

Developing a monitoring and verification plan with reference to the Australian Otway CO₂ pilot project

Kevin Dodds*, Tom Daley**, B Friefeld**, Milovan Urosevic***, Anton Kepic***, Sandeep Sharma****

*BP formerly CO2CRC/CSIRO, **LBNL, ***CO2CRC/Curtin University, ****CO2CRC/Schlumberger

Introduction

The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) is currently injecting 100,000 tons of CO₂ in a large scale test of storage technology in a pilot project in South Eastern Australia called the CO2CRC Otway Basin Project (Otway). The Otway Basin with its natural CO₂ accumulations and many depleted gas fields, offers an appropriate site for such a pilot project. An 80% CO₂ stream is produced from a well (Buttress) near to the depleted gas reservoir (Naylor) used for storage. The goal of this pilot project is to demonstrate that CO₂ can be safely transported, stored underground and its behaviour tracked and monitored. The monitoring and verification framework has been developed to monitor for the presence and behaviour of CO₂ in the sub-surface reservoir, near surface and atmosphere. This monitoring framework has been selected to address the areas identified by a rigorous process of risk assessment and subsequently verify conformance to clearly identifiable performance criteria. These criteria have been agreed with the regulatory authorities to manage the project through all phases addressing responsibilities, liabilities and to provide assurance of safe storage to the satisfaction of the public at large.

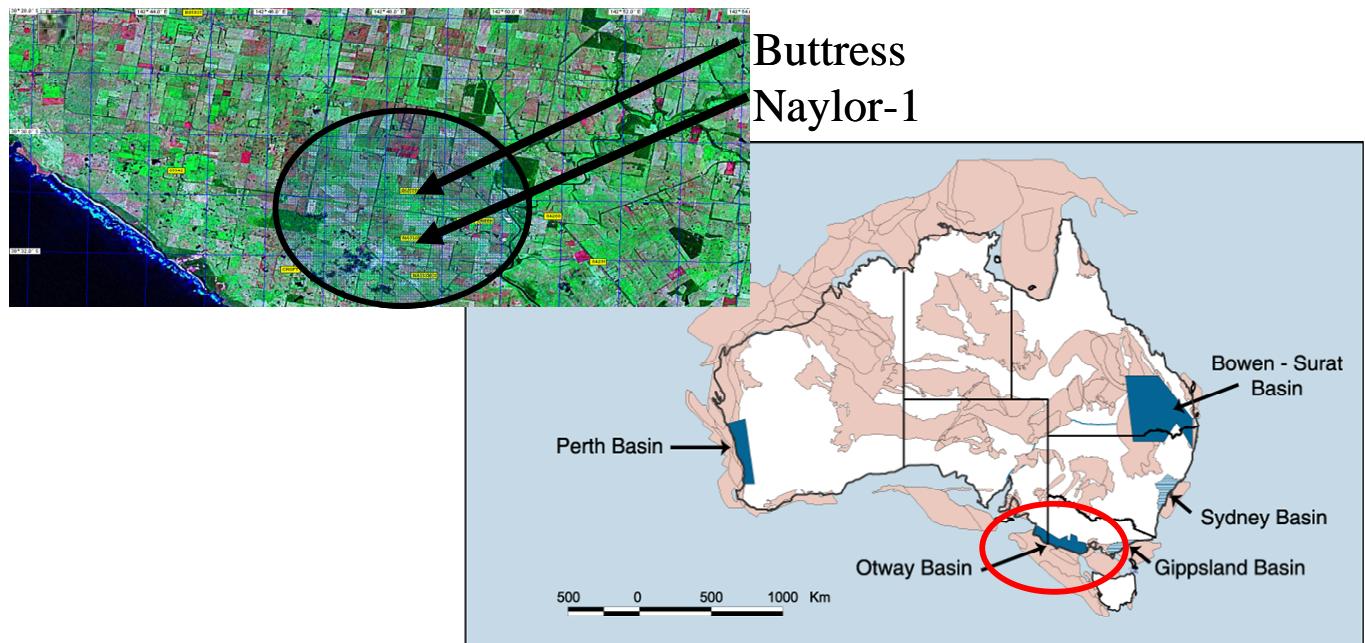


Figure 1. Site location showing location of Buttress CO₂ producer 3 km from Naylor-1 observation well Naylor 1, 2-3 km distance away. The Otway field is a gas producing field onshore Otway Basin in South-Eastern Australia.

Many aspects of the proposed monitoring will be discussed and this paper will provide an overview of the whole plan, with reference to progress in baseline measurements. An extensive range of established direct and remote sensing technologies deployed on surface and in the borehole are being used for repeat assessments from a reservoir, containment, wellbore integrity, near surface and atmospheric perspective. These involve seismic, microseismic, petrophysical well logs and geochemical sampling including tracer and isotope analysis, plus associated forward modelling. The presence of naturally occurring CO₂ in the Otway area makes it more difficult to identify injected CO₂. A regional survey of the distribution, type and origin of existing CO₂ will be carried out through soil gas sampling. The areal consequences of CO₂ migration and trapping are being addressed through characterization of the hydrodynamic properties of the region. The connectivity and fluid migration time scales of the potential fresh water reservoirs are being established using all available (and appropriate) well pressure and geological information. The Otway project has been selected as one of the Carbon Sequestration Leadership

Forum (CSLF) projects reflecting its global standing.

