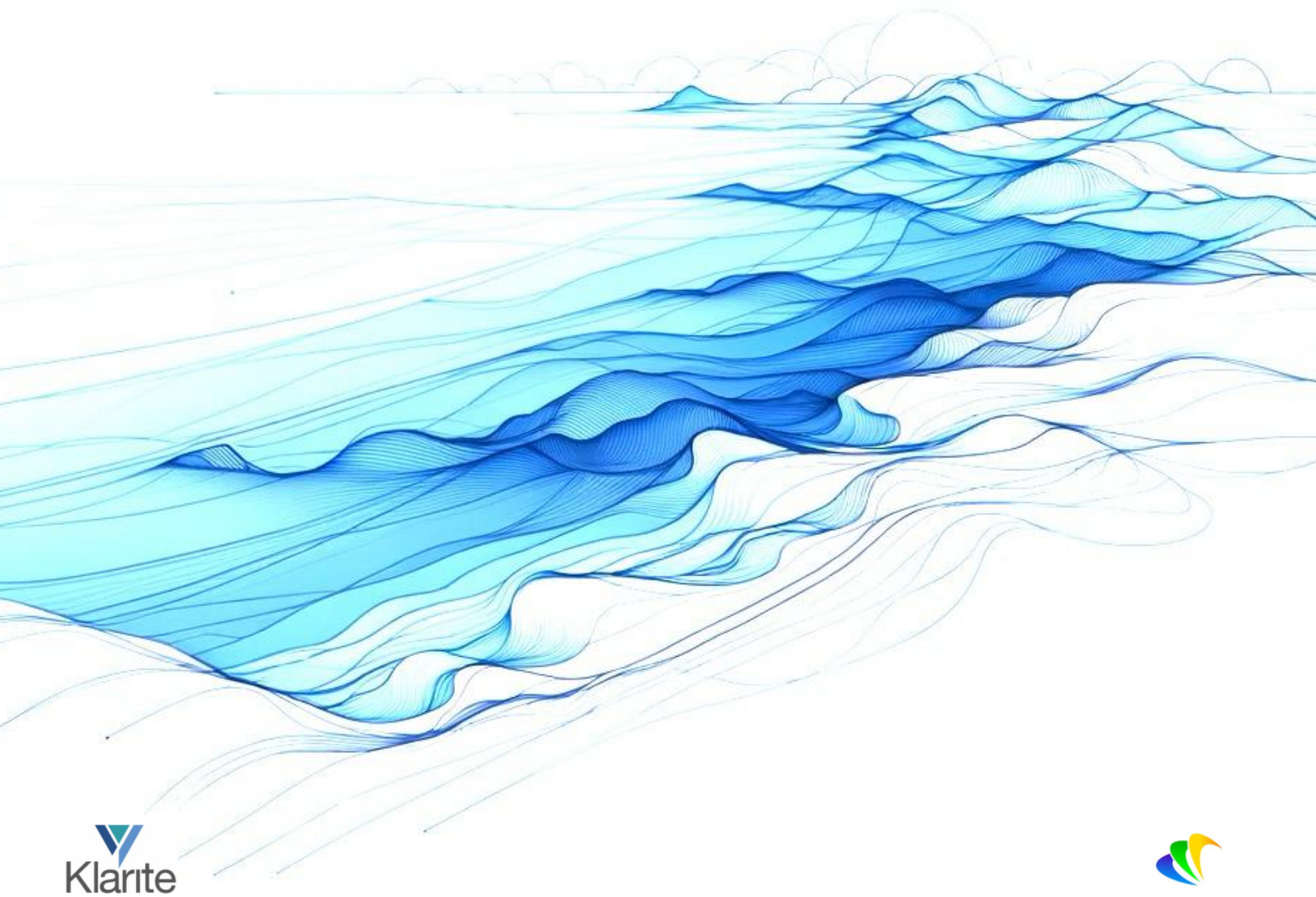
REGIA
Marine Seismic Survey

Seismic Studies Summary

Appendix B8: REG-EP-011-B8

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Klarite

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1 Introduction

Marine fauna use sound in a variety of functions, including social interactions, foraging, orientation, and responding to predators. The type and scale of effect of seismic sound emissions on receptors depends on several factors including the level of exposure, the physical environment, the location of the receptor in relation to the seismic source, how long the receptor is exposed to the sound, the exposure history, how often the sound repeats (repetition period) and the ambient sound level.

This document provides a summary of the available information that will be used to inform the acoustic impact assessment for the Regia Marine Seismic Survey (Regia MSS).

1.1 Baseline Soundscape in the Otway

Ambient noise in the ocean is the background sound that incorporates the broad range of individual sources, some identified and others not. There are three frequency bands under which different noise sources are generally categorised: low (10 to 500 Hz), medium (500 Hz to 25 kHz) and high (>25 kHz). The low-frequency band is dominated by manmade (anthropogenic) noise sources, with the primary source of low-frequency anthropogenic noise coming from commercial shipping. Seismic exploration also falls under this low-frequency band. Both commercial shipping and seismic sources contribute to ambient noise across ocean basins, as low-frequency sound experiences little attenuation, allowing for long-range propagation. The highest levels of ocean ambient noise within the band of interest (10 Hz to 100 kHz) are seen at low frequencies (Hildebrand 2009) For context and visualisation, Figure B8-1 below provides a general comparison of various sound sources as per their frequency and sound-type (natural, impulsive or continuous).

Because of greater attenuation, medium frequency sound cannot propagate over long distances, and only regional (10s of km distant) sound sources contribute to the ambient soundscape. Breaking waves, sea-surface agitation, spray, bubble formation and collapse, and rainfall are some of the main natural factors contributing to the makeup of ambient noise in the mid-frequency band. Other sources such as military sonars and small vessels also contribute anthropogenic noise at mid-frequencies. At high frequencies, acoustic attenuation becomes extreme so that all noise sources are confined to a localised region in close proximity to a receiver. Thermal noise is the dominant noise source above about 60 kHz (Hildebrand 2009). Other sources that significantly contribute to the natural marine ambient soundscape across all frequency bands include cetaceans, fish, and snapping shrimp.

Ambient sound sources and levels in the Otway Basin have been studied and measured as part of previous impact assessment activities for the petroleum industry. We describe these assessments below.

In a desktop review conducted by McCauley and Duncan (2001) to investigate the underwater sound sources likely to be prevalent in the Otway Basin, they concluded that natural noise sources are dominated by wind, rain, biological sources, and sporadic noise from earthquakes. Anthropogenic noise was found to be mainly derived from vessel traffic, both commercial and small, petroleum production, exploration drilling activities, and sporadic seismic surveys.

Erbe et al. (2016) present some key detections by the Integrated Marine Observing System (IMOS), where underwater sound was recorded in a region south of Portland, Victoria. Leading sound sources identified in these recordings included Antarctic and pygmy blue whales, fin whales, ship noise (at 20-200 Hz), and fish noise (at 1-2 kHz).

A sound monitoring study in the Gippsland Basin, Bass Strait indicated that the primary sources of background noise were wind, rain, and current and wave-associated sound. Considerable variation in background sound was observed at these study locations, but low frequencies reportedly dominated (Przeslawski et al. 2016a).

As part of a study to gain an understanding of the soundscape in the marine environment for a petroleum development project in the Otway, Woodside Petroleum Limited placed a noise logger in a shipping lane approximately 60 km south of Port Fairy, Victoria (Woodside 2003 cited in Beach 2024). This part of the study was conducted between November 2001 and March 2002 with the following results observed:

- Regular transiting of boats.
- Regular fish choruses throughout the dawn, day, and evening.
- Persistent blue whale calling that spanned several hours.
- Whale-calls from at least three other whale species.
- Baseline broadband underwater noise for the duration of the test was between 93 and 97 dB 1 µPa. Shipping increased the average noise level to above 105 dB re 1 µPa for 6% of the duration during which the logger was deployed.

JASCO Applied Sciences (Australia) recently conducted a study for Beach Energy Ltd with the aim of providing an acoustic characterisation of the offshore petroleum activity (drilling) and associated vessel activity within the Otway Basin. Results from a recorder stationed farthest from the rig (25 km) indicated median broadband ambient noise was 104.5 dB re 1 μ Pa, with a mean of 118.3 dB re 1 μ Pa, Noise levels ranged between 86.6 dB re 1 μ Pa, and 153.6 dB re 1 μ Pa (Beach 2024).

1.1.1 Regia MSS Operational Area Soundscape

In addition to natural sources of ambient sound as described previously, there are also anthropogenic activities that are expected to emit sound in the Regia MSS Operational Area. Sources of anthropogenic sound known to occur in this region of the Otway Basin include both permanent and temporary activities such as shipping traffic, commercial fishing and recreational activities, petroleum development/production and exploration-drilling activities and sporadic petroleum seismic surveys.

The nearest point sources of industrial noise are associated with existing offshore gas fields. These include the Beach Energy Otway Development which comprises subsea infrastructure and the Thylacine-A unmanned platform. and also, the Cooper Energy Casino Henry Netherby Development consisting of subsea infrastructure (Appendix B12 MAP-REG-EPM-082). Across an entire gas exploration program of which the Regia MSS is one component, there is the potential for sound-emitting exploration and development activities such as infrastructure maintenance and repairs, seabed surveys, seismic surveys, drilling, and installation of infrastructure using vessels and drill rigs, all in support of ongoing energy supply of gas and potentially renewables within the Otway Basin.

The main shore-based sources of industrial noise are at Portland (Victoria), where the Alcoa Aluminium Smelter operates, and the Port of Portland which handles the import and export of bulk commodities.

Noise will be generated from two primary sources during the Regia MSS: the survey vessel, and the active sound source. The active sound source typically generates much higher noise levels than the survey vessels and is predicted to dominate overall underwater sound emissions at times when data acquisition is occurring. The frequency of the sound produced from each seismic pulse is primarily less than 2 kHz, with the highest levels at frequencies in the range of 10-500 Hz (McCauley 1994). This frequency band is notably comparable with that described by Erbe et al. (2016) to have been related to ship noise at the IMOS site at Portland, Victoria.

While the soundscape will be altered during the Regia MSS, this effect is transient and will cease once the MSS is completed. Sound levels will return to natural levels with no expected lasting or long-term changes. While the change to ambient sound has been assessed as minor and, temporary, a change to the ambient soundscape nevertheless has the potential to impact several biological receptors. Impacts to these biological receptors from underwater sound have been assessed independently in appendices E2-E7.

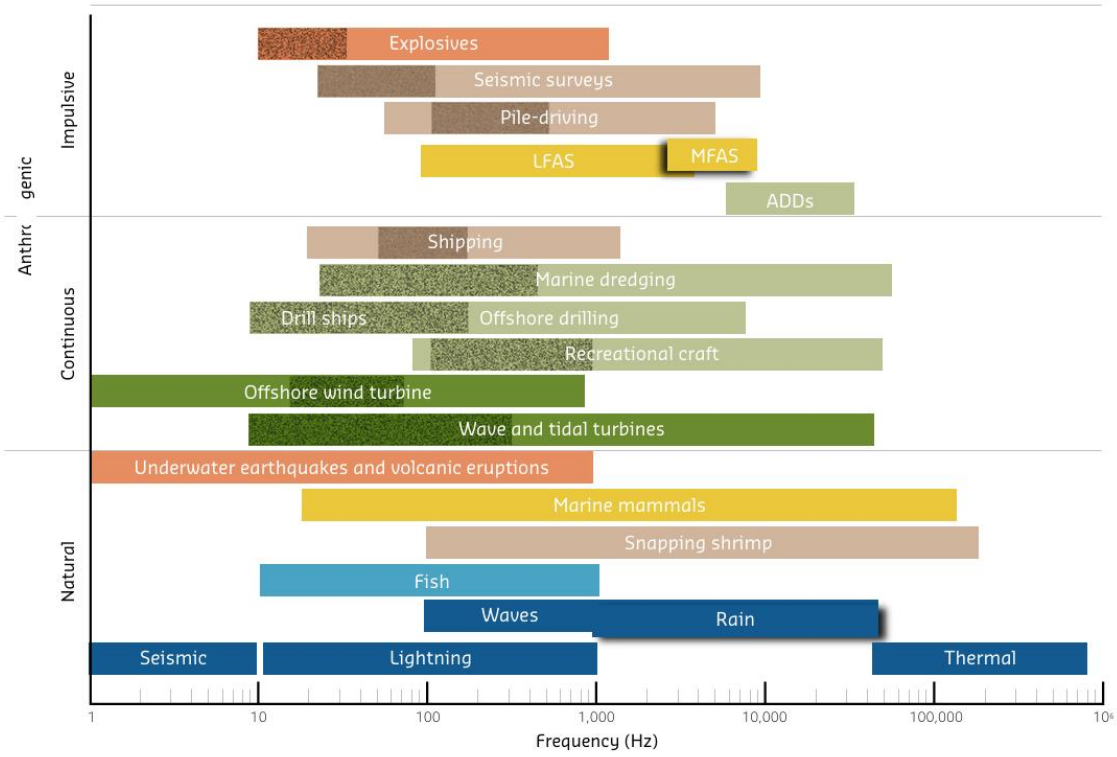


Figure B8-1: Comparison of sound sources, where the order shows the relative sound pressure levels (dB) of the noise sources and the colour code allows comparison of the levels between categories: orange (represents the highest dB level) to dark blue (represents lowest dB level). The areas with hatching indicate the frequency range with most energy. MFAS = medium frequency active sonar, LFAS = low frequency active sonar, ADD = acoustic deterrent device (Thomsen et al. 2021).

1.2 Overview of Seismic Acoustic Emissions

When underwater objects vibrate, they create sound-pressure waves that alternately compress and decompress the water molecules as the sound wave travels through the sea. Sound waves radiate in all directions away from the source like ripples on the surface of a pond. The compressions and decompressions associated with sound waves are detected as changes in pressure by the receiver.

Sound moves at a faster speed in water than in air because the mechanical properties of water differ from air. The reference level used in air (20µPa @ 1m) was selected to match human hearing sensitivity. A different reference level is used for underwater sound (1µPa @ 1m). Because of these differences in reference standards, noise levels cited in air do not equal underwater levels.

The energy, or intensity (loudness) of a sound is measured on the decibel (dB) scale. It takes about 61.5 times more energy to transmit a sound through air than through water. Because of this energy difference, there is a 61.5 dB difference between sounds transmitted through air and water, such that a sound intensity of 120 dB in water would be equivalent to an intensity of about 60 dB in air (Webb 2023).

Impulsive underwater acoustic emissions will result from the seismic source releasing compressed air (seismic pulse) that creates a sound wave that is directed downwards into the seabed.

Underwater acoustic emissions from a seismic source are characterised by high energy pulses of low frequency sound. The frequency of the sound produced from each seismic pulse is primarily less than 2 kHz, with the highest levels at frequencies in the range of 10-500 Hz (McCauley 1994).

The rate of sound attenuation from the seismic source is dependent on local sound propagation characteristics, including seawater temperature and salinity profiles, water depth, bathymetry and the geoacoustic properties of the seabed (McCauley 1994). While the seismic pulses are directed downwards, horizontal propagation may be detected over long distances due to the high intensity and low frequency properties of the sound.

Sound travels as a wave with the amplitude of the wave related to the amount of acoustic energy it carries. Figure B8-2 shows a representative sound wave and the sound metrics used in this studies summary. Table B8-1 provides definitions of the sound metrics and other sound related terms used in this studies summary.

The particle motion component of sound is also relevant to the assessment of potential impacts to marine fauna. Acoustic particle motion refers to the physical motion caused by a sound wave within the water, seafloor or other medium. Unlike pressure, particle motion is directional in nature, although the actual to-and-fro particle displacements that constitute sound are extremely small, in the order of nanometres (Popper & Hawkins 2018). Particle motion can be described in terms of particle displacement (m), velocity (m/s), or acceleration (m/s-2) (Popper et al. 2014; Carroll et al. 2017). Alternatively, it is sometimes expressed in dB with respect to a reference value of displacement (dB re 1 pm), velocity (dB re 1 nm/s) or acceleration (dB re 1 $\mu m/s^2$) (Nedelec et al. 2016).

Particle motion is important because marine invertebrates and most fishes are primarily sensitive to particle motion rather than sound pressure and, therefore, particle motion is the most relevant metric for perceiving underwater sound by invertebrates and most fish species (Popper & Hawkins 2019). It is of less importance to marine mammals as evolution of the mammalian ear operating in air has led to a greater dependence on pressure for hearing sound (Finneran et al. 2002). There is currently limited information available to quantify the particle motion sensitivity of fishes and invertebrates. It is complex and challenging to directly measure particle motion compared to sound pressure, hence most research is presented in the context of sound pressure or exposure levels instead of particle motion (Carroll et al. 2017; Popper & Hawkins 2018).

It should be noted that particle motion is most relevant close to the source where it is the dominant component of a sound wave (i.e., in the near field), while pressure will dominate a sound wave propagating over distance (i.e., in the far field) (Radford et al. 2012; Morley et al. 2014; Nedelec et al. 2016; Popper & Hawkins 2018). Sound pressure levels received at increasing distance from a source do not, therefore, provide a reliable representation of particle motion. Organisms that are sensitive only to particle motion have typically been found to be sensitive only at close range where these particle motions are greatest (Popper et al. 2014; Edmonds et al. 2016; Popper & Hawkins 2018).

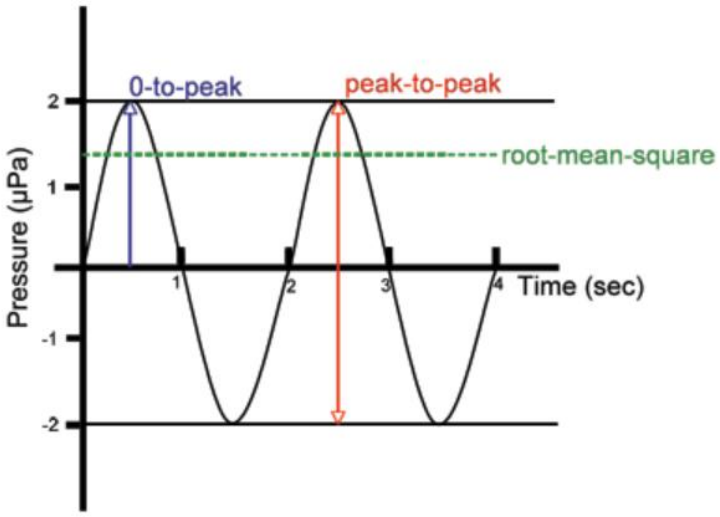


Figure B8-2 - Simplified Sound Wave and Sound Pressure Metrics (DOSITS 2023)

Table B8-1 - Underwater Sound Terminology

Term	Definition
0-to-peak or Peak sound pressure level (PK)	The peak pressure, also called the 0-to-peak pressure, is the range in pressure between zero and the greatest pressure of the signal. It is represented by PK and the unit dB re 1 µPa and summarised as dB PK.
Peak-to-peak sound pressure level (PK-PK)	The peak-to-peak pressure is the range in pressure between the most negative pressure and the most positive pressure of the signal. It is represented by PK-PK and the unit dB re 1 µPa or dB re 1 µPa2m2 and summarised as dB PK-PK.
Permanent threshold shift (PTS)	Permanent loss of hearing sensitivity at certain frequencies caused by excessive sound exposure.
Received sound level	The sound level measured at a receiver.
Root mean square sound pressure level (RMS)	The root-mean-square pressure is the square root of the average of the square of the pressure of the sound signal over a given duration. It is represented by sound pressure level (SPL) and the unit dB re 1 µPa and summarised as dB SPL.
Sound exposure level (SEL)	A measure of the sound energy that considers both received level and duration of exposure. SEL is specified in terms of either single pulse (SEL) or a defined accumulation period (SEL_{cum}). For this assessment 24 hrs is used for the accumulation period and is shown as SEL24h. Units are dB re 1 µPa2 s or dB re 1 µPa2m2s.
Source sound level	The sound pressure level or sound exposure level measured 1 metre from a theoretical point source that radiates the same total sound power as the actual source.
Temporary threshold shift (TTS)	Temporary loss of hearing sensitivity at certain frequencies caused by excessive sound exposure.

2 Assessment Input

2.1 Public Comment

The completed EP was published for public comment on the NOPSEMA website on 25 Jan 2024 for a 30-day period, closing 26 February 2024. Table B8-2 shows how this feedback has been incorporated into the environmental assessments.

Table B8-2 - Public comment input into the preparation of the EP

Matter	Matter ID	Changes made arising from public comment
Matter: Research on impacts of anthropogenic noise on marine mammals.	M11	CGG has considered these claims and has updated the EP Seismic Studies Report (Appendix B8) Section 8.

