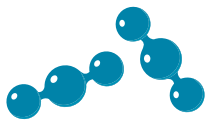


A NATIONAL INITIATIVE

# Enabling CO<sub>2</sub> storage for Australia



anlecr&d

Australian National Low Emissions Coal  
Research & Development

*A partnership between the Australian Government and Coal Industry.*

2010-2016



# Research Supporting CCS Deployment in Australia

## 2010

- Commonwealth and Coal Industry sign ANLEC R&D Funding Agreements
- Delivered with Department of Industry - EPRI Technology Cost Study for National Coal Council
- Otway 2 Huff-n-Puff experiment co-funded at CO2CRC
- Relationship Agreement signed for brown coal research in Victoria

## 2011

- Reported on flue gas quality and its control for Callide Oxyfuel Demonstration Project
- SW Hub CCS Flagship announced for Southern Perth Basin
- Commissioned study on environmental performance of amine based Post Combustion Capture
- Major initiative to reduce reservoir characterisation times by enhanced up-scaling workflows commences

## 2012

- Reported trace element speciation, partition and flow sheet impacts for Callide Oxyfuel Demonstration Project
- Delivered environmental regulatory review for Post Combustion Capture
- Reported on slag disposal and use from gasifiers
- Delivered Novel Capture Taskforce Report
- Published assessment of Oxy-CFB technology
- Estimated emissions to the atmosphere from amine based PCC processes for a black coal fired power station
- ANLEC R&D Strategic focus shifts to CO<sub>2</sub> storage
- CarbonNet CCS Flagship announced for Gippsland Basin
- ACALET Funding for CTSCo demonstration in the Queensland Surat Basin extended
- Co-funded report on CO2CRC Otway stage 2B - residual saturation and dissolution test
- Developed a state-of-art review of integrity of wellbore cement in CO<sub>2</sub> storage wells
- Delivered initial geo-mechanical modelling as part of the site investigation for CO<sub>2</sub> injection in the onshore part of the Gippsland Basin

### KEY

- Capture
- Storage
- General



## 2013

- Research validates lower cost options for oxyfuel technology at the Callide Oxyfuel Project Demonstration
- Updated 'EPRI Technology Cost Study' for ACALET and the National CCS Council
- Studies published showing emissions from amine based post combustion capture are lower than that from conventional power plants
- Pilot studies validate process control and operating parameters for stable performance of concentrated piperazine as a carbon dioxide capture agent
- Techno-economic study on the Direct injection coal fired engine completed
- Drilling of Harvey-1 well confirms unconventional stratigraphy
- Advanced geophysical data analysis at Harvey-1 and fault seal first order analysis delivered for the SW Hub
- Initial simulations of CO<sub>2</sub> storage and ground water flow in the Surat Basin, Queensland
- Interim assessment delivered on regional stress and predicted hydro-geochemical impact of CO<sub>2</sub> storage in the Surat Basin
- First results delivered on enhanced upscaling workflows using digital core assessments for the Surat basin
- Delivery of advanced core analyses for predicting CO<sub>2</sub> injectivity across prospective Australian basins

## 2014

- ANLEC R&D Funding Agreements extended to 2020.
- On-site measurements of trace element deportment on oxy-combustion for the Callide Oxy-fuel Project
- Guidelines delivered for estimating CCS Total Project Costs
- DICE fuel development research commissioned for pilot testing in 2017
- Novel contactor design proven to reduce costs for CO<sub>2</sub> capture
- Study demonstrates improved estimates of reservoir capacity enabled by more accurate use of tracers
- Recommended protocol for assessing resource interaction and management for CO<sub>2</sub> storage in existing reservoirs
- Desk-top study completed to inform SW Hub injection strategy
- Field validation of advanced seismic methods and analysis informs fault structures in the near-surface for the SW Hub
- First validated comparison of stratigraphic forward modelling with predictions from conventional approaches
- Dynamic seal capacity assessment delivered for the Gippsland Basin
- Published lessons learned from community level engagement for the SW Hub
- Preliminary near-shore aquifer modelling of CO<sub>2</sub> geological storage in the Gippsland Basin completed
- Feasibility and design assessed for robust passive seismic monitoring arrays for CO<sub>2</sub> sequestration

## 2015

- Callide Oxyfuel Project Demonstration data validates mechanisms for mercury removal in oxyfuel technology
- Delivered 'Strategic Country Review & Low Emissions Outlook' to inform export coal industry
- Co-funded updated 'Australian Power Generation Technology Cost Study for Australian Energy Stakeholders'
- Assessment shows chemical looping can deliver lower cost oxygen separation, though for power generation processes it remains uneconomic in the present carbon pricing environment
- Researcher patents alloy for a catalytic membrane reactor for hydrogen separation
- Assessments of geo-mechanical and geo-chemical testing shows prospects for enhanced injectivity in the Surat Basin
- Published updated monitoring well design for maximising long term acquisition of data
- Preliminary assessment of advanced processing and analysis of 3D seismic data delivered for the SW Hub
- Report shows using nitrogen as a surrogate for CO<sub>2</sub> in injection tests may overestimate reservoir capacity
- An assessment delivered on geochemical impacts and monitoring of CO<sub>2</sub> storage in low salinity aquifers
- Delivered scoping study for marine monitoring research supporting the Gippsland Basin
- Workflows and processing to deliver multi-scale reservoir characterisation in commercial software initiated
- Published pore-to-core upscaling methods for dynamic properties and integration from core to logs
- A desktop study of authigenic carbonates as natural analogues of mineralisation trapping in CO<sub>2</sub> sequestration completed

*This publication is supported by*



The Australian Government Department of Industry, Innovation, and Science through the National Low Emission Coal Initiative.



The Australian Coal Industry, through the COAL21 Fund managed by ACA Low Emissions Technologies Ltd (ACALET).

## ACKNOWLEDGEMENTS

The ANLEC R&D initiative is grateful to:

**The Australian Proponents of CCS** - The Executives and Technology Directors of CTSCo, Southwest Hub and CarbonNet who seek to deploy CCS in the Surat, Perth and Gippsland Basins respectively. They assist shape the relevance of the ANLEC R&D Research Program.

**The CCS Scientific Community** - The quality of ANLEC R&D outcomes are premised on excellent science and are a testament to the effort of all its contributing scientists.

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## Message from the Minister

I am pleased to introduce this catalogue of authoritative work on carbon dioxide capture and storage delivered via ANLEC R&D over the past six years. I am proud of the role the Australian Government, in partnership with the Australian coal industry, has played in supporting these achievements. This catalogue makes a significant contribution to the knowledge and skills that are required to accelerate the uptake of low emission fossil fuel technologies.

Coal is the world's second largest source of primary energy, and accounts for more than 40 per cent of the worldwide production of electricity. Coal-fired generation accounted for 61 per cent of Australia's electricity in 2013-14 and is an important contributor to the reliability of our electricity systems. Regional coal consumption forecasts remind us of the importance of fossil fuels to the Australian economy and our regions' growth and energy security. Australia, with its significant resources of high quality coal remains well positioned to help the region meet its development needs.

Coal needs to be used sustainably. Therefore, the availability and deployment of low-emissions coal technologies, including the storage of greenhouse gases such as carbon dioxide will be critical to meet emissions reduction targets.

Projections in the International Energy Agency's 2-degree scenario indicate that carbon capture and storage (CCS) applied to the power sector and in industrial processes will account for 12 per cent of the cumulative emissions reductions needed by 2050. The projections and opportunities are clear but the challenge is large. Efforts such as those presented in this catalogue build the scientific evidence needed to contribute to a low or zero emissions economy.

ANLEC R&D is playing an important role in providing the science that enables the sustainable use of coal in a low emissions future. I commend the Australian coal industry, for enabling this important ANLEC R&D initiative and I look forward to continuing the partnership to ensure our domestic resources are utilised in a sustainable manner to the benefit of domestic and regional economies.

**Senator the Hon Matt Canavan**

*Minister for Resources and Northern Australia*



*“Carbon capture and storage (CCS) is extremely critical technology if we want to meet the 2°C target...”*

**- Dr Fatih Birol**

Executive Director, International Energy Agency



## Message from Industry

An essential response to climate change must include research, innovation and a sustained endeavour to mitigate carbon dioxide emissions. The Industry is pleased to partner with the Commonwealth to deliver ANLEC R&D – a low emissions research partnership comparable with any other industry initiative in the world.

Electricity from coal fired power generation continues to underpin the growth and lifestyle of developing nations on Australia’s doorstep.

To balance the region’s growing demand for energy with carbon dioxide mitigation, high efficiency low emissions (HELE) technology is recognised as the initial step to deliver the first phase of large scale emissions reduction in the region. This technology is commercially competitive, available and deploying today.

The work of ANLEC R&D is important to preparing for the next phase of emissions reduction. If Australia is to meet its emissions targets and contribute to the global effort to limit average temperature rise below 2 degrees, Carbon Capture and Storage (CCS) is an essential technology for deployment.

Clean energy will cost more. The science delivered through ANLEC R&D has already validated the cost reduction opportunities that are to be derived from innovative capture - as demonstrated at the Australian Callide Oxy-fuel Project in Queensland.

Through this partnership, the ANLEC R&D initiative will deliver the science platform on which carbon dioxide storage in Australia’s most prospective geological reservoirs will be made possible.

Through supporting low emissions technology demonstration, ANLEC R&D continues to play an important role in reducing investment risk and accelerating technology deployment through focused and relevant research and development.

**Mr David Moulton**

Chairman, ACALET



Left to right: Luc Dietvorst, Noel Simento, Dick Wells, Alex Wonhas, Mick Buffier, Bruce Denney

## Governance

ANLEC R&D, formed in 2009, is a partnership between the Australian Coal Industry and the Commonwealth of Australia.

The primary objective of ANLEC R&D is to deliver the applied R&D that can reduce the risk of Low Emission Coal Technology (LECT) deployment, thereby underpinning and accelerating the early commercial deployment of LECTs. This focus is driven by the recognition that these early projects must succeed for LECT to be accepted as a viable option in the portfolio of approaches required to achieve substantial global reductions in CO<sub>2</sub> emissions while meeting growing energy demand.

ANLEC R&D identifies its research priorities from large-scale technology demonstration proponents of carbon capture and storage from coal fired power generation.

## Directors

Mr Mick Buffier - Glencore

Mr Bruce Denny - New Hope Coal

Mr Luc Dietvorst - Engie

Dr Noel Simento - Managing Director

Mr Dick Wells - Chairman

Dr Alex Wonhas - CSIRO



*"...there is no climate friendly scenario in the long run without carbon capture and storage (CCS)...We must get its true development right, here and now."*

- IEA CCS Roadmap



## Message from the Chairman

The Commonwealth Clean Energy Initiative of 2009 recognised Australia's abundance of fossil fuels and the importance of showing leadership in developing and deploying low emissions energy technology.

Having set down a path of strategic low emissions investment, ANLEC R&D was formed to support, enable and accelerate commercial scale demonstration of carbon capture and storage through the delivery of project technical decision support by the best scientific resources in the country.

Seven years on, ANLEC R&D has established a vibrant research program focused on three demonstration proponents - the SWHub in the Southern Perth Basin in WA, CTSCo in the Surat Basin in Queensland and CarbonNet in the Victorian Gippsland Basin.

It is delivering the science from which the technologies that enable low emissions from coal, and other high CO<sub>2</sub> emitting industries, may be deployed; with the highest levels of technical assurance, and lower levels of investment risk.

Importantly, scientists are able to bring their deep expertise and innovation out of the lab and into field operations. This is exciting.

The Commonwealth and the Coal Industry are to be commended for their initiative in setting up a unique governance model in ANLEC R&D, i.e. for prioritising research and development.

The journey of transforming Australia, and the world, to a low emissions energy system has only just begun. The success of an initiative like ANLEC R&D will only be realised through visionary energy leadership and continuing partnership among all stakeholders ; and such success is crucial, if the anthropogenic impacts of climate change are to be minimised.

**Dick Wells**

*Chairman - ANLEC R&D*

# Highlights



Photo courtesy of the Callide Oxyfuel Project

## Oxy-fuel Technology

### Flue gas quality for storage established at the Callide Oxyfuel Demonstration Project

Research funded by ANLEC R&D shows that most flue gas contaminants can be extracted as near food grade compression condensate, ready for geological storage. Research also established mechanisms for mercury and  $\text{NO}_x$  transformation reactions; resulting in possible elimination of de- $\text{NO}_x$  equipment. Due to low-sulphur Australian coals, de- $\text{SO}_x$  equipment may also be eliminated. In combination, these outcomes could result in significant capital cost savings.



Photo courtesy of CSIRO

## Post Combustion $\text{CO}_2$ Capture

### Environmental performance of amine solvents reported for $\text{CO}_2$ capture

Important tests and protocols have been developed for the accurate environmental monitoring of solvent use, including the chemical transformations likely to occur beyond the stack. Assessment concluded that emissions from the solvent will be very low, and likely lower than those from comparable industrial processes or conventional coal fired power generation.



Photo courtesy of CTSCo

## Geological Storage of CO<sub>2</sub>

### 3D digitising technology reduces reservoir characterisation times

ANLEC R&D funded research has delivered methods and procedures for faster characterisation of CO<sub>2</sub> migration and storage in reservoirs. Small scale measurements on rock types are translated to meaningful information at well and basin scale.

### Prospects for favorable injectivity reported in the Surat Basin

Initial research studies show that geochemical reactions between CO<sub>2</sub> and the precipice sandstone in the Surat Basin are unlikely to pose constraints to injection. There is also evidence for CO<sub>2</sub> improving the permeability of the system with time.

### Leading edge research informs containment for the Southern Perth Basin

Advanced signal processing has delivered data sets for CO<sub>2</sub> storage in the Southern Perth Basin, using modelling approaches to support conventional tools. Applying a similar strategy to fault analysis also helped optimise the location of exploration wells and validate model performance.



## Informing Regulation

### Minimising exploration costs & strengthening local relationships

Innovative mathematical processing has ensured that the ANLEC R&D work program has delivered better structural imaging, improved processes for lower cost data acquisition, informed state governments decision making and aided in the building of trust with local land owners in the Southern Perth Basin.

### Monitoring and verification - adaptation for local marine or off-shore conditions

The Gippsland Basin is one of the most prospective reservoirs for CO<sub>2</sub> storage, however, much of the resource is off-shore in marine environments. ANLEC R&D funded research has assessed the likely performance of the latest monitoring methods and instruments in near shore conditions, in Australian site-specific circumstances.

### Recommendations delivered for managing resource interaction

CO<sub>2</sub> storage in reservoirs of the Surat and Gippsland basins will need to consider interaction with many other industry resources such as gas production, coal seam gas, and water. To assist regulators to manage competing priorities for access to reservoir pore space, researchers have delivered a first analysis and recommended options for resource management decisions for these basins.



# Business Principles

## Making a difference

ANLEC R&D funds research at a relatively mature technology readiness level. In order to accelerate deployment, focus is on research that enables application rather than early stage fundamental science. It aims to take innovative ideas out of the lab and into the field.

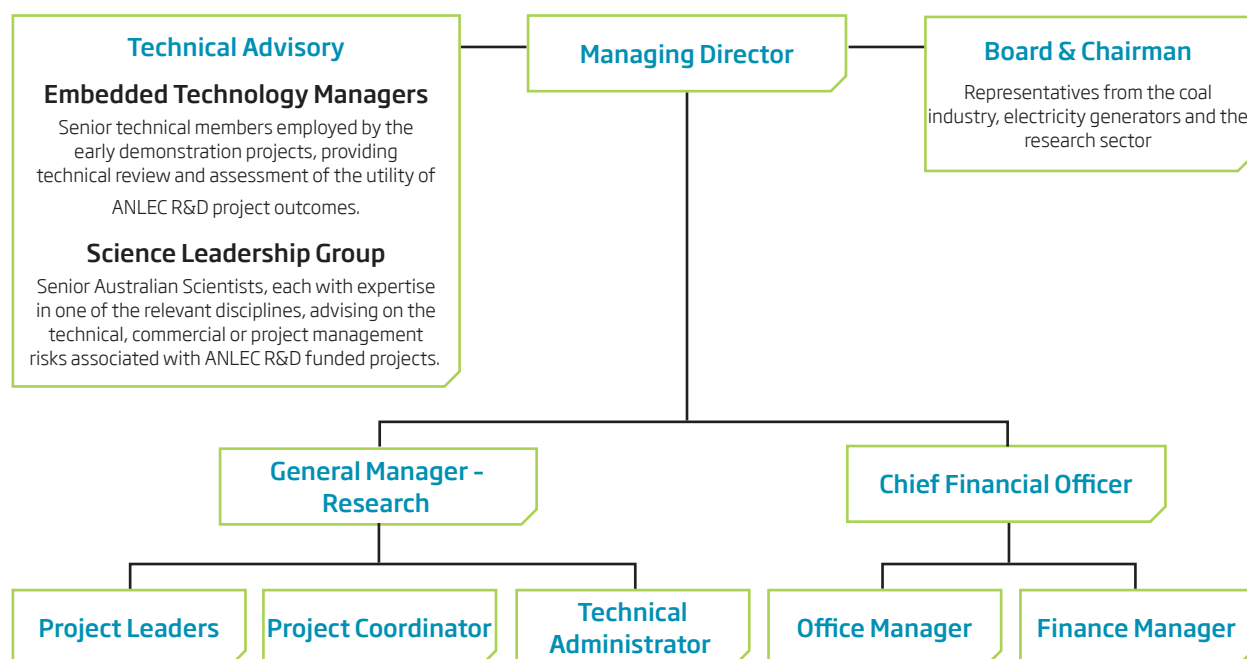
## Service Model

The ANLEC R&D business model is premised on the provision of research services to commercial scale carbon capture and storage (CCS) proponents. It sources research services principally from Australian infrastructure; targeting the best expertise, capacity and capability wherever they present.

## Priority setting

Focusing on the needs of CCS demonstration proponents is a powerful filter to balance the encouragement of scientific creativity with the relevance of application at commercial scale in the field. Undertaken in a competitive research environment, it allows for innovative science methods to reduce real investment risks to targeted CCS project proponents.

## Organisational Structure



## Transparency and Governance

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The Board of Directors is comprised of an independent Chairperson and representatives from ANLEC R&D's funding providers, the power sector and the research sector, ensuring robust and diligent governance.

## Customer Focus

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ANLEC R&D Embedded Technology Managers are senior technical persons from the demonstration proponents who recognise and advise on those project investment risks that would benefit from targeted research.

## Informed Decision Making

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Systematic reviews of research performance and progress are regularly undertaken by Management with the engagement of expertise from the commercial demonstration proponents, Australian science leadership and the funding providers. It delivers the demonstration proponent with the most up-to-date science and data relating to their project throughout the duration of the research.

## ANLEC R&D Management Team

### ***Managing Director***

Dr Noel Simento

### ***General Manager - Research***

Mr Kevin Dodds

### ***Chief Financial Officer***

Mr Trevor Smith

### ***Staff***

Arman Abdollahi

Gael Armour

Clarissa Niap

Luisa Powell

Merinda Woodburn



## Partnerships and Investment Leverage

ANLEC R&D delivers a unifying objective for research to support CCS deployment. It is achieved through coordinated advice, funding and memberships across several partnerships and collaborations.



Since 2015, the Coal Industry has retained ANLEC R&D to manage an additional \$10M investment into experiments at the Otway Pilot CO<sub>2</sub> storage site in Victoria. The facility is owned by CO2CRC, a leader in Australia's early CCS initiatives, and has operated as a subsurface laboratory for over 10 years. The industry, through many industry participants, has been an important sponsor of this work.



The Global CCS Institute has established a knowledge sharing platform to enable widespread dissemination of CCS related information. As a research member of the Global CCS Institute, ANLEC R&D has, since inception, made its own scientific studies available to the Global CCS Institute's audience.



Government of **Western Australia**  
Department of **Mines and Petroleum**

Through partnering with ANLEC R&D, the WA Department of Mines and Petroleum embeds technology management within the scope of its demonstration activities and has chosen to allocate funding for research purposes. ANLEC R&D is the agency of choice for administering such funds.





Photo courtesy of CO2CRC

*"The knowledge or 'learning' from demonstrating CCS technology in new applications at different sites and different settings is critical for reducing costs and strengthening investor and stakeholder confidence."*

- Global CCS Institute



Brown Coal Innovation Australia was set up by the Victorian Government to manage research for its vast resources of brown coal. The Commonwealth's commitment to enabling such innovation for Victorian brown coal was managed through ANLEC R&D. As a member and part of BCIA governance, ANLEC R&D was able to acquit its brown coal research requirements using local brown coal expertise.



ANLEC R&D coordinates the Australian membership of the IEA-Clean Coal Centre. The Centre is constituted in an implementing agreement of the International Energy Agency, Paris, and is funded by member countries and industrial sponsors. It is a foremost provider of information on the clean and efficient use of coal worldwide, particularly clean coal technologies. ANLEC R&D also funds a share of a second implementing agreement relating to the IEA Green House Gas R&D Program.



**Department  
of Industry**  
Resources & Energy

ANLEC R&D is a trusted advisor to Coal Innovation New South Wales (CINSW). CINSW is a \$100M initiative of the New South Wales Government to fund research, development, demonstration and community awareness of low emissions coal technologies. Membership of the governing Council and the Technical Working Group brings both expertise and a national perspective to inform decision-making.





# Storage Research Strategy

The importance of storage geology to early mover demonstrations cannot be overstated. Project timelines, and indeed the viability of the early demonstrations, will be strongly dependent on storage availability, how this storage can be proven, and how well the storage geology can be monitored and controlled.

The storage geology is the most critical technical component of any LECT project and the least well understood. Hence the need for a strong applied R&D effort.

Key targeted outcomes from the ANLEC R&D subsurface program include:

- » Reduced project development risk via increased acceptance of the project by stakeholders including financiers, regulators and the public;
- » Reduced cost and time required to find and define storage capacity;
- » Increased understanding of the opportunities available to enhance injectivity, thereby reducing the number of wells and reducing costs;
- » Reduced cost to operate storage capacity, through understanding opportunities to move away from an oil and gas industry cost basis to a cost basis that reflects the lower returns available in the power sector;
- » Reduced cost and time to close the injection site.



# CO<sub>2</sub> Storage in Australian Geological Basins

For decades, carbon dioxide capture and re-injection into subsurface geological formations has been a well-established practice for enhanced oil recovery. It is a technology well suited to carbon dioxide emissions from coal fired power generation. However, deployment will be required at engineering scales much higher than presently available.

The availability of pore space in a reservoir is, in general, related to the depth of its origin through geological time. Deeper rocks are more compacted and consequently less permeable. There are many other variables that also contribute to the viability of reservoir rock for storage purposes. Importantly, the storage of CO<sub>2</sub> must also consider interaction with other sub-surface resources present (coal, oil, gas, geo-thermal, etc.).

## Science underpinning the storage of CO<sub>2</sub> in Australian geological basins

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Each basin will have unique features that either advantage or disadvantage CO<sub>2</sub> storage. In considering first-of-a-kind deployment for Australia, decisions for exploiting the resource must be underpinned by sound scientific bases. The ANLEC R&D research program is designed to enable, and help accelerate, deployment of CO<sub>2</sub> storage in Australia by expediting that research necessary to deliver the required science to the public record.

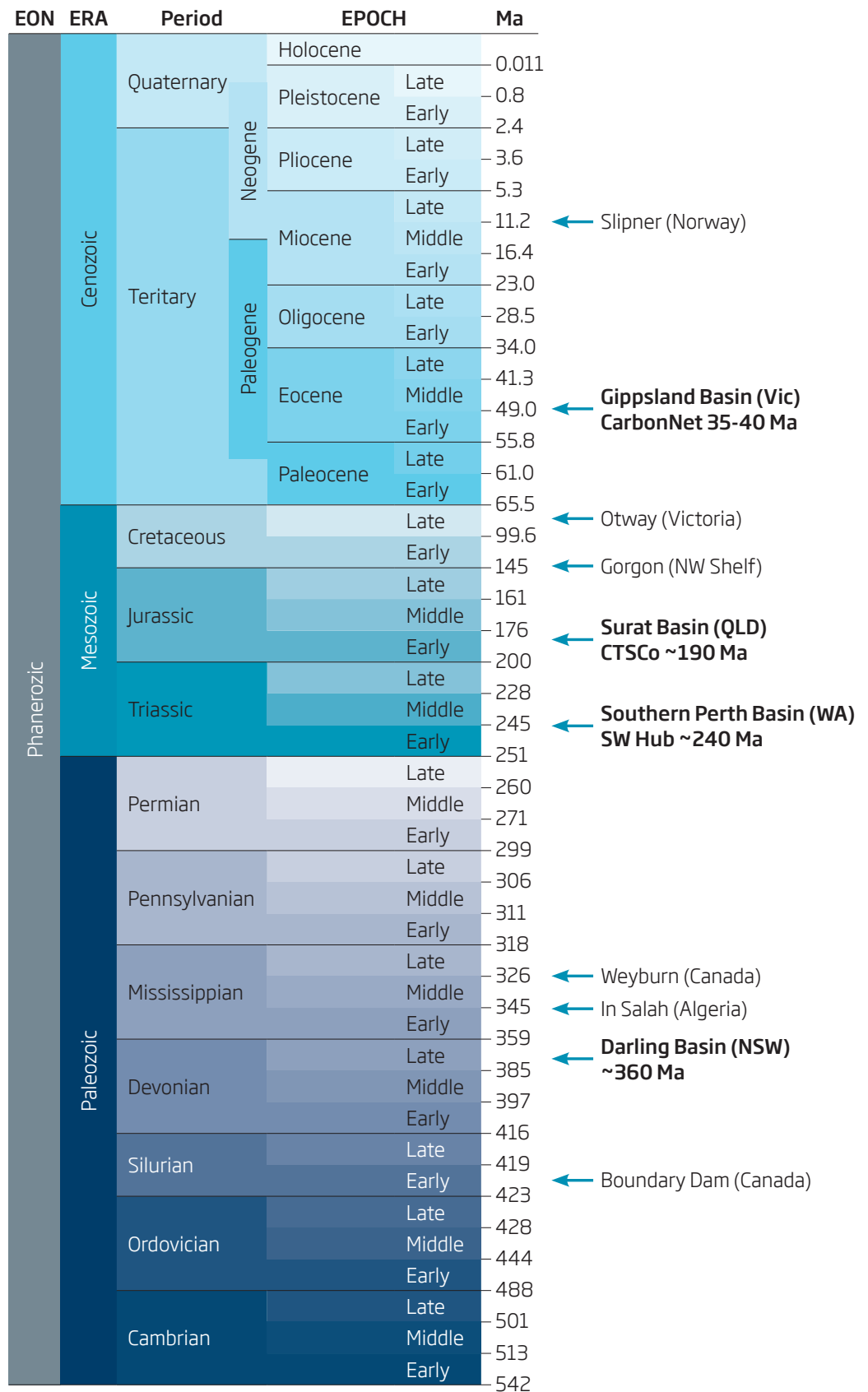
## Managing financial investment risk for carbon dioxide storage

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The financial investment risk for a CCS project can be categorised as;

- » Project Viability Risks: These are critical factors that can cripple the CCS project; typical examples are CO<sub>2</sub> containment and public acceptance, or
- » Project Engineering Risk: These are engineering cost factors that can be mitigated but would have impact on the project finances; typical examples are reservoir injectivity and capacity.

## Age of CO<sub>2</sub> Storage Reservoirs



## Surat Basin

An integrated Surat Basin carbon capture and storage project has been established to demonstrate the technical viability, integration and safe operation of carbon capture and storage in the region to benefit all emitters of CO<sub>2</sub>. CTSCo has been funded by industry to deliver the feasibility study and front end engineering design (FEED) stage. The company has been granted a single GHG exploration permit for tenement EPQ 7 in the Surat Basin as the preferred site for a pilot injection. Test injection of CO<sub>2</sub> is now scheduled to begin in 2020.