Background

The commercial oil and gas leases (tenements), in the Otway Basin in Victoria, selected for the pilot project, are in an undeveloped CO₂ field (Buttress), which is the source of CO₂, and a depleted gas field (Naylor), which is the injection/containment site (fig 2). The extracted and separated CO₂ stream is transported by pipeline and injected into a new well (CRC-1); drilled down-dip of the existing well; into the depleted Waarre reservoir in the Naylor field at a depth of approximately 2000 metres. The existing shut-in production well (Naylor-1) is being used as the monitoring well. Characterization of the site has involved the collection of a large quantity of geological, geophysical and other regionally relevant data and the construction of static and dynamic reservoir models. The regional formations provide an excellent porous and permeable geological formation that provides a highly suitable reservoir system for CO₂ storage. In summary, the site assessment results, indicating that the Waarre Formation is a suitable site for CO₂ storage, conclude the following key attributes of the site. There are no significant faults evident in the wells at the Waarre C level; there is a fairly uniform Waarre C thickness. The local and regional seals have contained a number of natural CO₂ accumulations in the eastern Otway Basin over geological time. The storage reservoir has enough porosity and permeability to be able to accept the injected CO₂ at rates forecast. The injected CO₂ is predicted to move updip from the injector location and migrate to the crest of the fault block and accumulate below the residual methane gas cap in the vicinity of the existing Naylor-1 well. The selected site has the major advantage of being onshore rather than offshore, allowing the project research teams to test and further refine the monitoring and verification techniques at a more accessible location.

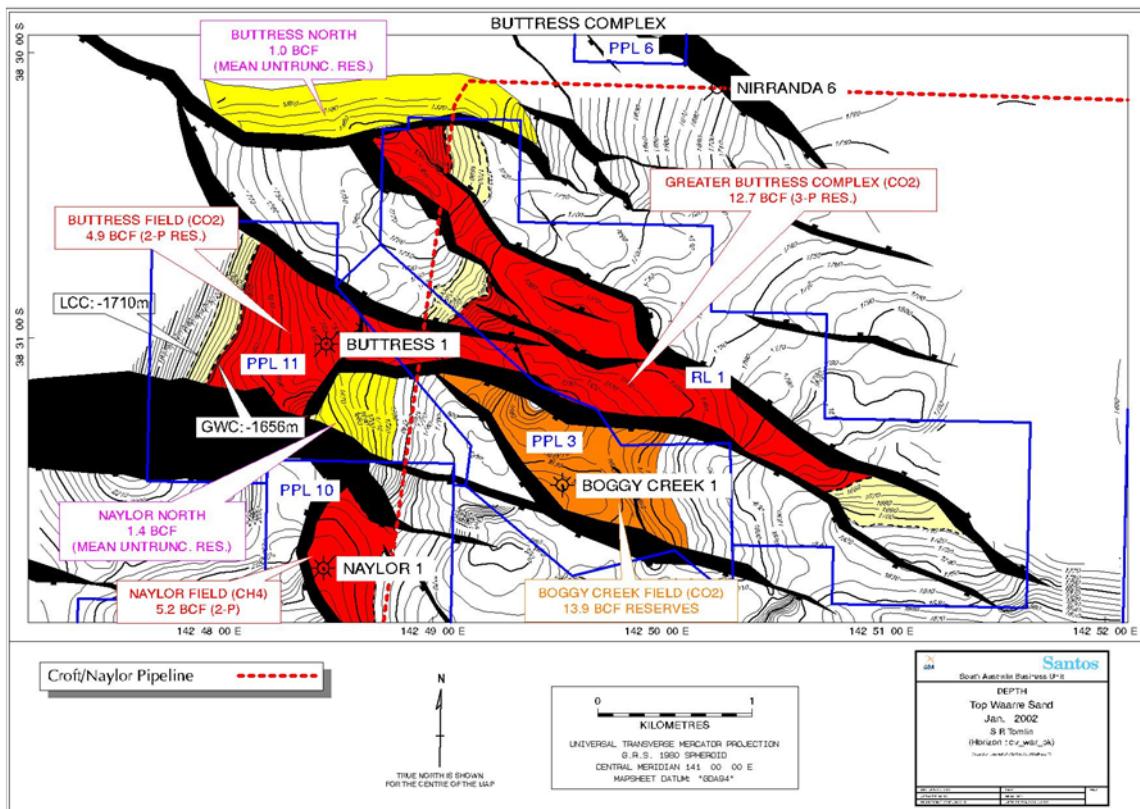


Figure 2 Top Waare sand structure map. Compartmentalised field provides a nearly pure CO₂ source in Buttress and within 2-3 Km a gas reservoir with old producer, Naylor 1. This latter well became the monitoring well.

