The impact of underwater noise on marine animals – and especially fishes

Tony Hawkins – The Aquatic Noise Trust

I began researching the importance of underwater sound to fishes at Lough Ine, County Cork

- Europe's First Marine Nature Reserve

Current concerns about our seas tend to focus on:

- Overfishing
- Climate change
- Plastic pollution

Noise Pollution is also very important but it is often ignored

The sea is not silent

Natural sounds are generated by:

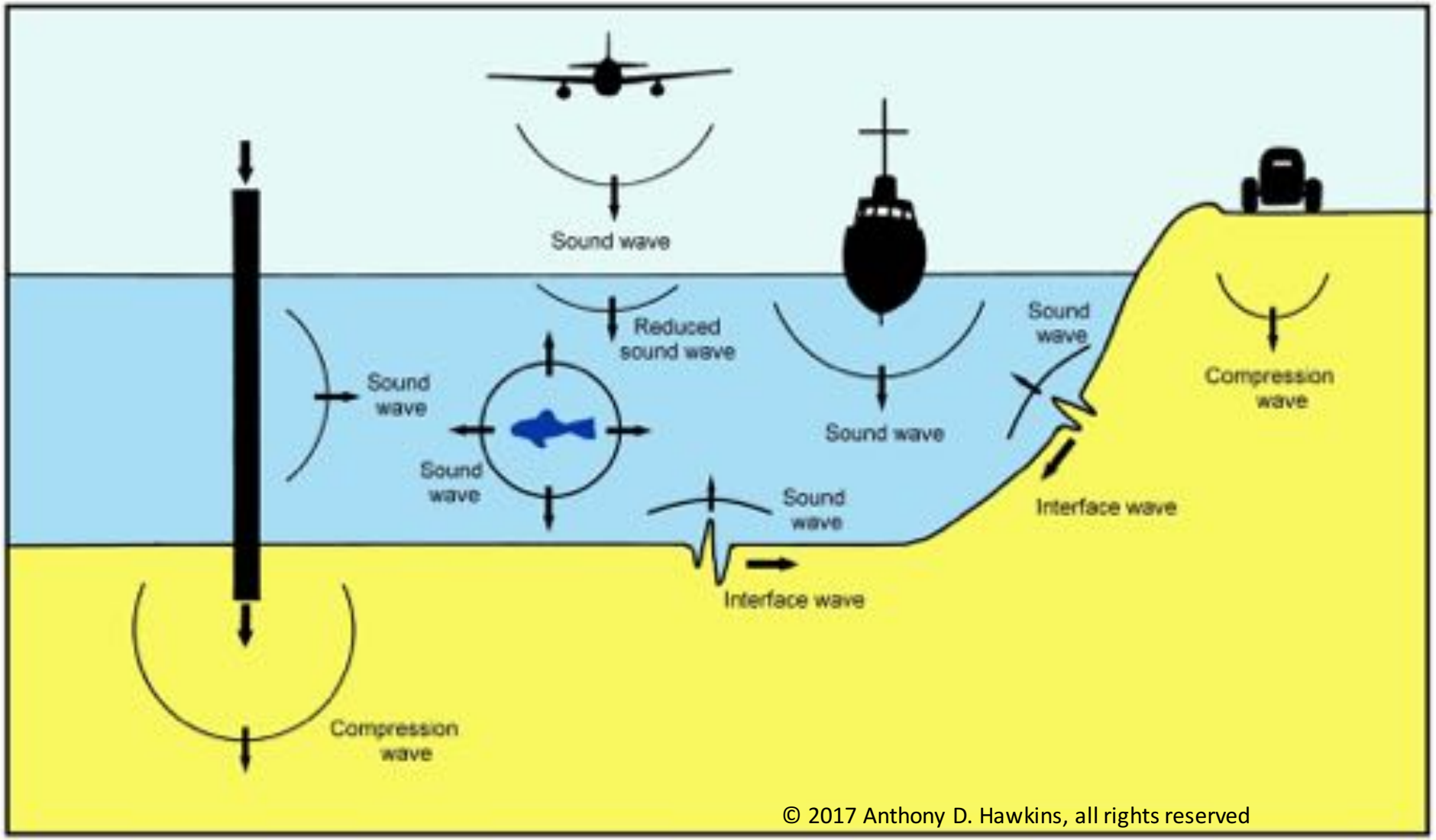
- Rain, surface waves & turbulence
- Natural seismic sounds
- Mammals, fishes and invertebrates

But there are also many anthropogenic (human-made) sound sources !

Anthropogenic sources include

- Ships & trawls
- Pile driving construction work
- Sonar systems
- Seismic surveys for oil and gas
- Offshore wind and tidal turbines
- Dredging & installing pipelines & cables

Sources of Underwater Sound



Underwater sound is made up of two elements:

Sound Pressure

Particle Motion

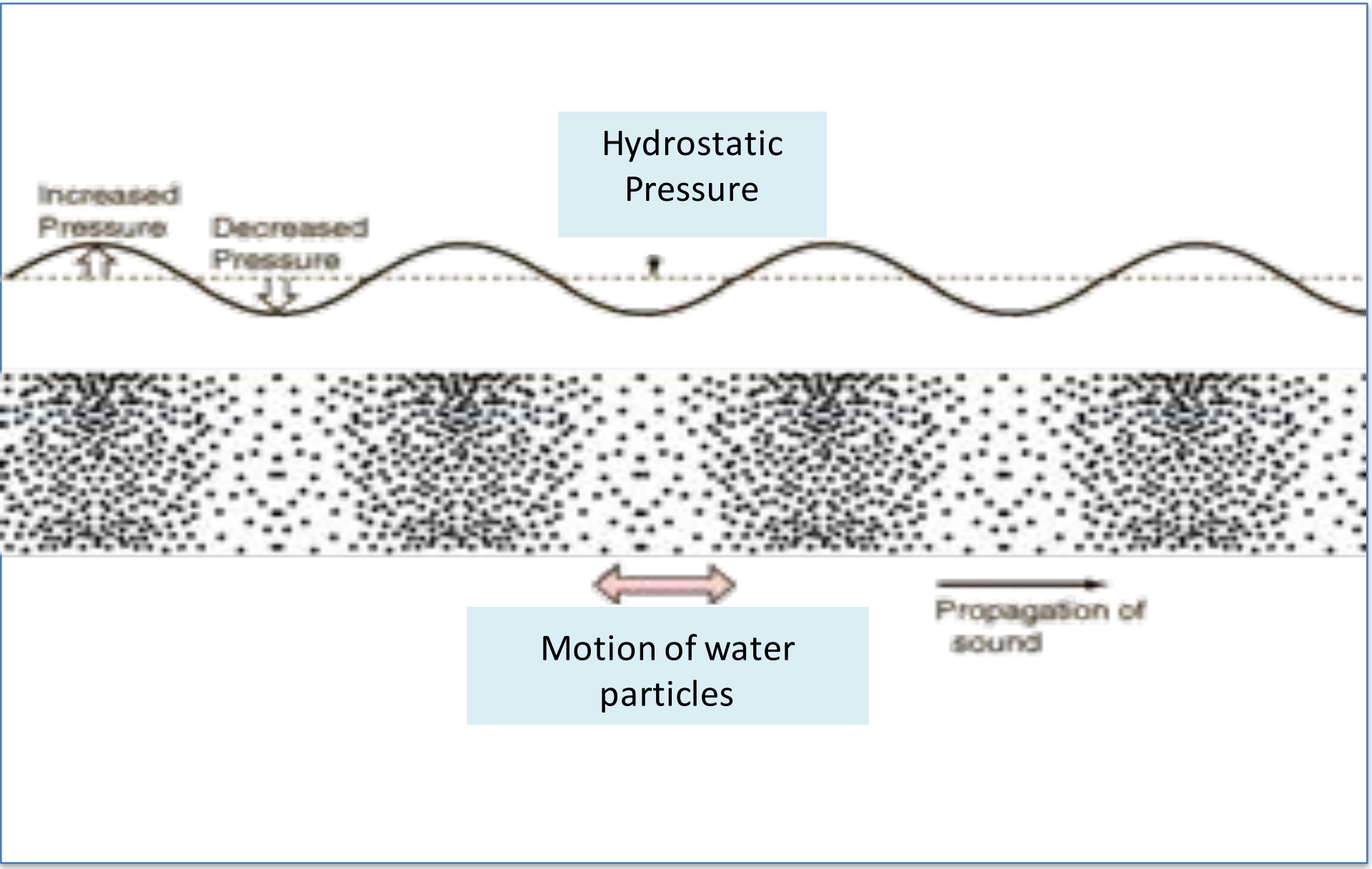
There are waves of compression and rarefaction – the Sound Pressure

But in addition

Particles of the water are alternately forced together and then apart – the Particle Motion

Mammals are sensitive to Sound Pressure

Fishes & Shellfishes respond to Particle Motion



Sound also Propagates Through the Seabed

- Pile driving and seismic surveys generate substrate sound – “ground roll”
- Substrate sound may travel great distances, generating particle motion in the water, especially at low frequencies
- **Environmental Impact Assessments often ignore the effects of particle motion, and the propagation of sound through the substrate**

Man-made underwater noise has been present since powered vessels appeared in the 1830s

Large modern ships are very noisy

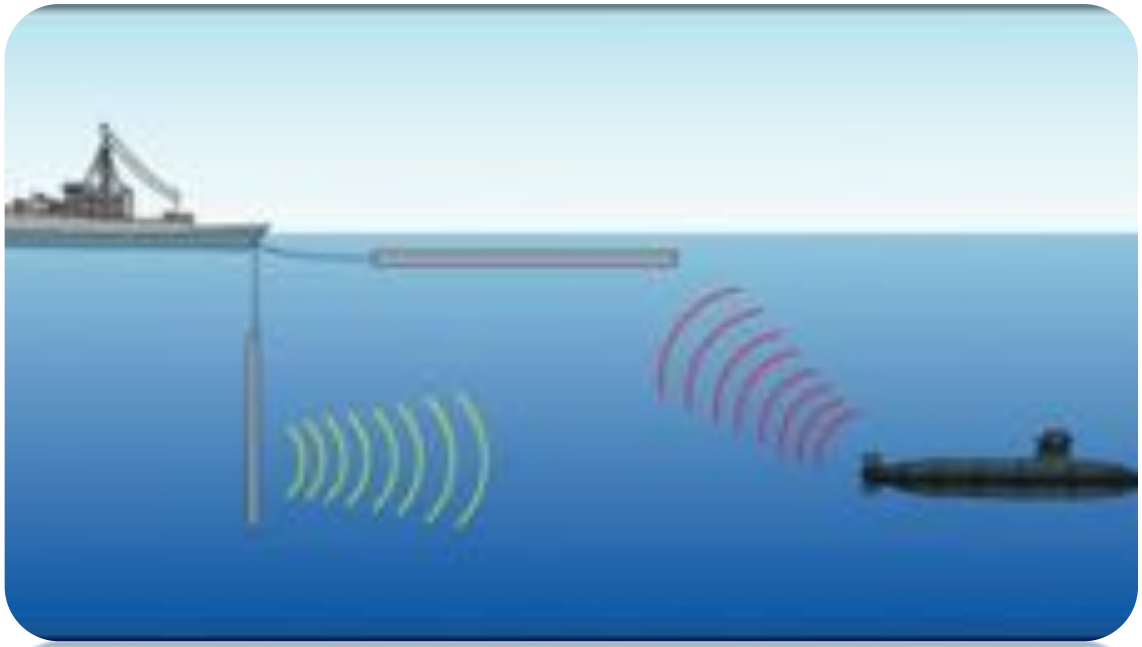
Shipping noise levels have doubled almost every decade

The Sounds are generated by engines, propellers, water flow and turbulence

Dredging for aggregates is noisy

Naval sonars used to search for submarines are noisy

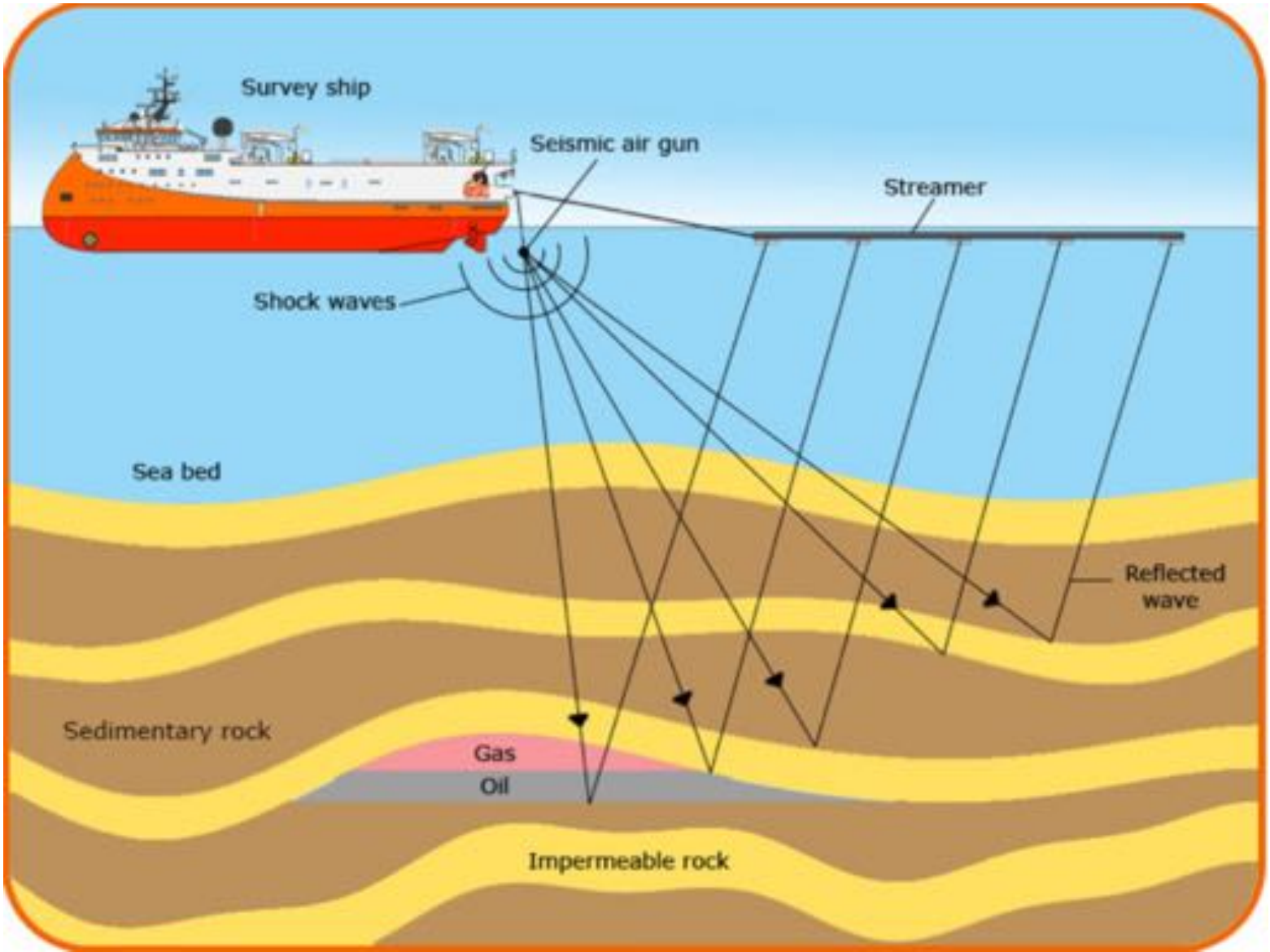
Stranding of beaked whales in recent months has been blamed on naval sonars!



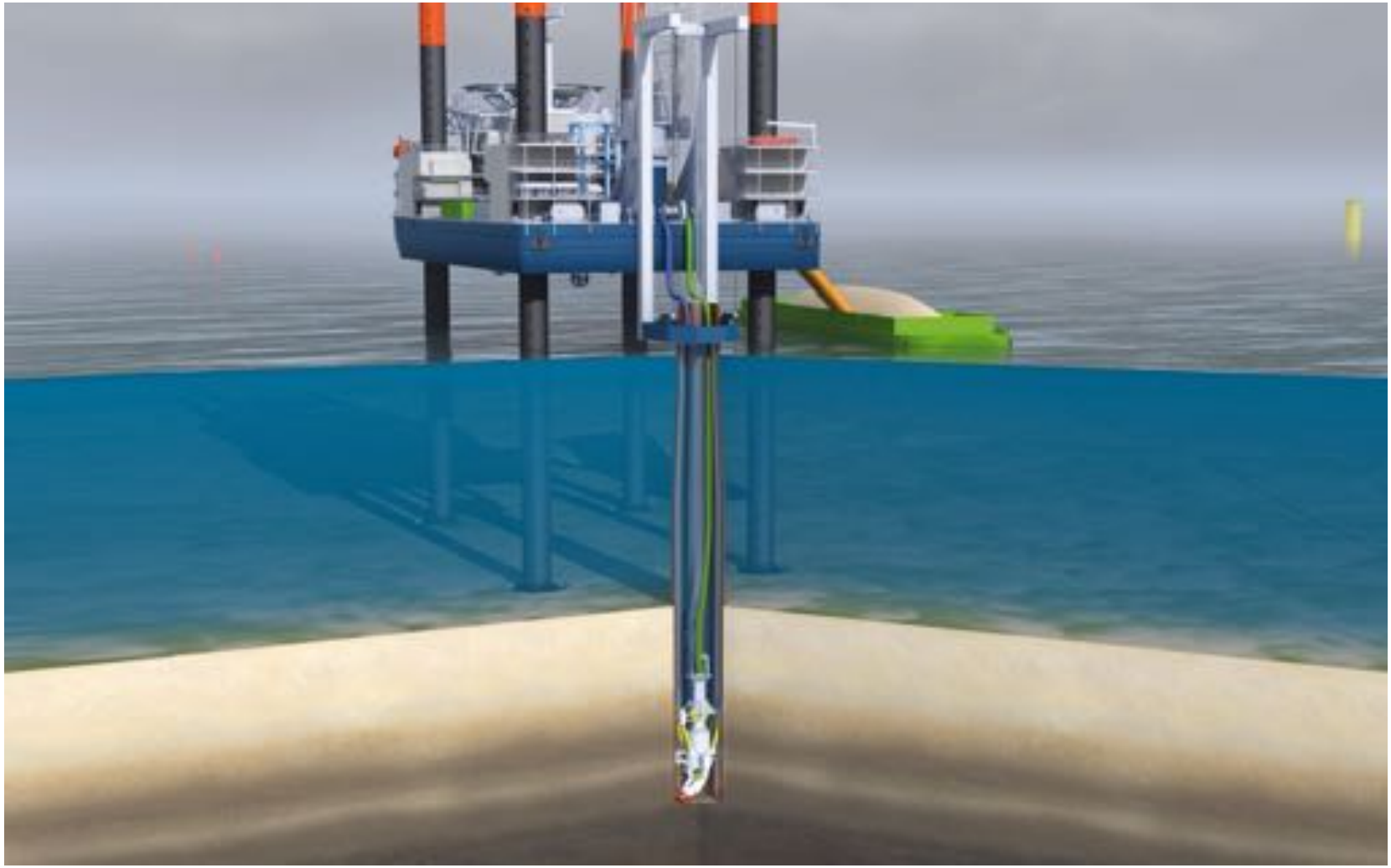
Offshore oil and gas activities are noisy and include sounds from drilling, shipping and other activities

