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GipNet – Baseline environmental data gathering and measurement technology validation for nearshore marine Carbon Storage

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Abstract

The GipNet assets are the foundation to research programs for observations and instrument tests aimed at defining practical and relevant shallow-marine Measurement, Monitoring, and Verification (MMV) programs as the CCS industry considers shallow offshore waters in the Gulf of Mexico and other basins, as well as meeting the specifics of CarbonNet Project options. The CarbonNet Project is investigating large volume storage (nominal 125 million tonnes of CO_2 over 25 years) in shallow waters within 20 km of the coastline, offshore Gippsland Australia. GipNet will research the levels of various types of noise and natural variation against which one seeks to detect a positive signal, or confirm a null signal.

In the well-understood, high quality and thick reservoirs of the Gippsland Basin, plumes are expected to be very predictable, relatively thick, and easily observable with the right techniques such as timelapse 3D seismic imaging and downhole monitoring, but provision must also be made for unexpected outcomes and technologies sought that have low detection thresholds to identify thin or diffuse plume offshoots or early warning of unexpected plume movements in order to provide assurance of storage security.

CarbonNet seeks to validate at this pre-commercial stage, an appropriate, but not excessive, range of measurements to characterise the pre-existing environments. For each proposed technology, the physics of detection was reviewed, as well as the practicalities of deployment in the shallow-water and nearshore environment with multiple sources of 'noise', of initial research and test instruments and later detection systems appropriate for a commercial project. Most importantly, each MMV technology was assessed for its value in monitoring CO_2 storage Integrity, Conformance and Assurance and adding to the proven technologies of 3D seismic and downhole monitoring.

Three key technologies were identified for trial deployments and further testing:

1. Natural Seismicity Monitoring Network
2. Atmospheric Monitoring
3. Baseline Marine Monitoring

In determining funding, the physics of detection for each proposed technology was reviewed, as well as the practicalities of deployment in the shallow-water and nearshore environment with multiple sources of 'noise', of initial research and test instruments and later detection systems appropriate for a commercial project. Most importantly, each technology was assessed for their value in monitoring CO2 storage Integrity, Conformance and Assurance.

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Keywords: CO_2 Storage; Marine Monitoring; MMV; Shallow water; Natural Seismicity; Atmosphere; Ocean; Baseline; Noise; Variation

1. Introduction

International Carbon Storage projects rely on Monitoring (MMV) to show that storage containment is being achieved and that unwanted migration of CO_2 does not occur. To date, projects have either been entirely onshore, or in distant "blue water" locations far from shore, with relatively deep water (100m or more). The testing and development of MMV methods has therefore been optimised for the characteristics of these wholly onshore or far-offshore sites. However, in many geological basins, attractive storage opportunities exist in shallow nearshore waters which will require a different selection of cost-effective MMV technologies. Examples include the USA Gulf of Mexico, The North Sea (especially on the European side), and offshore basins of China such as Bohai Bay, Donghai, and Nanhai.

Shallow water and nearshore locations offer lower facilities cost and significantly shorter pipelines than blue water locations, and also offer less land use competition and stakeholder interests than onshore locations. However, some established technologies may not work well in shallow water and in some areas, sensitive littoral environments are vulnerable to impact from activities, so technology needs to be optimised for this type of operating environment with minimal impact.

The CarbonNet Project [1] is investigating exactly this combination of circumstances, seeking large volume storage (nominally 125 million tonnes of CO_2 over 25 years) in shallow waters within 20 km of the coastline, offshore Gippsland Australia (Figure 1). This paper summarises plans to prove technologies for a range of pre-commercial measurements of the variability of natural “baselines” of the concentration and composition of atmospheric and water column CO_2 and related gases and chemical species, and of the natural background of earthquake activity or (micro-) seismicity. Further detail is contained within the reference report published by GCCSI [2]. The outcomes of the GipNet trials will shape not just the CarbonNet MMV plans, but will also significantly inform MMV plans in future international nearshore/shallow water projects.

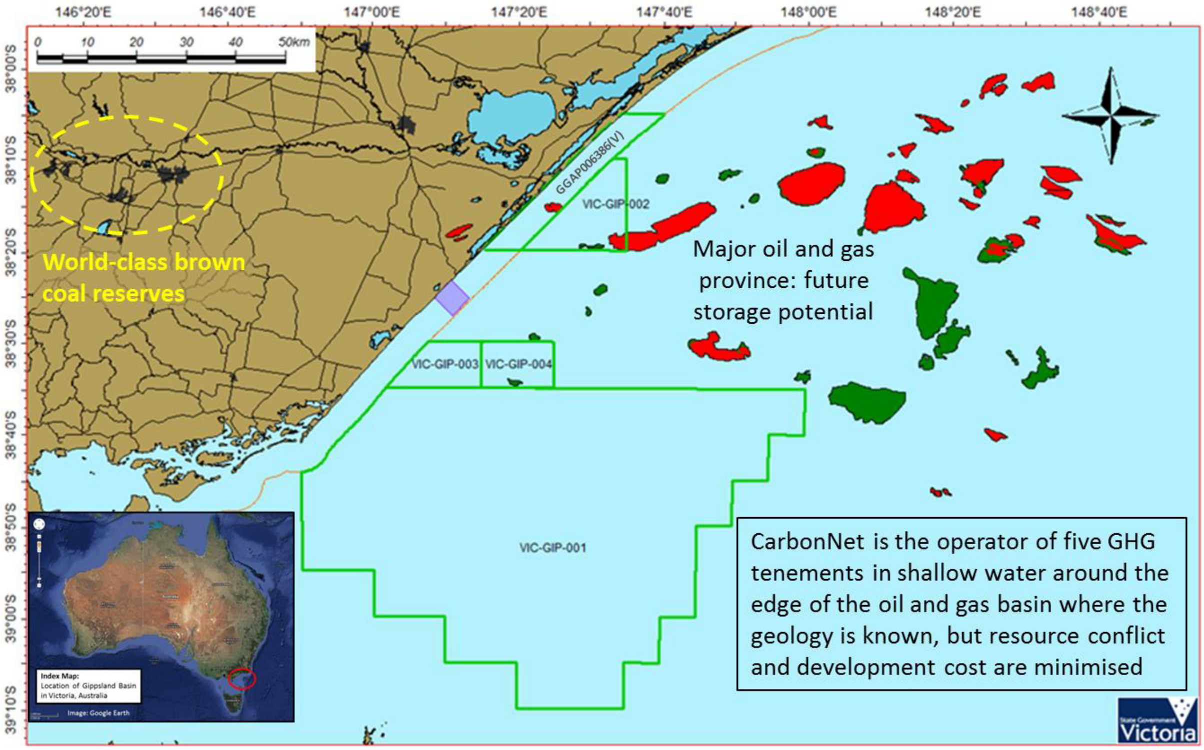

Figure 1: Location of CarbonNet GHG Assessment Permits

Storing CO_2 at CarbonNet sites is considered to be low risk due to multiple proven seals, good reservoirs with excellent pressure buffering capacity and well-defined structural geometries, all proven by extensive local and regional well and seismic data. However, it is necessary to continually work to reduce and manage any residual storage risks. A critical part of risk reduction is the continuous application of a site monitoring program, matched to a probabilistic expectation of plume paths through time [3].

A very useful summary of the progress of monitoring and verification [5] covers the decade since the publication of the IPCC Special Report on CCS [4]. For our current purposes, we note that monitoring activities can be separated into three categories: operational, verification, and assurance monitoring. Operational monitoring focuses on monitoring day-to-day injection operations to ensure the facility functions within specified safe-operating ranges and maintains accurate injection volume data. Verification monitoring provides confirmation that the CO_2 remains contained within the storage complex and also tracks the accumulation development over time. The goal of Assurance monitoring is to monitor the surface and near-surface to demonstrate the absence of any changes that would occur in the event of CO_2 migration towards the surface.

The technology and application of Measurement, Monitoring, and Verification (MMV) are both important. Sensors need to be able to be deployed at locations and times where they might observe the injected CO_2, and be sensitive directly or indirectly to the chemical, physical, or biological effect of the presence of CO_2. Changes may be observed in rock/fluid physics, in chemical composition, or of biological communities as a reaction to those underlying physico-chemical changes.

As examples of technologies that have been examined, but assessed as less prospective in the context of the measurement environment: Conventional gravity is too insensitive in the marine environment to return useful definition of where the plume might sit, although experiments at Sleipner have shown that it may have some value in very approximately measuring the total injected volume. Similarly, resistivity measurements are constrained in this basin because the formation water of the Latrobe Group out to 20-40 km offshore is low salinity [6]. If the formation water were significantly saline, it would be a good conductor and exhibit a resistivity contrast to non-conductive

CO_2, however, low-salinity water is difficult to distinguish from low-conductivity fluids like CO_2 or hydrocarbons. Therefore, the current understanding is that many conventional well log techniques offer low-resolution of plume presence or movement, as do cross-well tomography or magnetotellurics.

At the CarbonNet sites (the CarbonNet permits are shown in Figure 1), high porosity reservoirs at relatively shallow burial depths (1 km) have an excellent acoustic response to gas or supercritical CO_2 present in the pore space, as is shown by the strong DHI effects at nearby gasfields at equivalent depths [7]. Gassmann fluid substitution analysis demonstrates that the plume will be clearly visible on seismic data at the depths of interest [8]. The principal tool chosen for long-term plume monitoring is timelapse 3D seismic, as deployed for the Sleipner project [9, 10]. CarbonNet has invested significant effort [2] to demonstrate that the plume will remain at all future times, at high probability (95% or more), within areas that can be imaged directly by conventional marine streamer 3D acquisition (water depth limited at approx. 15m)

However, assurance monitoring also requires techniques that could detect changes over a wider area, if any were to occur, and the technologies that are used ideally need to have low detection thresholds to identify thin or diffuse plume offshoots or to give early warning of unexpected plume movements in order to provide assurance of storage security. At the same time, a statistically robust method of analysis is required that reduces the number of "false positives" that could raise concern without a genuine underlying cause [11, 12].

