



Government of Western Australia  
Department of Mines, Industry Regulation and Safety



# South West Hub CCS Project Research Outcomes 2017

Report to ANLEC R&D

Linda Stalker CSIRO

Dominique Van Gent Department of Mines, Industry Regulation and Safety

ANLEC R&D Project 7-0314-0225 South West Hub Stage 1 Integration  
February 2018



Geological Survey of Western Australia

National  
Geosequestration Laboratory



THE UNIVERSITY OF  
WESTERN AUSTRALIA



Curtin University







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**Geological Survey of  
Western Australia**

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**Cover image:** Harvey 1 location.

# Foreword

This document is the final submission for the South West Hub Stage 1 Integration Project 7-0314- 0225. Its purpose is to provide updated information on the carbon storage research activities conducted on the South West Hub CCS Project since the *Research Outcomes* document of August 2013. 'Call out' boxes have been used to provide additional background on key aspects of CCS and the project more broadly, so that a lay reader can access information that is assumed for technical readers.

Ongoing support will be provided to the Department of Mines, Industry Regulation and Safety (DMIRS) in the development of the materials for promotion and outreach. This document has been prepared in collaboration with Dominique Van Gent, DMIRS Coordinator Carbon Strategy. Technical data from seismic, drilling and analyses is available on the department's database at [www.dmp.wa.gov.au/wapims](http://www.dmp.wa.gov.au/wapims)



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# Acknowledgment of research and funding organisations

The South West Hub (SW Hub) is a government and industry partnership researching an economically and environmentally sustainable low carbon future for the South West region of Western Australia (WA). The SW Hub is Australia's first carbon capture and storage (CCS) Flagships project.

The WA State Government and the Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D) have provided funding for much of this research. Additional funding has come from the National Geosequestration Laboratory's research partners CSIRO, The University of Western Australia and Curtin University.

The National Geosequestration Laboratory (NGL) in Perth, WA is developing a world-class carbon storage research facility. The research and development NGL undertakes is a key component of the activities required to aid Australia achieving lower carbon emissions in the resources and energy economy. For further information on the NGL, visit [www.ngl.org.au](http://www.ngl.org.au). NGL is working with industry and government to provide research and development support and innovative solutions to carbon storage research.

ANLEC R&D is a research funding organisation supported by ACALET and the Australian Government through its Clean Energy Initiative. Its primary objective is to deliver the applied R&D that can reduce the investment risk and achieve low emissions from coal fired power generation at an acceptable cost. Working with proponents such as the SW Hub, ANLEC R&D enables Australia's best researchers to quantify and address items unique to Australian fuels, storage geology and other Australian environmental conditions. It provides independent and objective analysis, data and expertise necessary to inform decisions and development of Australia's CCS flagship projects.

The NGL has worked with the Department of Mines, Industry Regulation and Safety (formerly the Department of Mines and Petroleum<sup>1</sup>) and the Geological Survey of Western Australia (GSWA) to conduct a series of research projects for the SW Hub, which are summarised in this publication. All of the work reported here, and in fuller reports funded by ANLEC R&D, DMIRS, and NGL partners CSIRO, The University of Western Australia and Curtin University, contributes towards reducing geological uncertainty as the project progresses through the stage gates from feasibility to pilot tests to full commercial operations.



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<sup>1</sup> The Department of Mines and Petroleum became the Department of Mines, Industry regulation and Safety from 1 July 2017. For consistency, the former DMP is referred to as DMIRS throughout this document. However, the formal names for the wells referred to in this document may still be referred to as GSWA Harvey 1 and DMP Harvey 2, 3 and 4, often shortened to Harvey 1, 2, 3 or 4.

# Executive summary

Carbon capture and storage (CCS) is a means of taking carbon-rich emissions (typically carbon dioxide or CO<sub>2</sub>) generated from industrial processes or energy generation and storing it deep underground. The South West Hub Carbon Capture and Storage Project (SW Hub) is an investigation to obtain pre-feasibility information on the potential for the site to be a commercial scale carbon storage location. Broadly speaking, the site is north of the township of Harvey in Western Australia, and the current pre-competitive data-gathering phase of the project is managed by the Department of Mines, Industry Regulation and Safety (DMIRS). The research and data acquisition that is ongoing can provide much more information to inform government, industry and the public on how CCS works.

Methods used to evaluate potential geological storage sites come primarily from the oil and gas industry, where seismic data and wells may be drilled to obtain geological information about the subsurface. This approach is being used currently.

It is critical to note that this particular site of investigation is unique in the size of the target injection formation relative to many other CCS projects that have been undertaken or are in progress. Typically in oil and gas exploration, geologists look for areas where there are three key things: a source rock that is rich enough and deep enough to generate hydrocarbons, a reservoir interval, typically a sand or carbonate rock that has abundant porosity and permeability to contain large volumes of oil or gas, and a seal, or cap rock that retains the oil or gas, which would migrate upwards buoyantly to the earth's surface if there were no seal to stop it. Often, the reservoir interval may be thin and contain smaller amounts of oil, and the seal/cap rock is often very thick and does a good job of keeping the oil in place. Many carbon storage sites have this geometry also (Figure 1).

In carbon storage investigations, geologists are looking for a reservoir or storage interval that has those same porosity and permeability characteristics to oil and gas fields, but this time to contain large volumes of CO<sub>2</sub>. A cap rock or seal is also required to prevent the CO<sub>2</sub> from buoyantly migrating upwards. At the SW Hub storage site, the reservoir is far thicker than any of the current CCS projects, but is offset by having a potentially weaker sealing or cap rock package.

## What does this mean for CCS investigations?

Here we can begin to investigate geological situations that are not 'perfect' in all aspects; rather it is an investigation of a site that could be classified as challenging for some of the criteria. By investigating a site with such characteristics, researchers can investigate whether these characteristics, such as the large thickness of reservoir can be used to retard and retain the CO<sub>2</sub> through dissolution and migration assisted trapping or residual (capillary) trapping, which could reduce the reliance of a thick sealing unit at shallower levels within the defined storage complex. Researchers can conduct simple and step-wise investigations using laboratory, field and modelling scales to reduce uncertainty for such a geologically constrained site, but at the same time, provide major insights to be applied to other similar locations globally and open more areas for consideration of storage. In the future, this could mean that time spent on preliminary site investigations can be reduced saving on costs and time to evaluate potential carbon storage sites, and accelerate deployment of CCS to reduce emissions and meet Conference of the Parties (COP 21) targets.

## COP 21 targets

The Paris Agreement following the 21st Conference of the Parties (COP21) in late 2015 has resulted in many countries committing to set plans and targets towards mitigating emissions that may adversely impact climate. To date, 195 countries have signed and 148 ratified the document to deliver long-term change. CCS is one of the tools being adopted to do this, along with increased use of renewables, energy efficiencies, use of nuclear and fuel switching.

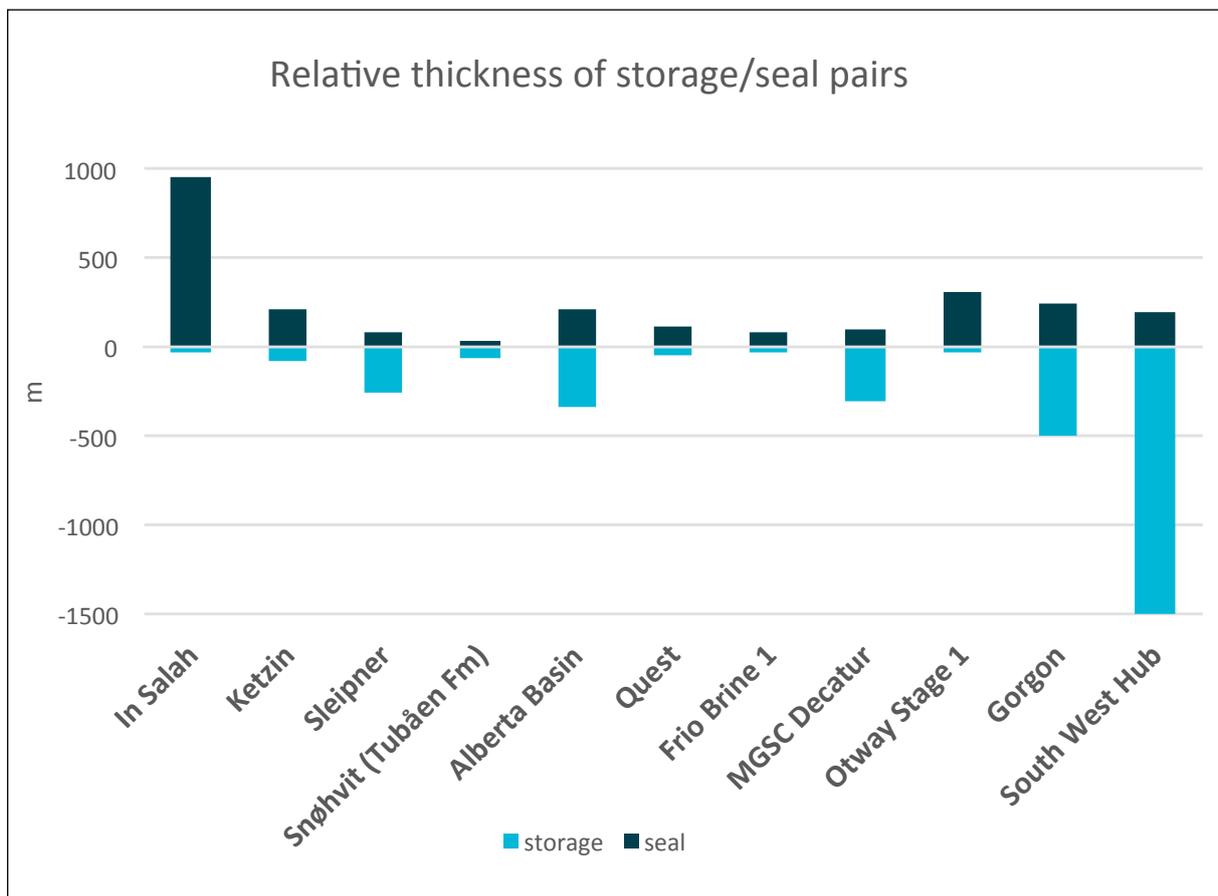


Figure 1: Examples of the different vertical thickness of the sealing unit versus the storage (reservoir) interval for some CCS projects. Data from Michael et al, 2010 and other sources referenced therein.

# Research outcomes and ongoing activities

This summary follows on from the previously published document 'Harvey 1 Stratigraphic Well – Research Outcomes August 2013' [http://www.dmp.wa.gov.au/Documents/Community-Education/CCS-Harvey1ResearchOutcomes\\_Aug2013.pdf](http://www.dmp.wa.gov.au/Documents/Community-Education/CCS-Harvey1ResearchOutcomes_Aug2013.pdf)

In 2013, the South West Hub Carbon Capture and Storage Project (SW Hub) provided an update of the activities that had taken place from 2010 to 2013 (Stalker & Ferguson, 2013). In particular, it summarised the activities conducted by the Department of Mines, Industry Regulation and Safety (DMIRS) as custodians of the pre-feasibility activities on the ground. In that period, some 2D Seismic was acquired to facilitate the placement of a deep, stratigraphic well, Harvey 1. The purpose of that well was to obtain a range of data and information on the geology in the area of investigation in the Southern Perth Basin. The rocks recovered from the well, the electrical logging data from inside the well bore and the seismic data acquired at that time all contributed to a better understanding of the geology with respect to the area's potential for carbon storage.

The Research Outcomes Report (Stalker and Ferguson, 2013) provided a consolidated overview of the results obtained and knowledge developed surrounding the area. This included a better understanding of the layers of interest in a three-dimensional mapping sense, (for example the thickness of layers and rock types encountered) as well as fundamental information on the rock properties at a fine scale.

The main rock formations of interest were deposited in the Triassic Period (251 to 199 million years ago). The Lesueur Sandstone Formation is made up of the older Wonnerup Member and the younger Yalgorup Member (Figure 2). The formation was laid down in a fluvial (river) environment.

The Wonnerup Member (Lower Lesueur Formation) is the unit of interest for potential storage and was investigated for its storage capacity based partly on its porosity and permeability characteristics within the formation, which range from 7-19% and 0.01-580 mD for the samples investigated in Harvey 1. However, the most distinguishing feature of this unit is its size; the Wonnerup Member is in excess of 1500m thick (Figure 1). The overlying Yalgorup Member (Upper Lesueur Formation) show qualities that could provide some sealing capacity, and was in fact more positive than had been expected prior to drilling Harvey 1. Thus, the project found that there could be major storage capacity opportunity, mainly in the form of residual (capillary) trapping and dissolution trapping and some degree of containment from the overlying paleosols.

The storage complex consists of the Wonnerup Member (injection reservoir), the Yalgorup Member as the lower confining layer and the basal part of the Eneabba formation as the upper confining layer. Primary containment is envisaged through residual and solubility trapping within the Wonnerup Member with added security of secondary containment through the Yalgorup Member and the basal Eneabba formation.

Ultimately, that report concluded that there were no 'show-stoppers' or particular features that could impact on the key aspects required for a suitable Commercial Scale Geological Storage site. The storage capacity (how much CO<sub>2</sub> could be placed in the rocks available), containment security (the ability to inhibit movement of CO<sub>2</sub> away from the storage area) and injectivity (ability of rocks to take in CO<sub>2</sub> at a suitable rate from a practicable number of wells) all seemed reasonable.

### **Commercial scale geological storage**

The Global Carbon Capture and Storage Institute (GCCSI) based in Australia has prepared some definitions for large-scale CCS facilities (<https://www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions>).

Large scale integrated facilities (those that involve capture, transport and storage activities for CO<sub>2</sub>) are anticipated to inject a minimum of 800,000 tonnes CO<sub>2</sub> annually for a coal-based power plant. At least 400,000 tonnes CO<sub>2</sub> per annum is the minimum volume for other emissions-intensive industrial processes (e.g. natural gas power plants, cement, steel-making, fertiliser production).

## New research and data acquisition

The certainty provided by the first tranche of work resulted in DMIRS proceeding with their investigation, by commissioning an extensive 3D seismic survey conducted in 2014, followed by the drilling of a further three wells in the area of interest in late 2014 to 2015.

The 3D Seismic Survey was conducted over an area of 115km<sup>2</sup>. To conduct such a survey, there was significant consultation with the community to obtain permission to conduct the survey on a large number of private properties. Of the 125 landholders, 75 granted permission and the views and opinions of the different landholders have been reviewed and assessed subsequently.

There were a number of research activities conducted to optimise the data acquisition parameters for the 3D survey, followed by research on the processing and interpretation of the information generated. The seismic survey provided information on the geological structure in the area to better define faults and relative thicknesses of formations, and provide the basis for locating future wells.

The information was used to define a drilling strategy, which was adapted to maximise geological coverage particularly across the shallower intervals. Three new wells DMP Harvey 2, 3 and 4 were drilled in 2015 using a combination of mineral and water well drilling rigs with a deeper well to be considered following model and associated uncertainty management plan (UMP) updates. These wells penetrated only the top 100-200m of the Wonnerup Member as DMIRS' objective for this campaign was to focus on understanding the complex layering of sand and paleosol sequences and containment properties of shallower horizons within different fault blocks, prior to investigating injection potential of the target deep reservoir.

The three 'shallow wells' obtained large amounts of core and electrical log data to compare with the 3D seismic information. Together, these large packages of data have been undergoing further investigation to enable firstly the development of a range of static geological models for the investigation, and secondly these models have been used to conduct dynamic modelling; to better understand what happens when CO<sub>2</sub> is injected and how it impacts on the geology within the area of investigation.

The SW Hub is in a pre-competitive data acquisition stage aimed at providing a certain level of technical confidence for acreage gazettal for industrial proponents to consider in the future. Thus, the following decision criteria is to verify the minimum acceptance criteria developed by the Petroleum Division of DMIRS:

- Deliver >P50 confidence to inject 800,000 tpa over 30 years i.e. 24 million tonnes.
- Deliver >P50 confidence that 'the plume' remains below the basal Eneabba unit or 800m and within the storage complex for 1000 years.
- Deliver a >P50 level of confidence that injectivity of > 100-300,000 tpa per well, i.e. no more than 10 wells in total would be required.

The results of these modelling activities show again that there are no obvious reasons at this more advanced stage of the project, to stop the evaluation of the site. Rather, there continues to be the potential for this area to fulfil the requirements for a commercial scale site for geological storage of carbon dioxide emissions at a future date. Furthermore, the unique geology in this location allows specific research to be undertaken that might not be possible in other locations due to the thickness of the reservoir and variability of the overlying units.

Research activities continue at the SW Hub field site, and include an additional project managed by CSIRO, to take one of the shallow wells that has already been drilled and prepare it to conduct a range of scientific investigations into the rock formations at a range of depths. The tests can provide further information on the potential of the area to act as a storage site through activities that include water pumping or even the potential to inject a small volume of CO<sub>2</sub> in a localised interval.

The site as it stands is well placed to do further evaluations with a view being a future research hub as well as a commercial scale demonstration site for carbon storage.

## Introduction

Researchers from the National Geosequestration Laboratory (NGL) a collaboration between CSIRO, the University of Western Australia and Curtin University – have been working in partnership with the Department of Mines, Industry Regulation and Safety (DMIRS) and with the Geological Survey of Western Australia (GSWA) to conduct a series of research projects to support the South West Hub Carbon Capture and Storage Project (SW Hub). There have been a number of detailed research projects conducted on the measurements made and samples collected from the Harvey 1 stratigraphic well, drilled in 2012, results of which were prepared and presented in 'Harvey 1 Stratigraphic Well – Research Outcomes August 2013'. This new document provides an update on the most recent work done at the site and at the research facilities at NGL.

A key feature of the storage site is its particular geology (Figure 1), where the large vertical thickness of the storage interval and absence of thick regional seal pose significant challenges to characterisation of the performance with respect to CO<sub>2</sub> storage. Figure 2 (left) shows the regional geology for the area, while Figure 2 (right) shows the formations encountered during the drilling of Harvey 1. Key to the area is the absence of the Jurassic age (140-180) Yarragadee Formation, which is a major drinking water aquifer for Perth and the South West Region. Why is its absence important? If CO<sub>2</sub> were to mobilise to that particular zone, its acidity could cause changes to rock chemistry and release unwanted elements into the aquifer. By investigating a site away from this important resource, the project eliminates the potential risk of contamination of potable water supplies.