Seismic surveys for oil and gas involve towing air gun arrays, that generate low frequency impulsive sounds

Seismic exploration also generates substrate sound - ground roll



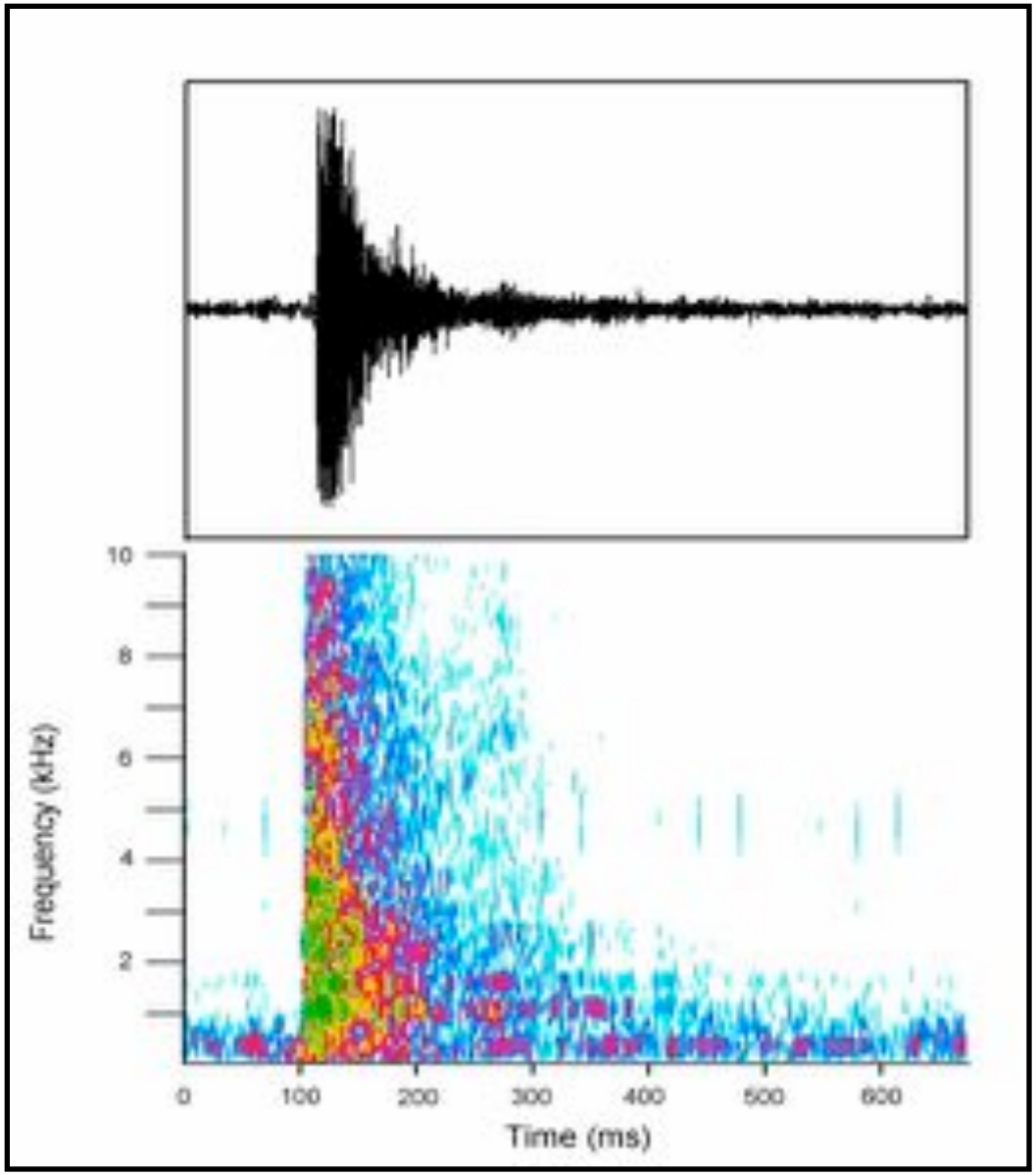
Much louder sounds are generated by Pile Driving – used for the installation of bridges, quays and offshore structures including wind farms



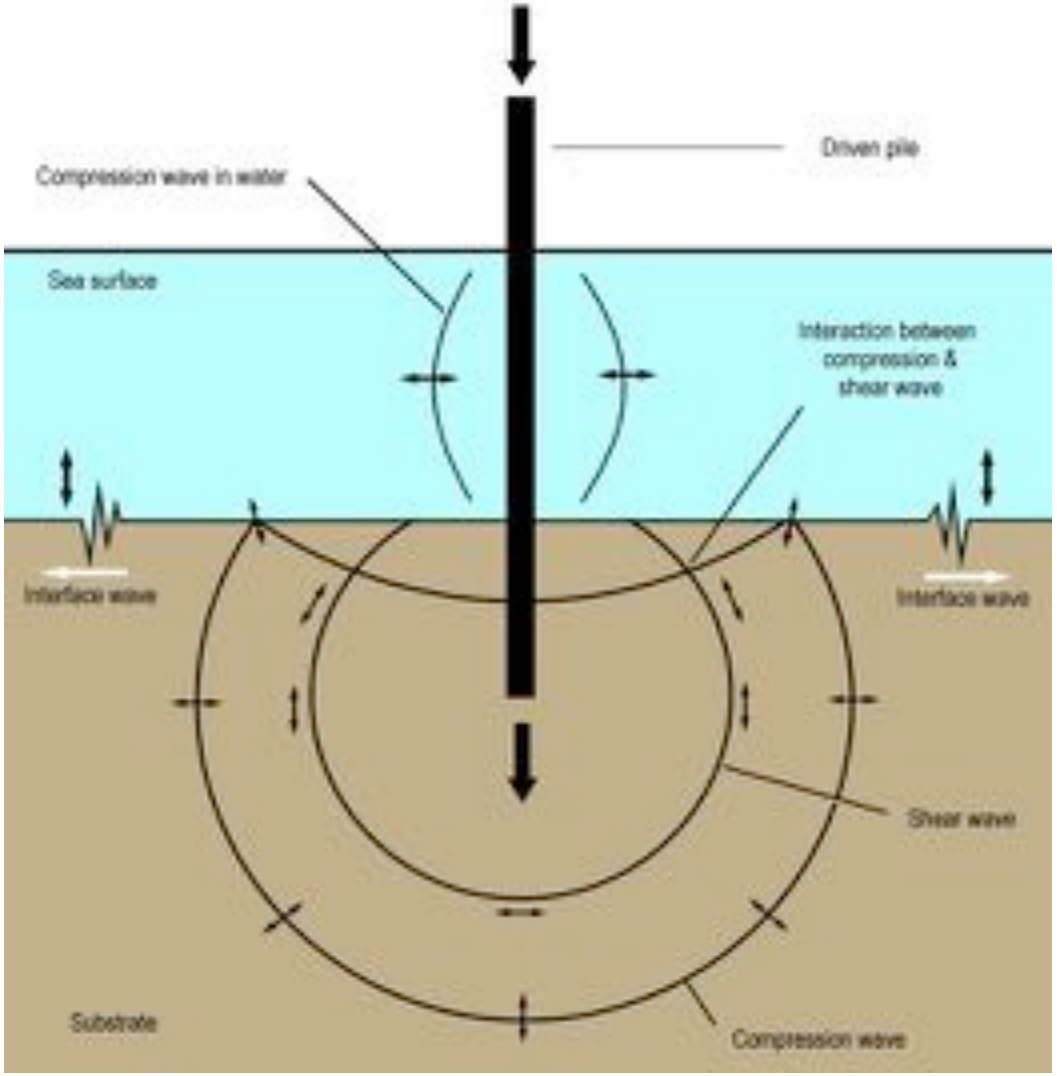
Pile driving sounds

Waveform

Spectrogram



Pile driving results in sound propagation through the seabed as well as through the water but often little attention is paid to this in assessing impacts



Construction of offshore wind farms can require extensive pile driving over many months

Operation of the wind turbines also generates sound and vibration

Many noisy developments are now taking place off our coasts, including:

Harbour Re-developments

Offshore Wind Farms

Tidal & Wave Energy Generators

Dredging and Cable and Pipe Laying

Seismic Surveys for Oil & Gas

Offshore Oil Developments

Noise levels in the sea have been changing dramatically as a result of human activities

What effects are these changes having upon marine animals?

The Sea is a dark, low-visibility world

Sound allows animals to communicate with one another.

They use the “acoustic scene” to locate natural underwater features including preferred habitats, prey and predators

The detection of underwater sounds is very important to most aquatic animals

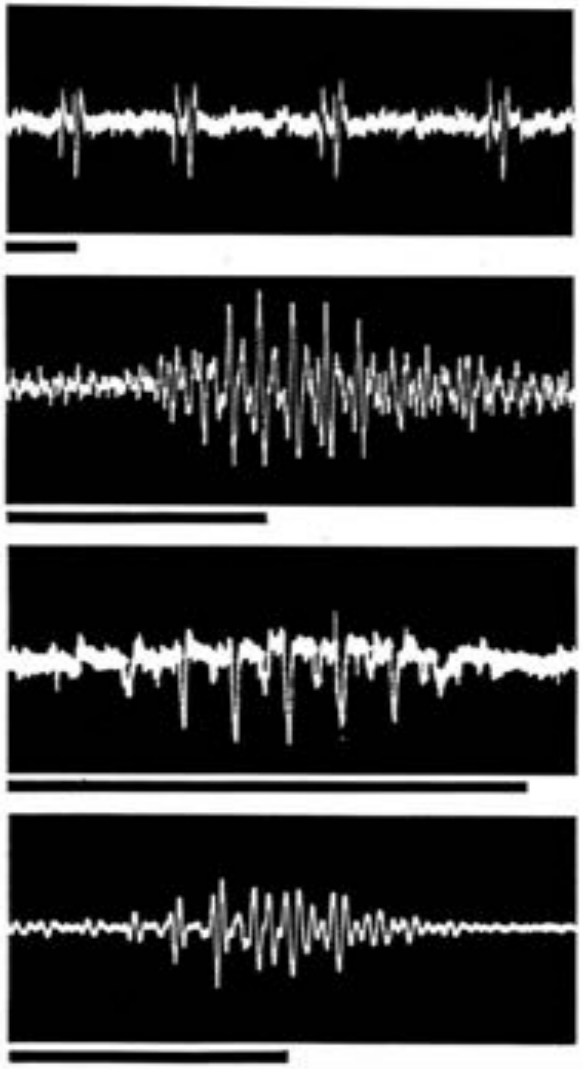
Sound travels further and faster through the sea than in air
Sound Detection is used by marine animals for:

- Communication and social interaction
- Foraging for prey
- Detection and avoidance of predators
- Orientation and navigation
- Habitat selection

