



Government of Western Australia
Department of Mines and Petroleum

Harvey 1 Stratigraphic Well

Research Outcomes August 2013

South West CO₂ Geosequestration Hub



Research and funding organisations

The South West Hub is a government and industry partnership researching an economically and environmentally sustainable low carbon future for the South West region of Western Australia. The South West Hub is Australia's first Carbon Capture and Storage Flagships project.

Funding for this research has been provided by the WA Government and the Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D).

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 South West 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 carbon capture and storage (CCS) flagship projects.

The National Geosequestration Laboratory (NGL) in Perth, WA is developing as a world-class carbon storage research facility. The NGL is a collaboration between CSIRO, the University of Western Australia and Curtin University, and the research and development it undertakes is a key component to Australia achieving lower carbon emissions in the resources and energy economy. For further information on the NGL visit www.ngl.org.au.

The NGL has worked with the Western Australian Department of Mines and Petroleum (DMP) and Geological Survey of Western Australia (GSWA) to conduct a series of research projects for the South West Hub which are summarised in this publication.

*Australian Coal Association's COAL21 Fund



This document was prepared by Dr Linda Stalker from NGL/CSIRO and Beth Ferguson from WA DMP.

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The State shall in no way be liable, in negligence or howsoever, for any loss sustained or incurred by anyone relying on the information, even if such information is or turns out to be wrong, incomplete, out of date or misleading.

Research papers summarised in this report

C. Delle Piane, H.K.H. Olierook, N.E. Timms, A. Saeedi, L. Esteban, R. Rezaee, V. Mikhaltsevitch, S. Iglauer, M. Lebedev. (2013). *Facies-based rock properties distribution along the Harvey 1 stratigraphic well*. Report to ANLEC R&D.

L. Stalker, R. Noble, D. Gray, C. Trefry, S. Varma, A. Ross, S. Sestak, S. Armand, S. Gong. (2013). *Geochemical characterisation of gases, fluids and rocks in the Harvey 1 data well*. Report to ANLEC R&D.

R. Pevzner, D. Lumley, M. Urosevic, B. Gurevich, A. Bóna, S. Ziramov, V. Rasouli, J. Shragge, M. Pervukhina, T. Mueller and V. Shulakova. (2013). *Advanced geophysical data analysis at Harvey 1: storage site characterisation and stability assessment*. Report to ANLEC R&D.

C.M. Griffiths, Z. Seyedmehdi, T. Salles, C. Dyt (2012). *Stratigraphic forward modelling for South West Collie Hub Phase One – Static Model*. Report to ANLEC R&D.

L. Langhi, B. Ciftci, J. Strand. (2013). *Fault seal first-order analysis – SW Hub*. Report to ANLEC R&D.

This document is available online through the DMP website www.dmp.wa.gov.au/ccs.

Further detailed technical results, including the research papers listed above, are available online through www.dmp.wa.gov.au/petroleum and geothermal information (WAPIMS). For assistance with obtaining the documents go to http://www.dmp.wa.gov.au/documents/how_to_download_documents_in_WAPIMS.pdf.

The research papers are also available from the ANLEC R&D website www.anlecrd.com.au.

We recommend using Google Scholar when researching carbon capture and storage online.

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Executive Summary

Analysing the data collected from a stratigraphic well is the geological equivalent of travelling back through time; the properties of various rock layers encountered today depend on the processes that formed them millions of years ago.

In early 2012 the Geological Survey of Western Australia (GSWA), which is part of the Western Australian Department of Mines and Petroleum, drilled the Harvey 1 stratigraphic well in order to gather core samples and important information about the Lesueur Sandstone formation.

A partnership of scientific organisations then spent 18 months carefully analysing samples and sifting through the data generated, and the results have confirmed geological expectations about the Lesueur and how it was formed during the Triassic Period 250 to 200 million years ago. Importantly, the Harvey 1 well did not unearth anything that would rule out the Lesueur as a suitable carbon storage reservoir at this stage.

The South West Hub and its private sector partners are investigating the feasibility of the Lesueur for the permanent underground storage of carbon dioxide (CO₂) emitted by South West industries. The area being researched is about 100 square kilometres within the Harvey and Waroona shires where there is a region of rocks that have been uplifted in ancient times, influencing the distribution of the rocks today.

This feasibility study is a gated project which only moves forward as each phase is successfully completed and outcomes of the project are evaluated to determine whether there are any features that could rule out CO₂ geosequestration in the Lesueur. Research outcomes from the analysis of data and core samples collected from Harvey 1 support the continuation of the feasibility study so far.

The Harvey 1 well was drilled by the Century Rig 7 between February 7 and March 23 of 2012 as part of the South West Hub's four-year feasibility study into storing up to 6.5 million tonnes per annum of CO₂ over a period of 40 years in the Lesueur Sandstone.

The well reached a depth of 2945 metres from Lot 1326 Riversdale Road in Harvey. Some 217 metres of core was recovered, and various measurements were made, achieving 95 per cent of the well's acquisition objectives before it was permanently sealed. (Drilling details are published in "Harvey 1 Stratigraphic Well Early Drilling Outcomes January 2013").

The multidisciplinary study of the measurements obtained and core sample analyses has concentrated on confirming the properties of the Lesueur formation which is a saline aquifer created by an ancient river system during the Triassic Period, 250-200 million years ago.

Lying underneath the Leederville and Eneabba formations, the Lesueur has two units which are the Yalgorup (704 -1380m) and Wonnerup (1380-2895m) members; the Wonnerup is the target formation for permanently trapping CO₂.

The research confirms that the Wonnerup is a massive 1.5km thick formation of clean, coarse-grained sandstone possessing good properties for a CO₂ reservoir in terms of porosity and permeability. CO₂ is able to move more freely in a horizontal direction than in a vertical direction through the Wonnerup which is a desirable property in such a reservoir.

In addition, the Yalgorup which lies above the Wonnerup is interbedded with sand and shale layers which appear to have further trapping potential. The variation in salinity levels between the Yalgorup and Wonnerup indicate that layers of shale provide a potential sealing unit and there is no connectivity between the layers.

Traces of hydrocarbons found in the well were so low that there are unlikely to be any basin resource management issues in relation to oil or gas. There are geological faults in the area however there is no suggestion that they will impede the geosequestration project. Further surveys will be conducted to map faults in greater detail.

In summary, the research outcomes from the data and core samples collected from the Harvey 1 stratigraphic well confirm the potential of the Lesueur formation as a CO₂ reservoir and support further research as part of the South West Hub feasibility project.

Geophysical analysis of the data collected from Harvey 1 will be used to inform the next steps of the South West Hub project which include a 3D Seismic Survey of the area and potentially further stratigraphic wells.

Introduction

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. Researchers from CSIRO, the University of Western Australia and Curtin University have been working in partnership with the Western Australian Department of Mines and Petroleum (WA DMP) and with the Geological Survey of Western Australia (GSWA) to conduct a series of research projects.

The goal of the multidisciplinary work presented here is to help enable and further understand the geological and geophysical parameters that will affect the safe and efficient storage of carbon dioxide (CO₂) at the proposed South West CO₂ Geosequestration Hub (South West Hub) site in the southern Perth Basin. In particular, the areas of interest covered by this work are related to the characterisation of the geological units intersected by Harvey 1 in terms of storage capacity, injectivity and containment security, elastic and mechanical properties and heterogeneity of the formations encountered.

The preliminary research has generated new materials and utilises information from the well including:

- Sedimentary logging of the cored sections of the well,
- Petrographic and mineralogical analysis of the sedimentary units and evaluation of their diagenetic history,
- Evaluation of the wireline logs collected from Harvey 1,
- Experimental measurements of the petrophysical properties of core plugs from Harvey 1 and comparison with those from the neighbouring well, Pinjarra 1,
- Flooding of core samples to evaluate rock reactivity in the presence of formation fluids and CO₂,
- Experimental measurement of geomechanical properties of Harvey 1 core samples,
- Experimental measurements of elastic properties and their dependency upon stress, fluid content and frequency,
- Evaluation of the presence of any hydrocarbon compounds,
- Characterisation of formation fluids for salinity, and
- First order analysis of the potential for sealing versus open fault systems.

The work done so far, described in more detail below, contributes towards the characterisation of the geology in the area as a potential carbon storage site, and so far the results indicate that there are no impediments to proceeding to the next stage of data collection and site characterisation for the South West Hub project. What remains uncertain is how continuous the rock properties are away from Harvey 1.

- Good reservoir properties are recorded in the lower Wonnerup Member (1380-2895 MDRT) of the Triassic Lesueur Sandstone with encouraging porosity values of 7 to 19%, permeability measurements of 0.01 to 580 mD and it shows lithofacies homogeneity with depth. Permeability anisotropy (i.e. how permeable the rock is vertically versus horizontally) measured in the laboratory can be very significant at the potential injection levels: across bedding permeability (vertical) ranges between 0.01 and 3 millidarcys while along bedding permeability (horizontal) ranges between 38-216mD, resulting in anisotropy of up to 3 orders of magnitude. Core flooding tests also give positive indications on the ability of the Wonnerup Member to store CO₂ by residual trapping (25 to 45%) as the principal containment mechanism.
- By contrast the overlying Yalgorup Member (679.5-1335.5m sub-sea) is far more diverse or heterogeneous. But due to the poor quality of the core samples from parts of this interval, particularly the shaly layers, the characterisation work only focused on the sandy intervals. Therefore the results cannot be regarded as representative of the whole stratigraphic unit at this stage, and future wells will aim to evaluate these materials better. So uncertainties remain regarding the geomechanical properties and containment potential of the different lithofacies within the Yalgorup. Nevertheless, the presence of interbedded sands and shale layers could be beneficial in terms of storage as they have the potential to act as baffles retarding the movement of CO₂. No data have been collected on what is regarded as the main seal of the geosequestration site, the Eneabba Formation, due to a lack of cored materials. Further research should be focused on the integrated characterisation of the different intervals to match the level of understanding attained for the Wonnerup Member.

All of the work reported here, and in fuller reports funded by ANLEC R&D and WA DMP, contributes towards reducing geological uncertainty as the project progresses through the stage gates from feasibility to pilot tests to full commercial operations.

1. South West CO₂ Geosequestration Hub – Research and Analysis Roadmap

In order to conduct a full investigation into the geology of the area adjacent to major CO₂ sources in the region, the South West CO₂ Geosequestration Hub (South West Hub) requires a detailed series of activities to provide relevant information. This latest update on the project is part of a sequence of these activities that make up the project roadmap. The roadmap (Figure 1) guides the activities of the project to help the project teams focus on appropriate tasks and activities so that when decisions are required, the appropriate information is presented to make sensible decisions.

In 2010 when the South West Hub applied to the Federal Government for Flagship status, a parallel submission was submitted by a collaborative group of scientists from CSIRO, the University of Western Australia and Curtin University for funds to support the South West Hub research. This group, established as the National Geosequestration Laboratory (NGL), was awarded \$48.4m to build new infrastructure and obtain equipment to advance research in carbon capture, utilisation and storage (CCUS), with the South West Hub as a primary focus.



Figure 1 Roadmap for the South West CO₂ Geosequestration Hub from concept to proving up storage.

Many of the NGL participants have worked together for a number of years in a collaboration with the Cooperative Research Centre for Greenhouse Gas Technologies (CO₂CRC) and worked on their CO₂ pilot-scale injection site in Otway Victoria. More information on that site can be found at www.co2crc.com.au.

These researchers have contributed significantly to the investigation into the Harvey 1 well where materials recovered and measurements made can be used to better understand the subsurface in the study area and provide a window on what is present deep underground in the project's study area.

The results of the studies on the Harvey 1 well aid in the following:

1. Informing the design of the 3D Seismic Survey to be conducted over a 100km² area to the north and west of Harvey, and
2. Develop a testing program to evaluate the geology to see if a suitable commercial scale CCS site can be identified, and use this information to reduce uncertainty in the geology.

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

1. Storage capacity – this defines the volume of CO₂ we expect the storage interval to hold over a given period of time (i.e. this could be enough storage to hold 240 million tonnes CO₂),
2. Containment security – where we define a range of possible mechanisms for CO₂ losses and assess their likelihood, and
3. Injectivity – this defines the rate at which we can inject CO₂ 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 CO₂.