Earthquake activity is also noted in the Gippsland region, albeit at relatively low levels, and understanding the pre-existing distribution (spatial, temporal, and magnitude) is important to demonstrate that natural earthquakes will have no effect on CO_2 storage – a likely outcome, since oil and gas has been safely stored offshore for millions of years, despite ongoing earthquakes. Additionally, a future project must demonstrate that the geomechanical context of that site will permit operations at the scale and timeframe planned, without appreciable induced earthquake activity.

A robust monitoring and verification program over a range of techniques may include monitoring of specific targets in the marine environment (seabed and water column), the atmosphere, and the stress and strain environment (micro-earthquakes), if technologies can be validated for cost-effective and informative data acquisition. Confirming storage containment and conformance will probably be achieved by deep surveillance methods, thus the function of near-surface monitoring will largely be for confirming that environmental impact has not occurred (assurance monitoring). Some specific leakage risks, for example defective wellbores, might be effectively monitored by methods operating in the water column or at the seabed, local to the known wellhead. In general, environmental impact monitoring may be useful for securing social licence when the storage sites are close to land and the area has multiple uses. Such assurance could potentially be established by high- precision measurement techniques deploying sensors on a range of platforms that provide adequate spatial and temporal coverage of key parameters, but the usefulness of this approach remains to be demonstrated by the research proposed here.

Designing cost-effective methods for implementing such a monitoring program is an active area of research and off-the-shelf solutions are still several years away. Overseas examples of offshore storage (at Sleipner and SnØvit) have implemented some aspects of monitoring (mainly seismic) and have experimented with some environmental monitoring. These sites are located in deeper waters (>100m deep) than those under consideration in Bass Strait by CarbonNet where water depths in the areas of interest are generally less than 45 metres, and so further research is likely to yield methods better suited to shallow waters.

The nearshore offers some challenges with respect to monitoring in the sense that assurance monitoring techniques intended to detect shallow leakage have not been tested for effectiveness in a similar littoral environment where physical constraints exist for deployment, and distinct sources of 'noise' or interference exist to the various technologies. Therefore, field testing of monitoring techniques is appropriate to document evidence that local conditions do, in fact, allow monitoring that is capable of detecting deviations from eventual planned operations.

In 2013, the CO2CRC secured a grant of $51.6 million from the Australian Government's Education Investment Fund for research assets. It has used some of this grant to fund the development of monitoring and verification technologies with its partner research institutions (CSIRO and the University of Melbourne). A criteria for funding was that the proposal was aligned with the priorities of CCS Flagship projects of which CarbonNet is one. A subset of funded assets is called GipNet, to be deployed in the local context of CarbonNet potential storage sites.

The GipNet assets are the foundation to research programs for observations and instrument tests aimed at defining practical and relevant shallow marine Measurement, Monitoring, and Verification (MMV) programs as the CCS industry considers shallow offshore waters in the Gulf of Mexico and other basins, as well as meeting the specifics of CarbonNet Project options.

Three key technologies were identified for trial deployments and further testing:

1. Natural Seismicity Monitoring Network managed by the University of Melbourne (UoM)
2. Atmospheric Monitoring managed by UoM
3. Baseline Marine Monitoring managed by the CSIRO

GipNet research seeks to define at this pre-commercial stage, an appropriate, but not excessive, range of measurements to characterise the pre-existing environments. In determining funding, the physics of detection for each proposed technology was reviewed, as well as the practicalities of deployment in the shallow-water and nearshore environment with multiple sources of 'noise', of initial research and test instruments and later detection systems appropriate for a commercial project. Most importantly, each technology was assessed for its value in monitoring CO_2 storage Integrity, Conformance and Assurance.

2. Context

The nearshore Gippsland Basin is well understood from an ecological and geomorphological perspective in a regional context. In environmental terms, a high-energy marine shoreline defines a barrier-bar system with a variably saline lake system trapped behind it. The sea bed is predominantly sandy with some hard rock outcroppings of lithified dune and marine sands and localised bioherms that are often referred to as "reefs", but are not corals. The area is predominantly rural with small townships and summer vacation properties dispersed along the coast and agricultural land use, with a major oil and gas processing plant nearby at Longford and large coal mines and electricity generating stations further afield in the Latrobe Valley.

The Gippsland Basin [13] (has a two-stage extensional history [14, 15, 16, 17] as a rift on the southern margin of Australia, in the Late Jurassic to early Cretaceous (Figure 2, modified after [18]). This initial rift stage saw the deposition of a thick sequence (3-8 km) of volcaniclastic sediments in east-west or NNW-SSE tending grabens. A Cenomanian unconformity preceded the second generation rift in the Upper Cretaceous, on east-west faults. Over 5 km of post-Cenomanian sediments have accumulated in these rifts in a dominantly terrestrial and retrogradational depositional system [19]. A paralic facies has backstepped across the basin sweeping a facies belt of high-quality beach and barrier-bar sands across the basin. This is capped after a condensed section with excellent quality smectite-bearing marls which form the regional petroleum seal. Additional intraformational seals are associated with shale and coal units, ponded behind the barrier bar system. In the Oligocene, cool-water marine carbonate deposition commenced [20] , and an extensive shelf sequence of 1-2 km built out over former deep water.

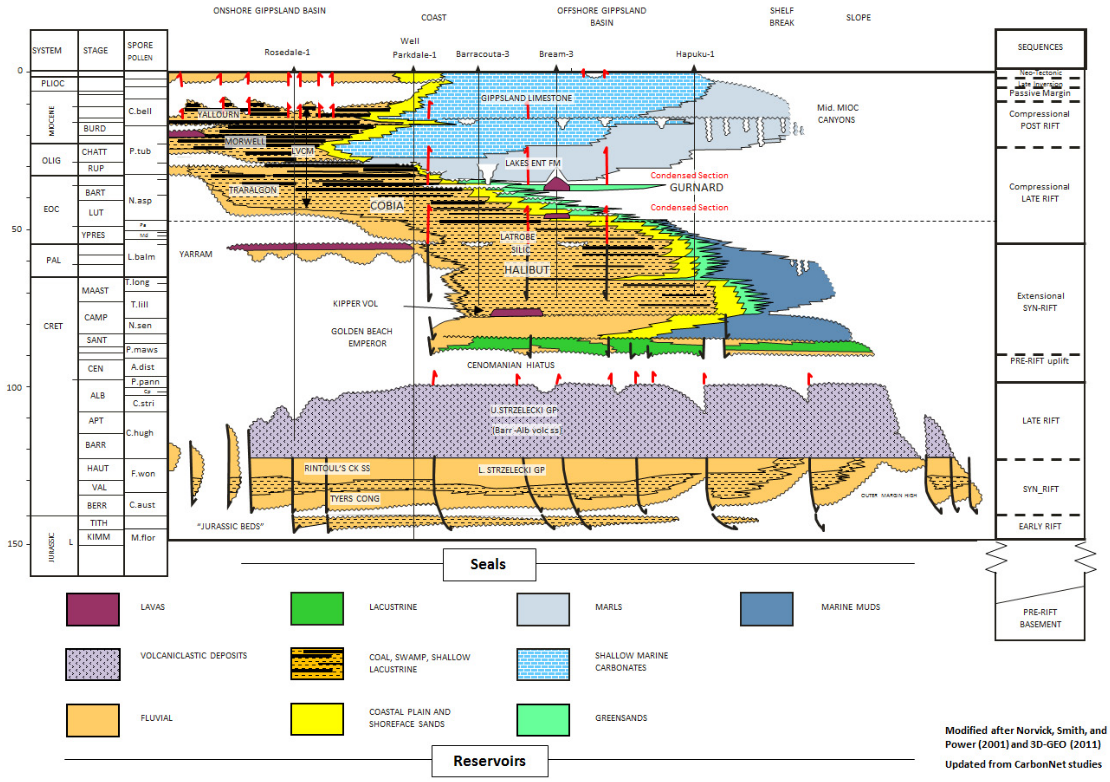

Figure 2: Gippsland Basin Chronostratigraphy and Tectonics

The Chronostratigraphic diagram illustrates the depositional environment and facies of rocks deposited from Cretaceous to modern times in the Gippsland Basin, projected onto an axis running WNW to ESE – approximately depositional dip direction. Sediments are supplied from highlands to the south (Tasmania) and North (the great Dividing Range). Black arrows are extensional tectonic events, red are inversion (uplift) events. The present-day is a time of continuing inversion, especially onshore.

3. Natural Seismicity Monitoring Network

The proposed GipNet Seismic network will involve deployment of surface deployable onshore seismometers, shallow borehole seismometers and shallow-water (<100m) Ocean Bottom Seismometers (OBS) in the region of potential nearshore storage sites in the Gippsland Basin.

The network will enable monitoring background seismic activity and other 'noise' sources in the region of prospective storage sites and any induced seismic events that might occur as a consequence of future injection activities. Hence, although largely an assurance monitoring method, there may be some insights into containment and plume conformance – but only in a minority of cases where detectable events are triggered. It is far more likely that no storage-related events will be recorded and that the network will prove to be of research and assurance value only. The infrastructure will facilitate research into the state of stress and controls on seismic energy release in the region, and a variety of associated geophysical properties such as crustal and basin velocity structure, and attenuation properties. An important research objective is to determine protocols for seismic monitoring of CCS in complex, noisy settings such as the Gippsland Basin.