Many fish make sounds

Haddock make sounds during spawning

Related Gadoids make different sounds



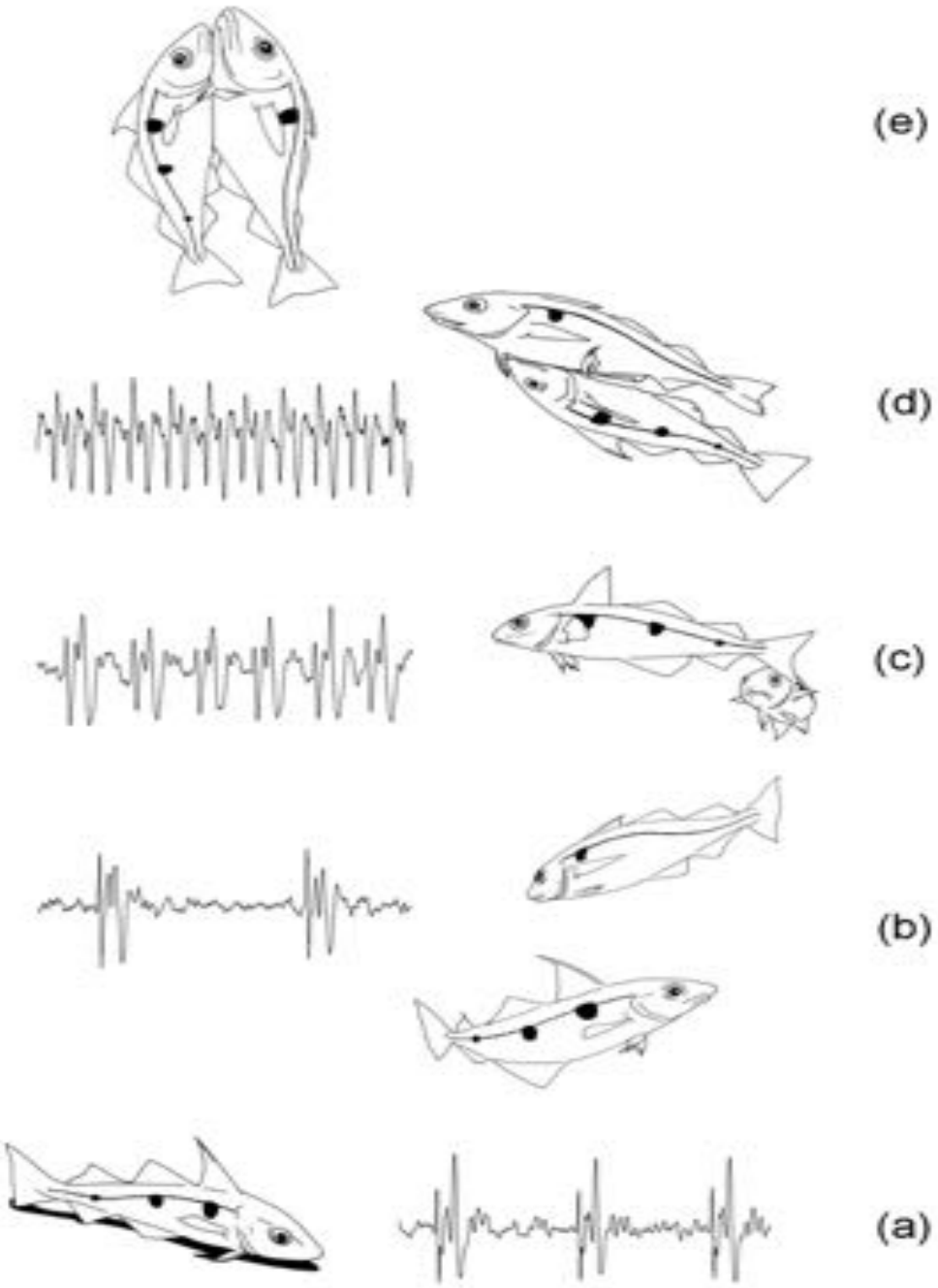
(a) haddock, *Melanogrammus aeglefin*

(b) cod, *Gadus morhua*

(c) pollack, *Pollachius pollachius*

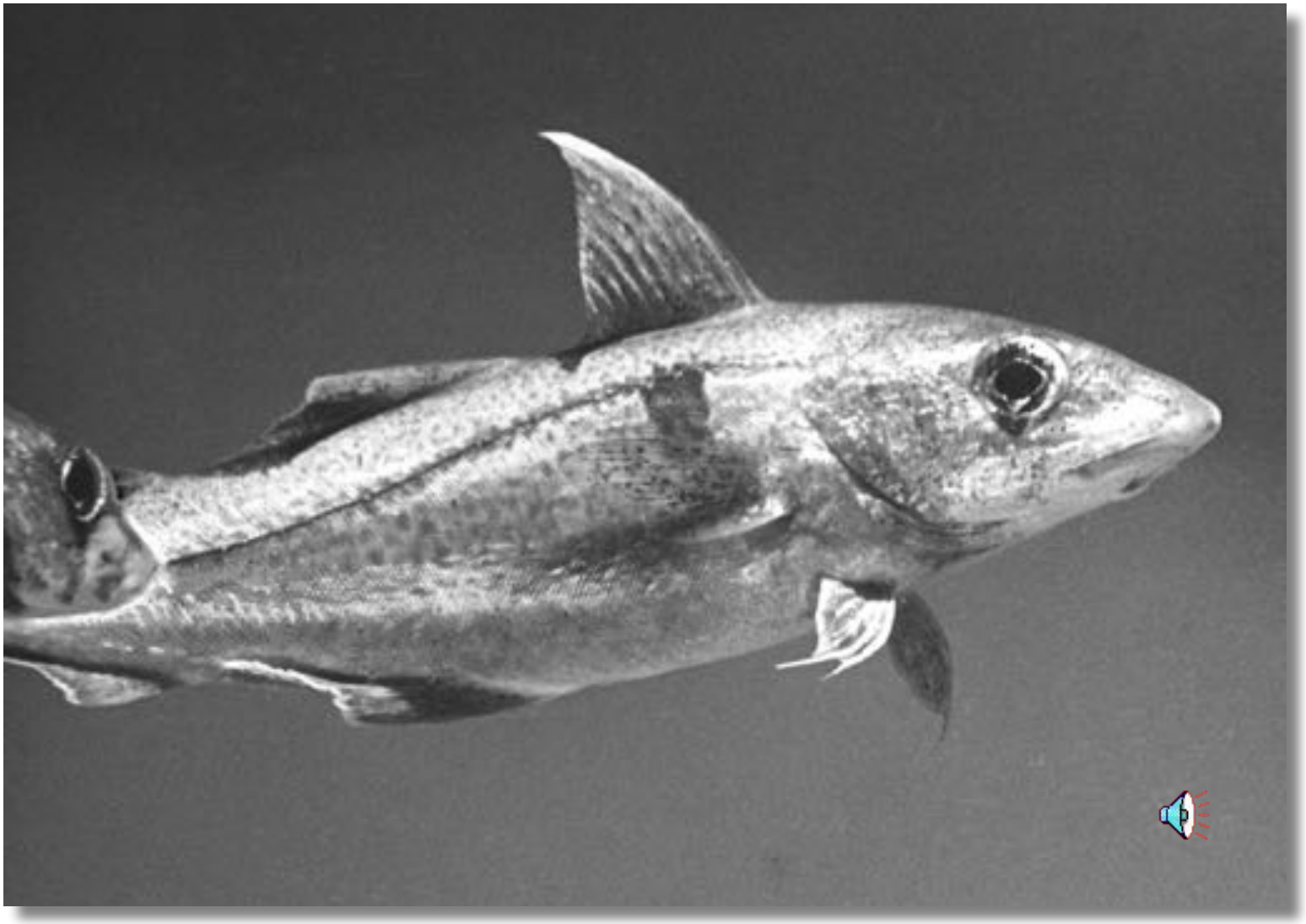
(d) tadpole fish, *Raniceps raninus*

Although the related saithe and whiting are silent

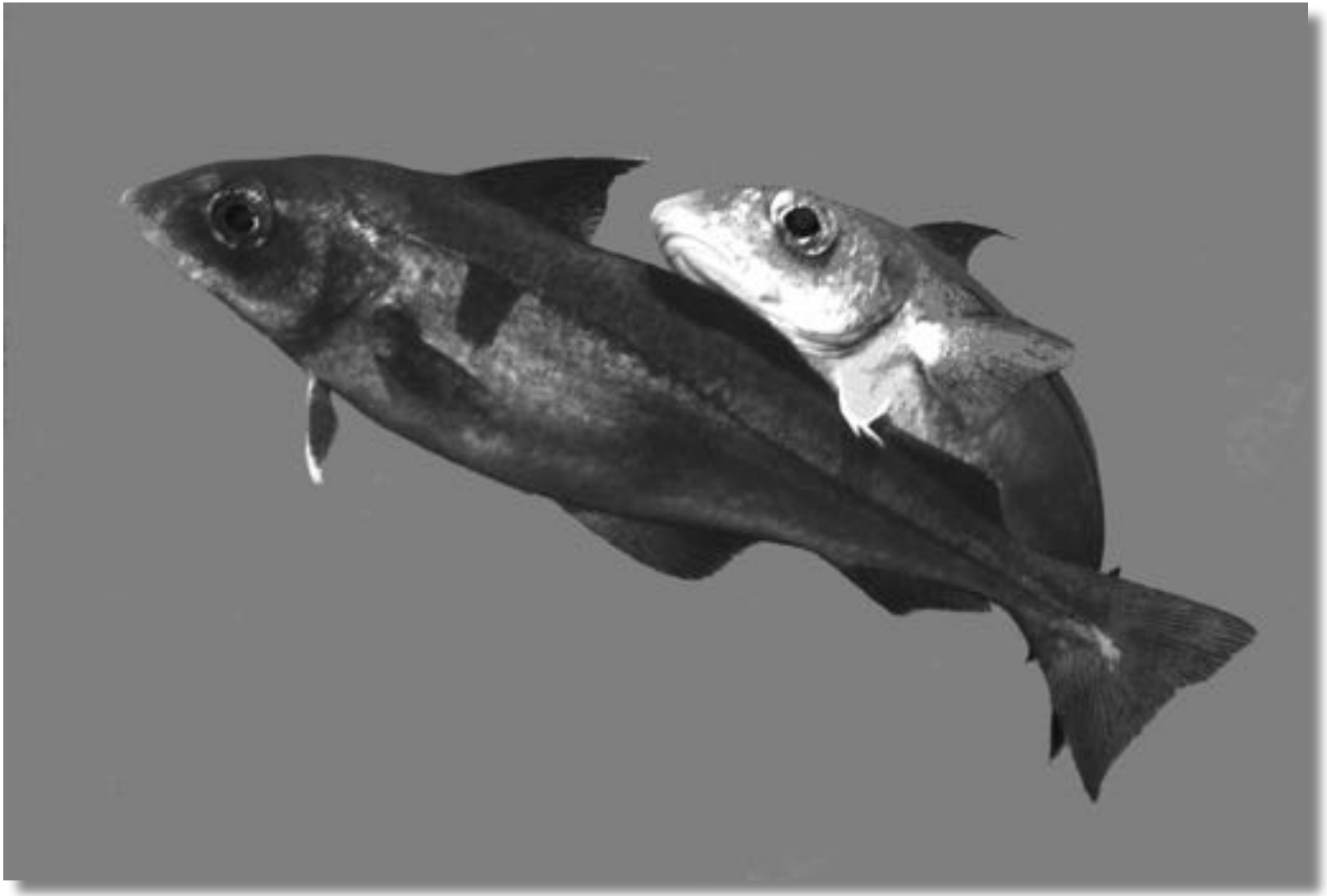


A species like the haddock varies its sounds during spawning behaviour

Male Haddock Flaunting to Female



Male Haddock Mounting Female

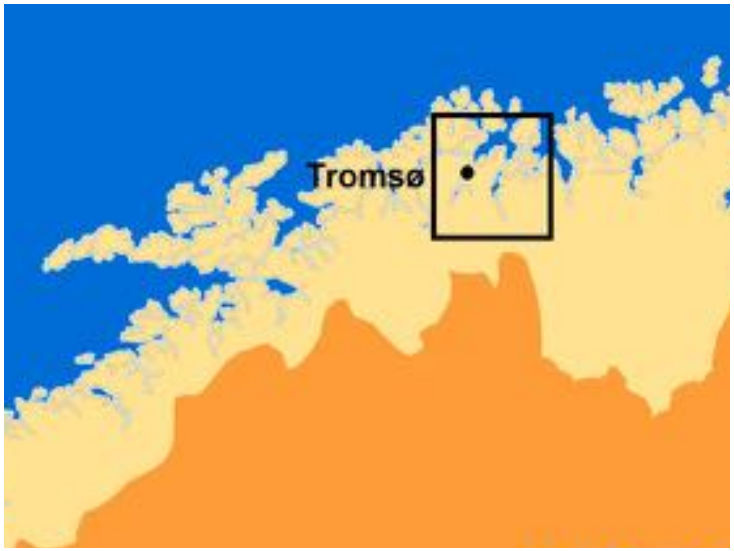


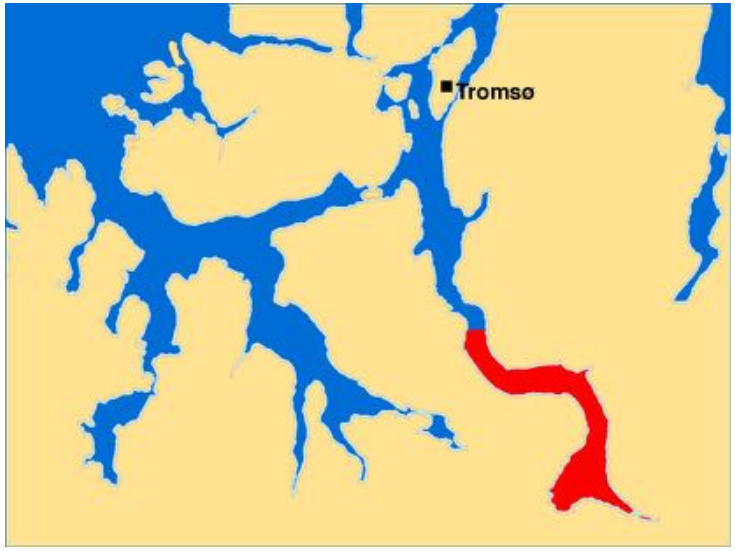
Spawning Embrace with

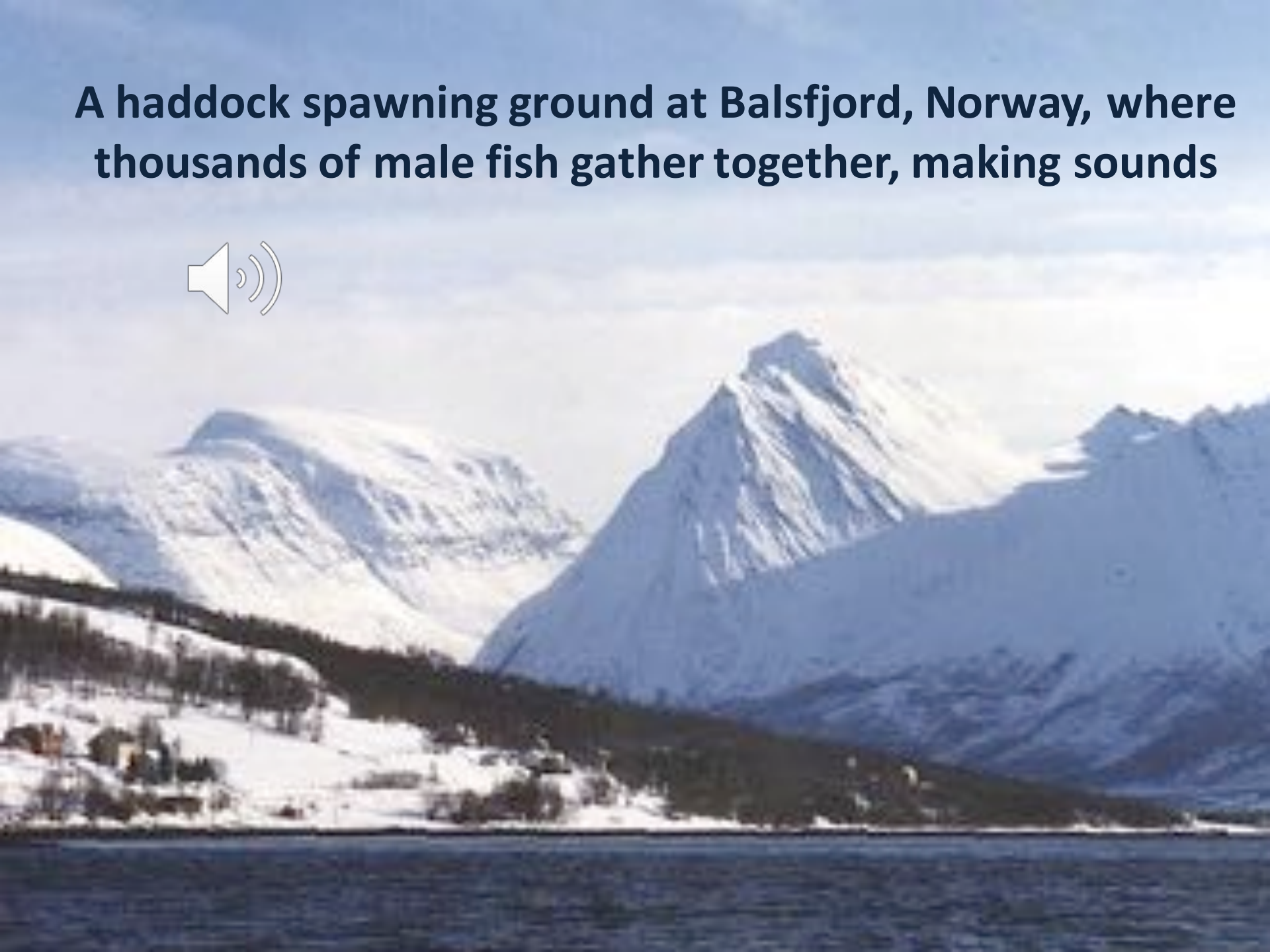
release of eggs and sperm


Drumming muscles are attached to the gas-filled swim bladder
Tendon
Swim bladder

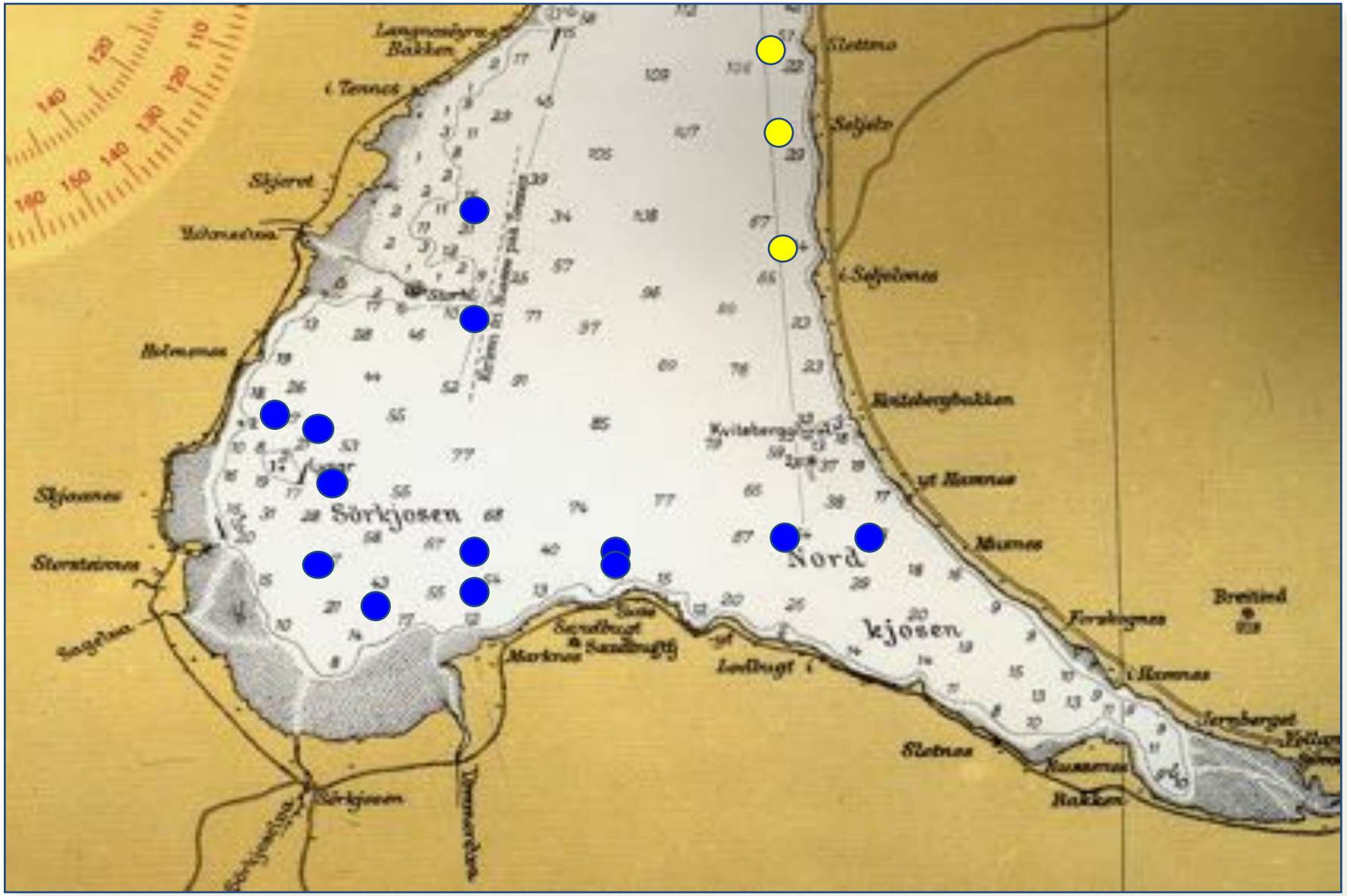
Searching for Spawning Haddock by listening



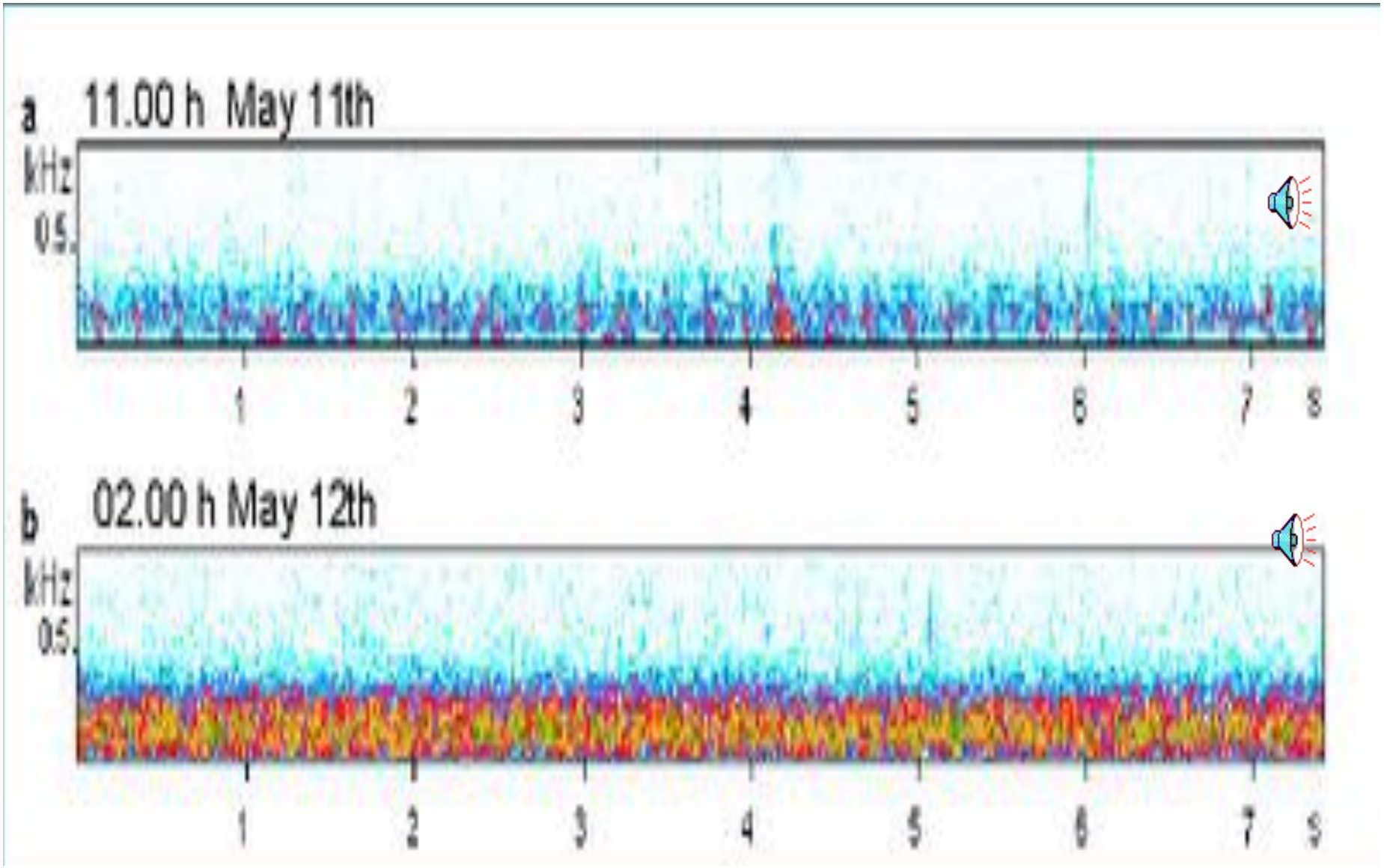



A haddock spawning ground at Balsfjord, Norway, where thousands of male fish gather together, making sounds

Presence ● and Absence ○ of Spawning Haddock



Changes between Day and Night



Haddock spawning behaviour is noisy and prolonged

Males compete for territories and females choose particular mates, with sound playing an important role

Human noise-making activities may affect spawning success by masking the haddock calls and driving haddock away from their spawning grounds

Other fishes also make sounds:

Cod & Pollack

Gurnards

Bullheads & John Dories

Gobies and Blennies

However, there have been very few studies of sound producing fishes in our waters

Marine mammals make sounds too

Beluga whales

Common Seal sounds recorded in Lough Ine

Some Invertebrates make sounds!

