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ACOUSTIC MONITORING TECHNIQUES FOR SUBSEA LEAK DETECTION - A REVIEW OF DATASETS

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Acoustic monitoring techniques for subsea leak detection - A review of datasets.

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CONTENTS

1 INTRODUCTION

Gas release from marine sediment into the water column can have natural or anthropogenic sources. Natural sources of gas fluxes include biogenic processes, the decomposition of organic material in the seabed and geophysical activity, e.g. in the vicinity of active volcanoes. Anthropogenic activities which cause fluxes typically are associated with a failure of some form, e.g. a leak in a gas transport pipeline (Bergès et al., 2015).

Carbon capture and storage (CSS) has been identified as a significant component of the UK's plan to decarbonise while maintaining its use of hydrocarbon fuels, avoiding further contributions to carbon dioxide emissions (Gough et al., 2006). Many potential CSS sites are located offshore in depleted hydrocarbon fields over a kilometre below the seafloor allowing for the utilisation of existing pipeline infrastructure.

Oceans cover two-thirds of the earth's surface and absorb the excess carbon dioxide from the atmosphere resulting in increased acidity; a process that will have a negative effect on marine ecosystems (NOAA, n.d.) and take tens of thousands of years to reverse (Raven et al., 2005). Leaks from marine CCS have been identified as a possibility but been evaluated to have a minimal localised impact in comparison to increased atmospheric carbon dioxide levels, provided that they are detected and repaired in a short window (Gough et al., 2006).

There are two types of acoustic monitoring methods that can be utilised to detect subsea leaks, passive and active (Malcher & White, 2023). Passive acoustic monitoring involves the use of hydrophones to record the acoustic signal generated by a bubble forming. Acoustic emission from individual bubble formation has previously been used to model the bubble size by looking at the dominant frequency (Leifer & Tang, 2007a; Leighton & Walton, 1987). Work has also been completed in quantifying complex leaks where there aren't individual bubble signatures using the source level of the leak (Leighton & White, 2012). Active monitoring involves emitting a sound at a target and analysing the signal reflected. Due to the large difference in the density between water and gas, bubbles in the water column have a high target strength allowing them to be easily picked up by active monitoring systems (Waarum et al., 2017). The appearance of a bubble on an active monitoring system can be maximised by tuning the emitted frequency to the resonant frequency of the bubble.

Experimentation into acoustic monitoring of subsea leak detection have used both active and passive methods for the detection, localisation, and quantification of gas flux. This report will outline the previous experiments conducted in-situ, the data they collected and how the data has been utilised.

2 LA GOLETA (2005)

La Goleta is a group of natural seeps off in the larger seep field of Coal Oil Point in southern California. Research aimed to explore the effectiveness of applying passive acoustics to the study of seeps (Leifer & Tang, 2007b). To do this, a hydrophone and optical equipment were mounted onto a submarine which was then navigated to be around 70 cm from the mega plume La Goleta which releases gas comprised of 76% methane and is at a depth of 62 m. The plume also releases approximately 80 barrels $\mathrm{oil/day^{-1}}$. The hydrophone recorded at 12 kHz allowing for approximately 5 hours of recordings over the deployment alongside a log of the depth and temperature every second. Optical Data was collected at 60 frames per second with images of 720×480 pixels. Bubble radii and timestamp for each bubble were derived from the optical information (Leifer & Tang, 2007b).

Due to the vehicular noise from the hydrophone being mounted to the sub, the signal to noise ratio of the bubble formation was substantially reduced. The bubble radii calculated from the passive acoustic data using the Minnaert equation. These radii were found to be around 20% greater than those observed in the optical data, this was hypothesised to be either due to surfactants from seawater (e.g. sediment, oil and algea) or acoustic coupling. Although optical sizing is not trivial and error rate could be the result of this process rather that acoustic inversion. This led the study to conclude that little is understood about the effect of surfactants on bubble geometry or formation (Leifer & Tang, 2007b).

3 NORTHERN GULF OF MEXICO (2010)

In 2010 three National Oceanic and Atmospheric Administration (NOAA) vessels equipped with single and split-beam echo-sounders surveyed the Northern Gulf of Mexico for evidence of submerged oil. The data collected discovered natural methane seeps not previously observed in the area mainly located on the edge of salt domes (Weber et al., 2012).

Two seeps in the Northwestern edge of the Biloxi Dome were imaged with Simrad EK60 split-beam echo-sounders at 18 kHz and 38 kHz (shown in figure 1). The methane was observed to rise from depths of 1340 m to 500 m. A study of these seeps was undertaken to further understanding of their evolution into the water column in the deep ocean. The study found it possible to use split-beam echo-sounder instrumentation to assess seep morphology and with multiple frequencies constrain normal bubble size as a function of depth (Weber et al., 2012).

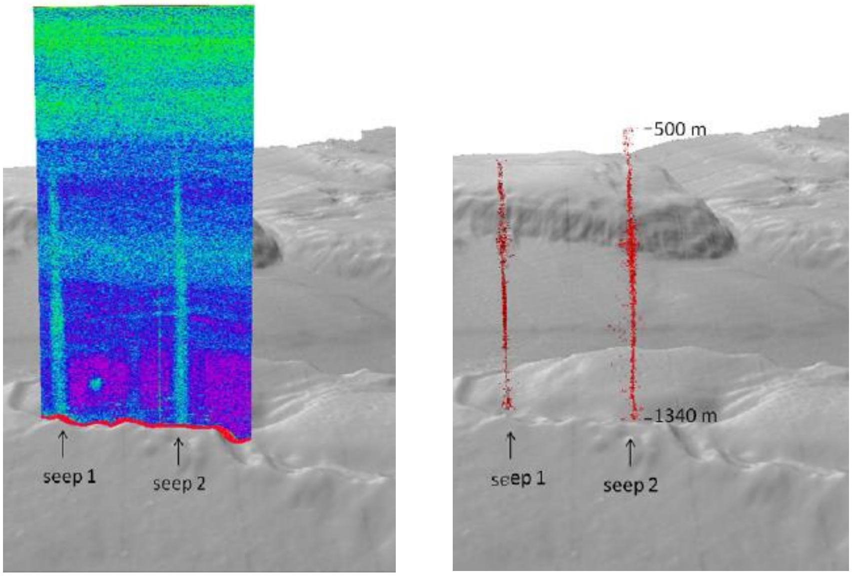

Figure 1: Left - echograms overlaying bathymetry data imaged at 18 kHz of seeps on edge of Biloxi Dome. Right – showing bathymetry data seeps overlayed and depths labelled (Weber et al., 2012).

