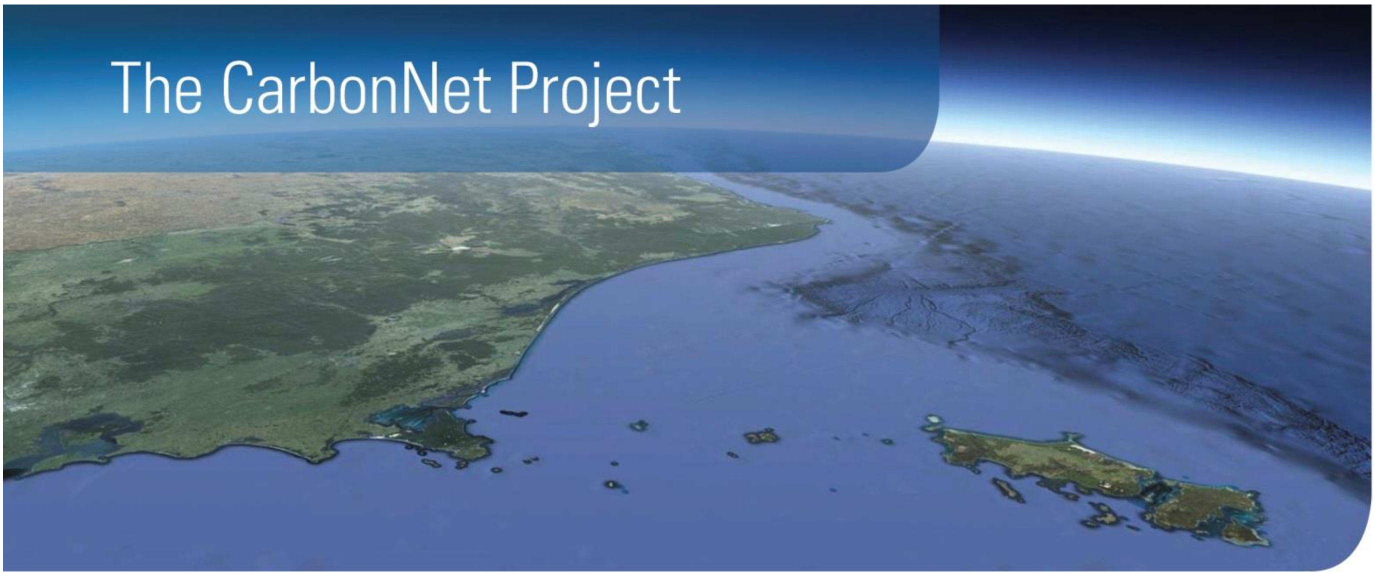

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GipNet – Baseline environmental data gathering and measurement technology validation for nearshore marine Carbon Storage.

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June 2016

Authorised by the Department of Economic Development, Jobs, Transport and Resources

Acknowledgement

The CarbonNet Project receives funding from the Australian and Victorian Governments as part of the Carbon Capture and Storage Flagships program.

The preparation of this paper is part of a funding agreement between the CarbonNet Project and the Global Carbon Capture and Storage Institute for Knowledge Share Activities.

The CO2CRC is supported by an industry consortium and by government. The Education Infrastructure Fund is supported by the Commonwealth government Department of Education and Training.

Technical input and discussions with colleagues and external experts have significantly assisted with the preparation of this report. In particular, CarbonNet would like to thank Nick Hoffman[1], Nick Hardman-Mountford[2], Charles Jenkins[3], Peter J Rayner[4], Gary Gibson[4], and Mike Sandiford[4]

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Executive Summary:

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 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 define 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

The GipNet Seismic Network will involve surface-deployable onshore seismometers and shallow water (<100m) Ocean Bottom Seismometers (OBS). The network will enable monitoring of background seismic activity and other 'noise' sources in the region of prospective storage sites and in the future will enable detection of any induced seismic events that might occur as a consequence of future injection activities. 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 nearshore Gippsland Basin.

Practicalities

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 also important to investigate methods for equipment installation that minimise noise (e.g. cemented into shallow boreholes, local noise-cancelling arrays, etc.).

Shallow marine seismometers will also be subject to weather and tide/current noise and will have limited time deployments. It is not yet clear whether they will allow a significant catalogue of events to be recorded, and modelling of the probability of useful detection is underway.

2. Atmospheric Monitoring

An open-path measurement system will be established for atmospheric trace gases and isotopic composition of CO_2. The research program will monitor sources and sinks of 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.

Practicalities

The coastal region is a low-density populated region with established agricultural and local industrial uses, but hosts significant summer vacation activity on lakes, beaches, and adjacent campgrounds and holiday homes. This activity 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.

3. Baseline Marine Monitoring

This project aims to utilise marine monitoring assets relevant to promising monitoring technologies, develop their use, test in the marine environment, and commence baseline definition activities.

The shallow coastal waters containing the GHG exploration permits 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. Records from nearby buoys show that the current direction is oscillatory with a range of timescales. The area is also subject to seasonal intrusions of water from the Tasman Sea with quite different properties to Bass Strait waters, increasing environmental variability substantially.

While Sleipner and Snøvit have tested and implemented several aspects of marine monitoring, these sites are located in deeper waters (>100m), and so the proposed research is aimed at shallow water sites such as exist in nearshore parts of many basins worldwide, including Gippsland, the North Sea, and the Gulf of Mexico. 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.

Practicalities

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 fishermen.

Introduction

The CarbonNet Project (CarbonNet 2015a) is investigating large volume storage (nominally 125 million tonnes of CO2 over 25 years) in shallow waters within 20 km of the coastline, offshore Gippsland Australia (Figure 1). There is a clear expectation that geological storage sites will be chosen after significant site investigation such that the risk of leakage is extremely low (Aarnes et al., 2010) and this is the case for the CarbonNet project (Hoffman et al. 2012, Hoffman and Preston 2014, CarbonNet 2015b, c, d). The current report details 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 CO2 and related gases and chemical species, and of the natural background of earthquake activity or (micro-) seismicity.

Storing CO2 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. Unlike other CO2 storage sites worldwide, the CarbonNet sites are neither onshore nor in deep and distant waters. Although storage will take place offshore, some degree of monitoring of the nearby onshore area may be warranted to provide public and stakeholder confidence in safe storage. Therefore, a non-standard and project-specific combination of monitoring technologies will be required to provide all the required data.

A very useful summary of the progress of monitoring and verification over the decade since the publication of the IPCC Special Report on CCS (IPCC, 2005) is provided by Jenkins et al., 2015. For our current purposes, we note that monitoring activities can be broken 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 CO2 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 CO2 migration towards the surface.

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 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 technology of Measurement, Monitoring, and Verification (MMV) is important. Sensors need to be able to 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 (Varma and Michael, 2012). 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. Ongoing research such as at the Otway Project (Stage 3) will investigate whether such technologies and techniques could be made available to commercial scale CCS projects in the medium to longer term.

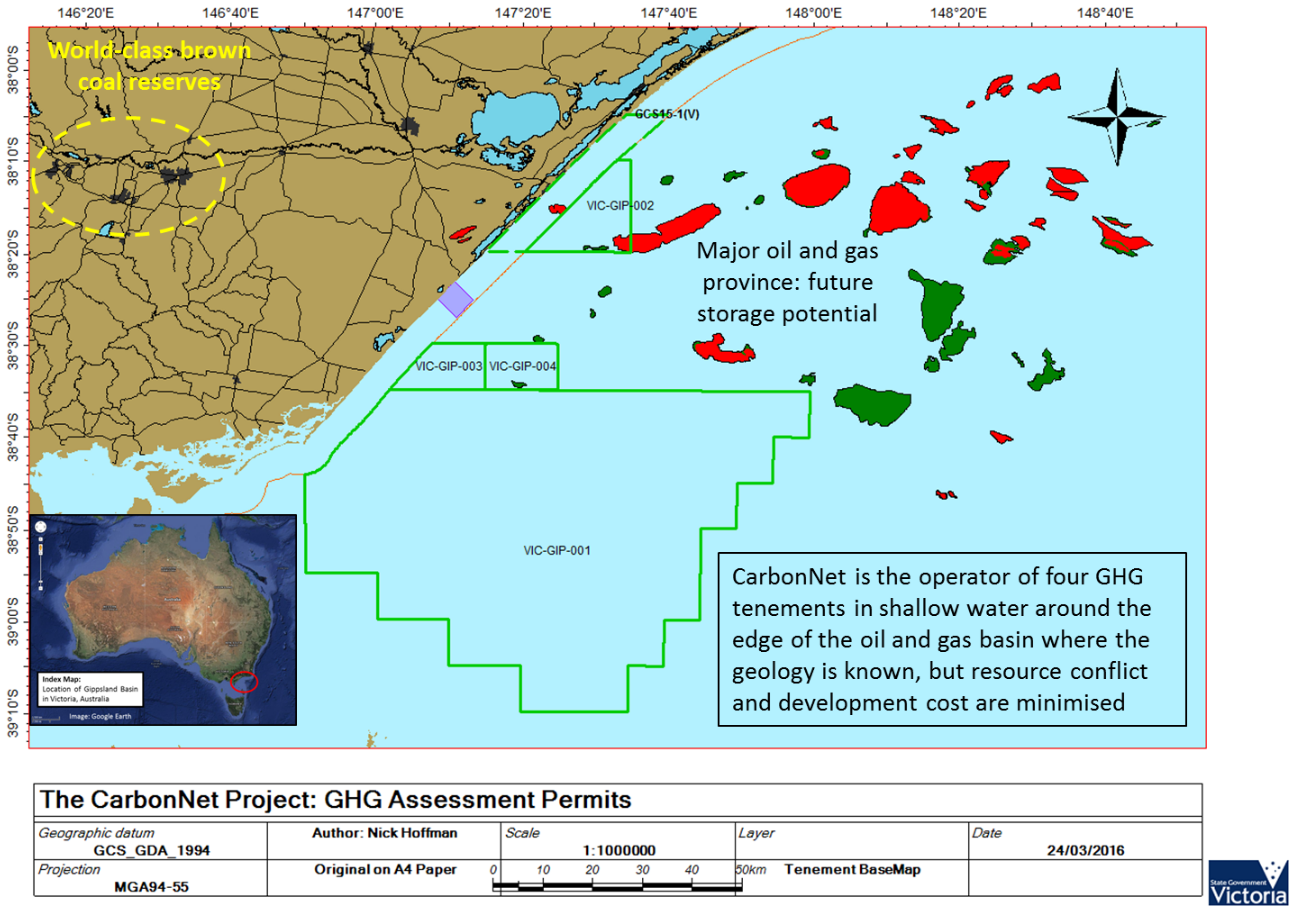

Figure 1: Location of CarbonNet GHG Assessment Permits

CarbonNet is the operator of four commonwealth GHG Tenements situated in shallow waters around the edge of the oil and gas basin where the geological factors that have stored oil and gas for millions of years are still in play, but resource conflict is minimised