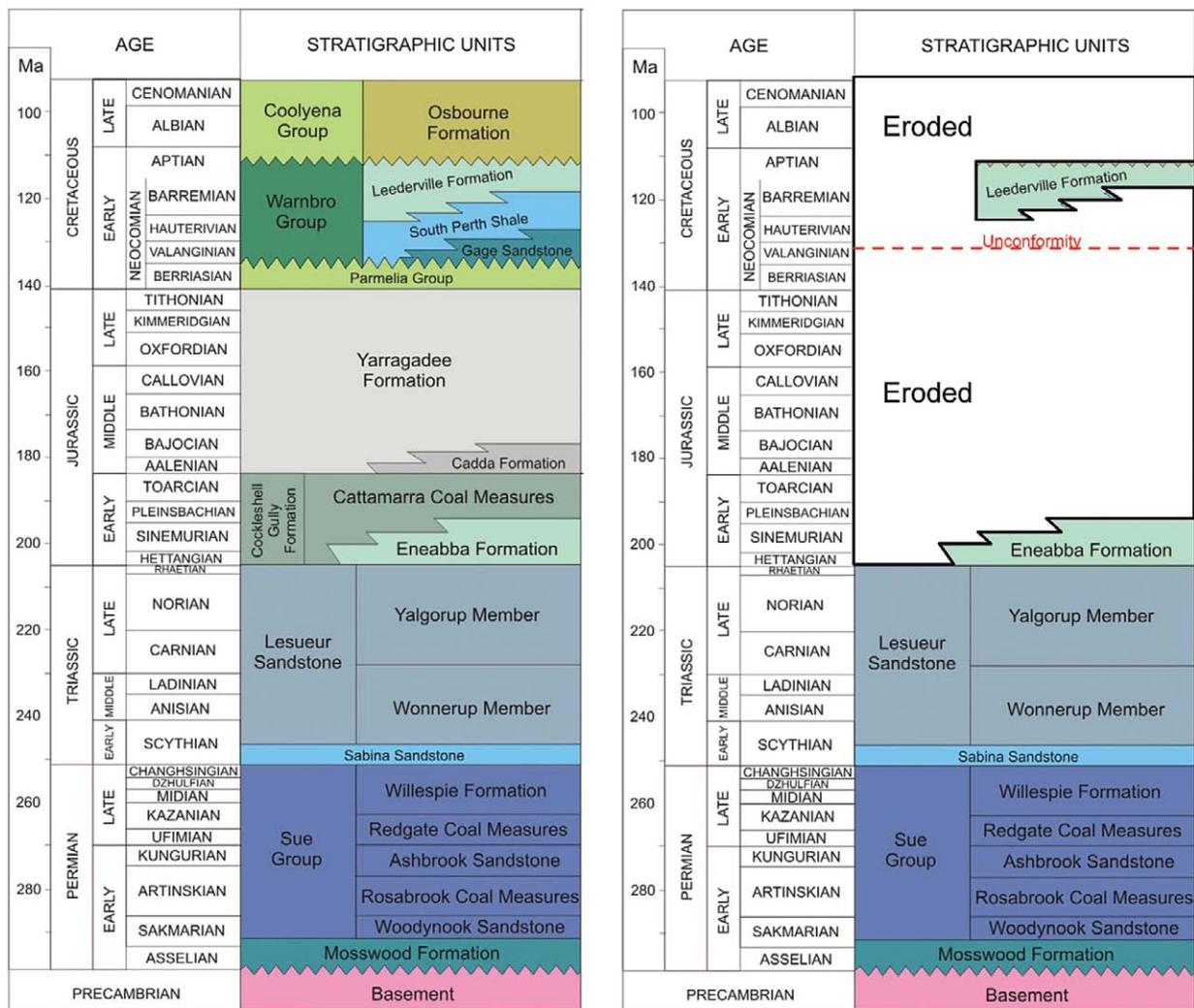


Figure 2: Stratigraphic column illustrating the age and type of rocks in the Southern Perth Basin. Image from Project 7-1111-0199.

During drilling of Harvey 1, some rocks underwent organic geochemical analysis to investigate the potential for hydrocarbons or the presence of gas. It was noted (Stalker et al, 2013) that there were no appreciable amounts of hydrocarbons observed in the rocks that were extracted, and there was no evidence of gas pockets during drilling (GSWA Harvey 1 Well Completion Report by Millar and Reeve, 2014). This further reduces risk of basin resource conflict.

The main feature of the geology in this area is the presence of the Lesueur Formation, made up of a younger member, the Yalgorup, an approximate 678m interval containing paleosols (fossil soils), sandstones and shalier intervals, and an older member, the Wonnerup, a >1500m thick interval of sandstones. This thick sandstone bed is the target injection horizon. The extensive thickness of this interval is what makes the SW Hub site globally unique in a portfolio of potential and active projects around the globe.

By way of illustration, Figure 1 shows a selection of current CCS projects, ranging from pilot, to demonstration and commercial scale, which have been involved in CO<sub>2</sub> injections. In many cases, the storage or reservoir interval may be a small as a few tens of metres (In Salah, Snøhvit or Quest), although some of the examples shown can be in the order of several hundreds of metres thick (Sleipner and Gorgon).

The presence of a massive thickness of sandstone at the SW Hub may significantly reduce the risk of encountering small disconnected storage compartments or unexpected migration direction due to more complex structure (in the case of In Salah). Further, the large storage thickness has been shown to be a positive advantage in the dynamic modelling assessments done to date; where dissolution and residual trapping can play a major part in retarding and retaining the migrating CO<sub>2</sub> such that it may not reach the upper zones. This observation is discussed below, as the new research and data acquisition reveals the current understanding of the geological environment at the SW Hub so far.

The goal of the multidisciplinary work conducted is to help enable and further the overall understanding of the geological and geophysical parameters that will affect the safe and efficient storage of carbon dioxide (CO<sub>2</sub>) at the proposed SW Hub site. Also, to understand more broadly the ways in which an efficient evaluation process might develop for both classical storage cases; the 'perfect cases', often depleted oil and gas fields, and for those less than perfect sites that are less easily characterised for potential storage.

For the SW Hub, the areas of interest covered by this work are related to the characterisation of the geological units first intersected by Harvey 1 in terms of storage capacity, injectivity and containment security, elastic and mechanical properties and heterogeneity of the formations encountered, and how some of these aspects impact on the behaviour of the rocks when CO<sub>2</sub> might be injected in commercial scale quantities.

The work done so far, described in more detail below, has contributed towards the ongoing characterisation of the geology in the area as a potential carbon storage site, and provided the information required to define and execute the next phase of data acquisition.

Harvey 1 demonstrated that there is potential to have an extensive storage interval that appeared to have reasonable porosity and permeability qualities over a large depth interval; thus suggesting that risks relating to injectivity may be secondary to that of containment security. With this in mind, DMIRS went on to commission a series of three shallow wells that would evaluate the upper intervals, in particular the shallier zones that had been difficult to sample in Harvey 1, but which might provide that containment barrier or baffle that would prevent CO<sub>2</sub> migration to the surface.

The large scale 3D seismic survey (2014), also discussed here, has enabled the considered placement of the three shallow wells that have been drilled to provide new geological information across a 15 x 10km<sup>2</sup> area as the characterisation of the region continues.

The results from the wells and the various seismic data acquisition activities contribute to the modelling, and collectively the observations to date indicate that there are still no geological impediments to proceeding to the next stage of data collection and site characterisation for the SW Hub project with the potential for drilling a second deep well (Harvey 5). Deeper samples are required as it remains uncertain how the rock properties change with depth and within the different fault blocks in the area, so that the best location (with respect to depth) for injection can be determined. This will enable a future demonstration trial or test injection to be conducted to provide some degree of certainty for commercial storage in the future. In the meanwhile, a new sub-project is being undertaken by CSIRO that will do small scale testing in one of the shallower wells during 2018.

# South West CO<sub>2</sub> Geosequestration Hub

## Research and analysis roadmap

In order to conduct a full investigation into the geology of the area adjacent to major CO<sub>2</sub> sources in the region, the SW Hub requires a detailed series of activities to provide relevant information. This has provided new insights and direction for subsequent research activities over time. The current roadmap (Figure 3) illustrates how the research and data acquisition packages link together and guides the data acquisition activities of the project overall. The project teams develop new innovative approaches to the tasks and activities in partnership with DMIRS and ANLEC R&D so that when decisions are required, the appropriate information is presented to enable robust decisions to be made. Note too, that where possible, industry relevance for the deployment of CCS is assessed as part of the discrete deliverables of these projects.

### Research Projects – Evolution from “Broad” to “Targeted”

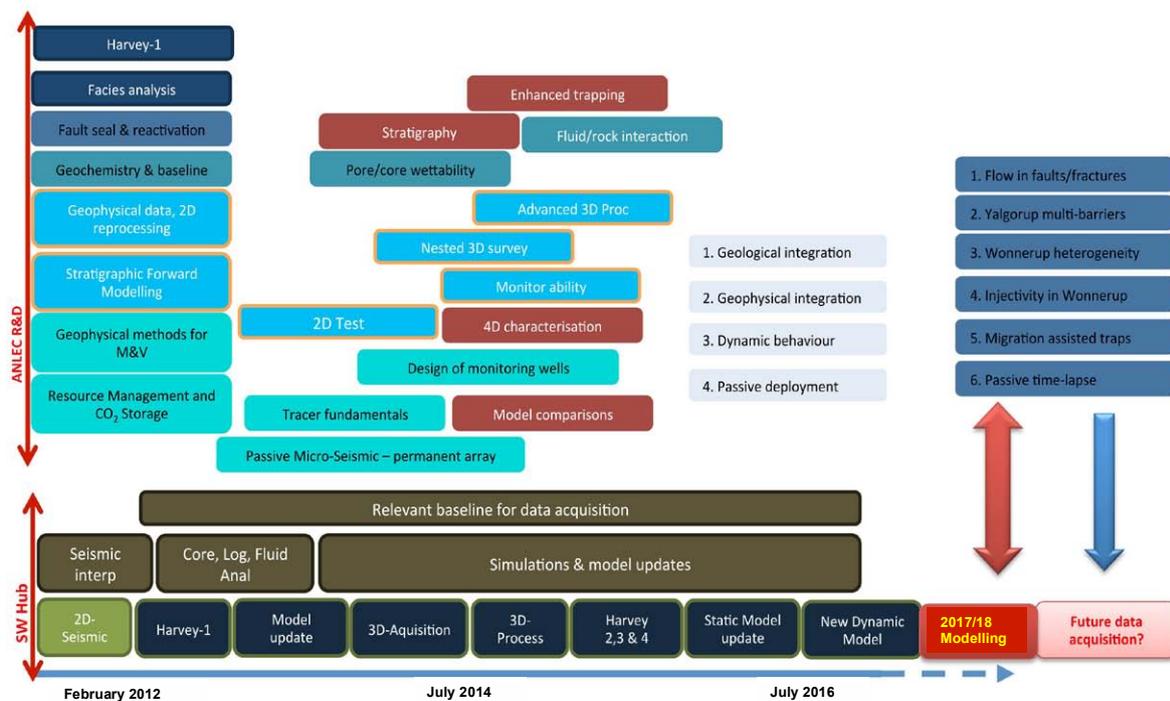


Figure 3: Roadmap of research projects conducted or underway for the SW Hub.

## Research reports summarised in this report

To date, more than 20 research projects have been commissioned by ANLEC R&D and DMIRS to identify uncertainties and provide information to allow a better understanding of the geology at the SW Hub. Of those, sixteen are already publicly available on the ANLEC R&D website. These are summarised in Table 1. This document will describe some of the highlights from these documents, and other discrete pieces of work conducted by DMIRS, that have led to the development of both a static and dynamic models that illustrate the potential behaviour of injected CO<sub>2</sub> should commercial volumes be stored at a future point in time.

Table 1: Overview of the research projects conducted to better understand the geology at the SW Hub by a range of researchers. \*Related uncertainties – see Table 3 where the uncertainties have been listed numerically according to CONTAINMENT, INJECTIVITY, CAPACITY & MONITORING. \*\*Any work involving social license and community engagement aids all data acquisition. The reports are available on the ANLEC R&D website at the time of preparing this document. [http://anlecrd.com.au/reports\\_storage/](http://anlecrd.com.au/reports_storage/)

|    | <b>Project title</b>   | <b>First Author</b> | <b>Project number</b> | <b>Date published</b> | <b>Key words &amp; Related uncertainties*</b>  |
|----|--|---------------------|-----------------------|-----------------------|--|
| 1  | Stratigraphic forward modelling comparison with Eclipse for SW Hub   | M. Feali            | 7-0212-0202           | November 2013         | Parameters for model input, static & dynamic model development, grain size, Eclipse, Petrel, rapid model development, SEDSIM           |
| 2  | Feasibility and design of robust passive seismic monitoring arrays for CO <sub>2</sub> geosequestration                          | D. Lumley           | 7-0212-0203           | June 2016             | Micro-fractures, stress, weak seismicity, baseline, geomechanics, faulting, monitoring   |
| 3  | Comparison of Eclipse & Updated SEDSIM Models  | H. Baz              | 7-0314-0226           | December 2014         | Dynamic simulations, static models, SEDSIM, industry standard, plume shape, residual, dissolved CO <sub>2</sub>                        |
| 4  | Advanced processing and analysis of South West Hub 3D seismic data   | R. Pevzner          | 7-0314-0231           | 2015                  | Acquisition, processing and interpretation, geophysical data, rock properties, well logging  |
| 5  | Understanding fluid rock interactions and their impact on rock properties as a result of CO <sub>2</sub> injection in the SW Hub | A. Saeedi           | 7-0314-0233           | July 2016             | Core analysis, core flooding, geochemistry, geochemical modelling, data acquisition, rock properties, injectivity, and fines migration |
| 6  | Stratigraphic forward modelling for South West Collie Hub  | C. Griffiths        | 7-0411-0129           | 2013                  | Modelling methods, workflows, porosity distribution, limited data, flow simulation   |
| 7  | Lessons from project level community engagement  | P. Ashworth         | 7-0414-0227           | October 2014          | Social risk, public acceptance, community engagement, stakeholders, CCS implementation**   |
| 8  | Estimating vertical permeability based on responses to barometric pressure fluctuations in the Lesueur Formation                 | Y. Zhang            | 7-0515-0246           | February 2016         | Permeability, integrity, passive monitoring, earth tides, barriers, heterogeneity  |
| 9  | Desktop design study on enhancing residual and dissolution trapping  | H. Baz              | 7-1012-0210           | June 2014             | Reservoir simulation, economic modelling, static model, residual saturation, dissolution<br>4, 6, 8, 9, 16                             |
| 10 | Desktop design study on South West Hub wells   | L. Ricard           | 7-1012-0214           | November 2015         | Data acquisition, monitoring methods, modelling, well design, well test design scenarios   |

|    | <b>Project title</b>   | <b>First Author</b> | <b>Project number</b> | <b>Date published</b> | <b>Key words &amp; Related uncertainties*</b>   |
|----|--|---------------------|-----------------------|-----------------------|---|
| 11 | Advanced geophysical data analysis at Harvey 1: storage site characterisation and stability assessment | R. Pevzner          | 7-1111-0198           | March 2013            | Rock properties, log evaluations, data analysis, improve processing   |
| 12 | Facies-based rock properties distribution along the Harvey 1 stratigraphic well                        | C. Delle Piane      | 7-1111-0199           | June 2013             | Facies description, characterisation, wireline logs, rock properties, core flooding, geomechanics, porosity, permeability |
| 13 | Geochemical characterisation of gases, fluids and rocks in the Harvey 1 data well                      | L. Stalker          | 7-1111-0200           | August 2013           | Gas geochemistry, isotopes, formation fluids, hydrocarbons, geochemical modelling, core flood                             |
| 14 | Fault seal first-order analysis – SW Hub   | L. Langhi           | 7-1111-0201           | May 2013              | Fault system, pore pressure, stress fields, sealing capacity, geological model development                                |
| 15 | Harvey 2D test seismic survey – issues and optimisations   | M. Urosevic         | 7-1213-0223           | August 2014           | Reducing acquisition impact, 2D survey, improving acquisition parameters, demonstrating technology, shallow structures    |
| 16 | Acquisition of the nested 3D seismic survey at Harvey  | M. Urosevic         | 7-1213-0224           | October 2015          | Mapping structures, high-resolution survey, 3D survey, advanced processing, well log integration                          |

Table 2: Projects underway or nearing completion related to research activities at the South West Hub. \*Related uncertainties are listed in Table 3 where they have been listed according to CONTAINMENT, INJECTIVITY, CAPACITY & MONITORING.

|   | <b>Project title</b>  | <b>First Author</b> | <b>Project number</b> | <b>Key words &amp; Related uncertainties*</b>  |
|---|---|---------------------|-----------------------|--|
| 1 | The Lesueur: Deposition, Rocks, Facies Properties   | C. Delle Piane      | 7-0115-0240           | Data integration, rock properties, storage potential, diagenesis, palaeo fluids, seismic behaviour, geomechanics |
| 2 | The Lesueur, SWH: Improving seismic response and attributes   | M. Urosevic         | 7-0115-0241           | Imaging small units, geophysical integration, monitoring evaluations, processing                                 |
| 3 | The Lesueur: vertical connectivity, injectivity and residual trapping                               | K. Michael          | 7-0115-0242           | Modelling options, plume migration, injectivity, heterogeneity, sweep efficiency                                 |
| 4 | Feasibility of monitoring an injected CO <sub>2</sub> plume at the SW Hub                           | A. Hortle           | 7-0314-0232           | Monitoring approaches, field testing, modelling the plume, workflows   |
| 5 | Passive seismic investigations  | E. Saygin           | 7-0215-0244           | Monitoring passive seismic, developing monitoring arrays, field deployment                                       |
| 6 | South West Hub CO <sub>2</sub> Geosequestration research program                                    | S. Whittaker        | 7-0314-0225           | Integration, geoscience, geophysics, modelling, stakeholder engagement   |
| 7 | Potential for preferential flow through faults and fractures  | B. Gurevic          | 7-1215-0261           | Near surface faults, geophysical data integration, well logs, hydrodynamic behaviour, novel monitoring tests     |
| 8 | Assessment of multi-barrier systems for CO <sub>2</sub> containment in the Yalgorup Member          | J. Bourdet          | 7-1215-0262           | Baffles, barriers, sealing capacity, rock reactivity, basin history  |
| 9 | The influence of heterogeneity and diagenesis on injectivity and containment in the Wonnerup Member | T. Dance            | 7-1215-0263           | Reservoir heterogeneity, diagenesis, injectivity, reservoir simulations, migration behaviour                     |

As the project has sharpened its technical analysis and research to more specific outcomes, based on the research project objectives, the SW Hub program has been refined to establish whether there is adequate confidence that:

- a) the Lesueur storage complex can safely store CO<sub>2</sub> as per the base case criteria outlined below:
  - i. modelling shows that injected volumes stay within the storage complex; and
  - ii. modelling and geological data support that 'residual trapping' can be an effective mechanism for securely storing CO<sub>2</sub> in a geological formation that has no conventional seal rocks.