4 SEA OF MARMARA (2009-2011)

The Marmara is an inland, non tidal sea in northwestern Turkey. The area had been previously thoroughly surveyed using side-scan, single beam sonars, sub-bottom profilers and multi-beam echo-sounders. Previous surveying illustrated that methane seep emissions in the area intensified after an earthquake in 1999 (Bayrakci et al., 2014).
The module named BOB (Bubble Observatory) consisted of Simrad ER 60 echo-sounder using a frequency of 120 kHz with the ability to insonify an angular sector of 7° as shown in figure 2. The active sonar was mounted on a 'pan and tilt system' and was programmed to cycle through a series of 7° sectors with a tilt of 4° to avoid seafloor reflections. After cycling through sectors the sonar was re-positioned to the first sector and the cycle started again (Bayrakci et al., 2014).

Two deployments of a module were undertaken in 2009 and 2011 to observe the temporal variations of the seeps. The 2009 deployment took place in the Cinarcik Basin at a with the module at a depth of 1250 m. During the 2011 deployment the module was deployed in the Central High at a depth of 332 m (Bayrakci et al., 2014).

For the 2009 deployment 22 7° sectors were chosen along the horizontal axis. Each sector was insonified for 72 minutes resulting in a 26 hour cycle of all sectors. The 2011 deployment 24 7° angular sectors each recorded for 1 hour resulting in a 24 hour cycle. An ocean bottom seismometer was also deployed alongside the BOB module to record seismographic events and evaluate if these are the cause of temporal events in the plume (Bayrakci et al., 2014).

During the 2009 and 2011 deployments, 4 and 7 cycles respectively were successfully recorded. The ocean bottom seismometer data for the 2009 was found to be noisy due to heavy shipping traffic but the 2011 deployment recorded 3.5 months of usable data alongside the BOB deployment (Bayrakci et al., 2014).

The data from the BOB 2009 deployment showed that gas emissions can be continuous or transient, with the rate of gas release. During the 2011 data identified two continuous seeps with estimated volumetric flow rates between 0.2 and 0.96 L/hour although spatial and temporal variations were observed which are hypothesised to be due to sea-bottom currents although not verified (Bayrakci et al., 2014).

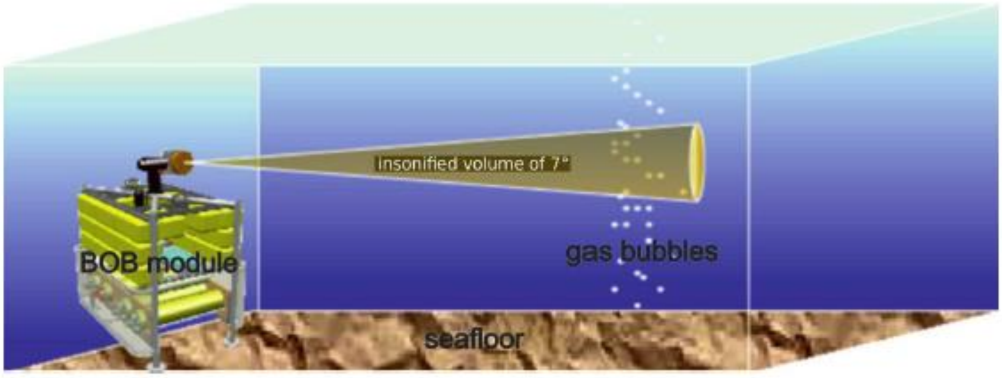

Figure 2: Schematic of the bubble observatory (BOB) module deployment in the sea of Marmara (Bayrakci et al., 2014).

5 QICS (2010-2014)

The QICS (Quantifying and monitoring potential ecosystem Impacts of geological Carbon Storage) project aimed to examine the detectability of gaseous carbon dioxide in sediments and the water column using acoustic, chemical, and biological methods (Blackford et al., 2015). The trial consisted of the controlled release of carbon dioxide into shallow subsea sediments off the coast of Scotland from the 17th of May to the 22nd of June 2012 (Blackford et al., 2014).

A 350 m borehole was drilled which was lined with stainless steel and positioned a 5 m diffuser 11 m below the seabed which averaged 10 to 12 m below sea level dependant on tide (see Figure 3). The diffuser was manufactured with 0.5 mm perforations ensuring diffuse gas flow into the sediment. Carbon dioxide was released through the diffuser over a 37-day period from a rate of 10 $\mathrm{kg\ CO_2\ d^{-1}}$ to 210 $\mathrm{kg\ CO_2\ d^{-1}}$ resulting in a total release of 4.2 tonnes (Blackford et al., 2014).

For the acoustic methods, high-resolution seismic sub-bottom profiling was conducted before and throughout the study comprised of 194 boomer and chirp profiles covering an area 600 m by 400 m centred on the diffuser location (Blackford et al., 2014). Passive acoustic data was also collected with a SM2M+ recorder at 48 kHz sampling rate, deployed approximately 1 m from the sea floor on the 15th of June in the region of bubble release and collected on the 29th of June, 7 days after the gas release concluded. Additionally, 2 days of recordings were taken before deployment in a region where no gas release occurred (Bergès et al., 2015).

As well as data from acoustic methodologies, the reading from the high precision mass flow controller was logged every 12 seconds as well as the biological and chemical methods of data collection where baseline measurements were also taken (Blackford et al., 2014).

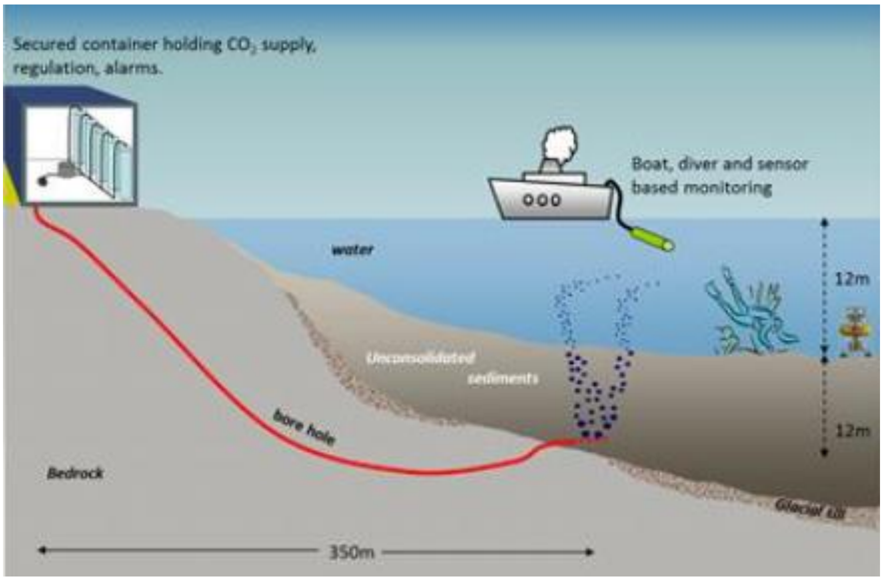

Figure 3: Diagram of QUICS experiment setup (Blackford et al., 2014).