3.1. Tectonic evolution and Seismological Background

After the initial two-stage rifting of the Gippsland Basin, a series of structural inversion episodes began in the Eocene, with a NW to NNW strain axis which have led to structural growth on inverted east-west normal faults. Depositionally-thickened grabens have been inverted to give E-W and SSW trending anticlines in the offshore and dominantly SW-trending structures in what is now the onshore. These inversion structures include the oil and gas fields offshore, the Strzelecki ranges onshore, where Cretaceous sediments outcrop in hills ranging to 740m elevation, and areas of more subtle inversion where thick Neogene lignites subcrop at shallow depth, forming an important economic resource.

The onshore area is still moderately seismically active (Figure 3), with events to a maximum just over 5 being recorded over the past 50 years [21, 22, 23]. The Strzelecki Ranges are quite active relative to other stable continental regions [24]. A >100-year record of significant felt earthquakes is available from widespread population centres.

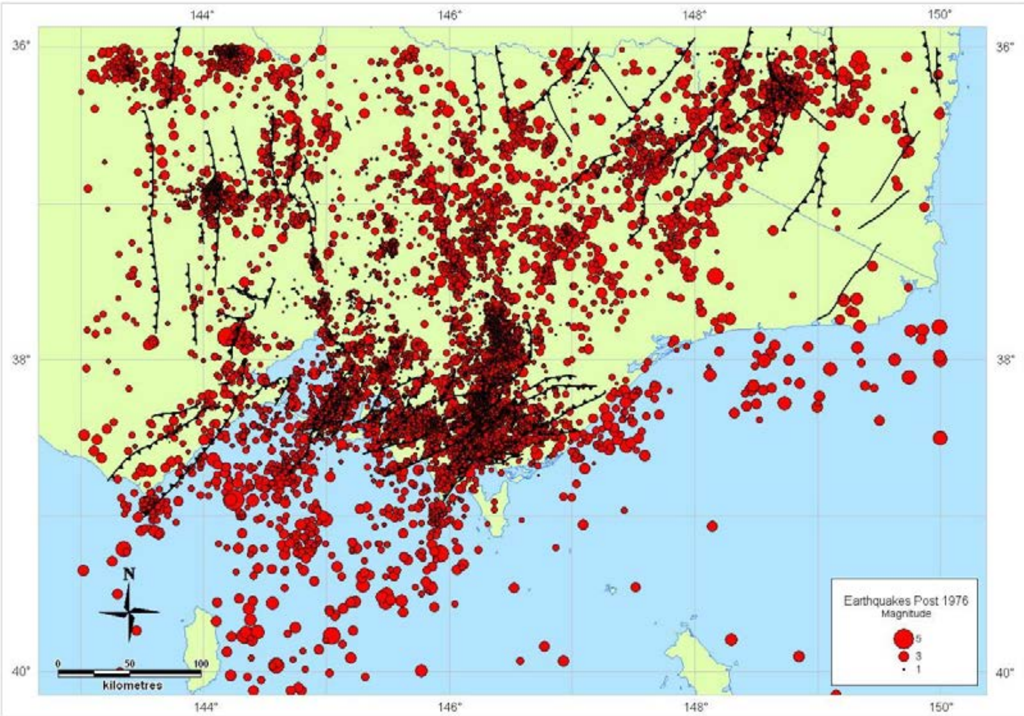

Figure 3: Earthquakes since the start of 1976 in SE Australia.

The regional tectonic stress in the Gippsland Basin is dominantly horizontal compression with minimum principal stress vertical, giving reverse faulting [25, 26, 27]. In the Gippsland basin, the modern maximum compressive stress is oriented NW-SE.

Rocks are relatively strong under compression, so high stress values (high density of stored tectonic strain energy) are required before compressional failure. The earliest failure occurs on optimally oriented oblique fractures where the stress exceeds the Mohr-Coulomb criterion. In the Gippsland Basin, the upper several km of sediments are relatively weak, and are not so highly stressed but nonetheless, earthquake hazard studies need to consider natural tectonic earthquakes, and those involving fluid injection or significant fluid production must also consider the possibility of triggered earthquakes since increasing pore pressure can lead to a previously stable situation exceeding the Mohr-Coulomb limit.

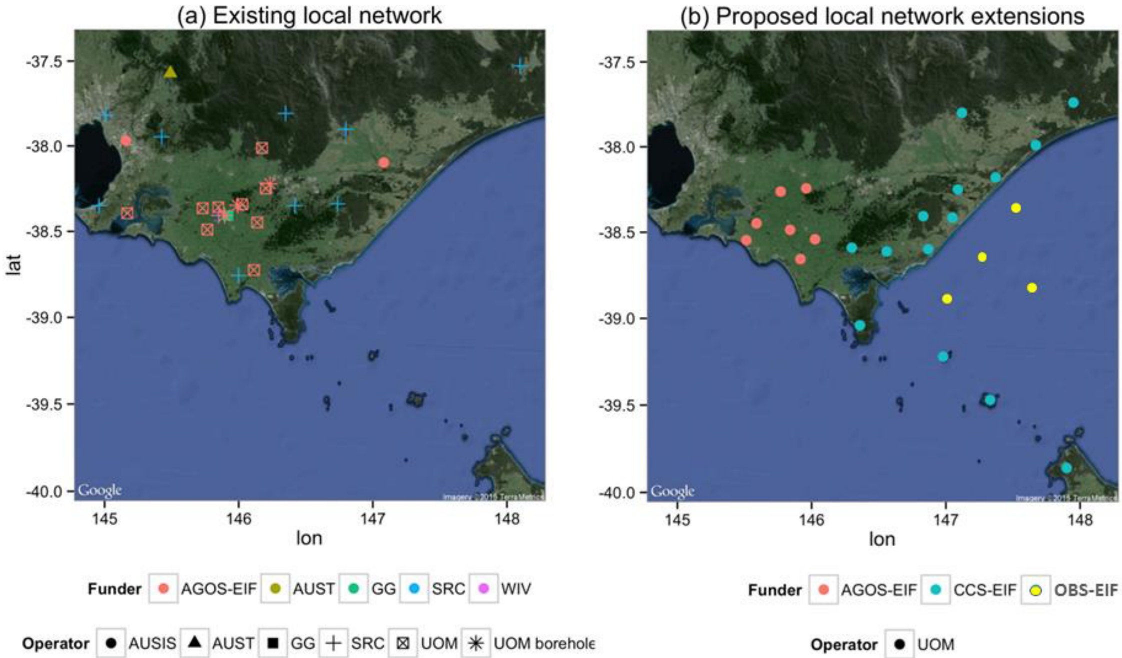

Figure 4: Existing (a) and proposed future (b) seismology monitoring networks

Local seismographs were installed in eastern Victoria from 1976 to 1990. Figure 4 shows the existing and proposed local network onshore component of the GipNet deployment shown in blue, offshore OBS locations in yellow, and proposed extensions of the AGOS network in orange. In addition to the sites shown here, the GipNet proposal will add part of a micro-earthquake network array in the coastal zone as determined by ongoing CarbonNet evaluation of potential storage sites.

The existing AGOS network includes micro-earthquake networks about Thomson and Dartmouth Dams, and a small network in the Strzelecki Ranges, allowing location of many more events with smaller magnitude. The dense activity centred about the Strzelecki Ranges compared with northeast Victoria is partly due to the better seismograph coverage allowing location of smaller earthquakes.

Coverage of the Gippsland Basin improved after the installation of more seismographs in the Strzelecki Ranges in 2000. Most of the activity recorded off the coast has been enabled in the past few decades by improvements in network coverage and sensitivity. The offshore locations are imprecise because they lie outside the network, but small events can be identified and approximately located, and there are many more smaller earthquakes than large as predicted by the Gutenberg magnitude-frequency scaling principle.

The offshore Gippsland Basin region in eastern Victoria, to the east of Wilson Promontory and north of Flinders Island, has a moderate level of known seismicity. There is a region of very low activity immediately northeast of Wilsons Promontory, a belt of higher activity 20 to 30 km off the Ninety Mile Beach, a zone of low activity south of Bairnsdale, then a region of enhanced activity from the coast to 40 to 60 km offshore to the NSW border. These belts are associated with the subsurface traces of known major E-W basement faults, fundamental to the architecture of the Gippsland Basin.

Because the seismic network covering the offshore and nearshore Gippsland Basin is very sparse compared with the network now operating in the Strzelecki Ranges, the marked difference in seismicity levels between the two regions likely over-emphasises the difference. There is very limited seismograph coverage about the proposed site between Wilsons Promontory and Sale, in East Gippsland, and no seismographs in Bass Strait or on Flinders Island.

The coverage of the basin is only complete for earthquakes with magnitudes above about ML 2.0, with the locations of individual events too poorly determined to explore any significant spatial relationship to the geology. The proposed network will both improve the quality of locations and significantly increase the number events recorded and accurately located. Given the recurrence period of earthquakes in this area, a timeframe of several years is desired to determine natural earthquake statistics.

3.2. Seismic Noise

Design of a seismograph network must consider the seismic noise that will be experienced, relative to the earthquake signals that will need to be recorded. Factors to consider include noise sources (wind and ocean waves, nearby machinery such as pumps), traffic, animals, etc. Some noise sources are continuous and others are transitory at various scales from passing of a storm or vehicle to the impact of a slamming door.

The local geology also is a major factor, with noise on the outcrop of strong rock, firm rock or soft rock being quite different in amplitude and character, especially with respect to the wave motion frequency.

The best measure of the significance of noise is the signal to noise ratio, best given as a function of frequency. The signal to noise ratio might be improved by increasing the signal, which for a seismograph network is done by using a high resolution network with seismographs relatively densely spaced so that the earthquake is surrounded by instruments at distances close enough that each gives a high amplitude signal. Depending on the magnitude of earthquakes under investigation, a network spacing of several km to several tens of km is ideal.