Pilot Project Risk Assessment

A comprehensive risk assessment has been undertaken for all stages of the Otway before commencing CO₂ injection. A systematic approach has been taken to risk assessment for the Otway considering both the engineered and natural systems. The engineered systems consist of the wells, the plant, the gathering line while the natural system includes the geology, the reservoir, the overlying and underlying formations and the groundwater flow regimes. Under the qualitative risk assessment approach, a listing of the potential risks, their specific issues and potential consequences was created. Mitigation measures were then defined to bring the risk levels down to acceptable levels. This was supplemented by a quantitative risk assessment (QRA) where probabilities assessed through Monte Carlo simulation were assigned to specific risk events and simulations run

to consider the range of impacts.

The qualitative assessment is developed through a “risk register” designed to cover all aspects of the project from the initial planning and pre-implementation, production, processing, transportation, drilling and injection risks, as well as personnel and decommissioning risks. Extensive geoscience work suggested that the source and sink are able to meet the project demands with high certainty. The area is not new for petroleum-type activities and there are several production wells, a gas injection and storage site and processing plants in the immediate vicinity of the project site that have been working safely for years and that are accepted by the local community. Long-term containment needs were assessed through an evaluation of the potential natural and man-made leakage pathways, their likelihood of being activated, and an assessment of the amount and duration of any leaked volumes. Natural pathways include permeable zones in the seal, faults either existing or caused by regional over-pressurisation or earthquakes. Incorrect mapping of the migration direction and exceeding the spill point can also be causal in allowing the CO₂ to migrate beyond its intended area. This risk is minimal as Naylor is a depleted oil/gas field which has previously held more fluids than are being injected and probably for many millions of years. There are also multiple barriers between the storage reservoir and shallow water aquifers.

The quantitative risk assessment follows the RISQUE method (Bowden et al, 2004), which is a systematic process that uses a formal group of experts to provide quantitative judgments that are incorporated into a risk analysis and management framework. The basic approach to this process is to characterize and quantify risk both in terms of likelihood of identified risk events and also their consequences. The “expert panel” assesses all available information against a list of containment risk issues. This list is used consistently for different sites, and hence provides a means to quantitatively compare different sites for containment risk. Overall, the risk analysis demonstrates that the Otway has low risk events with minimal consequences. The planned monitoring addressed risks by monitoring at the wells, for the potential of overpressurisation and by monitoring for the plume migration pathway.

Monitoring and Verification Role

The goals of a monitoring framework is to provide a comprehensive set of information from direct measurements and remote sensing of the process of injection and storage of CO₂, such that we can appropriately document the complete storage process to establish the safe transport, injection, containment of CO₂ and the subsequent safe abandonment and restoration of the site. Within this function we must meet the requirements of the Regulatory Impact Statement 2004 from the Commonwealth Organization of Australian Governments (COAG) (Morvell, G., 2006) that for the purposes of monitoring and verification, a regulatory framework should:

- Provide for the generation of clear, comprehensive, timely and accurate information that is used to effectively and responsibly manage environmental, health, safety and economic risks and to ensure that set performance standards are being met; and
- Determine to an appropriate level of accuracy the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of fugitive emissions

The range of monitoring technologies comprises an integrated framework of diverse methods and measurement systems crossing many disciplinary boundaries. We have categorized them by their means of measurement; either remote, or direct sampling, or by their domain of operation, of which there are three. The first is the sub-surface domain to monitor and verify the deep injection and migration behaviour of injected CO₂, from the surface or borehole. The second is the near-surface domain comprising sampling and remote measurements to verify the non-seepage to shallow zones and soils again from surface and borehole. Finally the atmospheric domain, comprising a baseline characterization of seasonal and diurnal variation of existing gas distribution and composition accumulated over suitable time which can be monitored by point source gas sampling, coupled with dispersion modeling or by spectral absorption and infra red detectors locally or by aircraft and satellite. The monitoring technologies are deployed in a number of modes across the project lifetime. Monitoring can be categorized into baseline and operational monitoring. While verification monitoring consists of both subsurface and environmental confirmation of performance criteria. (fig 3)