6 NORTH SEA WELL SITE 22/4B (2011-2012)

North Sea Well Site 22/4b is an abandoned drill site (Rehder et al., 1998) which is now the site of a persistent methane megaplume since its blowout in 1990 with emissions greater than 106L d^{-1}. The well site houses hundreds of individual vents that contribute to the plume, the majority of these vents are situated in an area of roughly 20 m diameter at the bottom of a cylindrical crater. The rim of the crater starts at approximately 96 m of depth and reaches depths 120 m (Wiggins et al., 2015).

Marine seepage has been observed to vary along a sub-second to decadal timescale. Long-term monitoring was utilised to assess the variability of the methane seep. An ROV was used to position a lander on a protected ledge deep in the crater at a depth of 112 m as shown in figure 4 (Wiggins et al., 2015).

The lander was deployed over two periods from June 13th to September 9th 2011 and again from September 9th to January 8th 2012. The lander was equipped with a calibrated hydrophone connected to a high-frequency acoustic recording package data logger, which continuously recorded throughout deployments. The continuous recordings were then broken down into 1 GB, 100 kHz, XWAV files, a lossless file format similar to .WAV but with additional metadata including the data time and location. The lander also housed equipment to record vertical and horizontal ocean currents, and record water salinity, temperature, and pressure. The acoustic data from long-term monitoring showed both anthropogenic and natural events occurring other than the seafloor seep noise e.g., marine mammals, ships and seismic surveys (Wiggins et al., 2015).

The recordings documented a series of major events that occurred at the seep, and a 10 dB increase in overall sound levels and spectral broadening on December 10th after an eruption lasting 2 seconds. Morphological changes of the crater were observed on the recovery of the lander. The study concluded that passive acoustic monitoring had great potential to understanding and quantifying seeps although further study into the relationship between acoustic spectra (Wiggins et al., 2015).

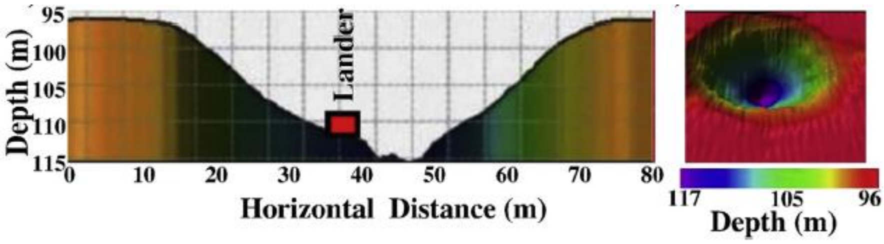

Figure 4: Cross-section depth profile through 22/4b crater with lander position (left) and crater bathymetry diagram (right) (Wiggins et al., 2015).

7 ECO2 (2011- 2015)

ECO2 was a European Union funded project triggered by member states expanding plans to store carbon dioxide captured at power plants in marine geological formations, aiming to assess the environmental risks associated with sub-seabed storage of carbon dioxide and provide guidance on environmental practices. ECO_2 investigated a total of six sites, three storage site and three natural seeps. Two of the storage sites (Snøhvit and Sleipner) were existing storage sites for captured carbon dioxide with the third being a potential future storage site (ECO2, 2019).

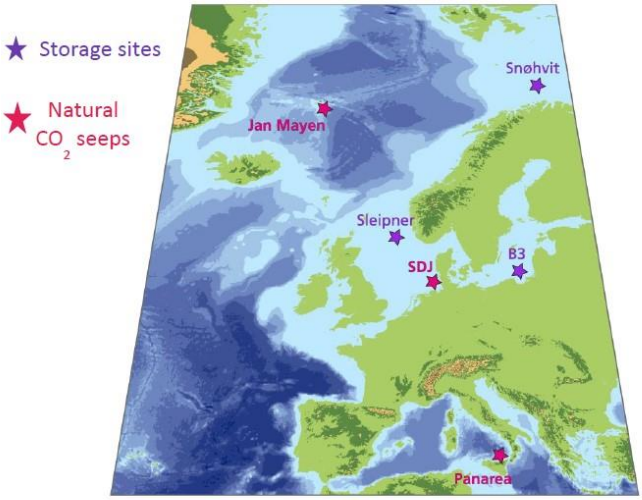

Figure 5: ECO2 study areas denoted by stars, with red stars being natural carbon dioxide seeps, and blue being storage sites (ECO2, 2019).

Studying these sites took two forms: surveys of the entire storage complex; and targeted studies of seeps and abandoned wells, these sites are shown in figure 5.The acoustic methodologies used in the studies included 3-D seismic, bathymetry/backscatter and hydroacoustic surveys using sub-bottom profilers and multi-beam echo-sounders. Alongside acoustic techniques, video/photo and chemical surveys were completed of the sites, with surveys being carried out using commercial AUV's retrofitted with survey instrumentation, or monitoring vessels (ECO2, 2019).

Landers featuring multi-beam echo-sounders were deployed to continuously record time-series data of active gas seeps over the course of a year in order to access the variability of emission rates from the gas seeps and the potential correlation between storage operations (ECO2, 2019). Figure 6 shows a sample of the multi-beam echosounder data recorded of a natural carbon dioxide seep.

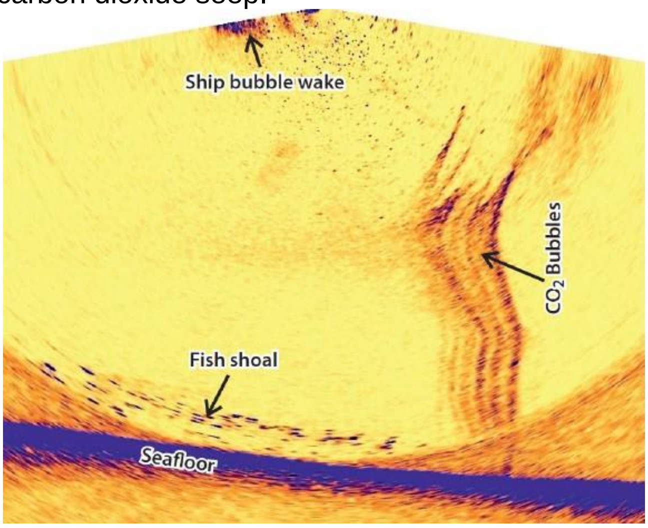

Figure 6: Example sample of multi-beam echo-sounder data takes in Panarea Italy for ECO2 project (ECO2, 2019).