### Goal

*To support carbon dioxide storage in the Surat Basin*

*Queensland*



### Scale Key

● In lab      ● In Field

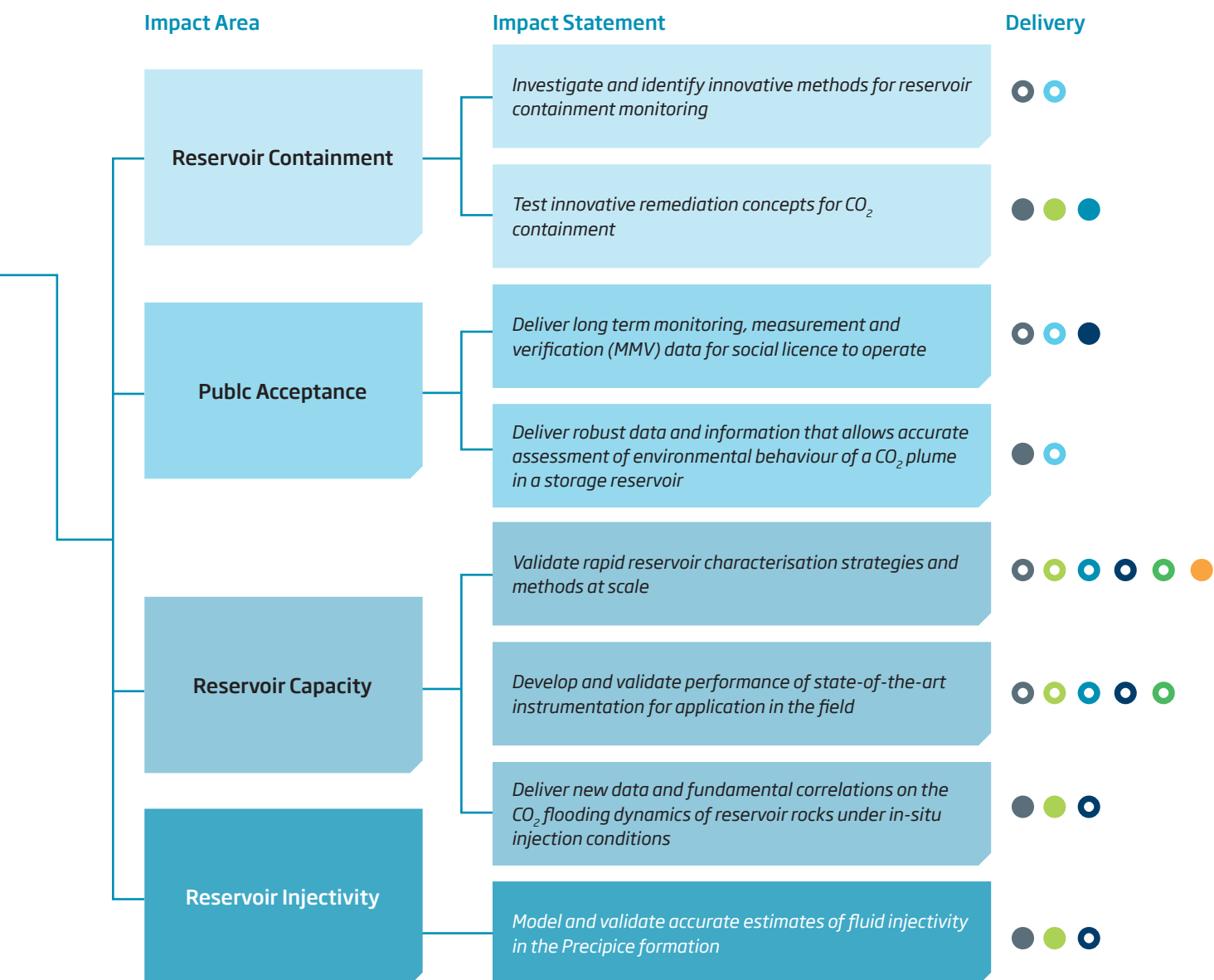
### Delivery Key

● New Data      ● New Application  
 ● Field Validation      ● New Service  
 ● New Correlation      ● New Software  
 ● Permitting & Public Communication





Photo courtesy of CTSCo



Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

## CASE STUDY

# Basin resource management and CO<sub>2</sub> storage

We will understand how to better manage several overlapping resources - such as land, water, gas, coal and CO<sub>2</sub> storage reservoirs - at the same time.

Geological formations are connected to their adjacent structures in one way or other. At one extreme, this connection allows material to move easily from one structure into another; at the other extreme, only indirect interactions may occur. Some of these interactions may be synergistic and helpful while others may be detrimental.

This two-part CSIRO report seeks to clarify the possible interactions in a range of potential geological settings. It aligns 'best in class' international studies to the Australian context, to propose relevant "resource interaction" decision flow-charts.

Coal, oil and gas are contained in various geological structures in addition to shallow and deep ground water resources.

This study recommends a risk based approach focusing on the potential for:

» Adverse interactions - which could include potential contamination by carbon dioxide, resource competition for water disposal reservoirs, brine displacement into adjacent reservoirs and seal compromises.

» Positive synergies - that may include increased formation pressure (re-pressurising), enhanced oil and gas recovery. Carbon dioxide may also provide a working fluid for geothermal applications.

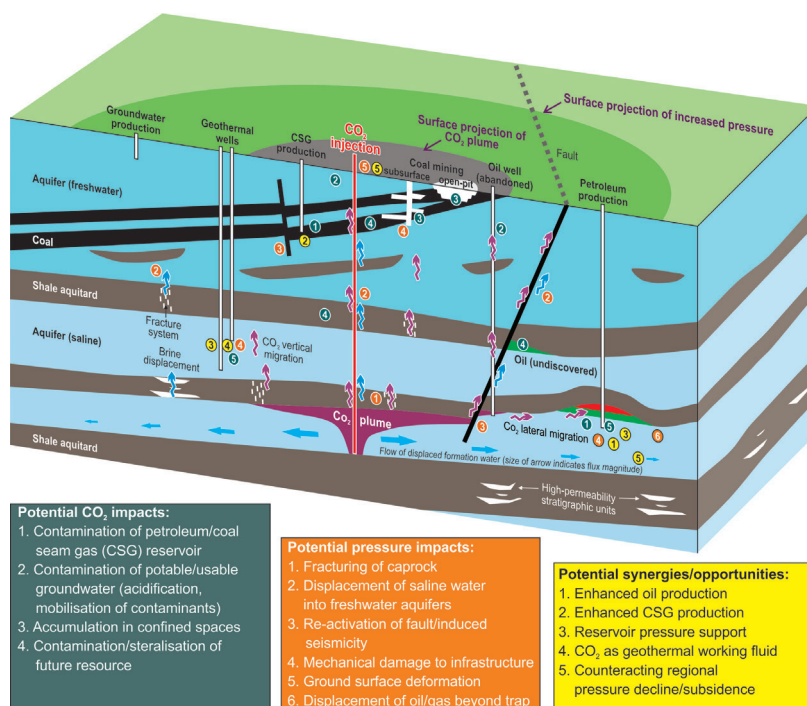
Decisions on the productive use of resources will require consensus to be drawn between various stakeholder interests. These would include private business, state and federal regulators, and local community groups.

High-quality information and transparent decision processes will be key to enabling these conversations.

This assessment provides initial recommendations on the nature of information and processes that could be adopted or adapted by custodians of the resources. It is likely that State "Advisory Bodies" could be the best customers to benefit from this study.

### Reference

K. Michael, et al 2013, Resource Management and Carbon Storage (3-0510-0057)



Cross-section illustration showing various subsurface features and hydrocarbon extraction methods.

## CASE STUDY

# Understanding CO<sub>2</sub> injectivity properties for the Surat, Gippsland and Southern Perth Basin

Improved CO<sub>2</sub> injectivity into reservoir rock will reduce the cost of storing CO<sub>2</sub> from coal fired power generation.

Seven cores from potential Australian storage reservoirs (plus one Berea sample for calibration purposes) were tested, using four different laboratory techniques; providing four sets of data – core flooding, CT scanning, geomechanics and geophysics.

The cores analysed are as follows:

- » The Berea sandstone
- » The Otway (CRC-1 well, Waarre-C formation) sandstone plug
- » The Pinjarra-1 well (Lesueur-Wonnerup member) sandstone
- » The Harvey-1 well (Lesueur plug 55H) sandstone
- » The Wandoan Precipice sandstone
- » The Golden Beach sandstone
- » The Hutton-1 sandstone
- » The Yalgorup sandstone

The initial four cores were analysed by a CSIRO CT scanner and, from then on, the second four cores were analysed by a Curtin University micro-CT scanner. The result was a new approach to CO<sub>2</sub> flood CT interpretation, with rather more complexities due to the higher resolution of the microCT machine.

Key conclusions:

- » Demonstrated understanding of how permeability may change as a function of CO<sub>2</sub> injection.
- » The results also highlighted the need to analyse the water produced from the core flooding experiments, as well as core mineralogy. This is needed when there are unexpected results.

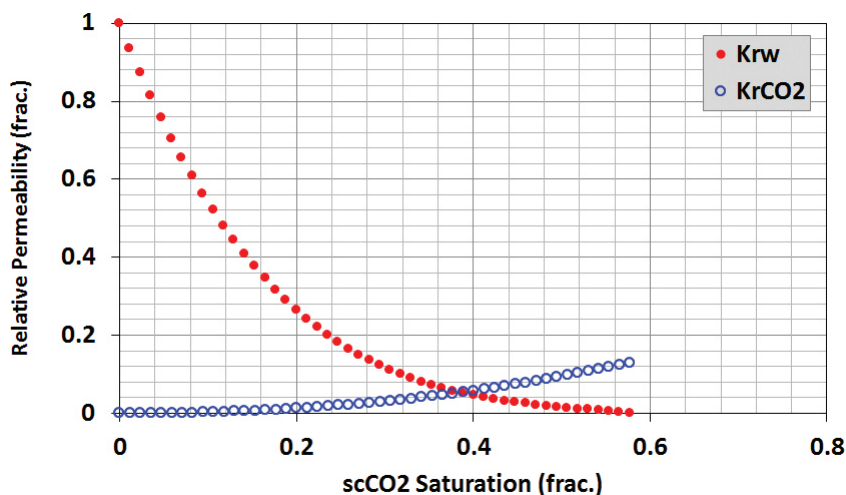
The recommendations:

- » A number of example reservoir cores must be taken from the same reservoir member, but from different wells.
- » They must initially be core flooded with scCO<sub>2</sub> and their permeability data then established.
- » If there are permeability changes both the core mineralogy and produced water must be analysed.

» In addition, it is clear that geomechanical core tests should be done before and after flooding to observe if there is any CO<sub>2</sub>-induced weakness in the cores.

### Reference

B. Evans, et al 2014, Predicting CO<sub>2</sub> injectivity properties for application at CCS sites (3-1110-0122)



Changes measured during CO<sub>2</sub> injection.



## CASE STUDY

# Surat basin reservoir analysis delivers new options for monitoring CO<sub>2</sub> containment

### Unique local geology delivers innovative methods for monitoring and CO<sub>2</sub> storage assurance.

Jurassic formations in the Queensland portion of the Surat Basin were used as a case study, representing prospective low-salinity, siliciclastic geological CO<sub>2</sub> storage reservoir systems. Geochemical investigations showed that the principle reaction pathways in low-salinity aquifers are the same as in high-salinity aquifers.

However, since more acid is formed in low-salinity water and the acid buffer capacity is low in formation water of the Surat Basin, Queensland, the formation water becomes relatively acidic, leading to a typical pH of 4. The prospective reservoir in the Surat Basin is the Precipice Sandstone, a very homogenous rock unit, largely dominated by quartz. As this mineral is hardly reactive under CO<sub>2</sub> storage conditions, the geochemical reactivity of this unit overall is very

low. Consequently, the long-term CO<sub>2</sub> trapping capacity in the form of carbonate mineral precipitation is very low as well.

Detailed mineral analysis of units above the Precipice Sandstone revealed the Boxvale Sandstone Member may be suitable for above-reservoir monitoring purposes.

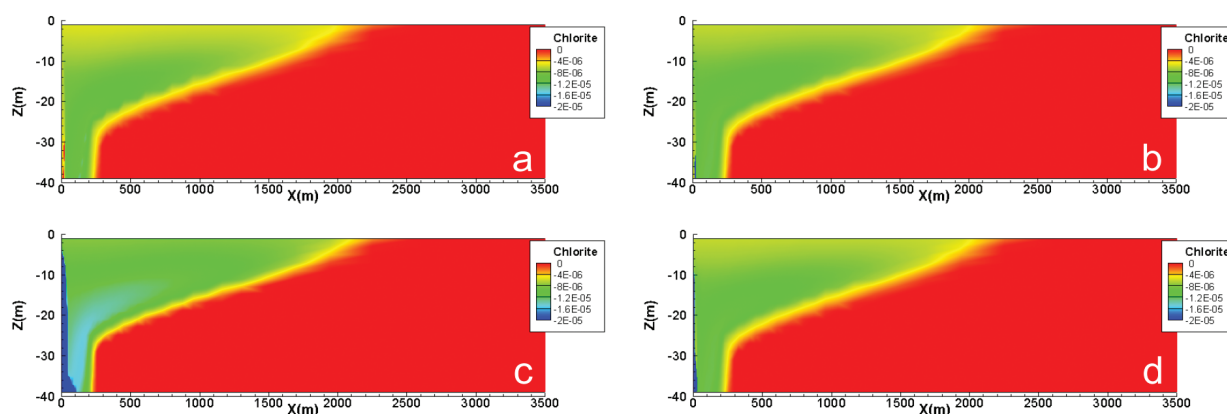
Relatively high porosity, permeability and a thickness of several meters are characteristic for the Boxvale Sandstone Member, making it a good secondary containment formation with the Evergreen Formation sealing strata above. This rock unit is also distinct in its mineral composition as it contains a large proportion of feldspar, a mineral known to dissolve relatively quickly in CO<sub>2</sub>-enriched water. This would lead to rapid changes in the water

composition and could serve as an indication of CO<sub>2</sub> leakage from the primary storage reservoir (Precipice Sandstone).

In addition, the compilation of stress field data led to a much higher data density in the Surat Basin than anything previously published and thereby reduced the uncertainty in predicting the rock mechanical response to CO<sub>2</sub> injection and storage. Preliminary rock mechanical considerations suggest faults with strikes that are approximately at 30 degrees to the maximum horizontal stress direction will be at greatest risk of reactivating due to the fact they have the highest shear to normal stress on the fault plane.

### Reference

R. Haese, et al 2016, Geochemical impacts and monitoring of CO<sub>2</sub> storage in low salinity aquifers (7-1110-0088)



Distribution of chlorite dissolution in volume fraction at 20 years for the pure CO<sub>2</sub> (a), CO<sub>2</sub> with 100 ppm SO<sub>2</sub> with calcite (b) and without calcite (c) and CO<sub>2</sub> with 500 ppm SO<sub>2</sub> (d) (3500 m radial).

## CASE STUDY

# Querying the influence of CO<sub>2</sub> storage on water flows and salinity

### Modelling helps understand how formation water is displaced by CO<sub>2</sub> injection for long term storage.

This project sought to quantify pressure fluctuations and fluid fluxes that could be expected in the far field for large scale CO<sub>2</sub> storage in the Surat Basin; in an effort to reduce the risk for implementing large-scale CCS.

It focussed on regional to basin-scale modelling scenarios of the Precipice Sandstone, the overlying Evergreen seal and potential for impacts to the overlying Hutton aquifer.

A commercial reservoir simulator (Eclipse300™) was used to run simulations of CO<sub>2</sub> injection into a water-filled formation. First, a series of simulations were run on a simplistic idealised generic numerical model to establish the key factors affecting groundwater resources. This was done in order to understand how different processes interact and it bears no relation to any real CO<sub>2</sub> injection site. Later, the methodology established from these simplistic generic simulations was applied to evaluate the effects of a large-scale CO<sub>2</sub> injection in a more realistic regional Surat Basin model. A static geological model which was built for the ZeroGen Project was made available by the Queensland Geological Survey for this study. This static model was

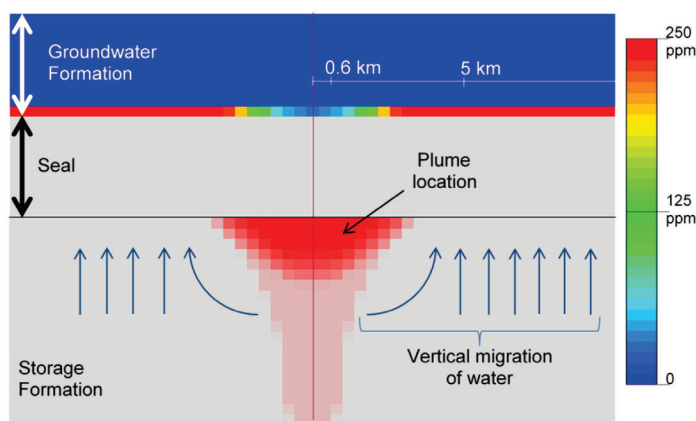
modified before use in the dynamic simulations. Pressure and salinity changes, at different locations in the groundwater and storage formations, were extracted from the numerical model forecast during and after the simulated CO<sub>2</sub> injection. All of the simulations in this study were at the basin-scale and plume-scale effects which require finer scale grids were not investigated.

Previous studies have shown that pressure propagation in CO<sub>2</sub> storage formations due to commercial-scale injection has a larger radius of influence than the plume of free-phase CO<sub>2</sub>. As a result, it is expected that some portion of the brine residing in storage formations migrates away either vertically through top seal or laterally in the storage formation potentially towards updip shallow sections of the reservoir or even to the surface.

Therefore, when considering the impacts of geosequestration on groundwater resources, the potential for lateral displacement of saline formation water in the far-field of the injection site and its migration through the seal needs to be characterised. A new method has been developed to assess the possible impact of CO<sub>2</sub> injection on groundwater resources by tracking salinity changes in a numerical model forecast. In all of the simulation scenarios the pressure build-up remains less than the fracture or threshold pressure of the seal.

#### Reference

F. Hussain, et al 2013, Impacts of Surat Basin geological CO<sub>2</sub> storage on groundwater flow (3-1110-0092)



Simulations investigated the impacts of CO<sub>2</sub> injection on pressure and salinity in overlying groundwater aquifers.

## CASE STUDY

# Mobilisation and fate of heavy metals released by injected CO<sub>2</sub>

### Research informs the development of fit-for-purpose regulation to ensure safe storage of CO<sub>2</sub>

A post-combustion captured greenhouse gas (GHG) stream, derived from the combustion of Walloon Coal, may contain up to 5–30 ppm SO<sub>x</sub>, 100 ppm NO<sub>x</sub> and 30 ppm O<sub>2</sub> along with other gases including N<sub>2</sub> and Ar.

When this fluid is injected into the quartz-rich Precipice Sandstone and interacts with the clay-rich Evergreen Formation seal at the Surat CCS Project, preliminary geochemical studies suggest that some heavy metals and metalloids may be released.

Site specific information about the processes that control trace element behaviour is essential. It is necessary to accurately predict the likely concentrations of heavy metals and metalloids present in formation water, as a result of reactions with rock and water at the site.

The results from this project will help understand the type, amount and fate of heavy metals and metalloids, both before and after GHG stream injection, and provide a baseline and calibration data for the site's environmental and groundwater impact assessment.

The project uses geochemical modelling, together with detailed geochemical and mineralogical analysis of Precipice Sandstone and Evergreen Formation core from the West Wandoan 1 well, and from laboratory batch experiments. This approach allows comparisons between simulations of water

chemistry and measurements from experiments, providing confidence in the validity of model predictions of long term water chemistry impacts. The project also evaluates the application of partial and sequential extraction methods as a rapid, cost effective approach for investigating labile trace metal abundances in reservoir and seal rocks at carbon storage sites.

There is limited information on sources and sinks of trace metals and non-metals, or mechanisms of release, even with pure CO<sub>2</sub> reaction under low salinity carbon storage conditions. Natural analogue studies of CO<sub>2</sub> leakage sites have provided valuable data on the behaviour and fate of specific metals. Several initially elevated metals, including Ca, Fe and Mn, were repeatedly observed in previous field trials and experiments. Nevertheless, the sources of metals and non-metals are site specific and depend on mineralogy, water chemistry and the composition of the GHG stream.

Recent results suggest four potential processes may occur (highlighted by natural analogues, injection trials and experimental studies). They are:

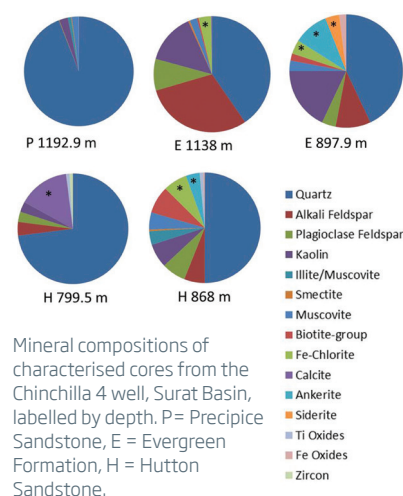
- » Dissolution/precipitation reactions are affected by pH and redox but are also important in controlling these parameters and may drive metal sorption and/or desorption on iron oxides, hydroxides and clay surfaces.
- » Ion exchange reactions of

reactive clays in response to fluid migration and mixing or elevated concentrations of Ca from calcite or plagioclase dissolution liberate major ions including Na.

- » Sorption of anions on Fe-oxides and hydroxides including bicarbonate, sulphate (and potentially nitrate) from the GHG stream may cause desorption of trace metals and metalloids.
- » Oxidation/reduction of the system as a result of injected CO<sub>2</sub>, O<sub>2</sub>, NO<sub>x</sub> and SO<sub>x</sub> (oxidizing) or H<sub>2</sub>S and CH<sub>4</sub> (reducing) makes some metals more or less soluble and will alter major and trace element behaviour. The precipitation of Fe-oxides under oxidising conditions can act as a sink for metals through co-precipitation and adsorption.

#### Reference

J. K. Pearce and S.D. Golding 2016, : Mobilisation and fate of heavy metals released by the GHG stream – Literature review (7-0115-0236)



\* indicates minerals which dissolved on CO<sub>2</sub>-water reaction as described in Farquhar et al. (2015) 10.1016/j.chemgeo.2014.10.006

## CASE STUDY

# Exploring a natural analogue to CO<sub>2</sub> mineralisation trapping

Knowing the mechanism of carbonate formation in the local geology can help control and immobilise carbon dioxide.

Differentiating between carbonate formed via different mechanisms, and determining controls on the extent of authigenic carbonate formation, could lead to options for engineered accelerated mineralisation in reservoirs.

This work recognises authigenic carbonates as a natural analogue of mineralisation trapping. It seeks to understand control mechanisms for their formation in low salinity, siliciclastic aquifers of the Great Artesian Basin (GAB).

More than 250 well completion reports were selected, from among tens of thousands of publically available petroleum, coal seam gas and stratigraphic drilling records, on the basis of spatial and geological coverage, the detail of included information, and type and availability of associated samples. The well completion reports were assessed in detail for the presence of significant carbonate mineralisation, and samples of carbonate cemented sandstone, as well as carbonate fracture mineralisation, were taken from some 50 localities. All Mesozoic units within the chosen wells were subject to sampling, whether the strong carbonate cement was sporadic or extensive. The samples included both chipped and cored intervals.

Key parameters derived from petrological and geochemical analyses of the carbonates were fed into a model for carbonate authigenesis within the GAB

Laboratory experiments were undertaken to explore processes of enhanced carbonate mineral trapping of CO<sub>2</sub> in Precipice and Hutton sandstone core.

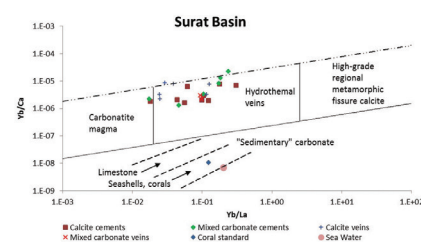
The study concluded:

- » The oxygen isotope values and fluid inclusion data for GAB cement and vein carbonates indicate that deeper, hotter fluids mixed with shallower and fresher fluids during, or just prior to, carbonate precipitation in a number of cases.
- » Most of the modelled fluid carbon isotope compositions are indicative of remobilised marine carbonate or mantle/magmatic CO<sub>2</sub>, whereas a subset of carbonate samples had very negative modelled carbon isotopes consistent with an organic carbon source.
- » Fault-assisted fluid migration apparently played a major role in the carbonate authigenesis, and a subset of samples was associated with hydrocarbon migration.
- » Elevated fluid inclusion temperatures  $\geq 120^{\circ}\text{C}$ , in samples from wells located within the Moonie-Goondiwindi and Leichardt-Burunga fault corridor in the eastern Surat, are anomalously high relative to what is known about the regional thermal history.
- » Gaseous hydrocarbons found in fluid inclusions in the Eromanga Basin samples are sourced from the underlying Cooper Basin.

- » The availability of cations for precipitation of dissolved CO<sub>2</sub> as carbonate minerals can be a rate limiting step in the process of CO<sub>2</sub> mineral trapping. Engineering injection, to take advantage of CO<sub>2</sub> migration paths (e.g. injecting below baffle units and down-dip from a structural closure), is one way to maximise carbonic acid dissolution of minerals encountered by the CO<sub>2</sub>-water mixing front.
- » Co-injecting CO<sub>2</sub> dissolved in brine or other waste water would increase the available cations for carbonate precipitation as would co-injecting a small quantity of SO<sub>2</sub> to form dilute sulphurous or sulphuric acid at specific depths, e.g. below baffle units.

### Reference

S. D. Golding, et al 2016, Great Artesian Basin Authigenic Carbonates as Natural Analogues for Mineralisation Trapping (7-1011-0189)



The different kinds of carbonate collected from the Surat Basin. Variation diagram modified after Möller (1983).



## CASE STUDY

# Prospects for improved CO<sub>2</sub> injectivity shown for the Precipice Sandstone

The near wellbore area is critical in CO<sub>2</sub> injection for geosequestration since most of the resistance to flow occurs in this region.

The fluid flux is high because the swept volume is low and any changes to the permeability in this region can have significant economic impact in terms of well utilisation efficiency and compression costs. In the far field regions, away from the well, the affected reservoir is much bigger and changes to permeability, through blocking or enhancement, have relatively low impact, though they can still affect the direction of CO<sub>2</sub> plumes over longer time scales.

This project supports Australian CO<sub>2</sub> geosequestration field demonstration and commercial projects by:

- » geochemical reaction investigations of the CO<sub>2</sub>-H<sub>2</sub>O-rock system of target host formations, identifying changes to mineralogy, porosity and permeability, with leading-edge tools and methodology;
- » measurement of the anisotropic mechanical properties and permeability of samples, investigating dynamic changes as a result of geochemical reactions; and
- » advancing the development of physicochemical and numerical models, to replicate the lab findings of fluid and mass transport, for application at different spatial and time scales.

Lab experiments were conducted on archived and fresh cores from the target formations of the Wandoan CCS project in the Surat Basin, Queensland and Berea Sandstone supplied by ANLEC R&D

for the purpose of benchmarking of permeability results across related ANLEC R&D projects.

Geomechanical tests provided the basis for stress/permeability relationships.

The experimental and kinetic geochemical modelling studies indicate that the injection of CO<sub>2</sub> into water-bearing reservoirs will reduce the formation water pH and cause dissolution of some minerals. Regarding pore-scale modelling that seeks to track more closely the actual physical transport through the porous media, the in-house extended LBM (XLBM) modelling provides a useful tool for understanding the fluid flow and local changes to the flow architecture at the mesoscale including the porosity change with calcite dissolution and feedback impacts on fluid flow. This, in turn, implies that small components within the samples, be these pore throats or fine particles, may be what is most affected by the applied stress prior to any geochemical reactions taking place.

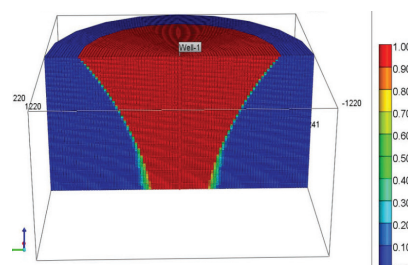
Key conclusions are:

- » Mineral dissolution far outweighs precipitation in the immediate wellbore area. This is usually not taken into account but is commercially important as it influences the decisions about the number and size of the injection wells.

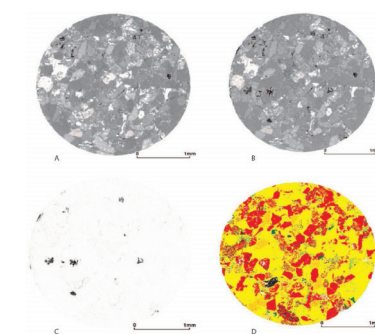
- » Near wellbore modelling, even using very conservative simplifying assumptions, shows substantial improvement in injectivity. More comprehensive dynamic modelling will push these predicted results to even bigger (more realistic) increases.
- » This is shown to have significant (beneficial) design and commercial consequences.

### Reference

G.K.W. Dawson, et al 2014, Geochemical and Geomechanical Testing of Near Wellbore CO<sub>2</sub> Injectivity Improvement (7-1110-0101)



Plume dispersion for case 1 after 2 years of injection.



Registered tomogram images of WW1-1043-Evergreen sub-plug slice, a) Pre-reaction, b) post-reaction, c) difference image (dark areas = loss of material), d) QEMSCAN after reaction with mineral key shown. Source: Golab et al. (2014), used with permission.

## CASE STUDY

# New instruments allow for more accurate measurements

This research delivers the spectral calibration parameters necessary for real time CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> measurements down hole using Raman spectroscopy.

Accurately quantifying the concentration of CO<sub>2</sub> and ancillary gases SO<sub>x</sub> (SO<sub>2</sub>, SO<sub>3</sub>) and NO<sub>x</sub> (NO, NO<sub>2</sub>) in formation water will be a good indicator of the extent and impact of a subsurface plume.

Raman spectroscopy is a powerful molecular vibrational application that has been employed widely for more than 70 years to analyse, non-destructively, various materials and mixtures in the laboratory.