Perth Basin Stratigraphy

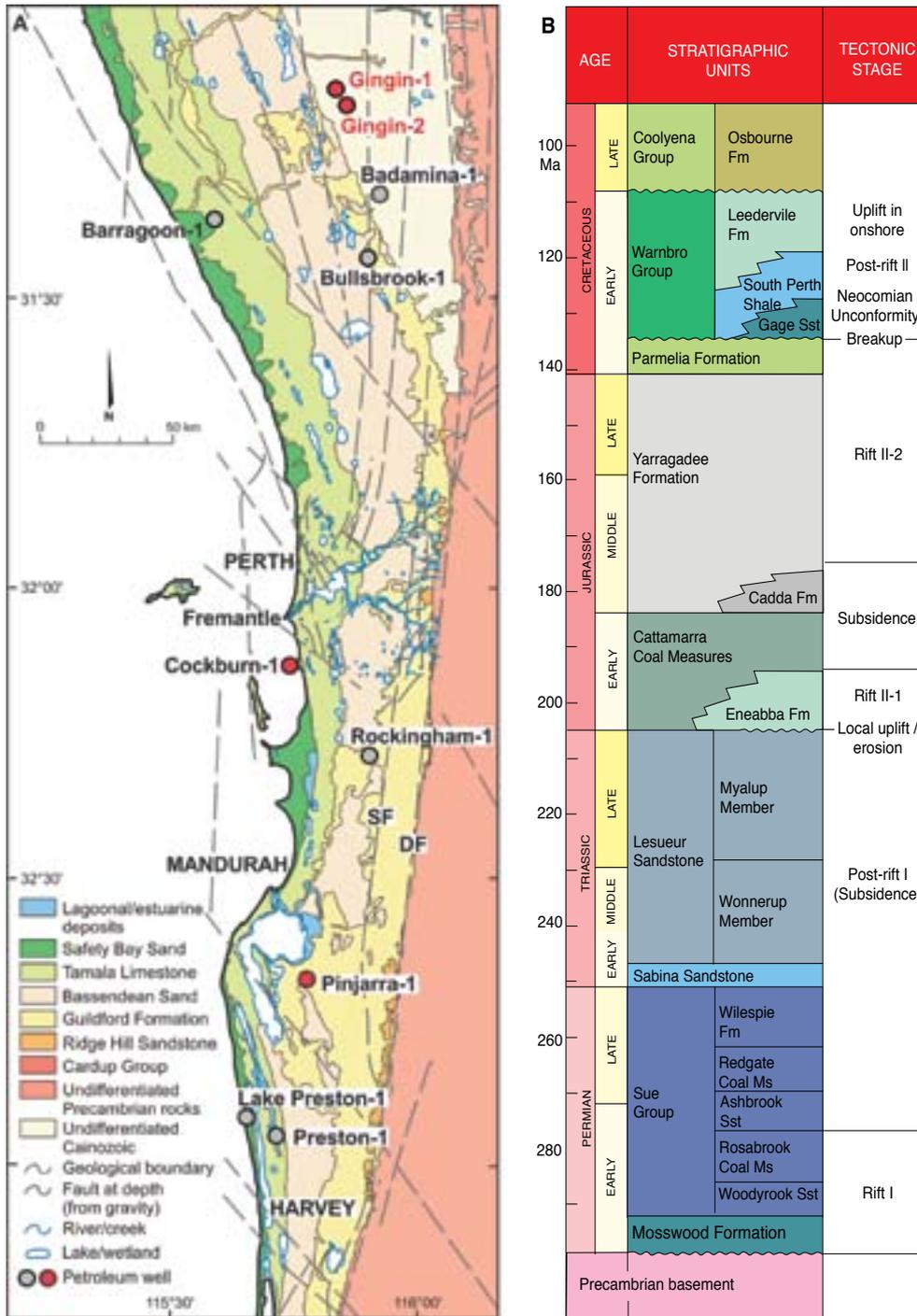


Figure 2 Map of the Perth Basin including the main wells drilled and a stratigraphic column showing the rock formations and main structural events in this region. Figure from Delle Piane et al., (2013).

Onshore Southern Perth Basin Stratigraphy at GSWA Harvey 1

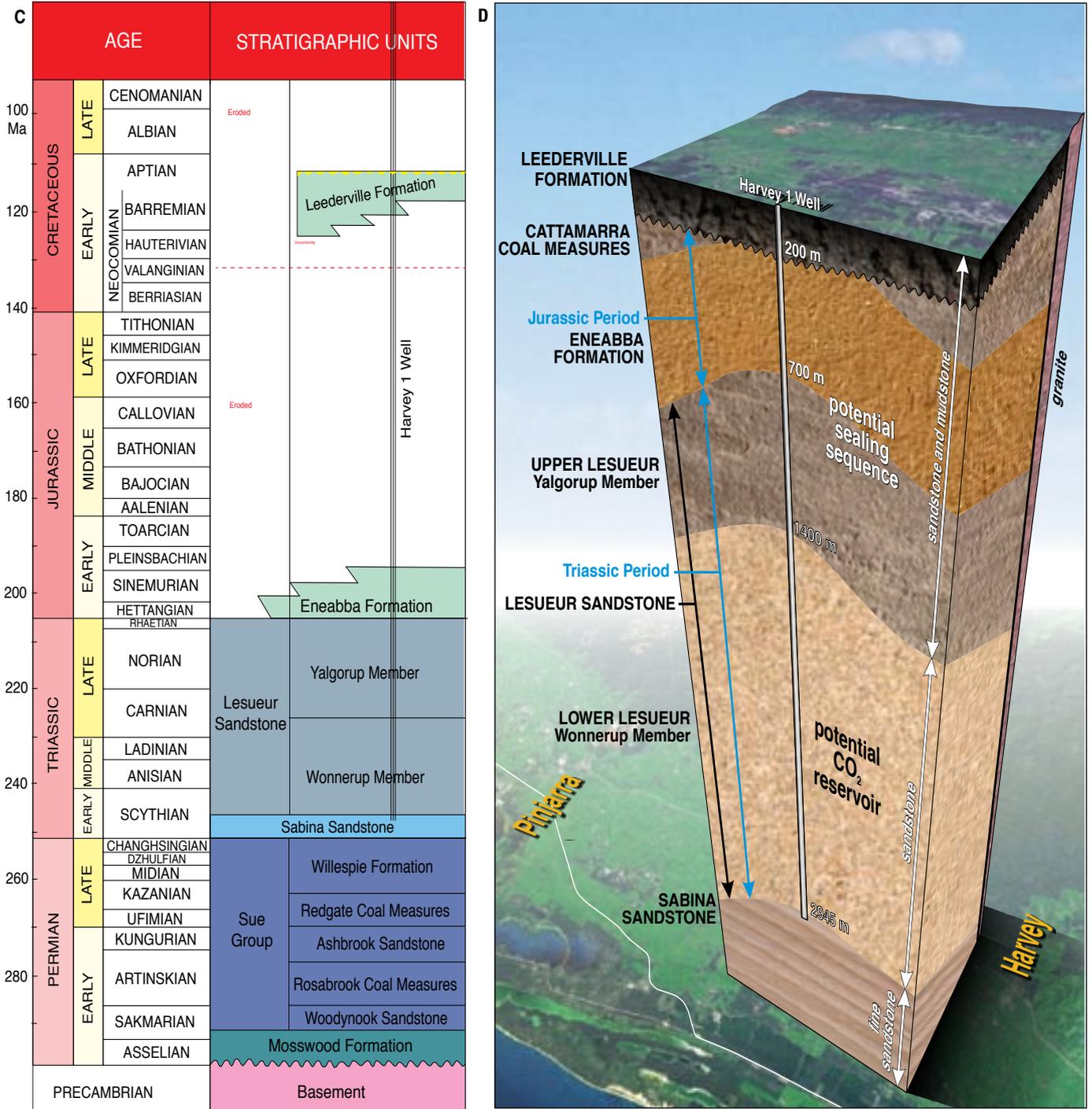


Figure 3 Stratigraphic layers within the southern Perth Basin as intersected by the GSWA Harvey 1 well.

2. Research Projects for the Harvey 1 Well

In the previous documentation published by the DMP 'Harvey 1 Stratigraphic Well, Early Drilling Outcomes January 2013', five major research projects were mentioned in connection with the testing of core (rocks), formation fluids (shallow and deep groundwaters) and wire line logging results (from in-well measurements).

1. Facies-Based Rock Properties Distribution Along the Harvey 1 Stratigraphic Well.
2. Geochemical Characterisation of Gases, Fluids and Rocks in the Harvey 1 Data Well.
3. Integration of Data from Harvey 1 Well to Support Decisions – Fault Seal.
4. Advanced Geophysical Data Analysis for the South West Hub Harvey 1 Well Site.
5. Stratigraphic Forward Modeling for the Lesueur Sandstone.

The materials from the wells have been tested and analysed and compared with existing information from the region to better understand the geology of the area. The research projects were funded by ANLEC R&D (Australian National Low Emissions Coal Research and Development) with assistance from WA DMP and conducted in a collaboration between NGL researchers, WA DMP and the GSWA. The projects are carefully defined in order to both increase our general understanding of the geology in the area and to address our questions regarding storage capacity, containment security and injectivity.

The projects themselves go through a strict process to verify the interpretation and outcomes reported (Figure 4) where projects are carefully defined and reviewed, and may undergo changes in scope part way through if preliminary outcomes suggest that a change is important.

These reports will be published in full on the ANLEC R&D website (www.anlecrd.com.au) and on the WA DMP website www.dmp.wa.gov.au. However a summary of the outcomes of these projects and the implications for the South West Hub Project are described here.

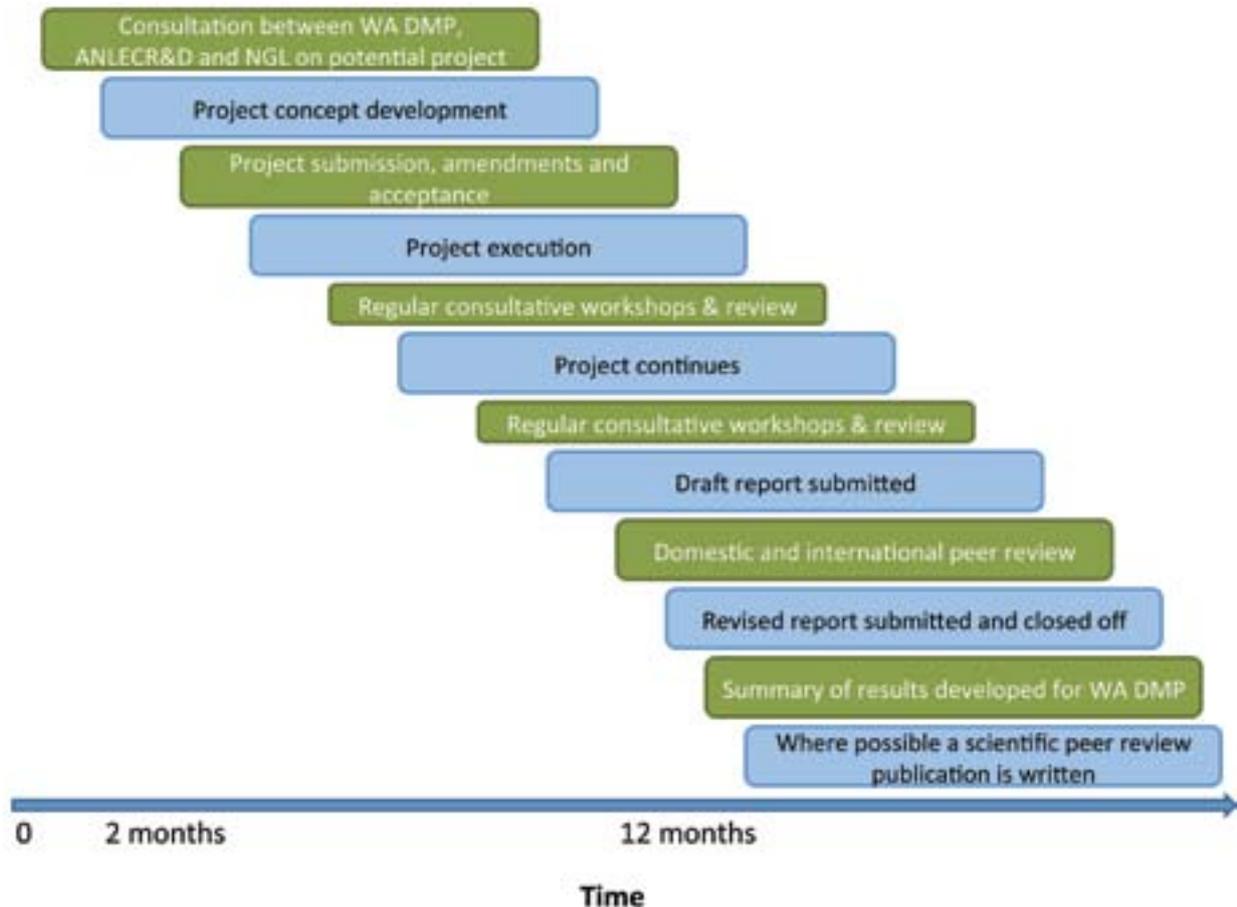


Figure 4 Evolution of Research Projects that contribute towards the decision making of the South West CO₂ Geosequestration Hub project.