8 ETI MMV (2014-2018)

ETI MMV (Energy Technologies Institute Measurement, Monitoring and Verification of CO_2 Storage) Project was a collaborative initiative between industry and academia to apply marine robotics to the task of monitoring carbon capture and storage sites (Energy Technologies Institute LLP, n.d.). The project resulted in a final phase involving a five week sea trial of an autonomous underwater vehicle (AUV) and two landers fitted with acoustic sensors at both Portland harbour in the UK and near shore close to Bridlington in the North Sea with simulated gas leaks (Dean et al., 2020).

The AUV was fitted with side-scan survey and optical imaging, one lander was fitted with a Sonardyne Sentry active acoustic sonar with the second lander holding a passive acoustic array and chemical sensors. The active acoustic lander was found to successfully detect leaks of 10 L/min at 110 m, the passive acoustic array also modelled to have a capability of detecting leaks of 10-50 L/min at ranges up to 60 m (Dean et al., 2020).

9 STEMM-CCS (2016-2020)

STEMM-CCS aimed to test detection methods and their sensitivity on a small scale using an in situ gas release with variable flow rates at a realistic water depth. The insitu experiment was setup on the site of the proposed Goldeneye carbon dioxide storage reservoir offshore from Scotland in the North Sea. A with a diffuser on the pipe was inserted approximately 3 m under the seabed. Gas release commenced on the 11th of May at 6 kg/d and was sequentially increased to 143 kg/d with each flow-rate maintained for approximately 2 days. Gas release was stopped on the 22nd of May (Flohr et al., 2021). Both passive and active methodologies were tested. Two passive landers were deployed containing an array of 5 hydrophones connected to an RS Aqua ORCA recorder in a frame with a height of 1.1 m and width of 1.3 m as shown in figure 8. The passive lander had a duty cycle of 5 mins on/5 mins off during its deployment. The aim of the passive acoustic array was that a hydrophone array would increase the range by allowing the enhancement of signal to noise of bubble formation. The array was also hoped to allow for localisation of seeps through beamforming (Connelly et al., 2022).

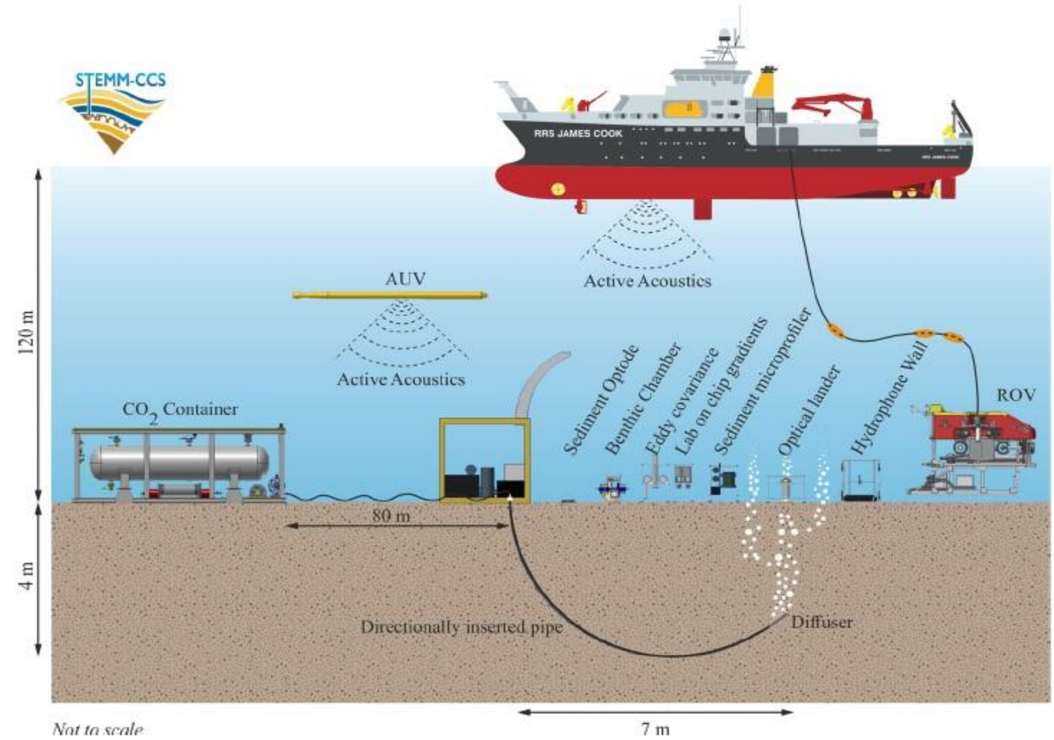

Figure 8: Diagram of STEM-CCS experiment setup (Flohr et al., 2021).

The active methodologies involved the use of sonar systems both AUV and ship based. The AUV was equipped with Geoswath bathymetric side-scan sonar, which conducted surveys of the area before, during, and after gas release at either 2 or 7.5 m above the seabed. One survey vessel was equipped with both a multi-beam (Kongsberg EM710) and single-beam sonar (Simrad EK60) both directed to collect bathymetry data of the seafloor. The second research vessel was equipped with an echo-sounder orientated to the seafloor (Flohr et al., 2021).

The deployment schedule for all the systems can be seen in Figure 9. The data collected from passive recording was produced quantification of bubble flux with radii between 0.15 and 0.3 cm inline with optical observations. The data collected from the AUV showed the development of gas pockets as injection rates increase as was as their later decrease with the development of open fluid flow conduits (Connelly et al., 2022).