3 Zooplankton (including Fish and Invertebrate Eggs and Larvae)

This section summarises the published studies in relation to seismic acoustic emission studies on plankton and fish and invertebrate eggs and larvae. Plankton is a collective term for all marine organisms that are unable to swim against a current. This group is diverse and includes phytoplankton (plants) and zooplankton (animals), as well as fish and invertebrate eggs and larvae.

Some zooplankton can sense pressure changes to some degree. Swim bladders may also develop during the larval stages of some fish species, rendering larvae susceptible to pressure-related injuries such as barotrauma (Popper et al. 2014). Data on the effects of sound upon eggs and larvae containing gas bubbles is, therefore, largely focused on barotrauma rather than actual hearing. Very few publications have considered the effects of particle motion or vibration on plankton (Popper et al. 2014).

Few studies have found significant negative impacts on zooplankton, fish eggs, larvae, or fry, and most have reported that impacts occur within a few metres or tens of metres from the source (Kostyuchenko 1973; Dalen & Knutsen 1987; Holliday et al. 1987; Kosheleva 1992; as cited in Parry et al. 2002; Pearson et al. 1994; Turnpenny & Nedwell 1994; Booman et al. 1996; Payne et al. 2004; Payne et al. 2009). These studies included exposures to sound pressures up to approximately 242 dB SPL. Larval stages of fish are often perceived to be more sensitive to stressors than adult stages, but exposure to seismic sound does not appear to result in any differences in larval mortality or abundance for fishes, crabs, or scallops (Carroll et al. 2017).

Kostyuchenko (1973) found up to a 17% increase in mortality of fish eggs of various species exposed to a seismic source, but no effect beyond 10 m. Kosheleva (1992; as cited in Turnpenny & Nedwell 1994) also reported that eggs and larvae died within 1 m of a seismic source producing sound pressures of 220-240 dB SPL, but no injuries were reported at greater distances. Dalen and Knutsen (1987) exposed eggs, larvae and post-larval stages of cod exposed to seismic source elements with source levels of 222 – 231 dB SPL at 1 m. At ranges of 1 – 10 m from the source, some specimens indicated temporarily impaired balance following exposure but with rapid recovery. Mortality was only observed in just one of the three exposure experiments, with 90% mortality when exposed at 2 m from the seismic source, but no significant impacts at 6 m from the seismic source. Overall, there was no significant change in the survival of eggs.

Holliday et al. (1987) obtained mixed results during studies undertaken over a two-year period, with eggs and larvae exposed to sound pressures of 221 – 235 dB SPL at 1.5 m from a seismic source. Either no significant impact was observed or a 9% reduction in the survival of eggs. Pearson et al. (1994)

reported no effects to crab larvae exposed to sound pressures up to 231 dB SPL at 1 m from a seismic source. Booman et al. (1996) exposed fish eggs and larvae to sound pressures of 220 – 242 dB SPL. High rates of mortality were observed at distances of 1.4 m from the seismic source, but low or no mortality rates at distances of 5 m.

In a review of the above studies, Payne et al. (2004) noted that injury and mortality to eggs and larvae is likely to be limited to within 5 m of the seismic source. Payne et al. (2009) found no statistical differences between controls and exposed larvae following exposure to mean sound pressure levels of 205 dB PK-PK, positioned 0.5 m from the seismic source element.

Parry et al. (2002) undertook studies on the effects of a marine seismic survey on scallop fisheries in Bass Strait, including on larvae. This study was undertaken in December 2001 and February 2002 during a 3D marine seismic survey undertaken by Esso Australia in the Gippsland Basin, which used a 3,542 m^3 source towed 6 m below the sea surface. Plankton samples (impact and duplicate) were collected from five sites located 500 m apart in water depths of 55 m in a Before-After-Control-Impact (BACI) experimental study. The study results found few bivalve larvae in the live plankton samples and there was no significant difference in the number of bivalve larvae found in samples collected before and after passage of the seismic vessel (the same was true for all planktonic taxa). Parry et al. (2002) postulated that invertebrates that do not contain gas spaces (like swim bladders in fish) appear to be very resilient to seismic pulses. The research also notes that while the study does not exclude the possibility that some changes to planktonic communities resulted from the seismic survey, the failure to detect any impacts occurred because impacts were small. Parry et al. (2002) also indicated there is no evidence of mortality-associated population effects such as reduced abundance in plankton a few hours after exposure.

Pearson et al. (1994) exposed crab larvae to single pulses from a seismic source array (840 m^3) with a measured sound pressure level of 231 PK-PK at 1 m. For immediate and long-term survival and time to moult, this study did not reveal any statistically significant differences between the exposed and unexposed larvae, even those exposed within 1 m of the seismic source.

Impacts to scallop larvae have been identified following intense and lengthy periods of exposure to low-frequency sound. Tank experiments by Aguilar de Soto et al. ((2013)) showed evidence of morphological abnormalities in early-stage scallop larvae from simulated seismic signals for a 6,920 in^3 seismic source. However, the lengthy exposure period of 3 second pulse intervals for an exposure duration of 90 hours and at 1 m distance from sound source is not realistic of an actual survey. Christian et al. (2003) found major developmental differences between control and treatment groups of snow crab eggs exposed to a peak pressure level of 216 dB SPL every 10 seconds for 33 minutes. Again, the exposure to a constant peak pressure level for a prolonged period is not realistic of an actual survey where the source is moving and so does not remain in one place.

Hawkins (2014) used continuous sonar to record zooplankton layers, comprising copepods, cladocerans, decapod larvae, gastropod larvae, and bivalve larvae, exposed to playback of pile driving sound (pile driving sound typically has a more rapid rise time, more frequent strike rates and therefore a greater sound exposure regime than a seismic survey). Zooplankton layers responded to sound by showing a 'dent' in the top of the layer at the onset of the sound sequence, although the change in depth often did not persist for the whole duration of the sound exposure and zooplankton distribution quickly returned to normal.

Day et al. (2016a) found no effects on the mortality, abnormality, competency, or energy content of lobster larvae after exposure of early embryonic stages to seismic exposure. In this study, egg-bearing female southern rock lobsters (*Jasus edwardsii*) were exposed to signals from three air gun configurations, all of which exceeded sound exposure levels (SEL) of 185 dB re 1 $\mu Pa^2 \cdot s$ (209-212 dB PK-PK). Lobsters were maintained until their eggs hatched and the larvae were then counted for fecundity, assessed for abnormal morphology using measurements of larval length and width, tested for larval competency using an established activity test and measured for energy content. Overall, there were no differences in the quantity or quality of hatched larvae, indicating that the

condition and development of spiny lobster embryos were not adversely affected by air gun exposure. Day et al. (2016a) detailed that the results suggest that embryonic spiny lobster are resilient to air gun signals and highlight the caution necessary in extrapolating results from the laboratory to real world scenarios or across life history stages.

Based on the studies discussed above, physical impacts to planktonic organisms have typically been found to be limited to within approximately 10 m of the seismic source. Using this 10 m impact range, a study by McCauley (1994) calculated the impact in a seismic survey area, assuming plankton mortality of 100% within 10 m of a seismic source. This suggested that the total mortality due to seismic testing would impact less than 1% of plankton in the survey area. DNV Energy (2007) and Hawkins & Popper (2012) conducted comprehensive reviews of a number of scientific studies, including those by Kostyuchenko (1973), Dalen & Knutsen (1987), Booman et al. (1996) and Saetre & Ona (1996); the effects of seismic activities on eggs and larvae were predicted to result in average and worst-case mortality rates of 0.0012% and 0.45% per day respectively, which were not deemed significant when compared to a natural mortality rate of 5-15% per day, as applicable to most species during early life stages. Natural mortality rates in larvae can be much higher than this—exceeding 50% per day in some species and commonly exceeding 10% per day (Tang et al. 2014). For example, in a review of mortality estimates (Houde & Zastrow 1993), the mean mortality rate for marine fish larvae was M = 0.24, a rate equivalent to a loss of 21.3% per day.

In 2014, noise effect criteria for fish eggs and larvae were established by the American National Standards Institute (ANSI) accredited report of sound exposure guidelines for fishes and sea turtles (Popper et al. 2014). The criteria from Popper et al. (2014) are from an offshore pile driving study by Bolle et al. (2012) that indicated no damage was caused by simulated repeated pile driving (100 strikes at 100 m) of 210 dB SEL_{cum}. Popper et al. (2014) also detailed that other studies suggest that eggs and larvae in proximity (<5 m) to a seismic source are likely to suffer mortality and tissue damage (Kostyuchenko 1973; Booman et al. 1996). Sætre and Ona (1996) concluded that mortality rates caused by exposure to seismic source sounds are so low compared to natural mortality that the impact from seismic surveys must be regarded as insignificant.

However, a study by McCauley et al. (2017) received notable attention for suggesting the potential for zooplankton mortality to increase two- to three-fold out to 1.2 km from a single seismic source element, with an estimated decline in zooplankton abundance of up to 64% and a “hole” in the zooplankton backscatter observed via acoustic detection methods. The 1.2 km range corresponded with pressure levels of 178 dB PK-PK (McCauley et al. 2017). However, the extent of such impacts is inconsistent with previously and subsequently documented effects to plankton.

The findings of this study have been questioned by several reviews (Richardson et al. 2017; IAGC 2017; Fields et al. 2019) particularly in relation to:

- There was no evidence of attenuation of impacts with distance from the source with no consistent decline in the proportion of zooplankton that were killed with increasing distance from the source.
- Sonar backscatter data indicated an immediate decline in zooplankton abundance (the “hole” in the data). However, if the zooplankton had been killed, they would not have sunk from the surface layers of the water column immediately, suggesting that some zooplankton may have moved, or they may have simply reorientated themselves to the sonar in response to the seismic pulses, which raises questions over the occurrence, magnitude, and extent of mortal impacts.
- The study was based on a relatively small number of tow samples on two separate days. On the second day, even before the use of the seismic source element, the zooplankton net tow abundance counts were significantly lower than the first day and, therefore, it is difficult to draw reliable conclusions from these data. On the second day almost all values at 80 m range presented greater plankton abundance from exposed samples and lower

abundance of control samples, indicative of a potential flaw in the sampling scheme and analysis protocol.

The McCauley et al. (2017) study was undertaken in early March 2015, using two replicated experiments in Storm Bay in southeast Tasmania. It involved the deployment of acoustic noise loggers to measure air gun signals and used an acoustic source volume of 150 in^3 and operating pressure of 2,000 psi. The study measured zooplankton abundance and the proportion of the population that was dead at three distances from the acoustic source - 0, 200 and 800 m. The experiment estimated the proportion of the zooplankton that was dead, both before and after exposure to acoustic source sound, using net samples to measure zooplankton abundance, and bioacoustics to identify the distribution of zooplankton. In this study, copepods dominated the mesozooplankton (0.2-20 mm), and impacts were not assessed on microzooplankton (0.02-0.2 mm) or macrozooplankton (>20 mm). There was movement of water through the experimental area, which made interpreting their results more difficult (Richardson et al. 2017).

The results of the experiment found that zooplankton exposure to acoustic sources increased the mortality rate from a natural level of 19% per day to 45% per day (on the day of exposure), with this mortality rate observed out to 1.2 km. This is more than two orders of magnitude greater than the 10 m previously assumed (McCauley et al. 2017). These results escalated the concerns that some stakeholders had about the effects of marine seismic surveys on plankton, particularly fishers and conservation groups.

This study postulates that the external sensory hairs that zooplankton possess may be extremely sensitive and in response to seismic sound, may 'shake' to the point where damage could accrue to sensory hairs or tissue. Importantly, the study notes that for anthropogenic sources to have significant impacts to plankton at an ecological scale, the spatial or temporal scale of the impact (i.e., the seismic survey) must also be large when compared to the impacted ecosystem.

In response to this research, the Australian Petroleum Production and Exploration Association (APPEA) commissioned the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to assess the potential local and regional impacts on zooplankton of a typical marine seismic survey. A large-scale marine seismic survey conducted on the North West Shelf of Australia was modelled in a hydrodynamic model using the McCauley et al. (2017) results, as reported in Richardson et al. (2017). The modelled survey parameters include a survey area of 2,900 km^2, 60 survey lines, waters 300 - 800 m deep, an acoustic source of 3,000-3,200 m^3 and operating pressure of 2,000 psi. This paper reports that impact is recorded within the survey area and within 15 km of it, but that these impacts are not discernible at the bioregional scale and barely discernible within 150 km of the survey area. Zooplankton populations recovered quickly after seismic exposure due to their fast growth rates and due to the dispersal and mixing of zooplankton from both inside and outside of the impacted region. The modelling undertaken by Richardson et al. (2017) found that while there was a maximum decline of 22% in zooplankton populations in the survey and a 14% decline within 15 km of the survey area, it took only three days following the completion of the survey for zooplankton biomass to recover to pre-seismic survey levels within the survey area and within an area of 15 km around the survey area. The study notes that because zooplankton growth rates are slower in colder regions (e.g., Bass Strait), the recovery rate of zooplankton populations following exposure to a seismic survey is likely to be slower in colder waters. It is important to note that Fields et al. (2019) and IAGC (2017) noted that the findings of McCauley et al. (2017) (which were used in Richardson et al. 2017) may provide an overly conservative estimate of the potential effects of seismic pulses to zooplankton.

Independently of the APPEA/CSIRO study, the International Association of Geophysical Contractors (IAGC) conducted its own review of the McCauley et al. (2017) study. This review came to the following conclusion: "*While we found the study interesting, we are also troubled by the small sample sizes, the large day-to-day variability in both the baseline and experimental data, and the large number of speculative conclusions that appear inconsistent with the data collected over a two-day period.*

Both statistically and methodologically, this project falls short of what would be needed to provide a convincing case for adverse effects from geophysical survey operations." (IAGC 2017).

An assessment of zooplankton was undertaken to determine pre- and post-seismic survey abundance of zooplankton at sites within CarbonNet's Pelican Marine Seismic Survey area in the Gippsland Basin and at reference sites during January and February 2018. Pre-seismic survey plankton samples collected were dominated by copepods, cladocerans and salps while post-seismic survey plankton samples were dominated by the dinoflagellate *Noctiluca scintillans*. Other groups present included siphonophores, fish larvae, fish eggs, polychaetes, ghost shrimps and cnidarians. There was variance between and within assessments, with samples exhibiting levels of diversity and abundance typical of healthy temperate coastal waters. Neither lobster nor scallop larvae were present in any of the samples assessed (CarbonNet 2018).

A study by Fields et al. (2019) exposed the copepod (*Calanus finmarchicus*) to seismic pulses at various distances up to 25 m from a seismic source. The source levels produced were estimated to be 221 dB SEL comparable to the far-field source levels associated with some commercial scale seismic surveys. The study observed an increase in immediate mortality rates of up to 30% of copepods in samples compared to controls at distances of 5 m or less from the seismic source. Mortality one week after exposure was significantly higher by 9% relative to controls in the copepods placed 10 m from the seismic source. Fields et al. (2019) also reported that no sublethal effects occurred at any distance greater than 5 m from the seismic source. The findings of the study are consistent with numerous other field studies, as referenced previously, indicating that the potential effects of seismic pulses to zooplankton are limited to within approximately 10 m from the seismic source. Fields et al. (2019) detailed that it is difficult to reconcile the high mortality reported by McCauley et al. (2017) with the low mortalities reported in the body of earlier studies and in the experiment they undertook. Fields et al. (2019) details that it is possible that their results can be attributed to *C. finmarchicus* having a high tolerance to air gun impulses and that other species would be more sensitive. Other possible causes for the high mortality observed by McCauley et al. (2017) could be bubbles because of cavitation or small-scale shear produced by the sampling boat, unrelated to the air gun impulses.

Day et al. (2021, 2022) undertook a study to determine whether early development and recruitment of southern rock lobsters puerulus and juveniles might be affected by exposure to seismic sound by assessing mortality rates following exposure; impairment of the righting reflex, and development through assessment of progression through the moult cycle. This study also undertook to respond to the finding by McCauley et al. (2017) of increased mortality in zooplankton following exposure to air gun signals that suggests that planktonic, early life stages of marine invertebrates may be more vulnerable than adults or developing embryos. Outcomes of this study are detailed in the section below on crustaceans.

Vereide et al. (2023) conducted a field experiment to assess mortality and naupliar body length of the calanoid copepod (*Acartia tonsa*) when exposed to an air gun array discharge. The air gun array treatment consisted of two 40 in^3 air guns fired at a pressure of 110 bar every 10 seconds for three hours. The air gun array was towed at 2 knots at a depth of 3–4 m along an oval transect (3 nm in total) by the research vessel *H.U. Sverdrup II*. The vessel sailed between 50 m and 1,220 m from the line holding the bags. During the boat control treatment, *H.U. Sverdrup II* followed the same transect without discharging the air guns. The boat control treatment was included to control for the sound generated by the vessel itself.

The sound exposure level (SEL) was 152 dB re 1 μPa^2 s furthest away and 183 dB re 1 μPa^2 s at the closest distance. Nauplii were placed in plastic bags and attached to a line at a depth of 6 m. For each treatment, three bags of nauplii were exposed to one of three treatments for 2.5-hours: Air gun array discharge, a boat control, or a silent control. After exposure, nauplii were kept in filtered seawater in the laboratory without food. The immediate mortality was significantly higher in the air gun array treatment than in the silent and boat control treatments. On average, 13.5 ± 3.8% of the nauplii in the air gun array exposed treatment died immediately after exposure, compared to 3.4 ±

1.3% in the silent control and 2.6 ± 1.7% (mean ± SD) in the boat control. There was a significant difference in delayed mortality between the treatments. On days 1 and 2 after exposure, nearly all of the nauplii from the control groups were alive, while 27.0 ± 14.2% and 14.8 ± 14.2% of the air gun array exposed nauplii had died in the aliquots from day 1 and day 2, respectively. Mortality started occurring from day 3 (5.7 ± 10.1%, boat control) and 4 (9.4 ± 14.4%, silent control) in the control treatments but with lower mortality than in the air gun array exposed treatment (day 3, 47.5 ± 19.2% dead nauplii). In the aliquots from days 5 and 6 after the treatments, almost all of the air gun array exposed nauplii were dead, in contrast to the control groups, in which the proportion of dead nauplii was 49.2 ± 12.0% on day 5, and 72.6 ± 21.8% day 6 in the silent control and 4.0 ± 10.1% on day 5 and 48.4 ± 17.9% on day 6 in the boat control.

There was a significant interaction between treatment and time (days) on the body length (µm) of the nauplii, with lower growth from day 1–4 in the air gun array exposed treatment than in the control treatments. On day 1 after treatment, the average body length was 125 ± 10 µm. After four days, the average body length in the air gun array exposed nauplii was 128 ± 7 µm, which differed from the silent control (144 ± 8 µm) and the boat control (146 ± 7 µm). Over the first four days after exposure, the growth rates were 1.7 (4.1% in total), 5.4 (12.5%), and 6.1 per day (18.7%) in the air gun array exposed, silent control, and boat control, respectively. Naupliar development stages (NI–NIV) were positively correlated with body length (µm). In all treatments, >50% of the nauplii reached stage NII one day after exposure. By day 4, 43 ± 26.9% of the air gun array exposed nauplii were still in NI, compared with 11 ± 12.7% in the silent control and 1 ± 3.6% in the boat control. Only four individuals reached stage NIV: 3 in the silent control and 1 in the boat control.

Immediate mortality in the air gun array exposed nauplii was approximately 14% compared to less than 4% in the silent and boat control. Similarly, there was higher mortality in the air gun array exposed nauplii up to six days after exposure compared to the control treatments. Nearly all of the air gun exposed nauplii were dead after four days, while >50% of the nauplii in the control treatments were alive at six days post-exposure. There was an interaction between treatment and time on naupliar body length, indicating lower growth in the nauplii exposed to the air gun discharge. These experiments indicate that the output of two small air guns affected mortality and growth of the naupliar stages of *Acartia tonsa* in close vicinity to the array.

Vereide et al. (2023) concluded:

- The results of this study suggest that air gun array discharges affected the growth and mortality of *Acartia tonsa* in early naupliar stages. However, the degree of impact is likely to be stage- and species-specific and may be difficult to separate from background mortality.
- The results observed are consistent with many previous studies that show small effects of air gun discharges on zooplankton mortality. For example, no effects were detected in bivalve larvae sampled 2 km away from the source after exposure to air gun discharges (Parry et al. 2002) or in adult scallops sampled up to 1 km from the source shortly after exposure (Harrington et al. 2010). Similarly, Fields et al. (2019) reported that the mortality of the copepod *Calanus finmarchicus* adults to a two air gun array discharge increased (<5%) compared to that of the control groups, but only at <10 m from the air guns and no effects at distances from 10 to 50 m.
- There were notable differences in these results from previous studies. For example, in contrast to Fields et al. (2019), this study found significantly higher mortality in the exposed animals compared to the controls at distances of 50–~1,200 m. Although the sound exposure levels were higher in Fields et al. (2019) than those in this study, the animals in this study were exposed to multiple air gun discharges that resulted in a cumulative exposure that lasted much longer. The cumulative exposure of multiple blasts coupled with the younger stage used in this study may help to explain the higher mortality.