The Snapping Shrimp at Lough Ine

Others vocal animals include squid, lobsters, sea urchins, and some crabs

Underwater Sound is Highly Relevant

- Marine animals listen to the “acoustic scene” and use this to orientate and navigate
- **Any interference with the acoustic scene can have a negative impact on fishes & invertebrates**

Hearing in Fishes

There are substantial differences in hearing sensitivity and frequency range between different fish species

Hearing Experiments on Fishes

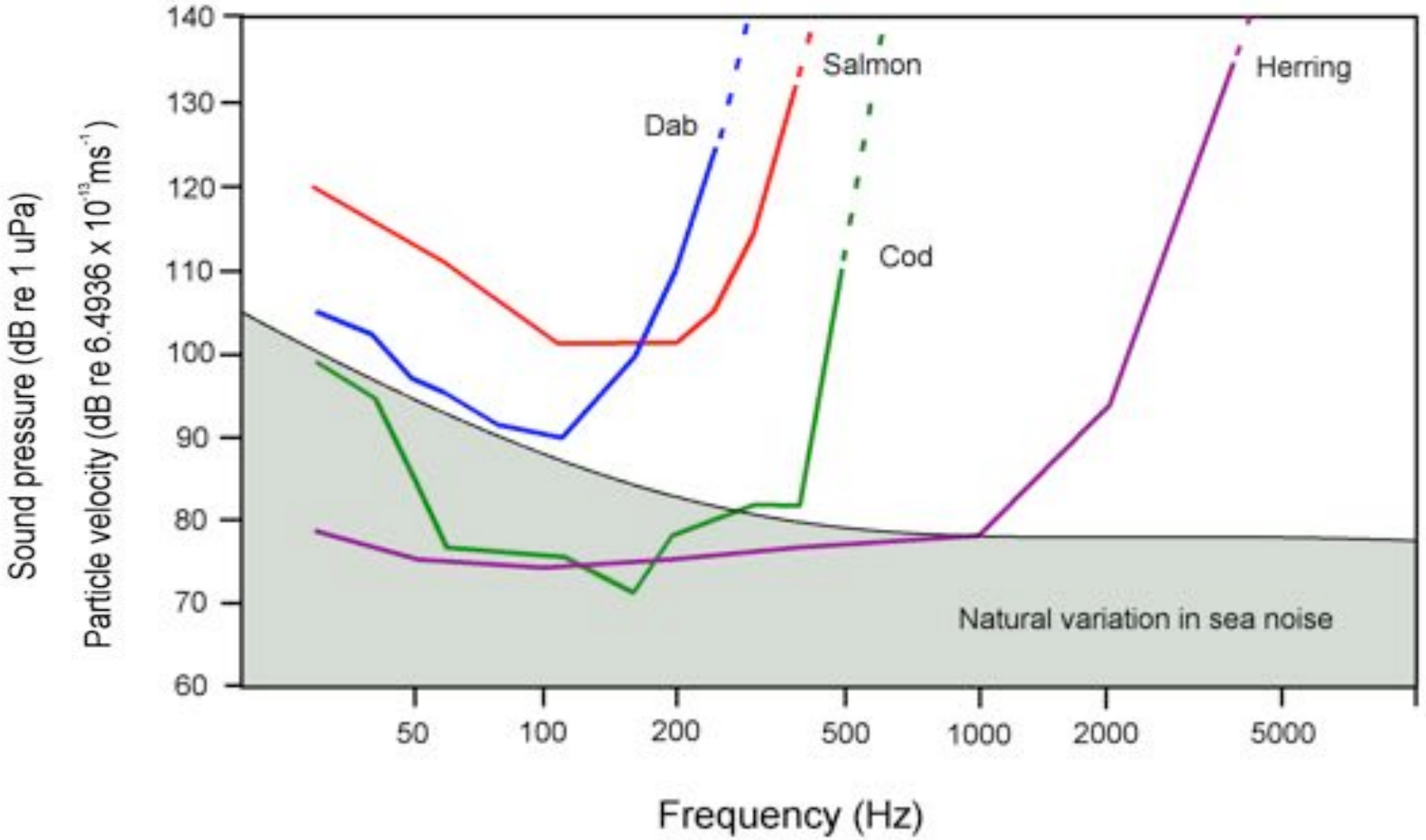
Fish can be trained to respond to pure tone sounds

The sound level of the tone can then be reduced until the animal no longer responds – yielding an **auditory threshold**

Thresholds are determined at different frequencies to yield an **audiogram**

Cod & Herring are sensitive to sound pressure & particle motion. Dab and Salmon only to particle motion

Fish audiograms obtained under good acoustic conditions



Some Fishes, and also Invertebrates are also sensitive to Infrasound
(sound or substrate vibration at frequencies below 20 Hz).

Infrasound is often not examined when testing hearing abilities

It is also ignored in most impact assessments

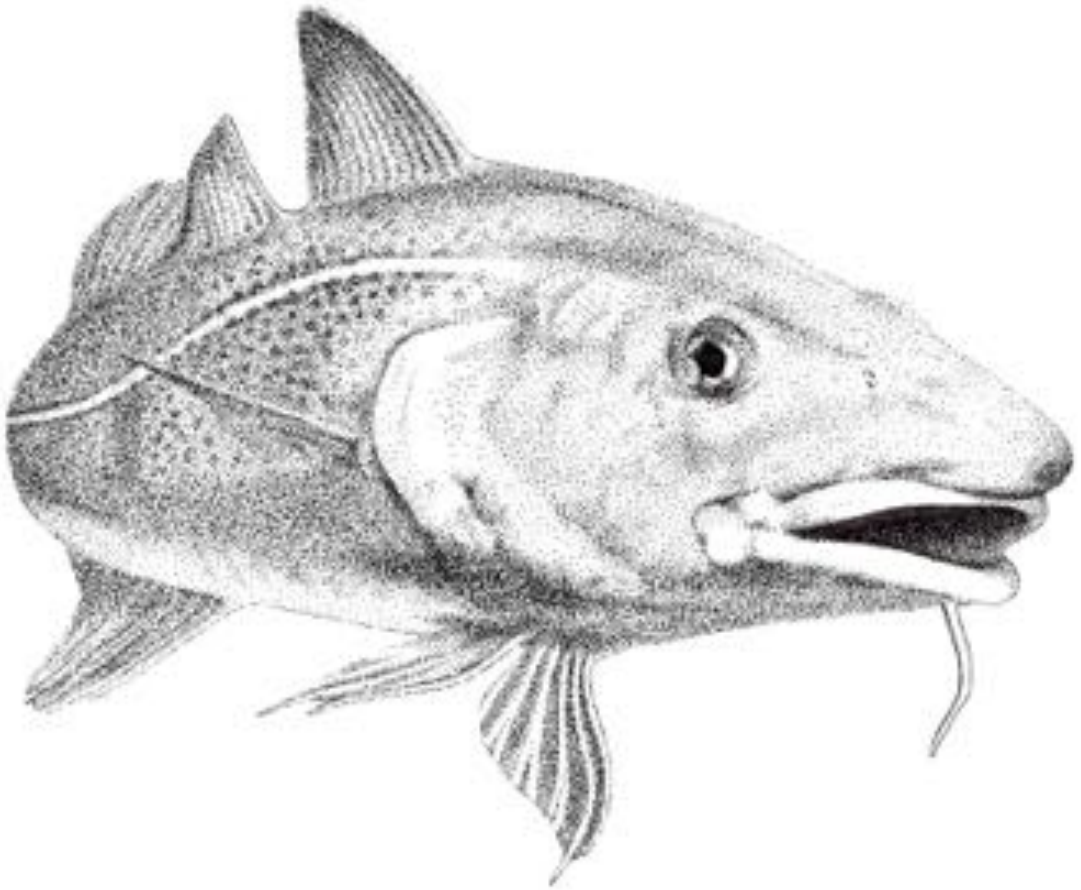
Fish are also able to:

- discriminate between different sounds
- Locate the position of sound sources
- detect signals by filtering the background noise

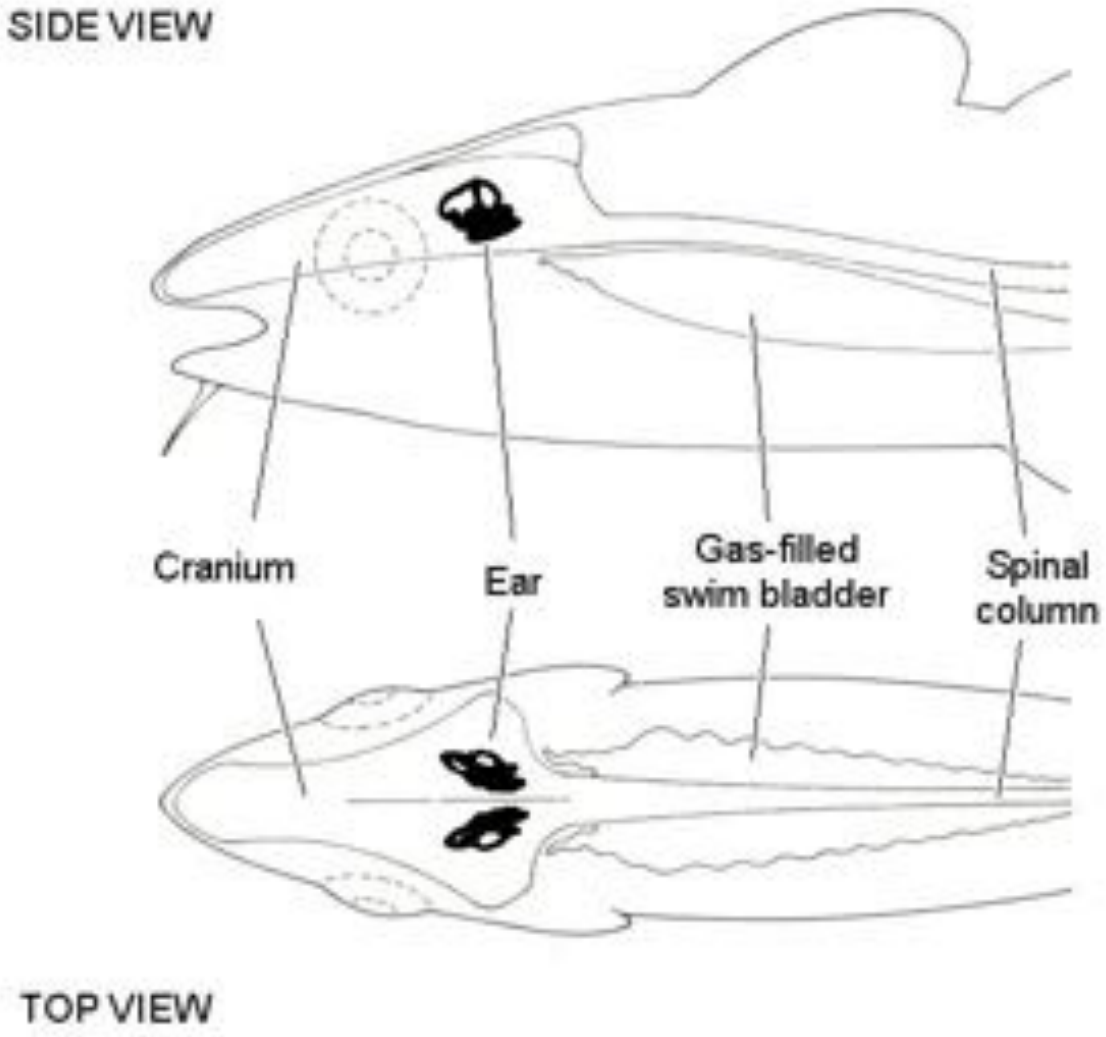
The Auditory System of Fishes

Fish ears are sensitive to particle motion

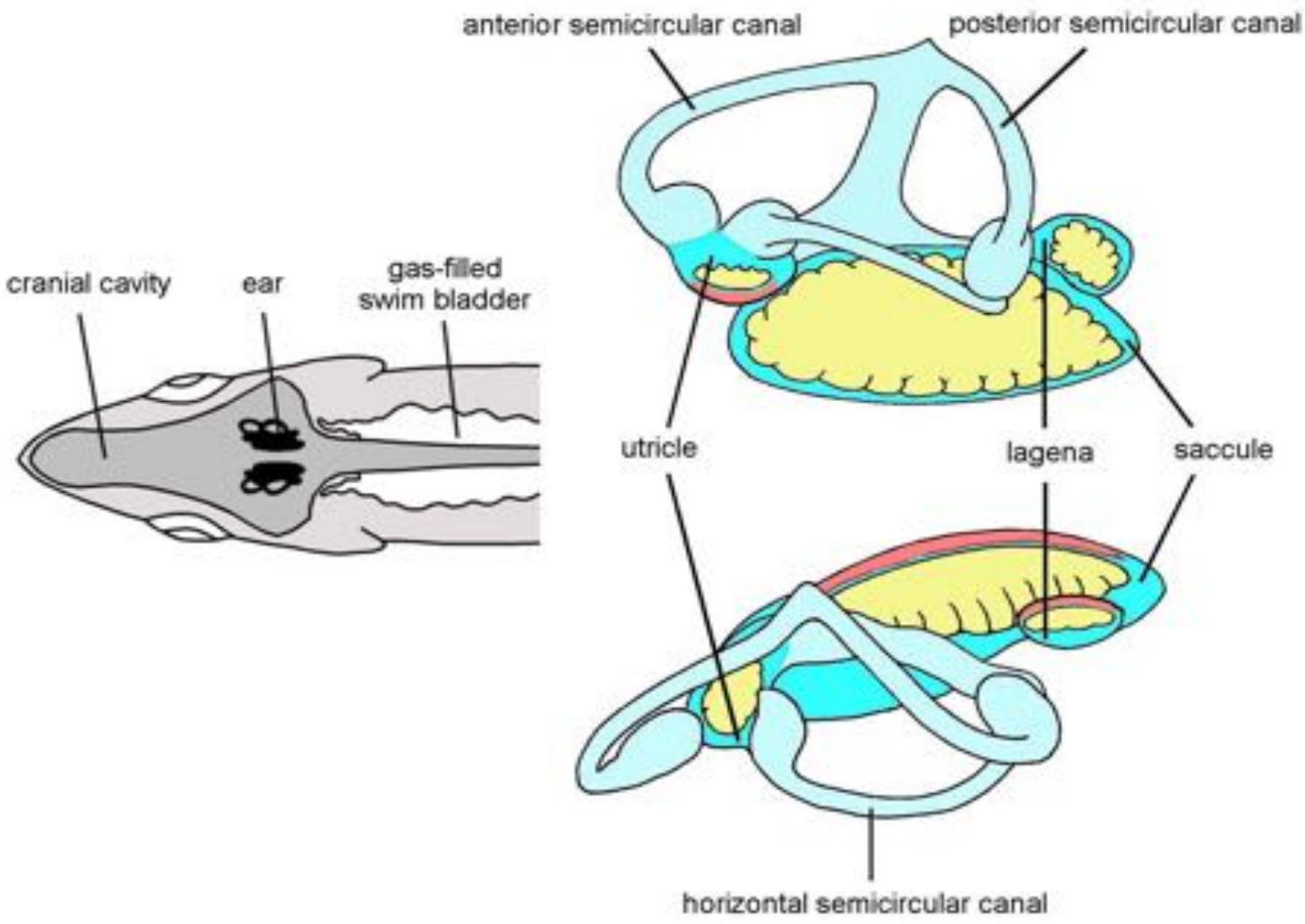
The ears are not visible externally, they are embedded in the head