3. Harvey 1 well

The Harvey 1 well, drilled in February-March 2012 was located at Lot 1326 Riverdale Road, in Harvey, in order to obtain new geological data for the Perth Basin (Table 1). The Perth Basin extends over 172,300 km² but relatively few wells are drilled across the region, so our understanding of the subsurface is limited (Figure 2). In order to increase our knowledge of the geology in the South West, and in particular the area around Harvey for the South West CO₂ Geosequestration Hub Project, Harvey 1 was drilled and geologically evaluated.

The focus of the well was to obtain sufficient rock and formation water samples to help in the evaluation of the regional geology. To do this, the well was drilled to

a total depth of 2945 m MDRT (or 2913.8m below sea level; see Table 2) so that the whole of the Triassic age Lesueur Formation could be fully evaluated.

The well provided 217m of core material, two formation water samples and a large number of wireline log measurements (where tools are sent down the well to measure rocks properties from the bottom depth of 2945m to surface). Together these materials provide a window into the subsurface where we can determine whether the geology in the region might be suitable for long-term, large-scale CO₂ storage. These pieces of information from Harvey 1 together with the data acquired from the 2011 2D seismic survey have been used in the projects described below.

Table 1 Harvey 1 Well 1 Data Record

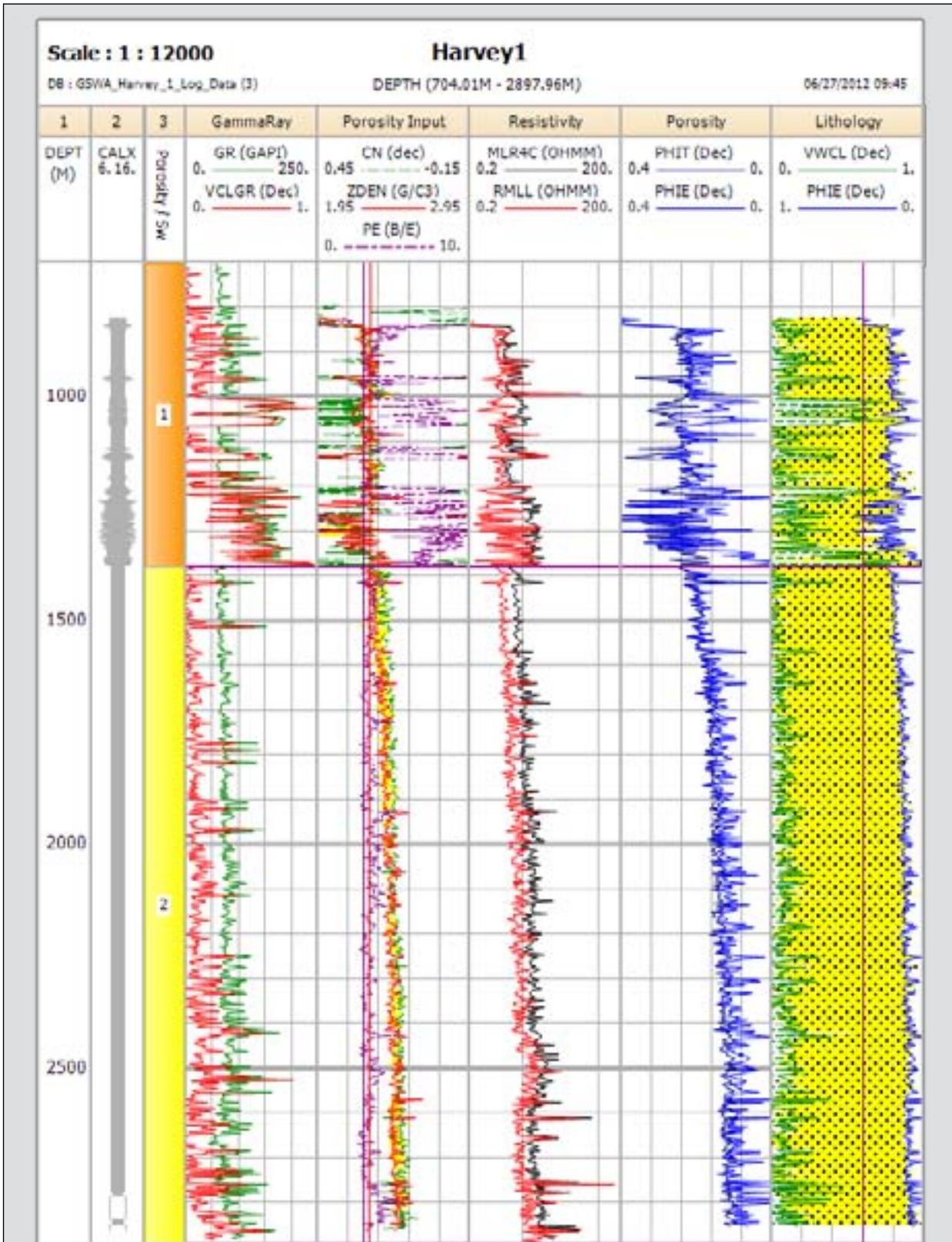
Well Data Record			
Well Name:	GSWA Harvey 1 (2066)		
Well Classification:	Stratigraphic	Spud Date:	00:00h 7th February 2012
TD Date:	22:00 h 8th March 2012	Rig Release Date:	06:30h 26th March 2012
Final TD mMDRT/mTVDSS	2945.0 / 2913.8	Total Rig Days	48
Completion Status:	Plugged & Abandoned	Permit / License:	N/A
Surface Coordinates:	Lat: 32°59' 30.730"S		
Long: 115°46' 28.093"E	TD Coordinates:	Lat: 32°59' 33.730"S	
Long: 115°46' 26.734"E			
Surface Location Coordinates (UTM):	385502.044E		
6348947.564N	TD Coordinates (UTM):	385467.77E	
6348860.13N			
Permanent Datum:	AHD	RT to GL:	5.38m
Ground Level (GL) to AHD:	19.10m	RT to AHD:	24.48m
19.10m RT to AHD:			

To correct MDRT to TVDSS - take 24.48 m from the MDRT value.

Table 2 Formation depths and thicknesses in the Harvey 1 Well

Formation	Depths		Thickness (m)
	MDRT*	TVD SS	
Guildford	5.18	19.3	
Leederville	36	11.5	214.0
Eneabba	250	225.5	375.0
Basal Eneabba Shale	625	600.5	79.0
Lesueur Formation	704	679.5	2191.0
Yalgorup Member	704	679.5	676.0
Wonnerup Member	1380	1335.5	1515.0
Sabina Formation	2895	2870.5	>50m
Total Dept (TD)	2945	2913.8	

*Depths are reported in wells as MDRT (measured depth from the rotary table) and TVD SS (total vertical depth sub-sea)



Wireline tools and measurements – the oil and gas industry have developed tools that can be lowered into wells, to depths of several kilometres to measure different aspects of the rocks exposed in the well. The data retrieved can help us understand the geology and rock properties. If core samples are taken, they can be used to calibrate the wireline tools and that information extrapolated to the whole depth of the well. Lots of different tools can be sent down together in one string to measure things like natural gamma rays, density, resistivity, sonic or magnetic behaviour in the rocks. The data tell us about porosity, permeability, sand to shale ratios and other features so maximising the amount of information we can obtain from the costly drilling of a well.

Figure from Delle Piane et al. (2013)

4. Facies-Based Rock Properties Distribution Along the Harvey 1 Stratigraphic Well

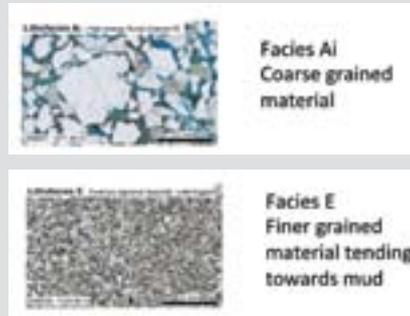
How were these formations deposited?

Geologists from CSIRO and Curtin University examined the 217m of core that now resides in the GSWA core store in Carlisle. By looking at the grain size distribution, grain roundness, structure and other features, a picture of how the Lesueur Sandstone was deposited can be built up (Figure 5 centre spread). Observations suggest that the depositional environment was fluvial i.e., transportation of materials from a higher area to flatlands by a river system during the Triassic period some 250-200 million years ago (Figure 5). By understanding how the Lesueur Formation was deposited, geologists can make some predictions as to the lateral extent of the different rock intervals.

For example, the deposition of facies that are higher energy (where the river water was faster flowing and can hold both more and larger grains of sand, for example) has resulted in large deposits of uniform sandy intervals that are likely to be very continuous over wide areas (Figure 5). We know that they are likely to be continuous because of comparisons with modern river environments and examination of other geological examples. Also, seismic surveys can begin to map the distribution of these sands in the deep subsurface. For Harvey 1 this means facies Ai, Aii and Aiii are most commonly high energy, have lots of sand and have good properties for carbon dioxide storage such as higher porosity and reasonable permeability. The observations provide confidence that the Wonnerup Member (Lower Lesueur), containing a predominance of these facies types (Figure 5), extends a long way across the region and can potentially provide a large storage container for CO₂.

By contrast, lower energy deposits mean that slow flowing rivers can only carry small particles of sediment resulting in more muddy or shaly deposits in the river systems such as facies E, F and G (Figure 5). These units have lower porosity and permeability so they can retard CO₂ movement or act as a sealing interval. The Yalgorup Member has more of these finer grained intervals than the Wonnerup Member (Figure 5 & 6). However, recovery of core from the Yalgorup and the shallower Eneabba shale was not as good as we would have liked to be able to fully characterise these potential sealing units. The formation process for these rocks gives us information on how far they stretch from east to west, and north to south and how thick these

intervals might be. The 3D seismic survey will facilitate the mapping of the extent of these units for the ongoing evaluation for the South West Hub project.



Porosity – refers to the void space between grains in a rock. It is measured in percentage (%) of void space relative to rock material. In Figure 16, the photos of the rocks under the microscope are stained so that the blue colour shows in the pore space to highlight the porosity, or amount of pore space, in the different types of rock.

Permeability – this is the degree to which a rock can transmit, flow or pass fluids through it. Permeability is measured in millidarcy (mD). It indicates the degree of connectedness between pores.