Raman spectroscopy is based on the process of scattering light off molecules, with each type of molecule having a specific fingerprint spectrum reflecting the molecular bonding and structure of the molecule. Higher concentrations of a particular molecule result in observation of more photons at the fingerprint (spectral) energies specific to that molecule. Hence, with the correct calibration, the concentration of specific dissolved species can be determined. Raman spectroscopy has been used to analyse dissolved methane *in-situ* and, to a lesser extent, nitrogen and carbon dioxide in coal seam reservoirs

This work initially combined a desktop study of Precipice Sandstone groundwater composition with batch reactor experiments at Surat Basin sequestration conditions (120 bar and 60 °C) for up to 35 days. Highly quartzose Precipice Sandstone core samples from the *West Wandoan 1* well were reacted in low salinity brine with both inert N<sub>2</sub> (for baseline equilibration) and

CO<sub>2</sub>/NO<sub>x</sub> gas mixture to determine CO<sub>2</sub> and NO dissolution species, concentrations and behaviour. Based on a determined post-combustion capture CO<sub>2</sub> stream composition, and current and previous work, a total of thirteen SO<sub>x</sub>, NO<sub>x</sub> and CO<sub>2</sub> dissociation products were identified which may be already present in Precipice Sandstone groundwater, or formed during injection of an impure greenhouse gas stream. These included seven sulphur derived, three nitrogen derived and three carbon derived species.

Results to date have:

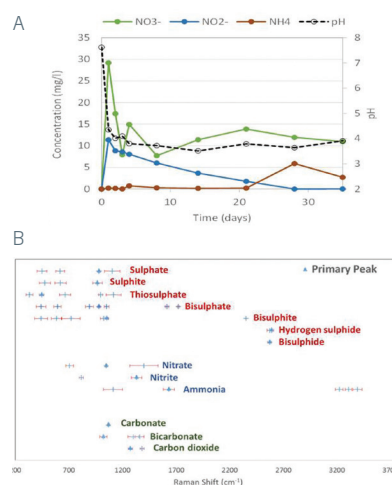
- » delivered a guide to the expected Precipice Sandstone groundwater near the site
- » determined concentrations, identities and time resolved behaviour of dissociation species during N<sub>2</sub> and CO<sub>2</sub>/NO Precipice Sandstone core reactions, for example nitrate (NO<sub>3</sub><sup>-</sup>) is the main NO<sub>x</sub> dissolution species (Fig. A)
- » determined calibration factors for adaptation of the proprietary Welldog DRRS technology and further understanding of its accuracy for application in a Surat basin geo-sequestration environment
- » identified thirteen dissolution and dissociation products of greenhouse gas streams injected into an aqueous environment and their theoretical characteristic Raman spectral features showed that twelve of the thirteen species

were found to exhibit unique Raman signatures (Fig. B) that will allow for qualitative and quantitative analysis of mixtures of these chemicals. An alternative to the monoatomic sulphide ion, which exhibits no Raman emission, was identified.

- » identified that these thirteen chemical species will be differentiable by Raman spectrum analysis, though advanced chemometrics will likely be necessary for quantitative analysis, especially in the case of mixtures of very similar components.

## References

- L. G. Turner, et al 2016, Desktop study and batch reactor experiments to determine baseline levels of CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> in Precipice Sandstone
- G. A. Myers, et al 2016, Theoretical basis for detection of products by Raman spectroscopy (7-0314-0229)



A) Dissolved N species and pH during Precipice Sandstone reaction with CO<sub>2</sub>/NO.  
B) Raman bands of 13 dissolved species of CO<sub>2</sub>/SO<sub>x</sub> and NO<sub>x</sub>.

## CASE STUDY

# Upscaling: multi-scale reservoir characterisation – from pore to core to geocellular models

### Multi-scale reservoir characterisation – seven scales from pore to core to geocellular models.

Provide within commercial software packages a quantitative and auditable translation between plug scale measurements, wireline log responses, and geocellular model properties.

Commercial scale sequestration into subsurface reservoirs depends critically on predicting the dynamic behaviour of the CO<sub>2</sub> plume. The plume dynamic behaviour is dictated at the large scale by the micro-scale facies and structures of the reservoir. Traditionally the general practice is to make measurements at core scale, find qualitative correlation with wireline logs and seismic, and then upscale into large geocell simulation models. Much of the fine-scale behaviour and physics are lost in this process, leading to uncertainties and idealised predictions.

The process of changing the scale of rock properties is known as upscaling. The only effective way to analyse the properties which control the transport of CO<sub>2</sub> in rock at the pore-scale is to undertake digital rock analysis (micro-CT) at scales much finer than core plug scale. Such analyses have been undertaken (see page 31). These results are rigorously and quantitatively correlated from the pore-scale to the core plug scale and then the whole core-scale before being cross-correlated with the wellbore wireline logs response over the full reservoir interval with a quantitative upscaling workflow.

To validly achieve this, it is necessary to classify (cluster) the rock at each

scale into rock types that can then be treated as distinct units in the upscaling process. This classification needs to be both mathematically exact and geologically meaningful. Currently employed approaches to upscaling bypass this requirement to classify before upscaling and thus frequently result in unrepresentative properties at the upscaled level.

This project delivers two auditable workflows to correctly and conveniently carry out the classification and upscaling processes:

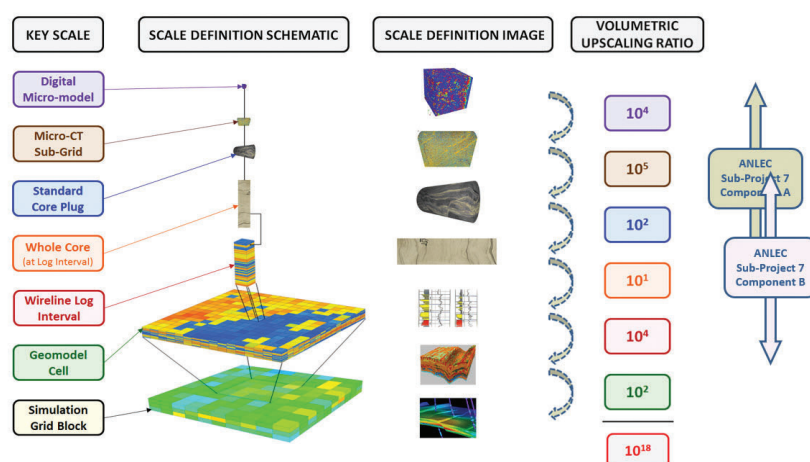
- » Component A: Methods to classify and upscale from pore to whole core
- » Component B: Methods to classify and move from core plug and whole core to the geocellular dimensions.

The workflows are designed to upscale simple single-value rock properties, as well as saturation-dependent properties (complex properties that depend on the relative saturations of the fluids in the reservoir including CO<sub>2</sub>).

The final products of this project are a module in FEI's software to implement the pore to whole core workflow and a second module in the eGAMLs software, called the "Classification and Upscaling of Saturation-dependent Properties" (CUSP) module, to move data from core plugs through whole core to geocellular models. The CUSP module will be made available to the industry by standard commercial software licencing and will be of major importance to successful CO<sub>2</sub> sequestration modelling.

### Reference

Curtis, et al 2016, Multi-scale Reservoir Characterisation - From Pore to Core to Geocellular Model, FEI, eGAMLs (7-0314-0128 Sub Project 7)



The 7 levels of scaling from micro level to geocell over 18 orders of magnitude. This project conducts a rigorous classification and correlation pore to wireline log scale.

## CASE STUDY

# Digital Rock Technology allows faster and cheaper assessment for CO<sub>2</sub> storage

This program's objective is to combine new Australian developed step-change technologies of 3D Digital Rock Technology (DRT) with conventional oil industry Routine Core Analysis (RCA) and Special Core Analysis (SCAL).

The DRT workflow presents a paradigm shift in the geoscience industry's approach to core analysis. The program has leveraged a comprehensive set of Surat Basin core material and multi-scale property data, along with an unprecedented understanding of the physics of CO<sub>2</sub>-brine systems at the pore-scale. Implications to quantitative understanding of properties at larger scales, whole core to log to geo-cellular scales have also been established. This workflow can be used to assess other potential CO<sub>2</sub> storage sites.

Research groups at ANU and FEI have pioneered a novel 3D image and analysis technology over the last 10 years. The collaborating groups at UQ, UNSW and CSIRO are leaders in the fields of conventional CO<sub>2</sub> flow analysis studies, geochemical trapping of CO<sub>2</sub> and upscaling data from pore to reservoir scales. The achievements of this program include:

- » Site-specific full suite of properties and multiscale images of core material from the Evergreen Formation (seal) and Precipice Sandstone (reservoir). Imaging was performed in 3D by X-ray computed tomography (CT; whole core, core plug, sub-plug) and in 2D by Scanning Electron Microscopy (SEM; pore-scale). Digitally calculated comprehensive dataset at the pore and core plug scale.
- » Accessible database of multiscale,

high resolution images and petrophysical and SCAL data. Developed an interactive catalogue for fast data retrieval/interrogation and 3D visualisation of data via direct online access.

- » Demonstrated site specific 3D imaging of in-situ supercritical CO<sub>2</sub> saturation at the pore scale. Conducted direct, 3D pore-scale imaging of supercritical CO<sub>2</sub> and brine within Surat Basin core material during CO<sub>2</sub> injection at aquifer pressure and temperature conditions, by microCT. Illustrated that capillary trapping is a significant mechanism for CO<sub>2</sub> storage in the Precipice Sandstone and likely to be stable over timescales of decades to centuries and that CO<sub>2</sub>-brine displacement properties are typical of a strongly water-wet system.
- » Developed robust flow simulators for CO<sub>2</sub>-brine flooding. A new, geometrically accurate pore-scale model for CO<sub>2</sub>-brine flooding was developed. CO<sub>2</sub>-brine relative permeability, saturation, and capillary pressure curves for different rock types were derived. Showed that DRT results are consistent with laboratory data from numerous labs (e.g., Stanford, Imperial College). Data sets allow identification of potential uncertainties associated with laboratory data (e.g. impact of wettability, initial water saturation).

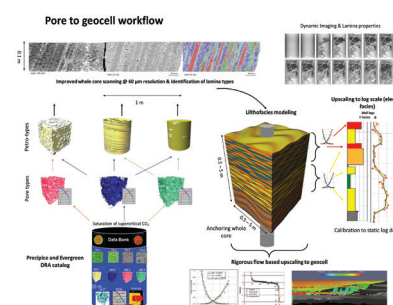


Illustration of pore to geo-cell workflow to support the Surat CCS project.

- » Performed time-step 3D imaging before and after geochemical reaction with CO<sub>2</sub>:brine. Performed pore-scale 3D imaging before and after reaction of the reservoir, seal and over-lying formation. Pure CO<sub>2</sub> and mixed gas containing SO<sub>2</sub> and O<sub>2</sub> were tested. The images show some localised changes including the dissolution of some carbonate minerals, degradation of some minerals and precipitation of others.
- » Validated application of DRT to CO<sub>2</sub> reservoir and seal characterisation with comparison to laboratory and provided correlations to wireline log data. Showed that DRT results are acquired in faster and at potentially reduced cost compared to traditional laboratory methods. Illustrated importance of rock heterogeneity at all scales to provide a quantitative bridge between plug measurements and log scale data.

### Reference

A. Golab, M. Knackstedt, A. Sheppard et al. 2016, Maximising the value of digital core analysis for carbon sequestration site assessment (7-0311-0128)



## CASE STUDY

# Adapting advanced hyper-spectral scanning technology to make in-situ rock measurements

The Precipice Sandstone, Evergreen Formation and Hutton sandstones make up important strata for the storage of CO<sub>2</sub> in the Surat Basin.

Dynamic simulations that predict the subsurface distribution of the injected greenhouse gas at Glenhaven will be influenced by the assumption of the distribution of the vertical component (Kv). Defining the distribution of clay layers and lenses, the clay and other minerals within and between lithological facies, their presence, continuity and extent will impact on modelling permeability and reactivity of the Precipice reservoir. These key sedimentological and diagenetic attributes are expected to impact the Kv of storage reservoir permeability.

Hyperspectral scanning of drill cores has recently become a popular method for understanding the mineralogy of rocks in addition to other complementary mineralogical methods such as X-ray diffraction (XRD). It has a variety of geological applications in mineral exploration, sedimentary geology, and hydrocarbon resources studies. In this study, we used the TSG-Core™ software to analyse hyperspectral data from HyLogger™ to study the Short Wavelength Infrared (SWIR) and Thermal Infrared (TIR) hyperspectral characteristics of the open file Woleebee Creek GW4 core in the Surat Basin in order to identify dominant and secondary minerals in the Precipice Sandstone, Evergreen Formation, and Hutton Sandstone.

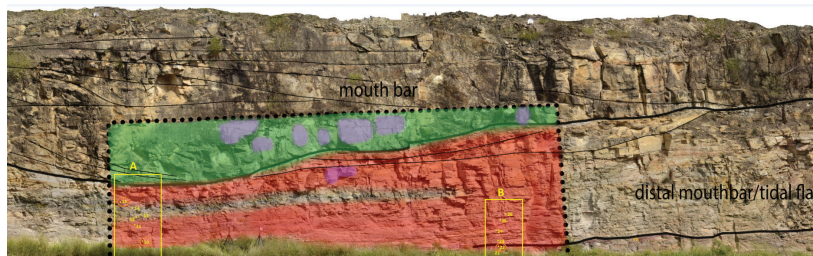
The main aim of the project is to test the use of hyperspectral sensors for investigating the mineralogical composition, in particular the occurrence of potentially low permeability or baffling layers containing clay and other reactive minerals, of the Precipice Sandstone at the outcrop scale. These data can be integrated with sedimentary interpretations of outcrop, wireline and other available core data and can be used to condition the interpretation and interpolation of reservoir properties within both static and dynamic 3D models of the Precipice and overlying formations. This technique is relatively new and although remote airborne and core-based sensors are widely available, field-based systems are rare and still require development.

Achievements to date include:

- » This field trial is a “first of kind” in Queensland and in Australia to collect mineralogical data from outcrop using hyperspectral scanning combined with photogrammetry.
- » Formation mineral details can be recognised based on the HyLogger™ data interpretation to a level needed to inform variations in permeability.
- » Demonstrated value and applicability of the technique to investigate an outcrop of the Precipice formation and derive more quantitative estimates of mineralogical variation.

### References

- D. Pistellato, et al 2016, Report on the trial hyperspectral images of the Precipice Sandstone
- A. Sansoleimani, et al 2016, Hyperspectral analysis of minerals in the Precipice Sandstone and overlying formations, Woleebee Creek gw4 and West Wandoan 1 boreholes using tsg core (7-0115-0237)



Processed Hyperspectral images acquired in the field trial on a Precipice Sandstone outcrop. Shown here is the interpreted kaolinite (red overlay), weathered iron oxides (green) and water (purple) features interpreted from the Short Wave Infrared (SWIR) spectra imaged on the outcrop. Sampling locations for validation shown in yellow rectangles at A and B.

## CASE STUDY

# Precipice Sandstone outcrops provide accurate measurements for reservoir modelling

The objective of this work is to allow the construction of the best possible static geo-cellular model of the Precipice Sandstone storage reservoir by maximising the geological data relevant to fluid flow that can be derived from detailed examination of relevant Precipice outcrops.

The results of this project will improve both the general understanding of the basin and the models that can be built to predict the behaviour of injected CO<sub>2</sub> in the basin. The project takes advantage of the fact that the reservoir unit for the Surat basin project can be seen at an outcrop not far from the proposed demonstration site, and can therefore be studied in more detail than is possible from just subsurface sampling.

To populate static geocellular models, the project has developed a series of outcrop models, using detailed interpretation of sedimentary geobodies, their bounding dimensions and internal fabric, and their grain-size distributions that define facies. A densely drilled area with open file data near to the Glenhaven area was selected to develop a workflow for modelling the distribution and connectivity of potential baffling units, using depositional concepts developed from the outcrop studies.

This is the first time that data gathered from the outcrop will be directly relevant to the construction of a static geological model which can be up-scaled to a regional model.

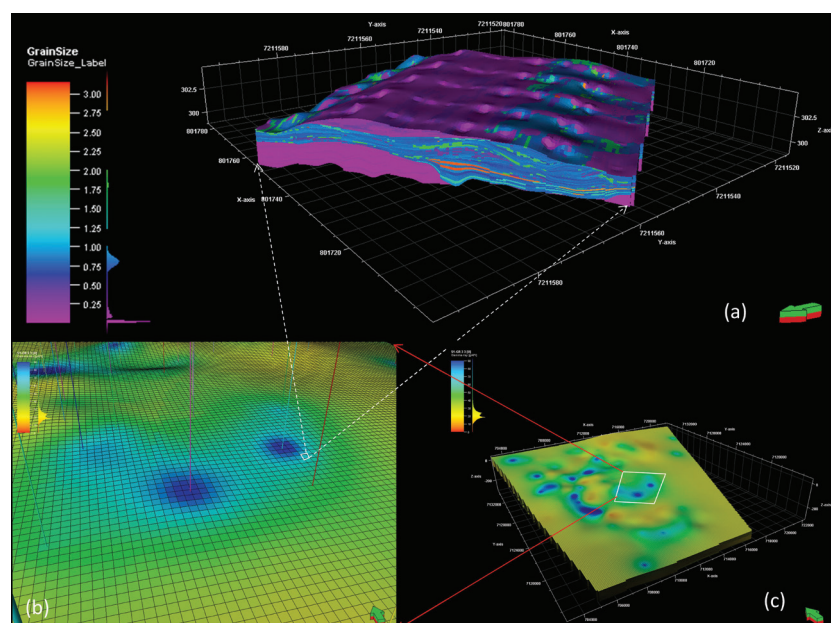
The study has:

- » challenged our understanding of the depositional setting of the Precipice Sandstone that leads to its reservoir properties,
- » developed a catalogue of sedimentary geobodies, their dimensions and their sedimentary features, to assist in subsurfacing modelling of the Precipice Sandstone reservoir flow units,

- » developed a workflow for further, more sophisticated, subsurface facies modelling for the Precipice Sandstone, and to test the influence of the variograms on the lateral connectivity of the baffling units within the Lower Precipice allo-stratigraphic unit, and
- » tested hypotheses for structures that may act to control flow pathways in the reservoir.

### Reference

V. Bianchi, et al 2016, Outcrop mapping and photogrammetry of the Precipice Sandstone (7-0314-0228)



Size comparison of local model and outcrop model. (a) Grain size distribution in outcrop of Isla Gorge Z; (b) GR distribution between wells; (c) local model with densely drilled well data. Note that Isla Gorge is not from the square area in figure b.

## CASE STUDY

# Assessing the longer term fate of dissolved CO<sub>2</sub>

Numerical simulations are an essential tool for assessing the long-term storage of CO<sub>2</sub> in saline aquifers, such as the proposed pilot project at the Wandoan site in Queensland's Surat Basin.

However, the robustness of the numerical predictions depends on accurately modelling the important physical processes involved. Numerical predictions of the amount of dissolved CO<sub>2</sub> during the early stages of a CO<sub>2</sub> storage project, particularly during the injection period where the CO<sub>2</sub> plume grows rapidly, overestimate the actual amount of dissolved CO<sub>2</sub> due to the use of finite-sized grid blocks. A simple theoretical scaling has been used to demonstrate that this discretisation error can be accurately accounted for and effectively removed in numerical simulations.

In the long-term, however, the necessary use of coarse grid blocks in a computational model prohibits the accurate simulation of enhanced dissolution due to density-driven convective mixing. This type of mixing typically occurs at a spatial length scale that is smaller than the size of the grid blocks necessary in a field-scale simulation. In order to improve the long-term numerical predictions of CO<sub>2</sub> dissolution in models that feature large grid blocks, a better understanding of the convective mixing process in heterogeneous reservoirs and the role of geochemical reactions is required.

A simple heterogeneity model consisting of a random distribution of impermeable horizontal barriers in an otherwise homogeneous

porous media was used to demonstrate that an equivalent anisotropic model provided an adequate approximation of the long-term flux. The long-term flux for an anisotropic reservoir was shown to scale as  $(k_v/k_h)^{1/2}$  times the isotropic estimate, a result that was confirmed by numerical simulations

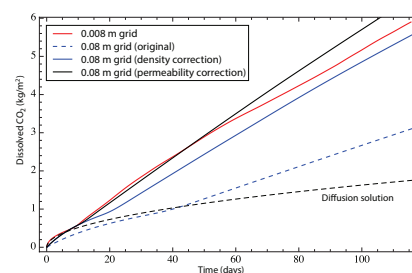
A sub-grid-scale scheme, for reducing the error in the numerical predictions of long-term CO<sub>2</sub> dissolution due to convective mixing, was developed. Several possibilities for implementing the scheme using grid-corrected properties were proposed and assessed using numerical simulations. This correction significantly reduced the difference between the fine-scale results and the results using much coarser models.

Key outcome:

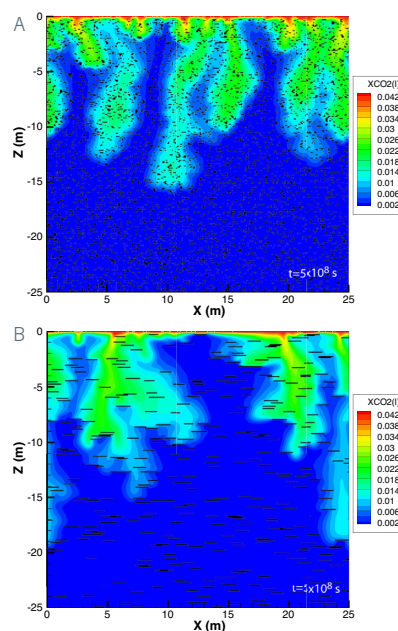
» The results obtained in this project can be implemented in commercial simulation software to improve the modelling of the short-term and long-term behaviour of injected carbon dioxide.

### Reference

C. Green and J. Ennis-King 2014, Improved discretisation and dynamic modelling of CO<sub>2</sub> solubility during injection and subsequent convective dispersion (7-1011-0190)



Dissolved CO<sub>2</sub> per unit cross-sectional area. Fine-scale 0.008m × 0.008m grid (solid red line); Coarse-scale 0.08m × 0.08m grid (dashed blue line); Coarse-scale 0.08m × 0.08m grid with grid-dependent density correction (solid blue line). This correction significantly reduces the difference between the long-term dissolution rate of fine-scale models (accurate but at great computational expense) and coarse-scale models (with much lower computational expense).



Dissolved CO<sub>2</sub> mass fraction for heterogeneous models with  $k_v/k_h = 0.6$  after  $5 \times 10^8$  s (15.8 years). A) Short barriers ( $L = 0.1$  m); B) Long barriers ( $L = 1.0$  m). Barriers are shown in black. CO<sub>2</sub> dissolution rate is similar in both cases.



## FUTURE RESEARCH

# Surat Basin

### ➔ **Techno-economic feasibility of concurrent injection of CO<sub>2</sub> and CO<sub>2</sub>-saturated CSG water**

The combined CO<sub>2</sub>-CSG water injection is demonstrated, a 'game changer' for geological carbon storage in the eastern Surat Basin if possible. This research will investigate if synergies are available from separate and mutual CO<sub>2</sub> and water injection into the Precipice Sandstone of the eastern Surat Basin.

### ➔ **Processing of large datasets of surface array-based passive seismic for CCS applications**

The project will aim to deliver a computational infrastructure, in the form of a software system, optimized for small sized compute clusters. This will allow for cost effective handling of large passive seismic data sets with a focus to CCS.

### ➔ **CO<sub>2</sub> solubility for dynamic modelling**

For dissolution of injected CO<sub>2</sub> into formation water, the fundamental time-dependent dissolution process on the sub-grid scale is not well understood. This project will use a pore-scale model of CO<sub>2</sub> distribution to match laboratory observations on dissolution of CO<sub>2</sub> in cores, and will investigate how this time-scale affects the coarser scale simulations.

### ➔ **Multi-scale static and dynamic modelling of Precipice facies**

The project proposes to address the critical impact of small scale-heterogeneity on fluid movement (in the absence of anticlinal trapping); ultimately creating greater confidence in the range of probable static models, and in the dynamic simulation of the extent of the GHG stream.

### ➔ **SBED dynamic modelling of Precipice facies**

The average effects of small-scale heterogeneities in large-scale numerical simulations of flow properties (static and dynamic model) must be accounted for through up-scaling. This work is expected to provide auditable methods for up-scaling from laboratory scale to basin scale application and recommend range properties for use in the Glenhaven Field Storage plan dynamic simulation.



## Southern Perth Basin

The SW Hub commenced as Australia's first flagship CCS project in December 2011. It considers the storage potential of the Lesueur sandstone formation in an on-shore location of the Southern Perth Basin. This is a fluvial sandstone, therefore reservoir quality can be expected to vary in the lateral direction. Historical data is sparse as the region is not well explored. The benefit of demonstrating and confirming the storage potential of this site is proving the significant increase in global storage potential of similar basins.

### Goal

*To support CO<sub>2</sub> storage  
in the on-shore  
Southern Perth Basin  
Western Australia*

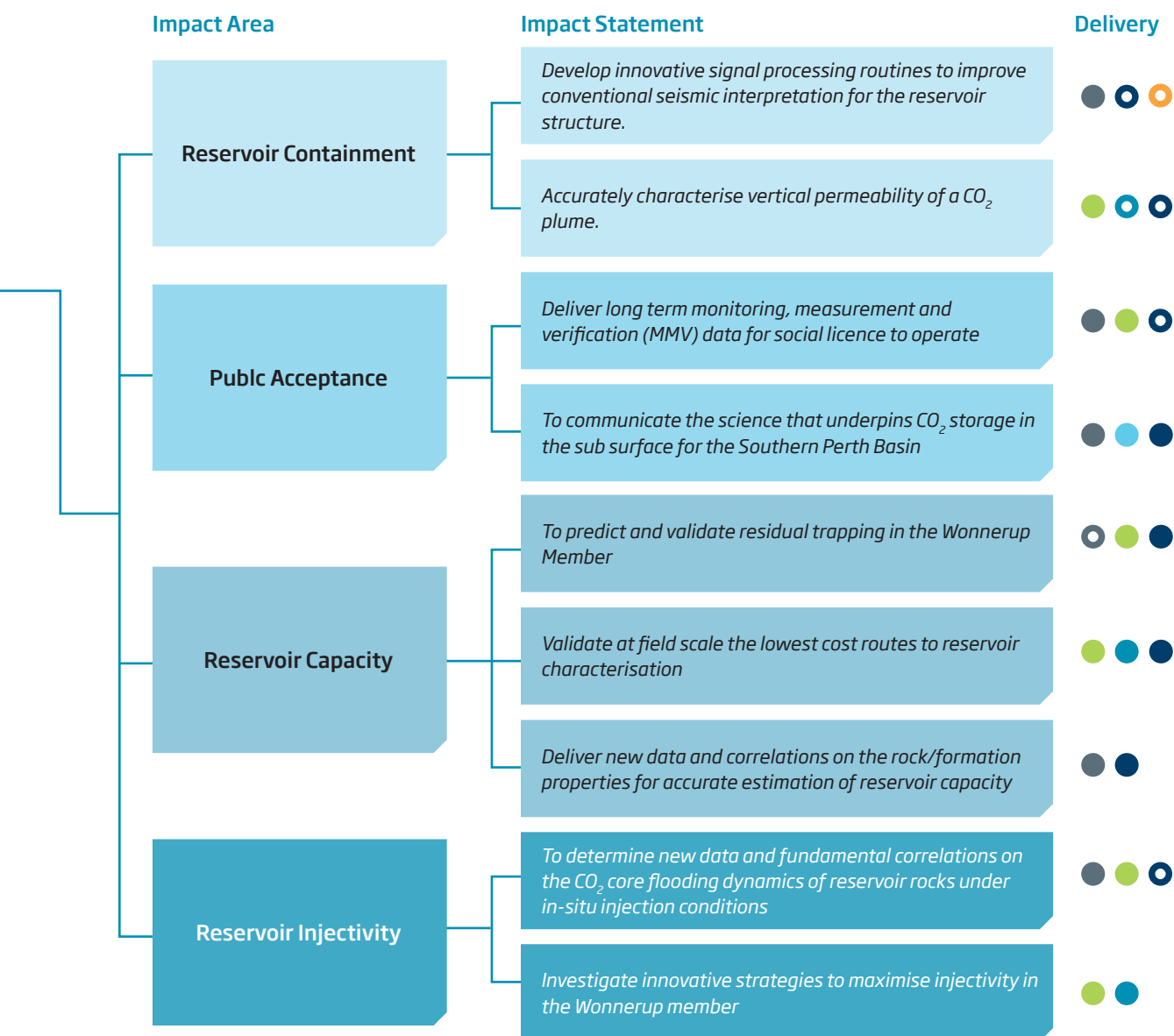


### Scale Key

● In lab      ● In Field

### Delivery Key

● New Data      ● New Application  
 ● Field Validation      ● New Service  
 ● New Correlation      ● New Software  
 ● Permitting & Public Communication



Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

## CASE STUDY

# Obtaining high quality data with a lower environmental footprint

### A large 3D seismic survey at the South West CO<sub>2</sub> Hub Project near Harvey was acquired.

The survey is of great importance for the characterisation of the reservoir, seals and structures in the area. Often, the positioning of the seismic source points is not easy or convenient. These issues arise because of the nature of the land and vegetation in the area (wetlands etc.), and also because the larger size of the commercially owned vibrating trucks is likely to cause significant disturbance to the landowners. Gate removal and fence demolition are both impactful, and the trucks may leave very large footprints over soft ground. It is therefore of high importance to investigate the use of alternative sources to replace conventional seismic sources in parts of the commercial 3D survey.

This project was planned to evaluate and demonstrate the effectiveness of the UNIVIB sources acquired under the EIF granting scheme to the National Geosequestration Laboratory (NGL). The broad band signal generated by the UNIVIB trucks, in combination with tight geophone spacing, provided a technical solution for resolving shallow structures and lithological variations. The latter are features of prime importance for the long term CO<sub>2</sub> storage program at this site. In addition, the system would be used to demonstrate to the community their low environmental impact.