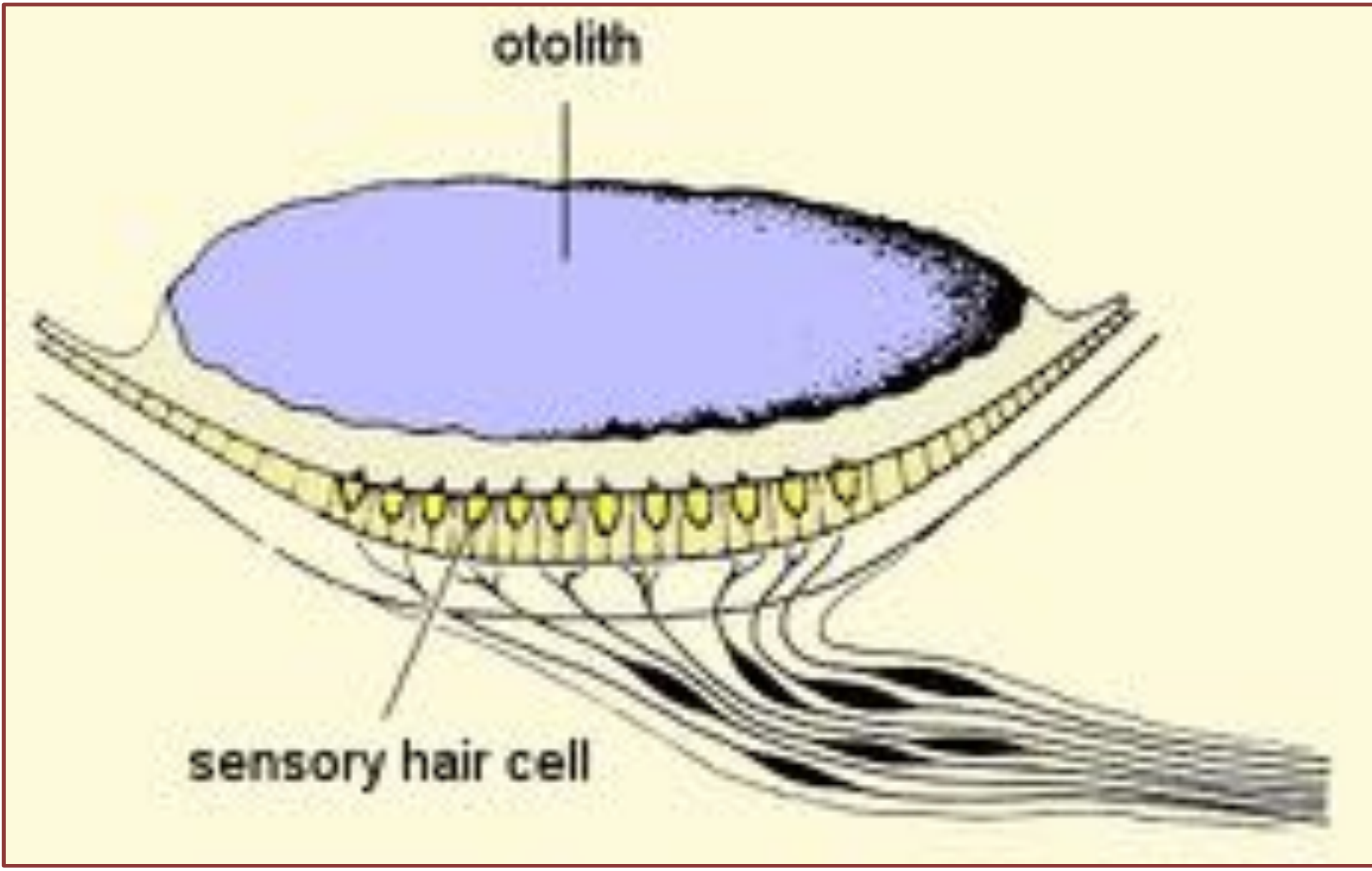
The paired ears of cod



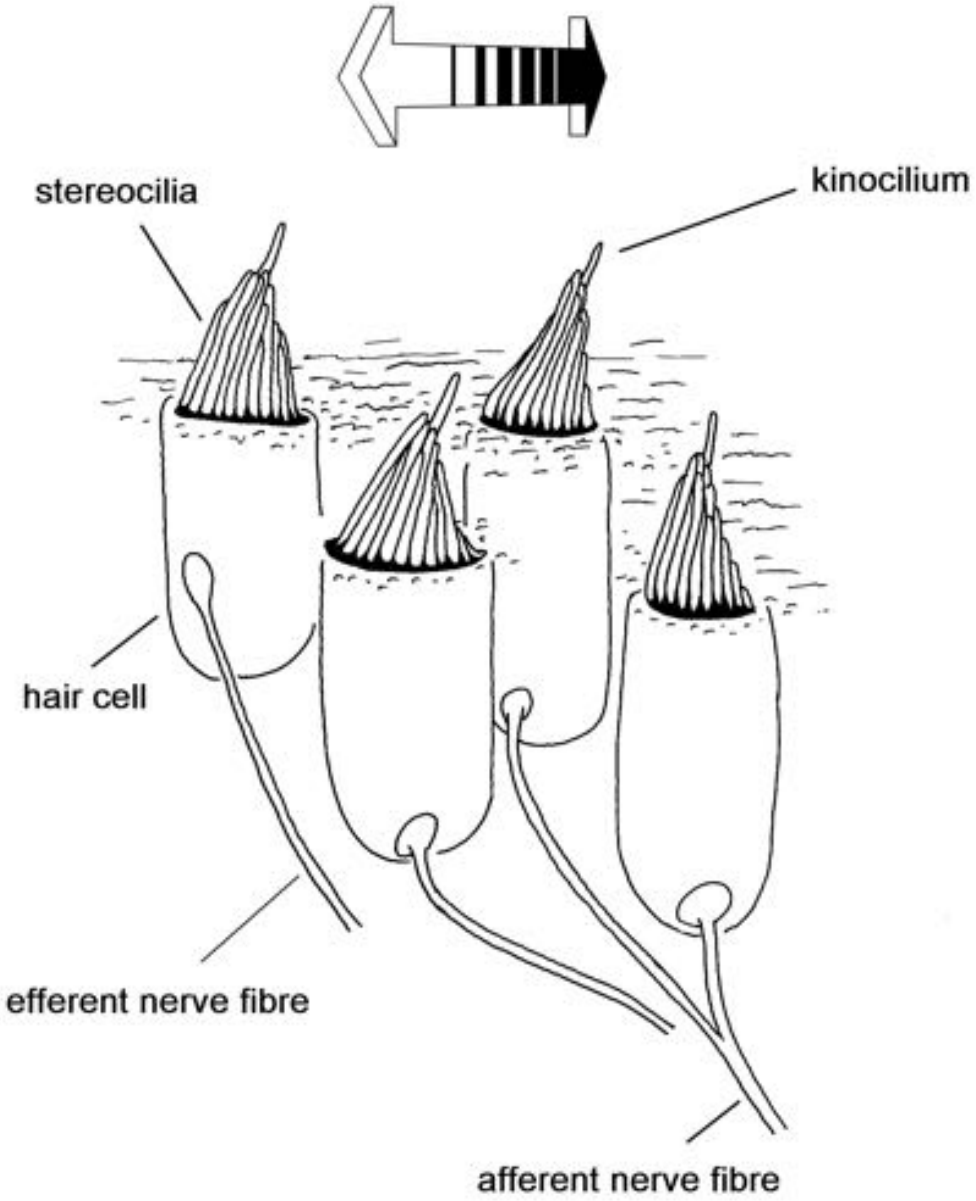
Structure of the cod ear

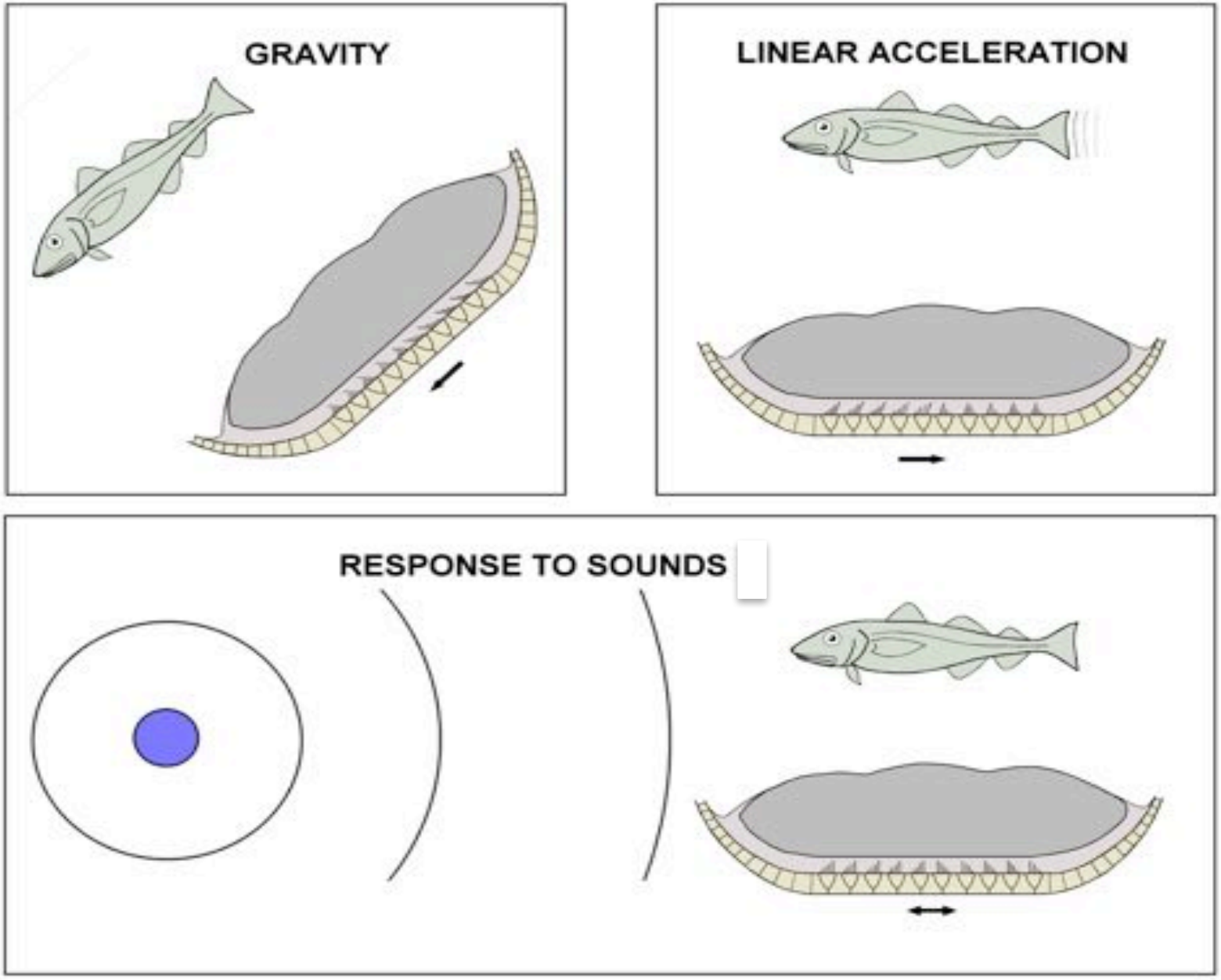


The Otolith Organs respond to Particle Motion "Shaking"



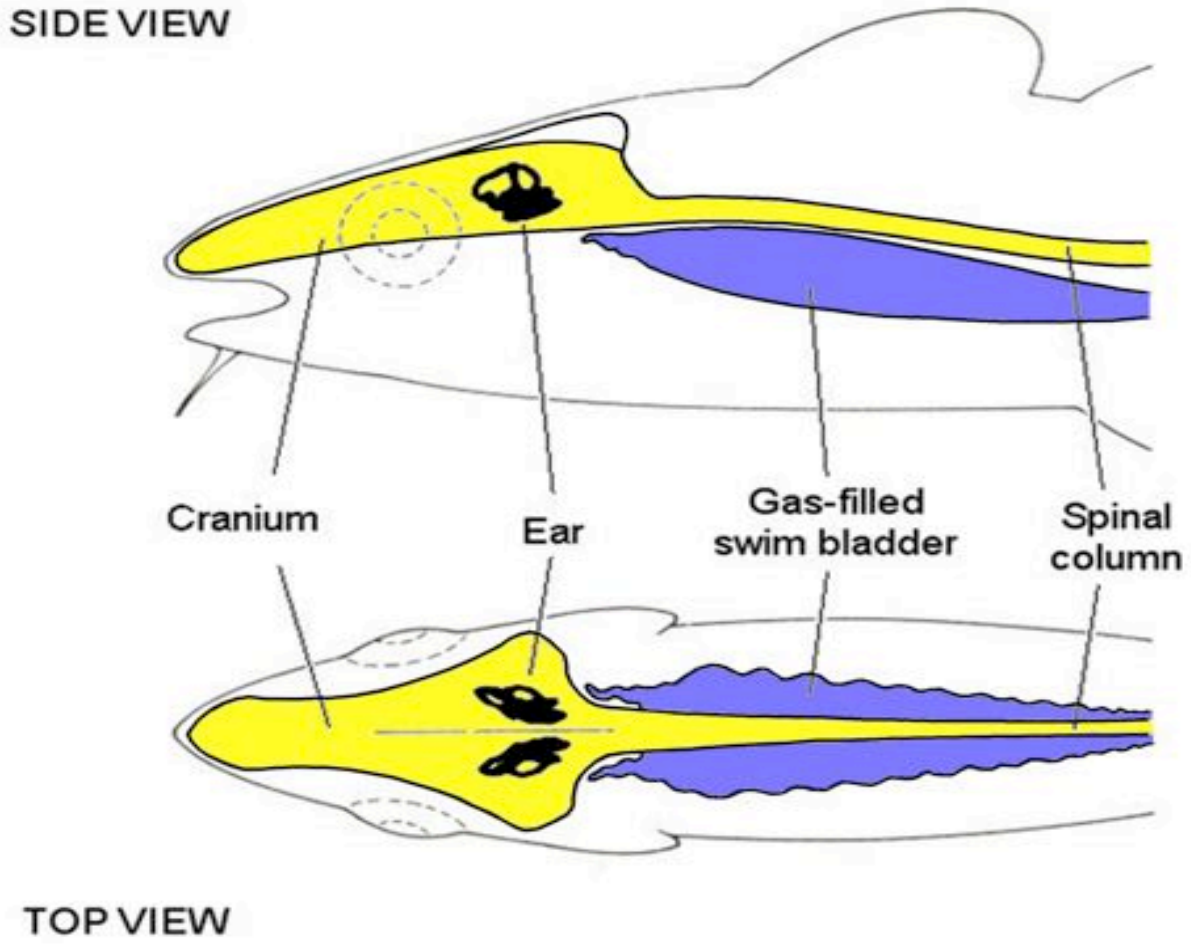
The hair cells are directional in their response





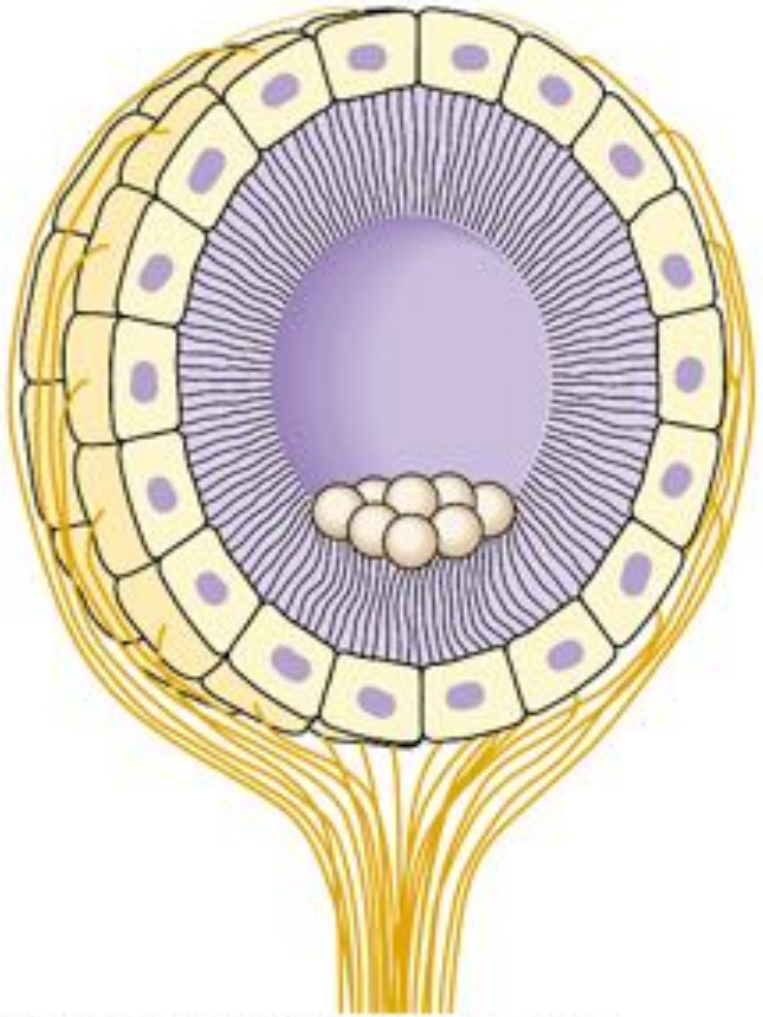
Otoliths are very sensitive to “shaking”

The otolith organs are sensitive to particle motion but some fishes with gas-filled spaces close to or connected with the ear respond to sound pressure



Many marine invertebrates, including plankton, are sensitive to particle motion

The statocyst organ & other hearing organs in Invertebrates respond to particle motion

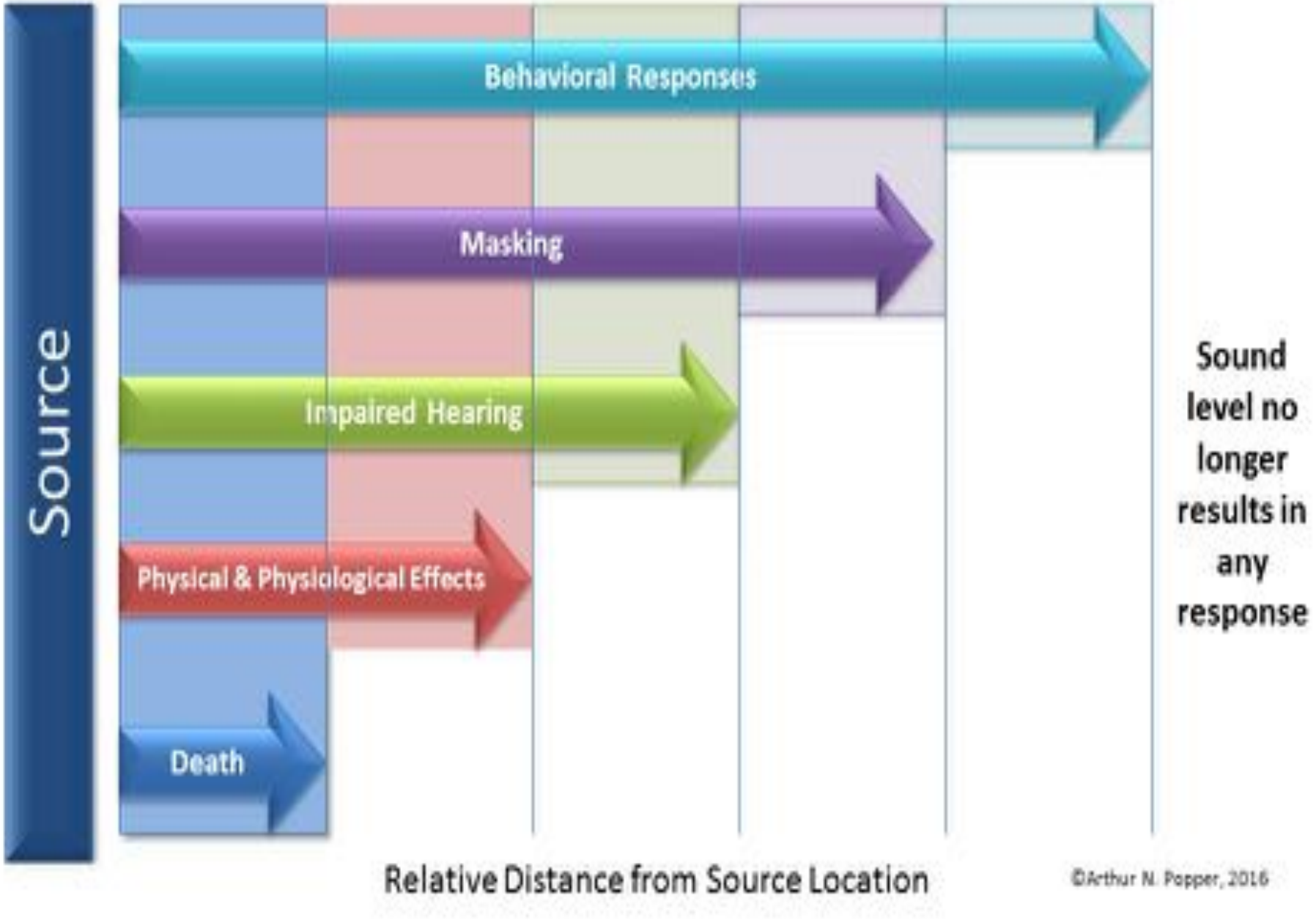


Effects of Anthropogenic Sounds

Sound can cause effects in terms of:

- Death
- Damage to Tissues
- Disturbance
- Interference with the Detection of Natural Sounds