The signal to noise ratio can also be increased by decreasing the noise level, especially by installing seismometers in boreholes at depths beneath the surface wave noise. For strong rock sites (e.g. basement outcrops) this is often not necessary, but for weaker sedimentary rocks with high frequency surface wave noise, a shallow borehole depth from a couple of metres to tens of metres can be useful.

The noise due to ocean waves is most significant for nearshore seismometer sites, and particularly for Ocean Bottom Seismometers in shallow waters, but if the distance to the earthquakes concerned is very short, then the signal to noise ratio may be adequate. As part of the GipNet asset deployment strategy, noise levels will be measured, and sites selected on the basis of adequate signal to noise ratios for events of the scale being monitored.

3.3. Potential for Induced Earthquakes

Earthquakes can be triggered by a variety of mechanisms, including by fluid injection and/or extraction, possibly including CCS [28, 29, 30]. One major factor in the response to injection is the ability of the aquifer to buffer local pressure changes and disperse them across the basin at low intensity. The Latrobe offshore aquifer is very active [31] and is highly effective in dispersing local pressure changes due to both abstraction and injection. In the 50+ years of high-volume oil and gas production in the Gippsland Basin there has been appreciable regional pressure draw-down of the offshore aquifer. Up to 120m hydraulic head reduction is reported in the vicinity of the major oilfields in the Central Graben [6], and 10-30m hydraulic head at the coast, but no induced seismicity has been recognised.

Local studies of fault reactivation potential [27] suggest that the strong aquifer support diminishes the risk of induced seismicity in this basin. CarbonNet studies show that the pressure increase due to injection operations will be very modest (0.6 Mpa for 125 Mt injection over 25 years) and beyond a near-field of a few km, the pressure “increase” will actually be realised as less drawdown against a background of large-scale fluid extraction from the aquifers for petroleum and agricultural purposes.

The proposed monitoring network would extend the existing seismograph network to give local coverage for the Gippsland Basin region, and to include a smaller scale micro-earthquake seismograph network around potential CarbonNet site(s) that should allow location of earthquake epicentres and depths to better than ±1km.

3.4. Proposed Seismograph Network Design considerations

Nearshore measurements will be strongly affected by surf noise and the ground conditions of soft dune sands. It will be important to characterise that noise and its variability in time and space so that noise floors can be established for different locations and weather conditions. It is important to investigate methods for equipment installation that minimise noise (e.g. cemented into shallow boreholes, local noise-cancelling arrays, etc.).

Shallow marine Ocean Bottom Seismometers (OBS) will also be subject to weather and tide/current noise and will have limited endurance of a few months on each deployment, unless surface data readout and power supply is incorporated in the design for a new generation of shallow marine OBS. It is not yet clear whether nearshore land installations and marine OBS deployments will allow a significant catalogue of events to be recorded, and modelling of the probability of useful detection is underway. Therefore, the sources of and level of pre-existing seismic noise in the nearshore needs to be catalogued as part of the research. The study will:

1. establish the protocols for instrumentation and network design for base-lining and monitoring in noisy storage offshore sites such as the proposed sites in the offshore Gippsland Basin.
2. better characterise the low-level natural seismicity in the Gippsland Basin and the state of stress by resolving many more focal mechanisms.
3. be used to estimate the hazard to the storage site due to normal earthquake activity;
4. assist in validating the likelihood of triggered earthquakes and their effects.

This proposal includes two complementary sub-networks with different aims, one based on a local scale covering the entire nearshore and offshore Gippsland Basin, and the other on a micro-earthquake scale covering parts of the Ninety Mile Beach coastline relevant to CarbonNet potential storage sites. The networks will complement and extend the range of existing Australian Geophysical Observing System (AGOS) deployments in Strzelecki Ranges in the onshore Gippsland Basin.

3.5. Micro-earthquake Network Details

An additional high-density network with seismograph spacing of five to ten kilometres will be specially designed to monitor earthquakes near to location(s) of interest. The instruments will use higher sample rates to record the higher frequency seismic waves from any nearby earthquakes. These frequencies will be higher than those from most natural wind and wave noise.

The magnitude for complete coverage depends on the area being covered, natural noise levels, and the density of the seismometer coverage. Local noise is mainly due to ocean waves and winds and varies with weather patterns, and is accentuated by soft surface sediments. Ocean currents introduce additional noise for OBS systems.

The micro-earthquake network should nonetheless allow location of all earthquakes within the network down to about magnitude 0.0 during quiet sea surface and wind periods, but deteriorating significantly during storms and high seas.

4. Atmospheric Monitoring

Atmospheric monitoring is principally an assurance monitor. It does not inform upon deep containment for which other primary monitoring technology may be deployed. CO_2 concentration in the atmosphere exhibits significant diurnal, tidal, seasonal, annual and decadal fluctuations due to its involvement in ecosystem sources and sinks and, to a lesser extent, to anthropogenic effects. Quantifying the pre-existing natural range of variation - often simply but misleadingly called a “baseline”- is one of the significant challenges of atmospheric monitoring. A multi-year database of these fluctuations is normally required to disentangle climatic forcing, ecosystem changes, and anthropogenic effects. This is clearly much easier if commenced prior to site injection operations since the background or baseline can then be established with confidence that no injection-related effects are contained in the observations. Constraints can then be set, based on that observed natural variability, to determine what magnitude of event could actually be detected. Isotopic typing of the gases is a powerful tool to assist in identifying fossil-fuel related carbon from modern atmospheric and biogenic carbon, but allowance must be made for other industrial sources of fossil carbon, such as the relatively local gas plants processing offshore oil and gas, the more distant coal mines and power stations, and any agricultural activity involving fossil carbon.

The inversion of atmospheric concentration data to develop source/sink models is a well-developed area of research, on scales from global to regional [32]. However these methods need to be adapted to the particular circumstances of CCS to become routine monitoring tools. In an early review [33], the options for atmospheric monitoring for CCS were set out; some helpful, more general ideas about surface monitoring were developed by [34]. Trials were made at the Ginninderra controlled release site [35]. Results from the CO2CRC Otway storage site [36, 37, 38], have been described for a single-station, concentration sensors [39, 40].

For this study, an open-path measurement system will be established for atmospheric trace gases and isotopic composition of CO_2. The research aims to:

1. Design and install an optimal network combining open path and in-situ measurements to monitor sources and sinks of CO_2 in the region of the proposed storage
2. Characterise the pre-existing natural fluctuations of $CO_2$for the region (i.e. the “baseline”)
3. Attribute any significant changes in local sources or sinks to oceanic or biogenic sources and identify, with 95% probability, whether they are due to the storage infrastructure

The research program will monitor CO_2 in the region, characterise the natural variability in atmospheric concentration and isotopic ratios, and characterise the baseline CO_2 fluxes for the region. In the future, project MMV can then attribute any changes in local sources or sinks to natural oceanic or biogenic sources or conversely identify whether they are due to the storage infrastructure

The coastal region is a relatively low-density populated region, but hosts significant summer vacation activity, farming, and boating, which may disturb installed equipment and lines of sight. Atmospheric impacts of open fireplaces, vehicle exhausts, and recreational activities need to be considered, as well as atmospheric drift from the nearby hydrocarbon processing plant and industrial sources further afield. The open-path network will trial measurement over both onshore and marine paths, with strategically-placed retroreflectors and establish whether shore-based marine atmospheric measurements are practicable in the presence of marine aerosols and other complications.

Developments in both models and instrumentation in the last 15 years have allowed a tremendous refinement of both scale and precision for these techniques.

- Atmospheric models are now routinely coupled or driven by high-resolution weather forecasting models with detailed and accurate representations of atmospheric transport
- Precise, stable and field deployable instruments, using modern spectroscopic techniques, have greatly democratised the task of making good concentration measurements
- Measurement costs have reduced by 1-2 orders of magnitude; especially the recurrent costs.

These developments have spurred new applications of these techniques to regions and even point sources.

4.1. Importance of larger scale networks

A problem with atmospheric methods is always the spatial attribution of any source. In a simple case where we can guarantee to measure up and down wind of a source this is easy but the advent of variable winds and spreading plumes of tracer from a priori unknown sources means the ideal case is rare. We must therefore characterise the background concentration which affects the measurement site but does not arise from the sources of interest. Here we face a trade-off. The more focused the measurement and modelling domain the more precise the inferences that can be drawn on location and magnitude of a source but the greater the influence of these background concentrations. These background concentrations must either be estimated or measured. We propose to use an intermediate observing network to refine global satellite observations to the scales we need. This network is provided by a baseline network for the Latrobe Valley funded by AGOS and currently being deployed.

4.2. Open Path and in-situ Methods

Most methods for measuring greenhouse gases in the atmosphere are spectroscopic and based on absorption. They are usually differential, using either a range of neighbouring wavelengths (with a range of absorption strengths) or a reference sample of air with a known concentration of the target gas. This is necessary because many other properties of the atmosphere can affect transmittance and these must be cancelled. A key division is into open path or closed path methods. The most common closed path or in-situ methods pump air samples into a cell and apply some spectroscopic measurement technique within the cell. Alternatively, the absorption of radiation can be measured along an open path in the atmosphere.

Satellites use reflected sunlight to measure the absorption on a two-way path from the sun through the atmosphere to the earth's surface and back to the satellite. A ground-based instrument pointed at the sun can measure the one-way absorption. This simplifies the atmospheric retrieval since light scattered by aerosols is not observed rather than contaminating the two-way path. A disadvantage of both of these vertical path methods is that much of the light path traverses a near constant field of the tracer in the middle and upper atmosphere reducing sensitivity to the lower atmosphere and consequently to local sources and sinks.

The open path method can also be applied with an artificial local source. This can be a laser or a polychromatic source. The same methods and instruments are used as for solar sources. An important difference is that the path can be near-horizontal, restricting the measurement to the most important lower layers of the atmosphere. The common technique is to co-locate the source and instrument and use a series of retro-reflectors to construct the two-way paths. An advantage is that, with automated pointing mechanisms, a single instrument can be used to sample many paths, with only the inexpensive retro-reflectors being duplicated.