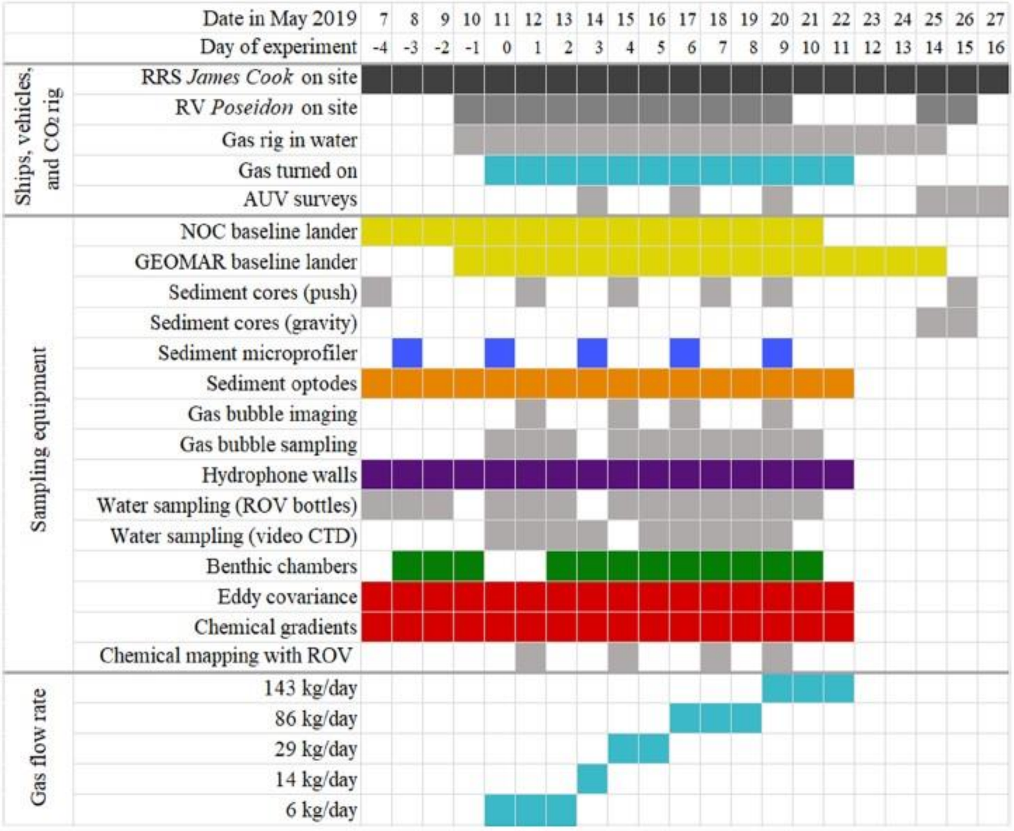

Figure 9: Timeline of ships, vehicles, deployment equipment, sampling and flowrates after the initial setup phase of the experiment (Flohr et al., 2021).

10 PANAREA (2018)

Panarea is an island located in the south Tyrrhenian Sea rising from the western section of a submarine stratovolcano. The seabed in the area features many volcanic craters with numerous gas leakages of a relatively stable composition around 98% carbon dioxide but varying flux rates. The 2018 study in Panarea looked to analyse the distance at which gaseous carbon dioxide can be detected and quantified using passive acoustics in the Bottaro Crater (map shown in figure 10), a previously identified continuous bubble plume (Li et al., 2020).

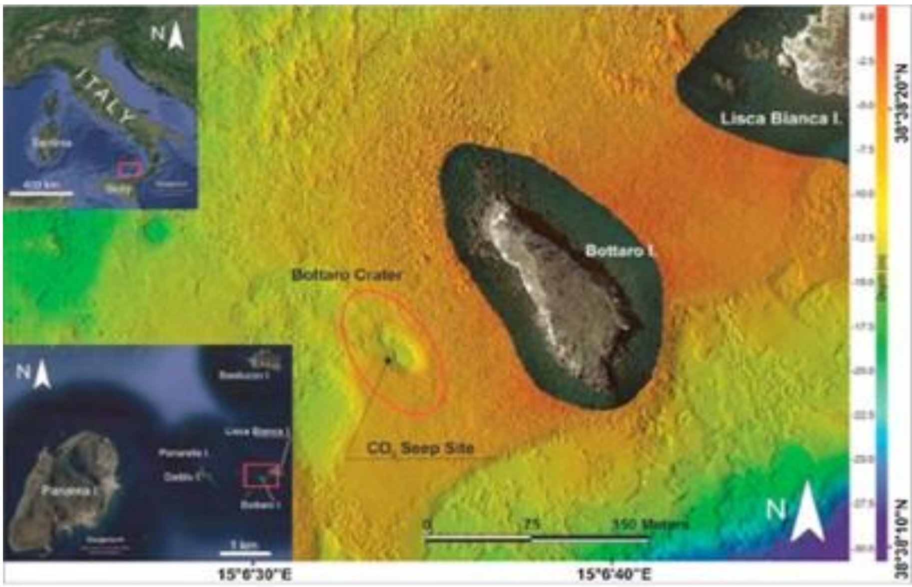

Figure 10: Map and bathymetry data of seep site (Bottaro Crater) and the surrounding area (Li et al., 2020).

Two hydrophones calibrated with a receive sensitivity of −164.5 dB re 1 V / µPa were linked to an RS Aqua ORCA acoustic recorder. Each input to the recorder was given a set gain of 15 dB and recordings were taken at a sampling rate of 96 kHz. The setup was deployed on May 16th 2018 with light winds and a sea state > 2 on the Beaufort scale. Hydrophones were fixed to tripods at a height of 0.75 m above the seafloor at 12.5 m water depth. Reference hydrophones were positioned 0.3 m from the flux and the second hydrophone positioned at various distances from the seep along a transect between 0.3 m and 8 m (see figure 11) (Li et al., 2020).

In addition to the acoustic data collected optical recordings were taken using waterproof action cameras alongside the gas flux measured by a diver using a funnel to collect rising gas bubbles.
The data collected was then used to display the ability to invert the collected acoustic data and detect a gas plume with a gas flux rate of 2.3 L/min at up to 8 m of distance and the quantification of gas flux and bubble size accurately at up to 4 m of distance where a bubbles sound pressure is 10dB above the ambient noise level (Li et al., 2020).

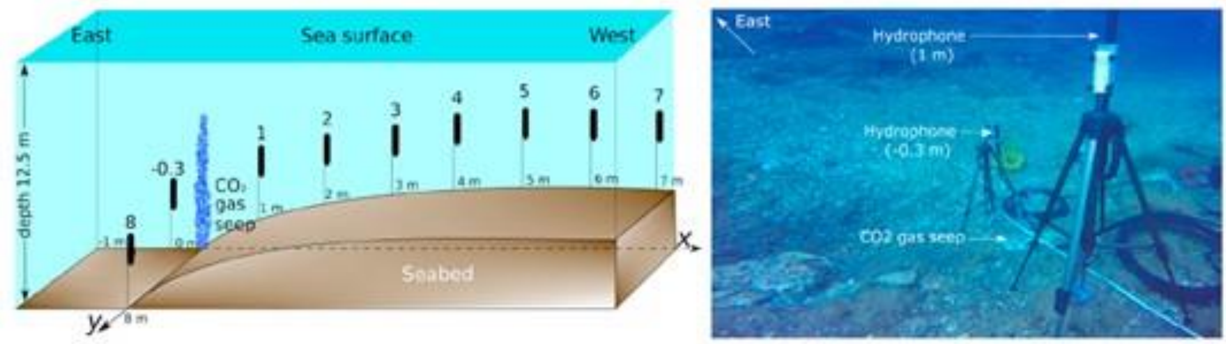

Figure 11: The hydrophone deployments for Panarea study of carbon dioxide seep. a - diagram of the transect and distances from seep of hydrophone positions. b - photograph of hydrophone deployment (Li et al., 2020).