Effects of sound vary with distance

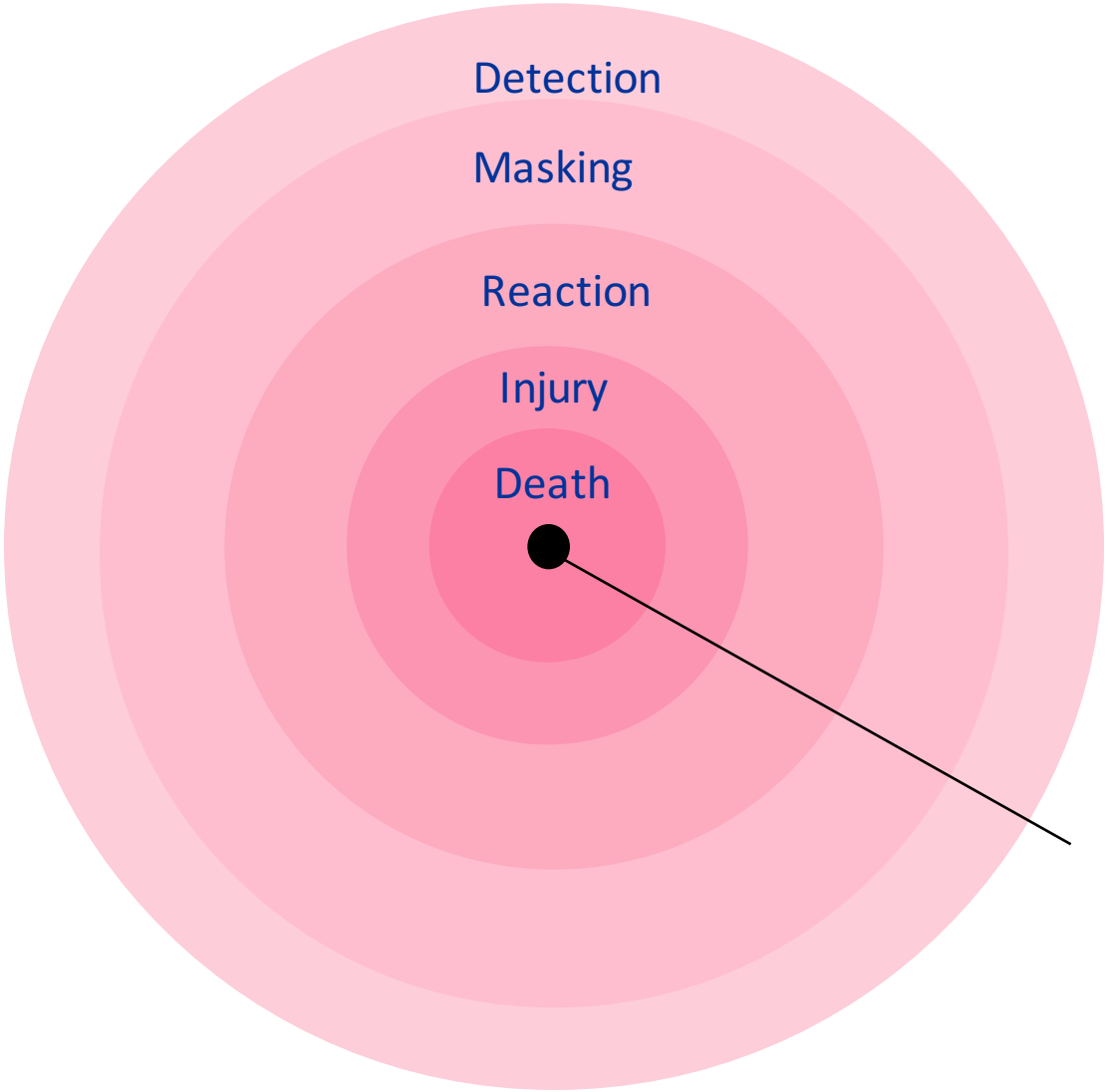


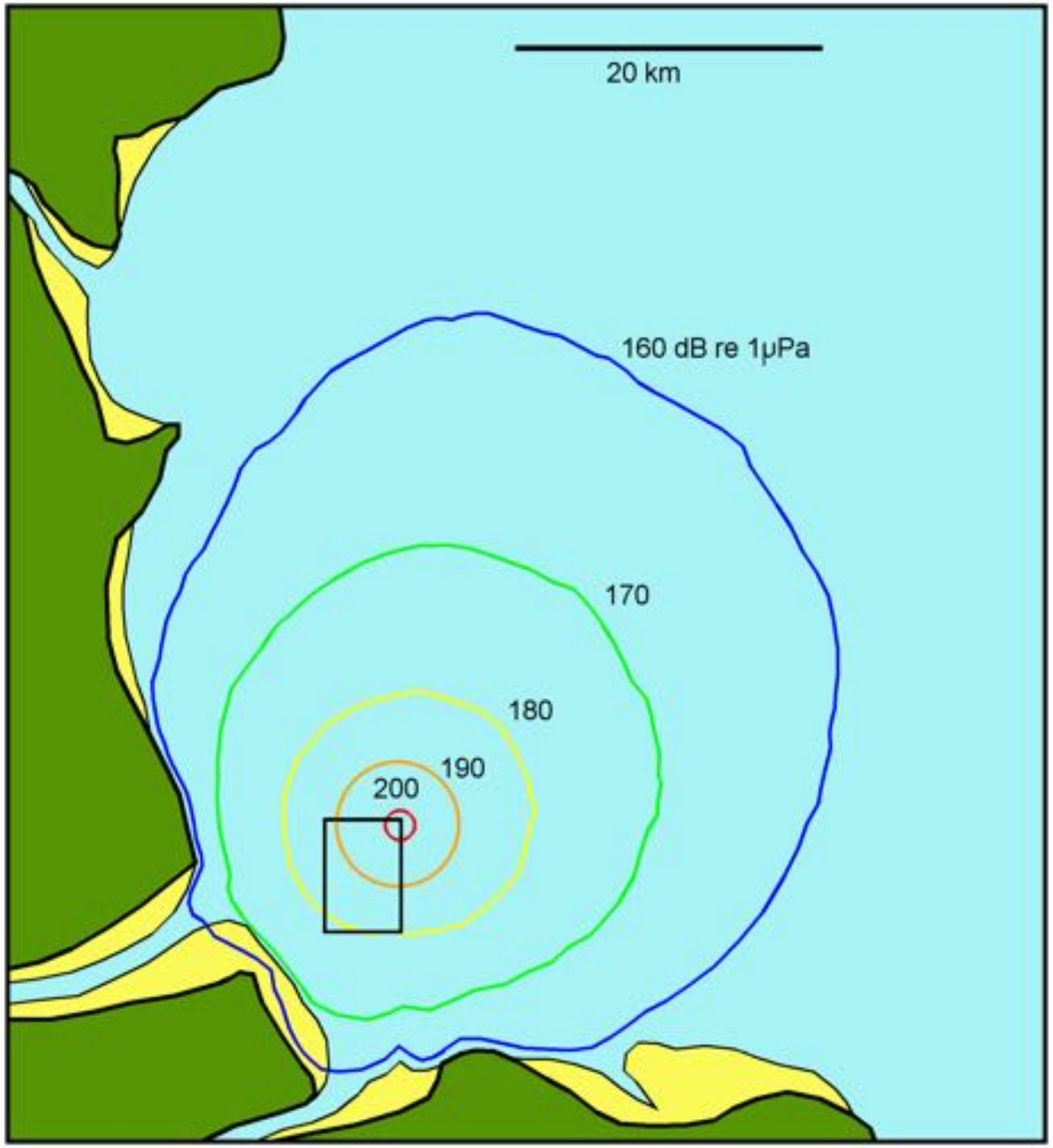
We should be especially concerned about Masking by man-made noise

- Sounds are very important to aquatic animals
- Many are active sound producers
- Sounds play an important role in vital activities like spawning

Fish sounds are especially vulnerable to masking by man-made sounds

It is possible to estimate zones of effect





Modelling of peak to peak Sound Pressure Level contours for driving a single pile

Some underwater sounds can injure fishes. Pile driving can even kill fishes close to the pile

A number of experiments have shown injuries to different tissues

Mild

A Eye Damage

B Fin Damage

Moderate

D Liver bleeding

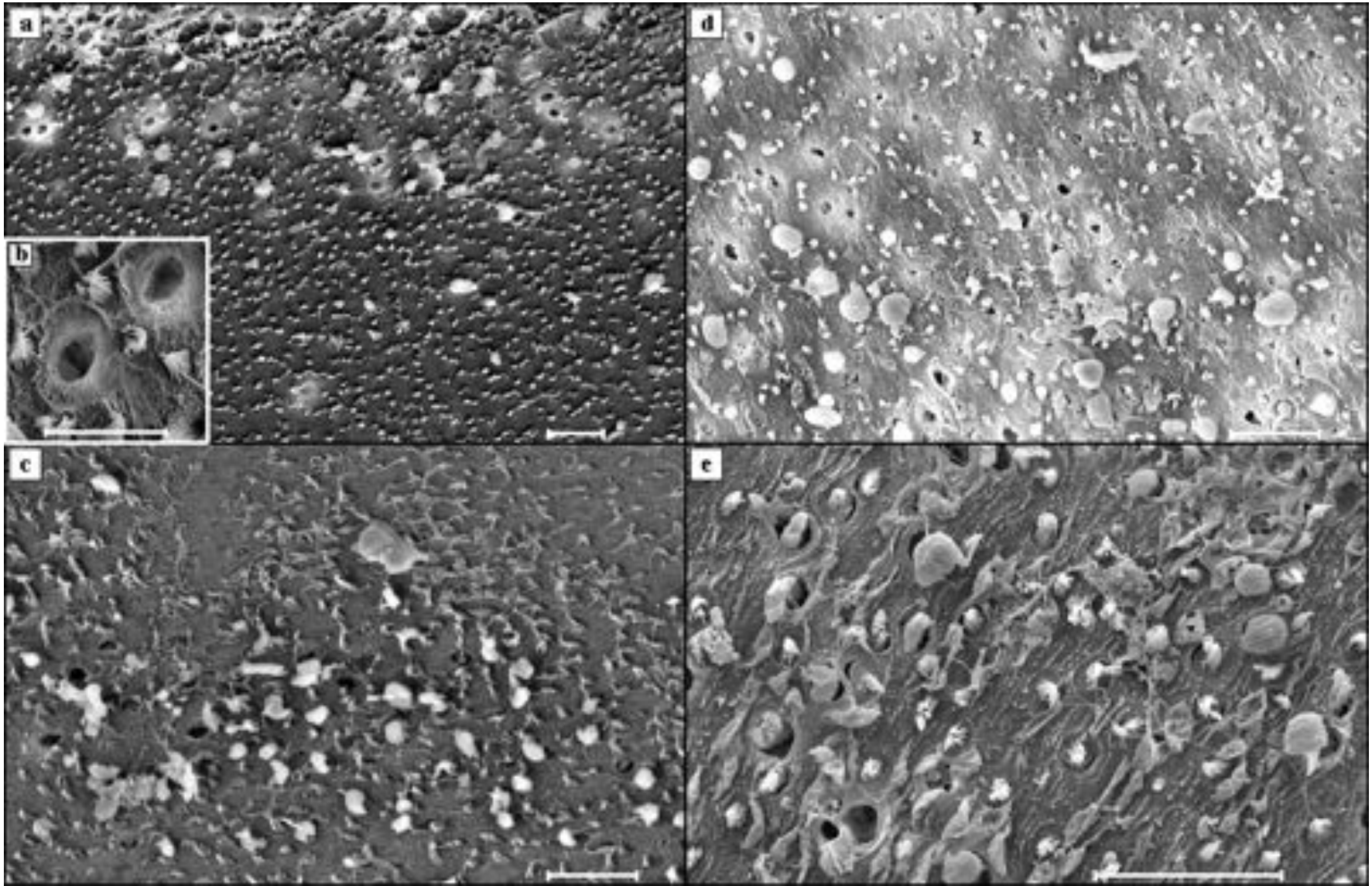
E Swim bladder Damage

Mortal

F Intestinal Damage

G Liver Damage

The hair cells within the ears may also be damaged, in this case by exposure to an air gun McCauley et al (2003)

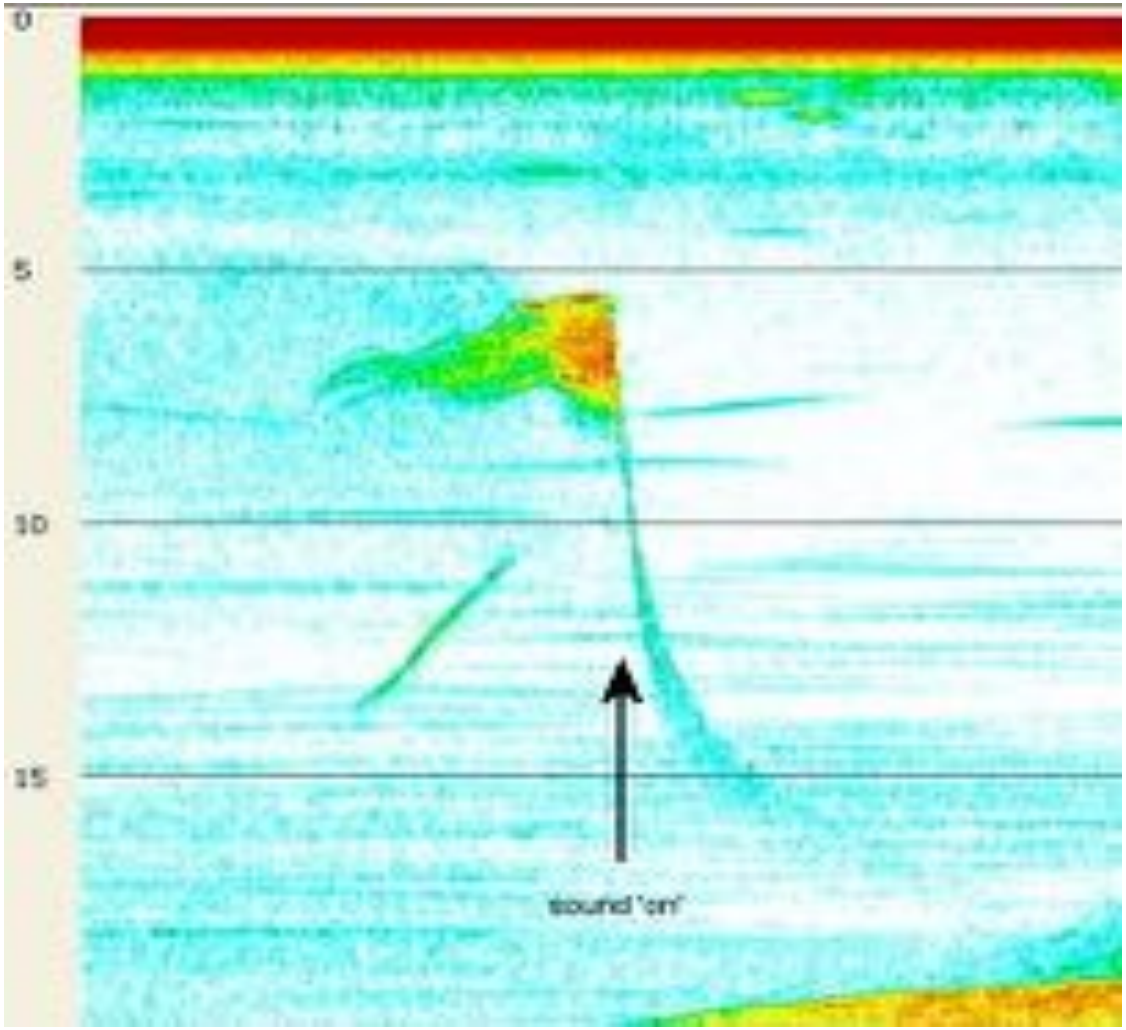


Fishes respond behaviourally to quite low levels of underwater sounds

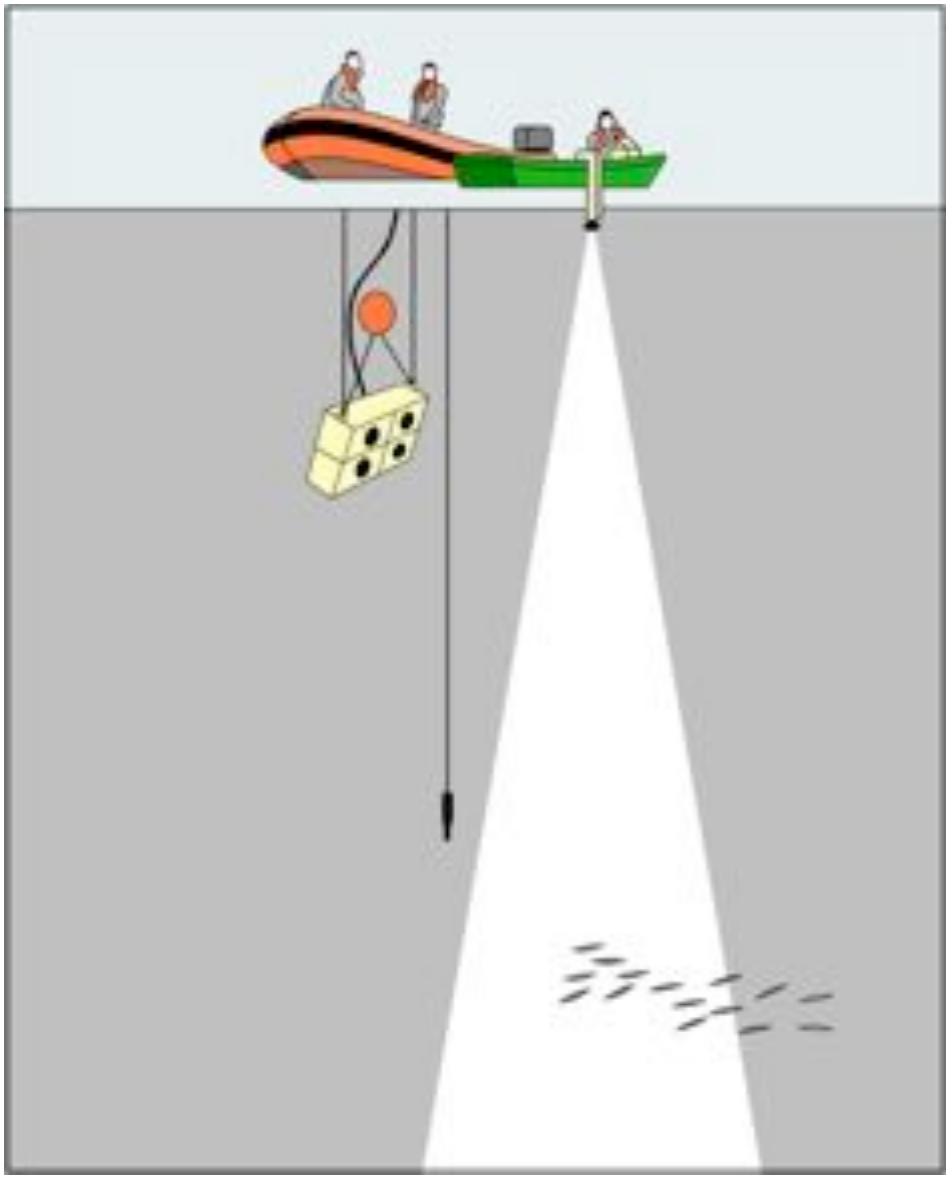
A number of experiments have shown strong responses, especially by pelagic fishes