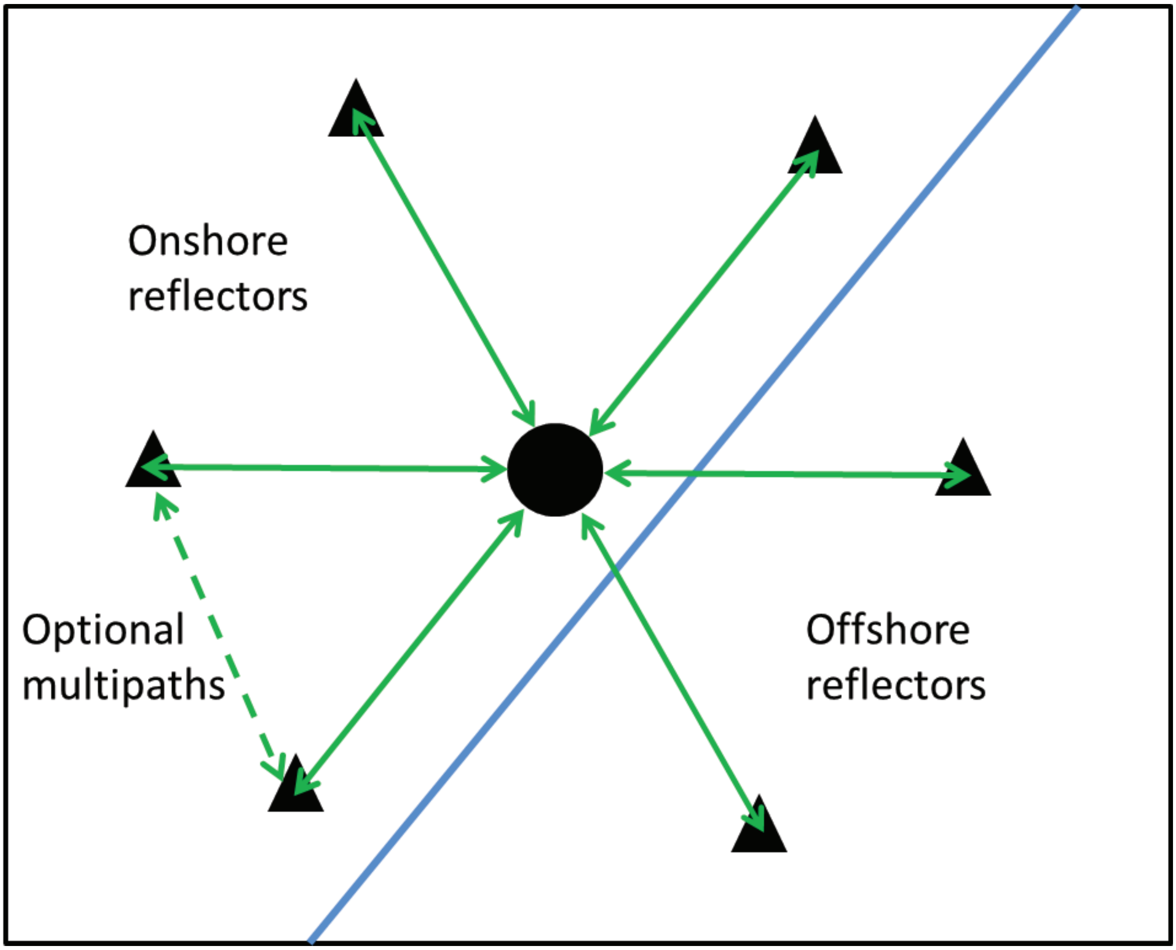

Figure 5: Open-path baseline concepts

Figure 5 shows the design concept for the proposed open-path atmospheric monitoring. A base station (circle at centre) has the optical transmitter and receiver and can be aimed at several different onshore or offshore retroreflectors (triangles) in line-of-sight. Optionally, a more complex multipath can be configured if the end-point stations are steerable reflectors rather than simple retroreflectors.

4.3. Limitations

The in-situ method measures concentration at a point. If sources are long-lived compared to changes in wind direction and speed then the meteorology acts as a differential sampler providing information on the spatial distribution of sources and sinks. This requires that we can measure at high frequency (e.g. minutes - hours) with the limit set by the fidelity of our wind model.

A limit of in-situ measurements is the restricted volume of the atmosphere which is probed. If the wind does not advect air from a source to a measurement site then we can gain no information about it. Open path measurements ameliorate this problem by making measurements (albeit at reduced sensitivity) of larger air masses. Not only does this weaken requirements on the connection between sources and measurements it also softens the demand on the model since modest errors in transport modelling may well simply relocate a given air mass along the observed path rather than switch its state between observed and unobserved.

Although all atmospheric techniques are able to quantify sources remotely (with information carried by atmospheric transport) the diffusive nature of this transport means information is lost relatively quickly with distance. Thus, if the region near the putative source is inaccessible (e.g. offshore) then we may get little information on that source. Horizontal open path methods can potentially measure concentrations closer to inaccessible sources including directly overlying a potential offshore source.

Open path atmospheric monitoring allows improved assurance monitoring of the successful storage of CO_2 over a wide area of observation. It will also allow overall monitoring of the local natural carbon cycle to demonstrate that it has not been perturbed by the project.

An obvious disadvantage of open path methods is that they do not locate a concentration anomaly precisely, although developing tomography techniques at University of Wollongong (UOW) and Geoscience Australia have improved this capability recently. In principle, for a horizontal path measurement, the concentration anomaly can occur anywhere between source and reflector. There are multiple approaches to dealing with this:

- Use whatever prior information we have on likely source locations. This is particularly relevant to a CCS application.
- Use multiple paths to triangulate the source, at least approximately. As already mentioned the ability to use one instrument for many paths makes this approach cost effective.
- Use knowledge of atmospheric movement to back-track anomalies at multiple locations and times to a common source

The open path method relies on comparison between measurements on known paths and/or to fixed points. Therefore, the open path measurements should be anchored at one end to an in-situ measurement which is well-calibrated with the rest of the network. Thus we will pair an open path instrument with an in-situ analyser calibrated to the same scales as the AGOS Latrobe Valley network. This network includes one mobile instrument which can also be used to calibrate the open-path measurements by taking continuous measurements along a road between the source and a test reflector.

There are concerns about the practical application of the methods and sensitivity over long distances (in the order of 20 km) in the offshore environment through marine aerosols, and the contamination of retroflectors by marine fouling and deposits. The technology may be better applied to specific targets (e.g. at an injector or legacy wells) rather than attempting to monitor the entire site. However, the proposed assets and research will provide data on local baseline CO_2 concentrations that may prove useful in the future.

4.4. Isotopic measurement

The atmosphere contains a distinct modern 14C signature from solar and cosmic processes, while fossil fuels have lost all their 14C. The dominant form of terrestrial photosynthesis (C3) also discriminates against 13C so that biogenic material, (including fossil fuel) is depleted in this isotope relative to the atmosphere and richer in 12C. Oceanic carbon is not depleted. Thus measuring the isotopic composition of CO_2 in baselines and comparing to later measurements has long been a means of source attribution.

Although leaks of any type are unlikely, and pathways to the atmosphere are slow and tortuous, any offshore leak will have a very different isotopic composition from nearby modern oceanic sources.

5. Marine Monitoring

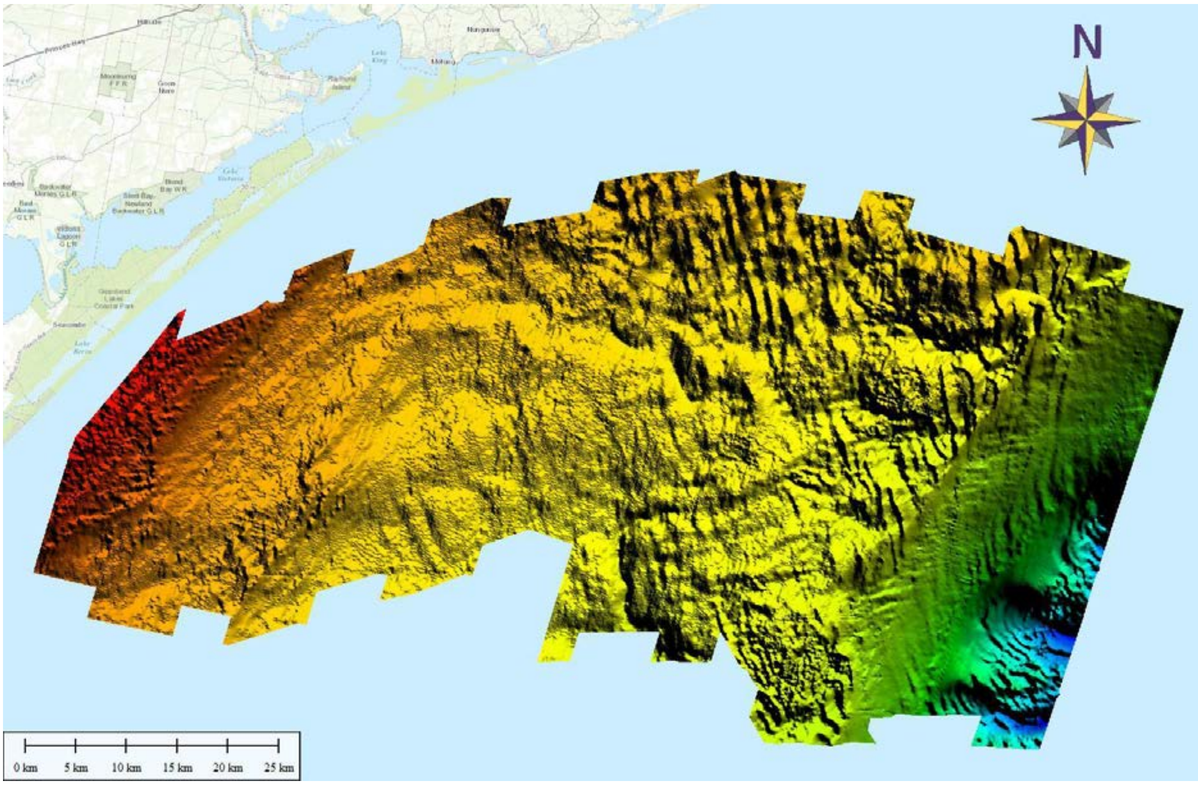

Figure 6: Gippsland Basin Bathymetry from oil industry 3D seismic echo-sounder. Depth range 20 to 580 metres

The marine context of the offshore Gippsland basin, the body of water known as Bass Strait, is illustrated in Figure 6. Bathymetry data from marine 3D seismic surveys – Depth scale from 20 m (red) to 580m (blue) – shows a wealth of detail including large (2 km wavelength) sand waves in the north and east of the basin where strong tidal and storm currents impinge on the shelf and the former course of the Latrobe River from the last ice age lowstand meandering across the shelf from top left to centre of the map.