At the CarbonNet sites (the CarbonNet permits are shown in Figure 1), high porosity reservoirs at relatively shallow burial depths (1 km) do have an excellent acoustic response to gas or supercritical CO_2 present in the pore space, as is shown by the strong DHI effects on nearby gasfields. Hart et al. (2006) demonstrate effective timelapse monitoring of the movement of gas-water contacts in large gasfields nearby to the CarbonNet potential storage sites. Studies of CO_2 storage in the nearshore demonstrate through Gassmann fluid substitution analysis that the plume will be clearly visible on seismic data at the depths of interest (Gendrin et al., 2013). Verification monitoring will therefore be undertaken with deep detection techniques and the principal tool chosen for long-term plume monitoring is timelapse 3D seismic, as deployed for the Sleipner project (Chadwick et al., 2004, 2010). However, assurance monitoring requires techniques that can detect changes over a wider area and the technologies that are used need to 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. 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 (see Jenkins, 2013, Jenkins et al., 2016).

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 may yield methods better suited to Victorian waters. Research into this topic is ramping up in the UK with multi-million dollar projects within the UK CCS Centre for the development of marine monitoring techniques, including the use of automated vehicles.

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.

There exist many monitoring technologies and techniques but not all are suitable for all sites. Therefore, investigation of the feasibility of potential monitoring technologies is important. CarbonNet proposes to test measures such as onshore soil gas sampling to determine if meaningful data can be collected in a beach/barrier island environment and sampling of local water supply and/or water monitoring wells for compositional analysis and hydrostatic head measurements to determine if initial baseline conditions can be established or existing studies updated.

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

CarbonNet 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.

Geological Context

The Gippsland Basin (Wong et al., 2001) has a two-stage extensional history (Ollier, 1995, Partridge, 1999, Bernecker and Partridge 2001, Power et al. 2001) as a rift on the southern margin of Australia, with the first stage originating in the break-up of Gondwana and movement of Antarctica on the southern margin of Australia in the Late Jurassic to early Cretaceous (Figure 2, modified after Norvick et al., 2001). 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 (Rahmanian et al., 1990). 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 (Mitchell et al., 2007), and an extensive shelf sequence of 1-2 km built out over former deep water.

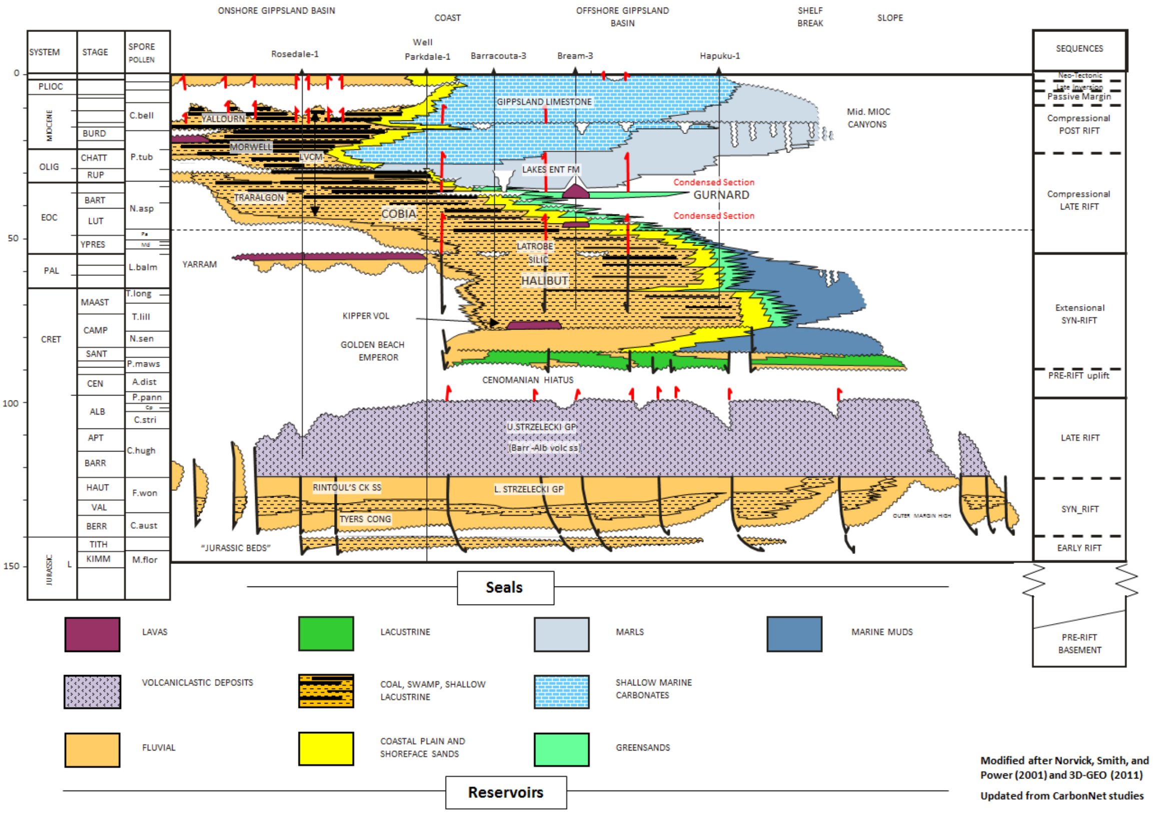

Figure 2: Gippsland Basin Chronostratigraphy and Tectonics

This 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.

1. 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.

There are two key aims to the research plan:

1. establish the protocols for instrumentation and network design for base-lining and monitoring in seismologically noisy environments such as the proposed sites in the nearshore Gippsland Basin. Network design will evolve from the first deployment of a local (sub-regional) network and develop to a high-resolution micro-earthquake network suitable for site observation .
2. to use the greatly improved network coverage provided by GipNet to much better characterise the low-level natural seismicity in the Gippsland Basin (i.e. the seismological baseline) and, in so doing, delineate its earthquake magnitude recurrence, evaluate the factors controlling the spatial distribution of seismicity, characterise the state of stress by resolving many more focal mechanisms.

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.

Three main episodes of inversion are noted: In the Early to Middle Eocene, in the Oligocene, and in the Mid- to Late Miocene. The onshore area is still moderately seismically active, with events to a maximum just over 5 being recorded over the past 50 years (Wilkie, 1970, Sandiford et al., 2012, Hoult et al., 2014). Figure 3 shows that outside of the Strzelecki ranges, the Gippsland Basin seismicity that has been recorded and located since 1976 is largely offshore. Onshore, the Strzelecki Ranges are quite active relative to other stable continental regions (Brown, 1995).

The regional tectonic stress in the Gippsland Basin (Nelson and Hillis, 2005, Nelson et al., 2006, van Ruth et al., 2007) is a local expression of the overall tectonic regime in Australia, which is dominantly horizontal compression with minimum principal stress vertical, giving reverse faulting. 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 failure. In the Gippsland Basin, the upper several km of sediments are not strong, 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.

The bedrock in SE Victoria is mainly strong Palaeozoic sediments, which under tectonic deformation can build up high levels of tectonic strain energy (or stress) before faulting. The hard rocks have high seismic velocities, low attenuation of wave amplitudes with distance, and give relatively little surface wave noise.

The Strzelecki Ranges have several kilometres of firm Mesozoic sedimentary rocks overlying the Palaeozoic rocks (Williamson et al., 1991, Collins et al., 1992), and most of the earthquakes in this region are beneath Mesozoic sediments in the Palaeozoic rocks (Brown, 1995). The firm rocks have moderate seismic velocities, moderate attenuation of wave amplitudes with distance, and give moderate surface wave noise with moderate period motion.

The Latrobe Valley and the Gippsland Basin have soft rock, poorly consolidated or unconsolidated, and are not strong enough to accumulate significant tectonic strain energy, so few earthquakes of any size occur within the sedimentary section. The soft sediments have low seismic velocities, high attenuation of wave amplitudes with distance, and give large surface wave noise with long period motion. Large earthquakes at depth beneath these sediments can transmit energy through to the surface, but with little energy input from within the surface sediments.