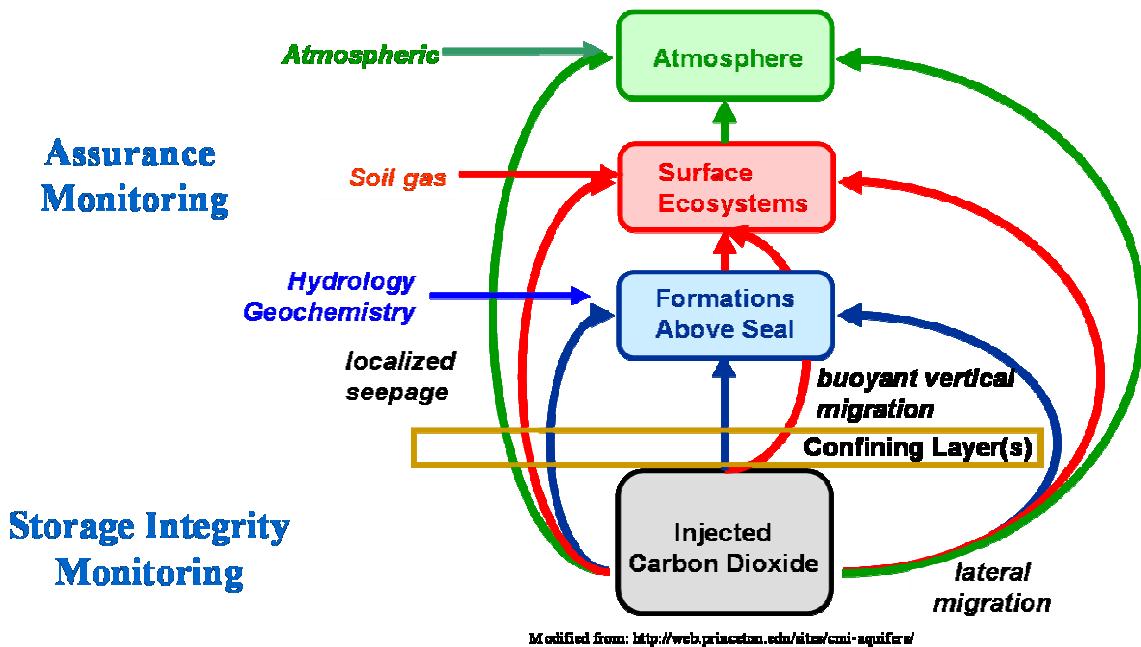


Figure 3. Monitoring and verification domain of application. There are three domains for monitoring and multiple pathways from reservoir; up the borehole, around and through the seal into potential potable aquifers and possibly to surface.

Pilot Project Phasing and Regulatory Performance Indicators

In discussion with the appropriate government regulatory authorities the project work scope has been divided into four project phases which reflect the focus of the project on storage and related monitoring activities. Each phase completion is assessed by verification of performance against objectives:

- Phase 1A Pre-Injection
 - Establish injection and migration models and uncertainties
 - Establish the baseline measurements data base.
- Phase 1B Production and Injection
 - Environmental impacts within regulatory bounds
 - Injection/Migration within model prediction bounds
- Phase 2 Post Injection
 - Verified stable plume within model prediction.
 - Appropriate decommissioning certificate(s) from the authorities
 - Wells decommissioned as per regulation
 - Sites restored as per regulation
- Phase 3 Post Closure
 - No evidence of injected CO₂ within specified period.
- Phase 4 Longer Term
 - No evidence of injected CO₂ within specified period.

The role of monitoring and verification of performance for Phases 1A, 1B and 2 will require a continuum of high intensity monitoring activities. The transition from one phase to another will be dependent on well defined engineering determinants. Phase 2 will see post injection closure (or sale) of the CO₂ production Buttress well and decommissioning of the surface facilities. Monitoring tasks will be ongoing in the Naylor site to validate the transition criteria to Phase 3. The validation that the plume is now stable will come from log based measurements showing no evidence of CO₂ in the overlying formation beyond secondary containment. In addition fluid samples collected from existing deep water wells should show no evidence of the injected CO₂. There are four such wells. Soil and air samples collected in the proximity of the monitoring well (Naylor-1) and the injector (CRC-1) wells also show no evidence of the injected CO₂. Phase 3 is focused on public assurance and monitoring for long-term storage security. It is planned to augment an existing program of water well monitoring by the local water authority with testing of soil samples near these wells for evidence of injected CO₂. If no evidence of the injected CO₂ is detected in 2 years, then this phase can transition into Phase 4. Monitoring for Phase 4 will continue to focus on public assurance through the augmented testing program in the deep wells as described above. Again, where there is no evidence of injected CO₂ for a further 2 years, this phase can terminate. These time-scales are pertinent for this project and may be longer for large scale storage projects. The project is currently at the beginning of Phase 1B. The injected CO₂ is magmatic in origin

and consequently it has a quite different isotopic signature than for CO₂ generated biologically and from fossil fuels, and hence can be discriminated.

Otway Subsurface Monitoring

The first task was to refine the uncertainties in reservoir properties. There has been a reasonable elapsed time between the original acquisition of 3D seismic and the subsequent production and shut-in of the Naylor-1 well. There is residual gas within the Naylor reservoir with uncertainty as to the gas-water contact. The presence of residual gas provides a significant challenge to direct detection of the CO₂ plume by seismic once it migrates out of the injection well water zone. More precise understanding of these properties will determine the monitoring options we have. Naylor-1 has been re-entered to establish gas water contacts with reference to a reservoir saturation log and the integrity of the cement bonds through casing and cement inspection logs. This provided the opportunity to test the viability of vertical seismic profiles (VSP) methods. A new injection well (CRC-1) has been drilled within 300 m of the monitoring well (Naylor-1). Data gathering activities include extensive coring above and through the top seal and reservoir. Openhole wireline logs, pressure measurements and fluid samples from the reservoir have also been taken. Pressure transient testing has been used to determine the hydrogeologic characteristics prior to injection of CO₂. The results have been used to modify the injection protocol. Cement inspection logs have evaluated, the integrity of the bonding of the cement. Downhole pressure and temperature gauges have been run to monitor injection conditions. Seismic geophysical monitoring for the Otway Basin Pilot Program (Otway) is being carried out in three distinct phases: prior to injection to establish baseline data; during injection ie between injection and breakthrough and post injection for comparison against the baseline data sets. The baseline data consists of a 3D surface seismic and 3DVSP acquisition. In collaboration with CO2CRC, Lawrence Berkeley National Laboratories designed and built an integrated seismic and geochemical sampling completion which was installed in the Naylor 1 monitoring well late in 2007. This equipment allows us to obtain both geochemical and seismic data during the injection period. (Fig 4). (Kepic et al 2007)