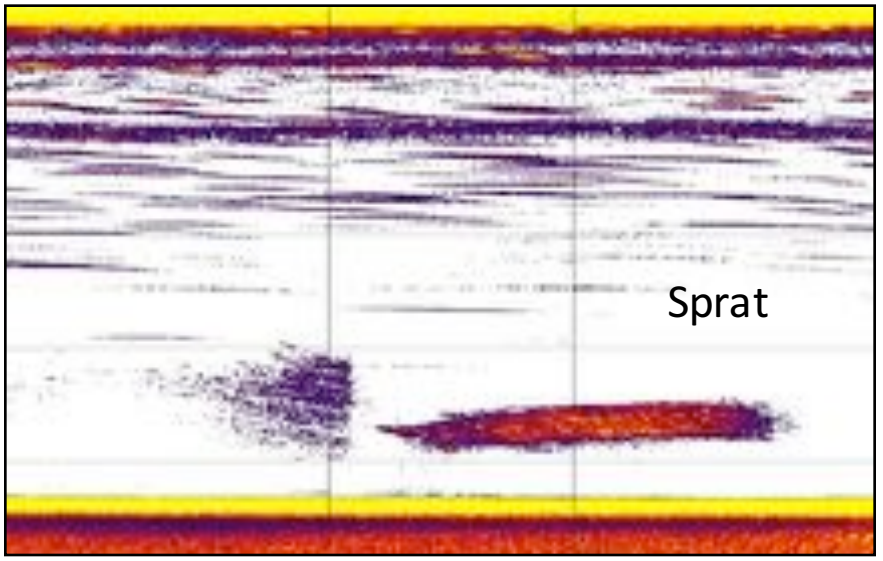
Reactions of fishes to man-made sounds

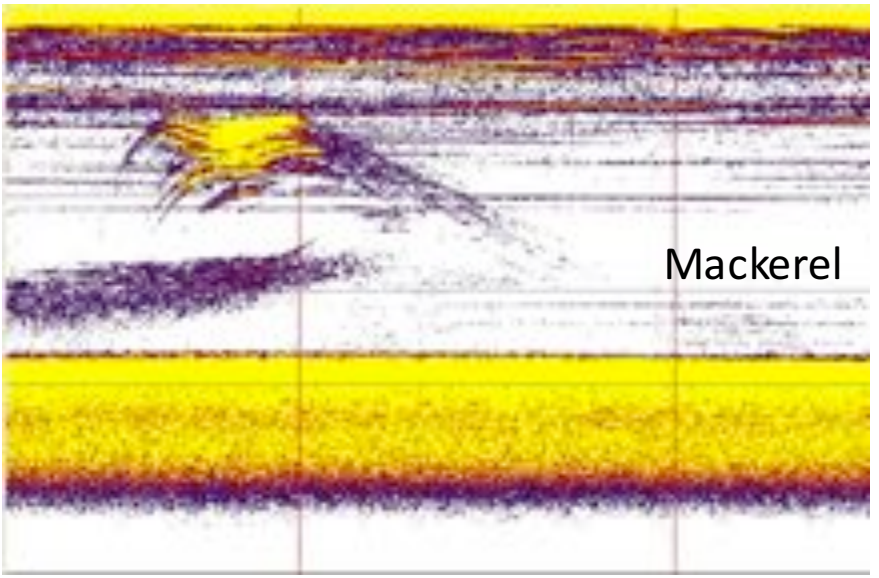
Here, a mackerel school at Lough Ine dives and breaks up in response to pile driving sounds



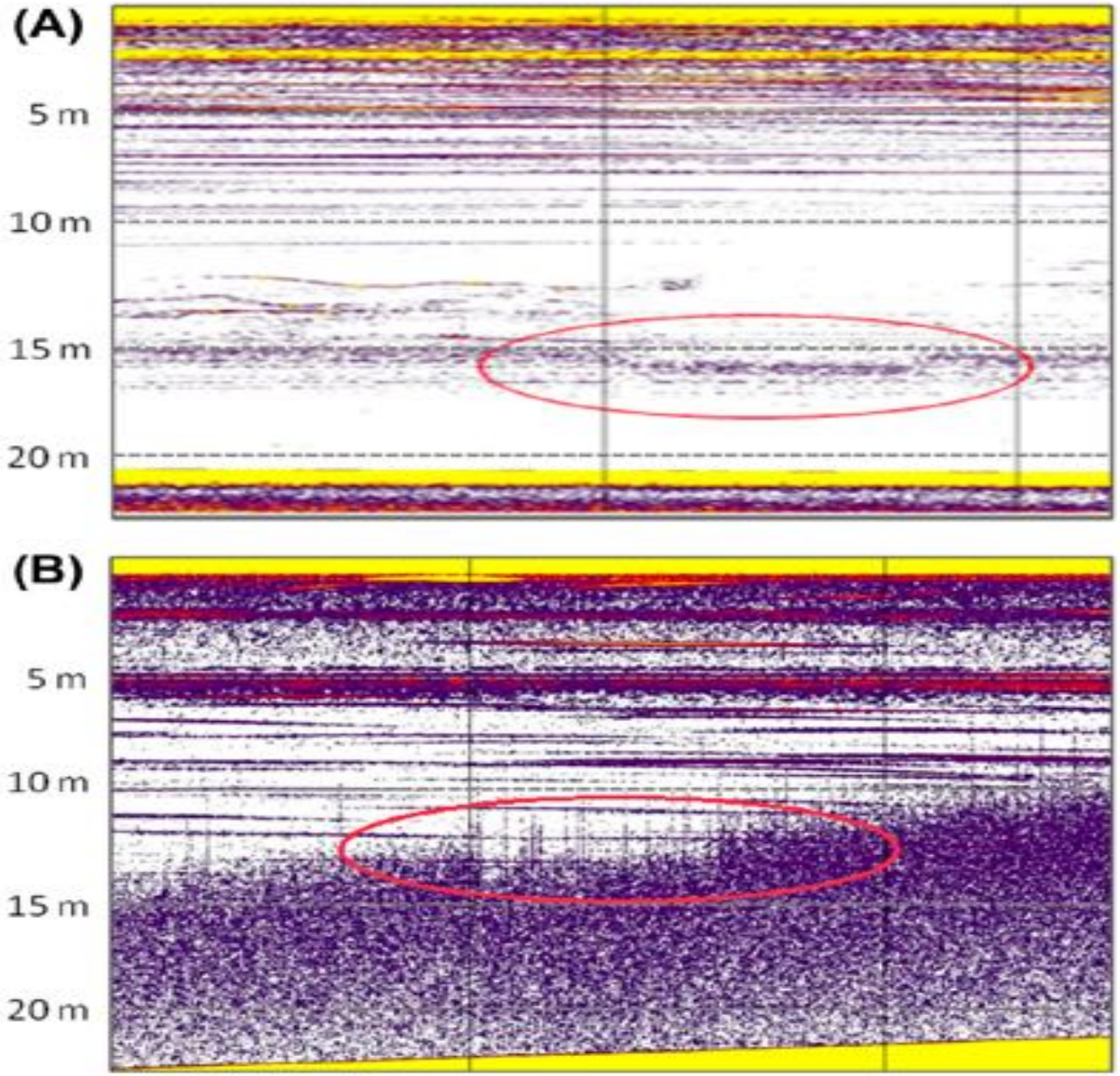
Recent Experiments on Wild Fishes
(Hawkins et al., 2014)







Effects observed upon Zooplankton



Sprat

Mackerel

50% Response levels to impulsive sounds

Sprat

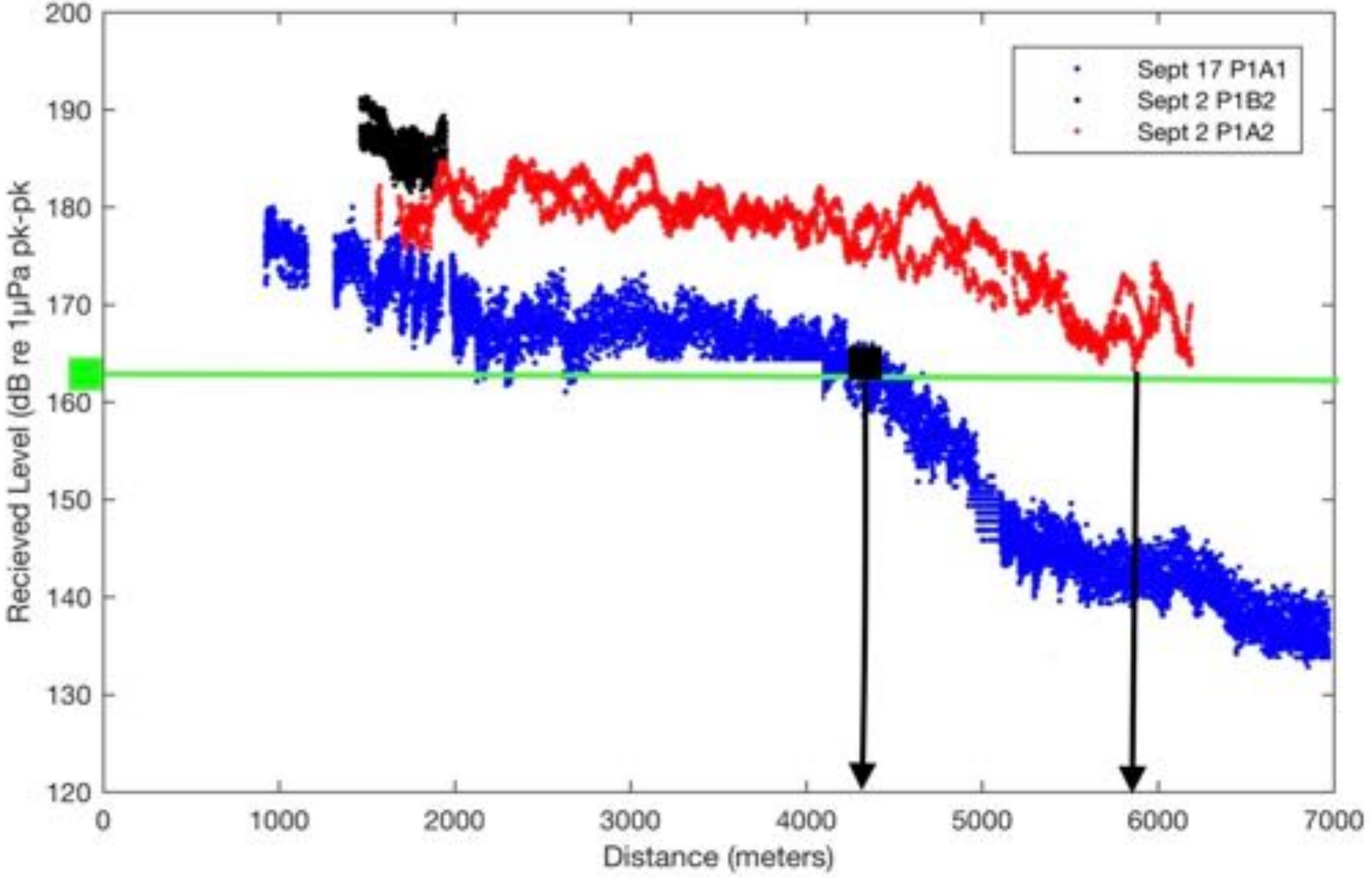
Peak to peak sound pressure level 163.2 dB re. 1 µPa

Mackerel

Peak to peak particle velocity level -80.0 dB re. 1 m s^{-1}

(equivalent to a sound pressure level of
163.3 dB re. 1 µPa)

How far away will they respond to pile driving?



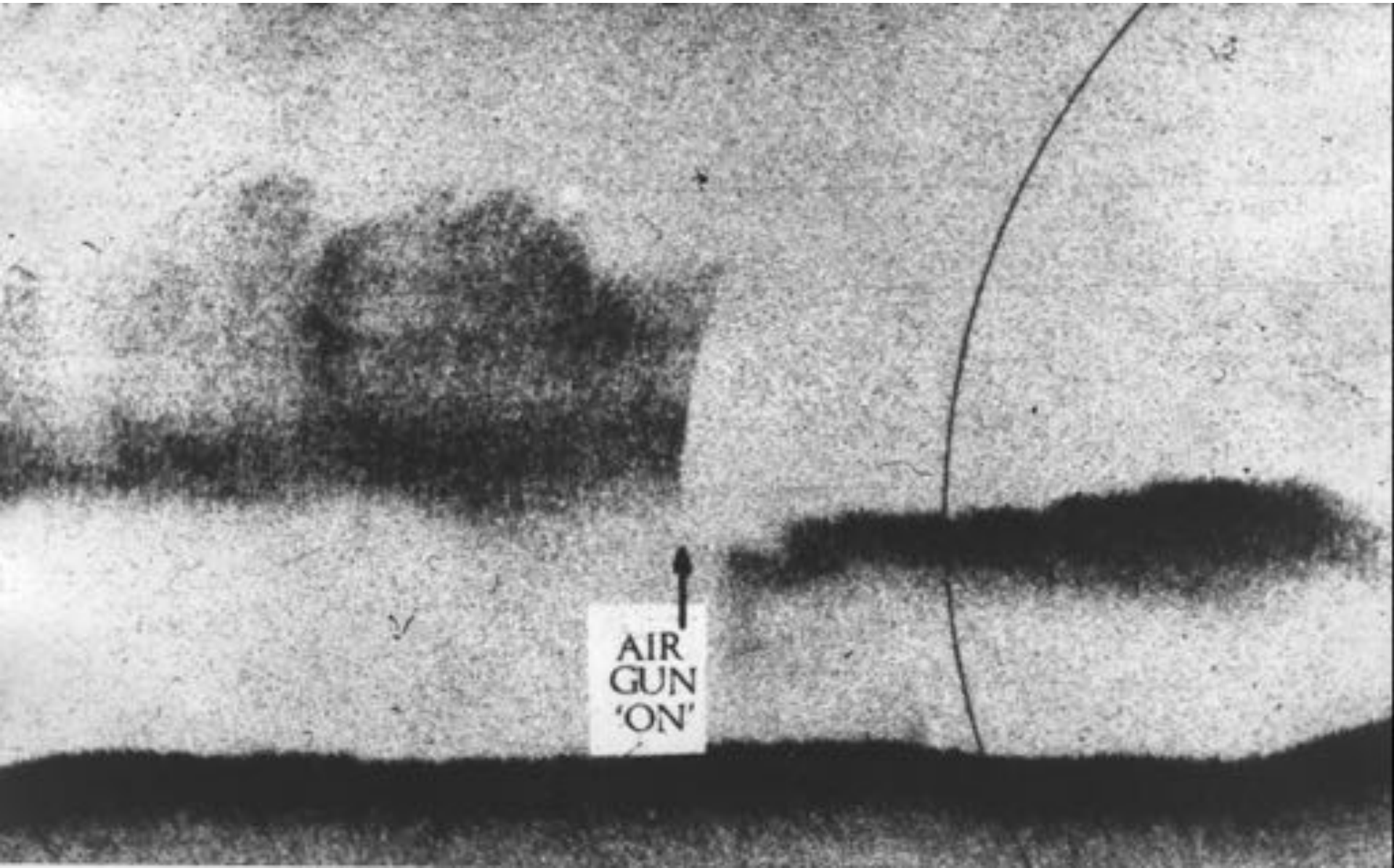
Responses of fishes to seismic surveys?

Experiments conducted in Norway were thought to show that air gun sounds affected the distribution, abundance and catch rates of cod and haddock (Engas et al., 1996).