11 PELICAN SITE (2018-2020)

The Pelican Storage site has been recognised as a potential carbon dioxide store located in the Gippsland Basin, a 46,000 km^2 area off the coast of southeastern Australia. The Pelican site is located 1-19 km offshore with a 12-35 m water depth, shown in figure 12. Nearshore ocean noise is acoustically complex due to the combination of multiple component sources both anthropogenic and natural. The Pelican site study aimed to use multi-year acoustic recordings to establish an ambient noise baseline, which in turn then can be used monitor deviations that may be attributed to gas seeps (Haris et al., 2023).

Three deployments of two passive acoustic landers were undertaken over a two-year period collecting recordings at a sample rate of 48 kHz. The passive acoustic landers contained SoundTrap 300 STD hydrophones calibrated to a frequency range between 20 Hz and 24 kHz. The landers were deployed in the positions illustrated in Figure 12 with each deployment's parameters shown in Table 1 (Haris et al., 2023).

Table 1: parameters for the three deployments to collect ambient passive acoustic data (Haris et al., 2023)**.**

Deployment		Lander	Sample Rate	Duty Cycle - On/Off
Start Date	**End Date**			
2018-05-09	2018-11-11	CCS SF 02	48 kHz	4/15 minutes
2019-05-08	2019-11-18	CCS SF 03		
2019-11-19	2020-04-13	CCS SF 02		

In June 2020 an in-situ gas release experiment was conducted 690 km away from the site of ambient data collection off the coast of Kingston Beach, Hobart, Australia. Carbon dioxide was released into the water column at a flow rate of 2 $Lmin^{-1}$, passive acoustic recordings were then taken at 1, 10 and 25 m range from the gas release source at a fixed height of 0.7 m above the seabed with a sample rate of 288 kHz. Environmental data was also congregated for the times and areas of the ambient and in-situ recordings including wave, tide and weather data (Haris et al., 2023).
The study of Pelican bay found that bubble sounds dominated the in-situ recordings between approximately 100 Hz and 24 kHz with a visibly elevated power spectral density levels between 300 and 1000 Hz in the 1 m range recording. The 10 m and 25 m recordings also displayed these characteristics but with reduced signal to noise ratio and signal attenuation (Haris et al., 2023).

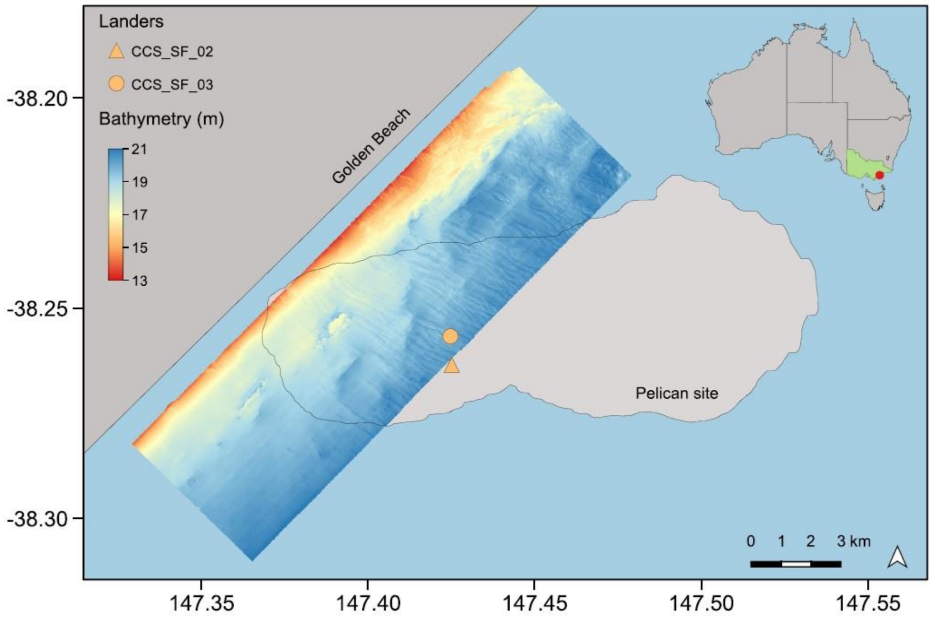

Figure 12: Top right corner shows map of Australia, state Victoria (light green shaded region), and Gippsland Basin (red dot circle). Main map is an enlarged view of study site showing locations of benthic landers with hydrophones. The subsurface geological Pelican storage site is marked. The bathymetry data were collected using a Kongsberg EM2040 multi-beam echo-sounder in the year 2017 (Haris et al., 2023).

12 GREENSANDS (2022)

Project Greensands is a collaboration between 23 Danish and international partners in the development of offshore transportation, storage and monitoring of carbon dioxide underground. As part of Greensands phase 2, a lander was developed for monitoring of marine carbon capture and storage facilities which held instrumentation for both acoustic and chemical monitoring as well as a battery and communication equipment (Roche et al., 2023).

Dockside testing of the lander was conducted Empress Dock, Southampton, UK over a two-week period in 2022. The active sonar used on the lander was a Kongsberg M3 multi-beam. A regulated amount of gas was released down a hose connected to a perforated pipe used to diffuse the gas. Initially gas flow was regulated to 2 L/min which was then increased to 5, then 10 L/min. the gas injection point was initially at a range of 20m which was then increased to 50 m and then 100 m. Figure 13 displays an example of swath data collected by the active sonar (Roche et al., 2023).
The testing demonstrated an ability for active sonar to detect gas plumes with flow rates as little as 1 L/min at a range of > 100 m (Roche et al., 2023).