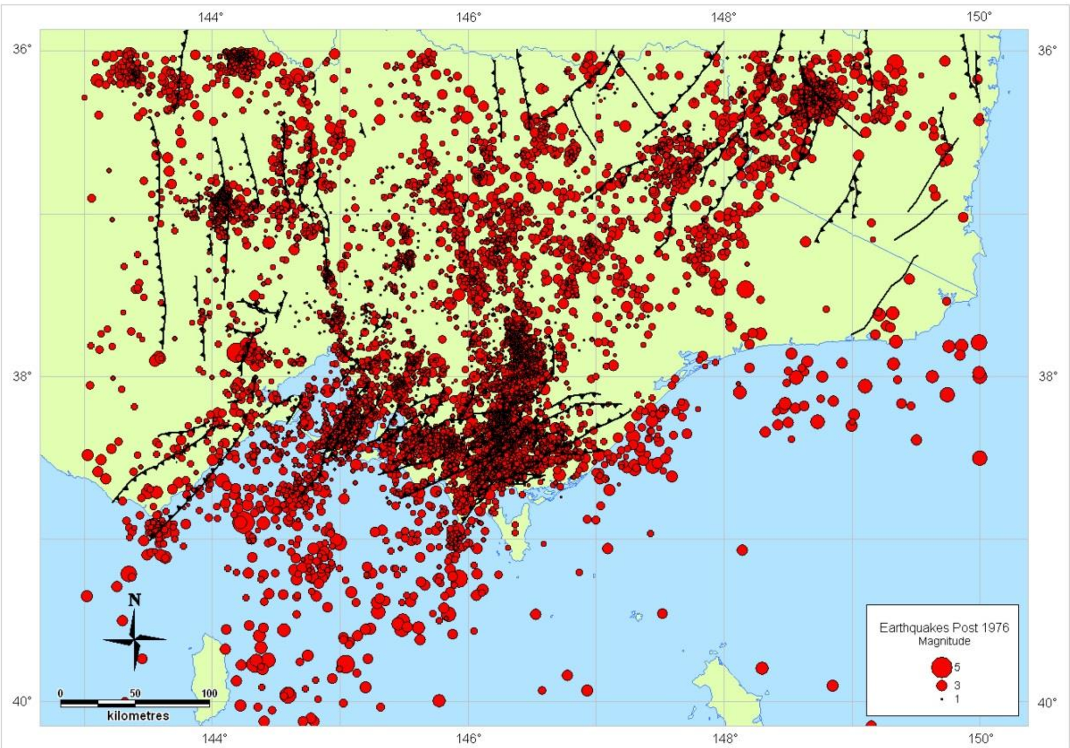

Figure 3: Earthquakes since the start of 1976 in SE Australia.

Earthquake hypocentres (the surface location above the epicentre) for events recorded after 1975. Locations are reasonably well defined, especially for more recent events. Note that small events are generally not detected in the offshore Gippsland Basin due to distance from the recording stations.

Figure 4 shows the epicentres of earthquakes located in SE Australia for the period to 1975, as extracted from the earthquake catalogue GGcat on 14 August 2015.

Most of the smaller earthquakes from the 1960 to 1976 period were located using limited seismograph data. All locations have high uncertainties, up to tens of kilometres until 1960, and the event locations were estimated from the locations of maximum ground shaking – see Gibson et al. 1981 for a useful summary and Wilkie, 1970 for a key study of a significant individual event.

Figure 3 shows the epicentres of earthquakes located in SE Australia for the subsequent period from 1976 to 31 May 2015, as extracted from the earthquake catalogue GGcat on 14 August 2015. Studies of a recent large event at Moe in 2012 have been published by Sandiford et al, 2012 and Hoult et al. 2014.

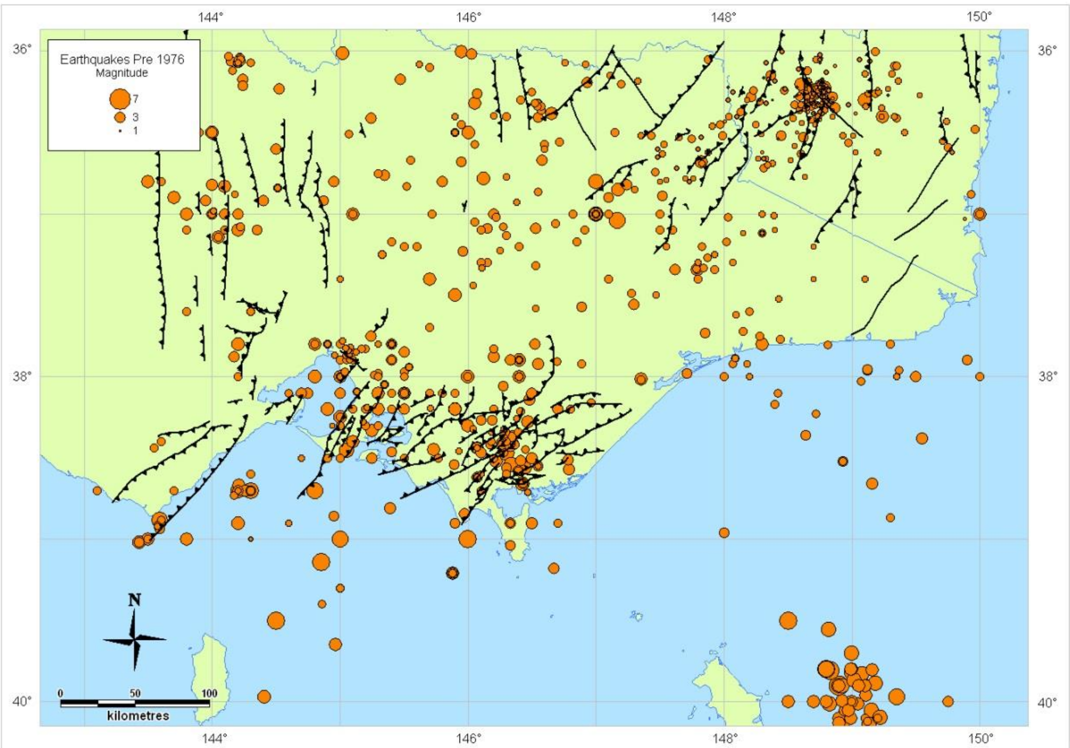

Figure 4: Historical earthquakes to the end of 1975 in SE Australia.

Earthquake hypocentres (the surface location above the epicentre) for events reported up to 1975. Many of the earliest reported events are highly uncertain due to a lack of a good instrument network at that time. Nonetheless, the number and magnitude of observed events is a good100-year record of earthquakes large enough to be noticed by the general public.

Local seismographs were installed in eastern Victoria from 1976 to 1990 (Figure 5a), including 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.

In seismic terms the offshore region appears less active than the onshore part of the basin encompassing the Strzelecki Ranges to the northwest (Brown et al., 2001). From 1969 to about 2000, the central part of the Strzelecki Ranges (south of Morwell) has been one of the most seismically-active regions of the continent, with several earthquakes exceeding magnitude 5.0. In comparison, during this period the western Strzelecki Ranges experienced a lower level of activity. However, from 2009 to the present, that trend has reversed. As in most places, spatial and temporal clustering is a feature of earthquake activity in the Gippsland region.

As an example of spatial and temporal variation and clustering, seismographs operated by the UoM and others are currently monitoring a significant increase in activity in the western Strzelecki Ranges to high resolution accuracy and down to more numerous small magnitude earthquakes.

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 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.

This enhanced catalogue of events will form the basis of a baseline for any future CarbonNet projects. Given the recurrence period of earthquakes in this area, a timeframe of several years is desired to determine natural earthquake statistics.

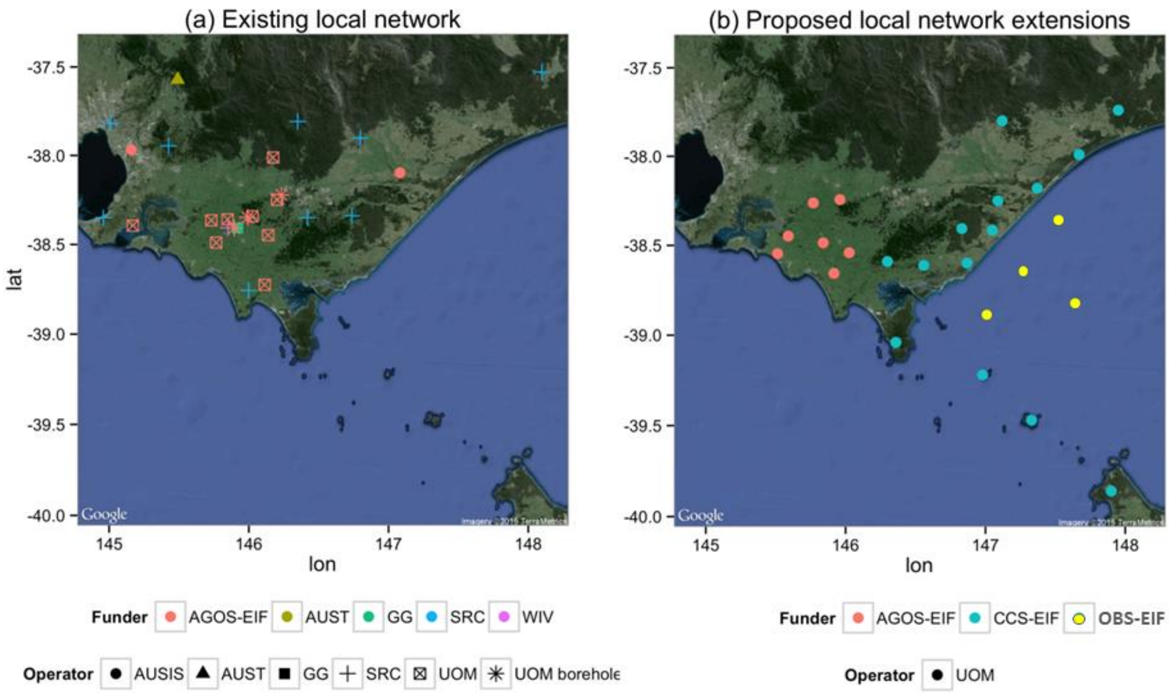

Figure 5: Existing and proposed future seismology monitoring networks

(a) Existing local seismic network in the Gippsland Basin, along with

(b) candidate sites for the proposed local networks

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.

Note that the smallest-scale local micro-earthquake array is not shown.

Seismograph Networks, Scale and Geometry

Earthquake seismology is undertaken on a wide range of scales, with significant variations in network design and coverage, depending on purpose and budget. Global seismic networks locate earthquakes with uncertainties, aleatory plus epistemic, that often exceed 10 kilometres, especially in regions of complex geology. Regional networks covering sub-continental scales, such an Australian state, usually locate earthquakes with an uncertainty of about 5 to 10 kilometres.

Local networks typically cover areas with dimensions about 20 to 100 km, and aim to locate events to within 1 to 5 kilometres. Micro-earthquake networks are usually within an area with dimensions less than 20 kilometres and aim to locate events to within hundreds of metres. On the smallest scale, mining seismic systems and networks designed to monitor hydraulic fracturing operations can have dimensions less than about 5 kilometres, and usually aim to locate very small events to within a few metres.