This project describes the results and findings from the experimental 2D seismic survey acquired along Riverdale Rd with newly acquired

NGL UNIVIB seismic vibrating sources (in 2013). Results are compared to previous work from 2011 involving conventional large size vibrating trucks.

A high quality, broad band, low impact seismic source produced very high resolution data in the first kilometre of depth along Riverdale Road, Cookernup. Despite the high ambient noise (traffic and farming machinery) this source, combined with unconventionally light-weight seismic equipment, produced high quality data. Shallow sediments were imaged with superior resolution. The main unconformity can now be mapped with much improved accuracy in comparison to the 2011 data, which was acquired with much stronger sources.

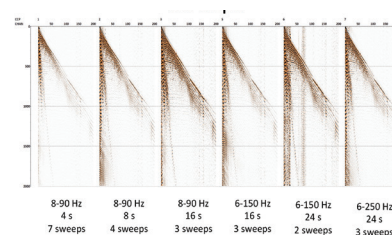
Key outcomes:

- » With a relatively low environmental impact, the lighter weight UNIVIB proved very successful in demonstration to the general community. A vibrator truck was exhibited at the Harvey Agricultural Show in late 2013 and attracted a lot of interest and positive comments from the local community.
- » The results of the new survey demonstrated that high resolution surveys were achievable for imaging the top 1000m of sediments and improving our understanding of the fault patterns.

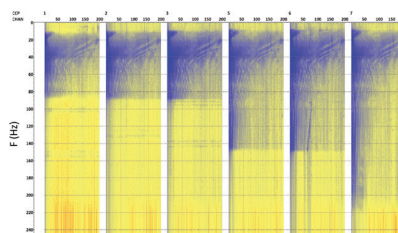
- » The new broad band source also proved to be quite a powerful source; capable of producing enough energy to record reflections from depths of over 3000m.
- » It showed it was possible to utilise UNIVIB trucks in the existing large-size 3D survey, to close the gaps in survey coverage where access is otherwise not possible, due to local land conditions.

#### Reference

M. Urosevic, et al 2014 Harvey 2D test seismic survey – issues and optimisations (7-1213-0223)



Sweep tests going left to right using conventional narrow to unconventional broad band sweeps. Standard commercial sweep is compared to a long broad band sweep. Long sweeps performed the best.



Log-Amplitude spectra for sweeps. Useful frequency range extends even to 250Hz. The optimum sweep is considered to be: 6-150Hz, 24 seconds long.

## CASE STUDY

# Reducing costs by assessing the validity of alternative models

It is standard industry practice to use three-dimensional geological models to predict rock properties of a reservoir.

These 'static' geological models contain information at high resolution about the distribution of rock types (facies) usually interpolated from core analyses, and wireline information, measured at discrete well locations often kilometres apart. Additional parameters such as porosity and permeability are distributed throughout the model according to the spatial variability typically associated with the interpolated facies or from inversion of seismic information.

An alternative method, stratigraphic forward modelling (SedSim), numerically simulates depositional processes such as erosion, transport, deposition, and compaction to predict lateral and vertical variations in reservoir and seal properties associated with predicted lithofacies distribution. An advantage is that forward numerical models may be constructed using a limited amount of data, useful for greenfield sites, and the resulting models may also reduce depositional uncertainty for the same amount of input data required by more conventional static methods.

Because of the initially limited well and seismic data in the South West Hub area, ANLEC R&D identified the need to study the utility of forward stratigraphic modelling and sponsored a two phase project to:

- » construct a static, cellular geological model for the area using SedSim stratigraphic forward modelling software; and

- » use this model as the basis for dynamic flow simulation and contrast the results with those obtained using a conventionally derived static model.

Phase 1 used SedSim to create a stratigraphic forward model from 250 Ma to 182 Ma (Triassic to Lower Jurassic), from the base Wonnerup equivalent to top Eneabba equivalent, that predicted the distribution of grainsize and primary porosity (and permeability via a transfer function) of sediments below seismic resolution around the Harvey-1 well.

Phase 2 used this model as a basis to perform a flow simulation of CO<sub>2</sub> into the Wonnerup Sandstones using a nested 500m grid and dynamic model area of 25 x 15km. The simulation of CO<sub>2</sub> injection used Eclipse 300 software and the results were compared to a previous simulation performed by Schlumberger based on a static model constructed using well data and geostatistical distribution of reservoir properties.

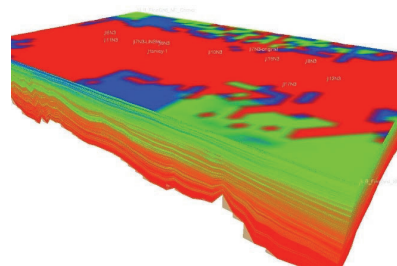
Both methods predict CO<sub>2</sub> plumes to develop and remain around the injection wells for the long term; the main difference being that the plume predicted by the 'SedSim' input spreads more than the conventional model.

This was the first time such a comparison of dynamic simulation of geological models generated by these different methods has been performed and has provided insights into dynamic models for CO<sub>2</sub> sequestration.

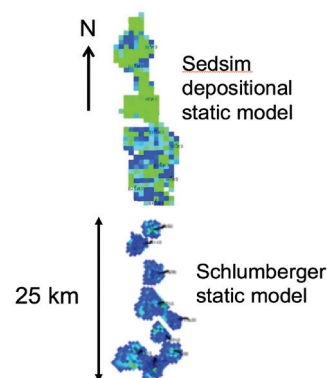
Having an alternative approach to depict the geological framework allows building confidence and reducing risk and cost of obtaining accurate representation of the reservoirs and the forward models.

## Reference

C. Griffiths and Y. Cinar 2014, Stratigraphic forward modelling comparison with eclipse for SW Hub (7-0212-0202)



SedSim depositional model of South West Hub region at Top Eneabba (182 Ma) at scale for dynamic reservoir modelling. Low total porosity is red and higher total porosity grades to blue. The model covers an area of 375 km<sup>2</sup> (Griffiths et al., 2012).



Comparison of dynamic simulation results of CO<sub>2</sub> plumes after 40 years using the SedSim un-faulted depositional static model and Schlumberger static model inputs. (Griffiths et al., 2014)



## CASE STUDY

# Advanced seismic processing discovers new reservoir features

The large-scale 3D seismic survey acquired in the first quarter of 2014 proved to be of great importance for characterisation of the SW Hub Project; mapping the main structures and key geological interfaces.

However, small to medium shallow structures were less clearly imaged in this survey, as the recording geometry was adjusted for the regional investigations and greater depths, rather than high resolution and shallower character of the formations.

A high-resolution 3D survey was undertaken to investigate whether the imaging of the shallow structures could be improved. The survey was centred at the Harvey-4 well. The principle objective was to image the complexity of the shallow structures in 3D. Close to 1600 seismic source positions were acquired over 5 days. Seismic receivers utilised single and 3-component geophones arranged into an odd-even receiver line pattern.

Preserved amplitude processing and pre-stack imaging proved to be a very effective processing approach for structural analysis. The same data can be used in the near future for more qualitative studies involving acoustic inversion and AVO studies after calibration to the Harvey-4 well logs. The Nested 3D data cube was inserted into the large, regional scale Harvey 3D survey (see images).

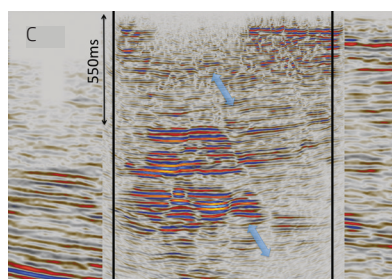
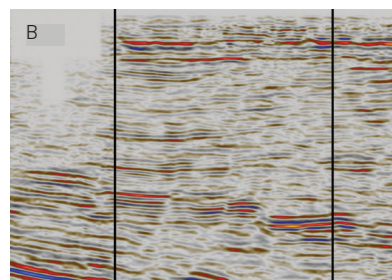
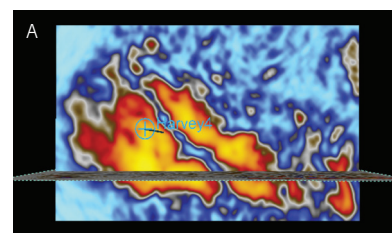
A comparative analysis showed the following:

- » Several faults are seen in the Nested 3D data, which were not previously identifiable in the regional 3D cube. This includes faults at different scales.

- » All discontinuities (large and small) are of a much higher fidelity in the Nested 3D survey.
- » Some faults appear to propagate near to the surface but are of a small-scale throw.
- » Faulting in the area is highly complex.
- » The Harvey-4 well appears to have drilled through a fault of a large throw (several tens of metres).

### Key conclusions:

- » These results demonstrate that high-resolution surveys are important for imaging the top 1,000m of sediments. The Nested 3D survey produced higher fidelity imaging of faults down to at least 1,500m in comparison to the regional 3D data.
- » New seismic images allow for the interpretation of faults, previously unidentified in the regional 3D survey.
- » Even some deep, large-scale faults are better imaged with the new high-resolution survey than the regional survey.
- » The fault complexity revealed by the new data suggests that a much higher data density and resolution is required in order to accurately analyse and characterise the SW Hub reservoir.
- » This data can enhance the static models to more accurately characterise the layering of the formations.



3D survey comparison: A) Time slice through similarity section, B) Regional Harvey 3D and C) Nested 3D inserted into the rectangular area. The location of the inline section shown is marked in A). The Harvey-4 borehole is shown as a green circle. The white in-fill small circle is added to enhance the borehole position only in this display. The blue transparent double arrow is used to denote "new" fault images, not seen in the regional data.

### Reference

M. Urosevic, et al 2015, Acquisition of the nested 3D seismic survey at Harvey (7-1213-0224)

# Improved seismic response and attributes with innovative processing and quantitative interpretation

The Lesueur formation has several distinctive features that complicate conventional seismic characterisation of the subsurface: the Yalgorup member consists of finely layered shaley lenses and not continuous impermeable layers; the Wonnerup member, has no seismic reflections inside; intense faulting in the area causes lateral variations of the subsurface properties and further complicates seismic imaging conditions.

Advanced methods of seismic quantitative interpretation and joint analysis of a broad range of available geophysical/geological data may provide a refined model of the Lesueur formation and its properties. The project uses the large commercial seismic and high resolution nested seismic survey around Harvey-4 to resolve a shallow part of the subsurface. To constrain static geomodelling, all available 3D surface seismic data, VSP data from Harvey 1, 2, 3, and 4, well log data and the results of the core analysis performed in a preceding study was dedicated to geological data integration.

To date, a conventional quantitative interpretation (QI) approach has been set up and applied to both seismic datasets. The principle goal of the study was the mapping of the concentration of potential fluid baffles – palaeosols. The workflow developed consisted of the following steps:

- » true-amplitude seismic processing to allow for adequate interpretation of the intensity of seismic events on the seismograms.
- » application of some conventional seismic attribute analysis,
- » sparse-spike acoustic impedance inversion of the commercial seismic
- » well-logs quality control and conditioning for seismic inversion,

- » feasibility study/correlation analysis between acoustic and petrophysical properties within the Yalgorup and Wonnerup formations;
- » matching commercial seismic to all four Harvey wells, wavelet extraction using reliable wells;
- » model-based acoustic inversion of the commercial seismic;
- » palaeosol bodies mapping in the acoustic impedance cubes;
- » modelling test of AVO-effect in the nested survey, selection of the most reliable range of offsets;
- » model-based elastic impedance inversion of the nested survey data, and
- » mapping of the palaeosol facies and determination of its characteristic lateral sizes.

Recent results:

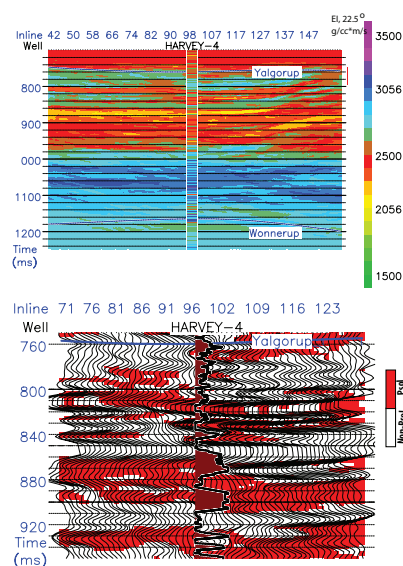
Fast-track QI of the available seismic data delivered the first approximations of palaeosol facies distribution within the Yalgorup and upper part of the Wonnerup formations. The study also provided the following recommendations for improved data acquisition for the SW Hub:

- » Conduct a high-resolution nested seismic survey around Harvey-3 with sufficiently large offsets to allow for AVO-inversion without near-offset data.

- » Well logs in Harvey-3 are of good quality, so we expect rather good well-to-seismic match;
- » Drill Harvey-5 through the whole Wonnerup formation to provide data on seismic properties of the assumed injection formation.
- » Drill Harvey-5 between Harvey-4 and Harvey-3, preferably within the nested survey.

## Reference

S. Glubokovskikh, et al 2016, The Lesueur, SWH: Improving seismic response and attributes. Fast-track quantitative interpretation for South West Hub (7-0115-0241)



Inverted EI along inline 23 (top); crossplot of  $dEI/\langle EI \rangle$  vs EI, used to interpret palaeosol geobodies (red on the bottom).

## CASE STUDY

# Research delivers more information on structure of the Lesueur storage complex

The South West Hub project is now entering an evaluation stage, aimed at reducing uncertainties related to the distribution of properties of the targeted subsurface formations.

Currently, data is sparse and more confidence is needed in the storage potential for the basin. Ambiguities are particularly evident in the following aspects of the subsurface basin characterisation:

- » Diagenetic history of the sediments and how diagenesis affected the pore space and therefore the injectivity and storage potential of the targeted units;
- » Current and past nature of the formation fluids and reservoir compartmentalisation between the different fault blocks identified in the subsurface of the SW-Hub;
- » Seismic constraints on the petrophysical character of the Lesueur Sandstone;
- » Geomechanical properties of the storage reservoir and overlying units.

Work is on-going and recent results show:

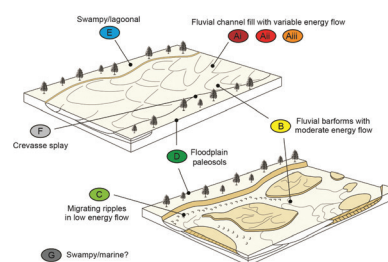
- » There is an overall consistency in terms of mineral content and interpreted diagenetic sequence from 4 wells relevant to SW Hub in the Southern Perth Basin. Similarities are also observed with material from the same formation currently buried at greater depth in the Pinjarra-1 well.

- » Notably, the values of porosity, permeability and elastic wave velocities are seen to be markedly different at Pinjarra-1, although a kink in the lowermost part of the Wonnerup Member induces a major decline in the velocity vs depth trend.
- » So far, fluid inclusion studies have been conducted on samples from Harvey-1 and Pinjarra-1 in an attempt to relate possible burial/diagenetic effects to the observed petrophysical characteristics of the rock.
- » It can be shown that palaeo formation water salinity at the two locations differs significantly, as do the homogenisation temperatures recorded in the diagenetic quartz cements. This may suggest a measure of compartmentalisation; not surprising given the 10's of kms distance between the wells.

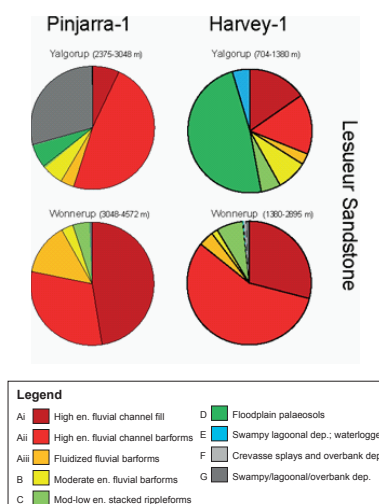
The drilling, coring and logging program comprising three wells: Harvey-2, Harvey-3 and Harvey-4 have been completed. Analysis is ongoing.

### Reference

C. Delle Piane et al 2016, The Lesueur: Deposition, Rocks, Facies, Properties 7-0115-0240



Block diagrams to illustrate the sedimentary depositional environment and architecture of lithofacies.



Comparison of facies distribution within the cored sections of the Lesueur Sandstone encountered in wells Pinjarra-1 and Harvey-1.

## CASE STUDY

# A fresh look at faulting to inform deployment decisions

The available seismic data for the South West Hub clearly indicates that multiscale faults affect the target CO<sub>2</sub> storage reservoir of the Lesueur Formations and the potential top seal Eneabba Formation.

Based on the integration of existing and new (2010 vintage) 2D seismic dataset and Harvey-1 well data, this project primarily targets the evaluation of the faults hydraulic behaviour, i.e. the faults sealing potential for across-fault and up-fault flows. A secondary objective is to investigate the distribution of sub-seismic fractures and their impact on the trap integrity and reservoir compartmentalisation.

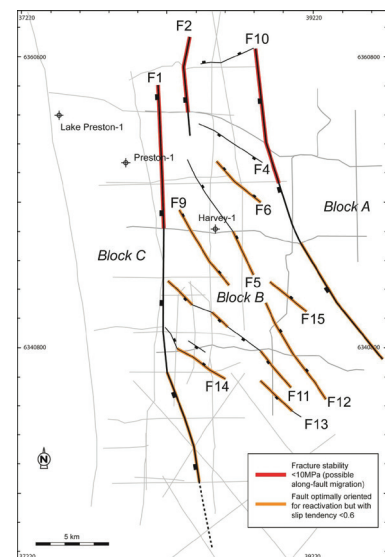
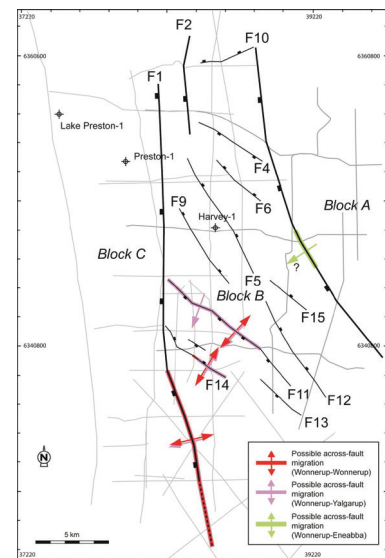
A new geological model, consistent with the integration of the latest 2D seismic reflection survey and available geophysical data, has been built. It integrates five stratigraphic horizons tied to formation tops in the new Harvey-1 data well (Neocomian UC, top basal Eneabba Shale, top Yalgorup, top Wonnerup and top Sabina Sandstone) and 13 main faults that can be correlated between at least two 2D-seismic lines that show constancy in dip, strike orientation and offset. This represents a first-order geological model, and the acquisition of additional seismic and well data is critical to reduce remaining geological uncertainty and further constrain the structural framework.

Key findings from the study:

- » The likelihood of lateral migration of CO<sub>2</sub> across faults between the Wonnerup Member and any interbedded sandstone (i.e. thief zones) in the Yalgorup Member can be locally high to the south of the SW Hub.
- » The likelihood of lateral migration of CO<sub>2</sub> across faults within the Wonnerup Member can also be locally high to the south of the SW Hub, with potential of westward migration beyond F1 if the CO<sub>2</sub> column exceeds the local offset.
- » Shale Gouge Ratio (SGR) values on the fault plane suggest an average to low likelihood of across-fault migration.
- » The slip tendency magnitude for the SSE-NNW-oriented faults in the SW Hub are low (typically between 0.15 and 0.3) suggesting a low risk of fault failure under the present-day stress.
- » The smallest critical pore pressure perturbations required to reach failure stress are located to the north of the SW Hub.
- » The study provides a useful input into dynamic models to test compartmentalisation and containment.

### Reference

L. Langhi, et al 2013, Fault seal first-order analysis - SW Hub (7-1111-0201)



Summary of across-fault (top) and along fault (bottom) CO<sub>2</sub> migration potential for the SW Hub.



## CASE STUDY

# Mapping lithofacies: validating storage potential in unconventional storage structures

The goal of the multidisciplinary work presented by this study is to understand the geological and geophysical parameters that will affect the safe and efficient storage of CO<sub>2</sub> at the proposed SW-Hub site in the Southern Perth Basin.

In particular, the areas of interest covered by this work are related to the characterisation of the geological units intersected by Harvey-1 in terms of storage capacity; injectivity and containment potential; elastic and mechanical properties and heterogeneity of the formations encountered.

The present work feeds into and supports a wider program aimed at the integrated evaluation of the SW-Hub encompassing a detailed analysis of the seismic data available in the region; an assessment of the potential for fault reactivation around the proposed injection area; a study of the possible fluid-rock interactions at reservoir conditions and the forward stratigraphic modelling of the area.

The outcomes of the work indicate significant differences between the Upper and Lower Members of the Lesueur Sandstone in terms of sedimentology, petrophysical, geomechanical and elastic properties. The deep saline aquifer equivalent to the Wonnerup Member of the Triassic Lesueur Sandstone represents the targeted reservoir, whereas the Yalgorup Member and the Basal Eneabba Shale may act as possible stratigraphic seals.

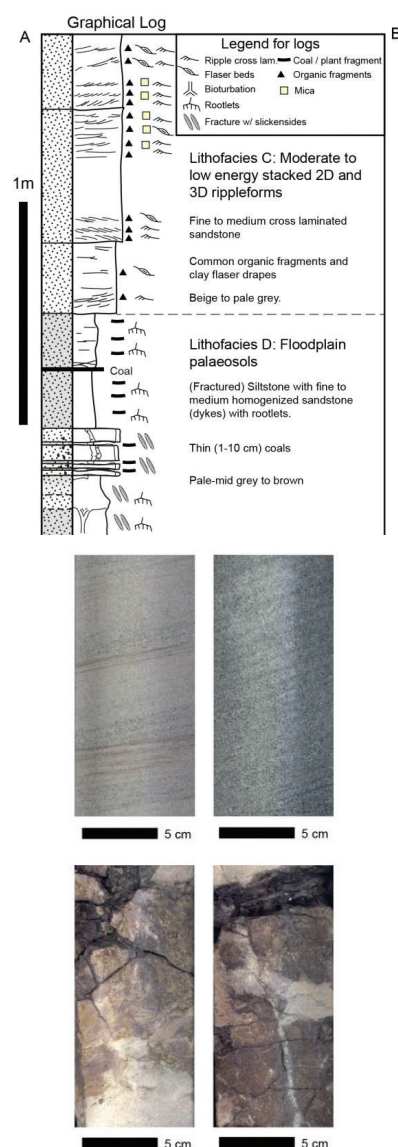
Good reservoir properties are recorded in the lower Member (Wonnerup 1380-2895m depth) of the Triassic Lesueur Sandstone with encouraging values of porosity (7 to

19%) and permeability (0.01 to 580 mD) and lithofacies homogeneity with depth. Permeability anisotropy measured in the laboratory can be very significant at the tentatively predicted injection levels: across bedding permeability ranges between 0.01 and 3mD while along bedding permeability ranges between 38-580mD, resulting in anisotropy of up to 3 orders of magnitude.

Core flooding tests also give positive indications for residual trapping (25 to 45%) as a principal containment mechanism. However, a marked decrease of permeability (up to 50%) was observed after sample flooding was also inferred from the tests. This phenomenon has been identified for future studies.

By contrast, the overlying Yalgorup (704-1380m) is far more heterogeneous and, due to poor core conditions of the shaly layers, the characterisation work only focused on the sandy intervals, and the results cannot be regarded as representative of the whole stratigraphic unit.

Uncertainties remain regarding the geomechanical properties and containment potential of the different lithofacies within the Yalgorup. Nevertheless, the presence of interbedded sands and shale layers could be beneficial in terms of storage.



A summary of the lithofacies scheme developed for the Mesozoic stratigraphy of the central Southern Perth Basin. (A) Graphical sedimentary logs and descriptions. (B) Example core photographs from Harvey-1.

## Reference

C. Piane, et al 2013, Facies-based rock properties distribution along the Harvey-1 stratigraphic well (7-1111-0199)

## CASE STUDY

# Monitoring the injected CO<sub>2</sub>: geophysical remote sensing of CO<sub>2</sub> sequestration

No single geophysical method in isolation has the capability to monitor CO<sub>2</sub> because most extant geophysical methods cannot detect CO<sub>2</sub> directly.

This means that an effective geophysical monitoring and verification strategy should incorporate one or more methods. For particular scenarios, the exact remote sensing combination will vary, but such methods will generally include reflection seismics, electromagnetics or gravity.

The objectives of this project were to:

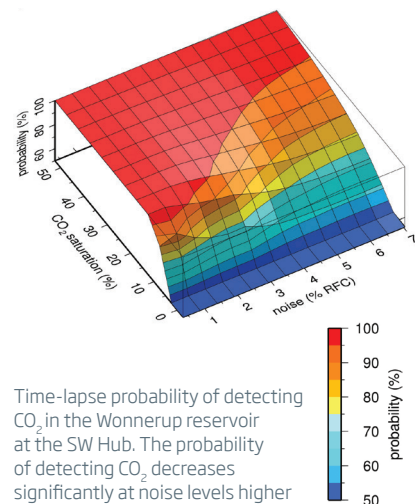
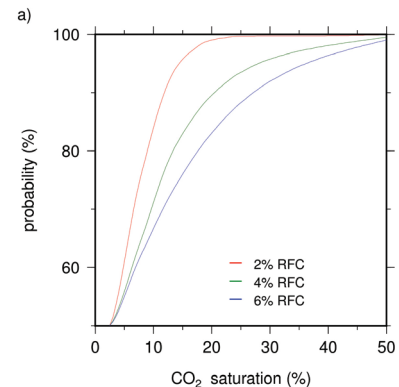
- » Develop conceptual reservoir models which spanned the likely geometries and performance of the potential demonstration flagships;
- » Forward model possible physical measurements;
- » Understand the sensitivity of the measurements to CO<sub>2</sub>;
- » Recommend the combination of geometries and physics to be used for the pilot project measurements, including notional costs; and
- » Recommend analysis and measurement technology that needs further development.

These objectives were addressed by modelling seismic, electromagnetic and gravity responses of idealised, conceptual models of two recently-approved flagship CCS projects; the SW Hub in Western Australia and the CarbonNet project in Victoria. Baseline and several data vintages (each representing the addition of increasing amounts of CO<sub>2</sub>), were modelled in order to assess

the suitability of each geophysical method to each flagship project. Geophysical data from different vintages were analysed in order to establish the sensitivity of each method to CO<sub>2</sub> injection.

This project found that:

- » Time-lapse surveys are required of all geophysical methods studied in this report. It was not possible to infer CO<sub>2</sub> saturation from a single geophysical data vintage. The requirement for geophysical time-lapse surveys is concomitant with establishing high-quality baseline models;
- » Extant high-quality well logging data are required to build high-quality geological models;
- » Accounting for uncertainties in seismic modelling improves the ability to evaluate CO<sub>2</sub> saturation and is required for robust risk assessment;
- » Permanent seismic arrays significantly improve S/N ratios, allowing for cost-effective acquisition of high-quality data with minimal impact to the community;
- » In shallow (typically < 100m) water columns, marine electromagnetic surveys would be unlikely to detect CO<sub>2</sub> variation; and
- » Due to the fall-off in response over distance, gravity and electromagnetic surveys should be conducted downhole. These need not be in vertical wells.



Time-lapse probability of detecting CO<sub>2</sub> in the Wonerup reservoir at the SW Hub. The probability of detecting CO<sub>2</sub> decreases significantly at noise levels higher than 2% of RFC.

## Reference

D. Annetts, et al 2012, A deployment strategy for effective geophysical remote sensing of CO<sub>2</sub> sequestration: Final report (3-0510-0030)

## CASE STUDY

# Using earth tides to sense reservoir connectivity

The vertical permeability of CO<sub>2</sub> storage formations, and specifically those of confining layers, are key parameters influencing the effectiveness of structural CO<sub>2</sub> trapping or the risk of leakage.

As a potentially attractive method to examine the integrity of a large CO<sub>2</sub> storage site, accurate and long-term passive monitoring of pressure variations in response to barometric pressure fluctuations and earth tide effects may provide a means to assess the continuity of the confining units and their hydraulic properties. This scoping study examines such responses, and their suitability for determining vertical permeability is then ascertained by numerical modelling combined with notional inversions and data-worth analyses.

The analyses suggest that the pressure fluctuations observed in deep boreholes may be used to infer hydrogeological and geomechanical properties. However, pore pressures induced by barometric and earth tide loading are controlled by the local hydro-geomechanical properties rather than the large-scale hydrostratigraphic features of the CO<sub>2</sub> storage system. This includes medium scale heterogeneity due to the deposition of high and low energy facies as well as small-scale heterogeneities within facies. It is concluded unlikely that reliable estimates of vertical permeability and/or continuity of the confining layer can be obtained by analysing pressure fluctuation data.