- b) such formations are amenable to being sufficiently well characterised to satisfy the acceptance criteria set by the regulator; and
- c) this type of geological structure has potential for future commercial development.

Where the base case focuses on the undertaking of a suite of data modelling in order to establish that the nominated area will contain injected CO<sub>2</sub>. The base case analyses will aim to:

- a) deliver >P50 confidence to inject 800,000 tonnes of CO<sub>2</sub> per annum over 30 years; and
- b) deliver >P50 confidence that 'the plume' remains below the Basal Eneabba Shale and within the storage complex for 1,000 years.

This fits closely within the definition of a major CCS project by the Global CCS Institute.

The criteria and outcomes described above will aid in our understanding of the following main criteria that define a good carbon storage area:

1. Storage capacity – the volume of CO<sub>2</sub> that the storage interval is expected to hold over a given period of time.
2. Containment security – where a range of possible mechanisms for CO<sub>2</sub> losses and assess their likelihood are defined.
3. Injectivity – The rate at which CO<sub>2</sub> can be injected into the storage interval without the pressure increasing excessively and without requiring too many wells. This depends on the rock properties, the number of wells drilled and how much of those wells are open to the formation to dissipate the CO<sub>2</sub>.

Aspects of all the completed projects and the projects that are still in progress have led towards the first meaningful model to evaluate how the CO<sub>2</sub> might behave with an injection deep in the Wonnerup Member of the Lesueur Formation. However, at this stage, researchers can only evaluate the CO<sub>2</sub> behaviour based on projections of how the rock formations behave at depth. Aside from samples taken from the Harvey 1 well, there are no deep samples (below 1800m) which is the depth that could act as the main CO<sub>2</sub> store at this time. It is possible that a further deep well, Harvey 5, could be drilled in the future to obtain the relevant samples and data. This would complete the precompetitive aspect of the SW Hub and provide further evidence for the decision as to whether the region is suitable for commercial scale geological storage. What follows in this document is some of the highlights of the work to date and how the information gained can help reduce that uncertainty as the area is investigated for commercial scale storage.

# Reducing uncertainty

Both the collection of data at the site and the research undertaken to date have a singular purpose: that is to reduce risk and uncertainty at the site so that the next steps can be taken on a pathway to commercial-scale CO<sub>2</sub> storage at the SW Hub. Examples of the workflow of this process are presented in Figure 4.

To successfully move to the next stage of each decision gate, a range of uncertainties have to be reduced to manageable levels, or the project may not be able to proceed. Some of the uncertainties identified by the SW Hub project are listed in Table 3. The project has addressed many aspects of the listed uncertainties. This is illustrated through Tables 1, 2 and 3 which shows the relationship between the research and the uncertainties being addressed.

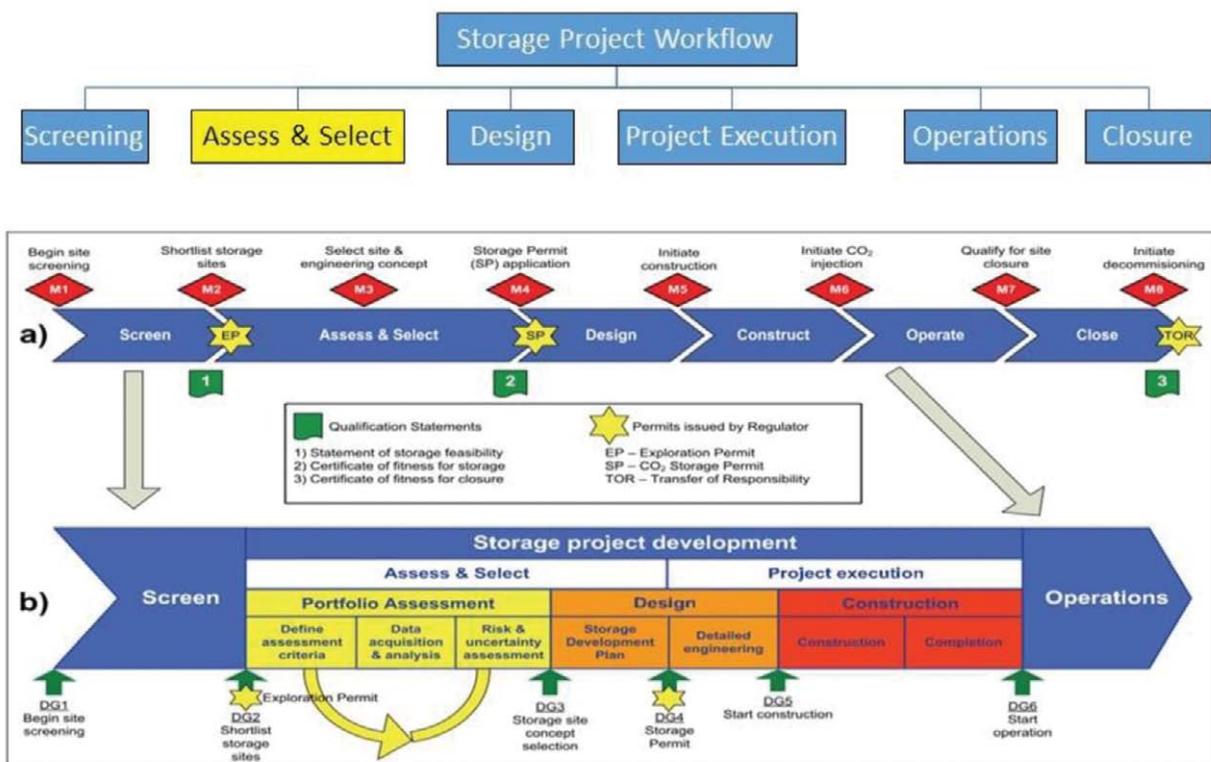


Figure 4: Examples of the workflow undertaken to drive a CCS project to a commercial decision. The upper part is simplified and illustrates the place where SW Hub is at currently. The lower part of the figure from the CO2QUALSTORE Guidelines (2009) shows more detail of the key elements, and areas where decision gates lie along the way. Note that the Assess & Select stage requires reiteration, collecting more data and review.

Table 3: Geological Uncertainties being addressed as the Project continues.

A range of examples are presented below. The list is not exhaustive but part of a larger risk register maintained by DMIRS.

|                    | <b>Uncertainty</b>                               | <b>Activity to Address Uncertainty</b>  | <b>Data Required</b>  |   |
|--------------------|--|---|---|---|
| <b>Containment</b> | <b>Faults</b>                                    | <ul style="list-style-type: none"> <li>• Their location</li> <li>• Reactivation potential</li> <li>• Pressures of reactivation</li> <li>• Juxtaposition of rock types</li> </ul>                              | <ul style="list-style-type: none"> <li>• 3D Seismic survey</li> <li>• Geomechanical information and modelling</li> <li>• Log data</li> <li>• Obtain rock property characterisation</li> <li>• Understand heterogeneity</li> </ul>   | <ul style="list-style-type: none"> <li>• Interpret 3D seismic data, image &amp; wireline logs data</li> <li>• Conduct rock characterisation tests</li> <li>• Map faults and fracture locations &amp; orientations</li> </ul>                        |
|                    | <b>Fracture Gradient</b>                         | <ul style="list-style-type: none"> <li>• Understanding the threshold pressure for pushing CO<sub>2</sub> into the formation</li> </ul>  | <ul style="list-style-type: none"> <li>• Drilling new wells to get a range of data points geographically</li> <li>• Conduct core analysis tests</li> <li>• Obtain well logs from new wells and integrate</li> </ul>   | <ul style="list-style-type: none"> <li>• Leak off tests in wells at range of depths</li> <li>• Rock strength characterisation geomechanical evaluations</li> <li>• MDT stress tests in wells</li> </ul>   |
|                    | <b>Basal Eneabba Shale<br/>Yalgorup Paleosol</b> | <ul style="list-style-type: none"> <li>• Define quality and continuity of these layers</li> <li>• Determine paleosol extent</li> <li>• Ability of units to act as baffles laterally and vertically</li> </ul> | <ul style="list-style-type: none"> <li>• Obtain a range of new cores</li> <li>• Well logs run in all new wells</li> <li>• Well tests – single well and multiwell tests using CO<sub>2</sub>, water or other fluids to test behaviour</li> <li>• 3D Seismic survey for interpreted well ties and correlations to generate maps &amp; models</li> </ul> | <ul style="list-style-type: none"> <li>• Core samples &amp; well log data from new wells</li> <li>• Identify formation tops</li> <li>• Obtain rock property data (porosity permeability, strength, heterogeneity diagenetic effects etc)</li> </ul> |
|                    | <b>Capillary entry pressures</b>                 | <ul style="list-style-type: none"> <li>• Information to aid CO<sub>2</sub> injection pressures for different facies types</li> <li>• Understand pressure constraints</li> </ul>                               | <ul style="list-style-type: none"> <li>• Lab core analysis</li> <li>• Core flooding measurements</li> <li>• Define heterogeneity ranges</li> </ul>  | <ul style="list-style-type: none"> <li>• MCIP measurements</li> <li>• Relative permeability measurements</li> <li>• Rock properties</li> </ul>  |
|                    | <b>Reservoir structure</b>                       | <ul style="list-style-type: none"> <li>• Understanding the dip, fault geometry and migration directions</li> </ul>  | <ul style="list-style-type: none"> <li>• Seismic 2D/3D, drill wells</li> <li>• Define volumes, and critical faults</li> </ul>   | <ul style="list-style-type: none"> <li>• Acquire check-shot data to improve mapping and model development</li> </ul>  |
|                    | <b>Trapping mechanism</b>                        | <ul style="list-style-type: none"> <li>• Understand and quantify over time the relative trapping</li> </ul>   | <ul style="list-style-type: none"> <li>• Comprehensive core flooding experiments for various lithologies</li> <li>• Water-rock interaction with CO<sub>2</sub> for reactive transport information</li> <li>• Diagenetic studies</li> </ul>  | <ul style="list-style-type: none"> <li>• Relative permeabilities data, hysteresis measurements, residual trapping quantification</li> <li>• Geochemical analyses</li> <li>• Mineralogical data</li> </ul>   |

|                    |  | <b>Uncertainty</b>   | <b>Activity to Address Uncertainty</b>   | <b>Data Required</b>  |
|--------------------|--|--|--|---|
| <b>Injectivity</b> | <b>Vertical vs Horizontal permeability behaviour (Kv/Kh) ratios</b>  | <ul style="list-style-type: none"> <li>Understand migration rates &amp; direction</li> <li>Identify injection horizons and relative permeability in overlying formations</li> </ul>  | <ul style="list-style-type: none"> <li>Coring</li> <li>Well tests</li> </ul>   | <ul style="list-style-type: none"> <li>Lab permeability measurements</li> <li>Multiple samples to determine heterogeneity</li> <li>Core flood measurements with CT</li> <li>MDT data interpretation</li> </ul>                                  |
|                    | <b>Absolute permeability</b>   | <ul style="list-style-type: none"> <li>Rates of vertical vs horizontal migration</li> <li>Constrain injection rates</li> </ul>   | <ul style="list-style-type: none"> <li>Wireline logs to give info on heterogeneity and baffle potential</li> <li>Image logs, and cores pictures to identify sub-seismic barriers</li> <li>Well test – smaller scale to understand near wellbore effects</li> </ul> | <ul style="list-style-type: none"> <li>NMR, MDT measurements to provide field scale data</li> <li>Core flood data and imaging for smaller scale information</li> <li>Pressure interpretation to constrain rates</li> </ul>                      |
|                    | <b>Relative permeabilities</b>                                       | <ul style="list-style-type: none"> <li>Understanding effective permeability with CO<sub>2</sub> at a range of saturations</li> <li>Initial Pore pressures</li> <li>Understand and constrain maximum pressure values</li> </ul> | <ul style="list-style-type: none"> <li>Core flood experiments under a range of conditions to improve heterogeneity range information</li> <li>Well Logs</li> <li>Well tests</li> <li>Core measurements</li> </ul>  | <ul style="list-style-type: none"> <li>Core flood data</li> <li>Relative permeability end point measurements</li> <li>Saturation curves, NMR data</li> <li>MDT, test Pressure data</li> <li>Field trials and well test</li> </ul>               |
|                    | <b>Reservoir fluid salinity, reactive flow and transport effects</b> | <ul style="list-style-type: none"> <li>Understand their impact on permeability over the duration of CO<sub>2</sub> injection</li> <li>Impact near and far well bore</li> </ul>   | <ul style="list-style-type: none"> <li>Coring</li> <li>Well Logs</li> <li>Fluid Samples</li> <li>Reactive transport Modelling</li> </ul>   | <ul style="list-style-type: none"> <li>Core flood experiments, mineralogical evaluation before and after flooding</li> <li>Characterising and quantifying change by a range of analyses (e.g. SEM)</li> <li>MDT samples and analysis</li> </ul> |
| <b>Capacity</b>    | <b>Faults – Location</b>   | <ul style="list-style-type: none"> <li>Understanding compartmentalisation and wells required to maximise capacity</li> </ul>   | <ul style="list-style-type: none"> <li>3D Seismic Survey refinement of maps and models</li> <li>Log data</li> <li>Conduct of interference tests to assess volume of compartment</li> </ul>   | <ul style="list-style-type: none"> <li>Interpreted 3D seismic survey</li> <li>Use of rock properties and geomechanics data</li> <li>Pressure interference data</li> </ul>   |
|                    | <b>Gross thickness of reservoir</b>                                  | <ul style="list-style-type: none"> <li>Volume available for storage</li> </ul>   | <ul style="list-style-type: none"> <li>Well Logs</li> <li>Seismic inversion</li> <li>Models and maps</li> </ul>  | <ul style="list-style-type: none"> <li>Lithology data</li> <li>Heterogeneity of mineralogy, porosity permeability etc</li> <li>Quantitative processing</li> </ul>   |
|                    | <b>Net to Gross</b>  | <ul style="list-style-type: none"> <li>Determine threshold volumes that can be most easily accessed by CO<sub>2</sub></li> </ul>   | <ul style="list-style-type: none"> <li>Well Logs</li> <li>Cores</li> <li>Maps and modelling</li> </ul>   | <ul style="list-style-type: none"> <li>Amount of shale to sand (Vsh) computation</li> <li>Log – Core calibrations</li> </ul>  |
|                    | <b>Regional Reservoir diagenetic trends</b>                          | <ul style="list-style-type: none"> <li>Loss of capacity due to cementation</li> </ul>  | <ul style="list-style-type: none"> <li>Well Logs</li> <li>Cores</li> <li>Reactive transport analysis</li> </ul>  | <ul style="list-style-type: none"> <li>Facies and other core information</li> <li>Mineralogical evaluations</li> <li>Predictive diagenetic events and porosity loss or enhancements</li> </ul>  |
|                    | <b>Fluid properties</b>  | <ul style="list-style-type: none"> <li>In-Situ chemistry of formation fluids limiting dissolution and storage</li> </ul>   | <ul style="list-style-type: none"> <li>Characterise the formation fluid chemistry in target areas</li> <li>Obtain pristine water samples for analysis</li> <li>Well tests and water production over time</li> </ul>  | <ul style="list-style-type: none"> <li>Water chemistry analysis of cations anions, isotopes, organics and particulates</li> </ul>   |

|                                    |  | <b>Uncertainty</b>  | <b>Activity to Address Uncertainty</b>   | <b>Data Required</b>  |
|------------------------------------|--|---|--|---|
| <b>Monitoring and verification</b> | <b>Observing plume evolution</b>                       | <ul style="list-style-type: none"> <li>Predict and confirm the migration pathways and rate of movement for regulatory compliance</li> </ul> | <ul style="list-style-type: none"> <li>3D seismic data and repeat surveys</li> <li>Model inversion</li> <li>Injection tests and monitoring</li> </ul>          | <ul style="list-style-type: none"> <li>3D seismic survey repeats and processing</li> <li>Calibration of seismic with well logs and core samples</li> <li>Nested high-resolution surveys and alternative monitoring methods</li> </ul> |
|                                    | <b>Pressure levels as indicator of plume migration</b> | <ul style="list-style-type: none"> <li>Use of pressure monitoring as early indicator of movement of CO<sub>2</sub></li> </ul>               | <ul style="list-style-type: none"> <li>Hydrogeology model</li> <li>Predict change to pressure in injection zone, and within identified compartments</li> </ul> | <ul style="list-style-type: none"> <li>Installation and monitoring of pressure sensors</li> <li>Atmospheric pressure data recorded on site for interpretation of downhole data</li> <li>Baseline measurements conducted</li> </ul>    |
|                                    | <b>Impact on groundwater quality</b>                   | <ul style="list-style-type: none"> <li>Understand any changes and timing of impact</li> </ul>   | <ul style="list-style-type: none"> <li>Model movement of CO<sub>2</sub></li> <li>Model reactive transport behaviour in shallower aquifer regions</li> </ul>    | <ul style="list-style-type: none"> <li>Collect water samples</li> <li>Conduct reactive transport modelling</li> <li>Measure baseline samples</li> </ul>   |

Assuming the project has passed through the screening phase and identified a shortlisted site for further investigation, the project reaches the 'Assess & Select' phase and acquires more data on site as per the storage project workflow (Figure 4). Much of the data acquisition comes from the drilling of wells or conducting seismic surveys. This means that the project needs to be 'on the ground' in the area.