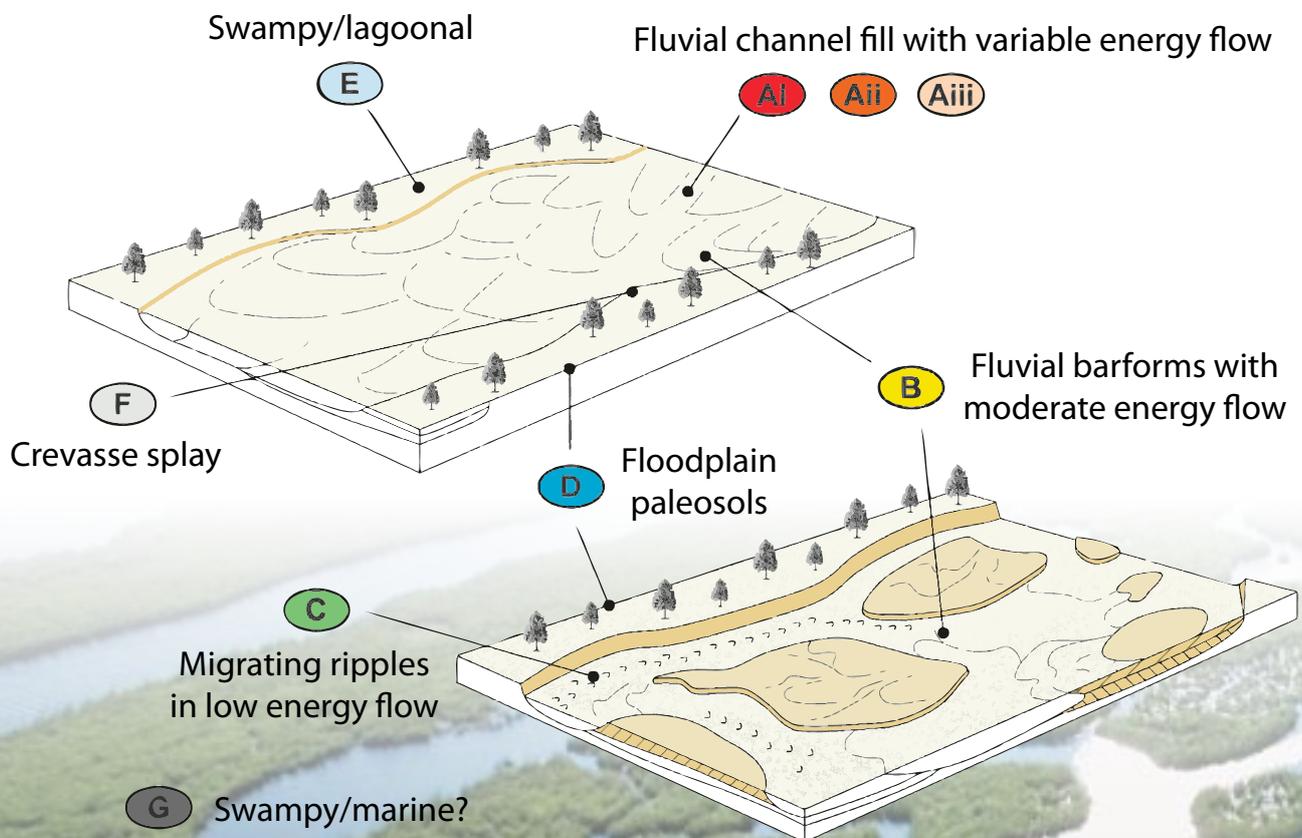
Seals – these are rock units that have small grain size, low porosity and very low permeability. They are mainly made up of quartz and clay minerals. Because of these characteristics, they tend to act as traps or sealing intervals stopping the movement of fluids. Oil, natural gas or CO₂ can be trapped by seals.

Baffles – are intervals that can check or reduce the rate of flow. They may be similar to sealing intervals, but are much thinner than a seal, and slow the movement of oil, natural gas or CO₂ rather than permanently stopping it from moving.

Sandstones – by definition they are made up of grains of sand deposited in marine settings (deep offshore, near shore, beaches), fluvial (i.e. river) or arid (desert) settings. The sand grains tend to be mainly quartz (silica), but there may be minor amounts of feldspars (other silica based minerals). Because sandstones can have higher levels of porosity and permeability, they make excellent reservoirs for oil and gas, store water as aquifers and their properties are also ideal for carbon storage.

Lesueur Sandstone – made by ancient rivers

Harvey in the Triassic. This may be how the area looked when the Lesueur was being formed 250 to 200 million years ago.

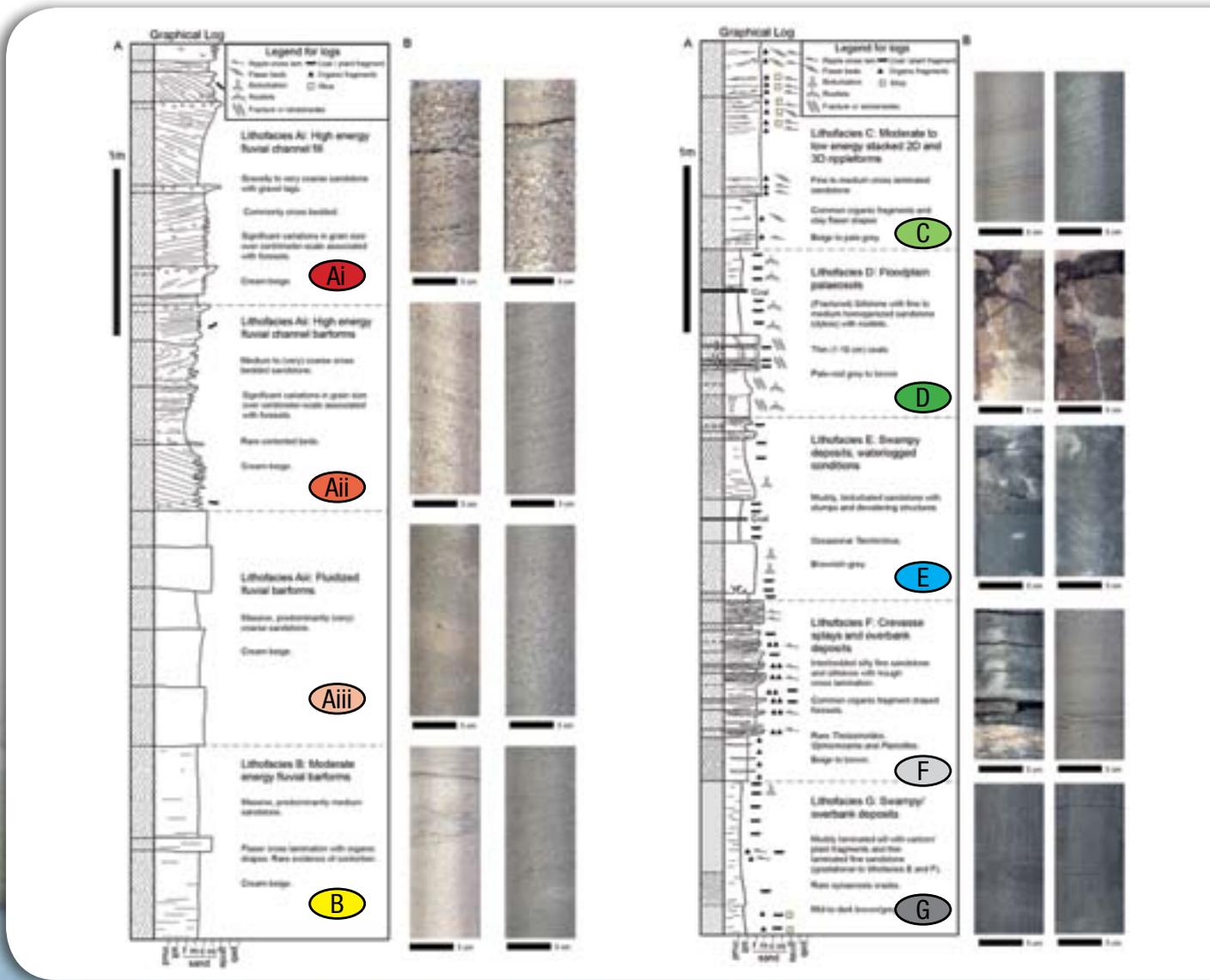


Facies – “Facies” is a geological term used to describe a unit of rock that has been laid down in a particular environment. In the case of the Harvey 1 rocks, the different facies describe features of fluvial (or river) deposits.

Some facies seen in the well are sandy and have been deposited as a result of the high energy movement of a lot of sand grains. Other facies are muddy or shaly which were deposited where an ancient river flowed more slowly, had less “energy” and so could only carry and drop small clay particles.

Understanding the process which produced the different facies types and mapping those facies over a wider area generates a subsurface picture showing which rocks are the potential sealing rocks and which are good intervals for storing carbon dioxide.

Figure 5 Facies description for the Harvey 1 well and the region. The interpretation suggests the Triassic aged rocks are from a fluvial (river) environment. Geological information from the core descriptions, core testing and photographs were used to build this picture of the landscape during the Triassic Period. Images from Delle Piane et al. (2013).



Facies types

- (Ai)** High energy channel fill, commonly cross bedded, gravelly to very coarse sandstone;
- (Aii)** High energy fluvial channel barforms, medium to very coarse cross bedded sandstone with significant grain size variation between beds;
- (Aiii)** Fluidized fluvial barforms, massive, coarse sandstone;
- (B)** Moderate energy fluvial barforms, massive, medium sandstone with flaser cross lamination;
- (C)** Moderate to low energy stacked rippleforms, fine to medium cross laminated sandstone, with common organic fragments and flaser-drapes;
- (D)** Floodplain palaeosols (often vertisols), fine to medium homogenized sandstone with rootlets, dessication cracks and slickensides;
- (E)** Swampy/lagoonal deposits, under waterlogged conditions, muddy bioturbated sandstone with slumps and dewatering structures;
- (F)** Crevasse splay and overbank deposits, interbedded silty fine sandstone and siltstone with trough cross lamination;
- (G)** Swampy/ overbank deposits, muddy laminated silt with plant fragments and thin laminated fine sandstone.

Rock Testing and Measured Properties

At the same time as identifying how the rocks were laid down, the core samples can be subjected to a number of tests that tell us important things about how strong they are, how much CO₂ they might be able to store and how they might respond if we subject them to an energy source (that is, when we apply seismic waves [i.e. noise] during a seismic survey). This information is being used to design and prepare for the 3D Seismic Survey to be conducted in the region during the summer of 2013-14.

By measuring the porosity and permeability we can calculate the likely volume of the storage interval, in this case the thick sandy Wonnerup Member. Porosity and permeability measurements made on a number of samples have given us a range of values. Porosity ranges from 7-19%, while the permeability of the Wonnerup Member is from 0.01 to 580 mD. Rocks used for the storage of CO₂ or good oil reservoirs (these rock bodies tend to require similar properties) have values similar to those observed.

The overlying Yalgorup Member is more variable, with lots more different facies types (Figure 6 and Figure 7). Direct and indirect measurements of rock properties, such as porosity and permeability, can be taken using wireline logging tools. These are sent down the well to measure the rock exposed during drilling. Results can be compared with the real rock samples measured in the lab to calibrate the wireline measurements to give a good indication of what the properties might be. Results from the laboratory measurements (Figure 6) show that the different facies have different ranges in porosity and permeability again adding information to our evaluation as to whether we have an interval that can take up large volumes of carbon dioxide over long periods of time. However, as the shale-rich samples could not be prepared for these measurements (they broke up into small pieces) there is a large representation of the sandy facies over the more sealing shale-rich facies.

Figure 6 Composition of the Yalgorup and Wonnerup Members of the Lesueur Formation by facies type. Note that the Yalgorup has a larger proportion of the finer sediments (facies D to G) which tend to be more muddy or shaly than the sandstone rich Wonnerup Member containing predominantly facies A. Images modified from Delle Piane et al. (2013).

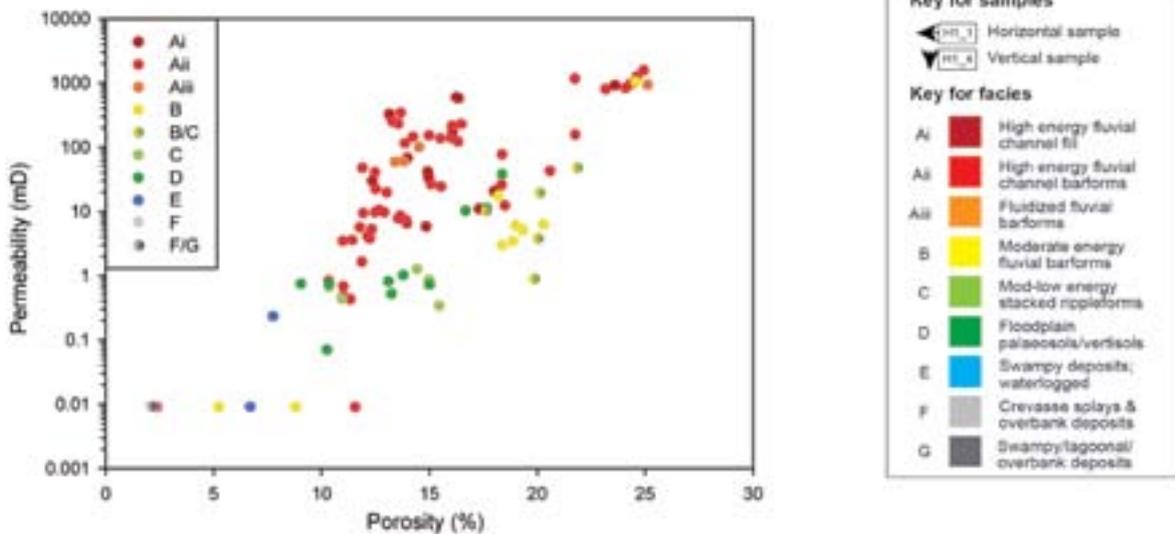
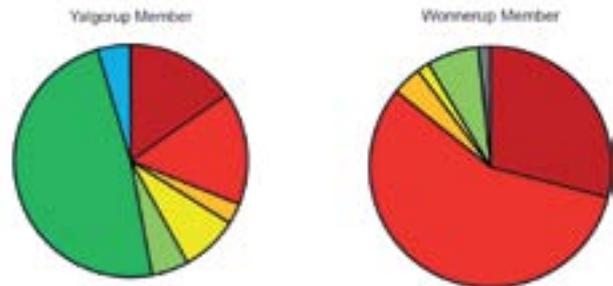


Figure 7 Porosity and permeability measurements for selected samples from the Yalgorup and Wonnerup Members in Harvey 1 measured in the laboratory by helium injection methods. Note that there were only a few samples that could be measured from the more shale-rich facies as they broke up on preparation and could not be measured. The data show that the facies Ai-Aiii (that make up most of the Wonnerup Member) have relatively higher porosity and permeability making for a good storage interval, while the low porosity and permeability of the more shale rich intervals of the Yalgorup Member will act as barriers or sealing units. Figure from Delle Piane et al. (2013).