Acoustic abundance estimates for pelagic fishes were higher outside than inside a seismic shooting area (Slotte et al., 2004)

However, very little valid work has been done on the effects of air guns sounds on fish behaviour

Response of a shoal of whiting to the firing of a seismic air-gun (Chapman & Hawkins 1969)



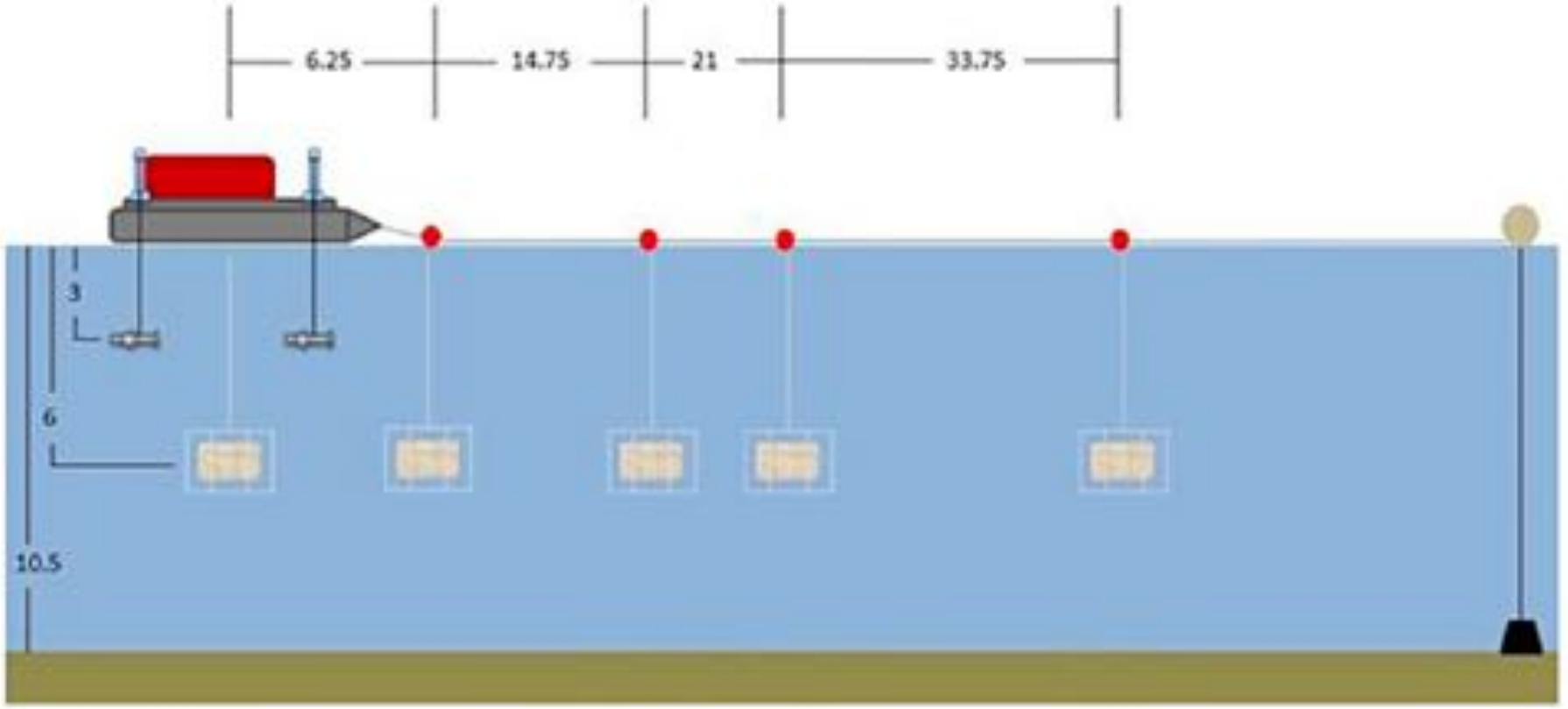
Fish catches can change during seismic surveys

Fyke nets were used to catch 8 fish species in Prudhoe Bay Alaska for many years

Significant changes in catch rates took place during an actual seismic survey (Streever et al., 2016)

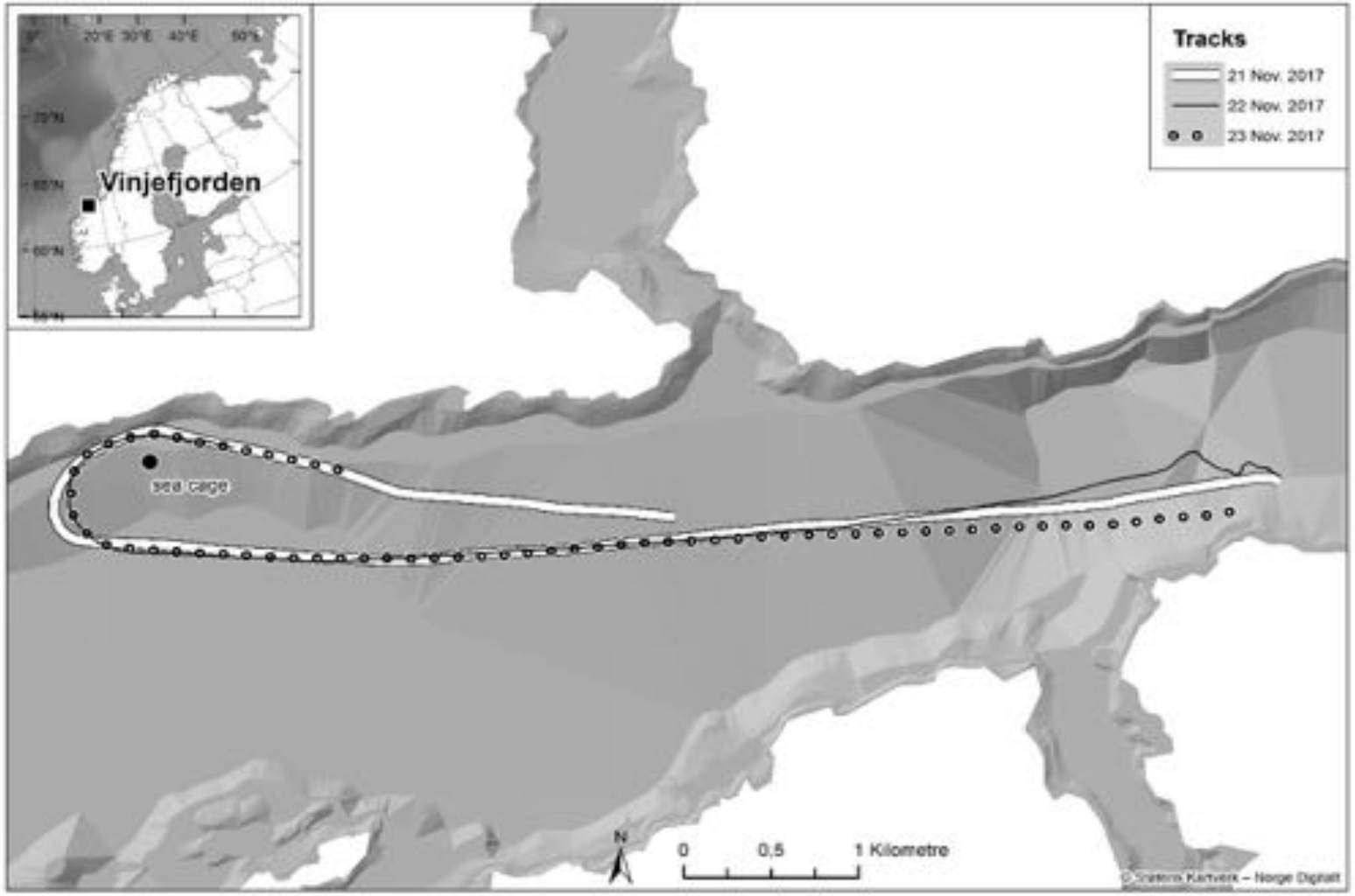
There were both increases and decreases in catch rates, perhaps reflecting displacement of the fish in response to the air gun sounds throughout the study area

Pallid Sturgeon were exposed to air gun sounds in Lake Sakakawea, North Dakota



No physical injuries were found, although earlier work had shown damage to hair cells in fish ears

Last year, cod and saithe were exposed to air gun sounds in a cage in Vinjefjorden, Norway (Davidsen et al., 2018)



Cod and Saithe showed reduced heart rates (bradycardia) in response to the particle motion from the airgun, indicative of an initial flight response

The fish also swam deeper and showed reduced schooling

However, there were no long term adverse changes in fish behaviour or physiology

Responses of scallops to seismic surveys

Recent experiments in Tasmania (Day et al., 2017) exposed captive scallops to an air gun right over the top of the animals in 3-10 meters of water, multiple times in rapid succession

The scallops did not die immediately but were said to show changes to natural reflexes, immune system failure, liver failure and some eventual died

However, the air gun was very close and the scallops were later kept under poor conditions

Recently, experiments were carried out on wild scallops exposed to an actual seismic survey (Przeslawski et al., 2017)

There was no evidence of scallop mortality, although sub-lethal effects could not be excluded

It was concluded that no adverse effects on scallops could be linked to the actual seismic survey

It is clear that more scientific research is needed to examine the effects of seismic surveys on both fish and shellfish

How Can We Limit the Impact of Noise?

We need to know which levels of noise have adverse effects, and which do not

In the USA, Sound Exposure Criteria are used to set limits to the received levels for particular sources, above which damage may be done

Noise makers are not allowed to exceed these levels in areas considered to be critically important

USA Sound Exposure Criteria

Limits to sound levels are set for particular sources above which animals may show:

Death or Injury

Hearing impairment

Masking of biologically important sounds

Changes in behaviour & other vital functions

Current Criteria for Effects upon Fish

US criteria for injury from pile driving

Sound Pressure Level	206 dB re 1 µPa
Cumulative Sound Exposure Level	187 dB re 1 $\mu Pa^2 \cdot s$

NB: the period of accumulation is generally the full driving of a single pile

These criteria are currently being reconsidered

There are not yet any Criteria for Shellfish, despite their importance

The Current Position

There are few data on which to base Sound Exposure Criteria. Different countries apply different criteria

Metrics for these criteria are not always well matched to biological effects

Sound propagation models are often inadequate for predicting received sound levels

New data are required on effects on animals

There is a real need to assess actual impacts

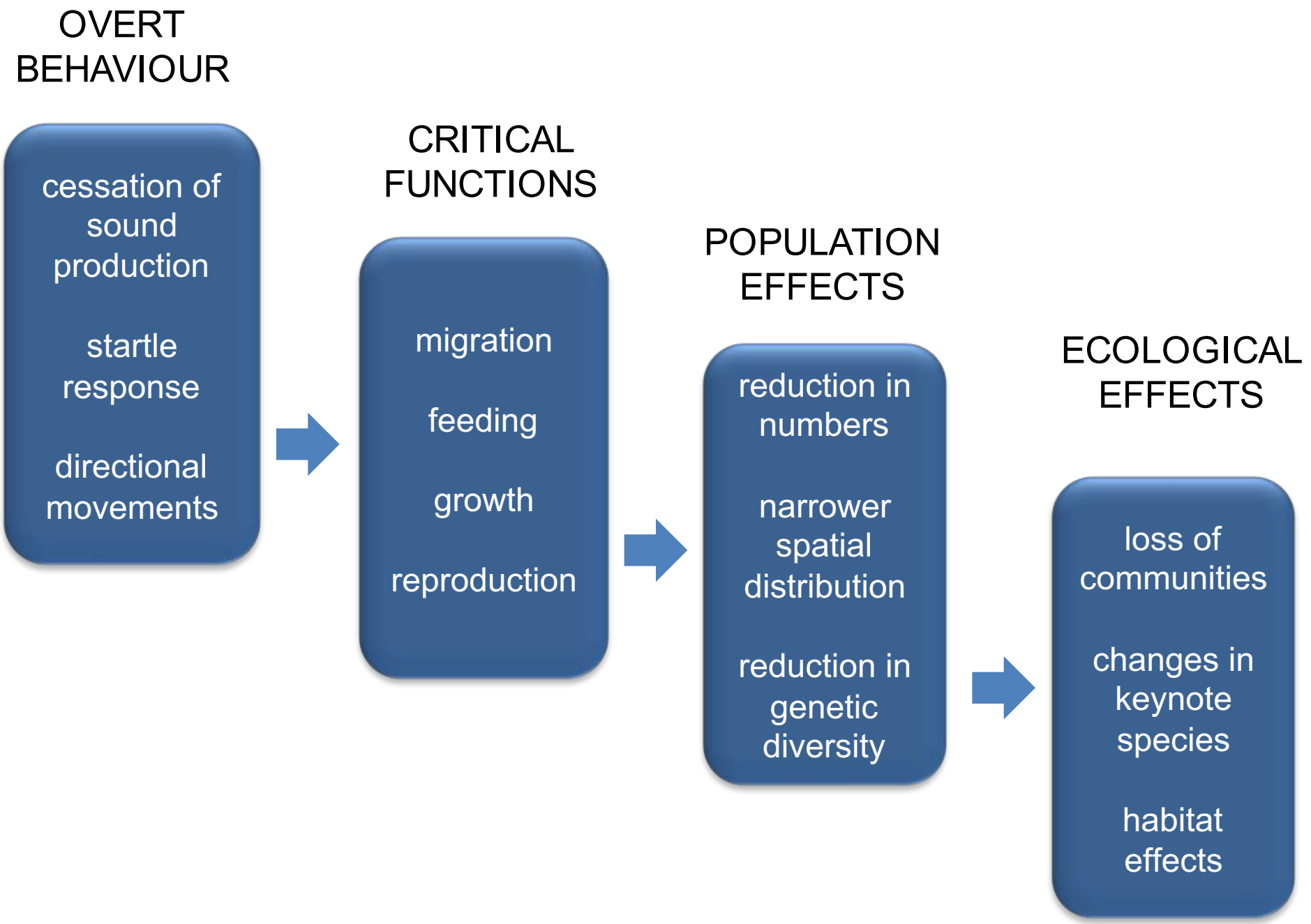
Effects and Impacts

An animal may respond to sounds but this does not necessarily mean that conservation interests are affected

It is necessary to show that there have been adverse effects upon:

- The integrity of a conserved habitat
- The sustainability of a species or population
- Or to show that a protected species has been disturbed

It is important to consider impacts on populations


OVERT BEHAVIOUR
cessation of sound production
startle response
directional movements
CRITICAL FUNCTIONS
migration
feeding
growth
reproduction
POPULATION EFFECTS
reduction in numbers
narrower spatial distribution
reduction in genetic diversity
ECOLOGICAL EFFECTS
loss of communities
changes in keynote species
habitat effects

Assessment of effects often involves dubious assumptions & predictions

Sound exposure criteria are often assumed rather than based on real data

The metrics employed are often inappropriate, especially for fish and shellfish

Sound propagation models have seldom been validated and they do not predict particle motion levels. They are especially poor for shallow water conditions

Actual impacts on populations are often unknown and difficult to assess

In Europe we need to manage man-made underwater noise to ensure that it does not have adverse effects upon aquatic animals

However, we do not yet have any Sound Exposure Criteria

The EU Marine Strategy Framework Directive is intended to help with this

The Directive sets out to endure that underwater noise, is at levels that do not adversely affect the marine environment

Two Indicators have been set, for:

Impulsive sounds (eg pile driving strikes, seismic signals)

Low frequency continuous sound (eg ship noise)

The Indicators

For Impulsive sounds: The proportion of days within a calendar year, over areas of a given size, in which the sounds exceed a particular level

For Continuous sounds: Areas where noise levels within narrow frequency bands centered at 63 and 125 Hz do not exceed a baseline value

Some monitoring of these two indicators is currently taking place

It will be necessary to define when Good Environmental Status occurs for these indicators

It is also necessary to develop valid Sound Exposure Levels that should not be exceeded for fish and shellfish

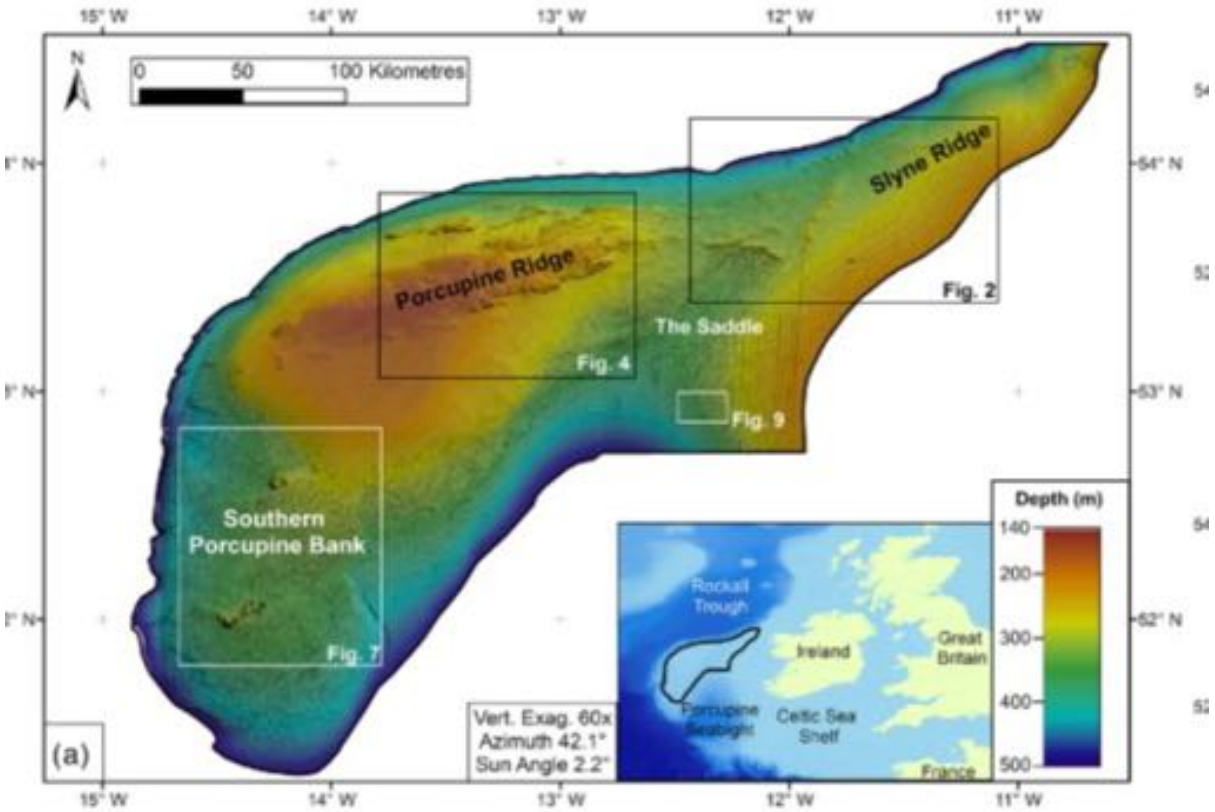
Perhaps some areas where vulnerable animals rely on sound need to be declared Marine Protected Areas?

It is important for Member States to determine whether noisy offshore activities are likely to have significantly adverse effects on the animals that live there


Soundscapes are as important as Landscapes and Seascapes
Lizard Island Australia

Important Areas to Protect

Under the European Habitats and Species Directive it is necessary to protect vulnerable habitats and species. Porcupine Bank is a Special Area of Conservation (SAC), part of the Natura 2000 network of sites



However

There are other areas that are not designated for protection that nevertheless deserve special consideration

These include areas with unique soundscapes, where man-made noise can cause problems. Such areas include those where vocal fishes gather to spawn.

It is important to monitor the soundscapes around our coasts, especially at the times of year when fishes and other animals may engage in mating behaviour involving the production of sounds

Future Work

Examine soundscapes that may need to be protected;

Characterise different Anthropogenic Sources;

Measure hearing abilities of more species;

Develop sound exposure criteria for injury, hearing damage and strong behavioural responses;

Examine the masking effects of man-made sounds;

Examine behavioural changes in response to sounds and assess their significance in terms of population impacts

There is an urgent need for experiments on fishes and Invertebrates to examine the effects of “shaking”

Most studies have exposed animals to high sound pressures, under conditions where the particle motion levels are minimal

The construction of the hearing organs in these animals suggest that “shaking” may be much more damaging than “squeezing”

Sensitivity to particle motion is often not considered in setting sound exposure criteria or modelling sound propagation

Conclusions

We have few data on which to base Sound Exposure Criteria for fish and shellfish

We now have some reliable data on sound levels causing injury for a few species

Criteria for hearing damage, masking, and behavioural effects require new data

There is clear evidence that adverse effects do occur as a result of exposure to some sounds

There is a real need for regulation of anthropogenic sounds to minimise their effects upon fishes and invertebrates

Current environmental impact assessments do not properly assess the effects of underwater sounds and often ignore the effects of particle motion and substrate borne sound

In 2018 the United Nations noted the environmental impacts of underwater noise. It accepted the need to invest more to bridge knowledge gaps

It was noted that high levels of noise were affecting marine species abilities to rely on sound for critical life functions.

It was agreed that it is important to map the distribution of endangered species, establish marine protected areas, and protect the migratory routes of species sensitive to noise

A key Scientific Conference on Underwater Noise is being held next year

The Effects of Noise on Aquatic Life

Den Haag
7-12 July 2019