This requires a great deal of communication with stakeholders and provision of information in order to obtain permission to go to a location and acquire that data. The next section addresses some of the 'on the ground' activities that enable the data acquisition, as well as some of the data acquired and results gained from the research conducted.

# Activities on the ground

Data acquisition has been continuing since the early 2D seismic acquisition in 2011, and the drilling of Harvey 1 in 2012. This has come about from both DMIRS commissioned data acquisition and the research value adding that has been funded by ANLEC R&D. The data acquisition components have included:

- large scale commercial 3D Seismic Survey from February-April 2014 covering approx. 115km<sup>2</sup> funded by the Commonwealth Government (the DoIS) and the DMIRS through the CCS Flagships Program;
- shallow Drilling Program of Harvey 2, 3 and 4 in late 2014 to mid-2015 commissioned by DMIRS;
- wireline and electric logging of each of the wells; and
- ongoing community engagement, consultation with the Lesueur Community Consultative Committee (LCCC), *CarbonKids – Sustainable Futures* workshops at various schools in the area, and other outreach activities including participation at regional shows (Figures 5 and 6).

The on-the-ground activities are clearly complimented by the engagement activities to provide additional research using the data and materials acquired. Many of the activities occur in parallel, and are essential components of any project that occurs within the community.



Figure 5: Linda Stalker (left) and Beth Ferguson (DMIRS) with an NGL vibroseis truck at the Brunswick Show in 2013.

## Community engagement and education

The on-the-ground activities, both seismic acquisition and well drilling could not have come about without significant support from the local community.

There are 125 landholders within the area identified for the large 3D Seismic Survey of whom 75 signed access agreements for the large scale 3D seismic survey conducted in 2014 (Figure 8). A specific community engagement program occurred over an 18-month period for the seismic acquisition program alone, and drew upon a number of industry standards, principles and guidelines. The land access negotiations by DMIRS were partly framed by their inability to provide any formal compensation. Technical aspects of the project were secondary to both community acceptance and meeting landholder requirements for access and were collectively and individually addressed. Along with environmental approvals and seasonal requirements, these aspects contributed to a 12-month deferral to the commencement of the 3D Seismic acquisition until February 2014.

During the activities, all contractors had a specialised induction and regular toolbox meetings to highlight the particular aspects of each of the landholders' situation and requirements. CCS researchers were made available to the community through a range of activities including a demonstration of the NGL vibroseis trucks along Riverdale Road as part of ANLEC R&D Project 7-1213-0223 and the Brunswick Show.

DMIRS conducts a proactive, but more importantly a reflexive and responsive approach to community engagement which played a large role in the ability to obtain permission from a majority of landholders' for access, either to allow trucks on site, or geophones to be laid out or both options (Ashworth, 2014: ANLEC R&D Project 7-0414-0227). The role of third party contractors to negotiate access continues to be particularly influential due to their demonstrable local knowledge and understanding of landholders' priorities.



Figure 6: CarbonKids Workshop at Leschenault Catholic Primary School.

An overview of the community engagement activities can be found in Burke et al, (2014) and Ashworth (2014: ANLEC R&D Project 7-0414-0227).

Within the community, additional engagement has come through CSIRO's *CarbonKids – Sustainable Futures Education Program*. A number of schools in the South West of WA including those in the Harvey and nearby Bunbury area have participated in a series of classroom visits and workshops (Figure 6). Groups of primary schools meet to learn about the carbon cycle from the perspective of agriculture, energy and CCS. This program is supported in WA by Bayer and DMIRS. The impact of this activity has included access to researchers by the schools to see firsthand Science Technology Engineering & Maths (STEM) applications to real world situations. The impact of this has been noted in a recent publication by Bloxsome et al (2017).

More broadly, there have been demonstrations of equipment at agricultural shows (Figure 5) and during data acquisition, the addition of equipment at a local school as part of the ANU 'Seismometers in Schools' program (<http://ausis.edu.au/>), one-on-one discussions with DMIRS staff and CCS Research experts, and regular communication with the Lesueur Community Consultative Committee (LCCC) established in 2011. Community engagement is a major component of the SW Hub project.

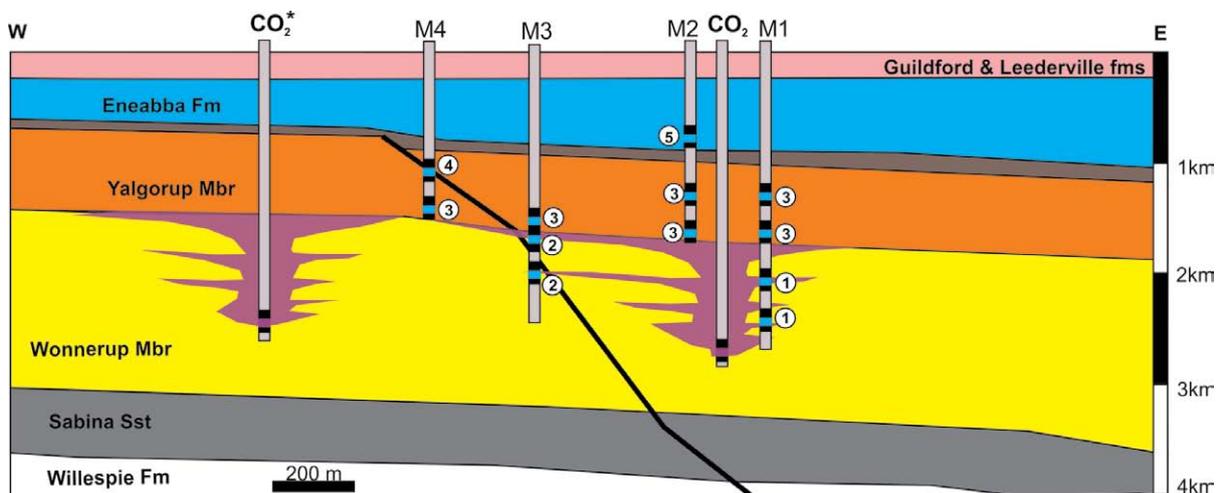
## Research contribution to specific data acquisition projects

Research support has also been added to many aspects of the project, in particular in preparation for the large 3D Seismic Survey in 2014 (the area highlighted in the green box in Figure 8). In this example, two projects provided design input, and reduced uncertainty for the survey, while demonstrating what a seismic survey can look like in advance of the major data acquisition phase:

- Conducting a test seismic acquisition along Riverdale Road December, 2013 as a part of project under ANLEC R&D Project 7-1213-0223 Harvey 2D Test Seismic Survey – Issues and Optimisations.
- Acquisition of the Nested 3D Seismic Survey to Determine Shallow Features at Harvey, in December 2014 under ANLEC R&D Project 7-1213-0224.

Similarly, in advance of the Shallow Well Drilling Program, the potential design and location of the wells were informed by a series of ANLEC R&D activities under Project 7-1012-0214 which included reports on:

- desktop Design Study for South West Hub Monitoring Wells (Figure 7); and
- data Acquisition & Research Requirements for SW Hub 2014 Drilling Campaign.



### Monitoring objectives

Monitor 1: Reservoir performance<sup>①</sup>  
Containment verification<sup>③</sup>

Monitor 3: Impact of fault on reservoir performance<sup>②</sup>  
Containment verification<sup>③</sup>

Monitor 2: Containment verification<sup>③</sup>  
Assurance monitoring<sup>⑤</sup>

Monitor 4: Containment verification<sup>③</sup>  
Containment verification along fault<sup>④</sup>

\*Second injector will require additional monitoring wells

Figure 7: Schematic design of potential well configurations for the SW Hub project to inform the Shallow Drilling Program. From Project 7-1012-0214; Table 1.

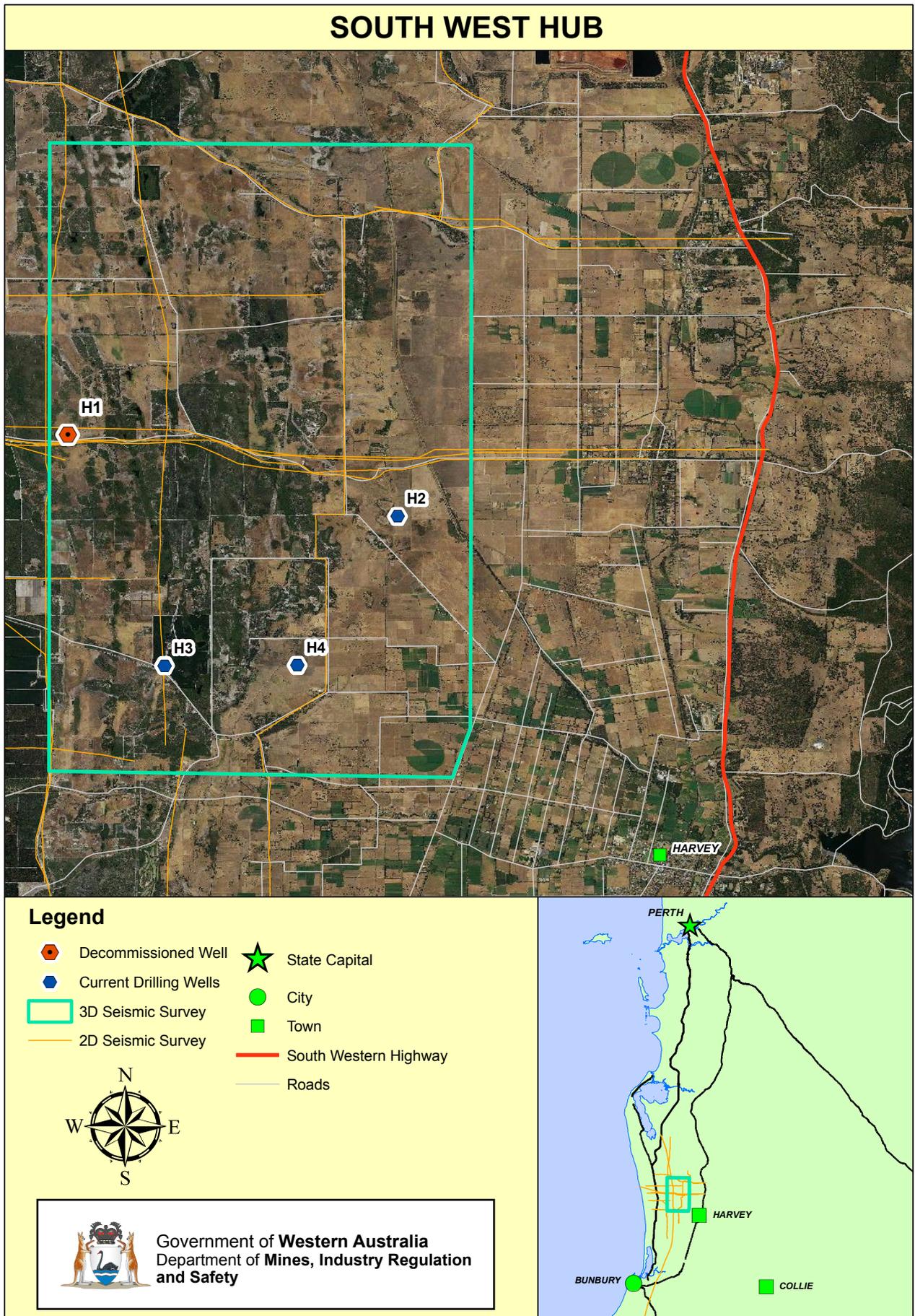


Figure 8: Location of the wells in the area of investigation and in the context of the region.

## Large scale 3D Seismic Survey

The surface activity with the largest impact to date has been the 3D Seismic Survey commissioned by DMIRS. While the on-the-ground activities occurred mostly between February and April of 2014, it came at the end of an extended period of consultation with landholders and significant community engagement. The consultation aided activities such as scouting, safety evaluations, environmental baseline monitoring, logistical/survey planning, permit acquisitions and determining the layout of equipment prior to conducting the actual survey.

The result of the negotiations was that access was provided by 60% of landholders impacted. Some of the key statistics associated with the survey are tabulated below.

Two of the significant outcomes of the 3D Seismic Survey are the:

1. high level of acceptance of the survey due to the manner in which the ground activities were conducted; and
2. high level of detailed data acquired for the storage interval over a wide area given the gaps in access and presence of inaccessible wetland areas.

The careful design of the large-scale 3D seismic survey resulted in a set of data that have been suitable to map the deeper sections of the area, with particular focus on the reservoir interval. The success with the landholder engagement allowed for over 80% of the Wonnepurup Member, the storage or reservoir interval, to become well characterised (Table 4).

The data collected has been used extensively by DMIRS and researchers to develop the geological model for the area, which is a critical component for any evaluation of resources in the subsurface. Projects have also been developed to conduct additional reprocessing and interpretation to provide robust geological models. Through activity funded by DMIRS, Odin Reservoir Consultants used the data gathered from the 3D survey and reports listed in Table 1, generate a static geological model for the SW Hub. Work conducted in projects 7-1213-0224, 7-0314-0231 and the currently underway project 7-0115-0241 have all utilised the large-scale 3D seismic survey data and additional data acquisition to improve the model. In some cases where there was uncertainty with the interpretation of the large-scale 3D seismic survey, the researchers involved in these projects contributed information and knowledge, which reduced uncertainty in the interpretation and made for a more realistic geological model.

### **Fold and methods to obtain seismic data**

The quality of the data is partly summarised in the 'fold' information. Typical 3D seismic data might have a fold of 10 to 120. Fold typically relates to the number of traces obtained for a given point and are related to the number of sources and receivers that are laid out on the ground. Sometimes it is not possible to obtain uniform access (e.g. the left hand side of this acquisition plan). Some areas may be unavailable due to land conditions (wetlands, surface infrastructure etc.). To compensate, additional sources can be laid out (e.g. top right of this image), which can compensate for the gap.

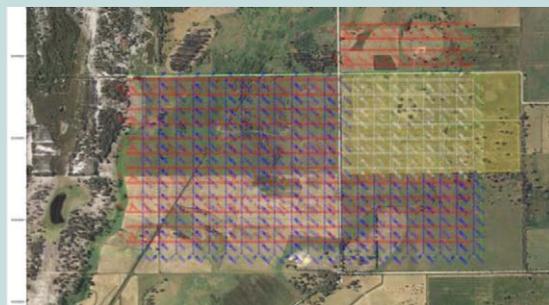


Table 4: Key parameters and measurements for the large 3D Seismic Survey in 2014.

| Parameter   | Observation/outcome                       |
|---|---|
| Landholders granting permission % (number)                  | 60% (75 of 125)                           |
| Properties granting permission % (number)                   | 63.5% (127 of 200 land parcels)           |
| Source/Receiver 3D Coverage                                 | 114.3km <sup>2</sup>                      |
| Number of receivers   | 8,000                                     |
| Source  | 2 fleets of 2 x 60,000lb AHV-IV Vibrators |
| Fold  | Up to 220 fold per sweep                  |
| Sweep length  | 12 seconds                                |
| Sweep frequency range                                       | 5 – 100 Hz                                |
| Base Leederville estimated seismic coverage (range of fold) | 60% (up to 109)                           |
| Top Yalgorup estimated seismic coverage (range of fold)     | 75% (up to 200)                           |
| Top Wonnerup estimated seismic coverage (range of fold)     | 85% (up to 278)                           |
| Base Wonnerup estimated seismic coverage (range of fold)    | 88% (up to 528)                           |

## Shallow well drilling program

More data was required to better characterise the area after the various seismic surveys and the single well drilled. Researchers were challenged with a project to investigate options for well designs in advance of DMIRS' next stage drilling program.

The project that conducted this evaluation was Desktop design study on South West Hub wells (ANLEC R&D project 7-1012-0214). The report resulting from this work considered what data acquisition would be required, the resultant research requirements, and a design study of the wells so that all well configuration scenarios and potential completions could be evaluated (Figure 7).

The information was used to define a drilling strategy, which was adapted to maximise geological coverage particularly across the shallower reservoirs. Three new wells DMP Harvey 2, 3 and 4 were to be drilled using a combination of mineral and water well drilling rigs with a deeper well to be considered following model and associated uncertainty management plan (UMP) updates. These wells would penetrate only the top 100-200+m of the Wonnerup Member as the DMIRS objective for this campaign was to focus on understanding the complex layering of sand and paleosol sequences and containment properties of shallower horizons within different fault blocks, prior to investigating injection potential of the target deep reservoir.

DMIRS developed a tender and evaluation process for commercial solutions to the well drilling program. Sufficient confidence developed that allowed for an innovative shallow well drilling program to be enacted, where these wells were expected to provide the following:

- Confirmation of the structure and stratigraphy over a wider area.
- Potential for gaining additional data (wireline logs).
- New core materials in different locations.
- Integration of the geological and geophysical information in the region.

Recommendations regarding data acquisition and associated drilling requirements for the proposed Shallow Drilling Program were proposed, in part leveraging from reviews of other case study examples. In an attempt to gain more information about some of the formations encountered in Harvey 1, it was critically important that the characteristics of the Yalgorup Member of the Lesueur Formation were better characterised. Few samples of the more shale-rich sections of the Yalgorup were able to be analysed as they were poorly consolidated and did not have sufficient integrity for the full range of analyses. Therefore it was important in the new drilling program to obtain samples from the Yalgorup Unit where the following could be measured:

- Petrophysical and mechanical (how strong the rock is) properties.
- Hydraulic capacity of the Yalgorup to serve as a potential barrier to vertical fluid movement (CO<sub>2</sub> or formation water).
- Areal extent and thickness distribution of the Yalgorup rocks over the region.
- General characteristics of the in situ fluids present, for example the formation fluid salinity and chemistry and how they might impact on storage of CO<sub>2</sub>.