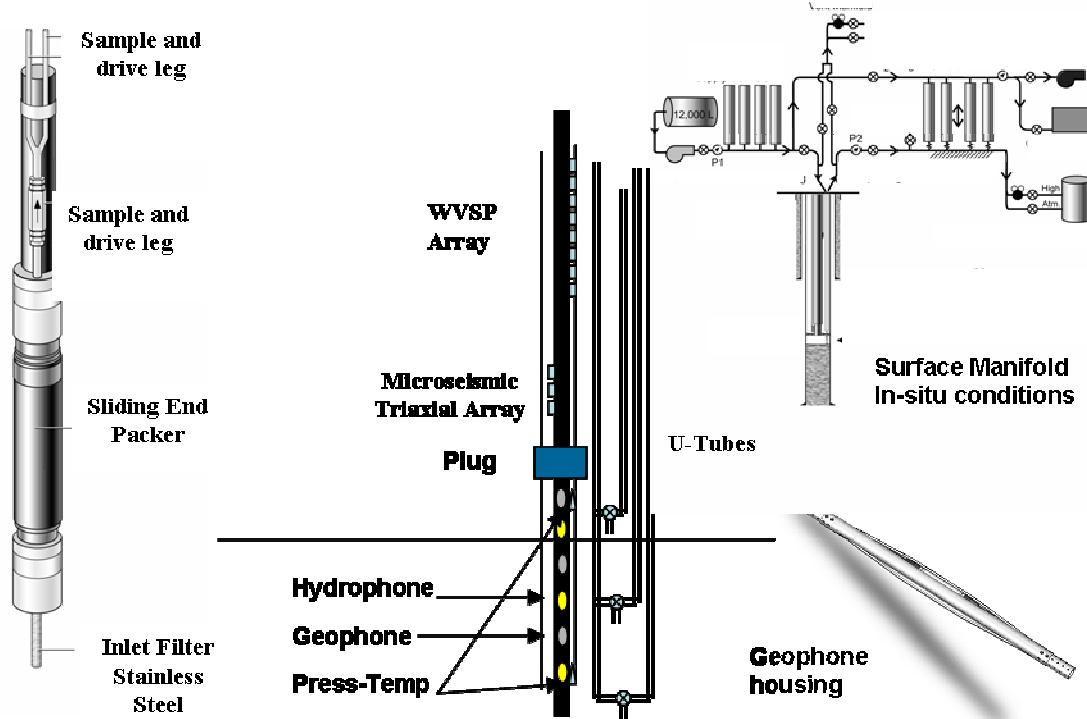


Figure 4. Integrated Seismic and Geochemical Completion showing U-tube downhole sampling, surface manifold and the integrated completion with diagrammatic u-tubes, seismic and other sensors. The horizontal line represents the methane water interface prior to injection.

This completion is designed to provide geochemical sampling at three distinct levels, combined with three types of geophysical monitoring activities. The geochemical sampling occurs through three sets of "U-Tubes" with inlets above and below the gas contact. There are also two sets of pressure and temperature sensors in these locations. The sampling occurs through one-way valves and the fluids are lifted by nitrogen to the surface retaining reservoir conditions. The first seismic activity addressed is an array of geophones at about 500m above the reservoir to provide the means to acquire walkaway data during injection. The second is a set of three triaxial geophones within 300m above the reservoir in an array to monitor for any microseismic events which signal changes in stress state associated with the injection and detect or rule out any signs of reactivation of the bounding fault ahead of time. The third consists of a set of hydrophones and geophones within the reservoir to look at high resolution travel times and changes associated with the changing fluid level at the monitoring well. The whole assembly was together with surface pressure control was brought together for deployment in October 2007, and was

successfully assembled and lowered over a 10 day period in quite adverse weather conditions (fig 5).