- Despite the higher mortality, the immediate mortality observed in this study is much lower than the 50% mortality in zooplankton at >1 km from the source (McCauley et al. 2017). Even though the absolute immediate mortality was lower than that reported by McCauley et al. (2017), the relative increase in mortality compared to the controls was somewhat greater in this study (greater than three-fold increase) than in McCauley et al. (2017) (two-to three-fold increase). However, in McCauley et al. (2017), the mortality in the controls was ~20% compared to less than 4% in this study.
- In this study, the mortality rate in nauplii directly after exposure was lower than the natural mortality rates observed in *Acartia* nauplii (up to 0.35 per day), although this is dependent on temperature, season, and region (Elliott & Tang 2011). This indicates that the population-level effect of air gun exposure might not be detectable from the background mortality.
- The air gun array exposed nauplii grew less and developed slower over four days than the boat and silent control groups. The slower development in the air gun array treatment nauplii was correlated with decreased growth. The progression through developmental stages and increase in body length observed in the control groups in our study is more similar to the development of naturally observed in *Acartia tonsa* nauplii cultured in 10–15° C water than is the development in the air gun array exposed nauplii. Slowed or arrested development at naupliar stages can reduce fitness or cause death. Thus, mortality could be affected long after seismic exposure. The population-level effects that this might have are uncertain.

4 Invertebrates

Research is ongoing into the relationship between sound and potential effects on benthic invertebrates, including the relevant metrics for both effect and impact. Marine invertebrates lack a gas-filled bladder and are unable to detect the pressure component of sound waves (Parry & Gason 2006; Carroll et al. 2017) or "hear" sound in the way that mammals and fish can. Instead, invertebrates detect sound by sensing the particle motion component of sound in water and seabed sediments through physiological structures such as sensory hairs, statocysts and muscles, and therefore detect sound at close range (McCauley 1994; Parry & Gason 2006; André et al. 2016: Roberts et al. 2016: Edmonds et al. 2016: Carroll et al. 2017: Popper & Hawkins 2018). Statocysts, found in a wide range of invertebrates, are utilised by animals to maintain their orientation, direct their movements through the water and may play a key role in controlling the behaviour responses of invertebrates to a wide range of stimuli. Although directly sensitive to particle motion and not to sound pressure, most available research on seismic impacts to invertebrates characterises received sound levels in terms of the sound pressure. Therefore, available literature suggests particle motion, rather than sound pressure, is a more important factor for benthic invertebrates such as crustacean and molluscs.

A range of physiological responses have been identified in some studies; however, the received sound levels are typically at levels that would be received within tens or a few hundred metres from the sound source or have been from repeated exposure at the same sound levels, which is not typical of an actual seismic survey (Carroll et al. 2017; Edmonds et al. 2016; Salgado Kent et al. 2016; Webster et al. 2018).

The most recent critical review of the potential impacts of marine seismic surveys on fish and invertebrates by Carroll et al. (2017) summarised the impacts of seismic sound emissions on marine invertebrates based on a literature review of 70 studies, which comprised a total of 68 species of fish and 35 species of invertebrates, including several studies that were not differentiated. Carroll et al. (2017) concluded that:

> *"Our review has identified scientific evidence for high-intensity and low-frequency sound-induced physical trauma and other negative effects on some fish and invertebrates; however, the sound exposure scenarios in some cases are not realistic to those encountered by marine organisms during routine seismic operations. Indeed, there has been no evidence of reduced catch or abundance following seismic activities for invertebrates, and there is conflicting evidence for fish with catch observed to increase, decrease or remain the same."*

4.1 Crustaceans

Specific studies examining the effect of seismic survey signals on crustaceans, including larval stages, are relatively rare, though recent Australian studies (e.g., Day et al. 2016b; Przeslawski et al. 2016b; Carroll et al. 2017; Day et al. 2019; Day et al. 2021, 2022), have aimed to narrow the knowledge gap. A recent study was undertaken to specifically investigate seismic survey impacts on Western Rock Lobster off the central WA coast (de Lestang et al 2024). These are being supplemented by global research, including ongoing projects such as Canadian Healthy Oceans Network Project 2.1.4 (Anthropogenic Noise in The Ocean Soundscape: Effects on Fishes and Invertebrates).

To understand interactions between marine seismic surveys and marine invertebrates, the Commonwealth Government's Fisheries Research Development Corporation (FRDC), Origin Energy Ltd and the CarbonNet Project contributed funding to a research program assessing the impact of marine seismic surveys on southern rock lobsters and commercial scallops. This program study was undertaken by researchers from the Institute for Marine and Antarctic Studies (IMAS) at the University of Tasmania (Day et al. 2016b).

The research program involved exposure of cohorts of southern rock lobsters to multiple seismic acoustic source pulses at two sites (sandy substrate and limestone rock platform), both in 10–12 m water depths off the southern Tasmanian coast. The exposed lobsters were captive and control

lobsters (no exposure) were also examined during subsequent analyses undertaken at 0-, 14-, and 120 -days post-exposure. Exposure experiments were undertaken in July 2013 (45 in^3 acoustic source, 2,000 psi), July 2014 (150 in^3 acoustic source, 1,300 psi and 2,000 psi) and February 2015 (150 in^3 acoustic source, 2,000 psi). The acoustic source was towed at approximately 5 m depth from 1 km away and at a speed of approximately 5.5–7.4 km/hr with a shot interval of 11.6 seconds. The seismic source circled near the lobster pots. The maximum calculated exposures were 212 dB re 1 µPa PK-PK, a per-pulse SEL of 190 dB re 1 μPa^2.s, an accumulated SEL of 199 dB re 1 μPa^2.s and maximum peak magnitude of ground acceleration of 68 ms^{-2}, though Day et al. (2016b) note this was an outlier.

Conclusions from the study are:

- Exposure to seismic sound did not result in any mortality from any of the experiments comprising this study.
- There was no difference in fecundity between control and exposed lobsters.
- The ability of exposed lobsters, and one cohort of control lobsters, to right themselves, a complex reflex, was compromised in the long-term (120 days post-exposure) in three of the four experiments. This response was linked to damage to sensory hairs of the statocyst, the primary mechano-sensory and balance organ in lobsters.
- Tail extension, a simple behavioural reflex response, showed reduction in exposed lobsters in one of the four experiments. The authors noted it is unclear how significant this finding is, as the warm summer water conditions during this experiment may have been a contributing factor.
- Haemolymph (blood) biochemistry showed little effects on metabolic and respiratory stress, or vitality following exposure.
- Haemocyte count (indicative of immune response function) in exposed lobsters showed a long-term decline to 120 days post-exposure. However, haemocyte counts subsequently recovered to double the number of haemocytes in control lobsters at 365 days post-exposure, which may indicate a possible immune response to pathogens.
- Seismic exposure did not cause any mass mortality. Not considering when both the control and exposed groups suffered mass mortality, the experimental mortality rates at 120 days' post-seismic acoustic source exposure were between 9.4% and 20%. These fall towards the low end of what might be expected from natural mortality rates. Even the highest levels of mortality recorded, 17.5% and 20% suffered by 4-pass treatments from the 2014 and 2015 experiments, were assessed by the authors to be modest compared to naturally occurring mortality rates.

Overall, no direct lethal effects to adult lobsters were observed and impacts were limited to statocyst condition, behavioural reflexes, and immune response functions in adult lobsters. Day et al. (2016b) note that these could have some effect on longer-term survivability.

Subsequent to the Day et al. (2016b) study, Day et al. (2020) undertook additional work to determine whether southern rock lobsters with pre-existing damage to their mechanosensory statocyst organs as a result of exposure to anthropogenic sound, incur further damage from exposure to marine seismic surveys. For this study, southern rock lobsters collected from a site subject to high levels of anthropogenic noise (a high shipping traffic lane used by cargo vessels and cruise ships, as well as pumping stations) were exposed to an equivalent seismic air gun signal regime as the Day et al. (2016b) study of lobsters, which was from an area of minimal anthropogenic sound ('noise-naïve' lobsters). Following exposure, both control and exposed treatments were found to have damage to the statocyst equivalent to that of noise-naïve lobsters following seismic exposure, leading to the conclusion that the damage was both pre-existing and not exacerbated by seismic exposure. Additional to the lack of further damage following marine seismic survey exposure, no disruption to

the righting reflex was observed, demonstrating the lobster's ability to cope with or adapt to the mechanosensory damage (Day et al. 2020).

The lobsters from the high shipping site showed a pre-existing level of statocyst damage equivalent to that of lobsters exposed to the seismic signals. These lobsters also demonstrated a resilience to further damage, with exposure to seismic sound not increasing the level of cell loss in the statocyst hairs (Day et al. 2020). There were also no significant differences in the time taken to right themselves (from 'belly up' to 'belly down') between the control and exposed lobsters from the shipping site, though righting time was slower and more variable than the lobsters at the control site.

Day et al. (2021, 2022) undertook a study to determine whether early development and recruitment of southern rock lobsters puerulus and juveniles might be affected by exposure to seismic sound by assessing mortality rates following exposure; impairment of the righting reflex, and development through assessment of progression through the moult cycle. This study also undertook to respond to the finding by McCauley et al. (2017) of increased mortality in zooplankton following exposure to air gun signals that suggests that planktonic, early life stages of marine invertebrates may be more vulnerable than adults or developing embryos.

The Day et al. (2021, 2022) study involved exposing puerulus and juvenile southern rock lobsters within oyster baskets on the seabed to a full-scale array (three 2,820 in^3 seismic sources at 2,000 psi at a depth of 8 m) during a commercial seismic survey in 51-58 m of water. Day et al. (2021, 2022) identified that:

- Exposure did not result in any elevated mortality for puerulus or juveniles and thus, seismic surveys are unlikely to produce significantly increased mortality in puerulus and juvenile southern rock lobsters.
- An impact to righting reflex occurred in the immediate vicinity (directly below the sound source) for puerulus and out to at least 500 m for juvenile southern rock lobsters. However, juveniles exposed at 500 m recovered after the first moult, indicating that the impact range extended to at least 500 m from the source, the maximum range tested in the study. The results from the combined puerulus and juvenile treatments indicated that puerulus and juveniles below the sound source did not show the capacity for recovery whereas juvenile lobsters at 500 m from the source recovered from impairment after the first moult, providing evidence of a range threshold for recovery.
- The intermoult period was significantly increased in juvenile lobsters directly below the sound source and appeared to be increased in puerulus, though the latter could not be statistically analysed.
- Juveniles at 500 m showed a moderate, non-significant increase in moult duration.
- Increased intermoult duration suggested impacted development and potentially slowed growth, though the proximate cause was not identified.

In another study focusing on southern rock lobster, Fitzgibbon et al. (2017) examined the impact of seismic acoustic exposure on the haemolymph physiology and nutritional condition of this species and found no effect of seismic exposure on 24 haemolymph biochemical parameters, hepatopancreas index or survival. However, this study did report evidence of:

- A chronic negative impact on immune competency for up to 120 days post-exposure.
- A potential immune response to infection after 365 days post-exposure.
- Chronic impairment of nutritional condition 120 days post-exposure.

These authors concluded that the biochemical hematological homeostasis of rock lobster is reasonably resilient to seismic acoustic signals; however, exposure may negatively influence the rock lobster's nutritional condition and immunological capacity. The impact of these results at an ecological level is not known.

The recently published study by de Lestang et al (2024) used cages to assess seismic effects on Western Rock Lobster (*Panulirus cygnus*) in shallow reef habitat adjacent to Dongera on the central WA coast. Juvenile lobsters were confined to cages and subject to seismic pulses from very close quarters (2-5m metres) after which they were released. A recapture program was followed to determine what effects seismic might have on catches. Results indicated a short-term reduction in catchability for the first month of the recapture program which subsequently disappeared. The recapture rates after the first month were very low (e.g. max of 1-3 animals per treatment) and not appropriate to draw any further conclusions from, as highlighted by the breadth of the 95% CI's associated with the analysis (6-68%). Treatment was not reflective of normal seismic activity nor were lobsters exposed while in their typical habitat such as a ledge or hole on the reef. It was not possible to draw any firm conclusions beyond a temporary reduction in catch levels.

Payne et al. (2007) conducted a pilot study of the effects of exposure to seismic sound on various health endpoints of the American lobster *(Homarus americanus*). Adult lobsters were exposed either 20 to 200 times to 202 dB re 1µPa PK-PK or 50 times to 227 dB re 1µPa PK-PK, and then monitored for changes to survival, food consumption, turnover rate, serum protein, enzyme and calcium levels. Lobsters were exposed to seismic pulses at very close range to the source (~2 m). The SEL that the lobsters were exposed to was not described in the report but can be estimated to be up to 207 dB re 1 μPa^2.s. Observations were made over a period of a few days to several months and found that:

- Results indicated no effects on delayed mortality or damage to the mechanosensory systems associated with animal equilibrium and posture (as assessed by turnover rate).
- There was a decrease in the levels of serum protein, enzymes, and calcium in the haemolymph of animals exposed to seismic sound. Statistically significant differences were noted in serum protein at 12 days post-exposure, serum enzymes at five days post-exposure, and serum calcium at 12 days post-exposure. Serum enzymes are valuable in detecting major organ damage whereby enzymes leak into the blood upon cellular rupture. Within this study two enzymes, aspartate transaminase and creatine kinase, were not elevated in seismic-exposed animals, reflecting the absence of major cellular rupture or necrosis being affected by seismic sound, including high exposure conditions. Similar results were obtained in studies with snow crabs (Christian et al. 2003). However, there was evidence of decreased serum enzymes in some trials, indicating the possibility of haemodilution or uptake of excess water by the animals. A similar decrease in serum protein and calcium was noted in some trials indicating a potential for disturbance to osmoregulation (i.e., the process by which the body regulates the osmotic pressure of any organisms' fluids to keep the homeostasis of the organisms' water level constant). Altogether, the results suggest a potential for osmo-regulatory disturbance in lobsters exposed to seismic sound. This study did not provide evidence for delayed mortality in lobsters several months after exposure, with some observations extending to nine months.
- During the histological analysis conducted four months post-exposure, no structural differences in hepatopancreatic tissues were noted, which would denote cell or tissue rupture, necrosis, or inflammation. There was also no evidence of tissue necrosis or inflammation in the ovaries. However, histology identified elevated deposits of carbohydrates, thought to be glycogen, in the hepatopancreas of seismic-exposed animals. Such abnormal accumulations are believed to be due to disturbance in cellular processes connected with synthesis and secretion; however, the report concludes that further research is required to assess whether this observation is due to organ stress. These

studies are noted as being exploratory in nature, with the authors cautioning against over-interpretation.

In 2018, the CarbonNet Project undertook the Pelican 3D marine seismic survey in waters 15 m to 35 m deep located between 1 km and 13 km from the Gippsland shoreline in Victoria. Underwater sound and its potential impact on the marine environment was a key issue raised by stakeholders, particularly the commercial fishing industry. In response, and among other actions, CarbonNet undertook southern rock lobster surveys before and after the marine seismic survey to ascertain whether any differences in abundance could be attributed to the marine seismic survey. The design of the survey was overseen by an independent advisory panel to provide advice on the survey methodology and interpretation of the survey results and its implications.

Ten sites (in areas of reef) were monitored, including six sites within the survey acquisition area and four reference sites located more than 15 km to the northeast. At all sites, more southern rock lobsters were retrieved during the post-survey assessment (four months after the survey), with 81 individuals trapped during the pre-survey assessment compared to 122 trapped post-survey. This increase in numbers post-survey was most likely due to seasonal effects rather than any impact of the survey (CarbonNet 2018). These results indicate no effect of the marine seismic survey on lobster abundance.

Morris et al. (2018) and Cote et al. (2020) undertook field studies in from 2015 – 2017 into the effects of marine seismic surveys on the behaviour of the snow crab (*Chionoecetes opilio*) on the shelf and slope habitats of Atlantic Canada using a BACI study design to assess the behavioural responses of snow crab to seismic exposure. A 4,880 in^3 seismic source operated at 2,000 psi, 9 m depth and fired at a frequency of 10 seconds (approximately 25 m apart). Animal movements were tracked using an acoustic positioning array consisting of 50 acoustic receivers. The study concluded that while effects of seismic exposure on snow crab movement could not be ruled out completely, effects were at most quite small relative to natural variation. In contrast, snow crab exhibited much clearer responses to handling, temperature, and time of day. Overall, the results suggested that seismic effects, specific to the behaviour of adult male snow crab, were at most subtle and are not likely to be a prominent threat to the fishery.

A pilot study on snow crabs (*C. opilio*) (Christian et al. 2003, 2004) exposed captive adult males, egg-carrying females, and fertilised eggs to variable SPLs (191–221 dB re 1 µPa PK) and SELs (<130–187 dB re 1 $\mu Pa^2.s$) under controlled field experimental conditions. The crabs were exposed to 200 discharges over 33 minutes and found that:

- Neither acute nor chronic (12 weeks post-exposure) mortality was observed for the adult crabs.
- There was a significant difference in the development rate noted between the exposed and unexposed fertilised eggs/embryos in this study with the egg mass exposed to seismic energy demonstrating a higher proportion of less-developed eggs than the unexposed mass. However, this experiment was performed on eggs stripped from a single berried female and cultured in a laboratory for six weeks prior to exposure and 18 weeks following exposure.
- Stress indicators in the haemolymph of adult males were monitored immediately after exposure of the animals to seismic survey sound (Christian et al. 2003, 2004) and at various intervals after exposure. No significant acute or chronic differences between exposed and unexposed animals in terms of the stress indicators (e.g., proteins, enzymes, cell type count) were observed.

Christian et al. (2003) also investigated the behavioural effects of exposure to seismic survey sound on snow crabs. Caged animals on the ocean bottom at a depth of 50 m were monitored with a remote video camera during exposure to seismic sound and did not exhibit any overt startle response during the exposure period. Eight animals were equipped with ultrasonic tags, released,

and monitored for multiple days prior to exposure and after exposure. None of the tagged animals left the immediate area after exposure to the seismic survey sound. Five animals were captured in the snow crab commercial fishery the following year, one at the release location, one 35 km from the release location, and three at intermediate distances from the release location.

In 2003, a collaborative study was conducted in the southern Gulf of St. Lawrence, Canada, to investigate the effects of exposure to sound from a commercial seismic survey on egg-bearing female snow crabs (DFO 2004). Caged animals were placed on the ocean bottom at a location within the survey area and at a location outside of the survey area. The maximum received SPL was ~195 dB re 1 µPa PK. The crabs were exposed for 132 hours of the survey, equivalent to thousands of seismic shots of varying received SPLs. The animals were retrieved and transferred to laboratories for analyses. Neither acute nor chronic lethal or sub-lethal injury to the female crabs or crab embryos was indicated. DFO (2004) reported that some exposed individuals had short-term soiling of gills, antennules and statocysts, bruising of the hepatopancreas and ovary, and detached outer membranes of oocytes. However, they were found to be completely cleaned of sediment when sampled five months later and any differences could not be conclusively linked to exposure to seismic survey sound.

In a field study, Pearson et al. (1994) exposed Stage II larvae of the Dungeness crab (*Cancer magister*) to single discharges from a seven-source air gun array and compared their mortality and development rates with those of unexposed larvae. For immediate and long-term survival and time to moult, this study did not reveal any statistically significant differences between the exposed and unexposed larvae, even those exposed within 1 m of the seismic source (with a mean peak pressure as high as 231 dB re 1 µPa).

4.2 Molluscs

Molluscs include benthic invertebrates such as marine bivalves (e.g., scallops, oysters, mussels and clams), gastropods (e.g. sea snails/trochus, sea slugs and nudibranchs) and cephalopods (e.g. octopi and squid). Like crustaceans, the mechanism of impacts for molluscs are unlikely to be from sound pressure, but rather from particle motion. The physiology and sensory structures of different marine bivalves and gastropods is similar and so results of studies on the effects of seismic sound are broadly representative for species other than those studied.

Wardle et al. (2001) monitored molluscs and echinoderms on a shallow water reef exposed to seismic sound with peak SPLs of 218, 210 and 195 dB re 1 µPa at distances of 5 m, 16 m and 109 m respectively. Video observations made over two weeks indicated that the sound did not result in invertebrates moving away from the reef and there was little effect on their day-to-day behaviour.