Furthermore, the process can provide an opportunity to 'predict' what the wells might encounter and compare those predictions with the observations made. This enables the project to test hypotheses and prognosed geological models before confirmation with hard data. This was partly addressed in Projects 7-0411-0129 and 7-0212-0202 where researchers used some of the early data from the 2D seismic acquisition in 2011 to predict which attributes such as grain size, porosity or permeability might be present at Harvey 1 (Figure 9). The new drilling and data acquisition allowed for further predictive work to be undertaken and confirmed when the new results came in and enables better calibration of models. The innovative

### Paleosols

A paleosol (or palaeosol) is in short a 'fossilised soil horizon'. At the time of formation the soil may have been exposed to the earth's surface for a prolonged period and may have dried and hardened to become lithified (rock-like). This happens when there is a long period of non-deposition, that is when there is no mountain-building or erosion generating materials that would deposit over the soil. Only later has the soil horizon been buried intact and formed part of the Yalgorup Member of the Lesueur Formation. As the soils have developed from overbank deposits along rivers, the paleosols may not be continuous.

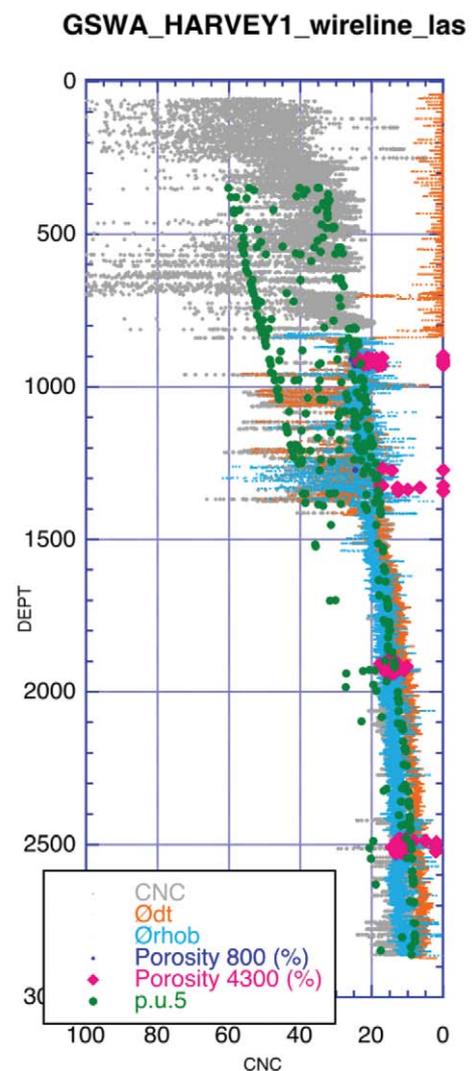


Figure 9: Example of prediction of subsurface properties, in this case porosity, as generated by sedimentary forward modelling (SEDSIM) to predict behaviours. From Project 7-0411-0129 (Table 1).

approach to different modelling methods, rather than simply using oil and gas industry standard opens up a number of different ways in which to de-risk or better predict rock properties in greenfield sites where there is little in the way of pre-existing data.

A series of generic well configurations were tabled along with their relative pros and cons. It is important to note that while information from other projects can provide valuable insight and learnings, local context, especially availability of industry standard equipment and other background such as previous experience drilling in WA, provides some specific constraints that have to be managed as well.

With this background, DMIRS engaged contractors to drill the Harvey 2, 3 and 4 wells. Well designs and completions for these wells are shown in Figures 12a, 12b and 12c and include information on where the wells encountered each of the major horizons, the width of each well (important to know to add monitoring instrumentation), and materials used to case the well (typically chrome steel is used as it is corrosion resistant to CO<sub>2</sub>).

The three new wells all encountered the top few hundred metres of the Wonnerup Member, the sand-rich storage interval. Evaluations of this uppermost part of the section are underway to better understand the regional burial and diagenetic history in the different fault blocks penetrated by each well (Figure 10).

Harvey 2 and Harvey 3 were both drilled using what is conventionally regarded as a 'mineral rig', a type of rig that allows shallow drilling to approximately 1500m, with the added advantage of bringing all the cored rock to surface. Harvey 4 was drilled by a rig typically used in the water industry to go to depths of up to 1800m, but can only retrieve discrete intervals of core, generally of the order of a few tens of metres.

Overall a total of 2136m core was recovered from Harvey 2 (1142m); from Harvey 3 (966m); and from Harvey 4 (28m) and these materials are being held at the GSWA Core Library in Perth (Figure 11). It is from there that researchers and consultant services have been viewing the core and taking samples for further analysis. Together with the wireline log data from the well bores, the core samples provide a large volume of information that is being integrated within a range of research projects that are underway or have recently been completed.

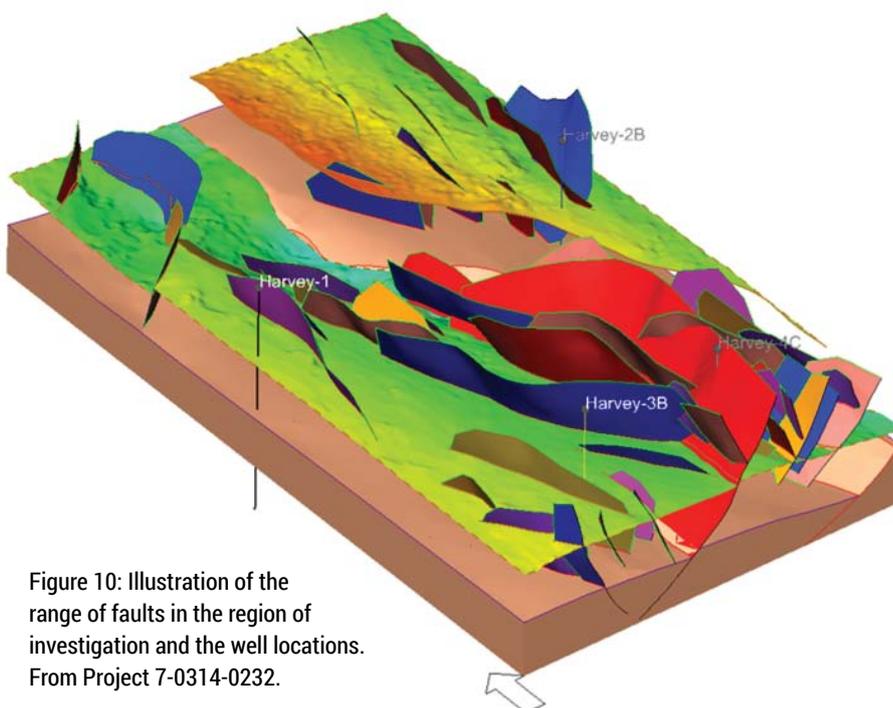


Figure 10: Illustration of the range of faults in the region of investigation and the well locations. From Project 7-0314-0232.



Figure 11: Core material from the shallow wells.

Table 5: Well parameters for the shallow wells drilled at SW Hub.

| Item                      | Harvey 2  | Harvey 3   | Harvey 4   |
|---------------------------|---|--|--|
| <b>Diameter core</b>      | PQ (85mm/3.3") to 1234m<br>HQ (63.5mm/2.5") to 1350m  | SQ (120mm/4.7") to 1461m<br>HQ (63.5mm/2.5") to 1550m  | SQ (120mm/4.7")<br>893.0–898.3m<br>898.4–908.4m<br>1325.5–1326.6m<br>1665.1–1666.7m<br>1793–1802m  |
| <b>Total cored</b>        | 1142.5m   | 966m   | 26.4 m   |
| <b>Total Depth (TD)</b>   | 1350.2m<br>106m into Wonnerup   | 1550m<br>132m into Wonnerup  | 1802.6m<br>223.6m into Wonnerup  |
| <b>Drilling method</b>    | Continuous core diamond mineral rig   | Continuous core diamond mineral rig  | Rotary water rig   |
| <b>Electrical Logging</b> | Resistivity-Neutron-Density-Dipole Sonic – GR-Calliper<br>Vertical Seismic Profile – Zero Offset and Offset to tie into seismic | Resistivity-Neutron-Density-Dipole Sonic – GR-Calliper<br>Vertical Seismic Profile – Zero Offset and Offset to tie into seismic<br>Formation Tester (HSFT) | Resistivity-Neutron-Density-Dipole Sonic – GR-CAL<br>Elec. Imager with multi-arm / pad CAL<br>MDT (pressures and samples), stress tests<br>NMR, SGR, Baseline RST<br>Vertical Seismic Profile – Zero Offset and Offset to tie into seismic |
| <b>Completion</b>         | Carbon steel to 419m<br>Cement plug, packer & backfill  | Carbon steel (114.3mm/4.5") to 1131m<br>CO <sub>2</sub> resistant chrome-steel (114.3mm/4.5") to 1461m   | Carbon steel (114.3mm/4.5") to 1470m<br>CO <sub>2</sub> resistant chrome-steel to 1796m  |
| <b>Coring</b>             | 250m to TD – 1200m of Core  | 250m to TD – 1200m of Core   | Interval (3 x 10m sections)  |
| <b>Final Status</b>       | Suspension – potential for ongoing M&V  | Potential for M&V, and future testing  | Potential for M&V, and future testing  |

# DMP HARVEY 2

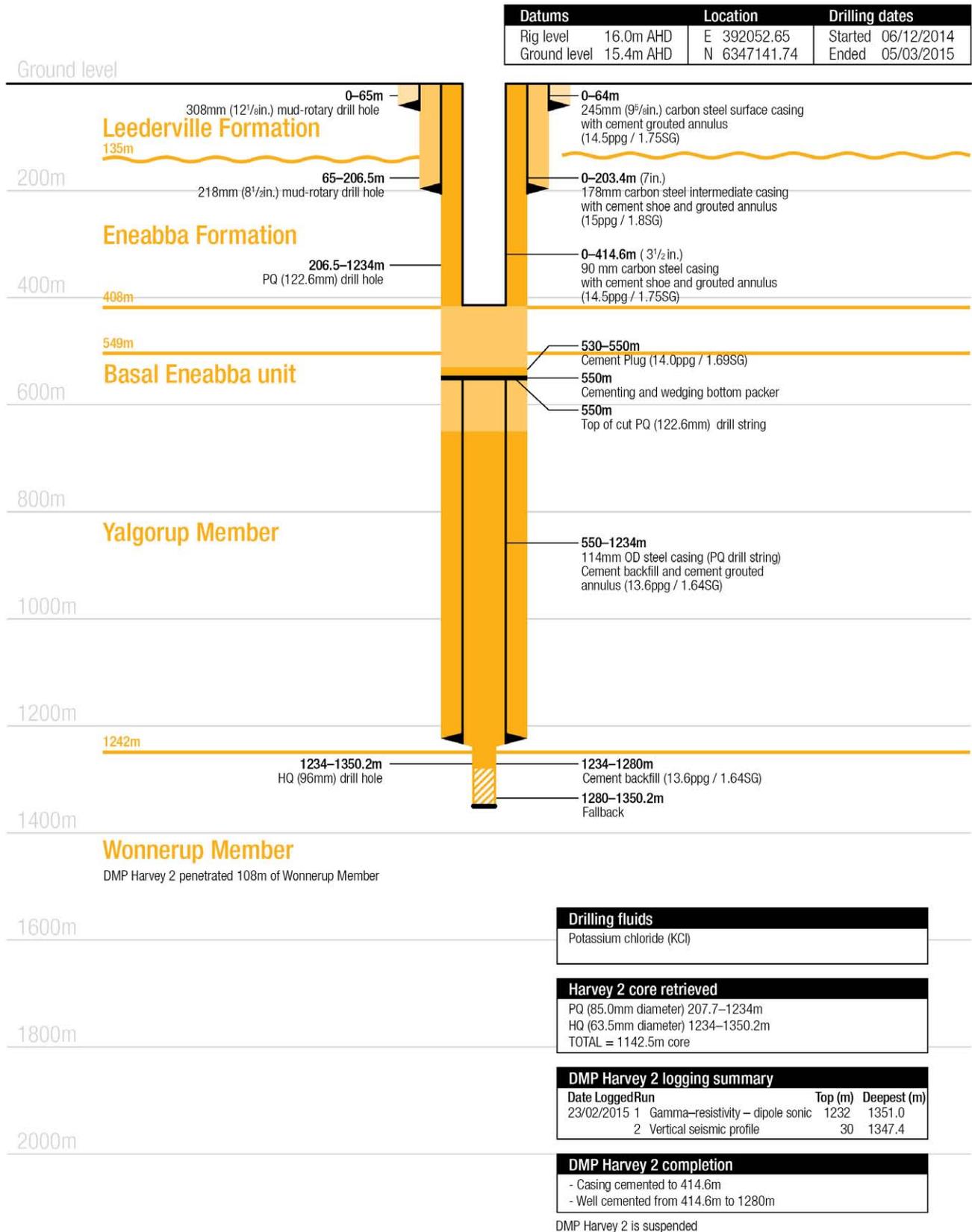


Figure 12a: Shallow well design, depths and core recovered (DMIRS).

# DMP HARVEY 3

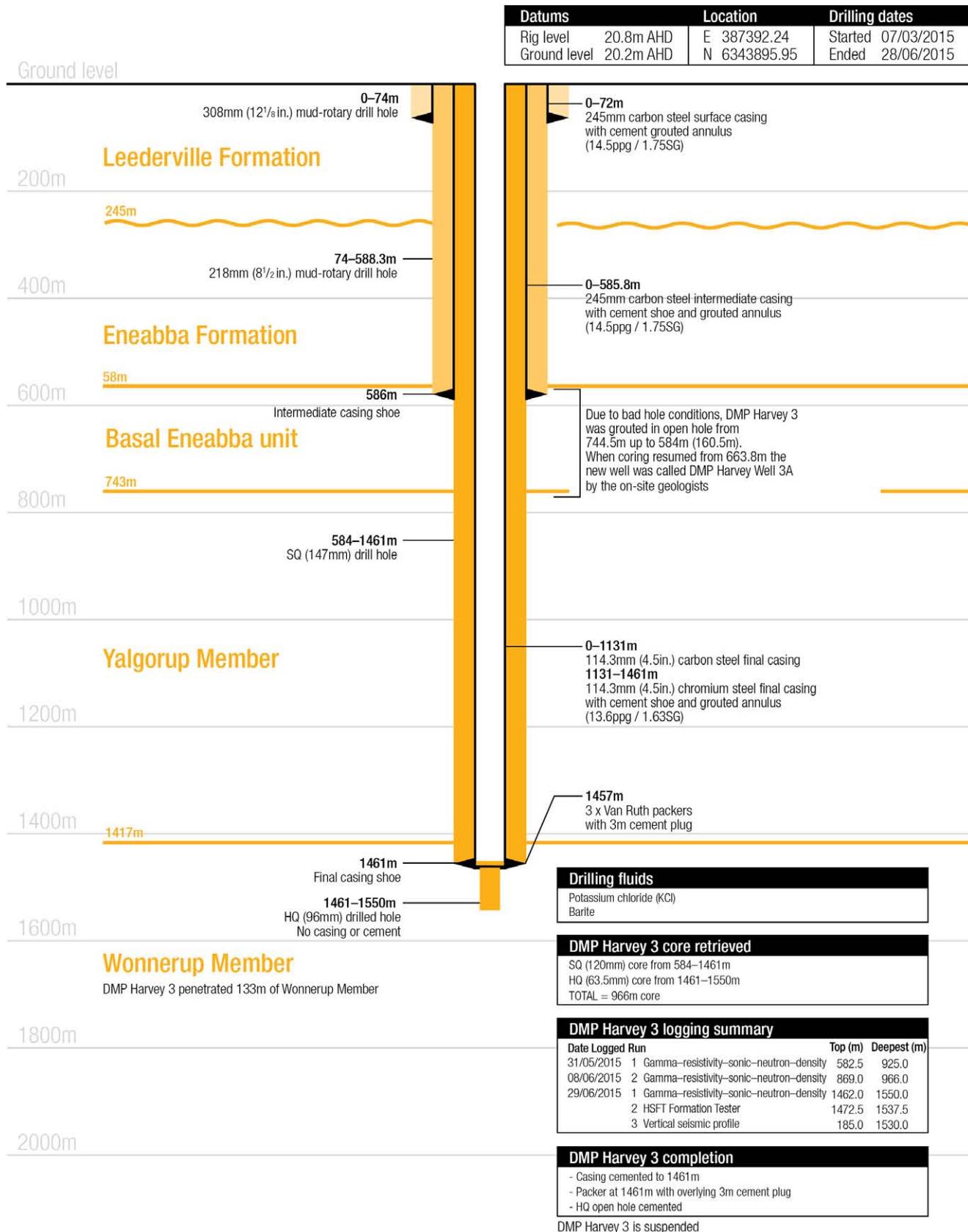


Figure 12b: Shallow well design, depths and core recovered (DMIRS).