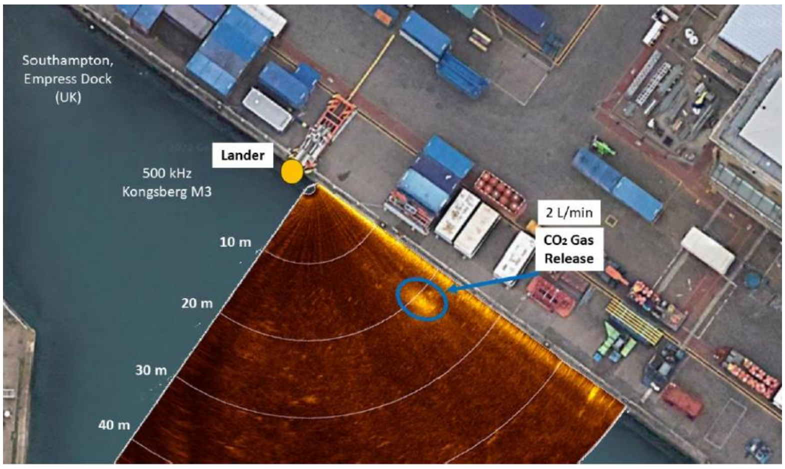

Figure 13: Acoustic swath data collected by the Greensands landers multi-beam echo sounder overlaid onto a map of the experiment site (Roche et al., 2023) .

13 CONCLUSION

This report details key datasets collected for subsea leak detection and the methods of collection. The report has also looked at how the data from each dataset was utilised and the key results.

Passive methods have been used for the quantification and localisation of subsea leaks. Hydrophones have been successfully used to detect and quantify single and overlapping bubble leaks in-situ in several instances e.g. Panera, Pelican site. ETI MMV applied passive acoustic arrays to localise leaks using beamforming (Dean et al., 2020). Further study is required to minimise uncertainties around leak quantification due to sediment noise, surfactants, and amplitude changes with depth. Further study is also needed to apply hydrophone arrays to extend the range of passive detection through the reduction of the impact of background noise.

Active methods have been shown to effectively detect leaks with some systems capable of providing approximate quantification using single-beam echo-sounders (Bayrakci et al., 2014). Further study could look into the effective distance of active detection and improved quantification abilities.

Further work also could include looking at the effect of gas species on quantification as well as the effect of depth on the sensitivity and effectiveness of acoustic detection and quantification. Application of machine learning models to passive and active acoustic data would also enhance the efficacy of acoustic monitoring.

14 ACKNOWLEDGEMENTS

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15 APPENDIX 1 – SUMMARY TABLE (ECO2, 2019)

Dataset	Dataset overview	Availability
Single hydrophone		
La Goleta	5 hour at 12 kHz sample rate recording of seep bubble formation at a distance of approximately 70 cm of natural methane seep. Dataset suffers from reduced signal to noise ration of bubble formations from the hydrophone being directly mounted to a submarine (Leifer & Tang, 2007b).	Not publicly available
QICS	Passive acoustic SM2M+ recorder at 48 kHz sampling rate deployed approximately 1m from the sea floor. 7 days of recorded during gas release and 7 days after experiment concluded (Flohr et al., 2021).	Available through the University of Southampton
Well site 22/4b	Data from two deployments totalling 10 months and at a depth of 112 m of static passive acoustic landers several meters away from a methane seep. Recordings split into 1GB 100 kHz .XWAV files (Wiggins et al., 2015).	Not publicly available
Pelican Site	Two years of ambient environment recordings at 48 kHz sample rate. In-situ gas release experiment hydrophone recordings at 1, 10 and 25m (Haris et al., 2023).	On Request (corresponding author - Haris Kunnath - haris.kunnath@csiro.au)
Hydrophone Array		
Panarea	Passive acoustic recordings taken 20 m from the exhaust from an underwater volcano near Panarea at a depth of 12.5 m. the lander used for recordings consisted of two hydrophones with a sampling frequency on 96 KHz (Li et al., 2020).	Available through the University of Southampton
STEMM-CCS	In-situ recordings from an array of 5 hydrophones deployed 3.3m away from a sub-seabed injection site in the North Sea (Connelly et al., 2022).	Available through the University of Southampton
ETI MMV	Two near shore trials of lander equipped with passive acoustic array (Dean et al., 2020).	Not Available – Industry Study
Active Sonar		
Northern Gulf of Mexico	Data from survey of northern Gulf of Mexico using single and split-beam echo-sounders. Raw data and echograms of two methane seep imaged with Simrad EK60 split beam echosounder operating at 18 kHz and 38 kHz (Weber et al., 2012).	Not made publicly available

Sea of Marmara	Simrad ER 60 echo-sounder using a frequency of 120 kHz from two deployments. A total of 4 recordings from each sector defined in the first deployment and 7 in the second (Bayrakci et al., 2014).	Not made publicly available
QICS	194 boomer and chirp profiles covering an area 600m by 400m centred on the diffuser location (Blackford et al., 2014).	Available through the University of Southampton
ECO2	Data from studies included 3-D seismic, bathymetry/backscatter and hydroacoustic surveys using sub-bottom profilers and multi-beam echo-sounders. Data from deployments over a year of lander equipped with multi-beam echo-sounders recording timeseries data of continuous seeps (ECO2, 2019).	Not available – confidential study
ETI MMV	Data collected from two near shore trials of MMV equipped with sidescan and a lander equipped with Sonardyne Sentry active acoustic sonar (Dean et al., 2020).	Not Available – Industry Study
STEMM-CCS	Data from deployments of AUV equipped with sidescan sonar and surveys conducted by ships of the area using multi-beam and single-beam echosounders (Connelly et al., 2022).	Available through the University of Southampton
Greensands	Echograms of gas flux from dockside tests at 20, 50 and 100m of range (Li et al., 2020).	Publicly available

16 REFERENCES

Bayrakci, G., Scalabrin, C., Dupré, S., Leblond, I., Tary, J.-B., Lanteri, N., Augustin, J.-M., Berger, L., Cros, E., Ogor, A., Tsabaris, C., Lescanne, M., & Géli, L. (2014). Acoustic monitoring of gas emissions from the seafloor. Part II: a case study from the Sea of Marmara. *Marine Geophysical Research*, *35*(3), 211–229. https://doi.org/10.1007/s11001-014-9227-7

Bergès, B. J. P., Leighton, T. G., & White, P. R. (2015). Passive acoustic quantification of gas fluxes during controlled gas release experiments. *International Journal of Greenhouse Gas Control*, *38*, 64–79. https://doi.org/https://doi.org/10.1016/j.ijggc.2015.02.008