The estimated epicentre of any recorded earthquake is much more reliable if it occurs within the seismic network, so ideally networks are designed so as to surround the region concerned. The estimated depth of an earthquake depends largely on the distance from the epicentre to the nearest seismometer - ideally this distance should not be further than double the earthquake depth. In countries like Australia where most earthquakes are within 20 kilometres of the surface this implies an ideal seismometer spacing of less than 40 kilometres.

Most earthquakes recorded by local area seismic networks are small, with the minimum magnitude for complete coverage depending on the network dimension and density. The recurrence rate of larger magnitude events decreases by a factor of about ten for a unit increase in magnitude. If a network is to be deployed for a short period (years rather than decades), the largest event recorded is unlikely to be larger than a moderate magnitude. However, a great deal more information can be derived from the records of a larger earthquake, so a seismic network is usually designed to accommodate this by recording long period and high amplitude motion using both broadband seismometers and strong motion accelerometers. The largest earthquakes recorded in the Gippsland region have been a little over magnitude 5, with recurrence periods of many decades to a century, so this is the design tolerance of the strong-motion part of the network.

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 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.

Potential for Induced Earthquakes

Earthquakes can be triggered by a variety of mechanisms, including by fluid injection and/or extraction. 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 (Kuttan et al. 1986) 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. Varma and Michael (2012) report up to 120m hydraulic head reduction in the vicinity of the major oilfields in the Central Graben, and 30-50m hydraulic head at the coast, but no induced seismicity has been recognised since all recorded earthquakes to date (Figures 3 and 4) are significantly deeper than the aquifer and there is no spatial association between the observed events and the area of highest pressure draw-down.

There is worldwide concern that CO_2 injection might lead to induced seismicity (Nicol et al, 2011, Zoback and Gorelick, 2012,). Local studies of fault reactivation potential (van Ruth et al., 2007) 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 seen as less drawdown against a background of large-scale fluid extraction from the aquifers for petroleum and agricultural purposes.

Injecting fluids under pressure is an effective way to trigger earthquakes in aquifers that do not effectively dissipate pressure, especially in strong rocks that are highly stressed. These events can occur very soon, within hours or days, of the injection, so attribution is obvious in these circumstances (e.g. Ladner and Häring, 2009). To produce a significant earthquake requires an existing fault of appropriate size (1 km^2 for a magnitude 4.0, 10 km^2 for magnitude 5.0), that is under stress with sufficient stored strain energy.

The number and size of induced earthquakes is usually limited by the depth at which injection/extraction takes place, with hydraulic fracturing at shallow depth giving some earthquakes up to a small magnitude, waste-water injection may give more earthquakes a little larger, and deep geothermal injection usually gives numerous earthquakes up to magnitude 5.0 or larger.

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.

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.

Local Seismic Network Details

The existing local network as shown in Figure 5a is proposed to be extended by additional onshore and offshore stations as noted in Figure 5b, designed so that earthquakes within the nearshore Gippsland Basin will be within the extended seismograph network, considerably improving the current limited onshore focus of the network. The density of this extended network will allow many more small earthquakes to be located than is possible at present. Determination of earthquake parameters for any earthquake requires data from seismographs at varying azimuths and distances. As well as providing this data for earthquakes throughout the Gippsland Basin, the local network gives the moderate distance coverage required at any specific location of interest within that network – i.e. any of the potential CarbonNet sites. Existing AGOS seismographs will provide data from greater distances.

The focus of the local network will be of the entire nearshore region, with the design specification such that all events larger than magnitude 1.0 should be locatable. Away from the centre of the network, all events larger than magnitude 1.5 should be locatable.

There are two ways to improve the signal to noise ratio for sites on soft sediments. The first method is to install seismometers in boreholes, at depths below the strongest surface wave noise. Deep boreholes, one kilometre or deeper, give a major reduction in noise level, but incur an extremely high cost penalty. Shallow boreholes, from 5 to 30 metres are likely to give an improvement in signal to noise that should be cost effective, compared to the cheapest option of surface mounted seismometers which carry a high noise level penalty (especially during storms) but allow for more sites and an increased seismometer density. The use of noise-cancelling arrays of higher-frequency geophones would limit the moderate to long period response for analysis of larger earthquakes.

The second method to improve the signal to noise ratio is by using filtering in the frequency band. The dominant frequency of ocean noise is relatively low compared with cultural noise experienced at many sites, while the dominant frequency of the signals from small earthquakes is also relatively high. High digital sampling rates and either specialised broadband feedback seismometers that have little noise below 200 hertz, or less expensive but less sensitive passive seismometers (geophones) will be best for small earthquakes.

Standard mid-range frequency feed-back seismometers are best for larger earthquakes due to their dynamic range, and accelerometers will be most useful for nearby larger earthquakes, so a small proportion of the network will record six-channels, with the high frequency seismometers for high frequency motion from the most numerous smaller earthquakes, accelerometers for nearby small or moderate earthquakes, and standard seismometers and accelerometers for recording weak and strong motion respectively from the relatively infrequent distant larger events.

Micro-earthquake Network Details

The micro-earthquake network is an additional high-density network with seismograph spacing of five to ten kilometres, specially designed to monitor earthquakes near to a specific location of interest, once selected. The instruments will use higher sample rates to record the higher frequency seismic waves from the nearby earthquakes. These frequencies will be higher than those from most natural wind and wave noise. At this scale, site selection must emphasise network geometry.

The micro-earthquake network is used to give more precise earthquake locations and mechanisms. It has a station spacing of five to ten kilometres, depending on the earthquake depths. The noise can be long-term (e.g. storm waves) or transitory (e.g. due to vehicles passing nearby), and a higher density network provides some redundancy for loss of signal due to transitory noise.

The magnitude for complete coverage depends on the area being covered, and the density of the seismometer coverage. The coastal location of the Gippsland Basin provides a noisy environment for any seismological monitoring, and provides a limit to the magnitude of complete coverage. This 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. In some applications, such as detection of signals from particular places, then relatively small surface arrays can provide improved signal recovery. If small events are concentrated at a particular location such as injection at an injection site, then small arrays can be used to reduce noise levels. If events are widely distributed then seismometer site density (in particular the average distance from event to the nearest site) becomes more significant.

The micro-earthquake network should 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 because all of the micro-earthquake network surface and the OBS sites will be affected.

Since the main area of interest in relation to storage will be offshore, there is a sound case for the use of OBS, despite their relative high costs of purchase and deployment, and risks of loss. Most existing OBS systems are designed for very deep water operation, and many of the expensive aspects relate to dealing with the water pressures in deep water settings (>> 100 metres). Identifying and procuring cheaper OBS for shallow-water operation will form part of the study

The 5-Year Research Plan

To optimise high frequency response from very small earthquakes, the Nanometrics Trillium Compact broadband seismometers record signal frequencies up to 200 Hz, compared with an upper limit of 50 to 100 Hz for broadband seismometers more typically used in the past. Although these have a very wide dynamic range, additional strong motion accelerometers will be installed at several sites to capture the details of any nearby moderate to large magnitude earthquake.

Meeting the objectives of the second aim will be somewhat dependent on the nature of the events recorded by the network. A particular focus will be on establishing the nature of spatial and temporal clustering associated with seismicity and micro-seismicity in the period leading up to any significant injection. Amongst other outcomes, it will focus in developing protocols for the discrimination of induced seismic responses during and following injection, from natural seismicity. We note that it is likely that there will be little detectable seismicity in the vicinity of the storage sites prior to or after injection, given the pressure response of the aquifer and the geomechanical state of stress observed for the basin.

Ongoing research is focussed on characterising the spatial and temporal pattern of seismicity across southern Victoria, particularly in our energy rich sedimentary basins. The new network will extend the spatial scope of research into the nearshore and offshore region of the Gippsland Basin. In so doing, the research will help build a better understanding of known geological faults across the basin, and especially in the regions targeted as potential storage reservoirs.

Crucial to achieving these aims is the development of protocols for routine determination of focal mechanism data from small magnitude events (~M 2) of the type that are relatively common across the basin. Enabling such determination will help build a better understanding of the nature of the in-situ stress field, which is a crucial issue in many subsurface reservoir operations.

In addition, new data will be incorporated into ongoing research aimed at better delineating the seismic velocity structure (Vp and Vs) of the region and for seismic attenuation analysis. Improvements in the velocity model are important for improving event location accuracy.

2. 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; a review is in Shankar Rao (2007).However these methods need to be adapted to the particular circumstances of CCS to become routine monitoring tools. In an early review, Leuning et al. (2008) set out the options for atmospheric monitoring for CCS; some helpful, more genera l ideas about surface monitoring were developed by Oldenburg and Lewicki (2005). Trials were made at the Ginninderra controlled release site (Loh et al., 2009). Results from the CO2CRC Otway storage site (Sharma et al., 2011; Jenkins et al., 2012; Cook, 2014),for a single-station concentration sensor have been described in Luhar et al. (2009) and Etheridge et al. (2011).

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 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.

Practicalities

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.

The technique of determining sources and sinks of tracers from their atmospheric concentration has been used for decades and has given us most of the large-scale information on the global cycles of CO_2 and methane (Shankar Rao, 2007). These techniques have highlighted the role of the northern hemisphere land in taking up large amounts of anthropogenic CO_2 and the tropical land in modulating the inter-annual variations in the growth rate of atmospheric CO_2. Most of this information came from flasks of air collected in-situ then measured in centralised laboratories or rare and expensive continuous in-situ monitors generally deployed at well-supported field sites. The inverse modelling techniques used to retrieve information on sources from these measurements were, for a long time, unable to interpret high-frequency signals in the data so these episodic flask collections were not a grave limitation. This modelling/measurement combination could only retrieve large-scale information however. 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. Many of the ideas were developed by Yee and collaborators in a series of papers which provide the theoretical foundation for later work (Yee et al., 2008; Yee, 2008, 2011; Yee and Flesch, 2010). An initial application to the CO_2 problem, where the variability of the background is much more serious than for the methane-based trials described by Yee, was at the Ginninderra test site (Jenkins et al., 2011; Humphries et al., 2012).The methods have been applied at the Otway site and to agricultural regions in France and the U.S., the cities of Sacramento and Indianapolis and, most pertinent, to a power-station in South Australia and a vented gas-well in New Zealand. In each case the estimates derived from atmospheric methods were verified against independent measurements or inventories.