Figure 5. Assembling and deployment of the complete system was a complex and successful operation, these figures show the wellhead with flow tubes and cable connections, while on the right shows control of the u-tubes while inserting the integrated assembly

Preliminary VSP Acquisition

In favourable conditions surface and borehole seismic are important survey tools, as the geological formations and structures can be defined and quite subtle changes associated with the presence of the supercritical fluid can also be detected. We have forward modeled the expected seismic response (Li et al, 2006) and predicted the travel time differences associated with the CO₂ plume with the gas, well below the detectability of conventional acquisition. We have studied in the laboratory the elastic response of the reservoir under different effective stresses and for sub and supercritical CO₂ together with methane in comparison to Gassman prediction (Siggins, 2006). Prior to acquiring the 3DVSP we calibrated the performance of borehole data carrying out walkaway VSPs with multicomponent surface lines to tie back to the existing 3D seismic. The VSPs have provided higher resolution imaging (bandwidth up to 140Hz at target) and in particular help us to infer fluid properties from elastic amplitude versus offset (AVO) data. Corridor sections of the VSP traces, surface seismic response and synthetics show the resolution compared to the surface seismic. We were also able to extract very valuable shear information from the VSPs which is also displayed on the left with the compressional (P) response is compared to fast and slow shear response.(S₁ and S₂) in depth. (Fig 6), (Urosevic et al, 2007a)

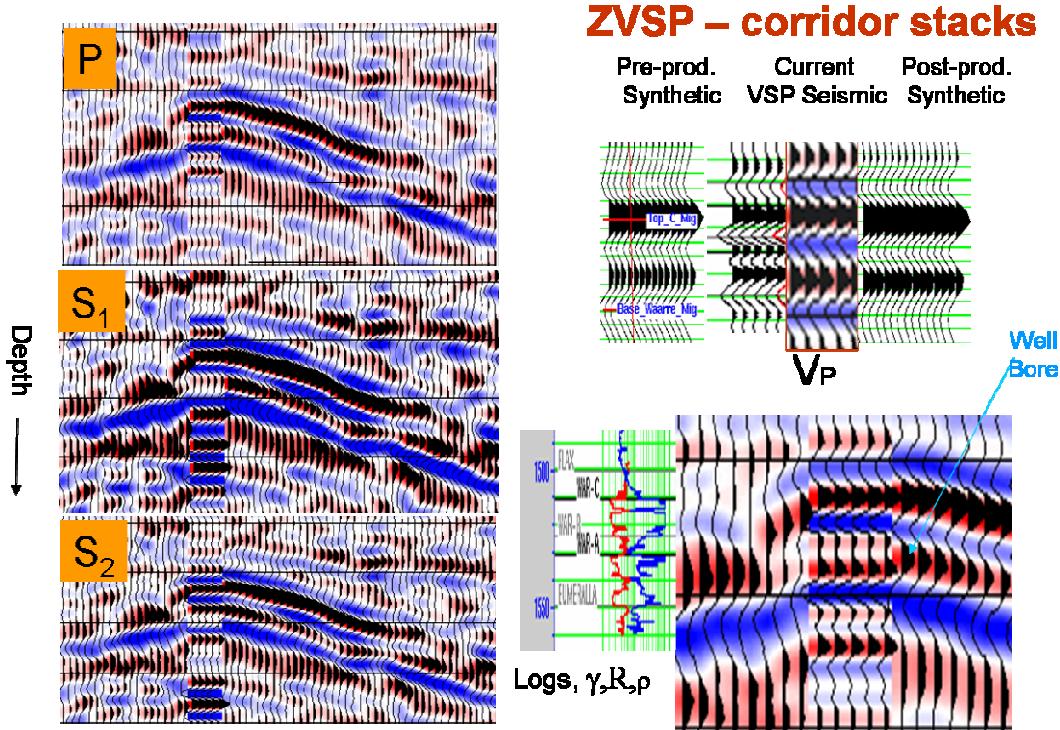


Figure 6. Surface seismic with inserted compressional and shear VSP stacks, the whole package is from 1500 – 1600 msecs

Downhole fluid sampling at the monitoring well through the integrated system's geochemical "U-tubes" is being carried out before, during, and after CO₂ injection. Both chemical and isotopic analysis is being carried out of both fluids and gases. The changes in the elemental and isotopic compositions are being used to monitor the geochemical reactions occurring in the reservoir, to establish the nature and amount of geochemical trapping of CO₂ (Perkins et al, 2006). The analytical results for tracers (both injected and natural) are used to confirm the arrival of the CO₂ plume at the monitoring well. In addition, their relative retardation provide a means to determine saturations in the region swept by the CO₂ plume, thereby showing the extent of gravity override versus uniform volumetric sweep. Tracers are also being inserted in the injected carbon dioxide stream. These will be significant in detecting movement beyond and through the seal, into overlying aquifers, soil leakage and atmosphere where that may occur. It is expected that each tracer will uniquely partition between the aqueous and supercritical CO₂ phases. If the partitioning between the phases is appropriate, the tracer may act as a precursor to the injection stream and provide an early signal of movement. A number of chemical tracers are currently being evaluated for injection in the supercritical carbon dioxide stream with detection limit, suitability, availability and health and safety as the primary concern, (Perkins et al 2006)