Kosheleva (1992; as cited in Parry & Gason 2006) identified no detectable effects to marine bivalves and gastropods (mussels and periwinkles) after exposure to a single seismic source element of source level 233 dB re 1µPa at 0.5 m or greater from the source. Conversely, Matishov (1992; as cited in Parry & Gason 2006) reported a single scallop shell splitting in a sample of three scallops, but this was located 2 m beneath a seismic source and therefore exposed to maximum sources levels.

Recent Australian studies (Harrington et al. 2010; Przeslawski et al. 2016a, 2016b, 2018; Day et al. 2016b, 2017) have focussed on commercial scallops (*Pecten fumatus*).

Harrington et al. (2010) conducted a BACI study of the short-term effects of seismic surveying on adult commercial scallops within the Bass Strait Central Zone Scallop Fishery between February and June 2010. The study aimed to determine the survival and health of adult scallops within impacted (directly below seismic survey transects), semi-impacted (within the seismic survey transect grid) and control (outside of the seismic survey transect grid) strata two months after seismic surveying. A before-seismic impact scallop dredge survey was conducted in February 2010 at both impact and control sites. In total, 45 sample dredge tows were conducted, with 15 sample tows being completed within each survey stratum. Between February 2010 and April 2010, the seismic survey vessel *M/V Aquila Explorer* completed 8,000 line kilometres of 2D seismic transects within eastern Bass Strait,

including areas within the Bass Strait Central Zone Scallop Fishery with high densities of adult scallops. The seismic source, 4,130 in^3 with an operating pressure of 2,000 psi was towed at a depth of ~6 m, with seismic discharges occurring at intervals of approximately every five seconds. The after seismic impact scallop dredge survey was conducted on the 2nd and 3rd June 2010, approximately eight weeks after the seismic survey had been completed within the vicinity of the dredge survey location.
Data on the abundance of live and dead scallops within the impacted and control sites were examined to assess whether any changes were evident and whether they may be attributable to effects of the seismic survey. Animals collected in surveys were separated into one of four shell categories; live scallops, clappers (very new dead scallops with two shell halves still joined together), new dead shell and old dead shell. Sub-lethal impacts were investigated by examining changes in roe and meat condition within each of the areas sampled.

No change in the abundance of live scallops (or related change in dead scallop categories) or macroscopic gonad and meat condition was detected after seismic surveying within either the control, impacted or semi-impacted strata. There was also no observable change in the size frequency distribution of scallops in the impacted and semi-impacted strata following seismic surveying. The conclusion was that no short-term (<2 months) impacts on the survival or health of adult commercial scallops (*Pecten fumatus*) were detected following the seismic survey.

Przeslawski et al. (2016a, 2016b, 2018) examined the short-term impacts on scallops and other marine invertebrates from a 2,530 in^3 seismic array and found no evidence of mortality or change in condition following exposure to a seismic survey. Analysis of images and samples revealed some site-specific differences in scallop abundance, size, condition, and assemblages, but these were not related to seismic operations.

From 2013-2015, a long-term study evaluated the acoustic impacts from seismic exposure on scallops in Australia (Day et al. 2016b, 2017). The experimental field research maintained the scallops in mesh enclosures while a vessel with the acoustic source passed close to the animals. Day et al. (2016b, 2017) exposed scallops to maximum received sound exposures of up to 213 dB re 1µPa PK-PK, 181 to 188 dB re 1 $\mu Pa^2.s$ per-pulse SEL, and SEL_{cum} of 188 to 198 dB re 1$\mu Pa^2.s$. The study also predicted ground acceleration of up to 37.57 m/s^2.

Day et al. (2016b, 2017) concluded that exposures did not result in any immediate mass mortalities; however, repeated exposures, not representative of typical survey conditions, resulted in a chronic increase in mortality over timeframes of approximately four months post-exposure, though not beyond naturally occurring rates of mortality. Separate experiments undertaken in 2013 and 2014 yielded mortalities of 3.6-3.8% in control scallops (no seismic exposure), 9.4-11.3% mortality in scallops exposed to a single pass of the seismic source, 11.3-16.1% mortality in scallops exposed to two passes of the seismic source, and 14.8-17.5% mortality in scallops exposed to four passes of the seismic source. The mortality rates were at the low end of the range of naturally occurring mortality rates documented in the wild, which range from 11-51% with a six year mean of 38% (Day et al. 2017). A third experiment in 2015 resulted in 100% mortality to both control scallops and exposed scallops, and accordingly was attributed to other causes and not to seismic exposure (Day et al. 2016b, 2017).

Sub-lethal effects to exposed scallops were also observed by Day et al. (2016b, 2017) indicating a compromised capacity for homeostasis and potential immunodeficiency over acute (hours to days) and chronic (months) timescales post exposure. Exposures did not elicit energetically expensive behaviours (i.e., extensive swimming or long periods of valve closure), but scallops showed significant changes in behavioural patterns during exposure, through a reduction in classic behaviours and demonstration of a non-classic “flinch” response to seismic signals. Furthermore, following exposure scallops showed an increase in recessing into sediment following exposure (Day et al. 2017).

Though Day et al. (2016b) recorded increased mortality with repeated exposure to a seismic source, it has not been established as to whether this was due to exposure to the seismic source or other mechanism related to the study design (Przeslawski et al. 2016). Using a precautionary approach, if

the increased mortality was due to exposure to the seismic source, then the increased mortality identified translates to an annual increase of between 9.4% and 20%. These fall towards the low end of what might be expected when compared with natural mortality rates in wild scallop populations, which range from 11-51% with a six year mean of 38% (Day et al. 2016b).

Scallops exposed to repeated seismic sound suffered physiological damage with no signs of recovery over the four month period, suggesting potentially reduced tolerance to subsequent stressors. In addition, changes in behaviour and reflexes during and following seismic exposure were observed. However, Day et al. (2016a, 2016b) cautioned that it was unclear from the study whether the observed physiological (and behavioural) impairments would result in mortality beyond the timeframes considered in their study.

Przeslawski et al. (2018) concluded that there was no evidence of increased scallop mortality, or effects on scallop shell size, adductor muscle diameter, gonad size, or gonad stage due to the seismic sound from an actual seismic survey. The authors concluded that the study provided no clear evidence of adverse effects on scallops, fish, or commercial catch rates due to the 2015 seismic survey undertaken in the Gippsland Basin. Przeslawski et al. (2018) further concluded that the study provided a robust and evidence-based assessment of the potential effects of a seismic survey on some fish and scallops.

Studies by Mooney et al. (2010) showed squid use their statocysts to detect low frequency, particle motion stimuli with a frequency response similar to the accelerometer ears of most elasmobranch and teleost fishes. Evoked potential response characteristics also parallel those found in many fish species that lack auditory specializations.

Laboratory studies that exposed two species of squid to seismic sound showed that *Alloteuthis sublata* was tolerant to a sound level up to 260 dB re 1 µPa (SPL) and *Loglio vulgaris* was fatally injured at levels of 246 – 252 dB re 1 µPa (SPL) within 3 – 11 minutes of exposure (Norris & Mohl 1983). However, received sound levels from a typical seismic survey do not reach these levels.

Fewtrell & McCauley (2012) assessed the effects of air gun noise on caged squid (*Sepioteuthis australis*). No sub-lethal injury or mortality as a result of exposures in this study was observed. Several squid showed alarm responses to the start-up of an air gun by firing their ink sacs and/or jetting away from the source, but this was not observed for similar or greater levels if the signal was ramped up. General habituation was observed with a decrease in alarm responses with subsequent exposures. During the trial the squid showed avoidance to the air gun by keeping close to the water surface at the end of the cage furthest from the air gun (within the sound shadow). Fewtrell & McCauley (2012) suggested a threshold of 166 dB re 1 µPa (SPL) would give an indication of the extent of disruption of a seismic survey by significant alteration in swimming patterns. They found that in one trial, where the received level of the first airgun impulse was 162 dB re 1 $\mu Pa^2 \cdot s$, the squid inked. This response was not observed again within this trial; however, the authors stated that it was unknown if this was due to depleted ink reserves or habituation. In two other trials, the initial received levels were lower (132 and 146 dB re 1 $\mu Pa^2 \cdot s$ per–pulse SEL), and although the cumulative received levels did exceed 162 dB re 1 µPa2 s, no inking behaviour was observed. The authors hypothesised that the results also suggest that a gradual increase in received levels and prior exposure to air gun impulses decreases the severity of the alarm responses in this species. This aligns with findings of general habituation in response to predators in squid (Long et al. 1989). Recent work (Jones et al. 2020) supports these findings as well, indicating potential rapid, short–term habituation by squid to impulsive noise, however, similar response rates were seen 24-hours later, which indicated that squid might re–sensitise to the noise.

The results presented in by Fewtrell and McCauley (2012) were stated by the authors to be preliminary, and while they stated that while it is possible that noise levels greater than 147 dB re 1 $\mu Pa^2 \cdot s$ are required to induce avoidance behaviour, the level associated with inking, of 162 dB re 1 $\mu Pa^2 \cdot s$ per–pulse SEL, has been considered as a startle response level for squid. In the absence of

additional studies and thresholds this level may be considered for other cephalopods; however, it may be limited when applied to other species.

André et al. (2011) exposed cephalopods (squid, cuttlefish, and octopus) to low-frequency sounds, 50–400 Hz sinusoidal wave sweeps with 100% duty cycle and one second sweep period for two hours in either a 2 L fiberglass reinforced plastic tank or a 200 L glass-walled tank, filled with natural seawater. The sweep was produced and amplified through an in-air loudspeaker, with measured received SPL of 157 ± 5 dB 1 µPa, with peak levels at 175 dB re 1 µPa. Following exposure, the individuals were decapitated at different intervals, ranging from immediately afterward to 12, 24, 48, 72, and 96 hours after exposure, respectively. All exposed individuals from presented the same lesions and the same incremental effects over time. The most pronounced lesions were visible in specimens observed 96 hours after sound exposure. In these individuals, the sensory epithelium was severely damaged, with very few hair cells remaining; most of the hair cells had been extruded. The epithelium only presented supporting cells, creating a holed mosaic, where residual hair cells showed either very few bent, flaccid, or fused kinocilia, or none at all. André et al. (2011) detailed that the lesions described in the study were new to cephalopod pathology and that their presence in all the noise-exposed individuals (versus their absence in controls) and their clear progression over time are consistent with the effects observed in other species that have been exposed to much higher intensities of sound.

Mooney et al. (2016) detailed that squid responded to sounds from 80 to 1,000 Hz, with response rates diminishing at the higher and lower ends of this frequency range. Animals responded to the lowest sound levels in the 200-400 Hz range. These results demonstrate that squid can exhibit a range of behavioural responses to sound include fleeing, startle, and protean behaviours, all of which are associated with predator evasion. Response types were frequency and sound level dependent, reflecting a relative loudness concept to sound perception in squid.

Solé et al. (2017) conducted offshore noise controlled exposure experiments on common cuttlefish (*Sepia officinalis*), at three different depths and distances from the source and particle motion and sound pressure measurements were performed at each location. Scanning electron microscopy revealed injuries in statocysts, which severity was quantified and found to be proportional to the distance to the transducer. These findings are the first evidence of cephalopods sensitivity to anthropogenic noise sources in their natural habitat. From the measured received power spectrum of the sweep, it was possible to determine that the animals were exposed at levels ranging from 139 to 142dB re 1µPa^2 and from 139 to 141 dB re 1µPa^2, at 1/3 octave bands centred at 315 Hz and 400 Hz, respectively. These results could therefore be considered a coherent threshold estimation of noise levels that can trigger acoustic trauma in cephalopods.

Dead beached squids have been documented in the vicinity of seismic surveys (Guerra et al. 2004) and from a seismic survey vessel (Leite et al. 2016).

Guerra et al. (2004) detailed that five giant squids were stranded between the end of September and the middle of October and four giant squid were found floating or stranded along the Asturian coast during a single week in September 2003. Guerra et al. (2004) examined seven of the nine animals, and did not find an obvious cause of death in any of these giant squid; however, internal examinations showed that two of the squids suffered extensive damage to internal muscle fibres, stomachs and digestive tracts were mangled. Some of the squids had also suffered severe damage to their statocysts that would have effectively disorientated them. Coincidentally, at the time of both mass strandings, vessels had been conducting seismic geophysical surveys in the vicinity, using ten compressed air guns that produced sound waves of low frequency (below 100 Hz) and high intensity (source level of 240 dB re 1 µPa at 1m per air gun) (Guerra et al. 2011).

Leite et al. (2016) reported that a squid, ~2 m long and identified as *Architeuthis dux,* was sighted as dead from a seismic survey vessel that had been operating in the area using a 5,085 in^3 seismic source with an operating pressure of 2,000 psi. Leite et al. (2016) detailed that while there is no

definite proof to link the death of this specimen to the seismic activity, its occurrence in an area of active surveys is suggestive of a possible link.

Given the similarities in physiology between squid and octopus, octopus are not thought to be at risk of physical injury even if individuals are exposed to several passes as noted by Fewtrell and McCauley (2012). There is limited information on the hearing sensitivity of octopus to sound stimuli. Kaifu (2008) studied *Octopus ocellatus* and concluded that the statocyst was responsible for the observed responses kinetic sound energy (particle motion). It is unknown how octopuses will respond behaviourally, but since they are benthic and territorial it is thought more likely that they will retreat into their lair as they normally do to perceived threats. They may also freeze and camouflage themselves if out in the open. Octopus are not expected to move very far from their territory and therefore will not be exposed to repeat close passes in short period of time since subsequent survey lines are about 4 km apart. If they remain in the same area, they may be exposed to sounds shown to elicit strong responses two to three times throughout the survey period and these events will be several days apart allowing the individual animals to recover.

4.3 Corals

A literature review by Dr Mardi Hastings stated that the primary mechanisms for injury of hermatypic corals from seismic sound emissions are: (1) breaking of the external coral skeleton which could also damage the polyp tissue, and (2) rupture or tearing of polyp tissues inside the corallites (Hastings 2008).

Although injury to corals is theoretically possible as described by Hastings (2008), studies on the actual impacts were limited prior to the Maxima 3D and Gigas 2D studies at Scott Reef (see below). A survey of coral reefs in Brunei that were subjected to seismic noise did not detect any damage to hard or soft corals, sponges, or other sessile benthic organisms (IEC 2003).

The most relevant data currently available are results from exposure studies that Woodside conducted during the Maxima 3D and Gigas 2D Pilot Ocean Bottom Cable (OBC) marine seismic surveys at Scott Reef offshore northern Western Australia.

In the Maxima 3D experiments corals in and around the lagoon were exposed to seismic signals (both experimental seismic lines and a full seismic survey) using a 2,055 in^3 source over a 59-day period. The experimental lines passed directly over the coral communities (source at 7 m depth, corals at ~60 m depth) whereas the full seismic survey passed within tens to hundreds of metres (horizontal offset). The maximum estimated received seismic signal levels at coral impact sites were 226–232 dB PK-PK, 214–220 dB SPL, 197–203 dB SEL, and a maximum cumulative SEL of 197–203 dB (Salgado Kent et al. 2016).

For plate corals, *Lobophytum* spp., and various soft corals including *Sarcophytum* spp., the proportion of dead and bare coral cover and the percent cover of red algae were documented, and no detectable effect was found from one or multiple passes of the seismic source (Battershill et al. 2008). Further, there was no evidence of coral breakage, no signs of physiological impairment in the corals (polyp withdrawal or reduction in soft coral rigidity) and no long-term change in coral community structure related to the experimental or full seismic survey activities (Battershill et al. 2008).

The Gigas 2D Pilot OBC coral monitoring study (SKM 2008) examined the potential for physical damage to a range of shallow water corals in North Scott Reef lagoon from seismic source emissions. This study used several sub-lethal indicators of stress and mortality (partial and whole colony mortality) to determine the effects of seismic source emissions on corals. The conclusion from this study was that emissions from the seismic source did not cause significant injury, tissue damage, sublethal stress or mortality to coral colonies, even when colonies were within a few metres of the seismic source (SKM 2008). This survey had a measured at source SEL of 206 dB (McCauley 2008).

Heyward et al. (2018) reviewed the research undertaken at Scott Reef and the analyses detected no effect of seismic activity measured as coral mortality, skeletal damage, or visible signs of stress immediately after and up to four months following the 3D marine seismic survey. Maximum received levels were 226 dB PK.

5 Fishes

Although hearing ranges and sensitivities vary substantially between species (e.g., Ladich & Fay 2013), all fish species tested to date can detect sound and vibration to some degree (Dale et al. 2015). Fish produce sounds in a wide range of context such as feeding, mating or fighting, and as a result anything that inhibits the detection of these sounds can have a negative effect on their fitness and survival (Popper & Hawkins 2019). The majority of fish species detect sounds from <50 Hz up to 500-1500 Hz (Popper & Hawkins 2019). A smaller number of species can detect sounds over 3 kHz, while very few species can detect ultrasound over 100 kHz (Ladich & Fay 2013). The critical issue for understanding whether an anthropogenic sound will affect the hearing of a fish is whether it is within the hearing frequency range of the fish and loud enough to be detectable above background ambient noise.

The hearing sensitivity of fish varies depending upon the auditory structures in the inner ear (otoliths surrounded by an epithelium of hair cells) and, if present, the swim bladder (Finneran & Hastings 2000; Nedwell et al. 2004). Otoliths are sensitive only to particle motion, while the swim bladder may provide an indirect route for sound pressure to reach the inner ear. The other main mechano-reception system in fish is the lateral line system, which runs along the side of the body and is more pronounced in some groups of fish than others. The lateral line system responds to particle motion produced in the near-field of a sound source, as well as to tiny water currents set up by the motions of the fish (Nedwell et al. 2004); therefore, all fish are sensitive to the particle motion component of sound at close range from a sound source. Particle motion is the most relevant metric for perceiving underwater sound for most species, but with the exception of a few species (Popper & Fay 2011; Popper et al. 2014), there is an almost complete lack of relevant data on particle motion sensitivity in fish (Popper & Hawkins 2018). Some more specialised fish with a swim bladder that they use for hearing are sensitive to sound pressure and are capable of detecting less intense noise and a wider range of frequencies, compared to less-specialised groups of fish (Popper et al. 2014; Carroll et al. 2017; Hawkins & Popper 2017). The susceptibility of fish to injury from noise exposure varies depending on the species and the presence and possible role of a swim bladder in hearing. Inter-specific variations in hearing range and sensitivity result from the different adaptations in these systems for perceiving sound pressure and particle motion information (Popper & Fay 2011).

Based on their morphology, Popper et al. (2014) classified fishes into three categories comprising:

- Fishes with swim bladders whose hearing does not directly involve the swim bladder or other gas volumes.
- Fishes whose hearing does directly involve a swim bladder or other gas volume.
- Fishes without a swim bladder that can sink and settle on the substrate when inactive.

The Popper et al. (2014) classifications can be assigned to the following families or species of commercial fish species, common in Australian waters:

- Fishes with swim bladders or other gas volumes, but whose hearing does not directly involve the swim bladder, e.g., snappers, emperors, groupers and rock cods (lutjanids and lethrinids such as *Pristipomoides* spp., *Lethrinus* spp., *Lutjanus* spp., and Family Serranidae), and some species of tuna (*Thunnus* sp.) (Tavolga & Wodinsky 1963; Higgs et al. 2006; Braun & Grande 2008; Engineering-Environmental Management, Inc. 2008; United States Department of the Navy 2008; Caiger et al. 2012; Bertrand & Josse 2000; Song et al. 2006).
- Fishes whose hearing does directly involve a swim bladder or other gas volume e.g., Family Clupeidae (herrings, sardines, pilchards, and shads) and some Haemulidae (grunters and sweetlips) (Nedwell et al. 2004; Braun & Grande 2008; Popper et al. 2014).

- Fishes without a swim bladder (e.g., mackerel, *Scomberomorus* spp., some species of tuna, *Thunnus* sp. and sharks) (Casper et al. 2012; Popper et al. 2014; Carroll et al. 2017).

Underwater noise levels significantly higher than ambient levels can have a negative impact on fishes, ranging from physical injury or mortality to temporary effects on hearing and behavioural disturbance effects.

The effects of underwater sound on fishes within the vicinity of a seismic sound source array will vary depending on the size, age, sex, and condition of the receptor among other physiological aspects, and the topography of the benthos, water depth, sound intensity and sound duration. The effect of noise on a receptor may be either physiological (e.g., injury or mortality) or behavioural, as described in the following sub-sections.