# DMP HARVEY 4

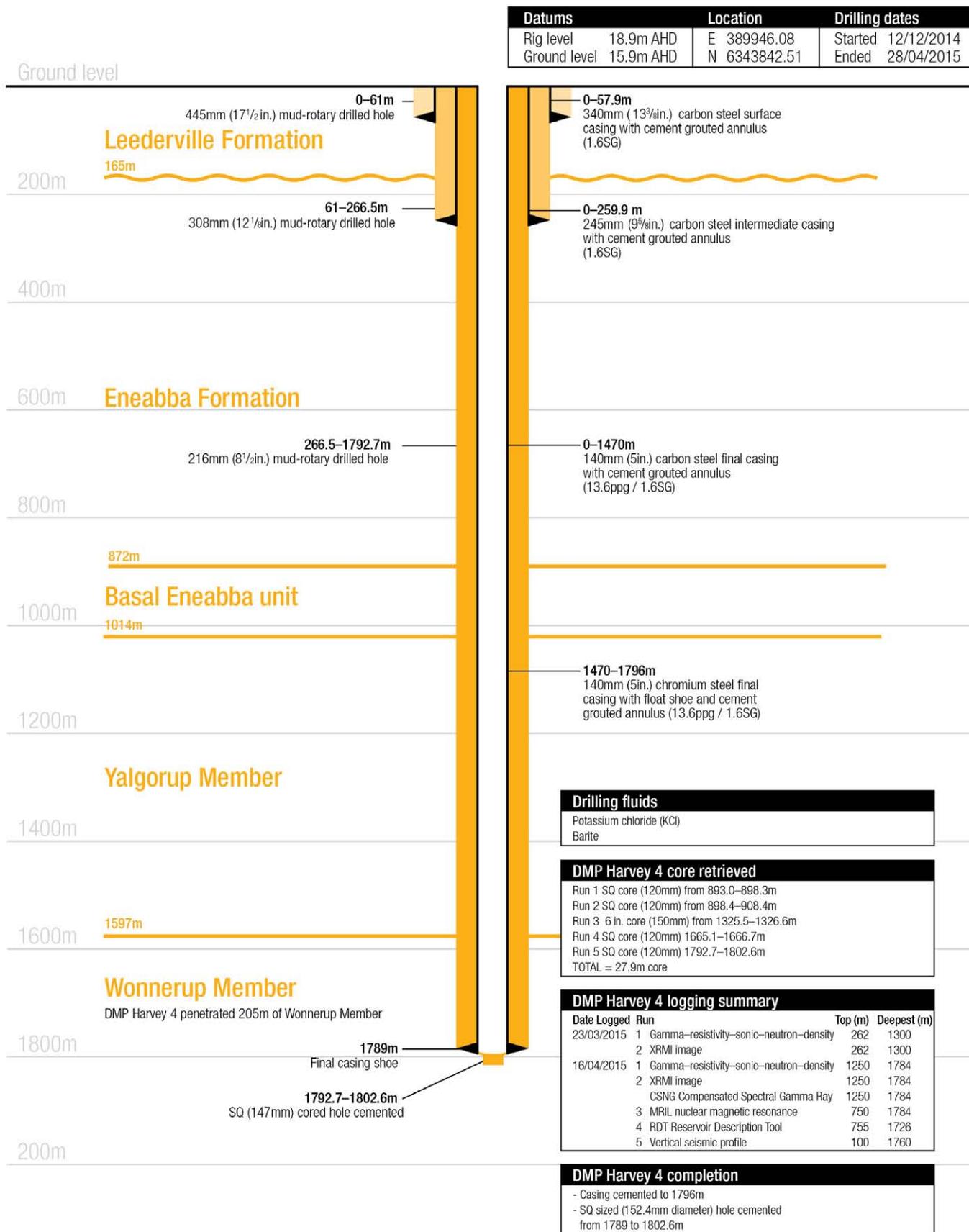


Figure 12c: Shallow well design, depths and core recovered (DMIRS).

# New data, samples and knowledge

The overarching purpose of the current data acquisition program is to continue to reduce risk and uncertainty with respect to the overall site characterisation at the SW Hub CCS Project. The parallel research projects are developed and executed to provide a better understanding for government, research and industry of the storage capacity, containment security and injectivity potential at this site. The data acquisition program discussed here relates to both the 3D Seismic Survey conducted in 2014 as well as the Shallow drilling program conducted over late 2014 into 2015. The graphical illustration (Figure 3) shows how the research projects parallel DMIRS on-the-ground data acquisition program.

## How the data is used to reduce uncertainty

As the SW Hub project has evolved, a running register of uncertainties has been maintained by DMIRS to focus the research and influence the types of data acquisition. An example of some of the uncertainties and approaches to addressing them is presented in Table 3. These primarily fall under the criteria of storage capacity, containment security and injectivity. The wells, as described above, provided abundant core material to test and conduct measurements on, and provided extensive wireline logging information that could be applied to both the measured rock properties and the seismic survey data.

The range of research projects described in Table 1 and Table 2 contribute to the collection and analysis of the uncertainties going forward. Some examples of how this information is improved is illustrated in the following examples of targeted research supporting the project.

### Site characterisation

**Storage capacity** – defining the amount of CO<sub>2</sub> which can be stored at a given geological location. This is often within a specific layer of rock. In the case of the SW Hub, the sandy Wonnerup Member of the Lesueur Formation is the storage interval.

**Containment security** – evaluating the geology to determine whether the CO<sub>2</sub> will be confined to the zone in which it is injected, and not migrate out of that storage interval. This requires a good understanding of the structure of the rock formations including any faults in the area, which could act as conduits for the CO<sub>2</sub> to migrate upwards out of containment.

**Injectivity** – estimating the rate at which CO<sub>2</sub> can be injected into the subsurface and migrate away from the injection point into the storage interval while keeping injection pressures below fracture pressure for the rocks. Factors that affect this include rock properties, the number of wells drilled and how much of those wells are open to the formation to dissipate the CO<sub>2</sub>.

## Seismic investigations and faulting

A high resolution 'Nested 3D Seismic Survey' (an additional detailed survey within an already surveyed area) was conducted as part of project 7-1213-0224 to both complement the large scale 3D seismic survey conducted by DMIRS completed in 2014. The 3D survey was designed to characterise the deep primary storage unit (i.e. Wonnerup Member) and main structural features in the area. In doing so, overlying strata were less well imaged, in particular the Yalgorup and any structures penetrating those upper layers. The high-resolution seismic acquisition capabilities of the NGL's UNIVIB trucks were used to better define the shallower intervals overlying the storage unit, and to resolve shallow structural features to help identify any potential risks to containment.

The small-scale 3D survey was performed in December 2014 near the location of the Harvey 4 well, and was nested within the region of the larger 3D. The nested survey used more than 2300 geophones (both 2D and 3D component) and was deployed in an array along 21 receiver lines. An eight-person crew performed the survey that took 11 days from mobilisation to demobilisation that included five active days of data acquisition. Almost 1600 seismic source points were acquired during the survey. Post-processing results imaged a fault that Harvey 4 had intersected, but which had not previously been observed by interpretation of the commercial survey (Figure 13).

The study suggests that nested 3D surveys are likely to be valuable to any project where subsurface data must be optimised such as for carbon geosequestration sites. For the SW Hub project, this work has led to a much-improved understanding of aspects of the structural geology and local faulting. Additional nested 3D surveys are being considered for other locations, such as near Harvey 3, as part of the SW Hub characterisation effort. Commercial scale 3D data, nested 3D data, and other information such as petrophysical well log data, VSPs (vertical seismic profiles), and core analyses all provide complementary information that leads to reduced uncertainty around subsurface characteristics and can be interrogated discretely and as a package to reduce uncertainty around the development of the geological models that are used during the process of site characterisation and assessment.

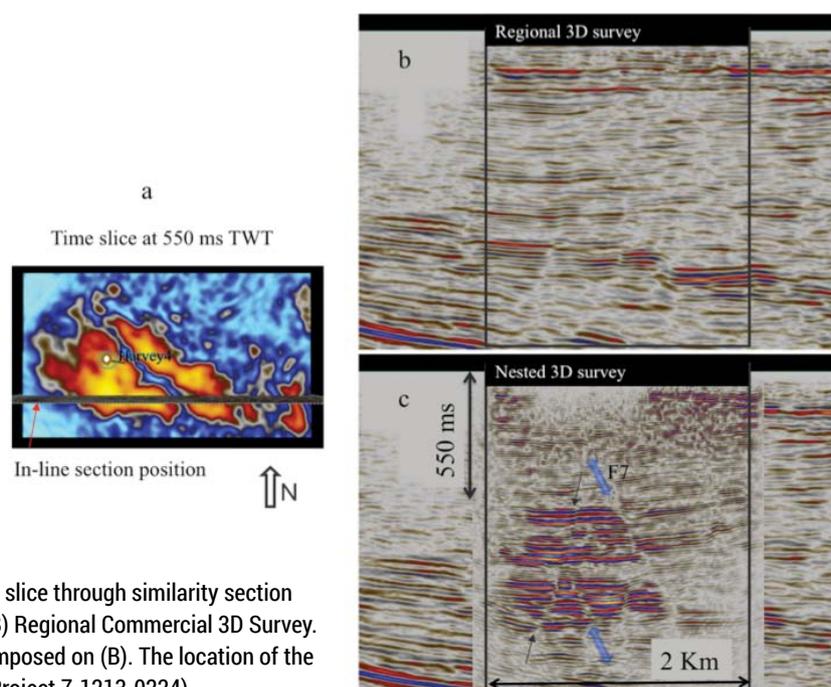


Figure 13: 3D survey comparison: (A) Time slice through similarity section showing fault expression near Harvey 4. (B) Regional Commercial 3D Survey. (C) Nested 3D Survey (PSTM Cube) superimposed on (B). The location of the inline section is the grey line in (A). From Project 7-1213-0224).

## Geological modelling

Geological models, or geo-cellular volumes, are one of the standard industry methods and tools used to predict and model the characteristics of a reservoir. Static geological models usually contain details about the interpreted regional depositional environments (for example braided fluvial systems) from core analyses and well data. Additionally, parameters such as porosity and permeability are distributed throughout the model according to the spatial variability typically associated with that environment or from inversion of seismic information. Numerous models are built during the lifetime of a project, and may begin with some very limited field data (as in the case of stratigraphic forward modelling approaches, to detailed, high resolution and dynamic models).

Because of the initial limited well and seismic data in the SW Hub area, the need to study the utility of forward stratigraphic modelling was conducted in two phases:

1. The construction of a static, cellular geological model for the area using SEDSIM® stratigraphic forward modelling software (7-0411-0129; Table 1).
2. Use this model as the basis for dynamic flow simulation and contrast the results with those obtained using a conventionally derived static model (7-0212-0202; Table 1).

A simulation test of CO<sub>2</sub> injection used Eclipse 300 software, this was compared to a previous simulation performed by Schlumberger, based on a static model constructed using well data and geostatistical distribution of reservoir properties. Using un-faulted models, both methods predicted 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 using SEDSIM input spreads more than the conventional model (Figure 14). While there were some issues transferring models between different software types, 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 early insights into dynamic models for CO<sub>2</sub> sequestration at the site.

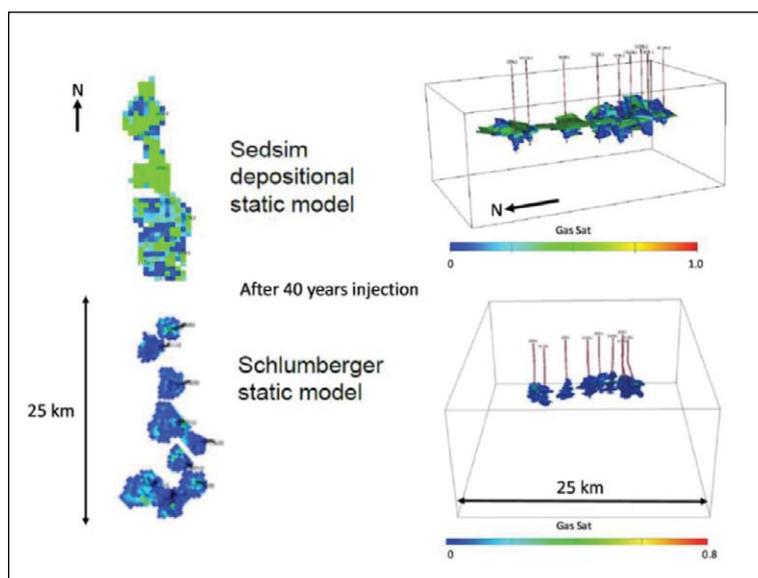


Figure 14: Comparison of dynamic simulation results of CO<sub>2</sub> plumes after 40 years using the SEDSIM un-faulted depositional static model and conventional static model 7-0212-0202; Table 1.

## Changing scale of observations and models – fluid rock interactions

Where static and dynamic modelling are usually performed to provide an understanding of large-scale processes, experimental methods are also needed to understand finer-scale phenomenon and constrain and define the parameters used by the modellers for their simulations. These processes could be physical or chemical changes.

A range of data and samples were investigated and used in a series of novel experiments (project 7-0314-0233 – Table 1) to measure the impact of injecting CO<sub>2</sub> on the minerals present in the storage interval at a range of depths. A series of steps to measure changes in the rock properties before and after injecting CO<sub>2</sub> in the laboratory have helped the researchers and SW Hub project to understand what might happen to the rocks and their properties during injection and to see if any changes in permeability resulted from:

- fines migration in which clay platelets or other minute mineral particles are mobilised and block access to pores reducing permeability; or
- mineral precipitation or dissolution; minerals may dissolve or grow in pores changing their geometry or blocking them partially or completely.

Porosity (the amount of space between the rock grains) and permeability (the connectedness of the spaces between the grains) are critical parameters to describing how CO<sub>2</sub> might flow through the storage interval. These parameters have been measured in samples from the storage interval (Wonnerup Member) both before being flooded with CO<sub>2</sub> in the laboratory and after. Figure 15 shows examples of results that indicate that sometimes there is a reduction of permeability, meaning that over time, it may get harder for the CO<sub>2</sub> to be pushed into and through the formation, making the process slower, more energy intensive and less economic (may require more injection wells to achieve the rates required by the owner of the CO<sub>2</sub>). In other samples, the permeability increased (improved). An example showing increased permeability is presented in Figure 16.

The investigation recognised that there were likely to be changes caused by altering the chemistry of the formation fluid, resulting in the dissolution of minerals, increasing permeability and porosity, or the opposite: precipitation of new mineral species such as calcite (calcium carbonate) that was increasingly blocking the pore space. Alternatively, the injection process could disturb particulates of clays or other minerals, pushing fine materials (fines) through the permeable conduits between the pores, and blocking the pore throats, locking off some of the permeability pathways.

Experimental and investigative methods (and equipment) to better understand the processes involved and their relative contributions included the following:

- Scanning electron microscopy (SEM; Figure 16)
- Nuclear magnetic resonance (NMR)
- X-ray diffraction (XRD)
- Mineralogical and petrological characterisation
- Measurements of porosity and permeability
- Medical CT
- Micro CT
- Core flooding of samples with CO<sub>2</sub>
- Chemical analysis of formation fluids and core flood effluents by inductively coupled plasma mass spectrometry (ICP MS)
- Ion chromatography
- Geochemical modelling methods.

The results demonstrated that for certain rock types (typically those buried deeper and more cemented by mineral precipitation; Harvey 1 samples) were more prone to being clogged by fines, while shallower, less cemented samples (like those shown for Harvey 3) tended to become more open as the particulates and fines were swept away through larger pore spaces. Quantitative analyses of the chemical changes have indicated that while there is some precipitation and some dissolution, chemical changes make up less than 0.03% of any changes observed and could be discounted as a major process for the SW Hub storage interval. Measurements were still sufficient to show that quartz and K-feldspar grains are fairly stable throughout the experiment, while the amount of kaolinite (a clay) decreased. By contrast, an increase in calcite content may have come from the precipitation of calcium carbonate, where the CO<sub>2</sub> can contribute to the formation of this mineral (Figure 17).

Ultimately, the project gives a better idea of the range of porosity and permeability characteristics that might be encountered at the study site, and that this information can be used to constrain models that are developed in the future to predict the movement and behaviour of CO<sub>2</sub>. Ongoing work is now being conducted to better predict which zones are likely to suffer from reduced permeability, and which zones might be preferred for injection in the future.

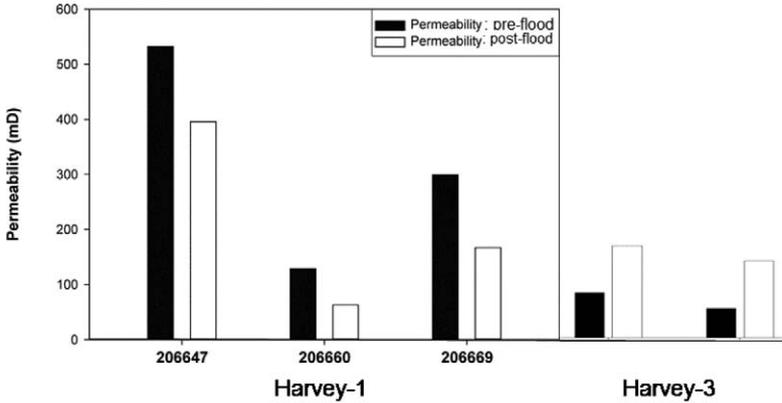


Figure 15: Change in permeability after flooding core samples with CO<sub>2</sub> and CO<sub>2</sub> saturated brine to mimic subsurface processes. From Project 7-0314-0233; Table 1.

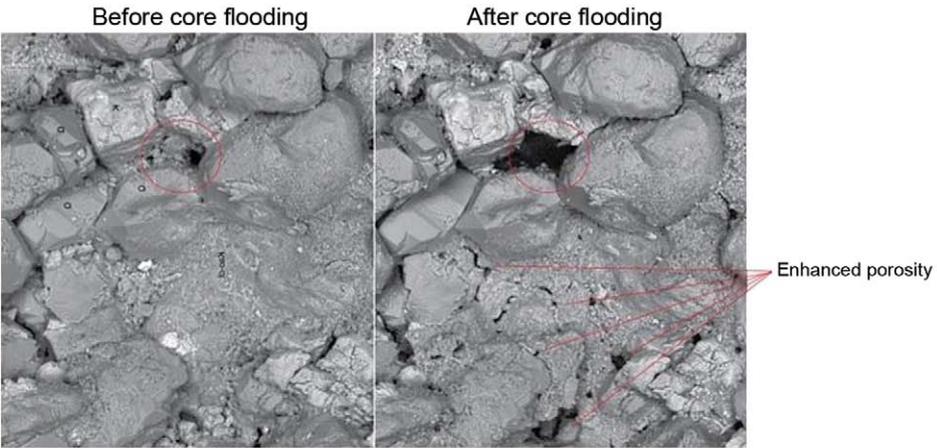


Figure 16: Scanning electron microscope (SEM) images of Lesueur Sandstone before being subjected to core flooding in the laboratory, and after. Note that there are larger spaces for the CO<sub>2</sub> to pass through the rock. The sample is from Harvey 3 1495m deep. From Project 7-0314-0233; Table 1.

