendency to stay farther away from the seismic vessels during shooting, than when there was no shooting with the air guns. The most common reaction observed during shooting with the air guns was fleeing or a change in swim direction away from the seismic vessels. On the part of the smaller beluga whales, swimming speed increased and the swim direction was also changed. For the large baleen whales, fin whales and sei whales, a change in the diving pattern was also observed, in which the animals stayed on the surface more during shooting as opposed to diving. In addition, grazing activities dropped for all of the species combined. Some indications showed that the orca exhibited a greater tolerance for seismic shooting when this took place in deeper water.

An interesting observation made was that the various species appeared to adopt different strategies for avoiding the sound sources. The smallest beluga species appeared to exhibit the strongest escape response, while the baleen whales and the orca showed a weaker tendency to flee. No behavioral changes could be seen in the sperm whale in connection with air gun shooting. Other studies refer to this same response on the part of sperm whale (Madsen et al., 2002) and it is uncertain whether this is an individual or a species-related response. Mate et al., 1994 observed that sperm whales swam away when seismic surveys were started at distances of up to 50 km.

The findings of Stone (2003) confirmed earlier studies carried out on species such as gray whales, Greenland whales, and humpback whales (Malme et al., 1988; Richardson et al., 1995; 1986; Ljungblad et al., 1988). Generally speaking, one can say that an escape response was observed in connection with air gun shooting, and that the response declined in proportion with increasing distance between the whales and the sound source. Weller et al. (2002) studied a population of gray whales off the Sakhalin Peninsula in the Pacific Ocean for a period before, during and after seismic survey activity was conducted. The result of the study showed that the gray whales withdrew from the grazing area where the activity took place and returned to the grazing areas after the seismic survey activity was concluded.

However, other studies indicate that the pattern of reaction depends on whether the animals are migrating or whether they are resting at the surface. McCauley et al. (2000) observed that groups of humpback whales, consisting of adults and calves in the resting phase, were more sensitive and exhibited escape reactions. Animals engaged in migration did not exhibit the same behavioral response. Some males appeared to be attracted to seismic sound as the sounds could be similar to the sounds produced by other individuals that jumped out of the water or beat their fins on the sea surface.

The effects of seismic survey activity on seals are less studied. In a study conducted in the Beaufort Sea off Alaska, no behavioral changes or escape reactions were observed. It showed that the population of animals remained largely the same within the same area, with only minor escape responses (Harris et al., 2001). Some observations have shown that the animals' natural instincts and activity level can override the direct effect of these disturbances. In connection with reproduction and the search for food, it was observed that seals can tolerate strong sound pulses before exhibiting an escape response (Richardson et al., 1995).

6.4 Masking

When the sound created by humans is within the same frequency range as the frequencies used by marine mammals, this can reduce the possibility of e.g. communication between individuals and echo localization. Such an effect is often called masking. An animal located near a sound source will only be able to perceive animals that are close by.

The problems associated with masking are reduced when marine mammals are able to change the strength of the signals they emit. Studies of individual species in captivity have shown that this is the case for echo localization sounds. The animals could vary the level of the echo localization pulses in relation to the background noise so that they sent stronger signals when there was strong background noise (Richardson et al., 1995). Other studies have shown that orcas can also increase the duration of their calling signals when there is a significant increase in the level of background noise (Foote et al., 2004).

Directional hearing can probably also affect the masking effect so that it becomes more pronounced when the animal tries to take in sounds coming from the same direction as the disturbing sound source, while the masking effects are less if the signals come from a different direction.

Sound created by humans occurs more often at lower frequencies than the echo localization signals used by beluga whales. Baleen whales can be more vulnerable as they utilize communication signals in a lower frequency range than beluga whales.

6.5 Summary

There is limited knowledge regarding the effects of seismic surveys on marine mammals. This is connected in part to the fact that it is difficult to conduct controlled experiments on marine mammals, and particularly the larger species of whales, to determine the effects of seismic shooting.

There are few indications that marine mammals suffer injury to internal organs as a consequence of sound created by humans. The data base builds on studies of three mass strandings that occurred during the same time period as marine exercises involving sonar. There are no such observations for seismic surveys.

Behavioral studies indicate that marine mammals react to seismic noise by leaving the area where such activity is taking place. Effects on both breathing rate and time spent at the surface have also been observed. As regards grazing behavior, changes have been observed in connection with increased activity at/near the surface.

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Appendix I – Names of species

English species names	**Latin species names**
Fish	
Anchovy	*Engraulis mordax*
European sea bass	*Dicentrarchus labrax*
Whiting	*Merlangius merlangus*
Haddock	*Melanogrammus aeglefinus*
Blue whiting	*Micromesistus poutassou*
Pollock	*Pollachius pollachius*
Turbot	*Psetta maxima*
Pink snapper	*Pagrus auratus*
Plaice	*Pleuronectes platessa*
Coalfish	*Pollachius virens*
Herring	*Clupea harengus*
Sandeel	*Ammodytes marinus*
Cod	*Gadus morhua*
Redfish species	*Sebastes spp.*
Salmon	*Salmo salar*
Rainbow trout	*Salmo gairdneri*
Crustaceans	
Dungeness crab	*Cancer magister*
Snow crab	*Chionoecetes opilio*
Gammarus locusta	*Gammarus locusta*
Molluscs	
Mussel	*Mytilus edulis*
Flat periwinkle	*Littorina obtusata*
Edible periwinke	*Littorina littorea*
Marine mammals – Baleen whales	
Blue whale	*Balaenoptera musculus*
Fin whale	*Balaenoptera physalus*
Gray whale	*Eschrichtius robustus*
Greenland whale	*Balaena mysticetus*
Humpback whale	*Megapthera novaeanglia*
Sei whale	*Balaenoptera borealis*
Minke whale	*Balaenoptera acutorostrata*
Marine mammals – Beluga whales	
Pilot whale	*Globicephala melas*
Beluga whale	*Delphinapterus leucas*
Atlantic white-sided dolphin	*Lagenorhynchus acutus*
White-beaked dolphin	*Lagenorhynchus albirostris*
Bottlenose whale	*Hyperoodon ssp*
Orca (killer whale)	*Orcinus orca*
Sperm whale	*Physeter macrocephalus*
Harbour porpoise	*Phocoena phocoena*

Marine mammals – Seals	
Harp seal	*Phoca groenlandica*
Walrus	*Odobenus rosmarus*
Hooded seal	*Cystophora cristata*
Ringed seal	*Phoca hispida*
Harbour seal	*Phoca vitulina*
Bearded seal	*Erignathus barbatus*
Weddel seal	*Leptonychotes weddeli*

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