Key conclusions were:

- » Loading effects from earth tides and barometric pressure

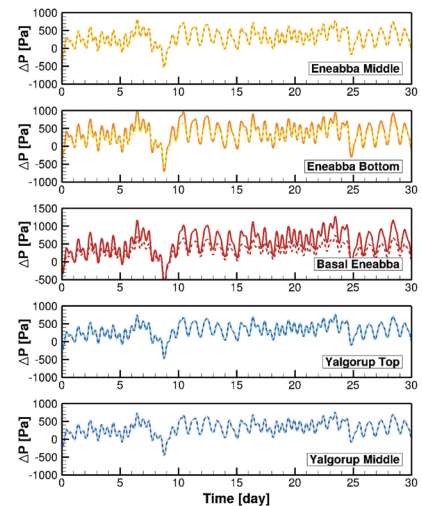
fluctuations are instantaneous everywhere in the sub-surface and not due to fluid flow and pressure diffusion from the surface.

- » Although these fluctuations are large-scale forcings, the induced pressure perturbations are controlled by local geomechanical properties and pressure dissipation, which is related to permeability and is determined by local hydro-geological properties.
- » Hence, even with sensitive sensors and regionally induced gradients, the permeability estimates are related to the local conditions.
- » Accurate long-term pressure measurements may be useful to estimate local permeabilities if analysed by a hydro-geomechanical forward simulator embedded in a robust inversion framework.

The study will also be useful in considering a future extended production/induction test design for the SW Hub project.

### Reference

Y. Zhang, et al 2016, Estimating vertical permeability based on responses to barometric pressure fluctuations in the Lesueur Formation (7-0515-0246)



Simulated pressure response to barometric and earth-tide above and below Basal Eneabba Shales, without (solid lines) and with (dashed lines) discontinuity in Basal Eneabba Shales.

## CASE STUDY

# The fundamentals of pore-scale processes revealed for Australian basins

The two primary CO<sub>2</sub> trapping mechanisms active during the first several hundred years of a storage project are structural and residual trapping. In the case of residual trapping the CO<sub>2</sub> plume is split into many micro-scale “bubbles” which are surrounded by brine and held in place by capillary forces.

In order to estimate leakage risk and storage capacities for a particular formation, buoyancy forces – which push the CO<sub>2</sub> upwards – need to be compared with the capillary forces that hold the CO<sub>2</sub> in place for such residually trapped CO<sub>2</sub>.

Until now, such estimates and related reservoir models, which predict reservoir multi-phase flow, assume that all storage rock is strongly water-wet, which means that water spreads completely on the rock surface. This means that water can surround CO<sub>2</sub> and trap it by pore-scale snap-off processes leading to residual trapping.

However, recent evidence suggests that under certain conditions the storage rock may not be strongly water-wet but can be intermediate wet or even CO<sub>2</sub>-wet. Moreover, pore-network modelling studies have predicted that CO<sub>2</sub>-wettability also strongly influences the efficiency of residual trapping i.e. with increasing CO<sub>2</sub>-wettability the amount of CO<sub>2</sub> that can be stored by residual trapping rapidly decreases.

This project utilised several different techniques in order to reduce the uncertainty in measurements of the CO<sub>2</sub> wettability of storage and seal rock and how this wettability is influenced by various parameters.

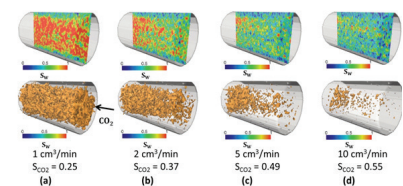
The nuclear magnetic resonance (NMR) response for a sandstone at reservoir conditions, at different CO<sub>2</sub> saturation stages, was measured for the first time. In addition, the project also measured supercritical CO<sub>2</sub>/sandstone/brine capillary pressures.

Key conclusions:

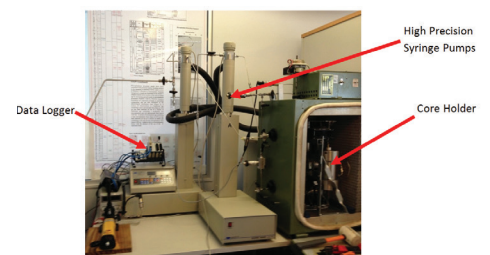
- » Understanding the wetting characteristics of in-situ reservoir rock is important if structural and residual storage capacities are to be known accurately.
- » Structural and residual trapping are likely to be viable storage mechanisms in clean quartz, and siliciclastic rock reservoirs that exhibit weakly water-wet characteristics.
- » Certain parameters have a greater effect on wettability than others. Rock surface chemistry is judged to have a very important effect, with pressure and brine salinity having important effects and temperature and surface roughness effects being significant.
- » It was proven by micro-computed tomography experiments that residual trapping is a viable storage mechanism at the pore-scale in clean sandstone.

### Reference

S. Iglauer, et al 2014, Pore- and core-scale investigation of CO<sub>2</sub> mobility, wettability and residual trapping (3-0911-0155)



Visualisation of 3D water saturation maps in the core during primary drainage (injections CO<sub>2</sub> in the right side).



Apparatus for capillary pressure measurements at reservoir conditions.



## CASE STUDY

# Alternating water and gas injection for CCS - help or hindrance?

In a typical carbon capture and storage project it is important to maximise residual and dissolution trapping to minimise the risk of leakage. In this project, a techno-economic analysis of residual and dissolution trapping for the SW Hub Project was carried out.

The methodology used technically feasible engineering designs to optimise both of the above trapping mechanisms in the Southern Perth Basin storage formation by determining the most feasible injection schemes. The aim was to estimate the relative economics of different injection schemes with different trapping results. The project did not assess the overall profitability of injection in absolute terms.

Continuous CO<sub>2</sub> injection is usually preferred for carbon capture and storage (CCS) projects. However, the literature shows that this option does not necessarily maximise residual and dissolution trapping. The project chose to analyse the engineering and economic effects of several injection schemes. Some injection schemes and processes, such as foam injection, carbonated water injection and fines migration, were ruled out early on because they are believed to be extremely costly. As a result, the options that were analysed included –

- » Vertical injection wells
- » Horizontal injection wells
- » Vertical injection wells and production wells for pressure relief
- » Water Alternate Gas (WAG) wells and production wells for pressure relief

- » Simultaneous Water Alternate Gas (SWAG)

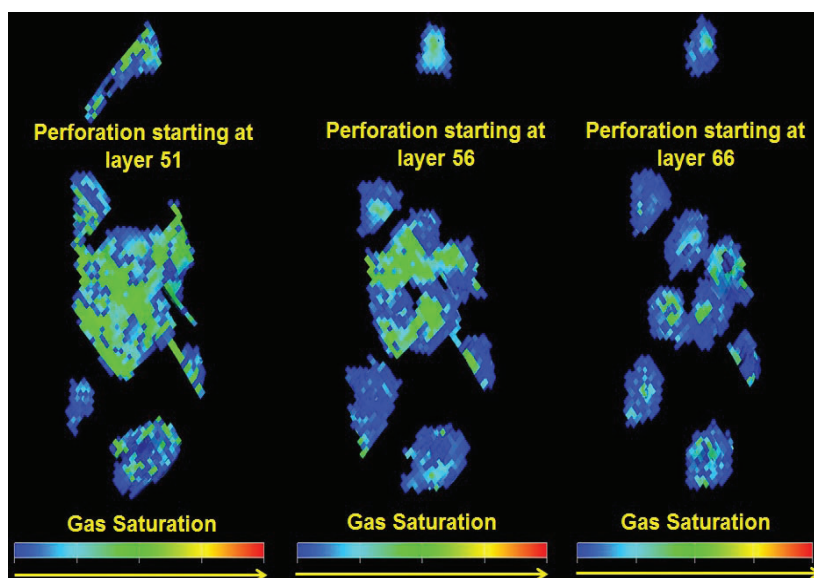
Key conclusions:

- » Most of the injection designs tested in this study show that injecting through perforations starting at the upper-middle of the Wonnerup Member provides the greatest potential for residual trapping, dissolution trapping and injectivity.
- » In order to minimise CO<sub>2</sub> production for the vertical CO<sub>2</sub> injection and water production well scenario, it is advantageous to locate the perforations in the middle of the formation.

- » Horizontal and SWAG well scenarios show the least injectivity because layers in the formation have very low permeability.
- » Vertical wells are the most economically attractive and show intermediate overall trapping benefit.
- » Although WAG wells are the least economically attractive, they do show the highest overall trapping benefit, especially early in the injection period.

### Reference

H. Baz, et al 2014, Desktop design study on enhancing residual and dissolution trapping (7-1012-0210)



Plan view of saturations for different depth layers of the CO<sub>2</sub> plume after 100 years of observation.

## CASE STUDY

# Long term data acquisition is important for CO<sub>2</sub> storage

Deploying CCS will require monitoring strategies over decades. Recognising this, ANLEC R&D commissioned a study to develop specifications for a set of well designs that included a range of complementary instrumentation with optimum configurations.

Specific features of the South West Hub (SW Hub) were used as the basis for design of such a system.

In Western Australia, 100km south of the city of Perth, the SW Hub is targeting the saline aquifer of the Lesueur Sandstone at a depth of 2-3km for commercial-scale CO<sub>2</sub> sequestration. In support of the drilling of these wells, there is a need to consider the relative location of the wells and the monitoring instrumentation required to maximise their contributions to the overall SW Hub objectives. This research project provided the technical specifications and costs for various measurement, with monitoring and verification options that can be incorporated into the SW Hub well-based monitoring process.

This research added value to the core activity being conducted by SW Hub by:

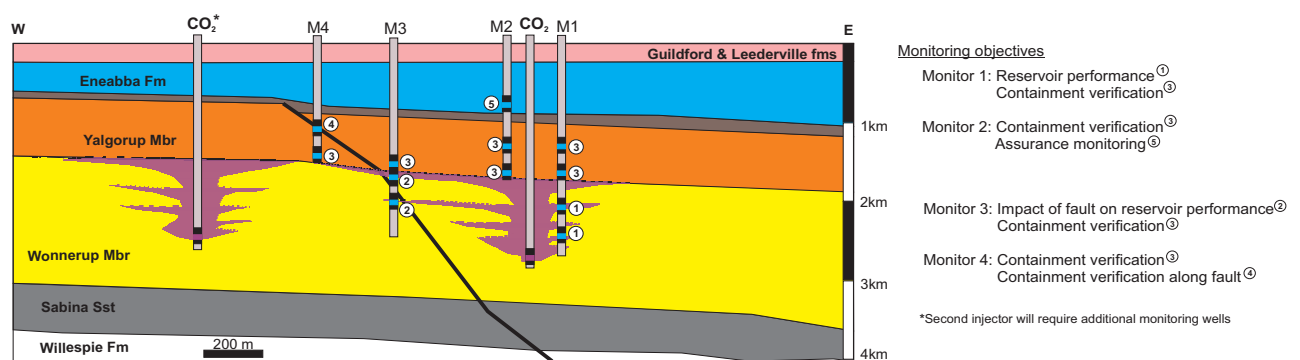
- » delivering a series of options for the well-based monitoring program including downhole and surface requirements;
- » considering optimal monitoring technologies and testing methodologies requisite for a potential early testing phase; and
- » providing a monitoring system that will allow long-term monitoring and research opportunities to be taken at the SW Hub.

Key results:

- » A critiqued list of data acquisition, monitoring technologies and applications for geologic carbon storage.
- » Monitoring options, with more than one monitoring scheme to address the current uncertainties around storage suitability.
- » An application-specific case study for the SWHub.
- » Considerations (economic and technical) for pre-existing wells to be converted into monitoring wells.
- » Monitoring emphasis on containment verification, with all four monitoring wells having completions in the Yalgorup Member above the storage interval.

### Reference

L. Ricard, et al 2015 Desktop design study on South West Hub wells (7-1012-0214)



Schematic monitoring scheme for the SouthWest Hub project that shows different types of monitoring wells that may be required to address monitoring requirements specific to the SWHub case.

## CASE STUDY

# Understanding geochemical baselines for the Lesueur Formation

This project reports on the geochemical evaluation of the Harvey-1 stratigraphic well, as part of the South West Hub demonstration project.

Two gas samples from a potential source of CO<sub>2</sub> (CSBP and BOC in Kwinana) that may be used for a pilot scale test have been analysed and found to contain almost pure CO<sub>2</sub>, in excess of 98.3 mol.%. The carbon isotopic composition of this gas is  $\delta^{13}\text{C} -37.6 \pm 0.28 \text{ ‰}$ , which is quite distinct from other background natural sources of CO<sub>2</sub> and might act as a tracer in the future.

Rock samples were extracted and the uppermost sample in the Yalgorup Member contained the highest concentration of liquid hydrocarbons (304.9 mg/kg rock). Other samples contained an order of magnitude less. Relative to commercial scale oilfields this amount is negligible, indicating that there is no active source rock of quantitative significance surrounding this well. This indicates that there is unlikely to be any form of basin resource conflict in relation to oil or gas finds in the immediate area. It is also possible that the hydrocarbons may have come, in part, from drilling mud contamination.

Only one unconfined formation water sample was recovered from the well at 856 m and it was also extensively contaminated by drilling fluids (Figure B).

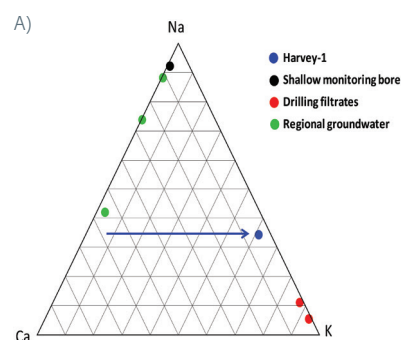
The sample from Harvey-1 is therefore on a mixing line between the drilling mud and the shallow bore water used.

Preliminary modelling of potential reactions in the Lesueur Formation samples suggests that the rocks have some capacity to maintain circum-neutral conditions, until all albite is converted to dawsonite (Figure A), with the removal of dissolved Na. Only after this point, do changes in pH occur. These reactions illustrate the importance of clays and feldspars contributing to changes in the mineralogy. These preliminary models contain a large number of assumptions (e.g. formation fluid chemistry is unknown).

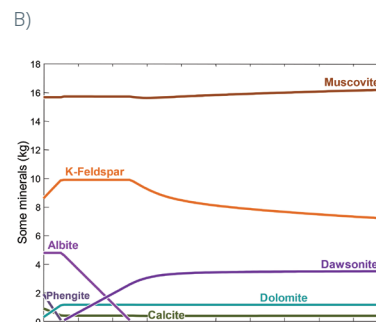
Core-flood analyses have been conducted to evaluate chemical and physical changes to some of the Lesueur Formation samples. One experiment conducted provided detailed analyses of core flood effluents far in excess of previous literature. Improved core flood experimental setup has allowed increased sampling and detailed geochemical analysis of > 60 cations and anions to monitor changes in chemistry when subjected to CO<sub>2</sub> injection. This workflow has provided “time-lapse” chemical data that enables us to see discrete changes in the mineralogy caused by the passage of CO<sub>2</sub>.

### Reference

L. Stalker, et al 2013, w (7-1111-0200)



Ternary diagram of major cation water chemistry in Harvey-1 at 856 m (blue), adjacent shallow bore 36 m (black), regional representative samples from the Binningup and Harvey Line water bores (green)\* and the drilling mud filtrates (red). The arrows represent the influence of contamination of Harvey-1 from the more representative regional sample groundwater chemistry. \*Data from Deeney (1989a & b).



Major cations and anions released into solution from the simulated injection of CO<sub>2</sub> into the Yalgorup rocks.

## CASE STUDY

# Establishing the natural variation of seismic signals for the Southern Perth Basin

Passive seismic monitoring is the science of recording and analysing natural or induced seismicity with networks of seismic sensors, without the need for active (man-made) seismic energy sources (like Vibroseis Trucks).

The University of Western Australia (UWA) Geophysics is deploying a sparse network of sensors over a period of 12 or more months in order to measure and interpret background seismicity and noise conditions for the SW Hub CCS project in the Southern Perth Basin; this is the first stage needed in a comprehensive seismic monitoring program.

The proposed network will comprise 8 or more near surface and autonomous stations located round the SW Hub project area.

Magnitude-frequency curves using historical seismicity catalogues and data collected during the monitoring phase will be developed to establish the rate of background natural seismicity in the project area.

As part of this research, seismicity data, within a 3D geological framework, will be interpreted in order to assess the association of natural and induced seismicity with geological structure. This information will be integrated with other ANLEC R&D studies of tectonic stresses, local faults and geomechanical lab measurements.

Comparisons of state of the art sensor technologies will be made to advance the techniques of passive monitoring and to assess monitoring limitations. Community engagement would also continue with information sessions and reports on the science of microseismicity.

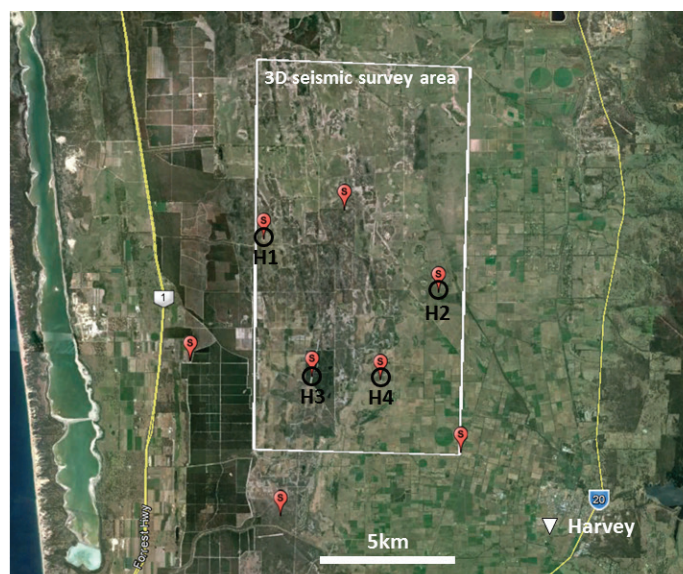
Passive seismic recordings can also be used to build images of the subsurface. This information can potentially be used for CO<sub>2</sub> injection monitoring directly (if the appropriate natural sources of seismic energy are present at the site) or used to design the active 4D seismic monitoring strategy. Towards this goal, an assessment of ambient noise sources at the site will be made with the available data and, where possible, 1D images will be made below the monitoring stations.

### Reference

N. Issa, et al 2016, Passive Seismic Investigations at the SW Hub: Project report at 6 months (7-0215-0244)



The seismic stations are relatively small and self-powered. Recorded data will be transmitted to UWA remotely using the mobile 3G/4G network.



Map of proposed network showing proposed UWA station locations (red S markers) and location of nearby Australian Seismometers in Schools station (white triangle). The Harvey-1 to Harvey-4 stratigraphic wells are labelled as H1, H2, H3, and H4.



## CASE STUDY

# Feasibility and design of robust passive seismic monitoring arrays for CO<sub>2</sub> geosequestration

This project is developing innovative approaches to optimise site-specific passive seismic array design, data analysis and imaging methods to apply for monitoring CO<sub>2</sub> storage.

Passive seismic monitoring can be useful in CO<sub>2</sub> geosequestration (storage) projects.

The objectives of the study are:

1. Measure and predict the expected microseismic energy at the SW Hub site by making geomechanical lab measurements on cores taken from wells at the site.
2. Measure and characterise the natural seismicity and signal/noise conditions at the SW Hub site with a small field test array of passive seismic sensors in shallow boreholes.
3. Simulate realistic 3D seismic wavefields using supercomputing algorithms, develop and test innovative 3D seismic wave-equation and VSP imaging methods to improve images of the subsurface with passive seismic array data.
4. Develop methods to optimise the sensor array design, in order to maximise the ability to detect/image microseismic events at the SW Hub and other CO<sub>2</sub> geosequestration sites.

Computational studies include:

- » High-performance computational (HPC) modelling of 3D elastic passive seismic wavefield data, using a highly optimised, parallel algorithm on the Magnus cluster at the Pawsey Supercomputing Centre.
- » Microseismic events were successfully simulated within

a reasonable computation time using 1,536 CPU cores in parallel. Hypothetical microseismic source events were simulated in 3D as if located along faults in the Wonnerup or Yalgorup members, with two types of common microseismic source mechanisms (extensional and double-couple shear).

- » Wave-equation based imaging of hypothetical microseismic events, using surface and borehole sensor arrays, including uncertainty analysis and velocity model analysis.

Field operations include:

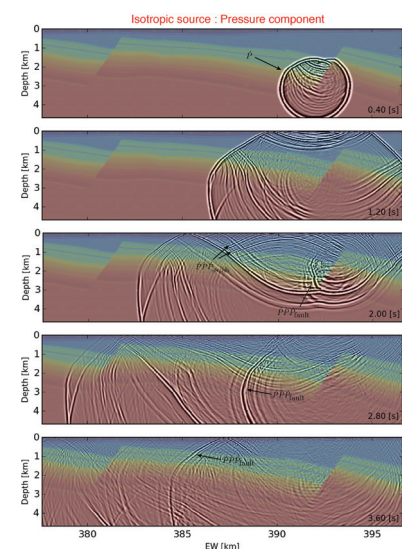
- » Successful deployment of a high-sensitivity broadband passive seismic array in a 50m shallow borehole array at the SW Hub site near the Harvey-4 well location.
- » Calibration of the passive array with surface check shots which shows that the array deployment is among the quietest in the world, and is sensitive enough to detect microseismic events of at least Magnitude -1 (M-1) at a distance of 2km (CO<sub>2</sub> injection depths).
- » Analysis of 75 days of passive recordings for analysis of site-dependent signal/noise conditions and ambient seismic noise versus time and sensor depth.
- » Ongoing deployment of near-surface broadband (0.01-500Hz)

earthquake seismic stations to detect local microseismic events M+1 or larger over the 200 sq.km. project area and surrounding areas, which fills a gap in the national Geoscience Australia network coverage to detect events smaller than M+2.

Background data collection has already commenced and will help define the natural low level seismicity of the area. The project will improve the potential of lowering monitoring costs for future projects through such non-invasive techniques.

### Reference

Lumley et al., 2016, Feasibility and Design for Passive Seismic Monitoring at the SW Hub CO<sub>2</sub> Geosequestration Site (7-0212-0203)



Snapshots of the complex 3D seismic wavefield generated by a hypothetical microseismic source on the F10 fault (superimposed on the P-wave velocity model). First arrival direct P-waves, reflected P-waves off the F10 fault, and multiply-reflection P-waves from the surface and sand/shale layers, are identified.

## CASE STUDY

# Understanding the influence of particle entrainment on CO<sub>2</sub> injectivity

In mid-2014, a review of some of the core analysis performed on rock material from the South West Hub (SW Hub) carbon capture and storage site was conducted.

There were still some key uncertainties remaining about the nature of the mechanisms, the causes of the identified fluid-rock interactions, and the extent to which they could impact on the future planning of the SW Hub injection testing. It was observed that the permeability of the Harvey-1 samples would decrease substantially (up to 60%) after undergoing a laboratory core-flooding procedure. Such results could have significant implications for the CO<sub>2</sub> injectivity in the future injection wells at the SW Hub.

The overall objectives of this new work included:

- » the identification and characterisation of the mechanisms behind the previously observed petrophysical variations in the post-flood samples;
- » characterisation of the in-situ geochemical reactions which may occur at the SW Hub;
- » identify the extent of fines migration that occurs, and thus,
- » estimation of the relative contribution of geochemical reaction changes versus fines migration as contributors to changes in porosity and permeability induced by flooding.

Interim conclusions suggest:

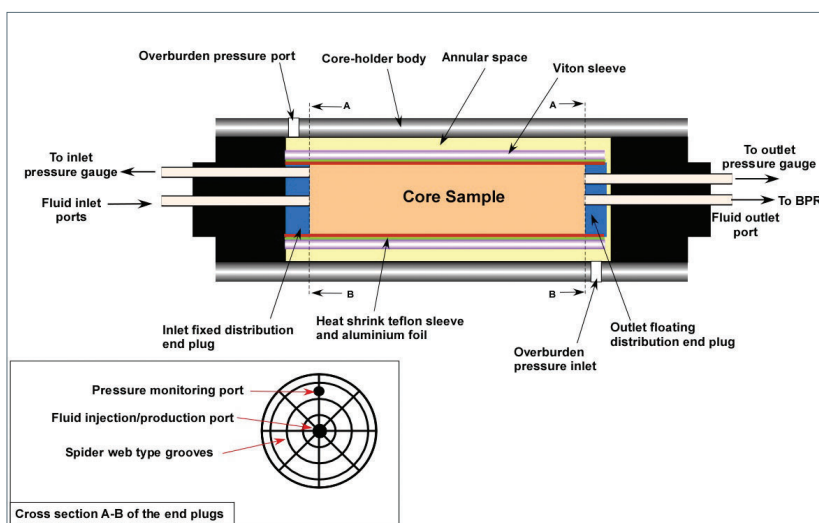
- » The Wonnepur exhibits a great degree of spatial diagenetic alteration. Such alterations have the potential to change the way the formation rock reacts to a CO<sub>2</sub>-rich injection fluid during injection.
- » The geochemical analysis of the fluid samples, collected during the core-flood experiments, have also revealed that the petrophysical alterations caused to the rock samples is due to the dislodgment and transport of the fine clay particles within the pore space of the rock.

» The computer modelling shows that the experimental conditions used are unlikely to result in major mineralogical and fluid changes, which is confirmed in the results of the core-flood eluent chemistry.

Further work continues to understand injectivity for this reservoir.

## Reference

A. Saeedi, et al 2016, Understanding Fluid Rock Interactions and Their Impact on Rock Properties as a Result Of CO<sub>2</sub> Injection in the SW Hub (7-0314-0233)



Schematic cross-sectional illustration of the core-holder assembly.

## CASE STUDY

# Communicating with Communities

A systematic analysis of all existing landowner communications was undertaken to consider and help shape the overall strategy.

This project reviewed the communications strategy of the South West (SW) Hub following their 2014 seismic survey. The SW Hub projects' communications strategy included:

- » Face-to-face contacts
- » Community meetings
- » Local schools
- » Attendance at local shows
- » Tours of the well site
- » Ensuring the Project manager was locally accessible
- » Responsive management

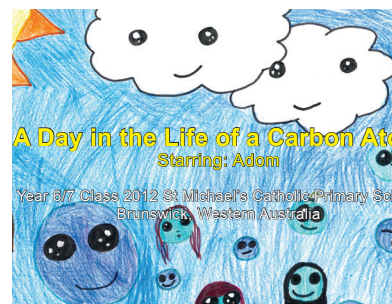
In total there were 125 landholders of whom 75 granted access for the 3D seismic test. Of the 125 customer file notes, every alternate file note was scrutinised in detail. This resulted in 63 records being analysed for this research. Of those, 37 allowed access for the 3D seismic testing while 26 did not. The analysis was then triangulated with secondary data from media articles and websites and 18 telephone interviews. These were conducted with a cross-section of impacted landholders, project proponents, contractors and representatives from the local consultative committee.

It is interesting to note that several key themes are common to both groups (those who granted access and those who denied access), which suggests such themes are not just project related. Examples of how DMP and contractors helped to overcome these are expanded on in the report.

Despite the positive outcome of the land access negotiations for the 3D seismic survey, many landholders were keen to ensure that everyone was aware that their granting access for the survey would not necessarily translate into support for the CCS project. Therefore, continuing to build and maintain a trusting and positive relationship will be essential if the project is to progress through its planned stages. A number of recommendations arose from this work for consideration by the project proponents, and these recommendations also have relevance for other CCS projects.

### Reference

P. Ashworth, et al 2014, Lessons from project level community engagement (7-0414-0227)



Front cover of children's book produced as a result of Carbon Kids' education activities.



Community meetings.



## FUTURE RESEARCH

# Southern Perth Basin

### ➔ Potential for preferential flow through faults and fractures

The expected outcomes of this proposed project are a ranking of faults in terms of their transmissivity and conditions under which they might become conductive. In addition, gaps and remaining uncertainties can be identified and additional data acquisition requirements developed.

### ➔ Assessment of multi-barrier systems for CO<sub>2</sub> containment in the Yalgorup Member

Research will consider an integrated view of the heterogeneity of palaeosols and gain a reasonable understanding of their propensity to act as barrier for the injected CO<sub>2</sub>. Data exists, across multiple scales, that needs to be integrated to provide reasonable constraints for the simulation models.

### ➔ Assessment of the heterogeneity and diagenesis on injectivity and containment in the Wonnerup

The vertical flow of buoyant CO<sub>2</sub> through the Wonnerup matrix is one of the most significant uncertainties in the project. The work will target an enhanced understanding of the Wonnerup injectivity, the effects of fault compartmentalisation, and the solubility and residual trapping potential during the CO<sub>2</sub> flow path.

### ➔ Assessment of the potential for reduced injectivity due to CO<sub>2</sub> injection in the Wonnerup

The project aims to determine the impacts of near well bore effects on injectivity with higher confidence than conventional methods.

### ➔ Assessment of options to understand and manage migration assisted trapping in the Wonnerup

The SW Hub containment is dependent on migration trapping mechanisms within the Wonnerup and the effectiveness of the Yalgorup to act as a barrier for mobile CO<sub>2</sub>. Research will target an integrated view of migration assisted trapping, to deliver better understanding of the parameters impacting Wonnerup trapping and determine the key parameters that influence it.

### ➔ Passive seismic monitoring of SW Hub well test

The SW Hub Project is likely to conduct a well test in 2016-17, potentially in a new well, Harvey-5. This will allow research to validate the configuration, calibration and optimisation of the passive seismic array geometry. It will also determine the sensitivity requirements needed to monitor CO<sub>2</sub> injection seismicity at the larger SW Hub site.