Mortality/Potential Mortal Injury

It is noted that while thresholds for fish mortality have been included for consideration in this assessment based on the Popper et al. (2014) guidelines, no studies to date have demonstrated direct mortality of free-swimming adult fish in response to seismic source emissions, even when at close proximity (within 1–7 m) (DFO 2004; Boeger et al. 2006; Popper et al. 2016; Carroll et al. 2017). Although some fish deaths have been reported during cage experiments, these were more likely caused by experimental artefacts of handling fish or confinement stress (Hassel et al. 2004). For free swimming fishes that can move away from seismic sources as they approach, the potential for lethal physical damage from air gun emissions is even further nullified. However, reef or bottom-dwelling fishes that show greater site attachment may be less inclined to flee from a seismic sound source and experience greater effects.

Despite mortality being a theoretical possibility for fish exposed to seismic source emissions, Popper et al. (2014) did not reference an actual occurrence of this effect. At the time of developing the guidelines, no quantified data on injury and mortality from seismic sources on fishes had been reviewed by the Working Group. Therefore, the Popper et al. (2014) exposure guidelines for mortality/potential mortal injury and recoverable injury for fishes exposed to seismic source emissions are based solely on data from pile driving conducted on predominantly temperate, freshwater fish species. Although seismic surveys and pile driving both produce impulsive sound, their sound characteristics are markedly different; pile driving impulses result in a more rapid rise time in sound pressure than seismic pulses and it is this rapid rise time that has the greatest potential for trauma (Caltrans 2001, 2004; Hastings & Popper 2005; Popper et al. 2006). Also, pile driving sound effects are usually more significant due to the fact that they usually involve a static source and static receivers (e.g., site-attached fishes).

Environmental Resources Management Australia (ERM) undertook a detailed literature review of potential fish mortality and physical injury because of exposure to seismic sources (ERM 2017). Of the 28 studies reviewed, only three observed direct mortality and in each case, mortalities occurred to fish that were caged at very close proximity to the seismic source (<2 m). This is clearly not representative of real-life exposures from seismic surveys given fish are free-swimming and therefore capable of moving away from a sound source if needed. The received sound levels that resulted in mortality ranged from 220 to 241 dB re 1 µPa PK; however, other studies reported no mortality or injury at levels as high as 246 dB re 1 µPa PK. Therefore, the sound exposure criteria proposed by Popper et al. (2014) for mortality and mortal injury are considered to be highly conservative.

Other than physiological stress responses or hearing loss, no other physical damage to adult fish or invertebrates have been directly attributed to exposure to seismic source emissions, even at close proximity (NSW DPI 2014). It should be noted that some reports of physical damage arise from studies undertaken using explosions and other high-pressure sound waves, and not from seismic source emissions that generate lower maximum pressures and pressure change (Popper & Hastings 2009).

There is some evidence that bony fishes can regenerate the sensory cells in their hearing system to a fully functional state within weeks after a detrimental exposure. The processes involved in the recovery are not fully understood, and there is conflicting evidence from sound exposure studies, such as McCauley et al. (2003). These findings could also suggest that the process of sensory hair cell death and regeneration is species-specific.

Recovery processes take a few days to a few weeks (Scholik & Yan 2001; Mackenzie & Raible 2012), and the time course for recovering from hearing loss likely depends on the species, its normal hearing sensitivity, the sound exposure intensity and duration, and the amount of sensory epithelial damage (Smith & Monroe 2016). Noise-induced PTS has not been reported for fishes yet, which may be explained by their apparent ability to regenerate hair cells.

Injurious effects caused by rapid pressure changes within the body are called 'barotrauma' (Stephenson et al. 2010; Halvorsen et al. 2011, 2012b). The range of barotrauma effects in fishes mostly depends on the temporal pattern of the pressure changes and the physiological state of the exposed fishes (Stephenson et al. 2010; Halvorsen et al. 2012a, 2012b); they range in severity from damage with full recovery to lethal injury (McKinstry et al. 2007).

Casper et al. (2012) showed that fishes can recover from less severe injuries under laboratory conditions, suggesting that minor injuries do not inevitably lead to mortality. Nevertheless, in open waters, they have the potential to reduce the animal's fitness to the extent that its ability to find food decreases and its risk of being predated increases (Halvorsen et al. 2011, 2012b).

Mortality is either a direct effect of barotrauma (in the case of severe injury) or indirect if an animal is moderately injured. Data on sound-induced mortality in fishes are scarce and mainly related to underwater explosions (see review by Popper & Hastings 2009). Caltrans (2001) documented fish mortality near underwater pile driving. There is no evidence for fish mortality caused by exposure to other sound sources such seismic source emissions, dredging, or vessel noise (Normandeau Associates, Inc. 2012).

Temporary Threshold Shift

The following is sourced from Popper et al. (2014):

> *"Temporary threshold shift (TTS) is a temporary reduction in hearing sensitivity caused by exposure to intense sound. TTS has been demonstrated in some fishes, and its extent is of variable duration and magnitude. TTS results from temporary changes in sensory hair cells of the inner ear and/or damage to auditory nerves innervating the ear (Smith et al. 2006; Liberman 2015). However, sensory hair cells are constantly added in fishes (e.g., Corwin 1981, 1983; Popper and Hoxter 1984; Lombarte and Popper 1994) and also replaced when damaged (Lombarte et al. 1993; Smith et al. 2006; Schuck and Smith 2009), unlike in the auditory receptors of mammals. When sound-induced hair cell death occurs in fishes, its effects may be mitigated over time by the addition of new hair cells (Smith et al. 2006, 2011; Smith 2012, 2015).*
>
> *After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure (e.g., Popper and Clarke 1976; Scholik and Yan 2001, 2002a, b; Amoser and Ladich 2003; Smith et al. 2004a, b, 2006, 2011; Popper et al. 2005, 2007). While experiencing TTS, fishes may have a decrease in fitness in terms of communication, detecting predators or prey, and/or assessing their environment."*

McCauley et al. (2003) demonstrated that exposure to repeated emissions of a single air gun (source level of 222.6 dB re 1µPa PK-PK) from 5 to 15 m at the closest approach caused extensive damage to the sensory hair cells in the inner ear of caged pink snapper (*Pagrus auratus*). Although no mortality was observed, the damage was severe with no evidence of repair or replacement of damaged sensory cells up to 58 days post-exposure. However, the study did not investigate the effects on fish hearing. The study acknowledged that the fish were caged and therefore not able to swim away from sound source, and that the monitoring video suggested the fish would have fled the sound

source if possible. The authors of the study also acknowledged that the impact of exposure on ultimate survival of the fish was not clear.

As part of Woodside's Maxima 3D marine seismic survey, an extensive field study was undertaken at Scott Reef. A component of this study investigated the potential physical, physiological, and behavioural noise-induced effects on fish assemblages. The results showed statistically more damage to the hearing in blue-stripe sea perch (*Lutjanus kasmira*) exposed to the seismic impulses than in control fishes. However, the damage found in these fishes was marginal, and—assuming a direct relationship between hair cell density and hearing capability—a negligible effect on the fishes' hearing capability. The damage was monitored through time out to 58 days post seismic exposure and did not increase significantly through time, with almost zero damage detected by 58 days (McCauley 2008).

A study of auditory sensitivity in four species of tropical reef fishes following exposure to emissions from the 2,055 in^3 array showed that none of the four species, including the pinecone soldierfish (a species with expected to have good hearing sensitivity) experienced any hearing sensitivity loss (i.e. TTS) following exposure to SEL_{cum} up to 190 dB re 1 $\mu Pa^2 \cdot s$ (Hastings et al. 2008; Hastings & Miksis-Olds 2012). No detectable gross physiological damage was found in individuals from any of the seven species (McCauley & Kent 2012). The results of the hearing tests are consistent with the sound exposure guidelines proposed in Popper et al. (2014), which indicated that TTS may occur at SEL_{cum} levels >186 dB re 1 $\mu Pa^2 \cdot s$ while other studies (Popper & Hastings 2009; Song et al. 2008) indicate that TTS may occur at levels as high as SPL 205-210 dB re 1µPa (PK).

Behavioural Effects

The sound-related factors influencing behavioural reactions in fishes can include its frequency content, intensity above background noise and temporal sound characteristics. If exposed to the same stimulus over a prolonged period, an initial behavioural reaction might fade as the fishes habituate to the sound. Behavioural reactions that are usually observed in fishes in response to sound are dispersion, directed movements away from the sound source (leaving the area of the noise source, aggregation and descending closer to the bottom), startle response (fast start escapes, C-start response) at sound onset (Wardle et al. 2001; Slotte et al. 2004). Effects can be acute (such as acoustic masking), or chronic (including altered distribution), lasting from the immediate duration of sound exposure to several days or weeks if fishes are displaced from their preferred areas during a survey (Engås et al. 1996; Slotte et al. 2004; Løkkeborg et al. 2012; Streever et al. 2016).

The onset level of behavioural responses in fishes varies greatly between and within species, including between fishes of different ages and sizes, the behavioural and social context, and the motivation of the fishes. Existing data on behavioural responses do not provide a clear dose-response relationship and, consequently, it is currently impossible to determine single value thresholds for the onset of behavioural reactions. Instead, broad response and effect categories such as those proposed by Popper et al. (2014) seem most reasonable and may guide regulatory decisions in this context.

Strong 'startle' responses have been observed in some fish species at received sound levels of 200-205 dB re 1 µPa, indicating that sounds at or above this level may cause more severe behavioural reaction such as avoidance. Sound levels of this intensity are likely to occur 100 to 300 m from an acoustic array. Based on this, an approximate range of 200 m was estimated as the minimum distance at which fishes may start avoiding the approaching seismic source (McCauley 1994). Wardle et al. (2001) documented that schooling reef fishes swam past a seismic source array at received levels that would be received at about 20 m below a survey array consisting of 30 air guns.

Pearson et al. (1992) showed that exposure to air gun sound can cause changes in schooling patterns and distribution. Løkkeborg et al. (2012) found changes in catch rates of fish species in Norwegian waters, indicating that these species all responded to seismic sound emissions. However, they also showed that gillnet catches were doubled for some fish species during seismic surveying and only longline catch rates fell slightly. Except for one species, they did not find any changes in abundance

or displacement from fishing grounds. Hawkins et al. (2014) used synthetic impulsive signals in a behavioural response study; they documented that sprat and mackerel reacted to the impulsive sound exposure generally by dispersal and depth changes (which would make it difficult to detect the true scope of effects in a study relying on fisheries technology).

Other studies looking at the behavioural response of sound pressure-sensitive Gadidae and Clupeidae species, such as whiting, Atlantic cod and herring, have reported changes in vertical position in the water column, potential avoidance responses and short-term changes in distribution. Chapman & Hawkins (1969) observed that the depth distribution of free-ranging whiting changed in response to an intermittently discharging stationary seismic source, which resulted in fish being exposed to an estimated SPL of 178 dB re 1 µPa. The fish school responded to the sound by shifting downward, forming a more compact layer at greater depth although temporary habituation was observed after one hour of continual sound exposure (Chapman & Hawkins, 1969).

Hawkins et al. (2014) exposed free-swimming sprat (a sound pressure-sensitive Clupeidae species with a swim bladder connected to the inner ear) and Atlantic mackerel (a particle motion detecting species without a swim bladder) to playback of impulsive sound. Sprat schools were more likely to disperse laterally in response to received sound levels of approximately 135 dB re 1 μPa^2.s SEL. Mackerel schools were more likely to alter their depth in the water column in response to approximately 142 dB re 1 μPa^2.s SEL. Hawkins et al. (2014) note how the two different species seemed to respond to the sound playback at similar sound levels despite the differences in sound sensitivity of the two species, but suggested that mackerel were simply more “flighty” than sprat and therefore more likely to react. The tests were also undertaken using low sound level playback in very close proximity to the schools of fish and it is not clear how relevant the sound pressure and sound exposure levels are in relation to mackerel given that their response was likely driven by particle motion. The study location, a very small, enclosed, quiet, coastal sea lough, where fish were not accustomed to heavy disturbance from shipping and other intense sound sources is also very different from an open ocean location.

Slotte et al. (2004) monitored the effects of a 3,090 in^3 seismic array on migrating herring (Clupeidae) and whiting (Gadidae), mapping their distribution and abundance in relation to the seismic survey lines. There was no significant evidence of immediate, near-field scaring reactions on the horizontal scale in response to acquiring survey lines, but there was some evidence that fish changed position in the water column, moving closer to the seabed. Some short-term changes in distribution were observed but weren’t statistically significant; fish consistently remained within the immediate vicinity of the survey area, but in a limited number of measurements there was an indication that fish abundance was lower near to the survey area and increased with distance out to a maximum range of 37 km. However, results were inconsistent, and clear trends were not observed in all cases. Slotte et al. (2004) concluded that it was not possible to determine how much abundance and distribution were attributed to the seismic survey or to the natural migration patterns and food availability of the fish, or other natural factors. Herring and whiting were found to be abundant in the survey area again after a pause in seismic acquisition and monitoring of fishes for three to four days, indicating that if any displacement did occur as a result of seismic sound exposure, the displacement was temporary (i.e. less than 3-4 days) (Slotte et al. 2004).

In similar studies, Engås et al. (1996) and Engås & Løkkeborg (2002) reported on the effects of seismic surveys on Atlantic cod and haddock (Gadidae) and found that the abundance of fish were lower in the survey area compared with areas outside of the survey area, which the authors hypothesize may be the result of an avoidance response. Some differences in abundance were still detectable within the survey area five days after the survey was completed (Engås et al. 1996; Engås & Løkkeborg 2002).

Santulli et al. (1999) exposed caged European sea bass (a demersal species) to a 2,500 in^3 seismic source. Limited response was observed at 2.5 km distance, a startle response was observed when the array was at a distance of approximately 800 m, but after passing within 180 m, fish behaviour appeared to return to normal within one hour. Increased biochemical stress levels were measured in some fish following exposure, returning to normal levels within 72 hours of exposure. It is noted

that exposures of fish in the wild would likely result in avoidance of high sound levels prior to the seismic source approaching to as close a range and to as high sound levels as the captive fish in the experiment were exposed to.

The behavioural observations of free-swimming fishes in Woodside's Maxima 3D survey at Scott Reef (Miller & Cripps 2013) show that seismic source emissions did not cause lethal or sub-lethal effects on fish near the operating array. At close range, the vessel approach caused fishes to cease their behaviours and move towards the seabed, but the effect was short-lived, and fishes began to feed and behave normally again within 20 minutes after the passage of the seismic survey vessel. Caged fishes displayed startle responses too infrequently to analyse. However, agitation levels increased with increasing received sound exposure level for the three holocentrid species (squirrelfishes and soldierfishes, suborder Holocentroidei) but were not detectable for the blue-stripe sea perch. Sonar observations of free-swimming fishes indicated that individual animals tended to move towards the seabed on approach of the operating seismic source, consistently out to 400 m either side of the survey test line. Schools of fishes moved towards the seabed within 200 m of the survey test line in response to the passage of the operating seismic source and stayed significantly closer to the seabed up to 63 minutes post-exposure. The vocal behaviour of fishes was unaffected from the seismic activity; fish choruses remained unchanged with regards to timing and chorus level (at daily, lunar and seasonal scales); these findings suggest that in the long-term the survey had little effect on the fish that produced the choruses. Underwater visual censuses (UVC) revealed that diversity and abundance of both Pomacentridae (damselfishes and clownfishes) and non-Pomacentridae fish species (inhabtiting shallow-slope regions) showed no significant changes after the seismic survey compared to the long-term temporal trend before the survey. Analysis of recordings from baited remote underwater video stations showed no detectable effects of the seismic survey on the diversity and abundance of deeper water fish communities at the spatial and temporal scales examined. Also, there were no signs of loss of individuals or of systematic re-distribution of individuals and species at any of the time scales examined.

The findings from the research at Scott Reef support those by Wardle et al. (2001), who exposed free ranging fishes inhabiting an inshore reef to sounds from a seismic source (maximum received levels of 195-218 dB re 1 µPa PK). The study found that fishes exhibited a startle response to all received levels, but no avoidance behaviours were observed, they showed no signs of moving away from the reef and exposure to the seismic noise did not interrupt a diurnal rhythm of fishes gathering at dusk. Slight changes were recorded to the long-term day-to-night movements of two tagged pollack (*Pollachius sp.*), particularly when positioned within 10 m of their normal living positions. However, the seismic sound had little effect on the day-to-day behaviour of the resident fishes and invertebrates.

Behavioural observations of two tropical snapper species and another coral reef fish species, spadefish, in field enclosures before, during and after exposure to seismic sound showed that repeated exposure resulted in increasingly less obvious startle responses (Boeger et al. 2006). This is consistent with the potential habituation suggested by McCauley et al. (2000) and by Fewtrell and McCauley (2012).

McCauley & Salgado Kent (2007) observed the behaviour of goldband snapper in fish traps in the Timor Sea using cameras placed inside the fish traps. A seismic vessel towed two 3,090 in^3 seismic sources. Maximum signals reached at the closest trap to each seismic pass-by were 200, 202 and 212 dB re 1 µPa PK-PK (equivalent to approximately 194, 196 and 206 dB re 1 µPa PK). No dramatic behavioural responses of fish to the passing seismic source were observed. Fish generally displayed increased activity immediately after entering a trap presumably as they searched for a way out, with this activity reducing with time. Fish that had been in a trap for some time showed increased activity levels as the operating seismic source approached but were 'quiet' when the array passed at the point of closest approach.

Fewtrell & McCauley (2012) showed that fishes tended to remain lower in the water column and/or swim faster and form tighter schools during periods of close air-gun emissions. Fish populations can

be potentially impacted if behavioural responses result in deflection from migration paths, feeding grounds or disturbance of spawning, thereby affecting recruitment of fish stocks.

Paxton et al. (2017) observed temperate reef fishes, including snapper and grouper species, in 33 m water depths located 7.9 km from a seismic survey line using video recordings. The authors observed fish abundance and habitat use during the evening hours for three days prior to a seismic survey and then during the evening of the day when seismic activity occurred. The authors attempted to measure sound at two other reefs in closer proximity to the survey, but the hydrophones malfunctioned. No video recordings were made at the other reefs where hydrophone measurements were attempted. No hydrophone measurements were made at the reef where video recordings took place, but maximum sound levels were estimated to be more than 170 dB re 1 µPa SPL. Despite no clear visual evidence of behavioural responses in fishes during the seismic survey, the authors noted a 78% decline in abundance in the evening following the survey. No further recordings were made to assess when fish abundance returned to pre-exposure levels or how far they may have moved. Therefore, with limited data, it is not clear from this study if reduced abundance is attributed to the seismic sound or other natural factors such as tidal influence or food availability. However, the study may indicate a possible avoidance response and temporary change in local abundance and distribution.

Bruce et al. (2018) tagged tiger flathead, which were monitored during a seismic survey undertaken in Australian waters. Minor behavioural effects were observed in exposed tiger flathead, which increased their swimming speed during the seismic survey and changed daily movement patterns after the survey but showed no significant displacement. Overall, there was little evidence for consistent behavioural responses (Bruce et al. 2018).

Davidsen et al. (2019) investigated the effects of seismic sound exposure on the physiology and behaviour of captive Atlantic cod (*Gadus morhua*) and saithe (*Pollachius virens*), both species from the Family Gadidae with a swim bladder directly involved in sound detection. Experimental sound exposures were 18-60 dB above ambient. The cod exhibited reduced heart rate in response to the particle motion component of the sound from the air gun, indicative of an initial flight response. No behavioural startle response to the air gun was observed despite some observed changes in swimming depth and position, and the fish seemed to habituate both physiologically and behaviourally with repeated exposure. The authors concluded that sound exposures induced over the three day study period appear unlikely to be associated with long-term alterations in physiology or behaviour.

Hubert et al. (2020) also exposed captive Atlantic cod to one hour of playback of seismic air gun sound pulses with a 10 second shot point interval. Results indicated no strong overall pattern of change in swimming patterns or immediate, short-term behaviours during the exposure, compared to baseline periods without playback. However, several individuals changed their time spent in several behavioural states during the one-hour sound exposure, which may be indicative of changes in energy expenditure.

van der Knaap (2021) investigated the effect of a 3.5-day, full-scale, seismic survey exposure on the movement behaviour of free-swimming Atlantic cod, using acoustic telemetry. The closest point of approach to the tagging location was 2.25 km. The study found that during the experimental survey, cod did not leave the detection area more than expected from baseline data. However, cod left more quickly than expected, from two days to two weeks after the seismic survey. Furthermore, behavioural analyses indicated that during the exposure cod decreased their activity, with time spent being locally active (moving over small distances, showing high body acceleration) becoming shorter, and time spent being inactive (moving over small distances, having low body acceleration) becoming longer. Additionally, diurnal activity cycles were disrupted with lower locally active peaks at dusk and dawn–periods when cod is known to actively feed.