Blackford, J., Bull, J. M., Cevatoglu, M., Connelly, D., Hauton, C., James, R. H., Lichtschlag, A., Stahl, H., Widdicombe, S., & Wright, I. C. (2015). Marine baseline and monitoring strategies for carbon dioxide capture and storage (CCS). *International Journal of Greenhouse Gas Control*, *38*, 221–229. https://doi.org/https://doi.org/10.1016/j.ijggc.2014.10.004

Blackford, J., Stahl, H., Bull, J. M., Bergès, B. J. P., Cevatoglu, M., Lichtschlag, A., Connelly, D., James, R. H., Kita, J., Long, D., Naylor, M., Shitashima, K., Smith, D., Taylor, P., Wright, I., Akhurst, M., Chen, B., Gernon, T. M., Hauton, C., … Widdicombe, S. (2014). Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage. *Nature Climate Change*, *4*(11), 1011–1016. https://doi.org/10.1038/nclimate2381

Connelly, D. P., Bull, J. M., Flohr, A., Schaap, A., Koopmans, D., Blackford, J. C., White, P. R., James, R. H., Pearce, C., Lichtschlag, A., & others. (2022). Assuring the integrity of offshore carbon dioxide storage. *Renewable and Sustainable Energy Reviews*, *166*, 112670.

Dean, M., Blackford, J., Connelly, D., & Hines, R. (2020). Insights and guidance for offshore CO2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects. *International Journal of Greenhouse Gas Control*, *100*, 103120. https://doi.org/https://doi.org/10.1016/j.ijggc.2020.103120

ECO2. (2019). *ECO2 Final Publishable Summary Report*. https://www.eco2-project.eu/ECO2(265847)%20Final%20Publishable%20Summary%20Report.pdf

Energy Technologies Institute LLP. (n.d.). *Measurement, Monitoring and Verification of CO2 Storage (MMV)*. Retrieved March 27, 2024, from https://www.eti.co.uk/programmes/carbon-capture-storage/measurment-modelling-and-verrfication-of-co2-storage-mmv

Flohr, A., Schaap, A., Achterberg, E. P., Alendal, G., Arundell, M., Berndt, C., Blackford, J., Böttner, C., Borisov, S. M., Brown, R., & others. (2021). Towards improved monitoring of offshore carbon storage: a real-world field experiment detecting a controlled sub-seafloor CO2 release. *International Journal of Greenhouse Gas Control*, *106*, 103237.

Gough, C., Shackley, S., Holloway, S., Bentham, M., Bulatov, I., McLachlan, C., Klemes, J., Purdy, R. W., & Cockerill, T. (2006). An integrated assessment of carbon dioxide capture and storage in the UK. *In: 8th International Conference on Greenhouse Gas Control Technologies [Proceedings] / [Edited by Greenhouse Gas Control Technologies. Trondheim, Norway : GHGT8*, *6*. http://nora.nerc.ac.uk/id/eprint/1524/

Haris, K., Shajahan, N., Bergès, B., & Kloser, R. J. (2023). Evaluation of passive acoustic methods for ambient noise baseline and gas flow rate quantification at a proposed nearshore carbon capture and storage site in Australia. *International Journal of Greenhouse Gas Control*, *129*, 103961. https://doi.org/https://doi.org/10.1016/j.ijggc.2023.103961

Leifer, I., & Tang, D. (2007a). The acoustic signature of marine seep bubbles. *The Journal of the Acoustical Society of America*, *121*(1), EL35–EL40. https://doi.org/10.1121/1.2401227

Leifer, I., & Tang, D. (2007b). The acoustic signature of marine seep bubbles. *Journal of The Acoustical Society of America - J ACOUST SOC AMER*, *121*. https://doi.org/10.1121/1.2401227

Leighton, T. G., & Walton, A. J. (1987). An experimental study of the sound emitted from gas bubbles in a liquid. *Eur. I. Phys*, *8*, 98–104.
Leighton, T. G., & White, P. R. (2012). Quantification of undersea gas leaks from carbon capture and storage facilities, from pipelines and from methane seeps, by their acoustic emissions. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *468*(2138), 485–510. https://doi.org/10.1098/rspa.2011.0221
Li, J., Roche, B., Bull, J. M., White, P. R., Davis, J. W., Deponte, M., Gordini, E., & Cotterle, D. (2020). Passive acoustic monitoring of a natural CO2 seep site – Implications for carbon capture and storage. *International Journal of Greenhouse Gas Control*, *93*, 102899. https://doi.org/https://doi.org/10.1016/j.ijggc.2019.102899
Malcher, F., & White, P. (2023). *Acoustic monitoring techniques for subsea leak detection. A review of the literature*. https://doi.org/10.47120/npl.AC21
NOAA. (n.d.). *Understanding Ocean Acidification*. Retrieved March 27, 2024, from https://www.fisheries.noaa.gov/insight/understanding-ocean-acidification
Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., John, S., Carol, T., Watson, A., Richard, H., Banes, R., & Quinn, R. (2005). Ocean acidification due to increasing atmospheric carbon dioxide. In *The Royal Society*. https://royalsociety.org/news-resources/publications/2005/ocean-acidification/
Rehder, G., Keir, R. S., Suess, E., & Pohlmann, T. (1998). The multiple sources and patterns of methane in North Sea waters. *Aquatic Geochemistry*, *4*(3–4), 403 – 427. https://doi.org/10.1023/a:1009644600833
Roche, B., Schaap, A., Morris, A., Bull, J., White, P., Eikeland, A., & Frederiksen, M. (2023). *Long-Term Monitoring of Relict Wells: the Development of a Real-Time Acoustic-Chemical Lander for Project Greensand*. *2023*(1), 1–5. https://doi.org/https://doi.org/10.3997/2214-4609.202321007
Waarum, I. K., Blomberg, A. E. A., Eek, E., Brown, J., Ulfsnes, A., Carpenter, M., Grimsrud, T. S., Park, J., Cornelissen, G., & Sparrevik, P. (2017). CCS Leakage Detection Technology - Industry Needs, Government Regulations, and Sensor Performance. *Energy Procedia*, *114*, 3613–3627. https://doi.org/10.1016/j.egypro.2017.03.1493
Weber, T. C., Jerram, K., & Mayer, L. (2012). Acoustic sensing of gas seeps in the deep ocean with split-beam echosounders. *Proceedings of Meetings on Acoustics*, *17*(1).
Wiggins, S. M., Leifer, I., Linke, P., & Hildebrand, J. A. (2015). Long-term acoustic monitoring at North Sea well site 22/4b. *Marine and Petroleum Geology*, *68*, 776–788. https://doi.org/https://doi.org/10.1016/j.marpetgeo.2015.02.011