The presence of naturally occurring subsurface CO₂ in the Otway sub-basin makes identifying the injected CO₂ more complex. A regional survey of the distribution, type and origin of existing CO₂ is being carried out through an integrated program of soil gas sampling, hydrogeology, water chemistry and atmospheric measurements. Sampling is carried out over a defined grid and repeated several times per year (to account for seasonal effects), before, during and after injection. The areal consequences of CO₂ migration and trapping is being addressed through characterization of the hydrodynamic properties of the region. The connectivity and fluid migration timescales of the existing fresh water reservoirs is established using available hydraulic head, well pressure and geological information. This provides input into establishing fluid pathways, flow timescales and identifying flow barriers due to facies changes and faults. A sentinel network of atmospheric monitoring equipment has been set up to provide the environmental background against which anomalous sources of CO₂ can be detected. The proposed location and layout in the Otway Project has some significant advantages for the assessment of possible impact of atmospheric monitoring. It is in a rural region with the coast only 4 km to the southwest. SW winds are prevalent. The short fetch across mainly pasture or lightly forested land will minimise the CO₂ concentration variations resulting from ecological exchange. The CO₂ source well (Buttress), and other sources of CO₂, and their associated infrastructure, which may release CO₂ and other gases, are downwind of the proposed geosequestration well when SW winds prevail. The Cape Grim Baseline Atmospheric Pollution Station, (a WMO Global Atmosphere Watch station, operated jointly by CSIRO and the Bureau of Meteorology) has monitored atmospheric composition for decades and can be used as a baseline reference. A CO₂ analyser system, LoFlo (Francey et al 2003), which provides high precision continuous CO₂ measurements, provides the data stream from Cape Grim which will be compared with a similar system installed at the Otway site. The origin of observed CO₂ can be determined through use of atmospheric dispersion analysis (Hurley et al, 2005). The strategy consists of measurements of CO₂ and tracer gas concentrations up- and down-wind of the source plus an understanding of the dispersion at small scales (tens to hundreds of metres, influenced by micrometeorology) to larger scales (several kilometers, influenced additionally by mesoscale and synoptic winds). The CO₂ is of magmatic origin and can be distinguished by its enriched ¹³C isotopic content compared to that derived from ecological exchange, biomass burning and fossil fuel. (fig 7) (Watson et al, 2008)

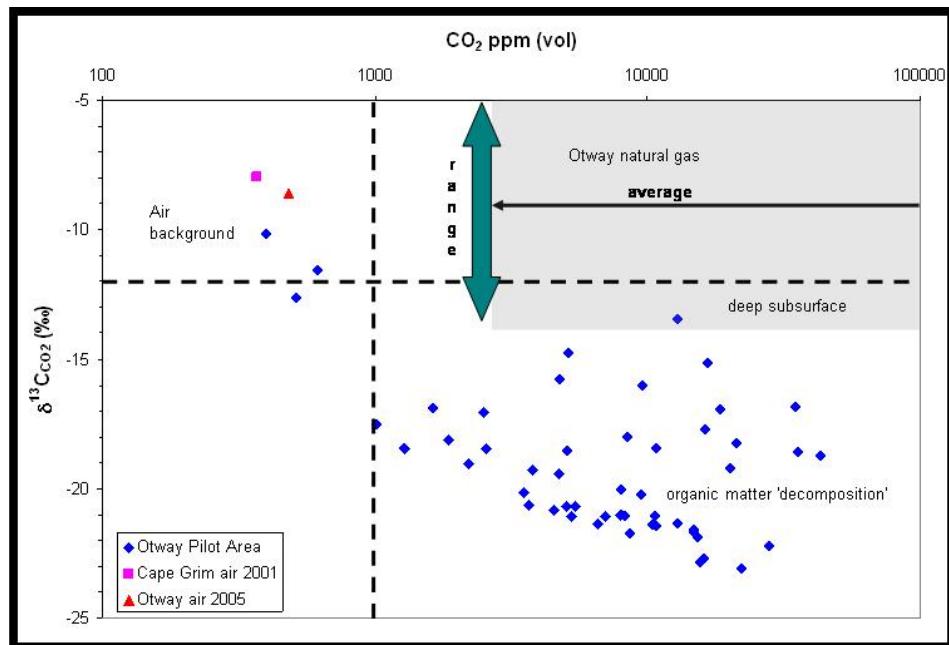


Figure 7. Soil sampling showing predominant biological signature

Establishing Repeatability for Time-Lapse Seismic (4D)

We established a test sequence to benchmark the performance of sources intended for use in both VSP and surface seismic. The first source, a minivibrator, was used for the VSP and a seismic line in 2006. The second was an hydraulic weight drop mountable onto a locally hired “Bobcat”. The choice of sources was primarily driven by being able to reproduce sources and locations over the lifetime of the project. Initial comparison of weight drop data in 2007 with the minivibrator data acquired in 2006 along the same line and occupying the same positions showed a 12 dB decrease in energy. (fig 8) (Urosevic et al, 2007b)