## Gippsland Basin

In February 2012, CarbonNet was announced as the second national CCS flagship. In Victoria, a substantial history of geological characterisation has occurred in the Gippsland Basin owing to conventional oil and gas development offshore, brown coal development and significant groundwater resource utilisation on-shore. Prior regional characterisation of storage capacity has described the off-shore commercial storage potential in the Gippsland Basin as arguably the best in Australia.

### Goal

*To support CO<sub>2</sub> storage  
in the off-shore  
Gippsland Basin*

*Victoria*



### Scale Key

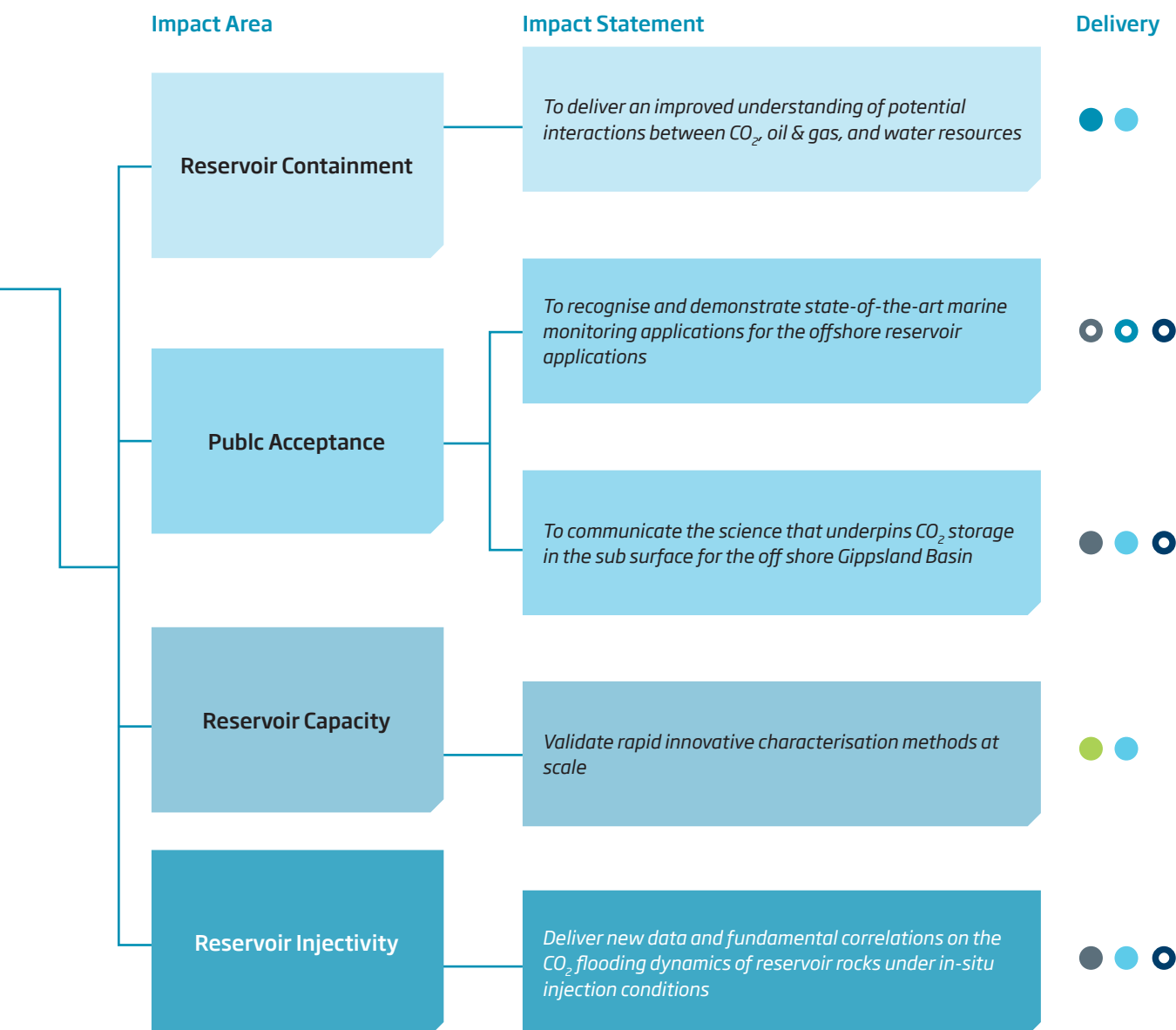
- In lab
- In Field

### Delivery Key

- New Data
- New Application
- Field Validation
- New Correlation
- Permitting & Public Communication



Photo courtesy of CO2CRC



Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

## CASE STUDY

# Marine monitoring for CCS will have to account for large natural variations.

Offshore Gippsland is widely recognised as one of the most promising CCS sites in Australia, with its proximity to large point sources and promising storage offshore.

Storage offshore at Sleipner and Snøhvit has been successful, but the monitoring techniques there focused on marine seismic, and did not fully investigate effects at the seabed or in the water column.

The project provides an assessment of some proposed techniques for this type of “shallow focussed” monitoring that may be used in offshore Gippsland. The methods considered may be useful for defining baselines and checking for some aspects of possible environmental impact. The study will inform the first phase of purchasing of marine monitoring assets, funded under the Commonwealth educational infrastructure funds (EIF), leading to more detailed investigation of their capabilities.

Existing expertise and databases in CSIRO Oceans and Atmosphere Flagship (O&A) have been used to assess the ability to measure the ingress of stored CO<sub>2</sub> into the water column, and to quantify the size and type of loss of containment at the seabed that could be detected. O&A has baseline data and experience, relevant to the likely storage areas, covering tide and current patterns, seasonal and spatial variations in seawater composition, instrumentation, and modelling. This report investigates some elements of a model monitoring programme, namely measurement of water chemistry, and acoustic mapping.

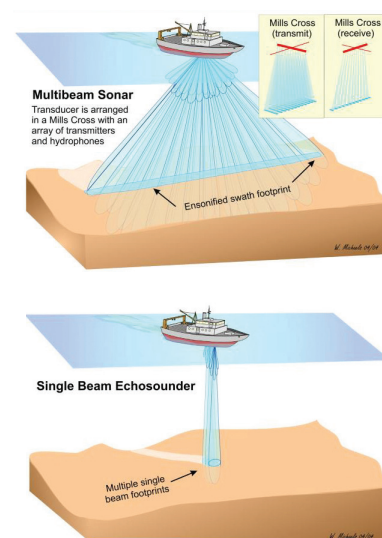
Key conclusions are:

- » Water sampling, from a combination of fixed moorings and gliders, would be able to monitor a region of order 10 x 10 km<sup>2</sup> and detect a specific type of leak to the seafloor (point source, 10 kt/yr) anywhere in that area with high confidence and low false alarm rate. Leaks of this size are very unlikely and would probably be detected in other ways much earlier.
- » Natural variability causes changes in water chemistry that are equivalent to much larger releases, so the main application of this type of monitoring would be to characterise the natural background (“baseline”) and hence show that environmental impact (in the specific sense of acidification of the water over a large area) was negligible.
- » Monitoring by acoustic methods is extremely sensitive to bubble streams. The background noise level (mainly biota) is very variable, but streams corresponding to only 10 t/yr should be readily detectable above environmental clutter with high confidence of low false alarm rates.
- » Seafloor mapping will reveal a multitude of features of unknown provenance or duration, and this type of monitoring would have to be approached with an awareness of the need to control false alarm rates.

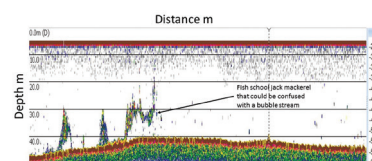
- » Field assessment of the technologies described will be a priority for future work along with the collection of baseline datasets for potential storage locations along the Gippsland coast.

### Reference

Hardman-Mountford, et al 2015, An initial study of the utility of some marine M&V methods for subsea CCS; Bass Strait Case Study (7-0314-0230)



Example of the operations of a multi-beam and single-beam echo-sounder for mapping the seabed and water column.



Example of 120 kHz Simrad EK 500 volume reverberation data in 40 m depth of a fish school located close to the sea floor. This feature may look similar to a low flow gas bubble stream and could only be verified with video or temporal sampling.

## CASE STUDY

# Modelling CO<sub>2</sub> geological storage in the Gippsland Basin

The key focus for this study was to examine uncertainties related to numerical simulations of the effect of CO<sub>2</sub> injection on shallow groundwater resources and petroleum fields in the near-shore area of the Gippsland Basin.

The Latrobe Group forms a sloping aquifer containing freshwater in the onshore area and becoming increasingly saline towards the offshore where the majority of petroleum fields are located. Assessing how CO<sub>2</sub> injection affects the flow of formation water in the transition zone from fresh to saline water is critical for the selection of an appropriate storage site and for determining safe injection rates.

This project aimed to investigate the potential impacts of CO<sub>2</sub> geological storage in the near-shore area of the Gippsland Basin. In particular, the study focussed on: the displacement of formation water; any change in the pressure system; the possible effects on both offshore petroleum fields and onshore ground water levels, and the effects on the salinity in the Latrobe aquifer.

Research strategy:

- » Numerical simulations of storage scenarios based on the basin-scale hydrogeological model.
- » Geochemistry of formation waters. A detailed analysis of the major and minor compositions, and their distribution and variation with salinity together with isotopic analyses, will help in understanding the evolution of formation water chemistry and underlying geochemical processes.

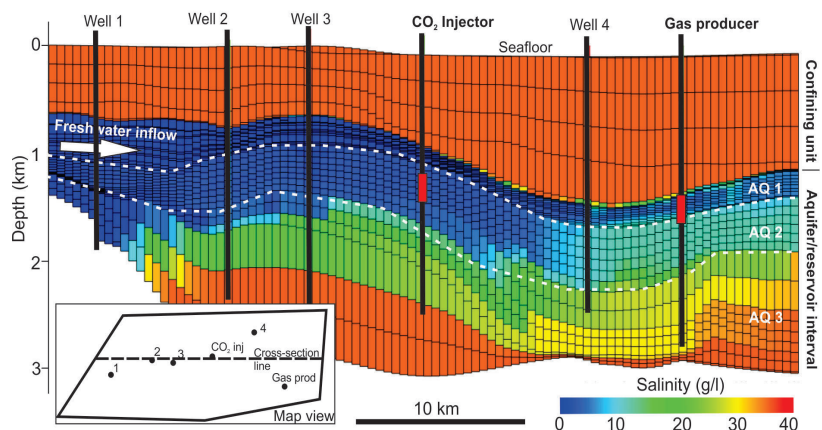
Following the simulation of injecting CO<sub>2</sub> for 20 years at 1-5Mt/year, the key conclusion were:

- » The fluid inclusion data demonstrate that paleo-salinities of formation water in the Latrobe aquifer were generally higher than present-day salinities, suggesting that the low-salinity wedge is younger than the formation of the fluid inclusions and must have formed sometimes during the last 5 million years.
- » No potential was shown for significant salinity increase in the onshore parts of the aquifer.
- » Changes in formation water salinity occur mainly along the transition between freshwater and higher salinity water.

- » CO<sub>2</sub> injection could introduce minor improvements to the production environment by creating a slight pressure increase in the onshore area to counteract the recent trend of under-pressuring due to petroleum production.
- » This could provide pressure support to petroleum industry and reduce water level decline rate to the onshore water users.

### Reference

K. Michael, et al 2015, Near-shore aquifer modelling of CO<sub>2</sub> geological storage in the Gippsland Basin (7-1011-0187)



Simulations investigated the impacts of 42 years of petroleum production (water volumetric equivalent) and 20 years of CO<sub>2</sub> injection (1-5 Mt/year) on the distribution of CO<sub>2</sub>, pressure and salinity.



## CASE STUDY

# Confirming the integrity of reservoir seal rock to fluid CO<sub>2</sub>

Since fluid transport is limited in shales or seals, due to very low permeability, then any chemical reaction will not proceed very far.

The Gippsland Basin has long been considered to have the potential as a major CO<sub>2</sub> storage site in Victoria, Australia. Some of the possible storage sites are characterised as storage complexes; having large anticlinal structures with four-way dip closure, a highly permeable reservoir and low permeability intra-formational seals and a regional top seal. One of the main leakage risks is likely to be the geochemical and petrophysical influence of the injectate on the seal strata. The cap rock seal efficiency evaluation is a vital part of the assessment of any CO<sub>2</sub> storage site. The main goal of this study was to examine dynamic seal capacity of several Latrobe Group intra-formational shales in the Gippsland Basin and to characterise their cap rock sealing efficiency before and after exposure to supercritical CO<sub>2</sub> (scCO<sub>2</sub>).

In this study, brine-saturated shale samples were exposed to scCO<sub>2</sub> under reservoir conditions for a limited time of approximately 3 months. The study was a laboratory-based core analysis research program focusing on examining any changes to the cap rock mineralogical composition, capillary threshold pressure, pore size distribution and specific surface area before and after being exposed to scCO<sub>2</sub>. Several analysis methods typically applied in the petrophysical assessment of seal rocks were used, including; x-ray diffraction (XRD), scanning electron microscopy (SEM) associated with energy

dispersive spectrometry (EDS), mercury injection capillary pressure (MICP), nuclear magnetic resonance (NMR), low pressure surface area measurements, and micro-CT scanning.

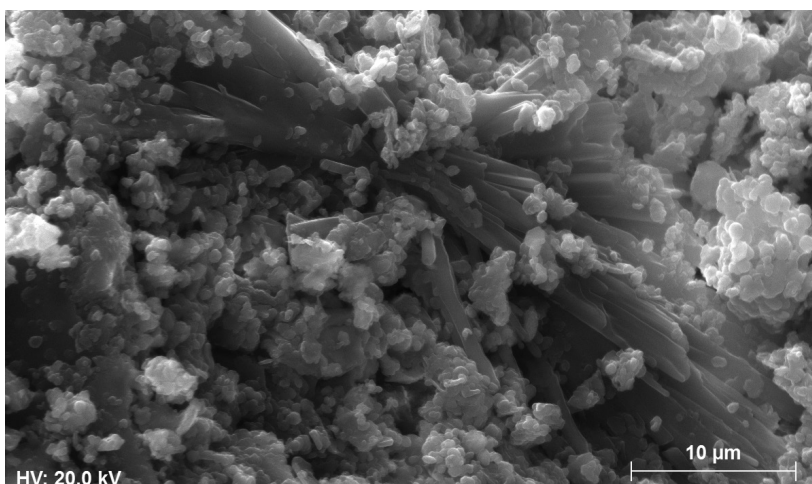
Key conclusions:

- » Scanning electron microscopy (SEM) examinations showed precipitation of kaolinite, gypsum and minerals from jarosite group after exposure to scCO<sub>2</sub>.
- » Mercury injection capillary pressure results show a distinct shift toward smaller capillary pressure values for samples exposed to scCO<sub>2</sub>. This is in agreement with a general shift on the MICP curves toward larger pore and pore throat sizes for most of the samples analysed.
- » Reduction of NMR signal after exposure to scCO<sub>2</sub> indicates that some of the waters inside the samples were reduced by CO<sub>2</sub>.

- » The low pressure nitrogen adsorption analysis shows the pore structure changed after shale samples were exposed to scCO<sub>2</sub>. In general, for most of the samples studied there was an increase in the pore surface area and pore volume, whereas a reduction in the pore diameter can be noted.
- » These results suggest that when some of the shale samples studied in this project come in contact with scCO<sub>2</sub>/brine mixtures they may lose their original integrity as a cap rock and their seal efficiency may reduce. But it has to be noted that since fluid transport is limited in shales, due to very low permeability, then any chemical reaction will not proceed very far. Therefore, the reactions only penetrate a few centimeters and the seal capacity will be unaltered for a thick cap rock.

### Reference

R. Rezaee, et al 2013, CarbonNet Dynamic Seal Capacity (7-1011-0186)



SEM images showing precipitation of fibrous gypsum and natrojarosite after CO<sub>2</sub> exposure, Sample 4.

## CASE STUDY

# Considering N<sub>2</sub> as a surrogate for CO<sub>2</sub> injection tests in geological formations

When it comes to underground CO<sub>2</sub> storage there are a number of factors related to the candidate storage medium which need to be thoroughly investigated before the commencement of the CO<sub>2</sub> injection, including: storage capacity, containment integrity, injectivity, the behaviour of the CO<sub>2</sub> plume and how it would evolve.

ANLEC R&D commissioned research to assess innovative ways to evaluate these uncertainties.

This project examined the concept of using N<sub>2</sub> as a surrogate for CO<sub>2</sub> in trial subsurface injections to characterise a storage resource. The technique would make regulatory compliance much simpler.

Methodology:

- » Two sets of four conventional unsteady state core-flood experiments were conducted, one set using CO<sub>2</sub>-water and the other using CO<sub>2</sub>-N<sub>2</sub>-water fluid systems.
- » Three x-ray imaged core-flood experiments conducted using the CO<sub>2</sub>-N<sub>2</sub>-water system.
- » Core-flood numerical simulations performed investigating the effect of a number of possible core-scale heterogeneities on the results of the core-flood experiments.

Dispersion coefficients were measured for the N<sub>2</sub>-CO<sub>2</sub> system under reservoir conditions.

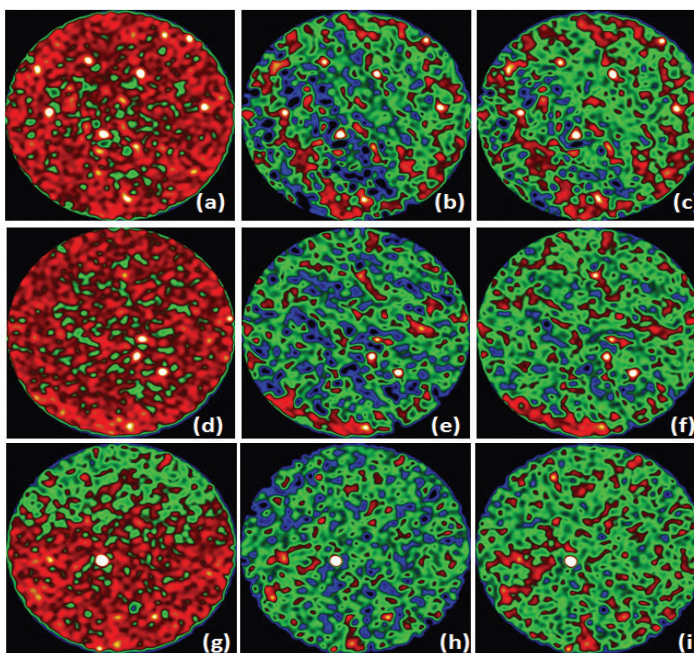
Key conclusions are:

- » The levels of residually trapped N<sub>2</sub> during an N<sub>2</sub> trial injection may be an overestimation of that which may be achieved during a subsequent CO<sub>2</sub> storage process.
- » Buoyancy forces during N<sub>2</sub> injection can reveal vertical pathways for subsequently injected CO<sub>2</sub> and therefore gain a better site characterisation.

- » Sensitivity to capillary pressure and heterogeneity appears to be determined by core properties rather than by invading fluid. Therefore, N<sub>2</sub> trial injection provides an inexpensive and low-risk way of understanding the heterogeneity structure of a reservoir, which is a critical unknown for CO<sub>2</sub> injection.
- » The concept of site characterisation using the injection of an inert gas such as N<sub>2</sub> may deliver valuable information to any CO<sub>2</sub> geo-sequestration site.

### Reference

A. Saeedi, et al 2014, Laboratory Core Flooding of Formation Water, N<sub>2</sub> and CO<sub>2</sub> (7-0912-0207)



Sodium iodide saturated core: a) after N<sub>2</sub> injection; b) after CO<sub>2</sub> displacement of N<sub>2</sub>; c) in three locations along the composite core. As can be seen, distribution of fluids after N<sub>2</sub> injection differs from that after subsequent scCO<sub>2</sub> injection.



## FUTURE RESEARCH

# Gippsland Basin

### ➔ **Optimisation of seismic monitoring for CCS applications in the Gippsland Basin.**

Through optimisation and development of design specifications for monitoring natural seismicity in a coastal-marine environment, this project will, for the first time, derive a record of natural small to medium magnitude seismic signals in a near-shore and off-shore area of the Gippsland Basin.

### ➔ **Characteristic trends in the evolution of reservoir water composition during CO<sub>2</sub> storage**

The research aims to predict the evolution of formation water composition for particular zones in the Latrobe Group, through the compilation of relevant properties and running reaction path simulations under variable reservoir conditions.

### ➔ **Seal potential of intra-formational seals for CO<sub>2</sub> containment, in the nearshore Gippsland Basin**

Using advanced analytical methods, the project will examine the performance intra-formational seals in the nearshore coastal zone of the Gippsland Basin.

### ➔ **Alternative dynamic modelling for structural and aquifer traps**

The objective of this work is to assess how using fully integrated thermo-hydro-mechanical-chemical (THMC) modelling can improve the predictive ability of reservoir models in CO<sub>2</sub> storage; with the results having potential to be applied to comparable settings in Australia and internationally.





# Otway Basin



## CASE STUDY

# Tracers to help quantify and monitor CO<sub>2</sub> storage volumes

Tracers are marker chemicals used for many processes. In CCS they are injected along with the CO<sub>2</sub> to help distinguish it from naturally occurring CO<sub>2</sub>.

They are useful to locate the plume and recognise its migration character. If well understood, they can also be used to determine trapping processes. When a tracer is injected with the CO<sub>2</sub>, some of the tracer dissolves (partitions) into the formation water whilst the rest of it remains in the CO<sub>2</sub> cloud.

Knowing the partition information for a range of tracer chemicals will result in:

- » Improved estimates and correlations for calculating reservoir capacity, and
- » Improved and accurate simulation of the tracers within a range of subsurface temperatures.

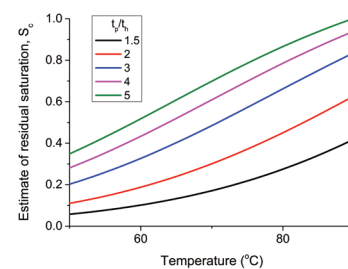
This project established general methods for determining the coefficients for other chemical tracers. The study has experimentally determined the partition coefficients for a number of chemical tracers relevant to CCS. These included both reactive ester tracers, useful for determining residual CO<sub>2</sub> saturation using the single well chemical tracer test, and inert gas tracers, useful for inter-well tests and reservoir to surface tests. This data was then incorporated into computational simulations of CCS scenarios to understand the impact of partition coefficients on the interpretation of tracer field data.

## Key conclusions:

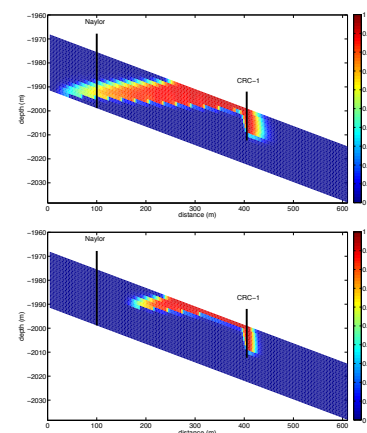
- » The temperature dependent behaviour of the partition coefficients for a number of reactive ester tracers was determined. This information will lead to more accurate predictions of residual CO<sub>2</sub> saturation in instances where these chemical tracers are used for the single well chemical tracer test.
- » In computational simulations of inert gas tracers, it was determined that, for bounded reservoirs, the behaviour of a chemical tracer is affected to a very minor extent by changes in the partition coefficient (air/water vs. supercritical CO<sub>2</sub>/water); while for unbounded reservoirs, the differences are somewhat significant and could possibly be differentiated in a field trial.
- » Future work could include slim tube experiments packed with various sediments to experimentally determine the breakthrough curves for chemical tracers. This information could be used with future field studies to determine the possible influence that sorption onto sediment surfaces actually has on the behaviour of chemical tracers.

## Reference

M. Myers, et al 2013, Chemical tracer partition coefficients for CCS (3-1110-0125)



Plot of the estimated CO<sub>2</sub> residual saturation vs. reservoir temperature.



Tracers in the reservoir for injection of mixed 80% CO<sub>2</sub> and 20% CH<sub>4</sub> into a depleted reservoir with a gas cap shortly before injected gas is detected at U tubes 2 and 3: 156 (top), and 303 (bottom) days.

## CASE STUDY

# Ground water monitoring is only effective close to the CO<sub>2</sub> injection site

The CO<sub>2</sub>CRC Otway project has been collecting water level data from three groundwater wells screened in the freshwater Dilwyn Aquifer since 2006.

The objective of this project was to investigate the usefulness of monitoring these wells for small leak detection, were it to occur, and to identify better locations for groundwater monitoring wells, were they to be purpose drilled. This was done through the application of spectral analysis techniques.

The water level dataset represents a continuous time-series prior to the injection of CO<sub>2</sub> and continuing post-injection. Spectral analysis of this dataset showed clear evidence of earth tides affecting the recorded water levels in the three wells. The spectra derived from this analysis were used to estimate aquifer properties, including specific storage and porosity. The values determined in this way compared reasonably well with published estimates from standard pumping tests and are significantly easier and less expensive to obtain.

A 2D TOUGH2 reservoir simulation model was built to investigate the spatial extent of the pressure pulse and chemical plume that would be generated were a slow, buoyancy driven, CO<sub>2</sub> leakage to occur from a slightly over-pressured storage reservoir. This model was originally intended to be based on the Dilwyn Formation. However, the initial simulations suggested that the current monitoring well locations in the Dilwyn Formation were too far away from the injection site to

detect either pressure or chemical composition changes due to the presence of leaking CO<sub>2</sub>.

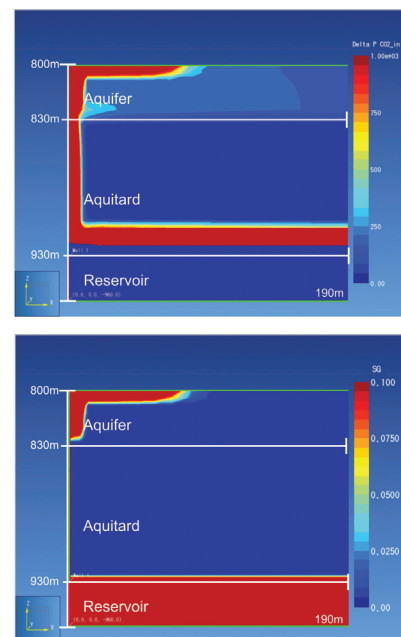
In this model, CO<sub>2</sub> was allowed to move via buoyancy from the storage reservoir into an overlying monitoring aquifer. With consideration for the minimum leakage criteria of carbon storage for climate abatement, a minimum detection limit (MDL) that a shallow groundwater monitoring system would have to achieve was defined, and found to be virtually undetectable within the time frame of between 1-10 years. Further, it was found that, at the MDL, there was no detectable difference between the pressure pulse in advance of the CO<sub>2</sub> plume itself.

Key conclusion:

- » The leakage rates in the scenarios developed here are primarily driven by buoyancy and are consequently so low as to be virtually undetectable in the short term. Therefore, for groundwater wells to provide effective short-term (less than 10 years) leakage indication or groundwater protection they would need to be located within a few metres of the site where CO<sub>2</sub> enters the aquifer.

### Reference

A. Hortle, et al 2012, Signal processing of hydrographs for monitoring the integrity of freshwater aquifers near the Otway CO<sub>2</sub> storage site (3-1110-0073)



CO<sub>2</sub> pressure signal (top) and plume (bottom) after 10 years of flow.

## CASE STUDY

# Pilot injection Huff n' Puff

This study (co-funded by ANLEC R&D) provides an account of the Otway Stage 2B residual saturation and dissolution test.

This is the first field test of this nature in the world and the study reports on its execution and summary of the data obtained from the field test.

The goal of the CO2CRC Otway Stage 2B project was to measure large-scale residual trapping of CO<sub>2</sub> in an actual field project, using five different methods, then compare the methods and make recommendations. It was realised during design that substantial information would be collected on dissolution trapping also allowing for analysis of this mechanism.

Following a lengthy design period, the field test program for Stage 2B of the CO2CRC Otway Project commenced on 17 June 2011 and finished on 12 September 2011. All the planned components of the field test were completed, including the five methods for measuring residual trapping. Extensive high-quality data has been obtained throughout the program that allows detailed analysis within each method. The responses at each stage show that the injected CO<sub>2</sub> was driven to residual saturation and was detected by each of the five measurement methods.

Key conclusions:

- » Excellent quality downhole pressure data were acquired throughout the field program from the permanent gauges. The high permeability of the injection interval did not cause problems with getting a sufficient pressure

response to give a good signal to noise ratio.

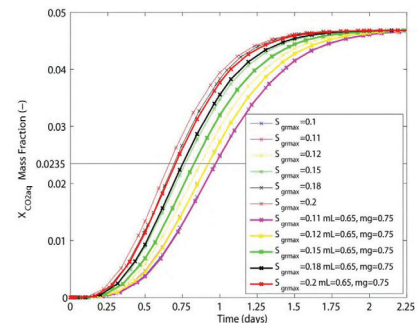
- » Excellent downhole temperature data were also acquired. The instantaneous readout of downhole temperatures proved extremely useful in diagnosing operational issues at several stages.
- » All three RST logs were run as intended. Current interpretation has residual CO<sub>2</sub> saturation around 0.18 in the lower half of the perforated interval and around 0.23 (average) in the upper half.
- » Fluid sampling using the U-tubes was completed consistent with the test plan. The noble and organic tracers were added to the injection stream as planned and were measured during production stages at concentrations that were more than sufficient for analysis.
- » The organic tracer test shows the partial breakdown of the three parent compounds, as hoped.
- » Sampling for the dissolution test, including the added methanol, was performed as intended.
- » Although not primary objectives of Stage 2B, the test sequence provided the opportunity to further test microseismic monitoring and provide controlled releases of CO<sub>2</sub> for atmospheric monitoring.