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 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. There are global estimates derived from satellite-driven analyses of the atmospheric state as part of global monitoring networks however these are at too coarse a scale to inform directly a local estimate. Instead we propose to use an intermediate observing network to refine this information to the scales we need. This network is provided by a baseline network for the Latrobe Valley funded by AGOS and currently being deployed.

Open Path and in-situ Methods

Most methods for measuring greenhouse gases in the atmosphere are spectroscopic, i.e. they rely on the absorption of electromagnetic radiation by the target molecules. 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 further division is into open path or closed path methods. The most common closed path or in-situ methods pump air into a cell and apply some spectroscopic measurement technique. Another method measures the absorption of radiation along some open path in the atmosphere. The source may be the sun for vertical paths but can be artificial for horizontal paths. 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 simpler measurement uses a ground-based instrument staring at the sun and using 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 measurements 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 sources and sinks.

The open path method can also be applied with an artificial source. This can be a laser or a polychromatic source. The same retrieval methods and indeed the same instruments are used as for solar sources. An important difference is that the path can be nearly 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.

Combination, Triangulation and Tomography

The in-situ method measures concentration at a point. This concentration is the result of inputs and removals of tracer by either chemical transformation or contact with surface sources and sinks. 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 ability of our model to capture variations in wind direction.

A limit of in-situ measurements is the restricted volume of the atmosphere which is probed. If the wind does not advect air between a source and 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 slight errors in transport may well simply relocate a given air mass along the observed path rather than switch its state between observed and unobserved. This advantage was clearly noticed with the solar measurements of the Northern power station at Port Augusta where the sun-staring open path measurement was able to correctly estimate emissions while the more sensitive in-situ measurements were not.

There is also one more practical advantage of open path measurements. 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 as we separate sources and measurements. Thus, if the region near the putative source is inaccessible (e.g. offshore) then we may get only a little information on that source. Horizontal open path methods can potentially measure concentrations closer to inaccessible sources including directly overlying a potential offshore source.

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

In any case the information in the open path measurements relies on differences either from other paths or fixed points. To this end it is critical that the open path measurements 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 be used to calibrate the open-path measurements by taking continuous measurements along a road between the source and a test reflector.

The use of Isotopes

The atmosphere contains a distinct modern ^{14}C signature from solar and cosmic processes, while fossil fuels have lost all their ^{14}C. The dominant form of terrestrial photosynthesis (C3) also discriminates against ^{13}C so that biogenic material, (including fossil fuel) is depleted in this isotope relative to the atmosphere and richer in ^{12}C. 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, the placement of the storage site offshore hence has a distinct advantage compared to land-based sites for leak detection. Any leak will have a very different isotopic composition from nearby oceanic sources. Modern spectroscopic techniques can monitor atmospheric $\delta^{13}C$-in-CO_2 continuously. Thus any leak will appear as an anomaly in an otherwise oceanic sequence of measurements. This plus the continuous use of atmospheric models to interpret the measurements will enable us to distinguish terrestrial sources from a submarine biogenic release.

Planned Infrastructure Details

As currently planned, this deployment will consist of an open-path measurement system for atmospheric trace gases consisting of:

a. Bruker EM27 Fourier Transform Spectrometer configured for long open path measurements of CO_2 and CH4
b. Ecotech Spectronus FTIR in-situ analyser for simultaneous measurements of CO_2, CH4, CO, N2O and $\delta^{13}C$ in CO_2
c. Tripod-mounted telescope with pointing system and retroreflectors

These deployments will be a combination of a single site with in-situ and open path instrument and a series of retro-reflectors attached to convenient points for surveying across areas of interest. The base station will likely be co-located with a station of the seismometry network.

The Open Path system (Figure 6) enables mapping of sources and sinks of the key greenhouse gases in a radius around the installation including nearshore locations. This will define the pre-injection natural variation of these emissions in this region ("the baseline"). As well as characterising the onshore and nearshore area adjacent to the potential offshore storage site, it will provide a detailed and dynamic view of the emissions in a complex agricultural and natural landscape, with localised industrial facilities. The open path method is particularly suited for this since it can monitor concentrations remote from the instrument base station.

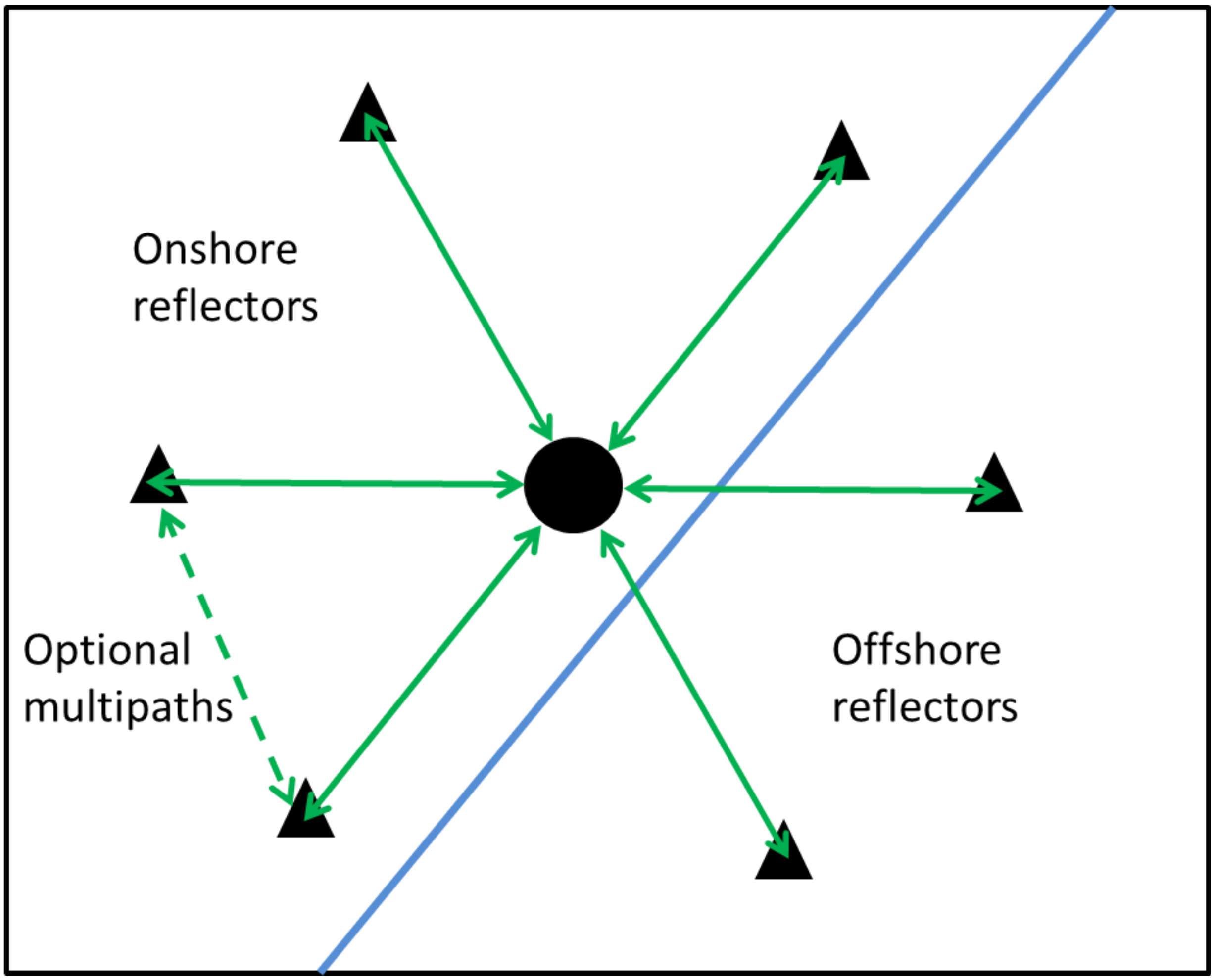

Figure 6: Open-path baseline concepts

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.

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. The open path method allows non-invasive, cost-effective and rigorous independent monitoring of dispersed sources including nearshore. Supporting its development will lower the cost of operation for future activities by automating monitoring and verification from a small number of instruments. The Open Path method has been tested over distances of a few kilometres. Establishing its feasibility over longer distances with in-situ verification is a research task in its own right.

Open path atmospheric monitoring may provide a cost-effective method for assurance monitoring of CO_2 injection and storage operations. 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 may provide data on local baseline CO_2 concentrations that may prove useful in the future.

The task of estimating point sources from atmospheric observations is a growing research area worldwide. There are a range of instrumental approaches ranging from satellite measurements (for detecting hitherto unknown but large sources) to in-situ measurements. There have been few applications of the technology to CCS but this reflects the scale of most CCS pilots until now.

The 5-year research program

This program allows for in-situ and long-path measurements of atmospheric concentration and isotopic composition of CO_2 in the vicinity of potential storage sites. These measurements will:

- Characterise the natural variability in atmospheric concentration so that changes can be attributed
- Use isotopic composition as a marker of deviation from oceanic background to attribute sources;
- Develop cost-effective methodologies for long-term monitoring of storage sites.
- Support the CarbonNet project and other CCS projects in Australia by providing cost-effective assurance of the stability of the storage.

The normal method for quantifying emissions does not assign a probability that an emission event is from a given source. We will extend the formalism to assign such probabilities. Thus we will be able to assign a probability that no leak above a certain rate has been detected and hence quantify and avoid false positives.