Outcomes of the Facies Project

- The targeted reservoir in the Wonnerup Member of the Lesueur Sandstone has thick continuous intervals of clean, coarse-grained sediments with very few mudstone intervals. This is confirmed via both sedimentary logging of the cores and interpretation of the wireline logs.
- The porosity, permeability and significant thickness of the Wonnerup Member suggests it will be a good storage interval.
- The Yalgorup Member shows strongly interbedded facies succession. The facies are relatively thin.
- Some of the shale/mudstone in cores 2-4 is significantly intruded by sandstone dykes and affected by brittle deformation at the centimetre to metre scale.
- Overall the presence of inter-layered shale and sands on top of the reservoir may act as a barrier to vertical fluid movement.
- Drilling operations have identified the presence of the Basal Eneabba Shale (625-704m) overlying the Lesueur Sandstone. The Basal Eneabba Shale was not cored but is thought to potentially provide additional sealing potential to the geosequestration site.
- Using the industry measure of Net-to-Gross (NTG) to describe the relative amounts of shale to sand (parameters used were a shale volume cut-off of less than 20% and effective porosity larger than 8%) NTG values of 78% and 48% were computed for Wonnerup and Yalgorup Members respectively.
- Assuming a laterally continuous and homogeneous reservoir, the permeability in the horizontal versus vertical directions observed (the anisotropy) may be beneficial in terms of CO₂ injection, as the fluid will move laterally with ease into the formation, while any vertical or upward movement of the CO₂ would be hindered by the more limited permeability vertically through the sediments.

The above evaluation indicates favourable conditions in the Wonnerup unit for potential storage of CO₂ and residual trapping as a realistic containment strategy.

No elements could be identified that suggest postponing or cancelling further investigations around the feasibility of the South West Hub geosequestration site. However, further research is required to evaluate the lateral continuity of the different facies across the wider area for sealing and reservoir units to be better defined.

5. Geochemical Characterisation of Gases, Fluids and Rocks in the Harvey 1 Data Well

Investigating the presence of oil and gas in the rocks

Geochemists from CSIRO found evidence of hydrocarbons in several core samples, however the highest amount of 305 mg/kg is still small compared with oil and gas finds. Other samples contained an average of only 38 mg/kg which is regarded to be of insignificant quantity.

Vitrinite data, where coaly particles are measured to see how deep and hot a formation has become over geological time, was limited but showed that at shallow levels (900m) there was no generation of hydrocarbons possible. By depths of 2500m any organic matter present would have been heated sufficiently to be able to expel oil.

However, as the various A facies in the deeper Wonnerup Member are very clean sands there is no organic matter present in them to act as a potential source rock that could be heated and converted to hydrocarbons near the Harvey 1 well, based on the current information.

Drilling Fluid Contamination – drilling fluids or muds are used to do a number of things during drilling such as:

- pressure control of any fluids coming out of the formation at deeper depths (e.g., oil and natural gas),
- cooling of the drill bit,
- aiding in the recovery of drill cuttings (rock fragments broken up during drilling and used to estimate which formation is being drilled), and
- limiting damage to the bore hole as it is drilled and before it is cased.

Drilling muds tend to contain relatively large volumes of potassium chloride (KCl) to add density to the liquid, or may even use barite (BaSO₄) to combat pressure in the well. Organic compounds may also be used to manage clays that can swell up on contact with water plugging the well. All of these compounds impact on the quality of the samples and basically cause them to become “contaminated”. The formation water sample and the core plugs were both found to be contaminated during geochemical analysis.

The Perth Basin does contain hydrocarbons, with several commercial fields found in the northern Perth Basin (Figure 8) such as the Dongara oil and gas fields towards Geraldton, while in the southern Perth Basin, the Whicher Range field is a prospective gas field that is under development.

No liquid hydrocarbons have been found in economic quantities in the general area, although this assessment is based on sparse data coverage. Future wells will continue to add information on the potential or absence of hydrocarbons in the area. The Harvey 1 well itself showed no evidence of gas during drilling and so there appears to be no basin resource management issues so far.

The Chemistry of the Ground Waters

A water sample was taken from the shallow bore adjacent to the Harvey 1 well which was accessing water from 36m depth. A deeper sample from the Harvey 1 well was taken at 856m. Both samples were pumped to the surface and analysed for their metals contents so that the salinity of the fluids could be determined.

The general area around the Harvey 1 well has fairly high levels of total dissolved solids (TDS) or salinity (Figure 9). The shallow bore reaches ground water from the boundary between the superficial aquifer and the Leederville Formation and has 458 ppm of total dissolved solids. This is in keeping with data from study bores in the region known as the Harvey Line and Binningup Line (Figure 10).

The deep water sample from 856m was contaminated with minerals from the drilling muds. As can be seen in Figure 10 there are very high levels of chlorine in the deep Harvey 1 sample which is from the potassium chloride (KCl) base ingredient in the drilling mud. The measured value for that sample is 52,320 ppm, some of which comes from the drilling mud contamination.

A comparison with all the available data from the Harvey Line and Binningup Line of bores, and some work on trying to “remove” the extra KCl by calculations and modeling, suggest that the water chemistry from HL2/A3 at 792m, shown in Figure 10, is probably the most representative of waters measured in the Eneabba Formation until new samples are acquired. Acquiring water samples from the Yalgorup and Wonnerup Members will be a major target for the next well drilled.

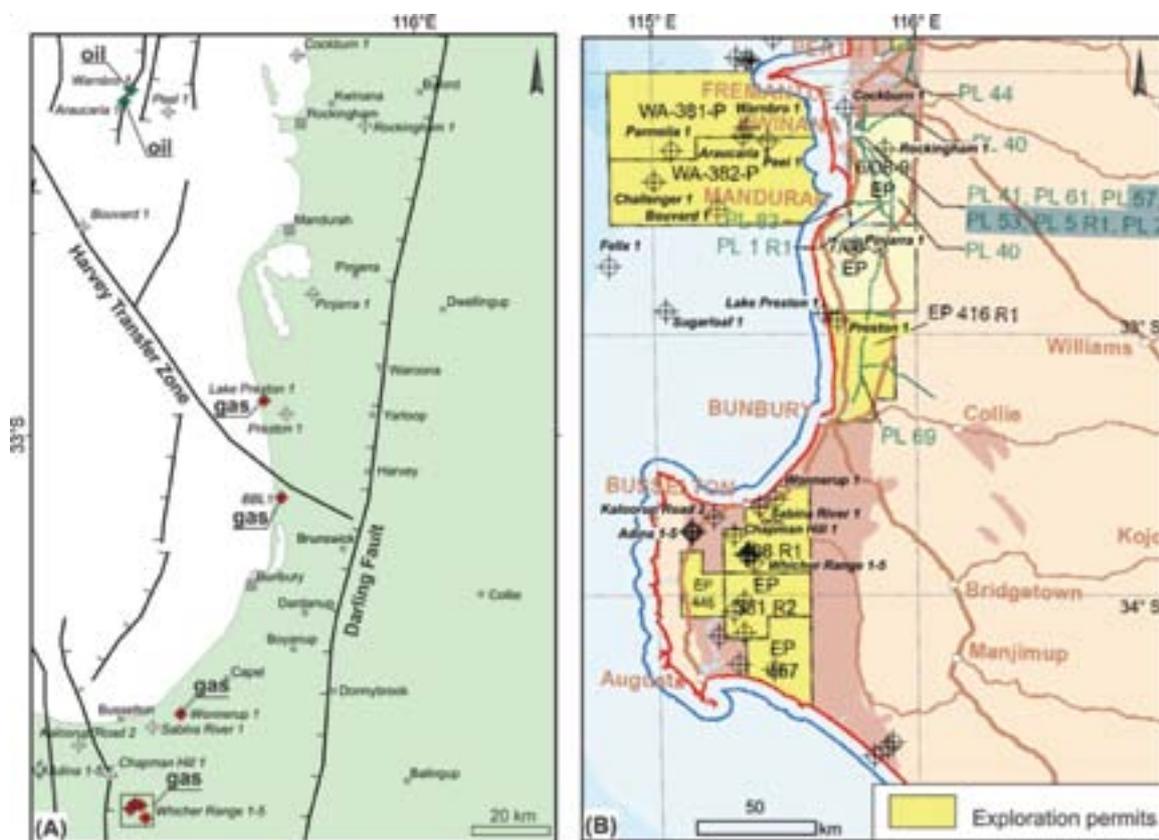


Figure 8 (a) A simplified map of the southern Perth Basin showing the wells drilled and encountered oil or gas shows (Crostella and Backhouse, 2000). (b) A map showing the exploration permits in the Southern Perth Basin (DMP, 2012).

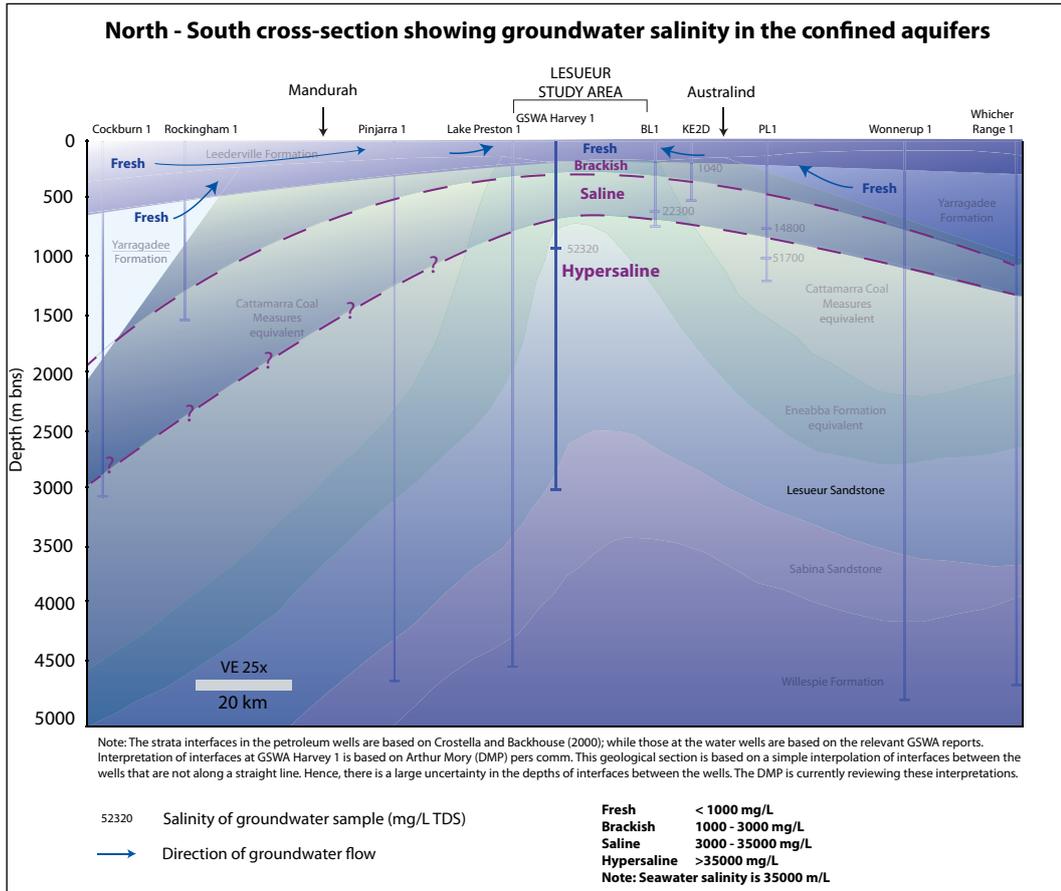


Figure 9 Schematic diagram of the salinity variation across the region from North (Cockburn-1) to South (Whicher Range) incorporating the structure and formation intervals with local wells and salinity information. Much of the data come from two papers by Deeney from 1989. Detailed results are presented in Figure 10. Source: Commander, P. 2013. Groundwater resources of the Lesueur carbon storage project area (SW Hub). April, 2013. Report for WA DMP