Meekan et al. (2021) undertook a large-scale experiment that quantified the impacts of exposure of an assemblage of tropical demersal emperors (Family Lutjanidae), snappers (Family Lethrinidae)

and groupers (Family Epinephelidae) targeted by commercial fisheries to a commercial-scale seismic source on the North West Shelf off Western Australia. Dominant species included spangled emperor (*Lethrinus punctulatus*), red emperor (*Lutjanus sebae*), and brownstripe snapper (*L. vitta*). A combination of Baited Remote Underwater Video Systems (BRUVS) and acoustic tagging methods were used to measure the behaviours and movements of fishes at high, medium, and low exposure sites, as well as at control sites. The high, medium, and low exposure sites were located at horizontal distances from the path of the seismic source of approximately 0 – 300 m, 2 – 10 km and 11 km respectively. The maximum modelled SEL values received at the high, medium, and low exposure sites were in the order of 180 – 200 dB re 1 $\mu Pa^2 \cdot s$, 130 – 160 dB re 1 $\mu Pa^2 \cdot s$ and 115 – 125 dB re 1 $\mu Pa^2 \cdot s$ respectively. There were no short-term (days) or long-term (months) effects of exposure on the composition, abundance, size structure, behaviour, or movement of fishes at any exposure sites. The authors suggest that it is a reasonable assumption that the behavioural responses of demersal fishes to the bait cue provided by the BRUVS are a realistic proxy of the likely response of the same species to baited hooks or traps used by the commercial fisheries that target them. The acoustic tags and telemetry found little evidence that fish were displaced by the exposure to the seismic source. Movements of tagged fish occurred over a limited area focused on two or three acoustic receivers, and there was no evidence for the departure of tagged fish after exposure. These multiple lines of evidence suggest that seismic surveys have little impact on the behaviours of demersal fishes in this environment.

A recent study examined behavioural responses in spawning Atlantic cod in Norway (McQueen et al. 2022, 2023). Atlantic cod (*Gadus morhua*) may be especially vulnerable to sound disturbance during spawning, as it is a soniferous fish species, with acoustic communication playing an important role in the cod mating system, and a low frequency hearing range (10 – 650 Hz). During the spawning period, male cod produce low frequency grunts (~50 Hz) that have been associated with aggressive and courtship behaviours. Low frequency noise associated with ship traffic has been found to reduce the effective communication range of spawning cod (Stanley et al. 2017; as cited in McQueen et al. 2023), and low frequency anthropogenic noise can elicit stress responses in cod resulting in reduced egg production and fertilization rates (Sierra-Flores et al. 2015). Additionally, cod tend to demonstrate high site fidelity to spawning areas. There have been reports that free-ranging cod move away from an area in immediate or delayed response to seismic surveys (Engås et al. 1996; van der Knaap et al. 2021).

To investigate whether airgun sound causes cod to leave their spawning grounds, McQueen et al. (2022, 2023) deployed acoustic telemetry arrays were on two cod spawning grounds: a test and a reference site. From 2019 to 2021, 136 mature cod from the test site and 45 from the reference site were tagged with acoustic transmitters. Intermittent seismic shooting of two 40 cui airguns for one week during the spawning periods of 2020–2021 resulted in fluctuating SELs at the test site, comparable to a full-scale industrial survey 5–>40 km away. Residency and survival of tagged cod were analysed with capture–mark–recapture models fitted to the detection and recapture data. Departure rate of the mature cod varied between spawning seasons but was similar between the test and reference sites. Cod demonstrated only weak responses to the disturbance from repeated three hour treatment periods over five days, swimming on average slightly deeper during seismic exposure compared to silent control periods. This response varied between individuals. Longer-term effects of seismic exposure on swimming depth were not detected. No changes in swimming acceleration, displacement, or area use occurred. Neither survival nor departure significantly differed between seismic exposure and baseline periods. The results indicated that exposure to airguns at received SEL of up to ~145 dB re 1 μPa^2 s, comparable to a seismic survey occurring several kilometres away, did not displace tagged cod from spawning grounds. These results suggest that relatively distant seismic surveys do not substantially alter cod behaviour during the spawning period at received sound exposure levels varying between 115 and 145 dB re 1 μPa^2 s over a five day period (McQueen et al., 2022, 2023).

The following conclusions are made regarding behavioural effects to fish from seismic airguns, based on the literature above:

- Different fish may exhibit different behavioural responses when exposed to seismic survey noise, depending on their activities, motivation and the context in which they receive sound.
- Fish may change position in the water column (i.e., move closer to the seabed) as a response to becoming aware of approaching seismic sound (e.g., Pearson et al. 1992; McCauley et al. 2000, 2003; Slotte et al. 2004; Fewtrell & McCauley 2012; Miller & Cripps 2013; Davidsen et al. 2019).
- Exposure to higher sound levels at close range to a seismic source may begin to result in more noticeable startle or alarm responses, such as changes in school structure, increased swimming speed and avoidance of the sound source (e.g., Simmonds & MacLennan 2005; McCauley et al. 2000, 2003; Fewtrell & McCauley 2012; Popper et al. 2014; Carroll et al. 2017).
- Many exposure experiments are undertaken using a single airgun and it is not clear how transferrable the behaviours and received SPL/SEL levels are to a full commercial-sized seismic array, particularly if observed behaviours are in response to particle motion close to the sound source rather than to sound pressure.
- There is some evidence that fish may also tolerate gradual increases in sound levels and habituate to repeated sound exposures (Chapman & Hawkins 1969; McCauley et al. 2000; Boeger et al. 2006; Fewtrell & McCauley 2012; Peña et al. 2013; Davidsen et al. 2019).
- Many studies indicate that fishes resume normal behaviour shortly after cessation of the acoustic disturbance (within minutes / less than an hour), with no evidence of long-term changes (e.g., Wardle et al. 2001; Pearson et al. 1992; Santulli et al. 1999; McCauley et al. 2000, 2003; Fewtrell & McCauley 2012; Miller & Cripps 2013; Davidsen et al. 2019).
- Meekan et al. (2021) found no short-term (days) or longer-term (months) effects of seismic sound exposure on the behaviour and movement of tropical demersal snapper, emperor and grouper species on the North West Shelf.
- There is some evidence that changes in distribution may persist for longer than the initial change in behaviour, i.e. position in the water column, schooling behaviours and swim speeds may return to normal relatively quickly (within minutes or hours), but their distribution may not return to normal for hours or days. Potential changes in distribution of fish has been observed in some studies for approximately five days following sound exposure, although such changes are limited to studies that focused primarily on migrating sound pressure-sensitive types of fish with a swim bladder-ear connection (e.g. Clupeidae, Gadidae). These studies also acknowledge that it is difficult to attribute these changes in distribution directly to the seismic survey or to natural migration patterns, food availability or other natural factors (Slotte et al. 2004; Engås et al. 1996; Engås & Løkkeborg 2002). However, it is possible that changes to the behaviour and distribution of some sound-sensitive prey species (e.g. herring, sardines) may have some indirect influence on the distribution of larger predatory fishes during the days following exposure and disturbance.
- Small changes in behaviour or disruption to diurnal activities of pressure-sensitive species of fish (Gadidae) with a swim bladder-ear connection may indicate that activities such as feeding and energy expenditure can be affected if exposed long-term (Davidsen et al. 2019; Hubert et al. 2020; van der Knaap 2021), although these species of fish may also habituate to the sound with repeated exposure (Davidsen et al. 2019).

Given the limited convergence in results from the available studies, the subjective nature of many assessments and the context under which fish received sound, the Popper et al. (2014) ANSI-Accredited Standards Committee Sound Exposure Guidelines for Fishes and Turtles determined

that it is not possible to define exact sound level thresholds for changes in fish behaviours. Instead, Popper et al. (2014) applies relative risk criteria. The criteria reflect the potential for substantial changes in behaviour for a large proportion of the animals exposed to a sound, which may alter distribution, and moving from preferred sites for feeding and reproduction. The criteria do not include effects on single animals or small changes in behaviour such as a startle response or minor movements. As such, Popper et al. (2014) indicate that fish without a swim bladder or with no connection between the swim bladder and the inner ear may experience substantial changes in behaviour within tens or hundreds of metres of a seismic source. These peer-reviewed and accredited sound exposure criteria are reflected in this risk assessment. It is acknowledged that some fishes with swim bladders may show varying levels of awareness of sound pressure at greater distances from the seismic source, but it is important to recognise changes in behaviour that may be of ecological significance from those that aren't.

Sand et al (2000) noted avoidance behaviour of glass eels when exposed to infrasound at a frequency of 11.8Hz and found during the periods with infrasound exposure, the proportion of silver eels entering the section closest to the sound source was reduced to 43% in the control. It should be noted this experiment was a caged study and not representative of a full-scale seismic survey.

Acoustic Masking

Masking impairs an animal's hearing impairment with respect to the relevant biological sounds normally detected within the environment and can have long lasting effects on survival, reproduction, and population dynamics of fishes. The consequences of masking for fishes; however, have not been sufficiently examined to allow a thorough assessment of effects caused in the context of this survey. Popper et al. (2014) surmised that "*It is likely that increments in background sound within the hearing bandwidth of fishes and sea turtles may render the weakest sounds undetectable, render some sounds less detectable, and reduce the distance at which sound sources can be detected. Energetic and informational masking may increase as sound levels increase, so that the higher the sound level of the masker, the greater the masking*." If impulsive sounds are generated repeatedly by many sources over a wide geographic area there is a possibility that the separate sounds might merge and that the overall background noise be raised (Nieukirk et al. 2004). However, acoustic masking only occurs while the interfering sound is present, and therefore, masking resulting from a single pulse of sound (such as seismic source impulses) or widely separated pulses would be infrequent and not likely affect an individual's overall fitness and survival.

5.1 Sharks

Myrberg (2001) stated that sharks differ from bony fishes in that they have no accessory organs of hearing such as a swim bladder and therefore are unlikely to respond to acoustical pressure. The study also suggested that the lateral line system does not respond to normal acoustical stimuli and is unable to detect sound-induced water displacements beyond a few body lengths, even with large sound intensities (Myrberg 2001).

Chapuis et al. (2019) detailed that the auditory apparatus of sharks comprises the paired inner ears that, as in all fishes, detect the particle motion component of a sound. However, unlike most bony fishes, cartilaginous fishes do not possess a swim bladder, which responds to the pressure component of a sound, and therefore are thought to only be sensitive to particle motion. Though Lobel (2009) noted that at very loud levels, an elasmobranch is able to discriminate between sounds based upon the phased difference between particle motion and acoustic pressure (Lobel 2009).

Two sensory maculae, the sacculus and the macula neglecta, have been shown to be responsive to particle motion detection in the inner ear of cartilaginous fishes which are known to be sensitive to low frequency sounds up to 1.5 kHz, peaking between 200 and 600 Hz, depending on the species (Chapuis et al. 2019). This range overlaps with seismic pulses which are primarily less than 2 kHz, with the highest levels at frequencies in the range of 10-500 Hz (McCauley 1994).

There is some indication that a sudden onset of sound can also cause a startle response in sharks (Myrberg et al. 1978). Klimley and Myrberg (1979) established that an individual shark will suddenly turn and withdraw from a sound source of high intensity (more than 20 dB re 1 µPa above broadband ambient SPL) when approaching within 10 m of the sound source.

Research by Bruce et al. (2018), which tagged two shark species and monitored their movements in response to a seismic survey in Australian waters noted that both control sharks and exposed sharks moved freely in and out of the study area which did not indicate any changes in behaviour or distribution as a result of seismic sound exposure.

A study by Chapuis et al. (2019) used a baited underwater camera rig to record the behavioural responses of eight species of sharks (seven reef and coastal shark species and the white shark) to the playback of two distinct sound stimuli in the wild: an orca call sequence and an artificially generated sound. The aim of the study was to look at sound-induced behavioural changes in sharks to potentially identify acoustic repellent devices. When sounds were playing, reef and coastal sharks were less numerous in the area, were responsible for fewer interactions with the baited test rigs, and displayed less 'inquisitive' behaviour, compared to during silent control trials. White sharks spent less time around the baited camera rig when the artificial sound was presented but showed no significant difference in behaviour in response to orca calls.

It is noted that there has been reported cased of sharks biting the seismic streamers, such as during seismic surveys conducted by the survey vessel *Pacific Titan* in New Zealand waters.

6 Marine Turtles

Morphological studies of green turtles (*Chelonia mydas*) and loggerhead turtles (*Caretta caretta*) (Ridgway et al. 1969; Wever 1978; Lenhardt et al. 1985) found that the turtle ear is similar to other reptile ears but has adaptations for underwater listening. In-air electrophysiological and behavioural studies on green and loggerhead turtles found their hearing frequency range is approximately 50-2,000 Hz, with highest sensitivity to sounds between 200 and 400 Hz (Ridgway et al. 1969; Bartol et al. 1999; Ketten & Bartol 2005; Bartol & Ketten 2006; Yudhana et al. 2010; Piniak et al. 2011; Lavender et al. 2012, 2014).

Underwater audiograms are only available for three species, all of whom have poor hearing sensitivity. Two of these species, the red-eared slider (*Trachemys scripta elegans*, freshwater, semi-aquatic) (Christensen-Dalsgaard et al. 2012) and the loggerhead turtle (Martin et al. 2012), demonstrated highest sensitivity at around 500 Hz (Willis 2016). Piniak et al. (2016) found that green turtles have maximum underwater sensitivity between 200 and 400 Hz. Very little research has been performed on the hearing capabilities of hawksbill turtles (*Eretmochelys imbricata*). Yudhana et al. (2010) measured auditory brainstem responses from two hawksbill turtles in Malaysia and found that peak frequency sensitivity occurred at 457 Hz in one turtle and at 508 Hz in the other.

There is no robust information on the susceptibility of marine turtles to noise-induced effects. Most studies researching the effect of seismic noise on marine turtles focused on behavioural responses, as physiological impacts are more difficult to observe in living animals. Turtles avoid low-frequency sounds (Lenhardt 1994) and sounds from an air gun (O'Hara & Wilcox 1990), but these reports did not note received sound levels. Moein et al. (1995) found that penned loggerhead turtles initially reacted to an air gun but then showed little or no response to the sound (i.e., habituated to it). Caged green and loggerhead turtles increased their swimming activity in response to an approaching air gun when the received SPL was above 166 dB re 1 µPa, and they behaved erratically when the received SPL was approximately 175 dB re 1 µPa (McCauley et al. 2000).

The 166 dB re 1 µPa level has been used as the threshold level for a behavioural response to marine turtles by NMFS and applied in the Arctic Programmatic Environmental Impact Statement (PEIS) (NSF 2011) and the Recovery Plan for Marine Turtles in Australia (DoEE 2017). The 175 dB re 1 µPa level from McCauley et al. (2000) is recommended as the threshold for behavioural disturbance. Sound levels defined by Popper et al. (2014) show that animals are very likely to exhibit a behavioural response when they are near an air gun (tens of metres), a moderate response if they encounter the source at intermediate ranges (hundreds of metres), and a low response if they are far (thousands of metres) from the air gun.

Mortality and potential mortality injury (PMI) impacts have not been reported to have occurred in turtles as a result of noise emissions during seismic surveys. Popper et al. (2014) suggested injury to turtles could occur for sound exposures above 207 dB re 1 µPa (PK) or above 210 dB re 1 $uPa^2 \cdot s$ (SEL_{24h}). However, (Finneran et al. 2017, updated by Accomando et al 2025) presented revised thresholds for turtle injury and hearing impairment from impulsive noise, considering both PK and frequency weighted SEL, suggesting that PTS may occur in response to received levels of 204 dB re 1 $uPa^2 \cdot s$ (SEL_{24h}) or 232 dB re 1 µPa (PK) and TTS may occur in response to received levels of 189 dB re 1 $uPa^2 \cdot s$ (SEL_{24h}) or 226 dB re 1 µPa (PK).

7 Birds

There is very little known about the effects of intense underwater sound (i.e. seismic surveys) on marine birds. However, impacts have not been observed during previous seismic surveys (Turnpenny and Nedwell, 1994), and it is generally thought that noise produced from activities associated with seismic surveys may impact only those species of birds that spend large quantities of time underwater, either swimming or plunge diving while foraging for food, for example penguins.

Pichegru et al. (2017) investigated the behavioural response of endangered African penguins (*Spheniscus demersus*) before, during and after a seismic survey conducted within 100 km of their breeding colony in South Africa, using a multi-year GPS tracking dataset.

Penguins foraging within 100 km of the active seismic operations showed a change of foraging direction during seismic periods, increasing their distance between their feeding area and the location of the seismic vessel. The avoidance behaviour by penguins observed in this study may be explained by either a direct disturbance from the noise generated by the operation or a change in fish distribution during that period (possibly as a result of seismic activities). Small-scale acoustic fish surveys assessing distribution and abundance of small pelagic fish in Algoa Bay around both penguin colonies did not show a significant change in distribution and/or abundance of small pelagic fish in the region in March 2013 compared to a few months prior to or after the seismic operations. Therefore, African penguins likely relocated away from their traditional feeding zone to avoid the disturbance generated by the noise of the seismic vessels, rather than to follow their prey.

The African penguins quickly reverted to normal foraging behaviour after cessation of seismic activities during this study, which suggest a relatively short-term influence of seismic activity on these birds' behaviour and/or that of their prey. Most bird and many fish species have the capacity to regenerate lost or damaged sensory cells of the ear, although the researchers could not rule out potential longer-terms impacts on the penguins hearing ability.

Stemp (1985; as cited in LGL 2012) conducted observations on the effects of seismic exploration on seabirds and did not observe any negative effects.

Lacroix et al. (2003) assessed the effect of near shore seismic surveys on the foraging behaviour of moulting long-tailed ducks in the Beaufort Sea, Alaska. Long-tailed ducks are not capable of flying during the moult and to compensate for the nutritionally costly moult process they increase their foraging. Lacroix et al. (2003) found that the abundance and distribution of ducks, in both the seismic and control areas, changed similarly following the start of the seismic operations suggesting other influencing factors such as wind were more important for duck distribution than seismic activities, and that seismic activities did not significantly change the diving intensity of ducks. Overall Lacroix et al. (2003) concluded that there was no evidence to suggest any displacement away from seismic operations.

In a controlled exposure experiment, Sørensen et al. (2020) exposed captive Gentoo Penguins (*Pygoscelis papua*) to impulsive signals, and most animals showed strong aversive reactions at received levels above 120 dB re 1µPa (SPL). While the experiment made efforts to reduce some of the limitations of captive experiments, the study is still difficult to reconcile exposures to sudden sound stimuli at close range (metres) in the absence of natural ocean background noise with a real-life exposure.

8 Marine Mammals

The potential impacts of anthropogenic noise on marine mammals have been the subject of considerable research (see reviews by Nowacek et al. 2007; Southall et al. 2007; Weilgart 2007; Wright et al. 2007; Southall et al. 2019; Southall et al. 2021).

Kavanagh et al. (2019) modelled over 8,000 hours of cetacean survey data across diverse offshore region of the Northeast Atlantic to investigate the effect of seismic surveys on baleen and toothed whales. They found a significant effect of seismic activity across multiple species and habitats, with an 88% (82–92%) decrease in sightings of baleen whales, and a 53% (41–63%) decrease in sightings of toothed whales during active seismic surveys when compared to control surveys. Significantly fewer sightings of toothed whales also occurred during active versus inactive air gun periods of seismic surveys, although some species-specific response to noise was observed.

Southall et al. (2007), Finneran & Jenkins (2012), Wood et al. (2012), Finneran (2015) and more recently NMFS (2018) and Southall et al. (2019, 2021) and most recently updated by Accomando et al 2025), reviewed available literature to determine noise exposure criteria, based on the onset levels of non-recoverable PTS and TTS in cetaceans. The NMFS (2018) criteria incorporate the best available science to inform assessment of PTS and TTS. However, a lack of a quality low-frequency (LF) cetacean audiograms has made it difficult to precisely determine hearing sensitivity, and the criteria for LF cetaceans are likely precautionary.

Hearing Sensitivity

Current data and predictions show that marine mammal species differ in their hearing capabilities, absolute hearing sensitivity and frequency band of hearing (Richardson et al. 1995; Wartzok & Ketten 1999; Southall et al. 2007). While hearing measurements are available for a small number of species based on captive animal studies, direct measurements of many odontocetes and all mysticetes do not exist. As a result, hearing ranges for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods, such as anatomical studies and modelling (Houser et al. 2001; Parks et al. 2007; Tubelli et al. 2012; Cranford & Krysl 2015), vocalizations (see reviews in Richardson et al. 1995; Wartzok & Ketten 1999; Au & Hastings 2008), taxonomy, and behavioural responses to sound (Dahlheim & Ljungblad 1990)

To better reflect the auditory similarities between phylogenetically closely related species, but also significant differences between species groups among the marine mammals, Southall et al. (2007) defined five groups of marine mammals, based on phylogenetic relationships and a combination of auditory, physiological, and behavioural characteristics, where known. A revised set of marine mammal hearing groups and associated frequency-weighting functions were proposed by Finneran (2016) and these groups were adopted in technical guidance (NMFS 2018) as a useful approach in developing auditory weighting functions and deriving noise exposure criteria for marine mammals. In 2019, Southall et al. reviewed these marine mammal hearing groups and modified them based on phylogenetic relationships and a comprehensive review of studies on hearing, auditory anatomy, and sound production (Southall et al. 2019). This review resulted in eight discrete hearing groups as detailed in Table B8-3.