The proposed instrumentation is integrated within a larger-scale network for quantifying the emissions of the Latrobe Valley funded by AGOS and managed by the UOM. The University has already developed the capability for storing, interpreting and modelling in-situ data to attribute local sources and sinks of greenhouse gases. It will extend this methodology, in conjunction with the UOW, to apply to data from open path measurements. The open-path method proposed for the site enables a single instrument to monitor a broad area by the use of positioned retro-reflectors. It also allows the monitoring of potential nearshore sources using onshore instrumentation.

Timeline for the research

Year 1: We will first complete deployment of the AGOS segment of the atmospheric network, adding the design criterion that it should provide optimal boundary conditions for modelling the CCS site

Simultaneously UOW will make the necessary modifications to the Bruker instrument for open path use. They will explore the possibilities of allowing dual use for the instrument, solar FTS by day and open path use by night. The instrument will be tested against either aircore measurements taken as part of the Early Career Researcher Award of Deutscher from UOW or using a Picarro G2401 analyser.

Year 2: Deploy the open path and in-situ instruments on shore near a potential CCS storage site. For validation of offshore open path measurements we will use the G2401 again, probably deployed during a cruise to install part of the seismometry network.

Year 2-3: Baseline the site with at least one complete seasonal cycle of concentration measurements.

Year 4: Commence routine calculation of local source anomalies.

4. Marine Monitoring

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 (Chadwick et al., 2004, 2010, 2014, (Eiken et al., 2011), pressure (Chadwick 2012, Hansen et al., 2013), gravity (Alnes et al., 2008, 2011)., seabed imaging, marine magnetotellurics, and seabed and water column geochemistry. Chadwick and Noy (2010, 2015) have demonstrated how detailed conformance studies can be conducted with a richly-sampled 4D timelapse dataset.

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 (Blackford et al., 2014, Special edition of IJGGC vol 38 introduced by Taylor et al., 2015a). The QICS site confirmed the high detectability of migrating CO_2 plumes and bubbles in the subsurface, prior to it emerging at the surface (Cevatoglu et al., 2015). 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 bathymetry of the offshore Gippsland Basin out to the shelf break at approximately 100m water depth (Hill et al., 1998), and Figure 8 shows the detailed bathymetry in the nearshore zone where LiDAR surveys were flown in 2004 and 2008 for commercial navigation and coastal subsidence studies (DSE 2009).

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 (e.g. Mori et al., 2015). Ocean currents in the Bass Strait are largely wind driven and direction is closely aligned with topographic contours, i.e. alongshore. Current meter records show an oscillatory shore-parallel flow due to tidal (Figure 9) and weather events. 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. LIDAR mapping of the seabed in the nearshore (to between 4 and 7 km offshore) shows water depths to deepen rapidly to 10m depth within a few hundred metres of the coast and the majority of the potential storage sites lie within the 1515-45m depth range.

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, 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. The subtidal sandy expanses characteristics of this area are recognised as having high species diversity levels, with 860 species discovered within 10 m^2.

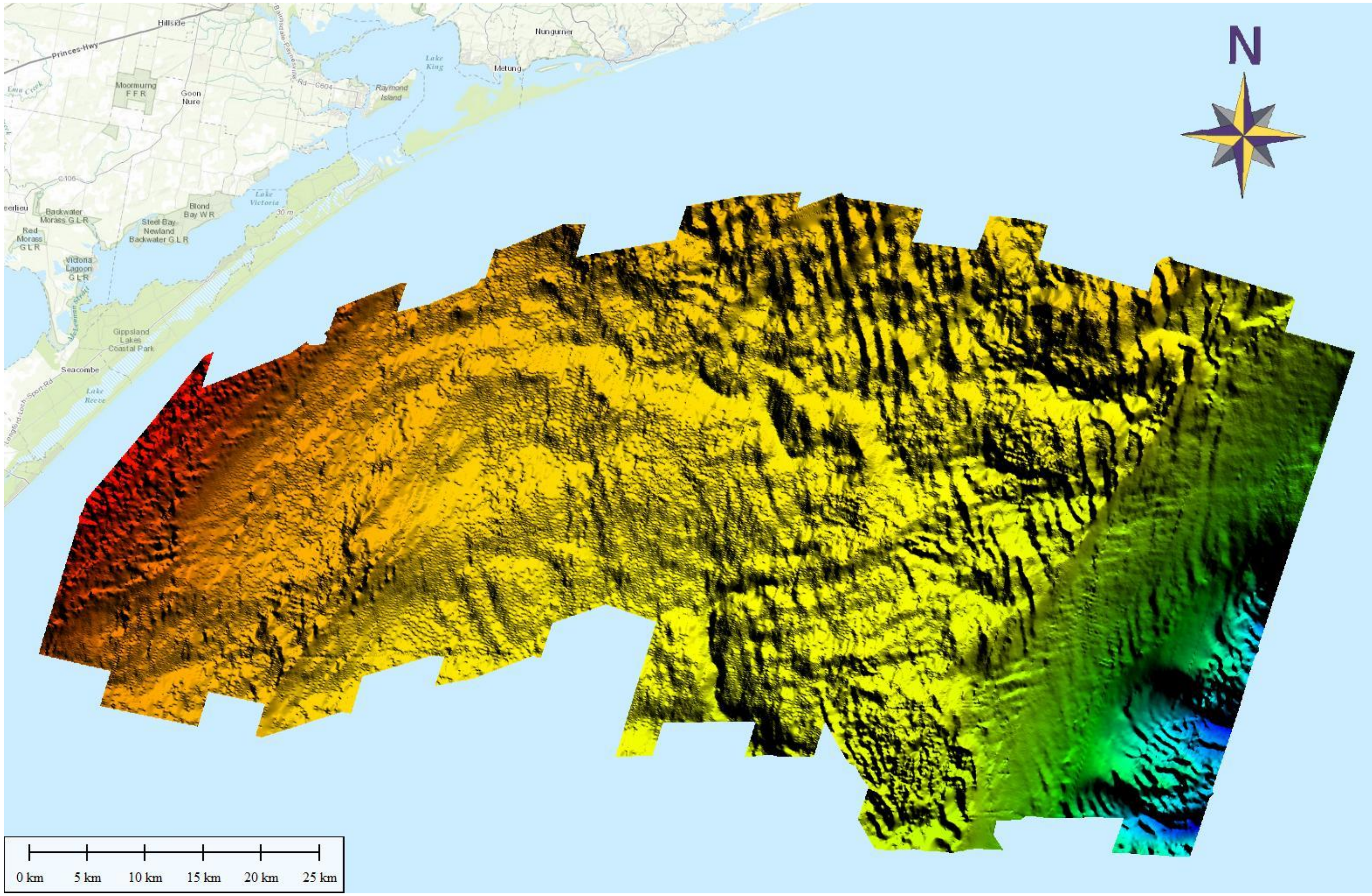

Figure 7: Gippsland Basin Bathymetry

Bathymetry data from marine 3D seismic surveys showing a wealth of detail including large (2 km wavelength) sand waves in the east of the basin where strong tidal and storm currents impinge on the shelf and the former course of the Latrobe River meandering across the shelf from top left to centre of the map. Data ranges from 20 m to 580m

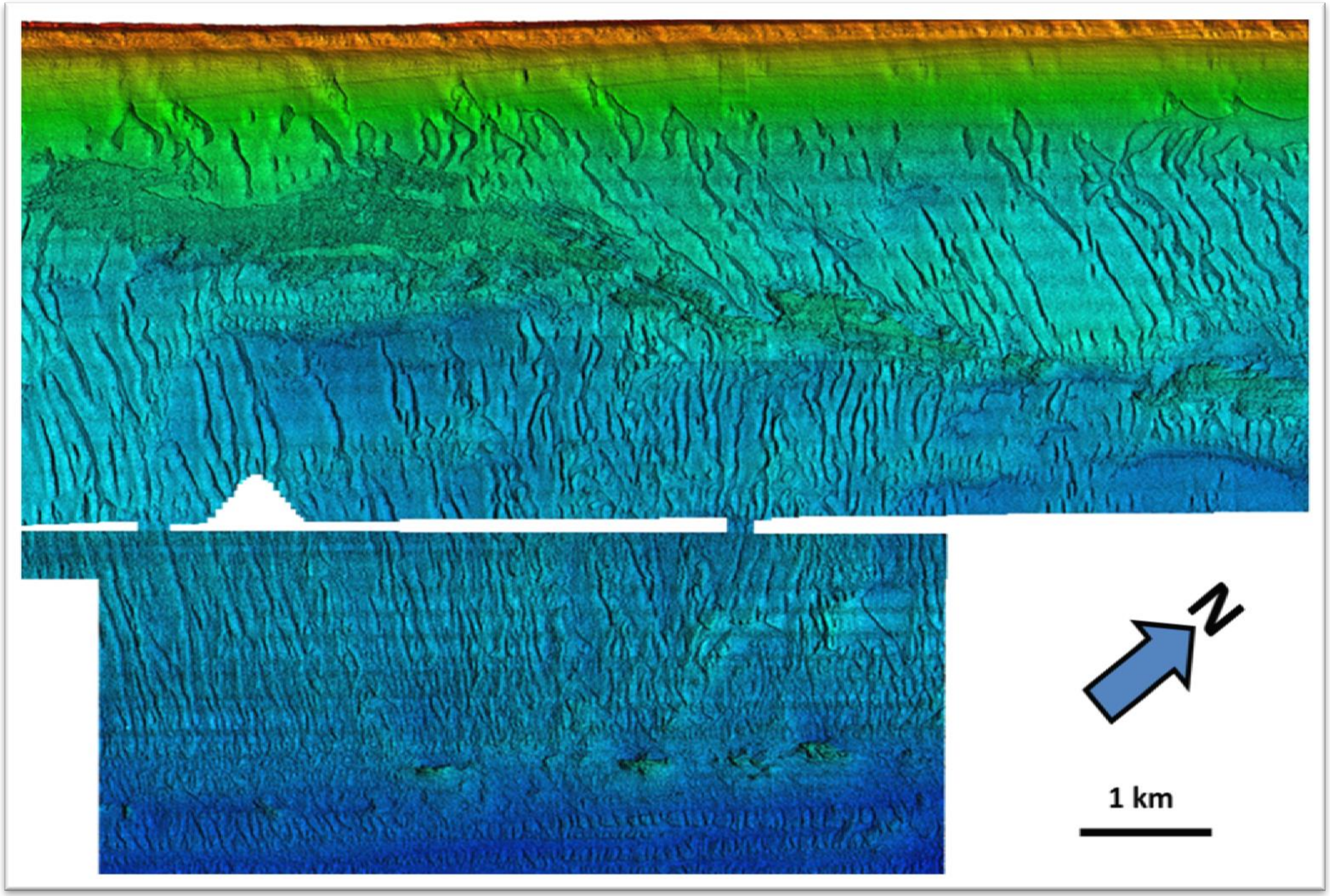

Figure 8: LiDAR nearshore bathymetry

Nearshore Bathymetry is defined by a 5m grid of LiDAR data. Smaller-scale features include hardgrounds, seabed mounds, inferred saline outflow channels and dredge scars