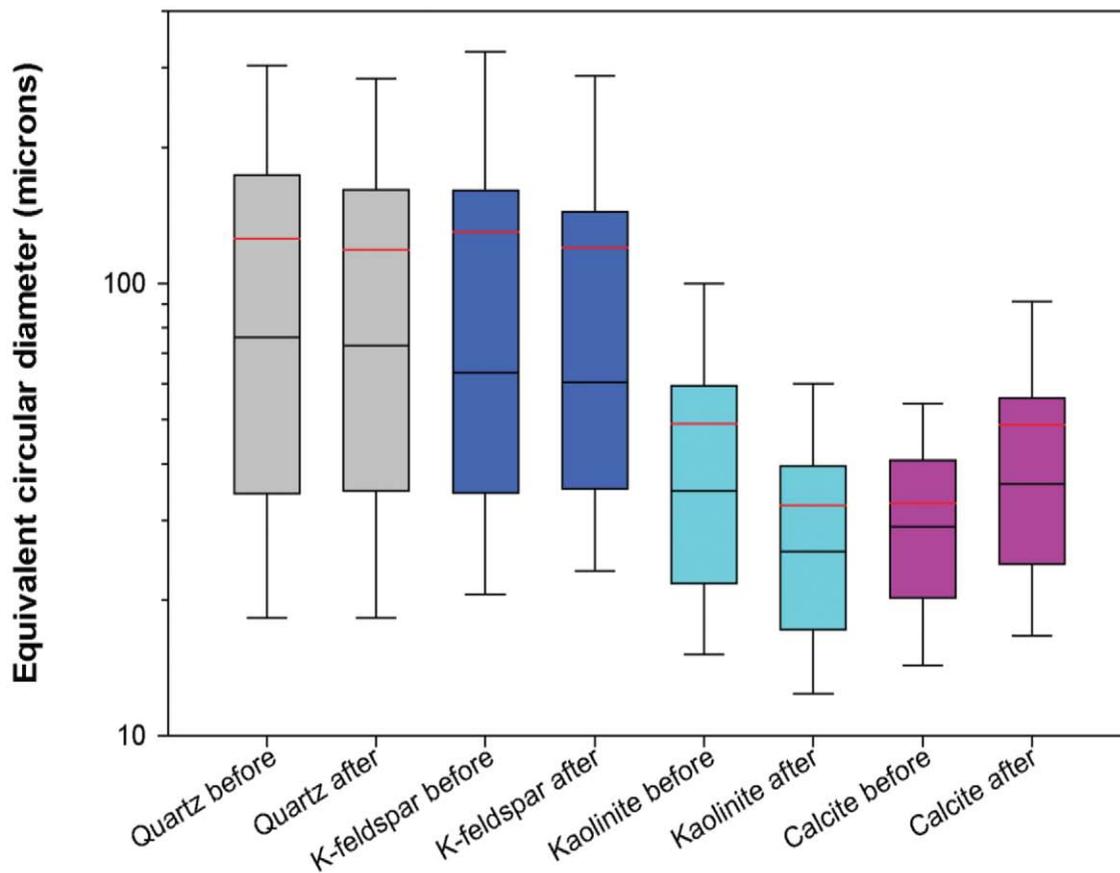


Figure 17: A box plot to show how the mineral content of the rock samples changes after flooding the rock with CO<sub>2</sub> in the laboratory. Quartz and K-feldspar remain stable, while the amount of kaolinite decreases and calcite increases. From Project 7-0314-0233; Table 1.

## Integrated research projects

The need to interrogate and interpret the abundant newly acquired data from both the seismic surveys and new wells, has led to the design of several large integrated science investigations.

### Geological integration

A geological integration program (7-0115-0240: Table 2) is building on the foundation work from 7-1111-0199 (Table 1) to update the geological understanding of the depositional environments of the Lesueur Formation and the characteristics of the storage interval. Some of the larger ambiguities being addressed by this study include investigating the diagenetic history of the Lesueur Formation. In doing so, we are able to determine and predict the extent that diagenetic processes may have impacted injectivity and storage potential of the site, and better constrain storage capacity estimations. This workflow involves understanding the current and past nature of formation fluids and other basin-derived fluids that may have been in contact with the reservoir, which may help identify whether compartmentalization was present and if faults acted as conduits or barriers to fluid movement. Projects 7-1215-0262 and 7-1215-0236 both contribute to this knowledge generation for the project and for the overarching static and dynamic models that have been developed by Odin Reservoir Consultants for DMIRS, and which are discussed in the following paragraphs.

The Shallow Well Drilling Program has provided critical new information to help define containment potential of strata, including the Yalgorup Member and overlying Eneabba Formation. There is still considerable work needed to understand the extent and barrier potential of the paleosols and other shaly units in the Yalgorup Member that will require improving stratigraphic correlation among the wells including Harvey 1, facies analyses, integration with seismic data, and depositional modelling.

The new core material will also enable this research to more thoroughly examine the geomechanical properties of the storage complex. It will attempt to develop an experimental protocol aimed at improving the determination of breakthrough pressure for supercritical CO<sub>2</sub> in clay-rich rocks – as currently there is no standardised methodology for this type of measurement. These analyses will be enabled by accessing new analytical equipment through the NGL. The investigation overall will be conducted through four integrated modules:

Diagenesis, fluid inclusion, and fault analysis that will involve petrography, microstructure, mineralogy and diagenetic analyses of core plug samples using optical and scanning electron microscopy, and fluid inclusion study using microthermometry and Raman spectroscopy.

Petrophysical core plug characterisation comprising a variety of non-destructive routine (RCAL) and special core analysis (SCAL) for use in subsequent modules and other research.

Geomechanical-acoustic core plug characterisation to improve the interpretation of seismic data for property distribution in geological models.

A feasibility study to develop an experimental protocol to measure the supercritical CO<sub>2</sub> breakthrough pressure in clay-rich strata.

### **Geophysical integration**

The integration of geophysical data with borehole data is the focus of another large integrated program (7-0115-0241) that follows on from the advanced processing work conducted in Project 7-0314-0231. In the study area there is uncertainty around physical rock property data, and integrating both the geophysical rock properties from core and well log data with the seismic data can calibrate the different types of information to enable a better overall interpretation of seismic data to generate new geological maps and models. By combining the different types of data, and doing a range of experimental measurements, the large scale 3D seismic survey has led to the development of robust structural maps and fault delineation over the Lower Wonnerup. While the survey was well tuned to focus on that deeper horizon, the definition of structural features within the shallower strata have been less well-defined. The shallower intervals are more relevant to understanding containment security or migration potential, with respect to the location of faults which could act as conduits for CO<sub>2</sub> movement.

The integrated geophysical research project (7-0115-0241) targets information gaps, and helps improve the data in the geological and reservoir models. The gap analysis is achieved by utilising all available 3D surface seismic data, Vertical Seismic Profile data from Harvey 1, 2, 3 and 4, well log data, as well as the results of core analyses from the geological integration program described above.

The seismic data is also being reprocessed to preserve key structural features using a variety of data sources. As noted earlier, some of the 3D seismic is sparse in some areas, so other techniques will be employed to determine a range of values for reservoir properties such as net-to-gross (NTG) and porosities will be estimated using velocity/porosity correlations derived from well logs.

Electromagnetic data will be investigated by acquiring a Magneto-Telluric geophysical survey in the Harvey area to further constrain the interpretations from the more conventional seismic methods. As a result, the project will expect to derive porosity estimates for reservoir models, constrained by all available geophysical information, core and log analysis, as well as improved understanding of regional stress field.

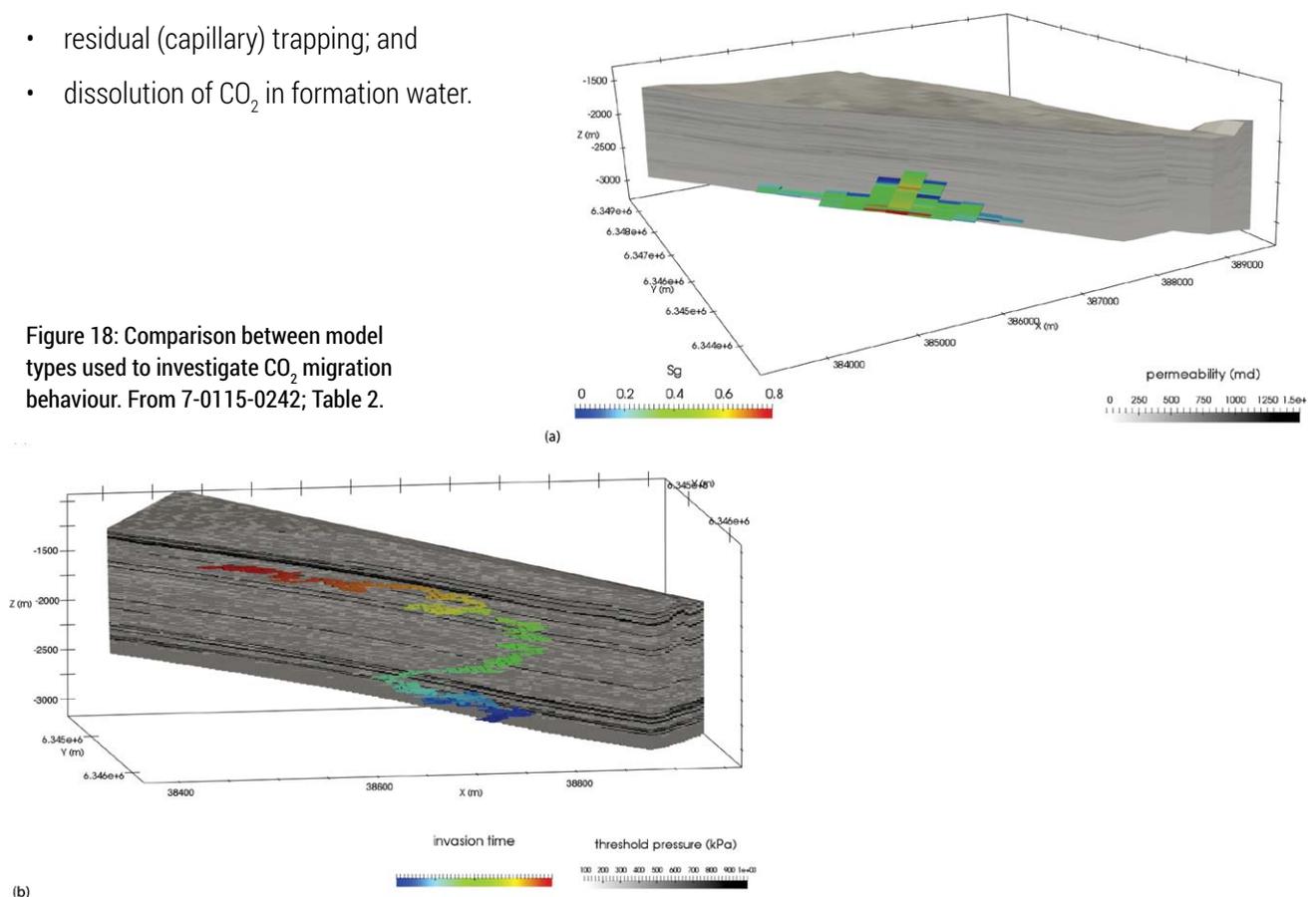
### Modelling vertical connectivity

The integrated Geology and Geophysical Programs are targeting methods to reduce uncertainty around the spatial distribution of rock units and their properties to help predict storage and reservoir performance. Dynamic simulation based around this information provides another means to test storage concepts for the SW Hub site. Project 7-0115-0242 (Table 2) is designed to simulate residual trapping and vertical sweep efficiency within the Wonnerup storage interval and overlying Yalgorup member, using a range of simulation methods to examine the influence that internal barriers may have on CO<sub>2</sub> migration (Figure 18). The left image shows how conventional modelling software such as TOUGH2 generates a 'bubble' like distribution of CO<sub>2</sub> as it buoyantly migrates upwards through the reservoir interval over a 500 year period, based on Darcy flow calculations. By contrast, invasion percolation modelling, where capillary entry pressures are modelled (Figure 18 right) is used to determine flow pathways. Reconciling how these two approaches work in CO<sub>2</sub> migration simulations is critical to overall understanding of the behaviour of CO<sub>2</sub> post-injection. These simulation activities can also provide information around options for configuring well-tests to enable in-situ well measurements of parameters that are useful for validation of models of the movement of the injected CO<sub>2</sub>.

The current concept of containment within the Lesueur Formation relies largely on a multi-barrier trapping system in the almost 1500m thick Wonnerup Member reservoir interval and the almost 700m thick overlying Yalgorup Member. Components of the system include:

- low-permeability intraformational seals or baffles;
- residual (capillary) trapping; and
- dissolution of CO<sub>2</sub> in formation water.

Figure 18: Comparison between model types used to investigate CO<sub>2</sub> migration behaviour. From 7-0115-0242; Table 2.



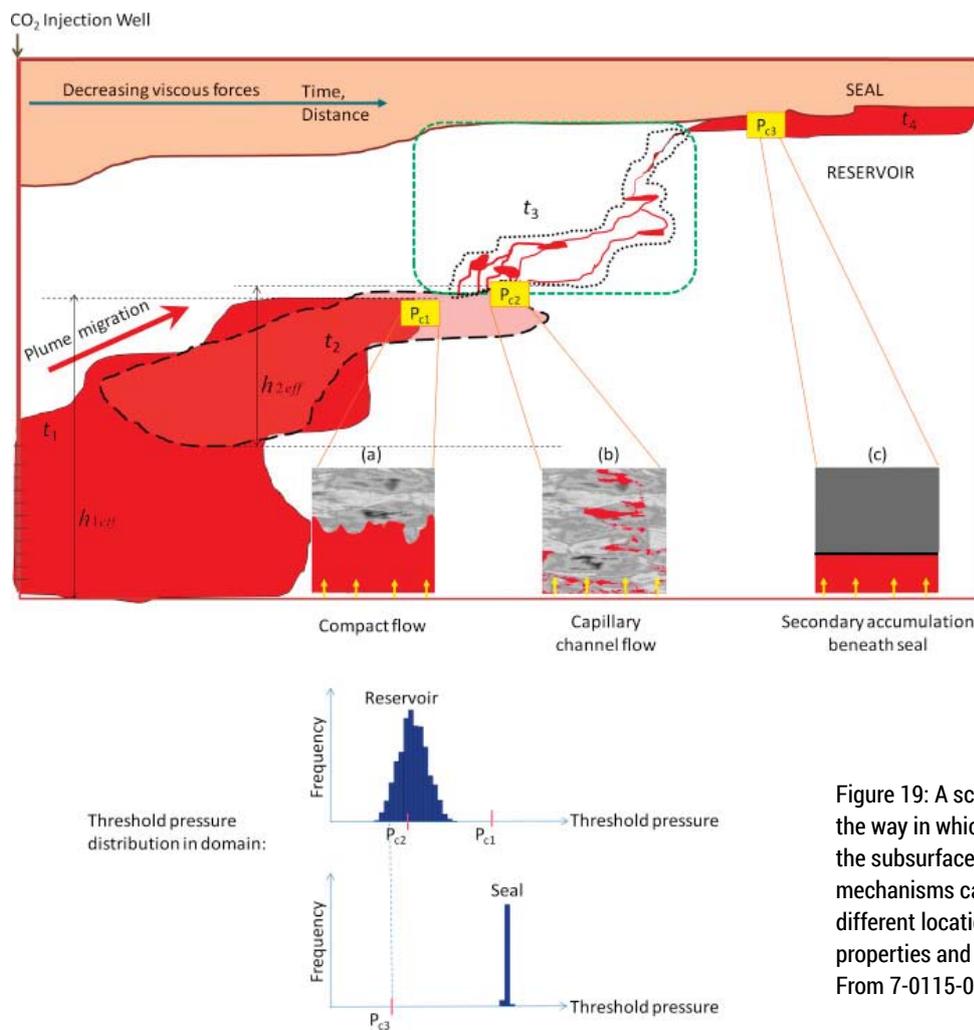


Figure 19: A schematic diagram showing the way in which CO<sub>2</sub> may migrate through the subsurface. The range in migration mechanisms can occur simultaneously at different locations, depending on the rock properties and volume of CO<sub>2</sub>. From 7-0115-0242.

Modelling the vertical and horizontal migration of CO<sub>2</sub> injected into the lower Wonnepur Member using multiple methods such as Equations of State (EOS) and invasion percolation theory can help identify the effectiveness of these trapping mechanisms and test their sensitivities to a range of geological uncertainties. In this project, a concept was established where it is expected that CO<sub>2</sub> would initially move laterally outward from the injection well predominantly through Darcy-type viscous flow that can be modelled using conventional reservoir simulators such as TOUGH2. Away from the injector, CO<sub>2</sub> migration may become increasingly vertical and dominated by gravity and capillary forces; this migration behaviour can be more correctly modelled using an invasion percolation code that considers both viscosity behaviour with that of the velocity of fluid flow. Figure 19 shows a novel, combined approach that could be used to better simulate CO<sub>2</sub> migration in the future, by trying to estimate when there is a transition from Darcy-flow to percolation to give a better prediction of the long term movement of CO<sub>2</sub>. The results of the project suggest that near the wellbore (Figure 19) left-hand side the main mechanism of movement for the CO<sub>2</sub> is 'compact' flow as modelled by Darcy-flow models, but as the CO<sub>2</sub> becomes more diffuse away from the well, the capillary flow/percolation flow starts to become the more dominant process (more towards the right of Figure 19).

Initially this approach will be evaluated using existing SW Hub geological models to identify reservoir intervals appropriate for applying these different modelling approaches. Comparison of results from both Darcy-flow and invasion percolation modelling approaches, and testing of different injection scenarios, will then provide an indication around sweep efficiency and residual trapping effectiveness in the Lesueur Formation, further reducing uncertainty with respect to storage capacity and containment security.

## Monitoring studies

### Feasible Monitoring Methods

While modelling injected CO<sub>2</sub> behaviour does provide a basis for predicting the extent of a CO<sub>2</sub> plume in the storage unit, the ability to actually detect and monitor injected CO<sub>2</sub> is required for model verification, as well as public and regulatory confidence in predictions of storage efficiency and long-term containment. Project 7-0314-0232 (Table 2) which is investigating the feasibility of monitoring injected CO<sub>2</sub> at the SW Hub will establish which monitoring techniques are suitable for the geological nature of the site, and for mapping injected CO<sub>2</sub> for the duration and volumes expected in the injection project. Considerations for the monitoring techniques will be based on how cost effective and non-invasive they might be, (i.e. monitoring from the ground surface or through wells above the primary container).