### Reference

L. Paterson, et al 2011, The CO2CRC Otway stage 2B residual saturation and dissolution test: test concept, implementation and data collected (7-0810-0066)



The reservoir saturation tool (RST).



Mass fraction of dissolved CO<sub>2</sub> (X<sub>CO<sub>2</sub>,aq</sub>) versus production time, which is the data that will be used in the dissolution test. The sensitivity to various parameters is shown, and this indicates that S<sub>gr</sub> is the parameter which has the greatest influence on X<sub>CO<sub>2</sub>,aq</sub>. The base case value of S<sub>gr</sub> is 0.2. Note, a maximum mass fraction of 0.047 is equivalent to 1.07 mol/L CO<sub>2</sub>.

## CASE STUDY

# Validating CO<sub>2</sub> plume detection limits and stabilisation commences at Otway

Australian saline formations have the capacity to store all of the country's CO<sub>2</sub>, provided uncertainties are addressed.

The CO2CRC Otway Stage 2C Project aims to inject up to 15,000 tonnes of CO<sub>2</sub> into a saline formation to demonstrate important aspects relevant to large-scale geological storage of CO<sub>2</sub> in saline formations; as proposed by Australian CCS Flagships and other large-scale CCS projects around the world. The project involves the installation of the permanent seismic array in the summer of 2014/15, the completion of injection by mid 2016 and the conduction of post-injection annual seismic surveys to monitor the plume to 2018.

The Otway Stage 2C project had three scientific objectives:

1. Detect injected CO<sub>2</sub> (Buttress gas) in the subsurface and ascertain minimum seismic detection limits.
2. Observe the gas plume development using time-lapse seismic.
3. Verify stabilisation of the plume in the saline formation using time lapse seismic.

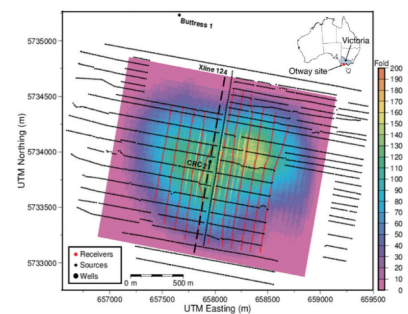
Progress to date has provided the required infrastructure for acquisition of the baseline data and for further monitoring and observation of the CO<sub>2</sub> injection. This included:

- » Deployment of buried seismic geophones along 11 receiver lines. Length of the receiver lines to 1460m, spacing 100m, and 15m between the receivers

- » Deployment of two types of Distributed Acoustic Sensing (DAS) fibre optic cables along the same 11 receiver lines
- » Installing powered seismic recording facility in a dedicated container (Seismic Lab) in the vicinity of CRC-2 wellhead, to house the seismic and iDAS recording equipment.

More recently, the CO<sub>2</sub> injection phase and the first seismic survey were completed.

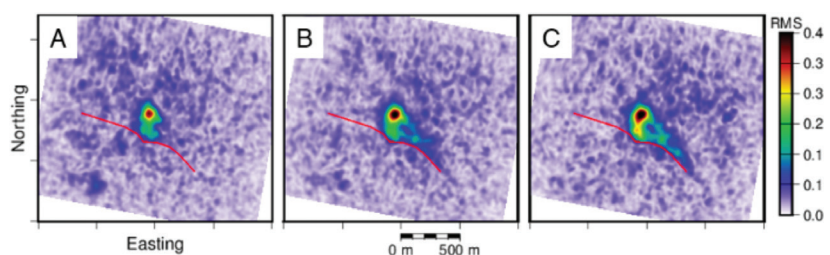
- » The baseline survey was acquired in March 2015 followed by three monitor surveys in January, February, March and April 2016 after injection of 5, 10 and 15 kt of CO<sub>2</sub>, respectively. Time lapse difference images show a clear anomaly localised around the injection well. The anomaly is initially approximately circular in shape, and as the injection progresses, the plume reaches a known sealing fault to the south of the injector and then spreads up-dip along the fault



Map view of the 3003 production vibroseis source points (black dots). The red dots are the 11 receiver lines.

### Reference

R. Singh and M. Watson 2013, Project Initiation Document (7-0212-0204)



Plan maps of amplitudes (relative to the baseline amplitude) after injection of 5 kt (A), 10 kt (B), and 15 kt (C) calculated from the difference cubes.









# Capture Research Strategy

Reducing the cost of CO<sub>2</sub> capture for coal fired power generation is very important if CCS is to remain a competitive low emissions technology. ANLEC R&D has completed over 65 concept testing projects.

To remain complementary with a global research effort, capture research in ANLEC R&D will pursue research enabling environmental performance and permitting in Australian conditions. High efficiency low emissions (HELE) coal technology concepts that offer disruptive opportunities for emissions reduction in established and emergent coal markets will also be tested.

It is especially important to consider technology developments that enable coal to integrate into a modern grid that requires fast ramp up and ramp down supporting high levels of renewables.

# CO<sub>2</sub> Capture Processes

## Managing Financial Investment Risk for Carbon Dioxide Capture

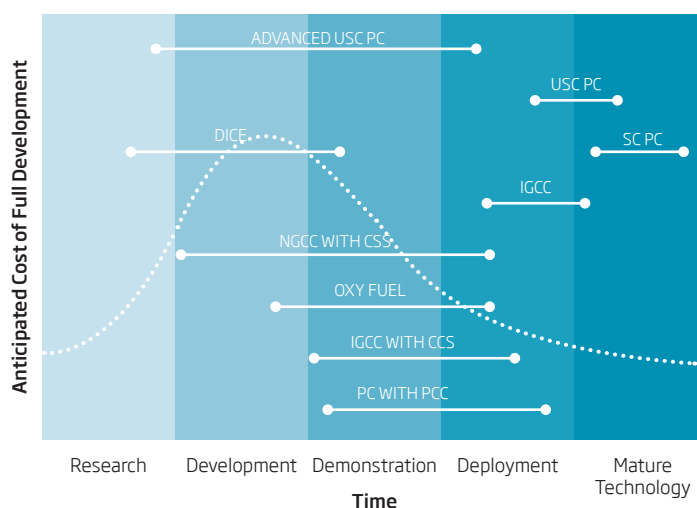
Power generation assets are long lived (40+ yrs) and the financial investments is counted in billions of dollars.

Investment risk is therefore closely linked to financial performance, engineering performance and regulatory certainty. Processes to capture CO<sub>2</sub> are relatively well established, with most of them beyond the laboratory. ANLEC R&D research aims to adapt these technologies to Australian conditions to enable permitting and deployment.

### Goal

*For CO<sub>2</sub> Capture processes to:*

- test cost reduction concepts
- enable environmental permitting
- and adapt to Australian conditions



### Scale Key

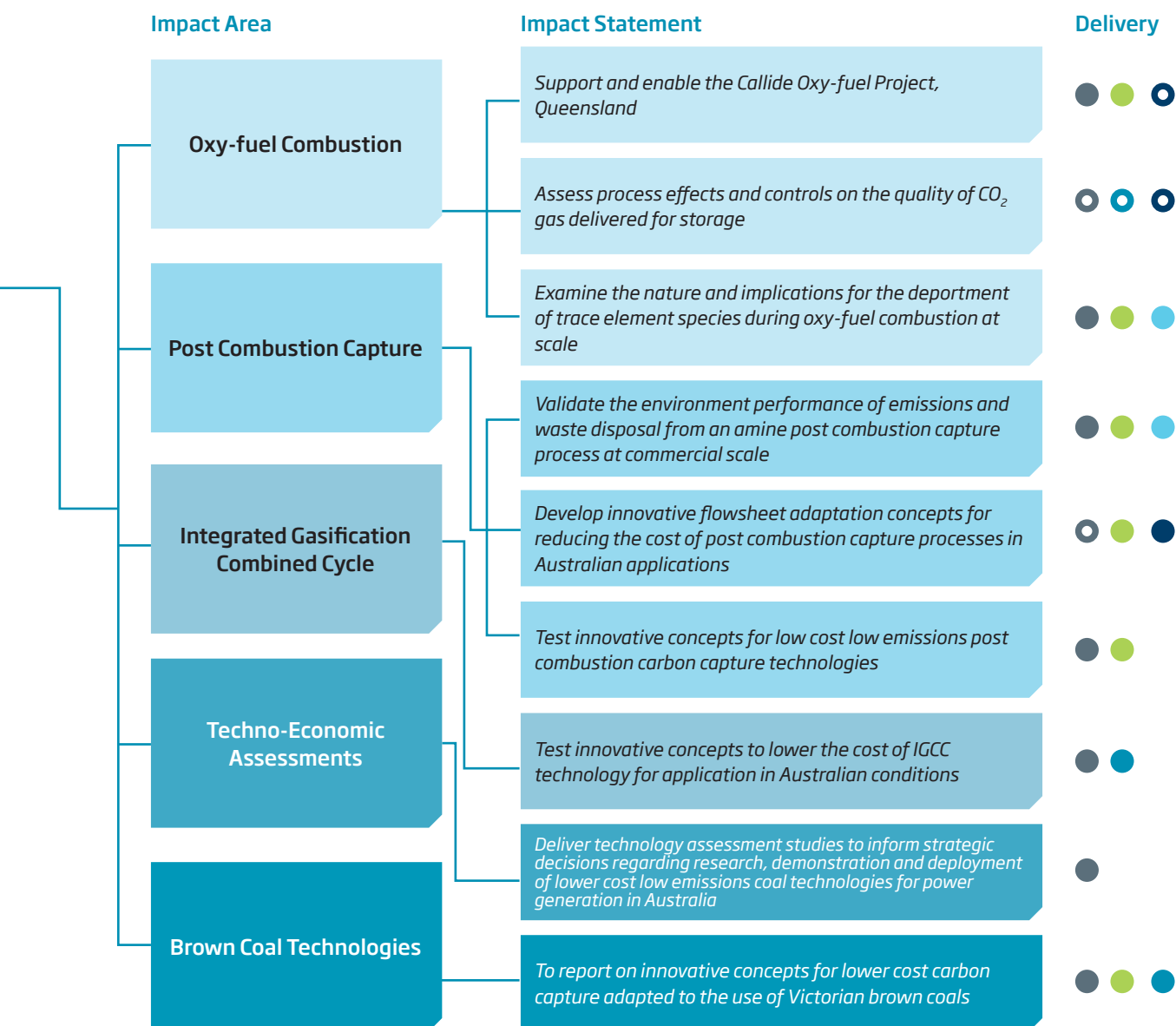
- In lab
- In Field

### Delivery Key

- New Data
- New Application
- Field Validation
- New Correlation
- Permitting & Public Communication



Photo courtesy of the Callide Oxyfuel Project



Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015



## CASE STUDY

# Australian Research plays a key role in the Callide Oxy-fuel Demonstration Project

Oxy-Fuel involves firing a conventional pulverised fuel coal boiler with oxygen and recycled exhaust gases instead of regular air. This produces a concentrated stream of carbon dioxide that can be "captured" by compression in a CO<sub>2</sub> Processing Unit (CPU) and safely stored, indefinitely, deep underground.

Oxy Fuel combustion produces approximately 75% less flue-gas than air-fueled combustion, and produces exhaust that consists primarily of carbon dioxide and water.

Unlike the other developing coal-based low carbon dioxide emissions technologies, Australian application of Oxy-Fuel does not have any inherent gas cleaning technologies built into the process. While additional existing controls are available, they add considerable expense and some complexity to a retrofit.

Since 2004, this world-class low emissions fossil fuel project has progressed to a fully completed demonstration scale project.

### 2004

- » Research delivered a techno-economic systems assessment confirming Oxy-Fuel as one (among many) low emissions CO<sub>2</sub> capture alternative.

### 2005

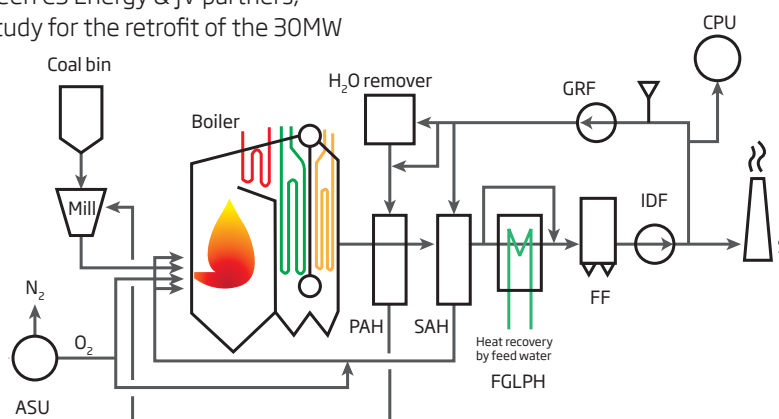
- » Research delivered technical performance of advanced power generation systems in Australian conditions, providing local mass and energy balances.

### 2006

- » Research trialled Australian coal performance in Oxy-Fuel combustion conditions, in the IHI pilot plant in Aioi, Japan. For retrofits, results indicated a burner modification was necessary to maintain heat transfer conditions in the boiler.
- » A memorandum of understanding, between CS Energy & JV partners, delivered an Australia/Japan feasibility study for the retrofit of the 30MW Callide A Demonstration Project.



Callide Oxy Fuel Demonstration Project.  
Photo courtesy of the Callide Oxyfuel Project



## 2007

- » Research provided a status report on Chemical Looping for lower cost oxygen production compared to the standard Air Separation Unit.
- » Low Emissions Technology Development Fund/ACALET funding for demonstration was established.

## 2008

- » Callide Oxy-fuel Project Joint Venture agreements finalised.
- » The variability of Oxy-fuel flue gas composition was examined, along with its effect on CO<sub>2</sub> compression and storage.

## 2009 - 2011

- » ANLEC R&D supported fundamental laboratory studies on gas cleaning options determined pH control was important for effective SO<sub>2</sub> scrubbing – a pH range of 4 < pH > 5.5 was recommended.
- » Laboratory and slipstream site-testing was designed.

## 2012

- » Callide Oxy-fuel Demonstration Project (COP) commissioned.
- » ANLEC R&D supported laboratory and COP slipstream site testing commenced.
- » Research and onsite testing established the feasibility of carbon dioxide quality control in Oxy-fuel, by the removal of mercury and NO<sub>x</sub> during compression. The presence of SO<sub>2</sub> had little impact on NO<sub>x</sub> capture during compression.

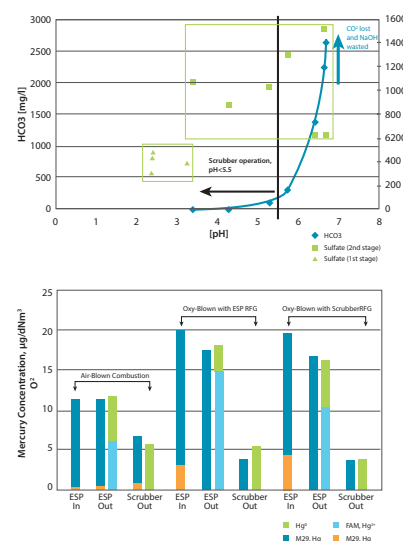
## 2014-15

- » It was found that gaseous mercury (Hg<sup>0</sup>) in the flue-gas could be effectively removed using the carbon dioxide compression circuit during 'back end' carbon dioxide processing and may result in making a dedicated mercury removal unit redundant.
- » The findings of the ANLEC R&D supported research at the Callide Oxy-fuel Project offer a paradigm shift in NO<sub>x</sub> and mercury control in Oxy-fuel carbon dioxide purity management while reducing cost and risk.

## Reference

R. Stanger, T. Wall et al, Gas quality impacts, assessment and control in oxy-fuel, 2015 (6-0710-0221)

R. Stanger, T. Wall et al, Impurities in Oxy Fuel CO<sub>2</sub> compression; stability, disposal and utilisation 2016 (6-0215-0243)



Mercury species distribution during air-blown and oxygen-blown combustion.

## CASE STUDY

# Environmental performance of Oxy-fuel technology rigourously tested

Oxy Combustion is one of the coal-based candidates for carbon capture and storage. As part of developing the Oxy Combustion technology, the environmental, health, and operational risks associated with trace elements need to be understood.

The focus of this research was to investigate the behaviour of trace elements during Oxy Combustion (oxy-firing) and CO<sub>2</sub> capture and processing. The environmental and operational risks associated with trace materials was to be the primary focus of this work. It is understood that the behaviour of trace components may have important implications for process options, gas cleaning, environmental risk and the resultant costs of Oxy Combustion.

This study was based on a field experiment carried out at the retro-fitted *Callide A* power plant in December 2012. The power

plant is capable of both oxy and air firing and the experiment involved both modes. Measurements were made of the trace metal and particulate matter emitted during the firing process, and the targeted metals included both mercury and chromium.

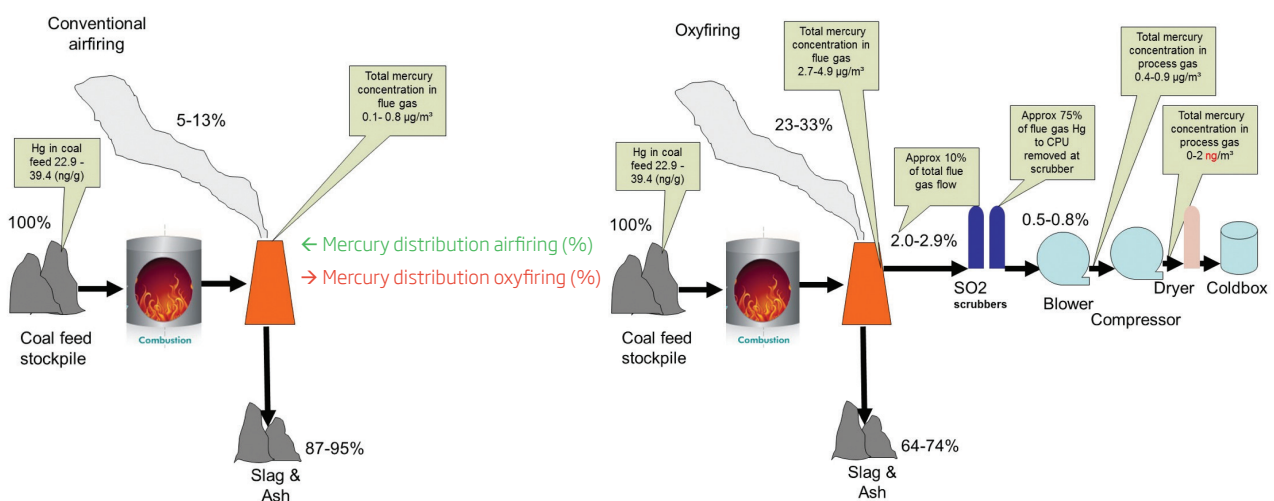
Key conclusions:

- » The trace levels of metals in the purified CO<sub>2</sub> gas stream should not pose significantly higher operational risks within the CPU;
- » Oxy-firing does not pose significantly higher environmental or operational risks than air firing;

- » Levels of metals, SO<sub>x</sub> and mercury are below levels of concern in the CPU, beyond the first low pressure scrubber, and
- » Mercury levels, measured in CPU produced gas, approach those measured in ambient air. However, in all cases the increased risks to the population of exposure were below the USEPA response level, such that no action would be required to reduce exposures.

### Reference

A. Morrison, et al 2012, Impacts of trace components on Oxy-combustion for the Callide Oxy-fuel Project - Further results and analysis from Callide field-trials, December, 2012 (6-0411-0130)







# Alternative Capture Concepts



## CASE STUDY

# Assessing the environmental emissions of post combustion CO<sub>2</sub> capture using amines

**Air emissions from power plants must be compatible with the environment to be a long-term viable solution.**

In time, commercial CO<sub>2</sub> capture systems for fossil fuel power plants will be deployed using current and novel solvents (some of these are still under early phase research and development).

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will influence their commercial and environmental viability.

Since many of these solvents have not been used at this scale on coal and natural gas flue gases it is important that we understand the emissions profiles of different solvent systems. This will not only inform research and development teams, as they trial new solvents, but also environmental monitoring agencies who will need to regulate, approve and monitor emissions. These agencies are accountable to ensure safe and 'air shed' suitable emissions targets.

What could potentially enter the environment is highly dependent on the actual solvent. In a controlled laboratory environment, CSIRO tested three Post Combustion Capture solvents, which they exposed to a simulated flue gas. Using similar operating conditions to a potential real world application the solvent and gas stream were then rigorously tested using some of the latest analytical equipment.

The two key solvents studied were:

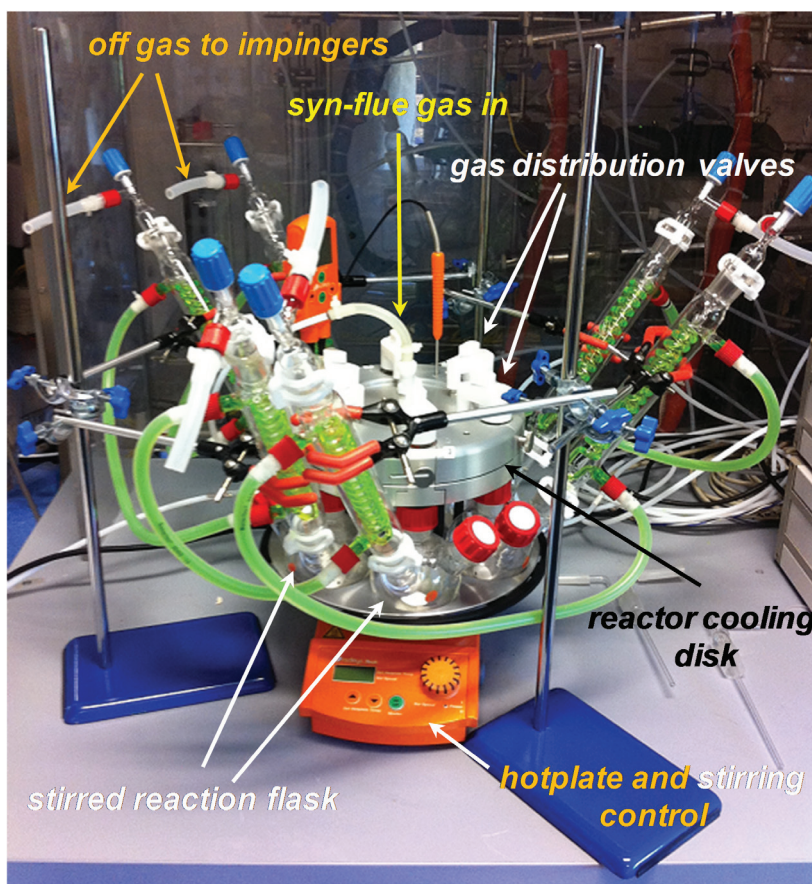
- » Methyldiethanolamine (MDEA)
- » Piperazine (PZ)

Importantly, in addition to the recommended chemical listing for emissions monitoring, the report concludes that, with the systems and analytical methods developed, amine-based solvent degradation products can be effectively screened and analysed.

What are the chemicals for which monitoring is recommended? For MDEA solvent applications, by far the most important degradation product is diethanolamine (DEA). For the PZ solvent, only two main products were found: ethylenediamine and 2-oxopiperazine. A list of other substances was also recommended to be monitored for both solvents.

### Reference

P. Jackson, et al 2013, Environmental Impacts of Amine based CO<sub>2</sub> Post Combustion Capture (PCC) Process (4-0910-0067)



Carousel six-port reactor system used in the solvent degradation (ageing) experiments.

## CASE STUDY

# Quantification and assessment of environmental risk in carbon capture and storage

Post combustion capture (PCC) of CO<sub>2</sub> using amine solvent scrubbing is the most mature technology that could be used for existing power stations.

Air emissions from power plants must be compatible with the environment to be a long-term viable solution. Since the reduction of carbon dioxide emissions from fossil fuel power plants will require the application of new technologies, emissions from these technologies must be understood.

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will impact their commercial and environmental viability.

Post combustion capture (PCC) of CO<sub>2</sub> using amine solvent scrubbing is the most mature technology that could be used for existing power stations. However, amine-based PCC technology has the potential to emit toxic organic compounds whose

environmental and health impacts must be assessed prior to regulatory approval.

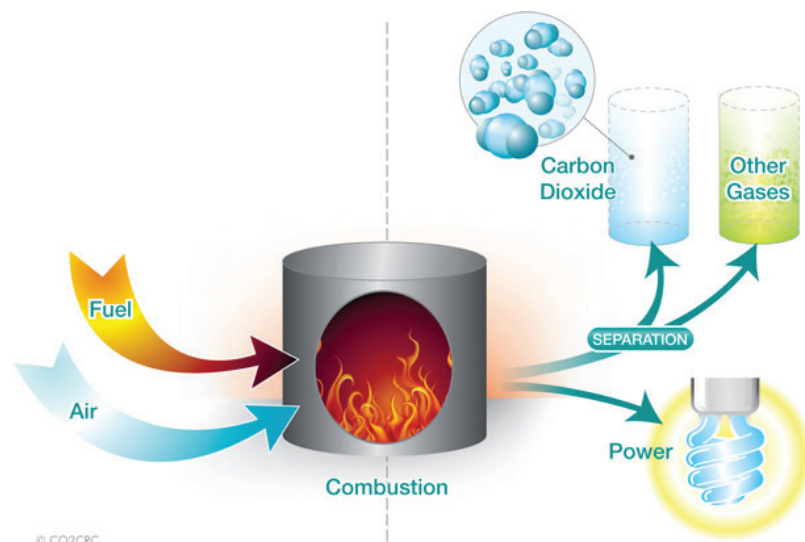
In this study a modelling framework for undertaking a risk assessment for population exposure to formaldehyde is described. The modelled results showed that after installing PCC technology there may be an increase in overall atmospheric concentrations of formaldehyde - however in all cases the increased risks to the population of exposure were below the USEPA response level such that no action would be required to reduce exposures. The ambient concentrations of formaldehyde would need to increase by a factor of approximately fifty times to bring it to the levels at which the USEPA would require action. The dispersion calculations also show that

maximum-modelled concentrations of MEA do not exceed health guidelines.

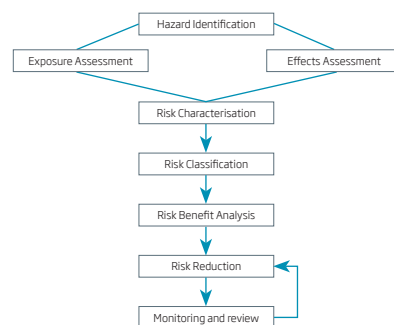
In summary, the implications of the increased regulatory focus on the environment for the traditional environmental issues associated with coal use in CCS will be profound. This study forms a solid foundation for environmental risk assessments, and more particularly information on formaldehyde and MEA emissions from a Post-Combustion Capture plant on a traditional coal fired power plant.

### Reference

P. Nelson, et al 2014 Quantification and Assessment of Environmental Risk in Carbon Capture and Sequestration - Development of Risk assessment procedures for trace PCC components (7-0311-0127)



© CO2CRC



Above: Steps in the Risk Management Process.

Left: Air emissions from power plants must be compatible with the environment to be a long-term viable solution. Since the reduction of carbon dioxide emissions from fossil fuel power plants will require the application of new technologies, emissions from these technologies must be understood.

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will impact their commercial and environmental viability.

## CASE STUDY

# Informing waste disposal from Post Combustion Capture (PCC) of CO<sub>2</sub>

There is currently very little quantitative data reported in the scientific literature relating to partitioning of trace elements in amine PCC systems.

The most comprehensive dataset in existence (at least in the public domain) is from a study made by the US DoE nearly ten years ago. The results of that investigation indicated that trace elements from coal combustion were likely to concentrate in the reclaim waste of the amine plant.

Despite the lack of data, it is apparent that most trace elements will be removed from the system by particulate emission control systems before they enter the CO<sub>2</sub> capture plant. However, volatile species, especially mercury, arsenic, selenium, along with fine particles not retained by the ESP (electrostatic precipitators) or fabric filter, have the potential to enter the CO<sub>2</sub> capture system.

Because of the effectiveness of flue gas desulphurisation (FGD) at removing trace elements, the solid product and process water will be major points for trace element discharge.