Marine monitoring is again an assurance technique, but is slightly more likely than atmospheric methods to record a signal in the very unlikely event that a leak to surface were to occur, since that CO_2 is likely to be dissolved into the water column and not arrive in the atmosphere at all, or arrive at much lower concentration than for an equivalent onshore event. Key targets for marine monitoring can be identified such as known legacy well locations where wellhead monitoring offers a useful known location where leakage would be detectable, if it occurred, and rectification actions can then be planned appropriately.

The Norwegian sites at Sleipner and SnØvit have tested and implemented several aspects of marine monitoring including 3D seismic [9, 41 to 43], pressure [44, 45] gravity [46, 47], seabed imaging, marine magnetotellurics, and seabed and water column geochemistry. Studies have demonstrated how detailed conformance studies can be conducted with a richly-sampled 4D timelapse seismic dataset [48, 49].

However, those sites are located in deeper waters (>100m), and so the new GipNet research is aimed at shallow water sites such as exist in many nearshore basins worldwide, including Gippsland and the Gulf of Mexico. A more appropriate reference study would be the QICS marine release experiment, where CO_2 was released in the shallow subsurface below a Scottish marine loch in 10-12m of water [50, 51]. The QICS site confirmed the high detectability of migrating CO_2 plumes and bubbles in the subsurface, prior to it emerging at the surface [52]. In this example, non-repeat 2D surveys were used but the 3D extent of the plume and its evolution through time could be mapped at reasonable spatial resolution.

Together the QICS and Norwegian sites straddle the range of water depths anticipated in Gippsland nearshore storage sites (15-50m), and offer insights into likely successful technologies and sources of noise and data artefacts that need to be processed away or weeded out. Figure 7 shows the detailed bathymetry in the nearshore zone where LiDAR surveys were flown in the nearshore to between 4 and 7 km offshore in 2004 and 2008 for commercial navigation and coastal subsidence studies [53]. Bathymetry is defined by a 5m grid of LiDAR data from the two separate surveys – one covering the shore-adjacent zone to ~3 km offshore and the second almost contiguous covering the next 2.5 km. Smaller-scale features include hardgrounds, seabed mounds, seabed waves and/or inferred saline outflow channels and dredge scars. The LIDAR data shows water depths to deepen rapidly to 10m depth within a few hundred metres of the coast. The majority of the potential CarbonNet storage sites lie within the 15-50m depth range.

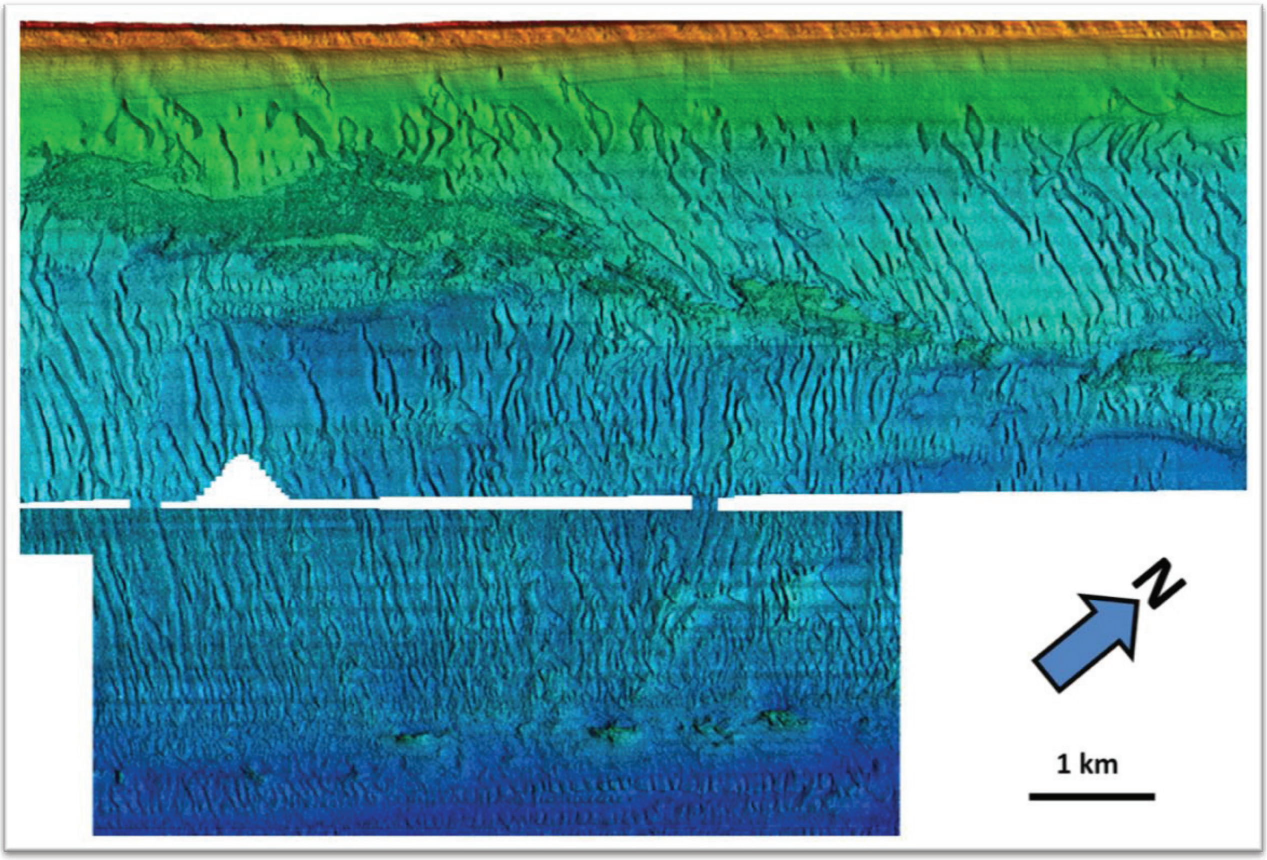

Figure 7: LiDAR nearshore bathymetry. Depth range 0 to 30 metres

Gippsland shallow coastal waters are well-mixed throughout the year due to tidal stirring, thus changes in water properties near the seabed should be reflected throughout the water column which will have advantages for monitoring in terms of detection at a distance, but difficulties in terms of dilution [54]. Ocean currents in the Bass Strait are largely wind driven and direction is closely aligned with topographic contours, i.e. alongshore.

Tidal flows in the Bass Strait are strong and oscillatory, parallel to the shoreline along Ninety Mile Beach. Figure 8 shows the SEA hydrodynamic model developed by ASR Ltd for GHD [55], visualising currents through Bass Strait generated by low-frequency oscillations and wind events.