Frequency weighting

Different animals are sensitive to different sound frequencies, which are measured in Hertz (Hz) and kiloHertz (kHz). Therefore, if an animal is sensitive to a particular frequency range, a sound in that frequency range will seem louder to that animal than to a different animal that is less sensitive to those frequencies. For example, some large baleen whales are sensitive to very low frequency sounds (7 Hz to 35 kHz), while toothed whales and dolphin species are considered more sensitive to mid-high frequency sounds (150 Hz to 160 kHz) with their peak hearing frequency somewhere between these frequency ranges (NMFS 2018). Therefore, how loud a sound will be perceived will differ between species.

As the hearing of different species of marine fauna is frequency dependent, rather than express received sound pressures in terms of their levels over a broad bandwidth, levels can be weighted by the frequency response of hearing for the animal. This approach has been widely used for examining exposure of humans to sound (Popper et al. 2014). Southall et al. (2007) developed M frequency weighting functions (M-weightings) for five functional hearing groups of marine mammals, with this method designed specifically to represent the broader bandwidth at which auditory effects (TTS and/or PTS) might occur for higher exposures. Southall et al. (2019) expanded on this approach to provide M-weighting functions for eight marine mammal hearing groups, including LF cetaceans, HF cetaceans, VHF cetaceans, sirenians, phocid carnivores and other marine carnivores (refer to Table B8-3).

Table B8-3 - Marine Mammal Hearing Groups

Group	Genera or species included
Low-frequency (LF) cetaceans	The LF cetacean group contains all of the mysticetes: Balaenidae (*Balaena* spp. and *Eubalaena*, Neobalenidae (*Caperea*), Eschrichtiidae (*Eschrichtius*), and Balaenopteridae (*Balaenoptera* spp. and *Megaptera*).
High frequency (HF) cetaceans	The HF cetacean group contains most delphinid species (e.g., bottlenose dolphin, common dolphin, and pilot whale), beaked whales, sperm whales and killer whales.
Very high frequency (VHF) cetaceans	The VHF cetacean group comprises the true porpoises, most river dolphin species, pygmy/dwarf sperm whales, as well as number of oceanic dolphins (Commerson's, Chilean, Heaviside's, Hector's, Hourglass, and Peale's dolphins).
Sirenian (SI)	The SI group includes the manatees and dugongs.
Phocid Carnivores in Air (PCA) and Water (PCW)	This group contains all the true seals, including harbour, grey, and freshwater seals; elephant and monk seals; and both Antarctic and Arctic ice seals.
Other Marine Carnivores in Air (OCA) and Water (OCW)	This group contains all non-phocid marine carnivores, including the otariid seals (sea lions and fur seals), walruses, sea otters, and polar bears.

Behavioural Effects

Differences between species, individuals, exposure situational context, the temporal and spatial scales over which they occur, and the potential interacting effects of multiple stressors can lead to inherent variability in the behavioural response of marine mammals to sound exposure (Southall et al. 2021).

Southall et al. (2007) presented a severity-index ranking the intensity of behavioural responses that was later amended by Ellison et al. (2012), Miller et al. (2012), and Sivle et al. (2015) and has recently been updated by Southall et al. (2021) based primarily on studies of free-ranging mammals.

The NMFS currently uses a step function with a 50% probability of inducing behavioural responses at an SPL of 160 dB re 1 µPa to assess behavioural impact. This threshold value was derived from the HESS (1999) report, which, in turn, was based on the responses of migrating mysticete whales to seismic sounds (Malme et al. 1983, 1984). The HESS team recognized that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above an SPL of 140 dB re 1 µPa. An extensive review of behavioural responses to sound was undertaken by Southall et al. (2007), which found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report.

In 2012, Wood et al. (2012) proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric (see Table B8-4). They designated behavioural response categories

for sensitive species (such as harbour porpoises, *Phocoena phocoena*, and beaked whales) and for migrating mysticetes.

Table B8-4 - Graded Probability of Response for Impulsive Sounds

Marine Mammal Group	Probability of response to frequency -weighted SPL (dB re 1 µPa)			
	120	140	160	180
Sensitive species	50%	90%		
Other species		10%	50%	90%

McCauley et al. (2000) monitored the effects of seismic survey sounds on humpback whales in the Exmouth Gulf region of Western Australia. They documented rapid swimming on the surface, breaching and localised avoidance behaviour by migrating whales during the seismic operation, indicating that the 'risk factor' associated with the marine seismic survey was confined to a comparatively short period and small range displacement. During their migration and breeding season, humpback whales rarely display deep dives. This tendency to stay close to the surface has been interpreted as actively utilising the 'sound shadow' (Lloyd's Mirror effect) near the surface; irrespective of the motivation for this behaviour, it reduces the risk for noise-induced effects unless at very short range from a large seismic source array.

A comparison of behavioural observations of humpback whale behaviour during seismic surveys shows the variability and context dependence of these responses (Richardson et al. 1995). McCauley et al. 2000) estimated that humpback whales would avoid seismic surveys in key habitat (such as breeding, resting, or feeding areas) at distances between 7 and 12 km, whereas migrating individuals generally showed an avoidance range of around 3 km. Some males have even been recorded approaching seismic survey vessels to within 1 to 2 km (McCauley et al. 2000). It is considered that avoidance behaviour represents a temporary and minor effect, unless avoidance results in displacement of whales from breeding, resting, or feeding areas.

The BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) project conducted studies at Peregian Beach in Queensland, and off Dongara in Western Australia, to better understand the behavioural responses of humpback whales to noise from the operation of seismic air gun arrays (20 in^3 and 140 in^3 arrays) (Cato et al. 2013). Results from the experiments are published in Dunlop et al. (2015, 2016, 2017a, b). The BRAHSS Project found:

- Humpback whale groups responded by decreasing both dive time and speed of southwards movement though the response magnitude was not found to be related to the proximity of the source vessel, the received level of the air gun, the tow path direction, or the exposure time within the during phase. There was no evidence of orientation of the groups towards, or away from, the source vessel in the during phase. Interestingly, this behavioural response was found in the control trials as well as the active trials suggesting a response to the source vessel.
- No abnormal behaviours were recorded during the trials. However, in response to the active seismic array and the controls, the whales displayed changes in behaviour. Changes in respiration rate were of a similar magnitude to changes in baseline groups being joined by other animals suggesting any change group energetics was within their behavioural repertoire. However, the reduced progression southwards in response to the active treatments, for some cohorts, was below typical migratory speeds. This response was more likely to occur within 4 km from the array at received levels over 135 dB re 1 μPa^2.s
- Humpback whales were more likely to avoid the air gun arrays (but not the controls) within 3 km of the source at levels over 140 re. 1 μPa^2 s, meaning that both the proximity and the

received level were important factors and the relationship between dose (received level) and response is not a simple one.

The results of the BRAHSS study are consistent with previous studies with humpback whales in different behavioural contexts. Feeding humpback whales, for example, responded at ranges up to 3 km from the source, at levels of 150-169 dB re 1 µPa (Malme et al. 1985). Resting female humpback whales with calves displayed avoidance reactions at 140 dB re 1 µPa, though other cohorts reacted at higher levels (157-164 dB re 1 µPa - McCauley et al. 2000).

Recent research has found that male humpback whales switch to singing in the presence of seismic airguns (Dunlop and Noad 2024). They found that during periods of active air guns, the number of male singing whales increased, and singers were more likely to be observed joining females, while conversely, non-singing males were less likely to engage in joining interactions suggesting that active air guns caused a switch in male breeding tactics.

Blackwell et al. (2015) found evidence for two behavioural thresholds in migrating bowhead whales responding to seismic operations in the Beaufort Sea. A moderate cessation or modification of vocal behaviour (interpreted as compensation behaviour) was found at received SEL over a 10 minute period of 94 dB re 1µPa²·s (increase of calling rates) and 127 dB re 1µPa²·s (decrease in calling rates). At received levels of >160 dB re 1µPa²·s; however, whales were completely silent. Robertson et al. (2013) detected changes in surfacing, respiration, and diving behaviour of bowhead whales in response to seismic survey activity but did not provide any qualitative information on the received levels. Castellote et al. (2010) documented avoidance behaviour in fin whales in response to seismic survey activity in the Mediterranean Sea lasting over 10 days.

Observations of sperm whale behaviour during seismic surveys provided conflicting results: Stone (2003) identified that while sperm whales were frequently (visually) detected during seismic surveys, these animals did not show any observable behavioural reactions. Jochens et al. (2008) found sperm whales tolerant of seismic activity; however, a decrease in foraging activity was observed for a small number of animals but no horizontal avoidance was measured. In a tagging study, Jochens and Biggs (2003) found that sperm whales did not show any behavioural reaction (horizontal avoidance of the seismic vessel, change in feeding rates) at maximum received levels of 148 dB re 1µPa.

In the Gulf of Mexico, sperm whales were equipped with multisensory tags to investigate their behaviour in response to seismic surveys. The animals did not show any statistically significant changes in horizontal movement, diving and echolocation behaviour at received levels of approximately 118–131 dB re 1µPa²·s ($SEL_{M\text{-}weighted}$) (Miller et al. 2009).

The hearing of dolphins (HF cetaceans) is less sensitive in the low frequency range of air gun impulses (<500 Hz) and seismic operators sometimes report dolphins and other small toothed whales near operating seismic source arrays. However, there is a component of seismic pulses in the higher spectrum and in general most toothed whales do show some limited avoidance of operating seismic vessels. Goold (1996) studied the effects of seismic surveys common dolphins (*Delphinus delphis*) in the Irish Sea. The results indicated that there was a local displacement of dolphins around the seismic operation. This observation is consistent with visual data compiled by Stone (2003) from marine mammal surveys in the North Sea that shows small toothed whale species tend to move away from operating compressed air seismic sources. In a review of behavioural effects of seismic surveys on marine mammals in UK waters, Stone and Tasker (2006) reported that small odontocetes (dolphins, HF cetaceans and porpoises, VHF cetaceans) showed the strongest avoidance response to the seismic survey activity, were seen less often during periods of seismic acquisition, remaining further from the air guns and showing altered behaviour (e.g., less bow-riding, orienting away from the survey vessel, faster swimming). The same study documented that killer whales also showed some localised avoidance to seismic surveys.

A reduction in feeding activity in response to seismic survey activity has been documented for harbour porpoises at estimated received SEL of 150 – 165 dB re 1µPa²·s (Pirotta et al. 2014). Due to the

permanently high energy demands of harbour porpoises (Wisniewska et al. 2016) a prolonged cessation of feeding can have significant effects on the fitness of affected animals.

Gotz et al. (2009) reported that controlled exposure experiments with small acoustic sources (215 - 224 dB re 1µPa) were carried out over one hour to individual harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*), and in seven out of eight trials with harbour seals, the animals exhibited strong avoidance reactions.

Two harbour seals equipped with heart rate tags showed immediate, but short-term, startle responses to the initial acoustic source pulses. The behaviour of all harbour seals seemed to return to normal soon after the end of each trial, even in areas where disturbance occurred on several consecutive days. Only one harbour seal showed no detectable response to the acoustic sources and approached the acoustic source to within 300 m, and seals remaining in the water returned to pre-trial behaviours within two hours of the end of the experiment (Gotz et al. 2009). General avoidance behaviour of other Northern Hemisphere seal species was exhibited at exposure levels above 170 dB re 1µPa.

Monitoring studies (Harris et al. 2001) undertaken on the behaviour of phocid seals (more sensitive to sound than otariid pinnipeds) during a nearshore seismic program in Alaska observed that:

- During daylight hours seals were seen at nearly identical rates during periods where there were no air guns firing, one air gun firing and the full array operational.
- Seals tended to be further away during full array seismic. Swimming away was more common during full array operation than no air gun periods, but relative behaviours (looked, approached, swam parallel to boat's track, dive or swam away when full array was firing) did not differ significantly among the distance categories.
- Approximately 79% of seal sightings were within 250 m of the seismic vessel. There was partial avoidance of the zone less than 150 m from the vessel during full array seismic, but seals did not move much beyond 250 m at any time.
- Received levels of noise pulses from the full array were ≥180 dB SPL out to a radius of 1 km. Despite this, many seals showed little or no obvious avoidance and no obvious tendency to avoid diving.

Darias-O'Hara et al. (2025) presents research conducted by a team of experts attempting to determine thresholds for Antarctic marine mammal species. The work conducted on LF cetaceans relied heavily on the extensive body of research on humpback whale responses to seismic airguns, using these studies as the primary evidence base. These results were then adjusted to infer how other low-frequency species may respond, drawing on comparative studies across marine mammals. This approach produced a median behavioural response threshold of 139 dB, driven predominantly by humpback whale data and supported by broader cross-species insights.

Darias-O'Hara et al. note the lack of consensus globally on the most appropriate behavioural thresholds for marine mammals, emphasising that different permitting agencies apply different metrics and, as a result, harmonising to a single universal threshold is not currently feasible. The study also recognises that the elicitation process revealed "*significant uncertainty – driven by a lack of data – on how marine mammal species respond to these sound sources*," particularly when attempting to apply results from different species, sound sources, or regions to Antarctic EIAs. The authors reinforce this point, stating that "*the distributions clearly highlight the uncertainty associated with these thresholds. Critically, these behavioural response thresholds are restricted to the scenarios and assumptions in this elicitation. Specifically, these thresholds are appropriate for use in applications in Antarctic waters where the definition of response is the same as applied here*."

The behavioural thresholds presented represent the average levels at which responses with potential fitness consequences may begin to occur, offering a reasonably conservative basis for delineating areas where significant behavioural changes could arise. However, whether these responses result in meaningful biological impacts depends on several external factors, including activity duration, individual health, prey availability, and recovery capacity. While the thresholds reflect expert judgement certainty, the accompanying dose–response functions capture variability and uncertainty within and between species. As Darias-O'Hara et al. acknowledge, this work represents a necessary early step toward refining impact assessment, but substantial knowledge gaps remain. Further research is essential for regulators to more confidently assess and mitigate the effects of anthropogenic noise on Antarctic marine mammals as research activity in the region continues to expand.

Physiological Effects

A study on the physiological response of Arctic Narwhals to anthropogenic noise found individuals had marked cardiovascular, respiratory and locomotor reactions in response to seismic pulses. Noise exposed Narwhals experienced a 2-2.2-fold increase in the energetic cost of diving, whilst paradoxically heart rate reduced (bradycardia). Williams et. al. 2022 compared these results to studies on trained harbour porpoises (Phocoena phocoena, Elmegaard et al., 2021) and a closely related species, the Beluga Whale (Delphinapterus leucas, Lyamin et al., 2011). In the harbour porpoise study, the cetaceans initially had intensified levels of bradycardia, however this response diminished as they habituated to the noise. In the Beluga Whale study, the continued noise exposure resulted in eventual bradycardia. These studies are impacted by variation in environmental conditions and type of fear stimuli (Williams et. al. 2022). [Paragraph has been added in response to Matter M11].

Acoustic Masking

Masking is the process by which the threshold of hearing for one sound is raised by the presence of another (masking) sound (Erbe & Farmer 1998; Erbe 2008; Erbe et al. 2016). This describes the reduction in audibility for one sound (termed 'signal') caused by the simultaneous presence of another sound (termed 'noise'). For this to occur, the sound must be loud enough, have similar frequency content to the signal, and must happen at the same time. Masking depends on the spectral and temporal characteristics of signal and noise and is reduced if the signal and noise are separated in time, frequency, or direction (space); it can occur if the noise happens shortly before or after the signal (forward and backward masking). The zone of masking can maximally be as large as the zone of audibility, as a faint noise might mask a faint signal. The masking effect can be reduced or remedied by various active or passive mechanisms for masking-release, such as spatial or temporal release from masking, the Lombard effect, or co-modulation masking release.

Auditory masking can lead to disruption of a behaviour, lack of appropriate behavioural reactions, increased vulnerability to predators, reduced access to prey, reduced communication, changes in vocal behaviour, disruption of spawning activities, and stress. The biological significance of acoustic masking is directly linked to the duration of the masking sound. While masking can be detrimental to the fitness, reproduction, and survival of individuals, it ends immediately after the masking sound ceases. Both anthropogenic and natural marine sound can affect hearing and partially or completely reduce an individual's ability to effectively communicate; detect important predator, prey, and/or conspecific signals; and detect important environmental features associated with spatial orientation (Clark et al. 2009). This is true for all marine fauna; however, masking is most frequently associated with marine mammals. Masking in fishes has not been studied in detail.

Masking reduces the communication space of marine mammals (Clark et al. 2009; Hatch et al. 2012). A calculation of reductions in communication range can be a useful proxy for impact. So far, a direct

assessment and quantification of masking effects in wild animals has proven impossible (Tougaard et al. 2015). It depends on the positions of the signalling and the receiving animal relative to the sound source and to each other. In humpback whales (*Megaptera novaeangliae*), tonal and grunting sounds acting as contact calls between a mother and its calf were recorded at comparatively low levels (Videsen et al. 2017). While there is controversy about the validity of conclusions, such low levels would create a small communication space (<100 m) which, in turn, would be sensitive to increases in ambient noise.

Most studies related to masking effects in marine mammals have investigated the auditory parameters that are most relevant in this context, such as auditory sensitivity, frequency-tuning (critical bandwidth and critical ratio), auditory integration time, and critical interval. Erbe et al. (2016) reviewed the current knowledge on masking in marine mammals, summarising data on marine mammal hearing as they relate to masking and discussing masking release processes of receivers. The variability seen in auditory sensitivity (see Hearing sensitivity) indicates the variability seen with respect to auditory masking.

Temporary Threshold Shift and Permanent Threshold Shift

In marine mammals, the onset level and growth of TTS is frequency specific, depends on the temporal pattern, duty cycle, and the hearing test frequency of the fatiguing stimuli. Exposure to intense impulse noise might be more hazardous to hearing than non-impulsive noise, and there is a positive relationship between exposure duration and the amount of TTS induced. TTS can accumulate across multiple exposures, but the resulting TTS will be less than the TTS from a single, continuous exposure with the same total sound exposure level. Sounds generated by seismic sources, pile driving and mid-frequency sonars have directly been tested and proven to cause noise-induced threshold shifts in marine mammals at high received levels. Finneran (2015) reviewed the current state of knowledge on TTS and PTS. TTS typically decreases in marine mammals relative to the logarithm of the increasing recovery time. However, there is considerable individual difference in all TTS-related parameters between subjects and species tested so far.

PTS is considered injurious in marine mammals, but there are no published data on the sound levels that cause PTS in marine mammals. Hence, PTS effects in marine mammals should be viewed as theoretical, as they have never actually been demonstrated in either captive or wild animals. Regeneration of sensory cells, as known to occur in fishes, has not been documented for any marine or terrestrial mammal. Onset levels of PTS onset are typically extrapolated from TTS onset levels and assumed growth functions (Southall et al. 2007). The NMFS (2018) criteria incorporate the best available science to estimate PTS onset in marine mammals from sound energy (SEL_{24h}), or very loud, instantaneous peak sound pressure levels. Criteria are given separately for each cetacean functional hearing group and discriminate between impulsive and non-impulsive sounds. Southall et al. (2019) undertook a comprehensive review of all available data on direct measures of hearing auditory anatomy, and emitted sound characteristics for all marine mammal species. The quantitative process undertaken resulted in exposure criteria, in many respects identical to those derived by Finneran (2016) and adopted by the NMFS (2016, 2018); however, the Southall et al. (2019) exposure criteria (Table B8-5) appear in a peer-reviewed publication and include marine mammal species for all noise exposures, both under water and in air for amphibious species.

Table B8-5 - TTS- and PTS-onset Thresholds for Marine Mammals Exposed to Impulsive Noise

Marine mammal hearing group	TTS onset: SEL (weighted)	TTS onset: Peak SPL (unweighted)	PTS onset: SEL (weighted)	PTS onset: Peak SPL (unweighted)
LF	168	213	183	219
HF	170	224	185	230
VHF	140	196	155	202
SI	175	220	190	226
PCW	170	212	185	218
OCW	188	226	203	232
PCA	123	138	138	144
OCA	146	161	161	167

The role of the temporal pattern of sound on TTS in marine mammals has been studied in MF and HF cetaceans (Mooney et al. 2009; Finneran et al. 2010; Kastelein et al. 2014; Kastelein et al. 2015). The results of these studies show that TTS can accumulate across multiple exposures, but the resulting TTS will be less than the TTS from a single, continuous exposure with the same total SEL.