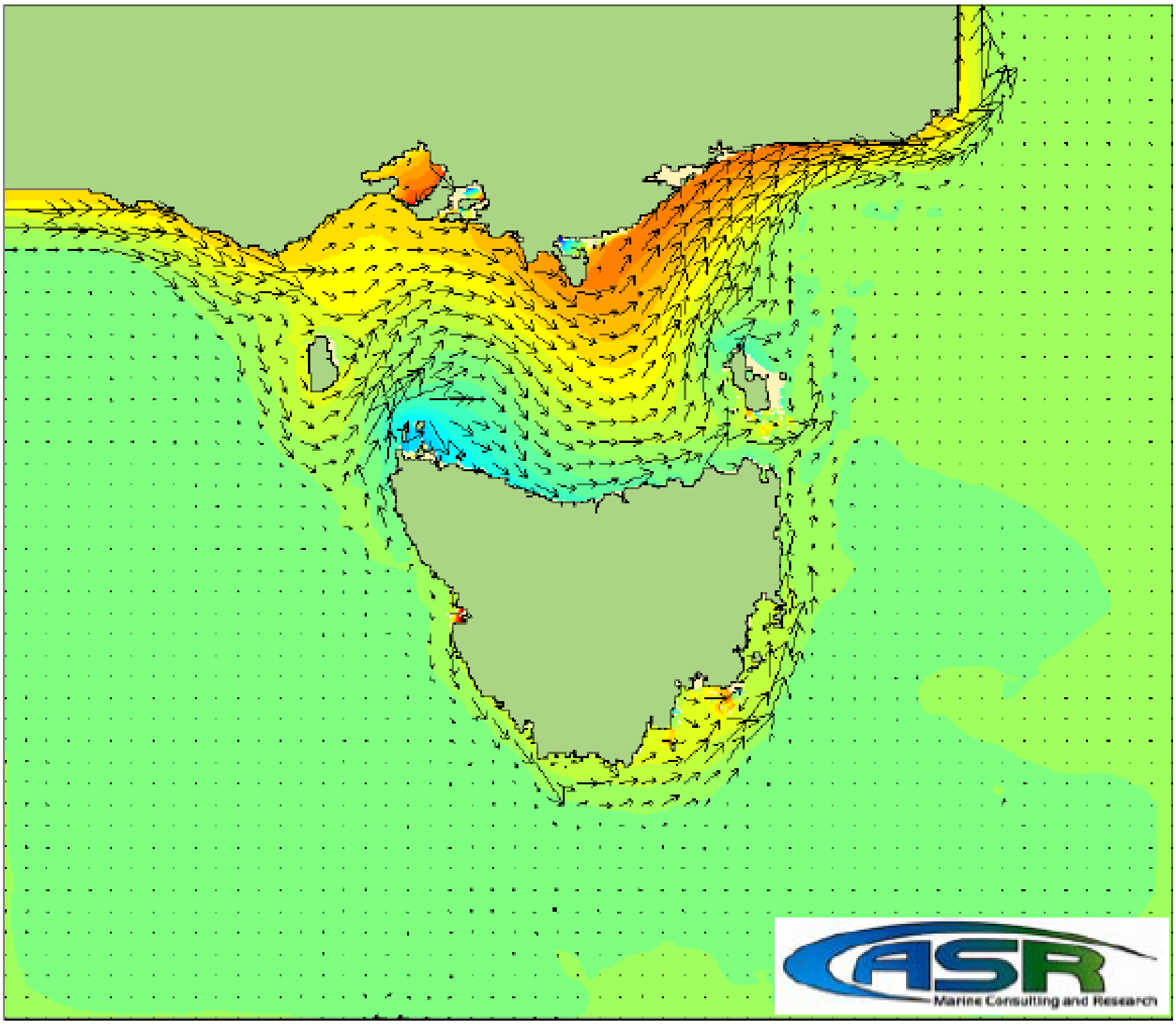

Figure 9: snapshot of Bass Strait tidal flow

Tidal flows in the Bass Strait are strong and oscillatory, parallel to the shoreline along Ninety Mile Beach. This image is of the SEA hydrodynamic model developed by ASR Ltd for GHD, showing currents through Bass Strait generated by low-frequency oscillations and wind. http://www.asrltd.com/projects/bass-strait-hydro.php

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, with sufficient density of measurements using a combination of fixed and mobile sampling platforms, measurement against the background of natural variability could be constrained to the level of instrumental analytical error, giving the lower limit of the size of a detectable leak (i.e. with acceptable 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 <10,000 tonnes of CO_2, and have the advantage of identifying any unwanted migration of CO_2 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 (Sellami et al., 2015, Dewar et al., 2015), and associated seabed geomorphic changes, were also the subject of a desktop study. Acoustic monitoring is a more local, but more sensitive technique (Bergès et al, 2015) for identifying areas where changes in seabed habitats could arise through changes in environmental forcing. QICVS observations showed, however that although there was a rapid response in microbial activity (Tait et al., 2015), there was only local change in macroscopic biota (Widdicombe et al., 2015, Kita et al., 2015) or metabolisms (Pratt et al., 2015), and recovery was rapid from any such change.

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.

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 (Atamanchuk et al., 2015, Shitashima et al, 2015) 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 (Blackford et al., 2014; Taylor et al., 2015). 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 (Figure 10) and hence detecting that a dissolved plume exists is likely to be easier than precisely locating a seabed source. 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.

Moored and mobile surface pCO_2 systems have demonstrated high accuracy due to their self-calibration against standard gases but repeat sampling is of the order of 10-30 mins which may not be sufficient to adequately resolve a plume. Queirós et al. 2015 have analysed the advantages and disadvantages of various technologies for pH sensing. We observe that submersible ISFET pH sensors provide stable pH measurements in seawater for prolonged deployments and at high accuracy. They can measure on the order of seconds rather than minutes, providing high-frequency measurement capability. 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 (e.g. Maeda et al. 2015), 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.

Wavegliders are driven by wave motion and can operate autonomously for months. The wavegliders can be directed remotely to target anomalies in CO_2 that may indicate a leak. These provide a more cost-effective platform for monitoring than fuel and labour intensive ship-based approaches and our modelling work shows them to be more effective than fixed moorings in detecting plume-related changes in seawater CO_2. 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.

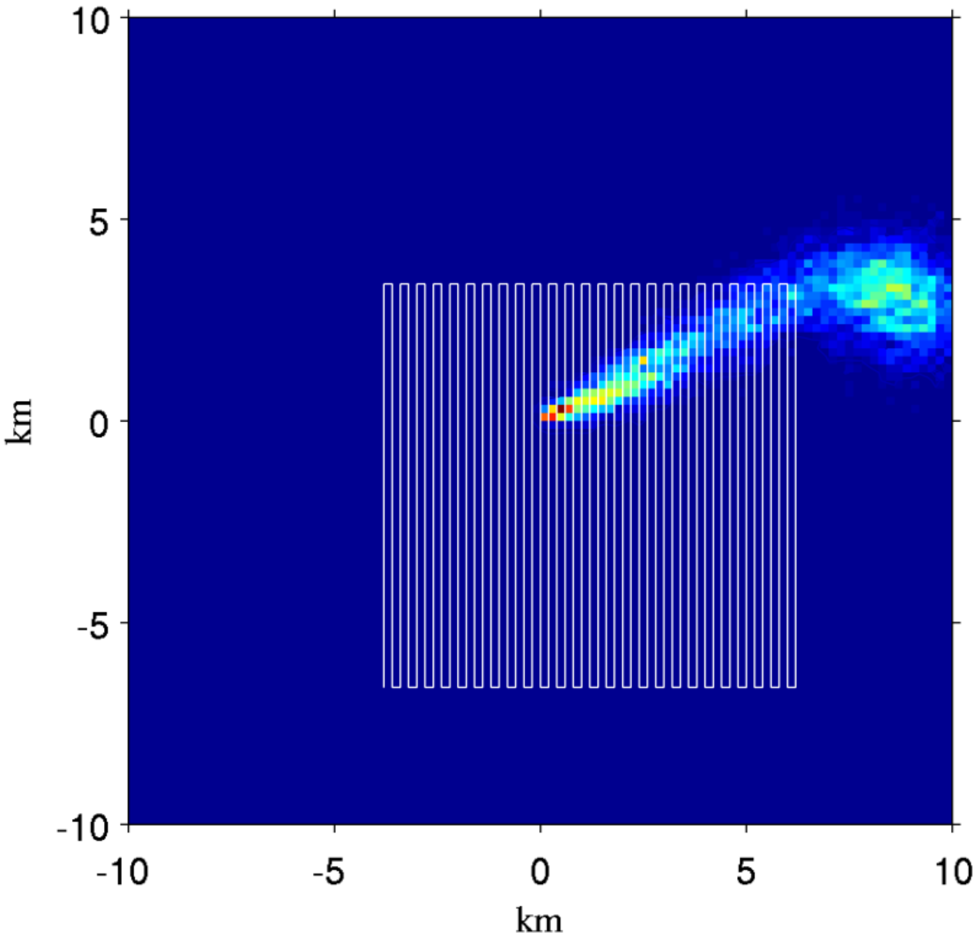

Figure 10: Example of integrated plume movement from CSIRO modelling

CSIRO modelling of a plume of released CO_2, dissolved in the water column. 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.