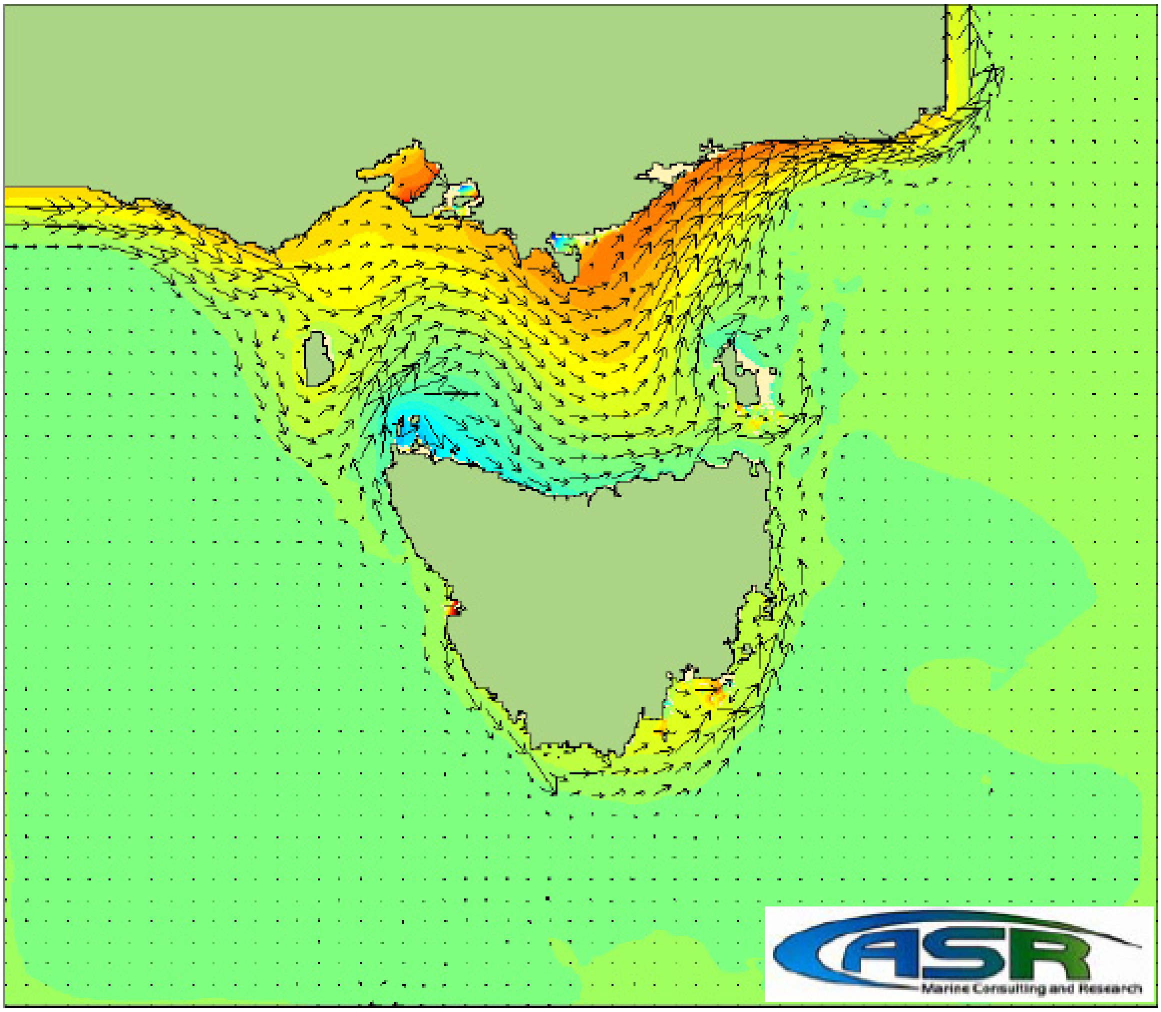

Figure 8: snapshot of Bass Strait tidal flow

The area is also subject to seasonal intrusions of water from the Tasman Sea and these waters have quite different water properties (temperature, salinity, dissolved CO_2) to Bass Strait waters, increasing environmental variability substantially.

A marine exclusion zone exists around oil and gas facilities in the basin, including subsea wellheads and pipelines. Shipping traffic can be predicted to a large extent with defined shipping channels and direct pathways between oil platforms and the service base, but non-scheduled traffic also exists, including leisure craft and commercial and recreational fishing.

Bass Strait is home to a diverse and highly endemic marine biota [56], and supports productive fin and shell fisheries. Many organisms have wide but patchy distributions across Bass Strait, indicative of heterogeneous conditions and diverse microhabitats that support distinctive communities.

Despite the Bass Strait waters along the Gippsland coast being home to multiple industrial activities, from shipping and offshore oil and gas production to fishing, aquaculture and tourism, little is known regarding baseline variability of the major parameters that would allow detection of, or indicate environmental impacts from, a seabed CO_2 leak. These baselines need to be established to underpin environmental monitoring programs, but research is needed into cost-effective and fit-for-purpose ways of doing so in the context of a commercial storage site.

CSIRO has undertaken two recent in-house desktop studies into the M&V requirements for the marine environment of Bass Strait. The analysis showed that, given uncertainties and natural variation, the lower limit of the size of a reliably detectable leak (false alarm rates of <1%) to be 10,000 tonnes per year.

This scale of leak is highly unlikely for a well-characterised storage site such as those studied by CarbonNet, and would be classified as "large" since it is of the order of 1% of the rate in injection for a commercial storage site (1-5 million tonnes per year) and if unchanged could lead to total loss of all stored CO_2 within 1,000 years – in contravention of IPCC guidelines. Leaks of this magnitude are better detected by 3D seismic methods, which have a visibility threshold of <1,000 tonnes of CO_2, and have the advantage of identifying any unwanted migration of CO_2 at earlier times and at depths of 1 km or more, before it comes anywhere close to being a leak to surface. The ultimate goal for water column detection is to detect much smaller leaks, but the technology is not yet proven at that level.

Because dissolved CO_2 changes the whole carbonate system of seawater, its variability can be detected through measuring changes in any of the four state variables of the carbonate system: partial pressure of dissolved CO_2 (pCO_2), pH, total alkalinity and total dissolved CO_2. Sensors are available to measure pCO_2 and pH continuously in-water, whereas measuring total alkalinity and total dissolved CO_2 requires samples to be measured in the laboratory. The laboratory-based measurements are important for quantifying the amounts of dissolved CO_2 related to measured changes in pCO_2 and pH.

The capabilities of acoustic monitoring for detecting bubbles in sediments and the water column [57, 58], and associated seabed geomorphic changes, were also the subject of a desktop study. Acoustic monitoring is a more local, but more sensitive technique [59] for identifying areas where changes in seabed habitats could arise through changes in environmental forcing.

Additional monitoring approaches can be used to further reduce the size of leak that is detectable. Naturally-occurring chemical tracers (e.g. stable isotopes, dissolved oxygen and methane concentrations) provide information on the source of measured changes in CO_2 in the water column to attribute CO_2 and other gases to natural or artificial sources and hence verify leaks and their magnitude.

5.1. Fixed or mobile sensors for continuous or episodic monitoring of CO_2

Measurement may be in real time with live data transmission onshore, or downloaded at intervals. Note that significant detection accuracy improvement will result through post-measurement processing. Measuring CO_2 in the water column [60, 61] can identify a leak of CO_2at the seabed because the CO_2 will mainly dissolve in the overlying seawater before any bubbles reach the sea surface [62, 63]. Modelling shows that the oscillatory nature of the currents in the region mean that the plume of a theoretical leakage event will be swept back and forth along the coastline and hence detecting that a dissolved plume exists is likely to be easier than precisely locating a seabed source.

Unpublished CSIRO modelling of a plume of released CO_2, dissolved in the water column (Figure 9) shows that the plume washes back and forth with the tide and other currents and is dispersed parallel to the shore. A nominal search grid for an autonomous waveglider is overlain showing how multiple transects of the plume would occur. The present study will investigate whether it is operationally simpler to have a single sentinel array of sensors perpendicular to the coast and allow the tides to bring the plume to the sensors.

Minimising the size of leak that can be detected requires state-of-the-art accuracy and high measurement frequency. The currently-predicted performance level might be useful in demonstrating no environmental impact (assurance), and the research goal of improving performance to a level of useful leak detection will require a combination of instrument types and further method development.

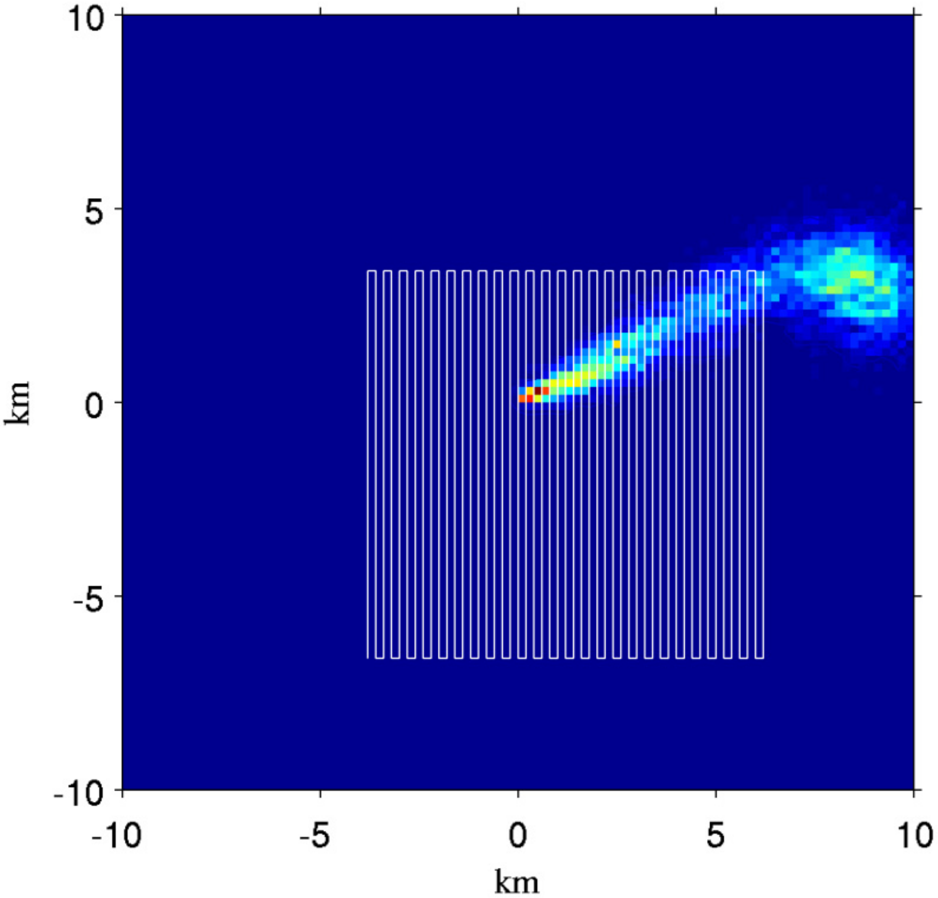

Figure 9: Example of integrated plume movement from CSIRO modelling

A combination of pCO_2 and pH sensors will provide both highest accuracy and highest frequency of measurements giving the highest probability of detecting a leak. Moorings can also be combined with long-term OBS locations for operational efficiency.

Autonomous platforms are a potential solution for increasing spatial coverage of measurements without needing multiple fixed platforms [64], but also have the downside that measurements are no longer at a fixed point. There is some trade-off between the value of the two types of information, which must be interpreted within the context of natural water body motions. For instance, patrolling a narrow strip perpendicular to the shore is likely to be an efficient strategy, given that natural water body movement delivers shore-parallel sampling opportunities. A limited patrol zone is also easier to manage in terms of third-party safety and permissions.