Only a few studies have investigated TTS in marine mammals in response to exposure to impulsive sounds such as seismic impulses. Lucke et al. (2009) tested the effect of a single seismic source on a male harbour porpoise. They documented onset of TTS at received (unweighted) SEL of 164 dB re 1 $\mu Pa^2 \cdot s$. This equates to a (HF) weighted SEL_{24h} of 140 dB re 1 $\mu Pa^2 \cdot s$ (NOAA 2016). The main energy of the fatiguing stimulus (seismic pulse) was centred below 500 Hz, but a substantial amount of energy was also present at higher frequencies. Kastelein et al. (1997) tested the auditory tolerance of a harbour porpoise to playbacks of broadband pile driving sounds. After one hour of exposure an unweighted SEL 146 dB re 1 $\mu Pa^2 \cdot s$ and a SEL_{24h} of 180 dB re 1 $\mu Pa^2 \cdot s$, a TTS of 2.3 dB and 3.6 dB occurred at 4 kHz and 8 kHz, respectively. The average weighted SEL_{24h} from these exposures was 144 dB re 1 $\mu Pa^2 \cdot s$.

In a study using playbacks of pile driving sounds, Kastelein et al. (2013) exposed harbour porpoises to a maximum single-strike unweighted broadband SEL of 145 dB re 1 $\mu Pa^2 s$ and a cumulative SEL_{24h} of up to 187 dB re 1 $\mu Pa^2 \cdot s$. TTS increased from 0 dB after 15 minutes exposure to 5 dB after 360 minutes exposure. Based on their results, they calculated an onset of TTS for this type of sound at a SEL_{24h} of approximately 175 dB re 1 $\mu Pa^2 \cdot s$. Kastelein et al. (2017) exposed a harbour porpoise to 10 and 20 consecutive seismic impulses at received SEL_{24h} of 188-191 dB re 1 $\mu Pa^2 \cdot s$ with a mean shot intervals of around 17 seconds. TTS of ~4.4 dB was measured at 4 kHz.

Finneran et al. (2015) tested the exposed three bottlenose dolphins to 10 impulses produced by a seismic source. The highest exposures were conducted at peak sound pressure levels (PK) of 210 dB re 1 µPa, peak-peak sound pressure levels (PK-PK) of 212 dB re 1 µPa, and cumulative (unweighted) SEL_{24h} of 195 dB re 1 $\mu Pa^2 \cdot s$. This exposure induced 9 dB TTS in one animal at 8 kHz.

9 Commercial Fishing Catch and Abundance Effect Studies

Some effort to relate fishing catch data to marine seismic survey effects has been undertaken, but to date none of the Australian efforts to relate catch data with marine seismic surveys have yielded significant results. Elsewhere, the potential effects of seismic operations on fish distribution, local abundance or catch have been examined for some teleost species with varying results (Carroll et al. 2017).

A range of behavioural responses have been observed in wild fish in the presence of anthropogenic sound. Studies suggest that fish will generally move away from a loud sound source to minimise their exposure, but this response may depend upon the animal's motivational state. Anthropogenic sound (including marine seismic surveys) has been shown to cause changes in schooling patterns and distribution (Engås et al. 1996; Engås and Lokkeborg 2002; Slotte et al. 2004; Lokkeborg et al. 2012; Popper at al. 2014; Streever et al. 2016) potentially altering the catchability of commercially valuable species or recreationally targeted species.

The following studies have relevance to commercial fish and invertebrate species with respect to their catchability:

- The effects of a marine seismic survey on demersal long-line and trawl catch rates of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in Norway after a marine seismic survey were shown to fall by 45% and 70% respectively five days after survey completion (Engås et al., 1996). Based upon this decline Engås et al. (1996) hypothesised a reduction in catch rates due to fish avoidance behaviour, but this was not quantified. Similar reductions in catch rates (52% decrease in catch per unit effort (CPUE)) relative to controls) has been observed in the hook-and-line fishery for rockfish during controlled discharges of a single air gun (Skalaski et al. 1992). The authors suggest that the CPUE decline may not be dispersal but a decreased responsiveness to baited hooks from alarm response behaviour. A companion behavioural study showed the alarm and startle responses were not sustained following the removal of the sound source (Pearson et al. 1992; Skalski et al. 1992) suggested fishing effects may be transitory, primarily occurring during the sound exposure.
- Lokkeborg et al. (2012) observed, following air gun exposure, gillnet catches increased substantially for redfish (*Sebates norvegicus*) and Greenland halibut (*Reinharditius hippoglossoides*) by 86% and 132% respectively compared with pre-shooting levels, while longline catches of Greenland halibut and haddock decreased by 16% and 25% respectively compared with pre-survey catch. These contradictory results were explained by greater swimming activity versus lowered food search behaviour in fish when exposed to air-gun emissions. Changes in catch rates of all species studied, including saithe and ling, found all species responded to air-gun sounds. Except for saithe (a pelagic hearing sensitive fish), acoustic mapping of fish abundance did not suggest displacement from fishing grounds.
- Sonar observations by Peña et al. (2013) observing real-time behaviours of Atlantic herring (*Clupea harengus* - a clupeid species with good hearing capability) schools exposed to an acoustic source approaching from 27 km to 2 km over a two hour period found no changes in school size, swimming speed or direction. The lack of response was interpreted as a combination of a strong motivation for feeding, a lack of suddenness of the air gun stimulus and an increased tolerance to seismic shooting.
- Catch studies undertaken as part of a marine seismic survey in the Gippsland Basin found no clear evidence of adverse effects on scallops, fish or commercial catch rates (Przeslawski et al. 2016a; Bruce et al. 2018) The study followed 15 species caught by Danish

seine and demersal gillnet and identified in the six months which followed the survey, six species showed increased catch. For Danish seine this included tiger flathead, goatfish and elephantfish. For demersal gillnet this included boarfish, broadnose shark and school shark. Three species showed decreased catch caught via Danish seine – gummy shark, red gurnard, sawshark. No change was observed in the remainder of species. No change to gummy shark catch was observed for demersal gillnet capture techniques. These results support previous studies in which the effects of seismic surveys on catch seem transitory and vary among species and gear types.

In October 2020, the FRDC released preliminary results of a Multiple BACI experiment that they funded to investigate the effects of a 3D marine seismic survey in eastern Bass Strait on Danish Seine catch rates (Fishwell Consulting 2020). The key targets for the Danish Seine fishery in the areas of the marine seismic survey are flathead (*Platycephalus* sp.) and whiting (*Sillago* sp.). The October 2020 report (Fishwell Consulting 2020) provided preliminary results of three phases of the four phase study and found that overall, the BACI analyses provide robust evidence for a negative impact of seismic acquisition on whiting catch rates in the Danish Seine Fishery up to ~100 days following the survey and on flathead rates up to ~200 days. Relative catch indices for both species in the years preceding the marine seismic survey were highly variable (temporally and spatially), and that relative catch index is a measure of catch per effort, not an absolute measure of abundance. As the relative catch indices for both species in the years preceding the marine seismic survey were highly variable it is difficult to determine the effect of the survey.

Specific studies examining the effect of seismic survey signals on invertebrate catch data are rare but include:

- Carroll et al. (2017) undertook a critical review of the potential impacts of marine seismic surveys on fishes and invertebrates. Carroll et al (2017) found no significant differences in any of the studies reviewed in catch rates from the potential effects of seismic signals (Christian et al. 2003; Parry & Gason 2006; Przeslawski et al. 2016a).

- Christian et al. (2003) investigated the behavioural effects of exposure to seismic survey sound on snow crabs. Caged animals on the ocean bottom at a depth of 50 m were monitored with a remote video camera during exposure to seismic sound and did not exhibit any overt startle response during the exposure period. Eight animals were equipped with ultrasonic tags, released, and monitored for multiple days prior to exposure and after exposure. None of the tagged animals left the immediate area after exposure to the seismic survey sound. Five animals were captured in the snow crab commercial fishery the following year, one at the release location, one 35 km from the release location, and three at intermediate distances from the release location.

- Parry & Gason (2006) undertook a statistical analysis of CPUE data collected over nearly 30 years in the Victorian southern rock lobster (SRL) fishery (in southwest Victoria) that showed no influence of historical 2D and 3D marine seismic survey activity. Analyses looked at short-term (weekly) and long-term variations (up to seven years) in CPUE to determine whether changes were correlated with the marine seismic survey. The surveys occurred in water depths ranging from 10 m to 150 m. The study included surveys occurring during the SRL spawning period as well as during the lobster fishing. This study found no evidence that catch rates were affected in the weeks or years following the surveys; however, Day et al. (2016a) suggest that catch rates would have had to decrease by around 50% for this study to detect a result.

- A study undertaken by the CSIRO and Geoscience Australia (Thomson et al. 2014) examined fisheries catches (10 species of interest) and catch rates for potential effects from 183 seismic surveys undertaken in the Gippsland Basin (Bass Strait). The authors found that there were no clear or consistent relationships between seismic surveys and subsequent

fisheries catch rates in their study. However, they cautioned that the results did not imply that such impacts do not exist, but that data was lacking. In terms of duration since a seismic survey occurred, significant positive and negative effects were found but could not be distinguished from inter-annual changes in stock size or availability to fishing gear resulting from other dynamics (Thomson et al., 2014).

- Przeslawski et al. (2016a) monitored scallop populations and fish behaviour before, during, and/or after an April 2015 seismic survey in the Gippsland Basin, commercial scallops (*Pecten fumatus*) and doughboy scallops (*Mimachlamys asperrima*) were assessed using dredged samples and underwater imagery from an Autonomous Underwater Vehicle (AUV) before and two and ten months after completion of the seismic survey. The study provided no clear evidence of adverse effects on scallops or commercial catch rates due to the 2015 seismic survey undertaken in the Gippsland Basin. It was noted that there were limitations with some of the analyses (e.g., large variance in scallop catch).
- Haddon (2017) further investigated the effect of the 2015 seismic survey in the Gippsland Basin on deepwater flathead catches and concluded that the significant drop in CPUE was very likely negatively influenced by the seismic survey. However, Haddon (2017) went on to add that the seismic survey did not appear to have had a lasting impact on deepwater flathead CPUE, which returned to typical values in the first month following the seismic survey.
- Morris et al. (2018) investigated the effects of 2D seismic acquisition on the snow crab fishery along the continental slope in Canada in a BACI study over a period of two years. Crabs were exposed to received levels of 187 dB re 1µPa^2 s (single shot) and 200 dB re 1µPa^2 s (cumulative over 24-hours). There was no negative effects on the catch rates in the shorter term (days) or longer term (weeks), and the authors concluded that seismic effects on snow crab harvest (if they do exist) would be smaller than changes related to natural spatial and temporal variation.
- In a further study, Morris et al. (2020) conducted a field experiment applying a series of comparisons conducted within a BACI study design to investigate the effect of prolonged industrial 3D seismic exposure on the catch rates of snow crab over nine weeks in 2017 and five weeks in 2018. Changes in catch rates at 3D seismic surveying sites were inconsistent across years, with reduced catches in 2017 and increased catches in 2018. Catch rates were similar at experimental and control sites within two weeks after exposure, and the potential effect of seismic surveying was not measured at a distance of 30 km. The large variation in catch rates across small temporal and spatial scales coupled with the absence of notable mechanistic responses of snow crab in past studies to seismic in associated snow crab movement behaviour, gene expression and physiology, the authors concluded that the observed differences owing to seismic surveying in this study design are likely a result of stochastic processes external to their manipulation.

10 Scuba Divers and Snorkelers

Scuba divers and snorkelers exposed to high levels of underwater sound can suffer from dizziness, hearing damage or other injuries to other sensitive (mainly air-filled) organs, depending on the frequency and intensity of the sound. The human auditory system is significantly less sensitive underwater than in air and is further degraded if diving equipment obstructs the ears or face (e.g., diving with a hood or full facemask).

Underwater, the human ear is about 20 dB less sensitive than it is in air at low frequencies (20 Hz), increasing to 40 dB at mid-frequencies (less than 1 kHz), and increasing to 70–80 dB less sensitive at higher frequencies (Parvin 1998). Divers who wear neoprene hoods have even higher hearing thresholds (lower sensitivity) above 500 Hz because the hood material absorbs high-frequency sounds (Sims et al. 1999). Exposure studies related to divers have typically focused on military sonar exposure, with little information on seismic survey operations, and as such care is required when considering thresholds for non-military divers, particularly for impulsive sounds such as seismic source impulses (Ainslie 2008).

Underwater auditory threshold curves indicate that the human auditory system is most sensitive to waterborne sound at frequencies between 400 Hz to 1 kHz (Parvin et al. 1994) and these frequencies have the greatest potential for damage. The auditory threshold of hearing under-water was lowest at 1 kHz (70 dB re 1 µPa SPL) and increased for lower and higher frequencies to around 120 dB re 1 µPa at 20 Hz (Parvin 1998).

Within the literature there is some variation in acceptable SPLs for divers (Ainslie 2008).

Fothergill et al. (2000) and Fothergill et al. (2001) conducted controlled acoustic exposure experiments on military divers under fully controlled conditions at a US Ocean Simulation Facility and an US Open water test facility. In all tests, the divers were covered with soft or hard shell dive suits and their position and distance relative to sound source, signal characteristics and received levels were controlled and documented (Pestorius et al. 2009). A total of 89 male Navy divers were exposed to pure tone signals and sweeps between 160-320 Hz at SPLs up to 160 dB re 1 µPa. The divers were exposed to these sounds over 100 seconds at depths from 10 to 40 m. The divers rated the sounds on a severity scale. For frequencies between 100 and 500 Hz, at a received SPL of 130 dB re 1 µPa, divers and swimmers detected body vibration. None of the divers tested rated levels of 140 dB re 1 µPa as “very severe”; however, at 157 dB re 1 µPa, sound was rated as “very severe” 19% of the time. No physiological damage was observed at the highest levels tested: 160 dB re 1 µPa (Fothergill et al. 2001).

In a subsequent study, recreational divers were exposed to tonal signals or 30 Hz sweeps at frequencies between 100 and 500 Hz at received levels of 130-157 dB re 1 µPa (Pestorius et al. 2009). Each exposure lasted for seven seconds. Nine female and 17 male scuba divers were tested, all wearing full body neoprene wetsuits. Diver aversion and perception of body vibration were used as test parameters. The results showed no sex-specific differences. The results differed as a function of frequency – while test results showed a strong overall variation between subjects, signals at 100 Hz elicited the strongest aversion in all tests and even at 148 dB a few diver ratings indicated extreme aversion. Due to this and the strong variation between test subjects, the following exposure limit for both military and recreational divers was suggested as a conservative measure: For frequencies between 100 and 500 Hz, the maximum SPL should be 145 dB re 1 µPa over a maximum continuous exposure of 100 seconds or with a maximum duty cycle of 20% and a maximum daily cumulative total of three hours. The trading relation between the maximum SPL and duration was 4 dB per doubling of duration (e.g., 141 dB SPL for a 200 second exposure) (Pestorius et al. 2009).

In alignment with these studies, and considering only frequencies between 100 and 500 Hz, Parvin (2005) suggested 145 dB re 1 µPa as a safety criterion for recreational divers and swimmers. This does not imply that this level is associated with the onset of injury not been established due to ethical

research protocols. Parvin (2005) reported vibration in forearms and thighs at 180 dB re 1 µPa but no physical injury.

Guidance issued by the Diving Medical Advisory Committee (DMAC 2020) suggests that adverse effects to divers may be experienced at distances of up to 27 km from the seismic source, which is a considerably greater distance than has previously been recognised. However, the basis for this conclusion is not provided.

11 Acronyms and Abbreviations

BRUVS	Baited remote underwater video stations
dB	Decibels
FRDC	Fisheries Research Development Corporation
HF cetaceans	High-frequency cetaceans
hr	Hour
Hz	Hertz
IMAS	Institute for Marine and Antarctic Studies
In3	Cubic inch
kHz	KiloHertz
km	Kilometre
LF cetaceans	Low-frequency cetaceans
m	Metre
m3	Cubic metre
MSS	Marine Seismic Survey
nm	Nautical mile
OCA	Other Marine Carnivores in Air
OCW	Other Marine Carnivores in Water
PCA	Phocid Carnivores in Air
PCW	Phocid Carnivores in Water
PK	Peak sound pressure level
PK-PK	Peak-to-peak sound pressure level
PSI	Pound per square in
PTS	Permanent threshold shift
RMS	Root mean square
sec	Second
SEL	Sound exposure level
SPL	Sound pressure level
µPa	Micropascal
TTS	Temporary threshold shift
VHF cetaceans	Very-high-frequency cetaceans

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Annex 1

Objections and Claims Raised from Consultation

During the consultation process relevant persons were invited to raise objections and claims about the adverse effects of the activity. An assessment of merit of each objection or claim has been made by CGG which can be found in the consultation report using the Feedback ID number shown in Table B8-6 If an objection or claim had merit and was relevant to this assessment it has been included in the table below.

Table B8-6 - Objections and Claims raised from consultation.

Feedback ID	Objection or Claim Summary	Titleholder Response	Event ID
4504	GMTOAC objects to the weakening and inconsistency of shutdown measures between the November 2024 and April 2025 versions of CGG's EP. The earlier EP committed to shutting down the sound source if any whale was within 2 km (with larger buffers for Southern Right and Blue Whales), but the April 2025 EP introduces a much smaller 500 m shutdown zone for most whales, which GMTOAC argues increases the risk of exposure to harmful sound levels. GMTOAC notes that the April 2025 EP creates confusion by implying that CGG's "shutdown zone" is actually a 2 km low-power zone, despite providing no explanation of what "low-power" means, what sound levels it produces, or how continuous low-power operation affects Karntubul, other cetaceans, or cumulative noise exposure. This contradicts Appendix G2, which states CGG will use a shutdown zone rather than a low-power zone, consistent with EPBC Policy Statement 2.1. GMTOAC warns that such internal contradictions undermine the reliability and enforceability of mitigation measures. GMTOAC questions CGG's assumption that a 10 km behavioural shutdown zone will protect Blue Whales, given scientific uncertainty about behavioural impact distances. They highlight evidence that seismic noise can mask baleen whale calls across thousands of kilometres, that ambient noise levels can be elevated by 25 dB over 40 km from air-gun operations, and that reverberated pulses can create	All relevant details of the sound source, including low-power mode, is in Appendix A2. We have also committed to a full shutdown if any whale enters the 2 km shutdown zone, far more precautionary than the EPBC Policy 2.1 requirement of a 2 km low-power zone and a 500 m shutdown zone. This approach exceeds industry standards and legislative requirements for mitigating potential impacts from seismic sound sources. Our EP applies a suite of measures designed to ensure impacts to Blue Whales and Southern Right Whales remain at acceptable levels. We will shut down the sound source immediately upon detection of any SRW, including cow–calf pairs, and we will manage to ambient sound levels in the SRW reproduction BIA to ensure those levels are never exceeded. The Regia MSS is a short, temporary activity, 90 days in total, including 60 days of acquisition, so any increase in ambient noise will be brief and localised. No exceedance of ambient sound levels will occur in the SRW reproduction BIA during the reproductive season, ensuring cow–calf pairs are not exposed to elevated noise or displaced from critical habitat. Our shutdown zones include highly conservative buffers well beyond standard requirements, further reducing potential impacts. Collectively, these measures ensure any short-term noise increases are managed to acceptable levels, consistent with the precautionary intent of relevant recovery plans. Appendix B8 addresses acoustic masking using recent scientific literature, not the older references cited by GMTOAC. For example, Nieukirk et al.	EVT352

	near-continuous noise for months. GMTOAC argues that such persistent elevated noise levels could impair communication, migration, and calf–mother cohesion, posing cultural and ecological harm, and that CGG's 10 km buffer is therefore not precautionary. GMTOAC is also concerned about ambiguity over whether shutdown means turning the source off or merely reducing power, noting that this ambiguity is not precautionary and risks behavioural impacts for Blue Whales.	(2012) showed that airgun signals detected thousands of kilometres from fin whales were unlikely to have direct effects, with the most probable impact being reduced communication range. Even then, the study had major limitations, including uncertainty about the actual distance between vocalising whales and receivers. Key context from Estabrook et al. (2016) is omitted, which analysed multiple seismic surveys over multiple years. That study does not represent received levels for animals closer to the sound source and therefore is not applicable to the Regia MSS. No other seismic surveys are currently planned in the Otway region, further limiting the relevance of that study's conclusions.	