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.

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 (REF), 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. QICS observations show that shallow seabed pH changes strongly when affected by leaking CO2 (Lichtschlag et al., 2015) and recovers within about 1 month of leakage ceasing (Taylor et al., 2015b). Therefore, establishing robust baseline measurements around these locations may be valuable for ensuring the security of these features.

Such seabed monitoring systems may also be useful for establishing baselines at locations deemed vulnerable to the impacts of CO_2 leakage, e.g. rocky reefs, scallop beds, but these are not valid targets for ongoing ***assurance*** monitoring. The small sensor packages are robust and measure pH, dissolved oxygen, salinity and temperature. The salinity and temperature measurements are required to finalise pH data and with oxygen are useful for identifying seasonal and regional changes in-water masses that could result in pH variability that is unrelated to CO_2 leakage. The sensors can be deployed on the seafloor in depths from 1-60m and additional sensors (e.g. methane) can be added.

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. The same ISFET pH sensors could be used at depth as at the surface, however, pCO_2 sensors available for such applications do not have such high precision as those used for surface monitoring. ROV's also require support vessels and trained operators and hence have a higher deployment cost.

Effective attribution of changes in the seawater carbonate system will be an important consideration for marine M&V programs. Measurements of natural tracers assist in the attribution of measured changes in CO_2 / pH from sensors deployed in the water, with benefits realised through reductions in false alarm rates and better understanding of the drivers of baseline variability. 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, providing a verifiable method for identification of leaks and attribution of perturbations to seawater carbon chemistry. One important "reality check" of the marine ecosystem is provided by Phelps et al., 2015 who point out that even in the case of large-scale marine leakage, the pH impact on a semi-closed sea is still less than the effect of unmitigated emissions.

This pre-commercial research activity is also fundamental for calibration data and maintenance of field deployed sensors. This activity would require a range of sensors that are not suitable for field deployment but could be used underway on periodic ship-based surveys and for laboratory analysis of collected water samples.

The measurement of total alkalinity (potentiometric titration) and total dissolved CO_2 (coulometry) are needed for calibration of in-situ pH and pCO_2 sensors and will be required to quantify the size of any leak that might occur and to determine if leakage is influencing the dissolution of sedimentary carbonates. Cavity ring-down spectrometry allows the measurement of a number of tracers including the stable isotopic composition of dissolved CO_2 (δ13C of CO_2), the oxygen isotopic signature of water (δ18O of H_2O) and dissolved methane. The δ13C of CO_2 is useful for distinguishing fossil fuel derived CO_2 from background seawater CO_2 due to the different naturally-occurring isotopic signatures. The δ18O of H_2O, dissolved methane, and radon (measured by radioactive decay) are potential indicators of porewater or submarine groundwater discharge that may be linked to natural variability or leakage.

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. 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 is 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. Unravelling the relationships between oceanographic water masses, primary production (which can be monitored using optical satellites) and carbon dynamics will be fundamental for statistically constraining carbonate system data and reducing false alarm rates in leak detection, as well as attributing changes in the carbonate system to non-CCS related drivers. Diagnosing and tracking detection anomalies will also require high-quality coupled hydrographic- biogeochemical models of the nearshore. CSIRO already operates such models for the Bass Strait but confidence in their outputs for anomaly diagnosis and operational decision making will require additional high-quality baseline data. Thus, having a fixed mooring with acoustic sensors to measure current velocities and tidal dynamics (ADCP, AWAC) together with vertically-resolved temperature and salinity structure of the water column using vertically profiling or fixed CTDs and thermistors and associated measurements indicative of phytoplankton biomass (chlorophyll fluorescence, optical properties, nutrients) presents an efficient means of generating this data, particularly when coupled with the chemical measurements described above.

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) and provide powerful methods for (a) detecting the presence of bubbles from a leak, both in the water column and in sediments and (b) for mapping the shape and acoustic properties of the seabed. 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. Well-tuned acoustic monitoring could therefore be important for providing early detection of leakage and for pinpointing sources of leakage.

Understanding the sensitivities of acoustic processes for detecting seabed anomalies above baseline variability will be a key component of our research plan, e.g. through gas release experiments at existing well-characterised locations away from Gippsland.

Equipment required includes multi-frequency, broadband split aperture acoustic systems for detecting bubble signatures, pinpointing bubble plumes and estimating the composition and size of the bubbles (to quantify dissolution rates). ROV-mountable underwater sonar will be required to validate and image any bubble plumes and determine their source (biological, natural seep, CCS leakage). CSIRO's existing multi-beam echosounder equipment can be used to seek bubble plumes and at the same time to swath map the seabed to provide a baseline of habitat type and variability. Alternatively, timelapse LiDAR surveys offer an opportunity to study larger spatial scales of seabed change.

Predicting and measuring impacts on benthic communities.

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.

However, low level chronic impacts would more likely manifest through subtle ecosystem changes that may be better detected using state-of-the-art molecular meta-barcoding approaches that can sample across the whole ecosystem, from microbes to higher trophic levels like fish, and provide an integrated view of perturbations. These approaches have matured substantially over the past few years and now provide a rapid and cost-effective solution to environmental monitoring.

A key aspect of attributing observed biological changes to CO_2 leakage is understanding what a particular impact may look like. To this end we also propose to undertake growth experiments on target commercial calcifying species. The results will help quantify the scale of leak that would be needed to cause significant damage to these commercially-valuable species.

The 5-Year Research Plan

The proposed research would be achieved in four phases: (1) procurement of state-of-the art sensors, instruments and monitoring platforms; (2) sensor integration, gear testing, protocol development and familiarisation of operating procedures for the assets; (3) development and testing of methodologies for MMV using these assets including preliminary baseline assessment, and (4) initiation of baseline monitoring and implementation of a trial MMV program utilising the assets.

The initial and primary focus of this project will be the nearshore Gippsland marine environment. We also seek to leverage other research programs and collaborative opportunities around Australia and internationally for implementing stages 2, 3 and 4 of the research plan, i.e. developing and testing methodologies, gaining experience with the assets and implementing a trial MMV program. Locations are planned in the nearshore Gippsland Basin, at CSIRO's established test site at Maria Island, Tasmania, or other areas of CCS development (e.g. Barrow Island, WA). At Maria Island, a controlled CO_2 release experiment may be conducted to test the technology integration and detection limits of various technologies as described above. The knowledge gained from undertaking this project will inform the design of offshore M&V programs in Australia and internationally. In Phase 3, An extended sea trial of the sensor-equipped platforms would assess statistical distributions of environmental variability for key parameters required by detection algorithms. Acoustic, ROV-video and grab systems would be used to characterise the structure of seabed features (pockmarks, biological-origin bubbles in sediments, etc.) to build up a statistical distribution of baseline variability associated with these features. Chemical sensors on mobile platforms provide statistical distributions of variability, particularly at high spatio-temporal frequencies, i.e. in the frequency range not covered by existing baseline measurements of CO_2 in Bass Strait. Data collected would be analysed to make recommendations on sensor payloads, deployment and operational methods (e.g. search patterns).

Baseline mooring data will be used to update models of the site and water body dynamics to ensure their adequacy for use in the M&V program. Biological samples for rapid-assessment molecular analysis would also be used to compare alongside traditional ecosystem baseline assessments to test the compatibility, redundancy and complementarity of these approaches. Experimental work may also be undertaken using CSIRO mesocosm facilities to determine the impact of CO_2 release on local shellfish populations (including screening for a range of biochemical and molecular markers) providing an expected biological 'leak signature' and impact assessment for these populations.

In Phase 4, previous results will be used to design and implement monitoring strategies and technologies at the seabed and in the water column. Establishing baselines will be an important part of these operations, and the variability and predictability of natural systems will help refine the monitoring plan as experience is accumulated. Verification and Assurance monitoring will both be evaluated, with a focus on determining false alarm rates and thresholds for further action. A database of statistics on anomaly detection rates, false alarm rates and ecosystem trends and variability would then be built up for chemical, physical, acoustic and biological data. The results of these would be assessed during periodic reviews of the baseline program and used to provide ongoing refinement to the program.

5. 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*** actually observable 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 (Mabon et al., 2015). Blackford et al. (2015) summarise the QICS experiment and its observations with three key points:

- 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. One important “reality check” is provided by Phelps et al., 2015 who point out that even in the case of large-scale marine leakage, the pH impact on a semi-closed sea is still less than the effect of unmitigated emissions.

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.

There is significant value in preliminary base-lining of natural seismic activity in the Gippsland nearshore region as a precursor to future commercial development of CO_2 storage sites. Establishing near-coastal noise levels from sources such as wind and waves in the context of local ground conditions (unconsolidated dune sands), requires local networks that can distinguish seismic signals from background noise.

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. For instance, atmospheric measurements of CO_2 over potentially long open paths can supplement more local measurements in the water column and at the seabed beneath that atmosphere, while seismic and micro-seismic measurements of local activity can serve to give warning of unexpected subsurface events which would lead to a more intense focus on near-surface MMV to check if those deep events had any adverse consequences.

A preliminary science definition phase for marine MMV in nearshore Gippsland is now underway, funded by ANLEC, assessing existing datasets to clarify options for monitoring strategies. This ANLEC study is investigating which mix and type of assets (onshore installations, fixed moorings, manned craft, robotic vessels and lab work) is best suited to the area.

Studies such as these will be required by global CCS activities across a variety of marine environments related to different CCS storage sites. They are specifically needed within Bass Strait. The baseline data collected will also improve environmental modelling capabilities and aid future monitoring design.

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. Firstly, testing the ability of state-of-the-art monitoring approaches to separate background environmental variability from leakage will be a fundamental benchmark for MMV. Secondly, the sensors and platforms are portable and could be deployed at other potential subsea CCS sites to aid development of local MMV programs. The data required 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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