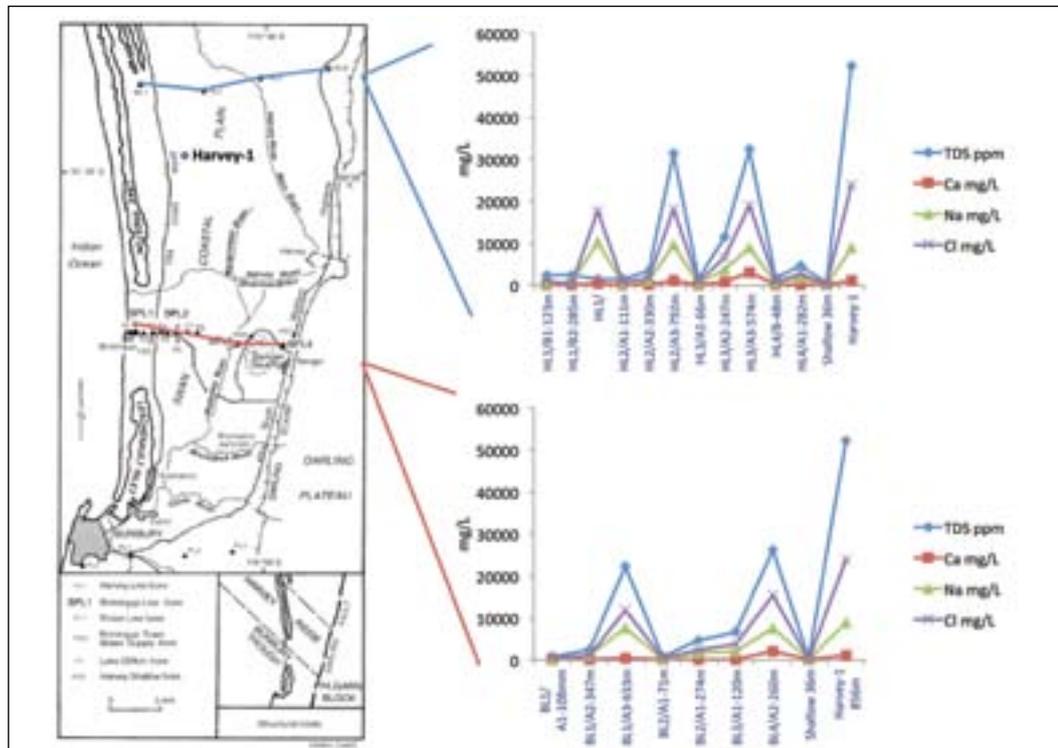


Figure 10 A map shows the location of the Harvey Line and Binningup Line of research bores as measured by Deeney (1989a & 1989b). The figure also shows the location of Harvey 1. The graphs show measurements of the formation waters from the Harvey Line, Binningup Line, shallow bore by Harvey 1 and Harvey 1 itself for comparison. Note the TDS are much higher in the deeper Harvey 1 well, partly due to drilling mud contamination in the case of the chlorine values and TDS. Calcium (Ca) and sodium (Na) values are unaffected by the drilling muds and are much more comparable for the deeper bores.

Do the rocks react or change when CO₂ is passed through them?

The research team were able to conduct one preliminary test on a core sample to see what might happen when CO₂ passes through the rock. The rock sample from the proposed storage interval, the Wonnerup Member, underwent a series of tests within the Facies Project for characterisation before being placed in a large core flooding device (Figure 11). This allows researchers to push water (made up with some “salts” to mimic the groundwaters and saturated with CO₂) through the rock and see what changes occur. Two things can happen; firstly the CO₂ which in water becomes carbonic acid, can potentially dissolve some of the minerals present in the rock, secondly the fluids being passed through the rock can push small clay particles around and they can get stuck in some of the small pores and reduce the permeability of the rock. Understanding how much mineral dissolution or clay and fines mobilisation is occurring can increase our knowledge about the injectivity of a rock when we start to store CO₂ in that formation in the subsurface.

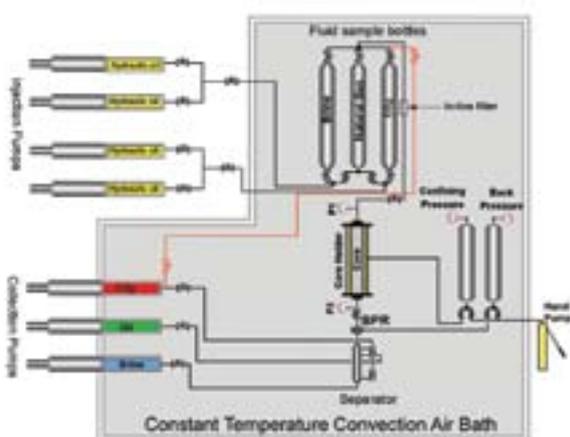


Figure 11 Photograph of the core flood equipment used to flood the Wonnerup Member sample, with a schematic of how the temperature and pressure of different parts of the system are controlled for the flooding (images from A. Saeedi, Curtin University).

The fluids were collected during this flooding experiment and measured for changes in chemistry. The results showed that some minerals did show signs of dissolving. This means that the passage of CO₂ can make more “space” or increase the porosity and therefore storage capacity of the rock. However, we also saw evidence for moving some of the fine clay particles which could reduce permeability or the rate at which we can inject. Only one sample has undergone this preliminary testing and it is expected that we will look at more of the core samples in Harvey 1 and in the future wells.

Outcomes of the Geochemistry project

- Extraction of the core plugs showed that while there were some hydrocarbons present in both the core and drilling fluids, the richest core sample has only a total extractable organic matter content of 304.93 mg/kg rock. The volumes measured were insignificant compared with source rock extracts or amounts seen in sandstone dominated hydrocarbon reservoirs which might contain upwards of 100,000 mg/kg rock.
- These low volumes indicate that there is no active source rock of quantitative significance in the immediate area of this well and means that there is unlikely to be any form of basin resource management issue in relation to oil or gas finds in the immediate area. Lack of organic rich rocks in the well indicate no local source rocks that could act as hydrocarbon producers.
- A shallow well adjacent to the Harvey 1 well was used as a water source for drilling Harvey 1. A sample from the slotted interval at 36 m was analysed and compared with regional data. The depth is close to the surficial aquifer/Leederville Formation boundary. It contained TDS (total dissolved solids) values of 458 mg/L and the chemistry of the formation compared broadly with the compositions reported for some wells in the area that intersect the Leederville Formation.
- Only one deeper sample was provided from the Harvey 1 well itself. The uncorrected value (i.e. impacted by drilling mud) for total dissolved solids (TDS) of 52,319 mg/L is higher than that calculated from wireline petrophysical log interpretation (40,000 mg/L in the Yalgorup and 30,000 mg/L in the Wonnerup Members).
- The variation in TDS, calculated using the wireline log data, between the Yalgorup and Wonnerup gives the first indication that there may be a barrier or seal between the units.

- Initial modelling of CO₂ injection into rocks from Harvey 1 showed that only moderate changes may be observed. Much more can be done with the data set in the future when better quality fluid samples can be obtained and analysed to confirm the chemistry of formation fluids for all the different intervals.
- The report provides one of the most detailed analyses of core flood effluents conducted and demonstrates the effects of the presence of carbonic acid on clay minerals. Both chemical changes and (based on results from Delle Piane et al, 2013) fines mobilisation has an impact on the behaviour of this single rock sample from one facies. Because this is only a first test of this approach, further work on more samples would have to be conducted to confirm the contribution and rates of change to any samples from Harvey 1.
- Initial modelling of CO₂ injection into rocks from Harvey 1 showed that only moderate changes may be observed. Much more can be done with the data set in the future when better quality fluid samples can be obtained and analysed to confirm the chemistry of formation fluids for different intervals.

In conclusion, this current geochemical evaluation of the Harvey 1 well has used a combination of standard and novel techniques to show that with the current data the geology in this area appears suitable for geological storage of CO₂. In future more samples will be collected, analysed and integrated with this information.

6. Advanced Geophysical Data Analysis for the South West Hub Harvey 1 Well Site

A team of geophysicists from Curtin University, the University of Western Australia and CSIRO collaborated to use a variety of data types and research methods to enhance the new and existing geophysical data from the South West Hub project. Drilling Harvey 1 has provided new data sets that include the wireline log data and specialised seismic profiling and these can be integrated with some of the physical rock measurements.

Furthermore, the team has also gone back to the data set from the 2D seismic survey acquired in 2011 (Figure 12). Basic image processing had been conducted on the 2D data set, but by applying a range of advanced data analysis techniques to both the 2D seismic raw data and the new Harvey 1 well log data, better processing and interpretation of the data could be conducted.

This allows:

- Improved storage site characterisation – with better subsurface mapping to be conducted,
- Leading to better defining storage capacity and resulting in containment security risk reduction, and
- Optimising the design of the upcoming 3D Seismic Survey to acquire the best possible new data set.

The team were able to show in their study that by improving the processing of the data (Figure 13) the raw data could be enhanced so that interpretation of the location of the formation intervals could be mapped more clearly. Faults could be better imaged so that their locations could be more precisely defined deep underground. The team also noted that there are some difficulties with the shallow coastal limestone near the surface (top 100m) in some areas – this formation disturbs the signal during acquisition and is difficult to correct for. Furthermore, surveys along crooked lines (Figure 12) for the collection of seismic data make interpretation and processing much more difficult and time consuming to correct.



Figure 12 Location of Harvey 1 and the 2D seismic lines run along a series of roads in the region to obtain preliminary information on the structure of the deep subsurface to locate the Harvey 1 well.

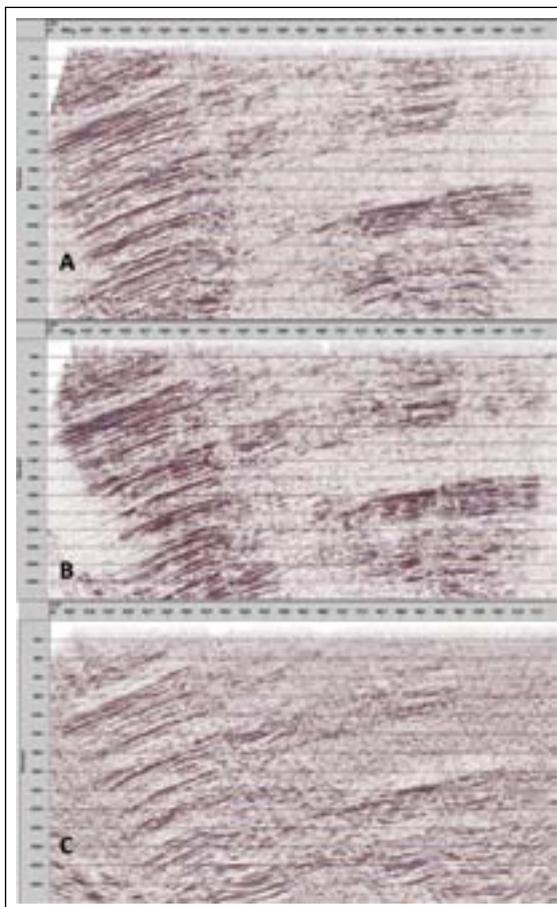


Figure 13 Different steps in the processing of the 2D seismic data from the 2D survey to improve quality for better interpretation. Line 11GA-LL2 CDP time stack before (a) and after migration (b - post-stack, c - pre-stack). Figure from Pevzner et al. (2013).