For nearshore sites there would be constraints, as wavegliders are limited to operation in water deeper than 10m (operational draft of 7m, equates to ~500m offshore) and may have difficulties in avoiding a lee shore during storm events. The presence of shipping, recreational activity and marine exclusion zones also complicates deployment, but wavegliders are proven technologies for some offshore industry applications in coastal waters. They have also undertaken ocean-scale transects, demonstrating their capability for long-term deployment under a variety of conditions. However, operational feasibility in the constrained nearshore Gippsland environment requires more detailed investigation.

In waters shallower than 10m (i.e. within ~600m of the coast) and in zones subject to random traffic or marine exclusions, fixed moorings present the most realistic option for monitoring. Retrievable carbon measurement systems provide real-time, high frequency, highest accuracy seawater $pCO_2$and pH data at fixed sites and are important as reference points in the monitoring system. Reference points provide continuous measurements at a single point through time, allowing mobile measurements to be cross-calibrated in order to separate spatial and temporal variability and improve interpretation of data. As with the wavegliders, a chain of moorings deployed perpendicular to the coastline is an effective geometry. The oscillatory nature of alongshore currents in the Gippsland region means these fixed moorings can still sample a large volume of water and would be likely to encounter a plume located close inshore. These moorings can also measure atmospheric pCO_2 to provide baseline measurements of the sea surface boundary layer for comparison to open path atmospheric measurements to retroflectors mounted on these buoys and elsewhere. Possible atmospheric pCO_2 anomalies can then potentially be correlated to seeped CO_2 reaching the surface in these shallower waters. Fixed moorings may also be used to combine functions, such as providing infrastructure for ocean bottom seismometers.

5.2. Seabed pH monitoring

Seabed pH monitoring provides high-precision local measurement of natural background sediment water exchange which allows interpretation of leakage-type events, including at natural fluid seepage sites, if any can be identified. The Gippsland Basin is not known for natural gas and oil seepage, but saline fluid seepage from onshore salt lakes and other types of seabed fluid exchange are possible.

Although CO_2 leakage is highly improbable, the most likely locations to experience leakage may be wellheads and pipelines. In these known locations (targets), near-field changes in the pH of seawater near the seabed relative to the surface are expected to be a characteristic response to CO_2 release.

5.3. Surface and water-column monitoring

It is inappropriate and impractical for a commercial project to routinely measure a large number of parameters over a wide area, but at the research stage this may be done to establish “baselines” (or the range of pre-existing natural variability). The protocols developed at this research stage would be used to define a more practical range of limited spatial and temporal sampling for later assurance monitoring, and as a contingent program of more detailed monitoring, if other MMV technologies suggested that there was a problem with the storage containment.

As a support for in-situ monitoring, the use of boats of opportunity and in-lab analysis is useful for verification of carbon changes in water, calibration of autonomous sensors, and tracing natural versus injection-related sources of seawater CO_2 changes. Submersible Remote Oceanographic Vehicles (ROVs) are another potentially useful mobile platform for monitoring pH and pCO_2 levels lower in the water column towards the seabed.

Effective attribution of changes in the seawater carbonate system will be an important consideration for marine M&V programs. CO_2 leakage is likely to perturb the ratio of gas concentrations in seawater as well as the ratios of natural isotopes and the concentrations of mobilised tracers. Therefore, it is important to assess high-precision measurement capabilities to identify robust CCS leak and non-leak signatures (e.g. groundwater seepage) in seawater.

5.4. Baseline oceanographic sensors

Only a single local long-term oceanographic buoy is available at present, and the extrapolation of this dataset to the local site involves a significant change in water depth and wave behaviour. It is therefore important to include general oceanographic data collection and new installations (mooring and seabed) to understand spatial and temporal oceanographic variability.

Understanding variability in surface and subsurface currents, wave fields, temperature, salinity, primary production and respiration, optical characteristics and other oceanographic variables in the immediate vicinity of the CarbonNet sites will be essential for monitoring, tracking and modelling in order to predict the dispersal and fate of any theoretical leakage, and to understand detection thresholds of fixed or mobile sensors.

5.5. Water column and seabed acoustics

Bubbles in seabed sediments and (in the case of a larger leak) in plumes emanating from the seabed are known signatures of subsea gas leakage and monitoring for them may be a useful part of a monitoring program. Acoustic sensors have limited spatial detection range but are extremely sensitive to small gas fluxes from the seabed (as demonstrated during the UK QICS experiment). A good understanding of baseline variability in features, such as any biologically-generated pockmarks and bubbles associated with burrowing organisms, would be essential for increasing confidence in these monitoring approaches and reducing false alarm rates.

5.6. Predicting and measuring impacts on benthic communities.

QICS observations showed, however that although there was a rapid response in microbial activity [65], there was only local change in macroscopic biota [66, 67] or metabolisms [68], and recovery was rapid from any such change [62].

Monitoring marine organisms may be useful for public reassurance and might provide early indication of leakage through rapid changes in community composition and stress responses. Whether this overall approach is useful requires further study and a good understanding of sensitivity and false alarm rates. Establishing good environmental baselines for habitat types and key species using a combination of remote (towed video, multi-beam swath, LiDAR) and direct (ROV, diver surveys, net, sled and grab sampling) approaches is costly and time consuming. In the context of CCS, leakages to the sea floor are likely to be rapidly detected using a combination of chemical and acoustic methods.

6. Discussion and Conclusion

The general requirements for MMV technologies in this study are to identify and refine the methods and application of the technologies in a cost-effective and fit for purpose manner for a full-scale commercial project. The purpose of this research is not primarily to define baselines of observable parameters, but is to determine what parameters are observable in practice, in the local complex shallow marine environment. Having proven that these parameters are observable and informative, then characterisation of the natural spatial and temporal variation (or “noise”) will allow assessment of what size of signal might be observable in a largely assurance-monitoring context.

This assessment of signal vs noise will allow regulatory and community understanding of which techniques are appropriate for containment, conformance, and assurance monitoring, and where and how often those techniques should be deployed to provide useful information when a future commercial project is operating.

The observations derived in this early research stage can be integrated with future project-specific baseline measurement to provide a longer temporal database and wider spatial coverage than a commercial project can provide. This will assist with regional understanding of the environments and demonstration of no adverse affect of the project operations.

A significant body of research exists but now must be matured through practical analysis and cost-effective deployment for commercial storage sites. These sites guarantee access to a high-graded set of technologies and deployments that are affordable and commensurate with the expected low risk of near-surface CO_2 migration and leakage, yet meet community expectations for an adequate degree of assurance monitoring. Some insight into community response and world-views of CCS can be drawn from the QICS study [69]. The QICS experiment and its observations are summarised with three key points [50]:

- Development of a marine monitoring system suitable for operational CCS is achievable.
- Monitoring should be hierarchical, starting with anomaly detection.

- Comprehensive baselines are required to support monitoring

We would agree with those observations and suggest that they apply equally to a shallow-water nearshore environment as to deeper more open-water sites.

Key to the identification of cost-effective technology are measurements in a pre-injection situation where leakage is impossible, and therefore all signals and fluctuations can be ascribed to pre-existing natural variations, or to the influence of nearby anthropogenic sources. This allows the detection limits and alarm thresholds to be set for the high-graded technologies and for credible analysis of false alarm rates and the minimum detectable leak event in different scenarios.

It is important to bear in mind throughout this process that the principal aim of near-surface monitoring is assurance that no environmental impact is occurring. Therefore the initial aim is to measure the pre-existing natural environment and describe its variation.

A significant product of this early measurement is the characterisation of the local natural environment and its pre-existing variability. This variation, often described as the “baseline”, is likely to be significant in magnitude and contain hourly to decadal components. It is, however, only by comparing new observations to this baseline that anomalies can be detected. The multi-annual to decadal climate and ecosystem variability require that a multi-year baseline dataset is available to compare and contrast with new observations.

The GipNet project will deploy monitoring assets relevant to promising monitoring technologies, develop their use, test in the nearshore environment, and commence baseline definition activities at potential carbon storage sites. Outputs will include a reference dataset from which to select appropriate measurable parameters and fixed locations or schedules for mobile measurements in the future, including reference to physical features such as wellheads and subsurface discontinuities, including faults.

No single monitoring technology is capable of monitoring for all risk scenarios or in all environments and project situations. Each monitoring technology has its own resolution, coverage, sensitivity and operational costs; therefore, understanding the strengths and limitations of these individual technologies is important when combining all the monitoring technology results into one unified interpretation of integrity, conformance and assurance.

The three research proposals have been assessed against the physics of detection and practicality of their deployment in the local nearshore environment. It is expected that not all aspects of each sub-project will prove successful, or demonstrate sufficient detection sensitivity and low false positive rates to be usable in this, or perhaps in any similar nearshore environment. In this way, the projects are a technology demonstration and selection process and some technologies will be downgraded while others will be high-graded for nearshore storage sites.

Field assessment of the capabilities of these technologies in terms of their sensitivity, verifiable accuracy and optimum configuration, in the context of background environmental variability, requires further development. There are concerns about the practical value, for instance, of autonomous wave gliders in near-shore shallow water operations adjacent to a surf beach, with constraints on navigation posed by nearby oil and gas platforms. Furthermore, the robustness and durability of all these technologies for long-term deployment requires significant testing. These aspects are covered in the proposed research as well.

The three GipNet projects are interlinked and overlap, both in the use of some common observation sites and deployments, and in the complementarity of measurement.

The knowledge gained from testing of sensors and techniques will directly inform the design of MMV programs in other areas, both within Australia and internationally. The knowledge gained will improve process understanding of potential leakage detection in the nearshore marine environment, required for both impact assessment and relocatable model development as part of a national and international approach to CCS.

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