An earlier remote sensing project by Annetts et al. (2012) provided an initial assessment of non-seismic geophysical technologies for monitoring CO<sub>2</sub> at the SW Hub based on conceptual models and legacy geophysical and well data. The subsequent data acquisition by DMIRS and interpretations through various ANLEC studies have since reduced uncertainty about fundamentals of the SW Hub geological framework. The current project will use an update of the SW Hub geological model based on the new 3D seismic and well data to perform simulations of various injection scenarios to predict the thickness and lateral extent of resulting CO<sub>2</sub> plumes and their evolution with time. Using these parameters the project will assess the ability of various surface geophysical and well-based monitoring techniques to detect and visualise the CO<sub>2</sub> plume. It will also produce feasibility studies for seismic, gravimetry, magnetotelluric, electromagnetic, and Interferometric Synthetic Aperture Radar (InSAR) monitoring methods. An updated geomechanical model will be integrated in the program to examine the potential for ground surface uplift to be mappable by InSAR.

### Passive seismic for microseismicity baseline

In addition to the geophysical monitoring techniques described above, projects have been conducted to evaluate the feasibility and design for passive seismic monitoring at the SW Hub site. Passive seismic is a promising method for monitoring CO<sub>2</sub> storage projects as it has potential to monitor the injected pressure front, CO<sub>2</sub> plume and any potential CO<sub>2</sub> migration or fault displacement activity. Passive seismic may also be helpful to estimate the in-situ stress conditions in the subsurface to help constrain geomechanical model-based predictions of fault and caprock behaviour, and determine potential for induced seismicity. Further, it also obtains baseline information for the potential seismicity of the region prior to any CO<sub>2</sub> injection.

In order to identify the optimal passive seismic array design project 7-0212-0203 conducted a small field test by deploying a 50m borehole array in a purpose-drilled shallow well near the Harvey 4 wellsite (Figure 20). They measured passive seismic activity for 75 days and determined that the signal to noise characteristics markedly improved below a lithological boundary at about 30m depth between shallow unconsolidated sands and deeper, harder sandstones. Observations concluded that only small amounts of low frequency (<15 Hz) ambient seismic noise impacted the sandstones which indicates that the characteristics for passive seismic monitoring at the SW Hub are favourable even given its complex geological environment.



Figure 20: Preparing to deploy borehole geophone array in shallow well near Harvey 4 in the SW Hub project area. From 7-0212-0203.



A second phase of the passive seismic work under project 7-0215-0244 (Table 2) has commenced with the deployment of 6 to 8 passive seismic monitoring stations around the perimeter of the SW Hub project area to detect natural seismic activity from within and up to 10 to 50km around the study area. The data collected will be useful for establishing baseline values for natural seismic activity and future monitoring.

# The impact of research and data acquisition on uncertainty reduction at the SW Hub

DMIRS commissioned independent third party, Odin Reservoir Consultants (Odin), to undertake a suite of activities to enable a 'Go/No Go' decision to be made on the assessment of the suitability of the Wonnepur Member to act as a storage interval for a commercial quantity of CO<sub>2</sub>.

To do this, Odin conducted an interpretation of the large scale 3D seismic data set (post-processing). They then developed a static geological model using the data generated through both DMIRS commercial requests for data analysis, and from the large data sets generated through the range of ANLEC R&D projects listed in Table 1 and Table 2. Together the information enables the development of a dynamic geological model that can be used to test a variety of scenarios where a number of variables might be changed prior to each run of the model (Table 6).

**Table 6: Examples of the different modelling cases tested and evaluated by Odin.**

The reference case stated first and the changes made to test the extreme cases for injection of 800,000 tonnes per annum over 30 years scenario. From Odin Reservoir Consultants, 2016.

| Case      | Model name    | Geological model   | Trapped gas saturation (Sgr) | Brine salinity (ppm NaCl equiv) | Internal faults                          | End point gas rel. permeability |
|-----------|---------------|--|------------------------------|---------------------------------|--|---------------------------------|
| Reference | Reference     | Reference  | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 1         | Holey faults  | Vertical permeability of cells adjacent to faults is increased x10 | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 2         | High Krg      | Reference  | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 3         | LowHyst       | Reference  | 0.10                         | 45600                           | Not sealing                              | 0.23                            |
| 4         | High Perm     | Proportion of high energy facies in Wonnepur increased to 90%      | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 5         | High KvKh     | Vertical and horizontal permeability are equal                     | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 6         | Seismic trend | Used seismic trend to populate paleosols in Wonnepur               | 0.19                         | 45600                           | Not sealing                              | 0.12                            |
| 7         | Fault Trans   | Reference  | 0.19                         | 45600                           | Fault transmissibility multiplier of 0.1 | 0.12                            |
| 8         | LoSol         | Reference  | 0.19                         | 200000                          | Not sealing                              | 0.12                            |

For example, the top half of Figure 21 shows the Base Case of the result of injecting CO<sub>2</sub> under specific circumstances. In the Base Case, a number of assumptions are made based on the data provided to Odin. It is assumed that a maximum number of nine wells would be used to inject the CO<sub>2</sub> in a commercial scale operation; and the cost of additional wells could exceed the economic viability of the site. The formation water is assumed to have an average concentration of 45,000 parts per million (ppm) salts dissolved in the water, based on the wireline log data, fluid inclusion data, some limited fluid sampling during drilling and information from other wells in the region. This amount of mineral salts dissolved in the water (e.g. NaCl or Sodium Chloride) naturally occurs in the formation waters and reduces the ability of the formation water to dissolve and hold a volume of dissolved CO<sub>2</sub>. Thus the salt concentration impacts on the gas saturation levels in the formation waters, and new values or ranges have to be considered for the model input assumptions.

It is also assumed that within the reservoir storage interval, that any faults that cut through the Wonnerup Member are open to cross-flow between different compartments, so that there is no undue build-up of pressure. In the model, injection is set to occur at the base of the Wonnerup Member near the locations of Harvey 3 and Harvey 4 where there is currently the most accurate geological data, which puts the base of the Wonnerup at approximately 3200m deep. Commercial scale injection quantities, (i.e. 800,000 tonnes per annum over 30 years) are modelled and the movement of CO<sub>2</sub> is then calculated for a further 1000 year period after injection stops in order to evaluate where the CO<sub>2</sub> might first migrate to, and then stabilise over that time.

In the Base Case, the model was observed at a range of time periods up to 1000 years, and a key observation made was that the CO<sub>2</sub> effectively stops moving or migrating after about 500 years. The CO<sub>2</sub> tends to move due to buoyancy, and so can be seen in these examples to move northwards towards Harvey 1, which is up dip or structurally higher than the hypothetical injection point. This is shown in Figure 21a. Figure 21b is a cross-section representation that shows both the migration through the section vertically and laterally up dip, and the colours represent the concentration of CO<sub>2</sub> dissolved in the formation water. The concentration diminishes with migration vertically and laterally away from the injection points as some CO<sub>2</sub> stays behind, trapped both as dissolved CO<sub>2</sub> in the local formation waters it comes into contact with, or is residually trapped by capillary action at grain boundaries. So, with increasing movement, more CO<sub>2</sub> is left behind and less is available to migrate further, leading towards eventual stabilisation of the plume.

The most striking observation in the Base Case is that after the CO<sub>2</sub> plume stops migrating (essentially having run out of energy), the plume is still only two thirds of the way up the Wonnerup Member. There is a further 560m transit to the Wonnerup-Yalgorup boundary. This means that the requirement for a thick, laterally continuous seal, typically seen in the best case geological examples for CCS projects (Figure 1) is not critical if the CO<sub>2</sub> stays within the very thick storage interval.

During evaluations of this type, when modelling a range of scenarios to reduce uncertainty, the object is not to find the 'most correct' model. Rather, the approach typically taken is to develop a most representative Base Case as described above, then stress that case by altering the parameters to a reasonable but often 'worst case scenario'. Odin conducted a range of these stress cases where each of the main parameters found to impact on the model were altered to see the overall effect on the injection of 800,000 tonnes per annum over the 30 year injection period. The results, though varied, did not generate an example where the top of the Wonnerup Member was breached by CO<sub>2</sub>. These case examples included changes to relative permeability, vertical permeability, amount of different rock types or facies

present that could alter vertical migration behaviour, changes to trapped gas saturation, or changes to formation fluid salinity. Notably change to the total volume of CO<sub>2</sub> injected were evaluated as well. Taken in turn, each of these changes to the base case scenario had little impact on the lateral extent of the plume at the final height that the CO<sub>2</sub> migrated to within the Wonnerup storage interval.

The final stage of the modelling evaluated a high level stress case where the three most significant factors that contributed to modelled changes in migration behaviour of the injected CO<sub>2</sub> were combined to see the collective worst possible case scenario. Figure 21c and d show the output of that case. The number of wells remained at 9, and the fluid salinity of the formation water was increased from approximately 50,000 ppm to 200,000 ppm, which impacts on the ability of gas to dissolve in the formation water. So this value too was halved from Sgr 0.19 to Sgr 0.10. Finally, the total volume injected over 30 years was increased from 800,000 tonnes per annum to 3 million tonnes per annum and the model run. Figure 21c shows how much larger the plume footprint becomes. More importantly, the vertical and lateral migration in the cross section (Figure 21d) shows that the plume moves much higher through the section, but still does not reach the Wonnerup-Yalgorup boundary.

Remembering that each of these worst case scenarios had to be combined, and the volume of CO<sub>2</sub> increased 3 times, the modelling illustrates the low likelihood of CO<sub>2</sub> leaving the storage interval during the injection of base case commercial CO<sub>2</sub> operations. This reduces uncertainty for the project and enables DMIRS to pass through the Go/No Go stage gate to proceed to the next activities.

Based on the typical workflows for CCS projects (Figure 4) this could mean further risk and uncertainty reduction by drilling a deeper well in the region to conduct a pilot or demonstration scale injection to evaluate and confirm performance of the storage interval.

All data is available on DMIRS's WAPIMS Database at [www.dmp.wa.gov.au/wapims](http://www.dmp.wa.gov.au/wapims)

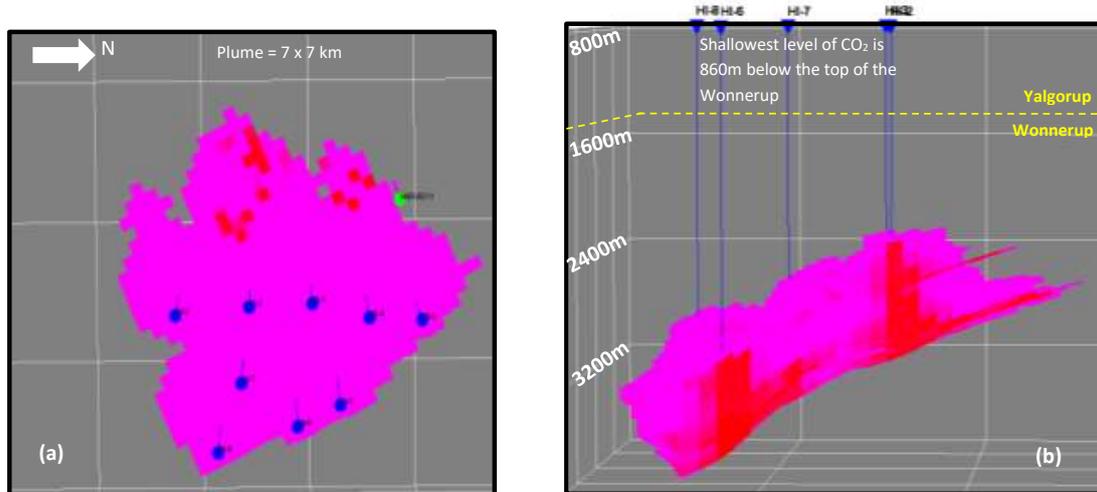
While the WA State legislation for injecting CO<sub>2</sub> has not yet been passed within Parliament (an amendment to the Petroleum and Geothermal Act has been underway for some time), there is the ability to conduct small scale tests of the order of a few 100 tonnes up to < 100,000 tonnes test that could be conducted under separate legislation. The tests would still be subject to a rigorous range of permits and regulation before they could be conducted, and consultation would be required to enable any activity.

DMIRS in collaboration with the Environmental Protection Authority, Department of Water, and other agencies act as regulator for carbon storage activities, and will be the body awarding onshore permits for carbon storage in the future (subject to the new legislation passing). By conducting the pre-feasibility activities at the SW Hub (the screening and assess & select phases; Figure 4) and through their current activities with Chevron for the upcoming Gorgon CCS project on Barrow Island, DMIRS has had the opportunity to participate first hand in CCS related research and activities that define potential CCS sites. They have developed skills and expertise to be able to act as a knowledgeable regulator and provide more authority and guidance with respect to the legislation in the future.

**Base Case: Plume movement effectively stops about 500 years after injection stops.**

Conditions:

800,000 TPA over 30 years / 9 wells / injection depth 3200m, gas saturation 0.19 / salinity 50,000 ppm / open faults / Wonnerup – Yalgorup in communication.



**Stress Case: Plume movement effectively stops about 500 years after injection stops.**

Conditions:

3 MTPA over 30 years / 9 wells / injection depth 3200m, gas saturation 0.10 / salinity 200,000 ppm / open faults / Wonnerup – Yalgorup in communication

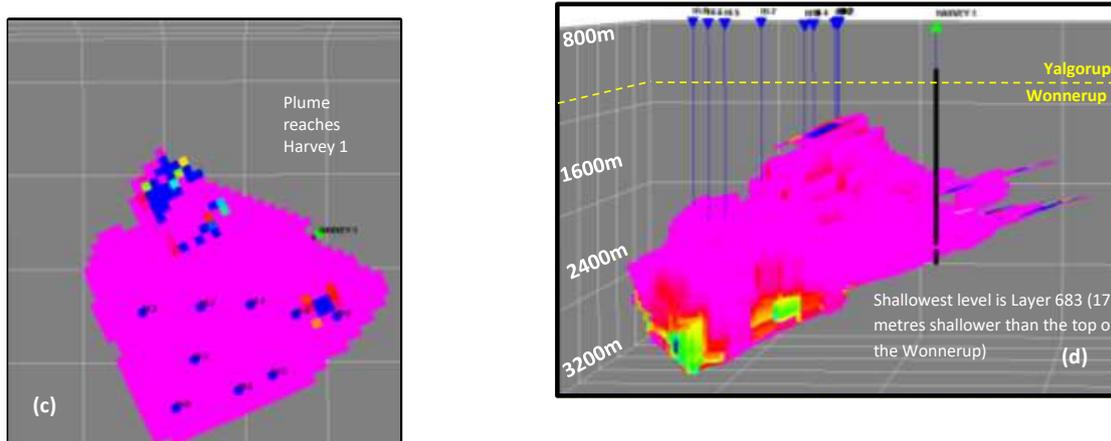


Figure 21: Base case model (upper figures a and b) and composite stress case model (lower figures c and d). Figures a and c show the areal extent of the CO<sub>2</sub> plume 1000 years after injection ceases in a map view format. Figures b and d show a cross-sectional view at the end of the same time period. Images from Odin Reservoir Consultants, 2016.

# Conclusions and future work

This document set out to provide an overview of the work conducted to reduce uncertainty at the SW Hub CCS project site for the potential to inject commercial volumes of CO<sub>2</sub>. DMIRS has coordinated much of the data acquisition and the topics for research during this early phase of the work (pre-feasibility studies). The results contribute to the site 'Assess & Select' phase of the program of work that CCS sites undertake globally. The results from the SW Hub suggest that there is still ongoing potential for the SW Hub to act as a commercial scale storage site for future emission-intensive industries to utilise the site for CO<sub>2</sub> storage.

However, further work needs to be done before this site can be awarded any formal permitting to enable CO<sub>2</sub> storage. The work, both from the modelling and research perspective that needs to be done to reduce the greatest uncertainties is around the deep target injection area. In other words, the drilling and testing of a Harvey 5 well.

## Where does the SW Hub sit within the current portfolio of Australian Projects?

Figure 22 shows that there are a range of projects that many are familiar with in Australia. Due to their site specific nature, the success of these projects will each help to assess and resolve different investment risks to deliver their reward of carbon dioxide abatement.

The off-shore CarbonNet project in Victoria can deliver fit-for-purpose monitoring strategies in a unique marine environment. The CTSCo project in Queensland can deliver the regulatory and commercial framework for CCS deployment in the Surat Basin where several important resources such as water, CSG and coal co-exist. This research and investigation into the SW Hub location, where the type of geology is usually regarded as 'less-than-perfect' (through the absence of a large thick regional seal), – if successful – can deliver the basis to re-define carbon dioxide storage resources globally.

Research and Development for the SW Hub has advanced the understanding of how to evaluate CO<sub>2</sub> storage potential in a range in geological situations, and developed novel ways with which to characterise and assess atypical geological sites. This will enable faster, cheaper, better characterisation of sites in the future, whilst improving the skills and capability of researchers and government regulators, to investigate future potential CCS sites.

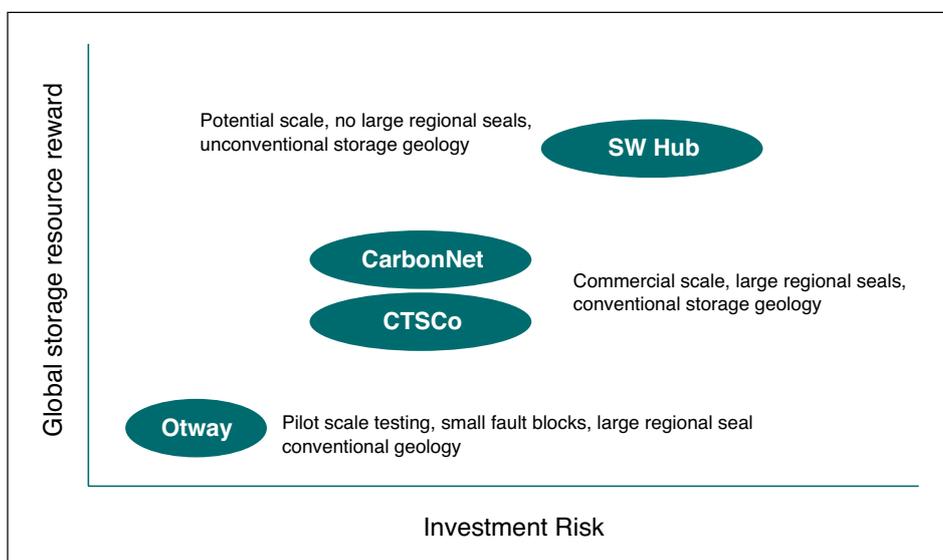


Figure 22: SW Hub: The opportunity to re-define carbon dioxide storage resources through CCS deployment.

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