Evaluations of the stresses in the region were updated based on the new information acquired in the Harvey 1 well. The variation in stress fields at different depths and different formations was complex, as is the process of assessing those stresses (Figure 14). The stress regime proved complex and caused significant problems during drilling. In fact, this contributed to the loss of the MDT tool when breakouts occurred in the open well, jamming the tool. (See wireline tools on page 10).

Integrating this data with regional information showed that the stress regime observed in Harvey 1 was broadly consistent with existing data reported for the Perth Basin.

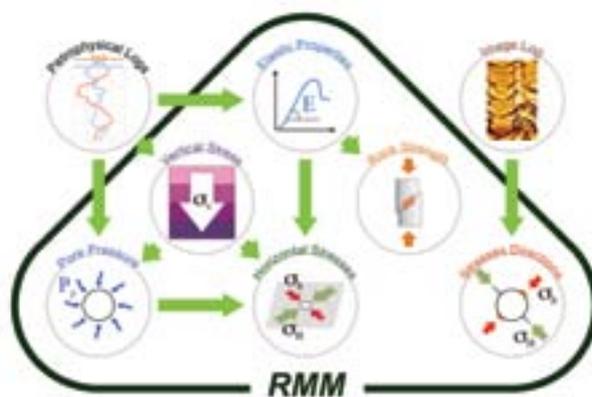


Figure 14 Work flow used to build a Rock Mechanical Model. Figure from Pevzner et al. (2013).

Most of the borehole breakouts and adverse drilling events occurred during drilling of the Yalgorup Member, so the wireline data is poor in this interval. This is consistent with the problems of preparing good Yalgorup samples in the Facies project when attempting to make some of the laboratory measurements. This means that for future wells new drilling programs need to be developed to define and overcome the difficulties of collecting data in the Yalgorup Member so that it can be better characterised.

The research on the geophysical aspects of the 2D seismic survey and the Harvey 1 well logging data have provided many recommendations on how to better utilise the existing data and how to prepare, design and execute the 3D Seismic Survey to be commissioned by the WA DMP in early 2014.

Outcomes of the Geophysics project

- The seismic data quality varies strongly with spatial coordinates, generally improving from west to east,
- Major faults tend to strike NW-SE,
- Strong near-surface (e.g. top 100m) velocity variations are present in the area, probably due to the shallow coastal limestone (high velocity) layer which dips from west to east. This interference is not easily corrected so advanced techniques will be required to develop the 3D Seismic Survey and subsequent data processing.
- Careful processing of all seismic data is required based on the experiences of working with the 2011 2D seismic data.
- The mechanical properties of the Yalgorup member are significantly weaker than that of the Wonnerup member.
- The results of rock mechanical modelling (RMM) confirmed that the dominant stress regime in the study area is a strike-slip regime.
- Most of the breakouts and drilling events observed from calliper logs and reported in the drilling and well reports were in the Yalgorup member, so the next well drilling program will have to be modified to ensure the best possible bore hole conditions to retrieve data from the upper, more shale-rich layers to characterise the potential sealing intervals.

The results of this project suggest that there can be major improvements made to the 3D Seismic Survey to be conducted in 2014 and that future wells can provide even more high quality data to characterise the storage capacity, containment security and injectivity going forward.

Geophysics – is the study of the physical aspects of the earth. This includes using seismic (noise), magnetic, gravity or electrical properties of different rock layers to survey the near- and subsurface so that geologists can understand the properties of rocks at depth without actually sampling them.

Geochemistry – is the chemical study of rocks and materials in the subsurface. Here the chemical data can provide abundant geological information to help in the understanding of how rocks were formed or how they might react if the rocks are changed (buried deeper, heated up, fluids passing through the rocks etc.)

7. Stratigraphic Forward Modelling – Static Model

There are a number of ways to attempt to map the geological intervals and structure in the subsurface and a variety of data sources can be used to develop those models. One approach which is unique to CSIRO is to use a software tool called SEDSIM, which simulates the sedimentation of rock bodies to build up a conceptual model of how the geology evolved from the deposition of the first grains of sand to the solid rock bodies we drill through today. Information used to develop the current model includes:

- Wells drilled over a large area containing information on the formation depths and key rock properties (Figure 2),
- Seismic data obtained at different times, which may undergo re-processing for better definition of current day surfaces of the different intervals,
- Other examples of ancient features that might be geologically similar,
- Modern analogues – i.e. current day features such as looking at active river systems in environments that would have been equivalent to the conditions in the Triassic period some 250-200 million years ago when the Lesueur Formation was deposited (Figure 15), and
- Conducting a blind test of the model to see if it could predict the observations in Harvey 1 to assess model suitability before refining it further.

The goal of the project was to build a static model that can determine the distribution of grain size, porosity and by calculation methods to predict likely permeability for a large area including and away from the Harvey 1 well. But, to test whether the model is sensible, the data from Harvey 1 was not included in the initial build.

Instead, with the knowledge described in the bullet points above and information in Figure 15 the model was built. The model (Figure 16) was then used to qualitatively and then quantitatively predict the spatial variation of different rock intervals or facies and their rock properties (are they low porosity shales or high porosity sands?) across the region, including the location of the Harvey 1 well.

This information can be used to better characterise the overall capacity the area has for CO₂ storage. The relative distribution of sandstones to shale intervals can be used to improve our understanding of containment security by providing input information to work out the extent of any sealing layers and the sealing versus open nature of faults in the area in the absence of 3D Seismic data or other wells in the area.

Testing the prediction of the model against what was found in the other projects reported here allows us to evaluate whether the predictions in the area around Harvey 1 were reasonable and if it is a good match, we can be confident that our predictions across the broader area are representative and can help us address the main issues of storage capacity, containment security and injectivity in the region for CCS.

Developing a static geological model takes a lot of information including facies data and considers the depositional environment – as mentioned, the Lesueur Formation is made up of a fluvial or river system deposit. The depositional system is defined by the energy of the system.

By this method, we try to understand the river's capacity to erode, transport and deposit materials (think of large boulders and pebbles as high energy activity while a sluggish, slow moving river will lack the energy to carry anything but mud particles). The direction of flow, how continuous the energy is maintained or changes are all part of trying to understand how the rocks were deposited and distributed.

By understanding natural systems and comparing with the limited subsurface data, a model is created that can be used to help us visualise the subsurface and be used in the data integration for the region and allow us to see what is beneath the southern Perth Basin (Figure 16).

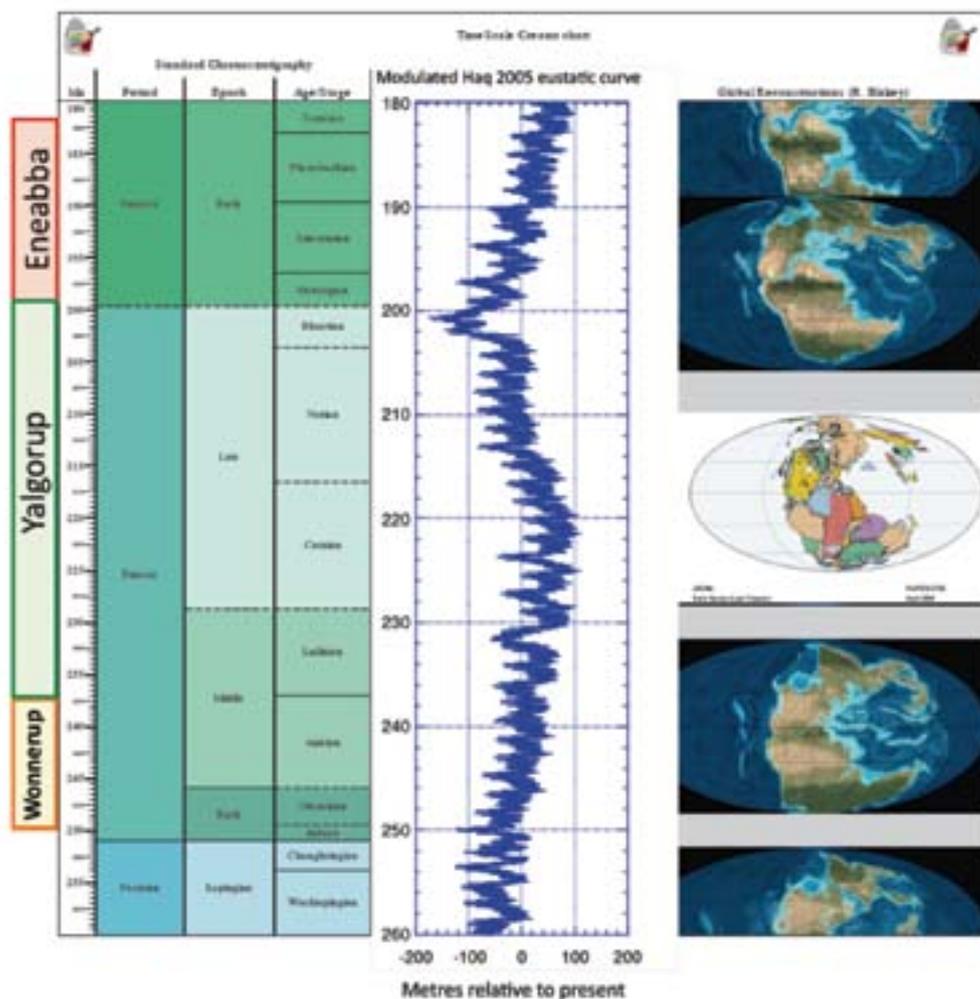


Figure 15 Examples of some of the information used to construct the model. Local geology is shown on the left and the key timelines. In the centre is a sea level curve (indicating the relative rise and fall in sea level over the Triassic). On the right, the likely location relative to different continents, latitude and longitude that impact on the climate in the area during the Triassic Period of the Perth Basin. Figure from Griffiths et al. (2012).

In Figure 16, one output from the static model that provides some insight into the amount of porosity in each interval, is the layers of sandier versus more shale-rich intervals in the area estimated by the model. Shallower sediments/rocks in general tend to have higher porosity because there is less rock above to compact the sediment “squeezing” all the particles together and minimising pore space.

Deeper rocks are relatively less porous because the weight from the overlying rocks provides higher pressures to more effectively squash the rocks together and reduce pore space. This reduction in porosity with depth is relative to the type of rocks, as the photomicrographs show (Figure 16), with differences in porosity due to the grain size of the rocks where larger grains in sandstones tend to allow for bigger pores.

Also consider that the shale layers in the higher intervals could act as baffles or seals restricting any upward movement of CO₂ from the sandstone layers that act as good storage containers deeper in the formation.

Even with the new data from the 2D seismic survey and the Harvey 1 well, data was quite limited in the region. That said, with the drilling of the new well, and the information obtained from the Facies-Based Rock Properties Distribution Along the Harvey 1 Stratigraphic Well Project reported above, allows some level of integration of the data to make good approximations for parameters for the model that make reasonable

geological sense. For example, using the observed sand to shale ratios from the facies analysis and descriptions to test the preliminary models and fine tuning them with the observed data from Harvey 1 adds to the robustness of the model.

Outcomes of the Sedimentary Forward modelling project

- The first ever stratigraphic forward model has been created for the southern Perth Basin of the Triassic and Early Jurassic sediments (from 250 million to 182 million years ago).
- A blind test has been conducted that does a reasonable prediction of the porosity distribution in the area, through predicting the likely patterns in Harvey 1 and then comparing it with observations made in the Facies Project. This shows that the model makes sense and can suitably predict key geological features with which to understand the area for potential CCS activities.
- As well as the porosity, shale and sandstone intervals have been predicted that facilitate the narrowing down of areas for locating future stratigraphic wells.
- A new project has commenced to develop this model further and will at some point integrate future wells and the upcoming 3D Seismic Survey information.