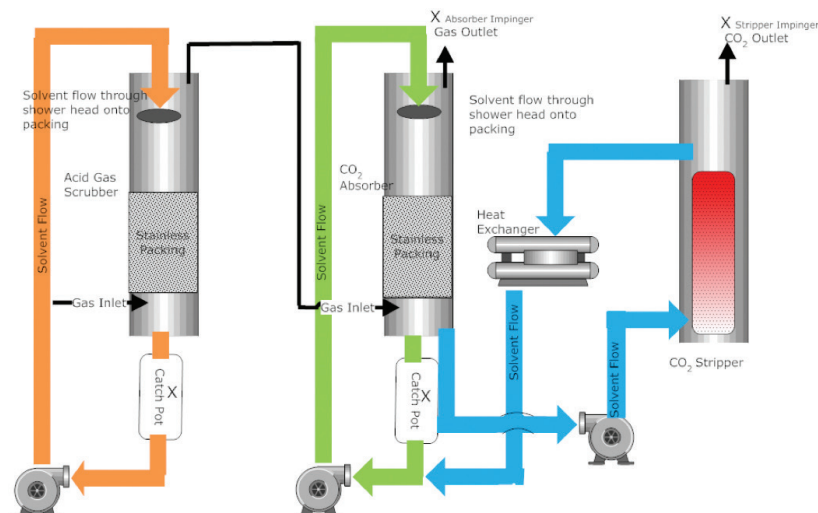
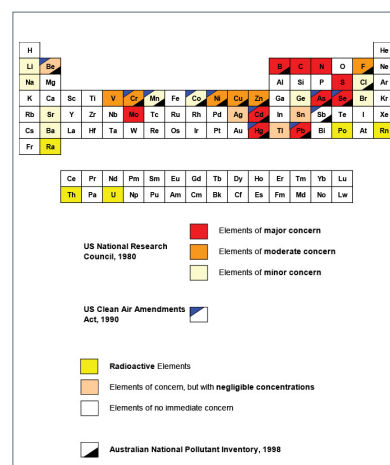
The conclusions from the laboratory study showed that:

- » Apart from mercury, the selected elements are mostly retained within the Acid Gas Scrubber (AGS), with very little carry-over into the ASE (absorber/stripper).
- » Some elements also show concentration changes in the AGS solution, possibly reflecting corresponding changes in pH of the absorbent solution.

- » Mercury remains in a volatile phase passing through the system with very little or no retention.
- » There is some variability in trace elements deportment related to the nature of the solvent, which is most likely due to the pH of the absorbent, precipitation and to carbonate formation, during the course of the experiment.
- » The behaviour of the trace elements in the ASE, particularly in the stripper, most likely reflects the volatility of the selected trace elements and solubility in the solvent matrix.

### Reference

M. Azzi, et al 2013, Impact of Flue gas impurities in PCC plants (4-0411-0131)



## CASE STUDY

# Reporting more accurate cost estimates for early mover CCS projects

## Many proposed carbon capture and storage (CCS) demonstration and commercial projects have failed to be constructed.

Reviews of these projects have shown that, in most cases, the cost estimates for these projects have increased markedly from the initial cost estimates to the final proposed cost. This has resulted in cost uncertainty, misinformation and a general lack of trust surrounding the costs and economics with regard to CCS project costs.

A robust cost estimate of carbon capture and storage projects is essential for public, regulator and investor confidence in the technology, which is critical to the deployment of the technology.

The study provided framework and guidelines for project scoping and cost estimation for early mover CCS projects.

The work reported on the results from scrutinising previous “new technology” introductions in the energy and process industries. From this work it was evident that:

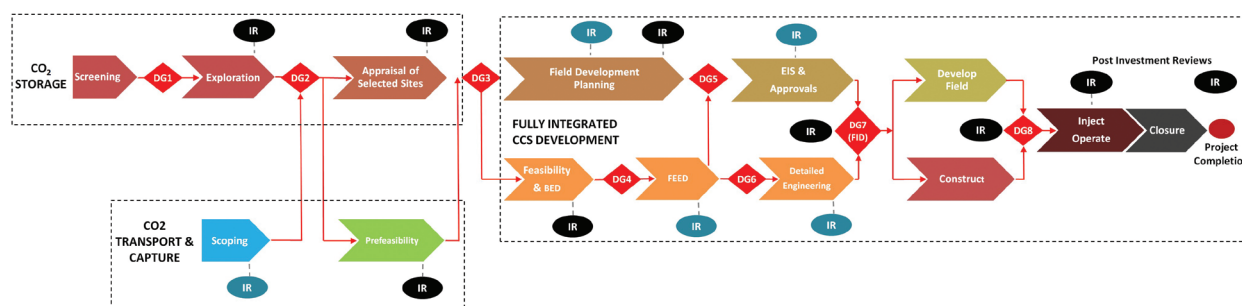
- » Uncertainty and increase in cost estimates are typical in first-of-a-kind and early mover projects.
- » Behavioural issues amongst stakeholders, in relation to early underestimates and final costs, range from honest delusion to deliberate deception.
- » Notwithstanding ‘better’ application of best practice in preparing cost estimates, known costing pitfalls continue to be a feature of modern day complex energy projects.

» The level of study detail in publicly available reports, with regards to cost estimates, is frequently not entirely transparent. This can lead to information being taken and used out of context or misunderstood.

The report recorded that carbon dioxide capture technologies are commercially available today, despite the assertion that carbon capture and storage is an ‘unproven’ technology that will never be deployed. In addition, the storage of carbon dioxide in geological formations is also very well established.

### Reference

C. Greig, et al 2014, Guidelines for scoping & estimating early mover CCS projects (1-0512-0205)





## CASE STUDY

# Innovative Rotating Liquid Sheet delivers significant capital and operating cost savings for CO<sub>2</sub> capture

Reducing the cost of CO<sub>2</sub> capture from flue gas is essential if carbon capture and storage is to be widely deployed as a low emissions coal technology for power generation.

The premise of developing a novel gas-liquid contactor is that without a “radical rethink” of the capture technology substantial cost reductions will not occur.

The gas velocity sets the contactor column diameter of a gas-liquid contactor and has a large influence on both the capital and operating costs.

The overarching objective of this study was to test a novel contactor concept. A new gas-liquid contactor was designed to widen the gas velocity operating window, which significantly restricts conventional contactor technologies, but not at the expense of higher pressure drop.

The novel Rotating Liquid Sheet (RLS) contactor developed not only achieved a significantly wider gas velocity operating window, it also eliminated the need for the solid packing elements used in conventional packed beds.

The potential cost reductions are as a result of eliminating conventional column packing, reducing or eliminating the need for external flue gas pumping and smaller contactors.

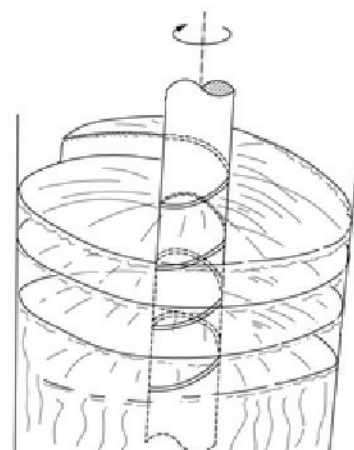
Overall capital cost savings are estimated to be approximately 30%, based on the elimination of the packing and the reduction in column diameter. Elimination of the flue gas blower provides a minor capital cost saving and, additionally, it provides the opportunity of a net reduction in electrical power consumption of 25%.

Other benefits include:

- » The RLS contactor can be readily designed to deliver operating savings in other conventional chemical processes.
- » Fluids with viscosity up to 50 mPas have been successfully run showing similar behaviour to low viscosity fluids and improved liquid sheet stability.
- » The shorter residence time and the cyclonic nature of the gas flow may be particularly advantageous in dealing with flue gas streams with high ash, high SO<sub>x</sub> and high NO<sub>x</sub> levels as are typical of flue gas streams in Australian conditions.

### Reference

L. Wardhaugh, et al 2015, Novel gas-liquid contactor concepts for PCC capital and operating cost reduction, (3-1110-0069)



Rotating Sheet Capture Concept.

## CASE STUDY

# A techno-economic review of Direct Injection Carbon Engines (DICE)

**Diesel engines have run on coal in the past. High thermal efficiencies and fast response times reportedly make this a potentially useful route to low emissions power generation, if the engine wear issues are resolved.**

This study was commissioned to gain understanding of the techno-economic prospects for developing such a technology.

Micronised Refined Coal (MRC) fuel for DICE engines was successfully made from a range of black coals, and from brown coal.

The report analysed scenarios of the engine life required to compete with available thermal generation processes. Engine run hours, that must be achieved for breakeven economics with the alternatives, gave an indication of the degree of engine development effort required.

The results suggested that with relatively little development, DICE could be competitive for remote area power where the alternative is trucked diesel.

Markets relying on imported LNG for power appear to be the “sweet spot” for DICE; requiring modest engine development and opening new markets for engine manufacturers and coal producers.

The study determined that should there be a demand for new-build plant, DICE could be competitive with combined cycle gas turbine (CCGT) at run lengths similar to the best available heavy fuel oil engines.

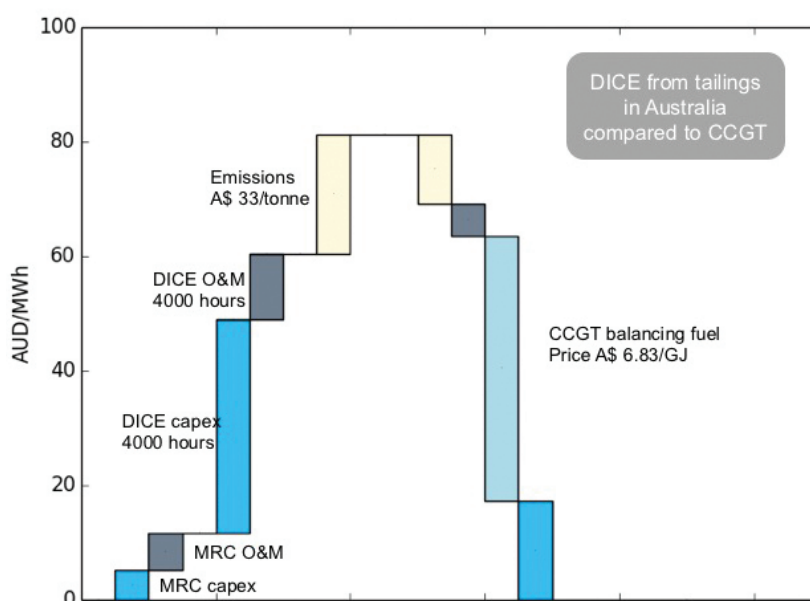
DICE emissions are lower than conventional pulverised coal technology. Carbon Capture and Storage (CCS) offers the possibility of deep emission reductions with the potential of reduced cost. The small modular nature of DICE may open the potential for a matched CCS module that can be manufactured in the same low cost locations as the engine, and shipped as a complete package.

Required run lengths, as estimated in the report, may be used to set targets for an engine development program. DICE can be used as an enabling technology for a lower cost pathway to reduced emissions from coal.

This report analyses the commercial performance of a number of DICE scenarios and sensitivity to their market variables.

## Reference

L. Jeffery 2016, A techno-economic review of Micronized Refined Coal fuelled Direct Injection Carbon Engines. (MRC DICE) (1-DICE-00SS)



MRC from tailings compared to CCGT in Australia - 4000 hours between overhaul.

## CASE STUDY

## Chemical looping air separation

Current commercial oxygen production systems have relatively high-energy demands and, as such, represent a significant parasitic load when integrated with either Integrated Gasification Combined Cycle (IGCC) or Oxy-fuel Combustion.

This study sought to test the chemical looping concept to deliver integrated high purity oxygen production at low energy and high throughput, based on their recent breakthrough work on air separation based chemical looping.

The study delivered results from laboratory and pilot scale experimental trials, in addition to a preliminary assessment of techno-economic feasibility for the technology.

The study showed:

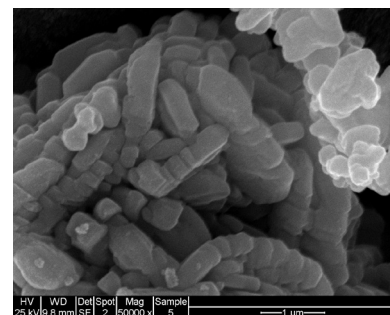
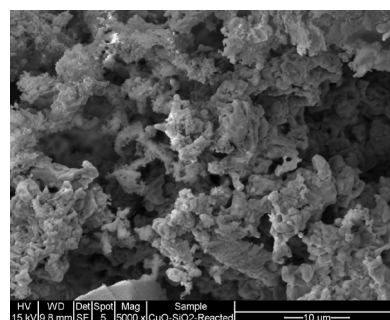
- » That chemical looping air separation is a viable technique for the production of industrial scale oxygen.
- » Suitable copper oxide species were demonstrated as oxygen carriers and enhanced material could be delivered from additional research.
- » A spray drying technique for the production of high quality metal oxides proved very effective.
- » Scale-up rules for chemical looping air separation were determined from data collected in a 10kWth facility.
- » Detailed assessments of scaling parameters for the reduction reactor were carried out by a combined set of theoretical analyses and mathematical modelling.

While suggesting a positive potential for the technology in the report, several techno-economic variables require additional data to ensure that a more accurate and up-to-date assessment is possible.

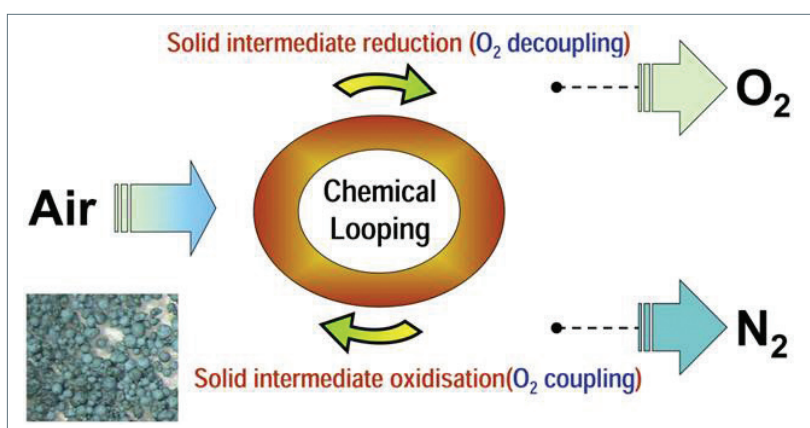
Consistent with most other low emissions technologies, the study suggests carbon pricing is necessary before such processes can become economically viable.

## Reference

B. Moghtaderi, et al 2015, Chemical Looping Oxygen Generation for Oxy-fuel Combustion and Gasification (3-1110-0089)



Fresh and used CuO/SiO<sub>2</sub> oxygen carriers.



## CASE STUDY

# Seeking synergies in coal and solar energy generation with carbon capture

A primary objective of this work was to test concepts that led to significant reductions in the cost and energy penalty to capture carbon dioxide from coal-fired power generation.

Using modelling, design and optimisation, this work specified control criteria for process integration and operation of low emissions coal power plants with solar-thermal technology.

A key outcome was the development of real-time routines, to inform the techno-economic performance of Post Combustion Carbon Capture (PCC) integrated with solar-thermal systems.

Outcomes from the study included:

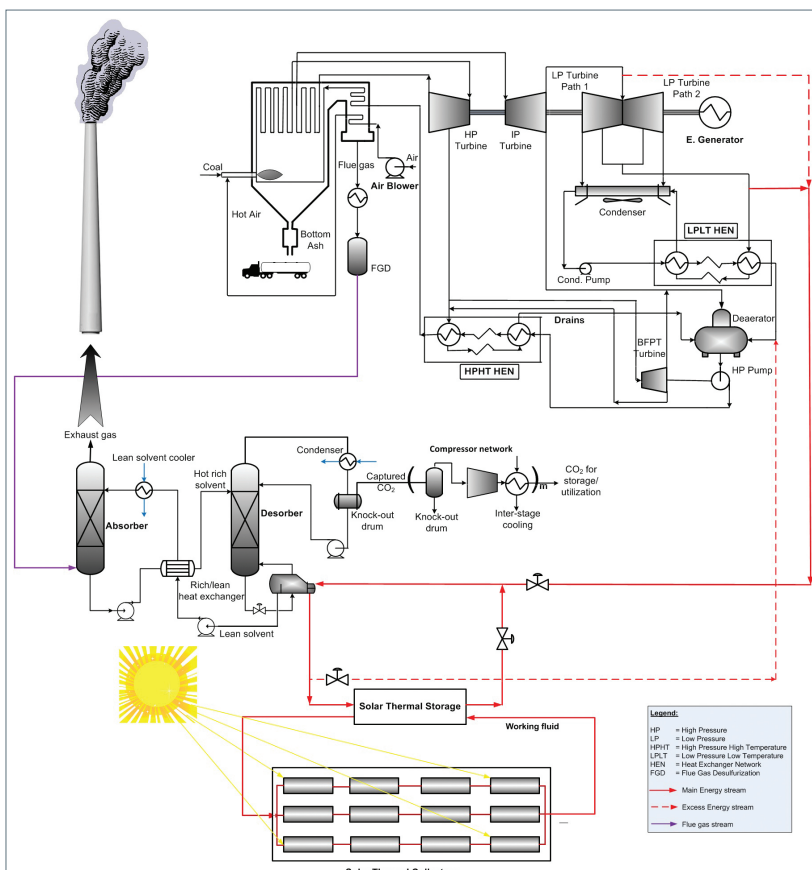
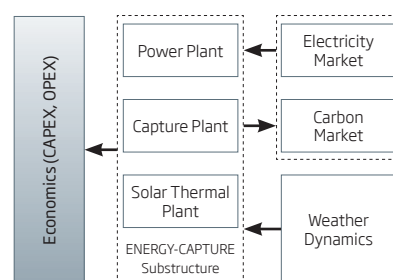
- » Process integration and simulation analysis showed valuable efficiency improvements could achieve sound integration of a solar-thermal plant with coal-fired power generation, including capture.
- » For the first time, a detailed dynamic model was developed, to simulate a solar-thermal plant, to repower the high pressure feed water heaters of a 660 MW power plant. It enabled the solar plant system to provide the thermal load dictated by the power plant.
- » Five possible operating modes were recognised and discussed in detail, to provide a clear perspective of the solar-thermal plant operation in this integrated process situation.
- » Using innovative control algorithms, the study showed scenarios where an integrated plant (power plant with PCC), subject to forecast 2020 electricity and carbon prices, can

be profitable. Without a carbon price these solutions are not economically viable.

- » Coal-fired power plants can operate sustainably in the future using carbon management systems built on model-based optimisation, such as the one proposed in this work, for flexible operation of PCC plants.

## Reference

A. Abbas, et al 2016, Model-based optimisation of highly-integrated post-combustion carbon capture processes (3-0911-0168)





## CASE STUDY

# A new metal membrane reactor for H<sub>2</sub> production

Coal gasification is used widely for the production of chemicals.

The Integrated Gasification Combined Cycle (IGCC) technology also has potential to deliver much improved efficiencies for power generation. Further, it captures CO<sub>2</sub> ready for transport and storage.

Hydrogen production, separation and reaction is an integral part of the IGCC process.

This project targeted the development of membrane reactor technology that can contribute to both aspects of CO<sub>2</sub> emission reductions, efficiency and storage. The project also developed a prototype catalytic membrane reactor (CMR), a device which combines a hydrogen-selective alloy membrane with a water-gas-shift (WGS) catalyst.

The current benchmark alloy membrane material is palladium (and its alloys). Vanadium has higher hydrogen permeability and lower cost than palladium, but its susceptibility to hydrogen embrittlement has limited its application in hydrogen-selective membranes.

By alloying vanadium with aluminium, the susceptibility to embrittlement is drastically reduced. These findings are the subject of a provisional patent lodged in several jurisdictions. Although membrane durability has not been assessed during this project, this new alloy will prolong membrane lifetime considerably, and will increase the likelihood of meeting the durability target of 5 years.

Key outcomes:

- » CSIRO has developed a patent-pending vanadium alloy, which has equivalent hydrogen permeation properties, much improved resistance to embrittlement, and enhanced ductility to allow manufacture by tube extrusion.
- » Several reactor geometries (planar or tubular) were evaluated, and determined that tubular geometries have the best prospects for low cost fabrication.
- » Various surface finishing techniques for effective catalytic coating were tested.
- » A 2-dimensional, axis-symmetric model of a membrane reactor has been developed using computational fluid dynamics (CFD). The model incorporates several sub-processes for heat transfer, mass transfer, hydrogen permeation and water-gas shift conversion, and has been validated against experimental data.
- » A hydrogen flux of 0.4 mol m<sup>-2</sup> s<sup>-1</sup> at 400°C has consistently been achieved using Pd-coated vanadium tubing. This flux is independent of membrane thickness. Several hydrogen separation modules, up to 1000 cm<sup>2</sup> in total membrane area, have been fabricated and tested.

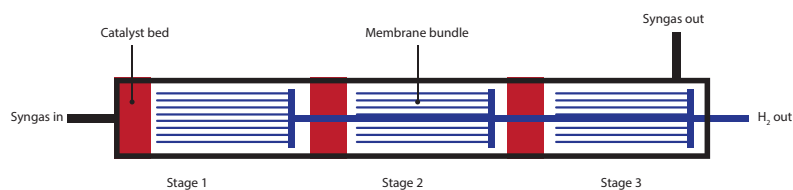
» A 3-stage membrane reactor was demonstrated, in which catalyst and membranes were physically separated. Greater than equilibrium CO conversion was achieved in this multi-stage configuration, despite modest CO conversion and H<sub>2</sub> yield per stage. This configuration is scalable and will protect vanadium-based membranes from mechanical or temperature-related damage.

### Reference

M. D. Dolan, et al 2015, Alloy membrane reactor for pre-combustion CO<sub>2</sub> capture (3-0510-0040)



Prototype 7-tube, 700 cm<sup>2</sup> membrane module



Schematic diagram of multi-stage CMR with separate conversion and separation zones.

# Concept testing for CO<sub>2</sub> capture cost reduction

CO<sub>2</sub> capture can amount to nearly 70% of the cost of a low emissions power generation project using fossil fuels. Demonstration and deployment will help reduce these costs.

ANLEC R&D has implemented a concept testing program of research that has canvassed the best ideas for cost reduction to capture, in an Australian context of fuel, environment and grid systems. This wide ranging program has reported on several innovative ideas including:

## Solvents

- » Solvent precipitation system
- » Designer amines for post-combustion carbon dioxide capture
- » Novel ionic liquids for CO<sub>2</sub> capture
- » Development of an advanced aqueous ammonia based post combustion capture technology
- » Novel gas-liquid contactor concepts for PCC capital and operating cost reduction

- » Enhanced CO<sub>2</sub> capture from coal-fired power stations with enzymes
- » Pre-treatment of flue gas and capture of CO<sub>2</sub> from brown coal-fired power stations
- » Development of froth generator gas/liquid absorption technology

## Membranes

- » Alloy catalytic membrane reactors for H<sub>2</sub> production
- » Membranes for tonnage oxygen separation, suited to supply oxy-fuel and coal gasification applications
- » Carbon Capture Shift reactor
- » Membrane processes for amine contaminant removal
- » CO<sub>2</sub> Capture with high performance hollow-fibre membranes from flue gas

## Adsorbents

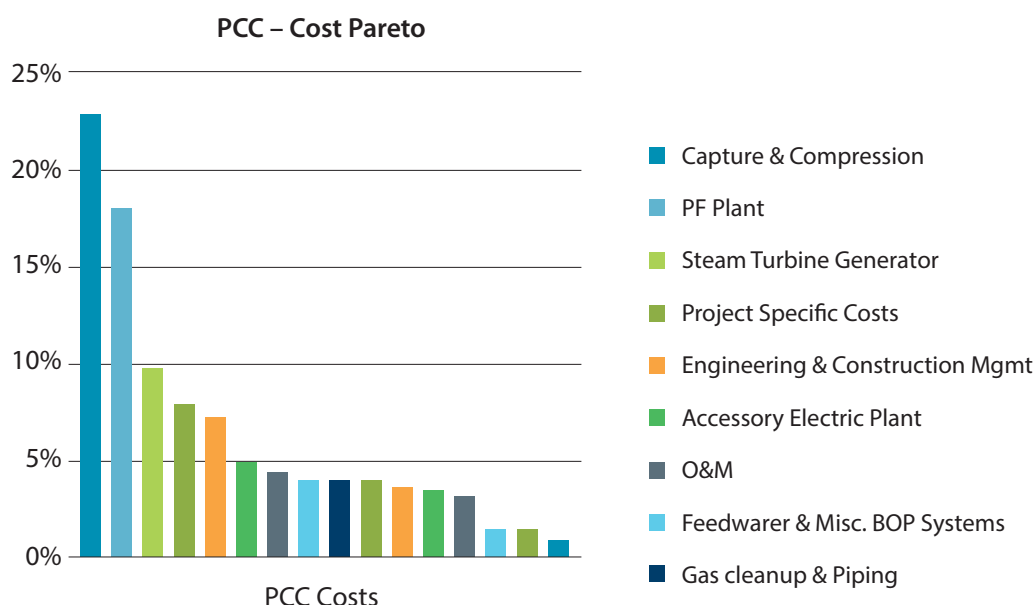
- » High efficiency post combustion capture of carbon dioxide using solid sorbents
- » Low cost hybrid CO<sub>2</sub> capture technology
- » Adsorption based oxygen generation technology
- » Nano-structured carbon nano-tube composites for CO<sub>2</sub> capture

## Engineering

- » Pilot-scale oxy-fuel combustion of Victorian brown coal
- » Solids disposal and utilisation in IGCC
- » Metal foam heat exchanger for dry cooling

## Reference

Internal ANLEC R&D Research Portfolio



# Australian CCS Research Services 2010-2016

Gorgon Project\*  
*Commercial CO<sub>2</sub> injection project*

*\*not ANLEC R&D related*

Curtin University

**SW Hub**

WA ERA

University of Western Australia

WA DMP

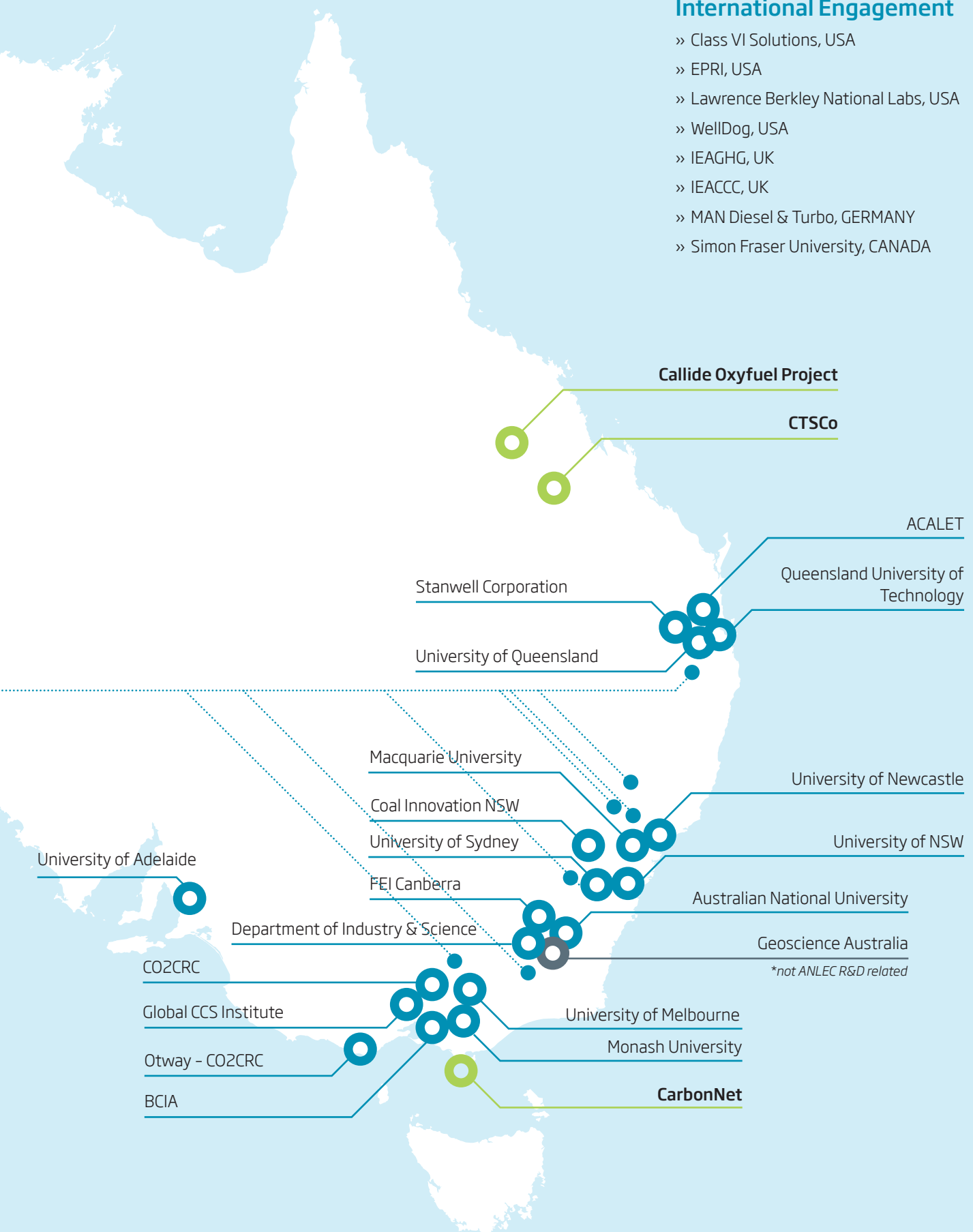
CSIRO



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## International Engagement

- » Class VI Solutions, USA
- » EPRI, USA
- » Lawrence Berkley National Labs, USA
- » WellDog, USA
- » IEAGHG, UK
- » IEACCC, UK
- » MAN Diesel & Turbo, GERMANY
- » Simon Fraser University, CANADA







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