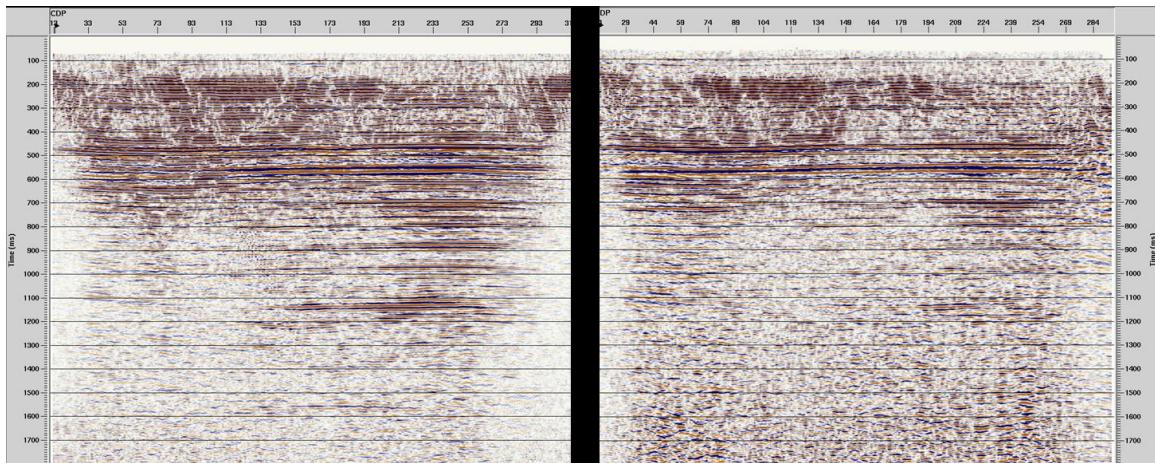


Figure 8. Comparison 2006 minivibrator source (wet) with 2007 weight drop data (dry)

Since we had already compared both systems in Western Australia showing very little difference in frequency response and energy, then we immediately drew conclusions that near surface conditions were responsible for the difference. The major difference, besides not reoccupying positions precisely, was that the 2006 data was acquired after a normal wet season while the 2007 data was acquired after a prolonged drought. In fact the water table had dropped several meters. In order to establish this supposition we then proceeded to retest the line now using the minivibrator. Near identical results confirmed the environmental problem of water table change was the culprit. (fig 9). The operational consequences of this trial were substantial. Given the considerable drop in energy due to water table drop, we were no longer able to image the target horizon well, and consequently, we postponed the 3D survey to when the environmental conditions were more comparable to when we acquired the initial survey in 2006. This was when there was more soaking rain to provide better coupling of the source signal to the subsurface. An important scientific outcome was to document the influence of the near surface on the data repeatability. This is critically important for time lapse-surveys, since we are looking for the differences from two identically acquired surveys, before and after injection.

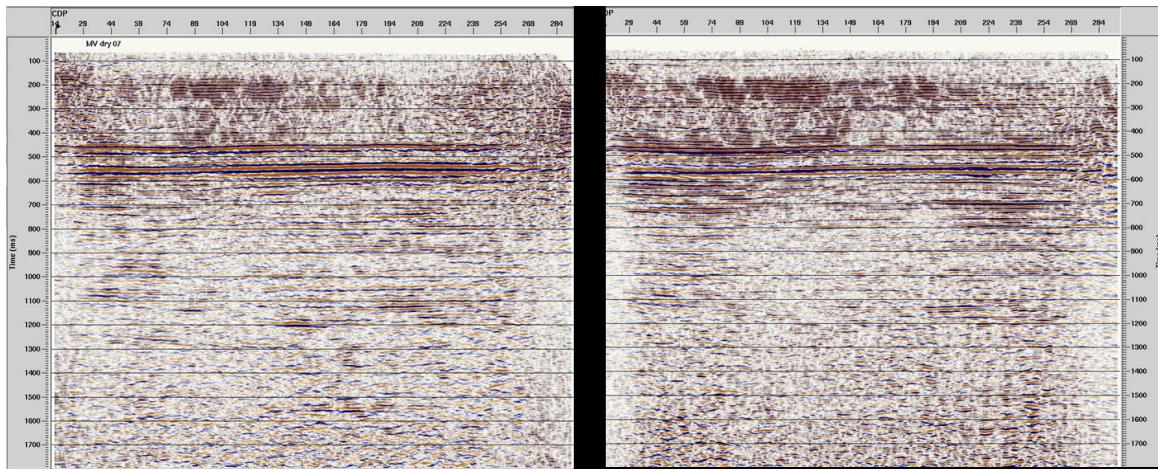


Figure 9. Comparison 2007 minivibrator source (dry) with 2007 weight drop data (dry)

Conclusion

The Otway Basin Pilot Project is currently providing the opportunity to comprehensively test all phases of a large scale geosequestration project. The project also addresses near-term and long-term monitoring issues raised by the necessary time of containment. This monitoring provides confirmation of performance objectives necessary to transition from phase to phase. The monitoring comprises established technology, but has also provided the opportunity to develop an innovative integrated geochemical and geophysical completion for the monitoring well. A comprehensive program of surface and borehole 3D seismic as baseline has been acquired in anticipation of subsequent time-lapse surveys. Management of the quality of the time-lapse data has been achieved by thorough pre-testing for repeatability factors. The latter testing program has shown that the repeatability of subsequent surveys as well as bandwidth are critically dependent on repeating the near surface environmental conditions of water saturation.

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