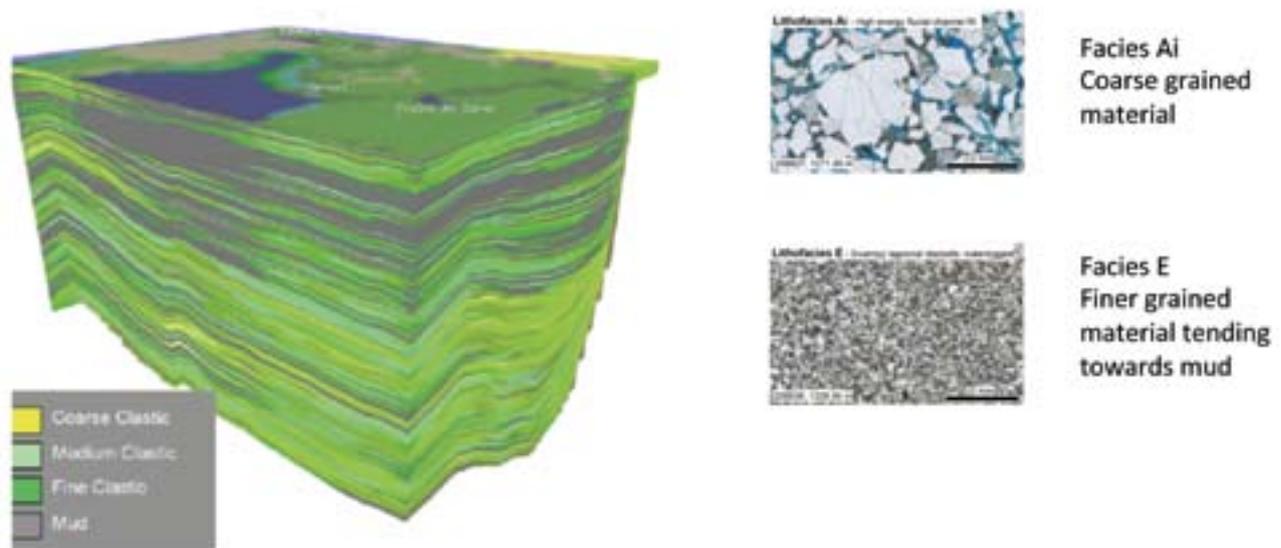


Figure 16 A SEDSIM model prediction shows a representation of the level of sandy versus more shale-rich intervals across the region, and how they are distributed across part of the area including the Harvey 1 well. The photographs of the coarsest Ai highest energy facies has large grains and lots of pore space (the blue staining on the slide) while the lower energy Facies E material is much finer grained and has far less porosity (much less blue). Figure from Griffiths et al. (2012).

8. 1. Integration of Data from Harvey 1 Well to Support Decisions – Fault Seal

This project relies on the available subsurface data and carries out a first-order assessment of the CO₂ containment potential for the South West Hub. In this data integration project, conducted by CSIRO, a range of information sources are used to further understand the regional geology and structure in the area including;

- Stress data from the Geophysics Project,
- Geological depositional models, facies characterisation and rock properties from the Facies project, and
- 3D models from the Stratigraphic Forward modelling project.

In this project, data from the 2D seismic survey and the Harvey 1 well have been combined to carry out a first pass at assessing the CO₂ containment potential for the area of investigation around the South West Hub.

A new geological model has been built that is consistent with the 2D seismic data from 2011, but also looks at

An unconformity – is the name for a geological feature where during sedimentation there is an unexpected break. This break can be the result of a body of rock being exposed to the earth's surface and then some of the rocks are subsequently eroded away, followed by new sediments being deposited over the top. A long period of non-deposition, resulting in the rocks being exposed to the surface and then being weathered also produce these features (see Figure 17 where the Neocomian Unconformity is shown).

older vintage seismic lines to cover a wider area. Some of this information was used to develop input parameters for the Stratigraphic Forward Modelling project discussed above. Other geophysical data from the recently drilled Harvey 1 well has been added in.

Well data (core samples and wireline log data) from Harvey 1 allows the integration of five key horizons or intervals to be tied between the well and the 2D seismic data to enable mapping of major intervals across the region (Figure 17). Main intervals include the top of the Eneabba shale, top Yalgorup Member, top Wonnerup Member, top Sabina Formation as well as a shallow unconformable layer called the Neocomian (Figure 2 & 17). These can all be mapped and locations of faults superimposed as is seen in Figure 17 & Figure 18.

Only faults that could be correlated between at least two of the 2D seismic lines (Figure 12) that show appropriate characteristics for mapping on a large scale were included in this study (i.e. those with constancy in dip, strike orientation and offset), resulting in the investigation of 13 main faults (Figure 18).

From this activity the researchers were able to begin preliminary investigations into the following;

- What would the impact be on any membrane seal capacity of faults (either across the faults or along the faults) with injection?
- What is the impact of pore pressure and stress field changes caused by CO₂ injection?
- Could slip along the faults be triggered by CO₂ injection leading to leakage from the storage interval into an overlying formation?

Membrane fault seal capacity has been assessed using a predictive method where the Shale Gouge Ratio (SGR) is calculated for sections along each fault (Figure 19). This approach is used to see at which point the fault will begin to allow movement of CO₂. In brief it measures the ratio of sealing type rocks (such as shales and clays) pressed against non-sealing rocks (sandstones). As the faults move there is grinding up of the rocks on either side and the type of gouge generated may be a thick enough layer of fine material to act as a seal.

This approach is frequently used in the oil and gas industry; if faults are open across the oil field, fewer wells need to be drilled, saving on costs; but if some faults are closed, a well has to be drilled into each fault block to recover hydrocarbons from that isolated area.

In the case of research into CO₂ storage, understanding when a fault might become open to migration of CO₂ can be described as how much CO₂ has to push on the fault before it transitions from sealing to open. This can be measured as the number of metres high the column of CO₂ would be, pushing against the fault, increasing the pressure.

SGR values on some of the fault planes suggest an “average to low” likelihood of across-fault migration and the supported CO₂ column before breaching the membrane seal is between 110m and 1100m.

Taking all this into consideration with the understanding of the stress fields and likely changes in pore pressure, if CO₂ were added during injection, the integrated interpretation shows a summary of the possible fault behaviour (Figure 18).

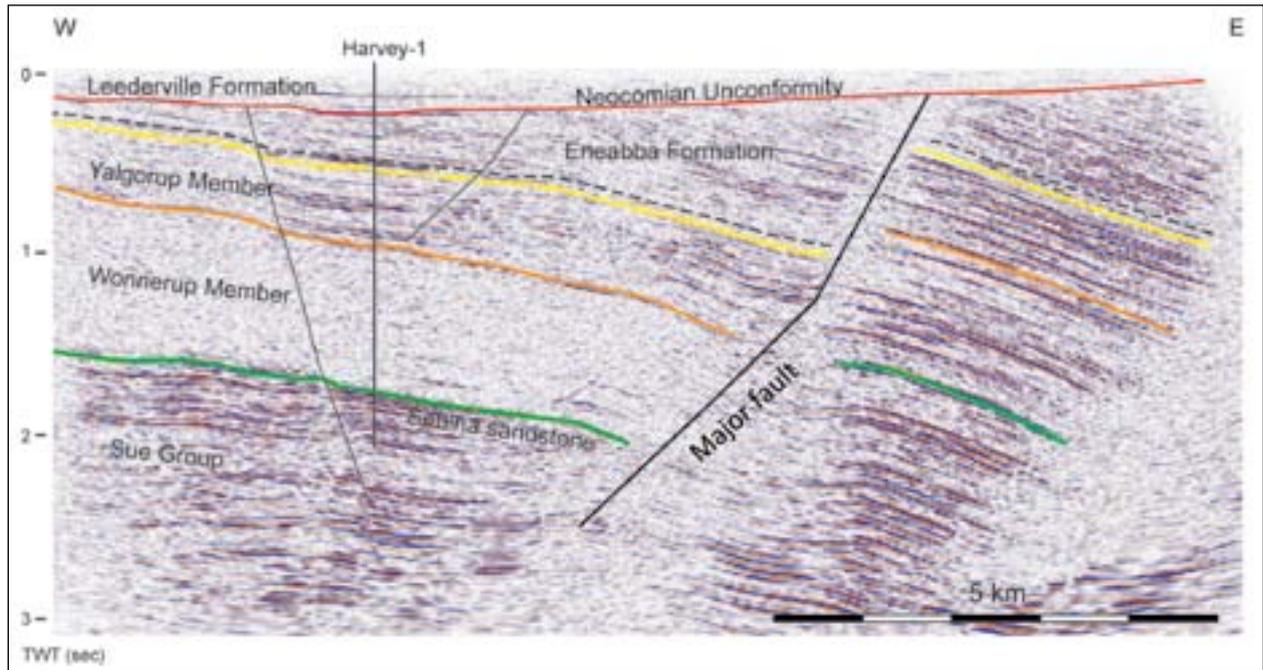


Figure 17 Seismic line 2011 2D GA L2 through Harvey 1 showing the mapped horizons to ~4km depth. The 2D Seismic Line is from west to east just south of Harvey 1 11-GA LL2 (see Figure 12). The depth is not shown, instead, two way time (TWT) in seconds (how the data is acquired) is shown which can be converted to depth using the Harvey 1 data to convert. Figure from Langhi et al, (2013).

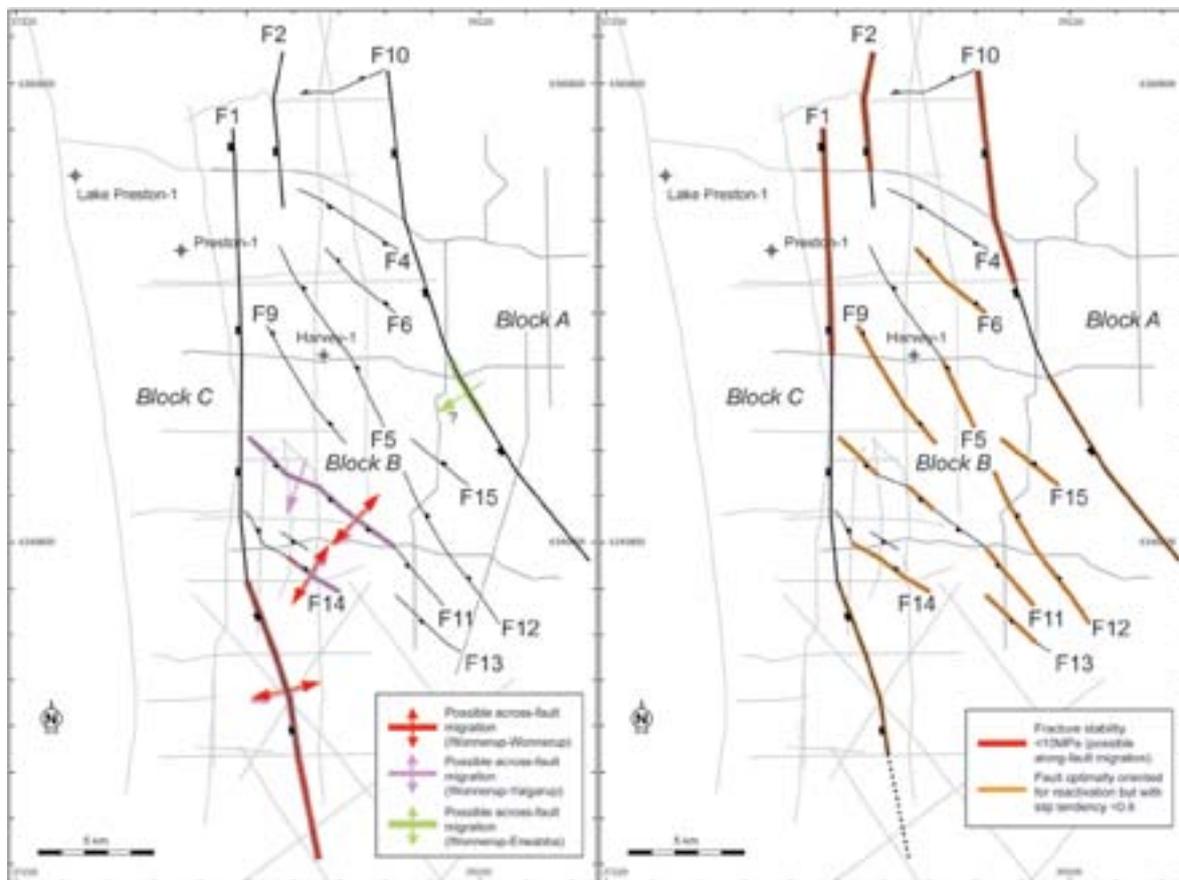


Figure 18 Summary of across-fault (left) and along fault (right) CO₂ migration potential for the South West Hub. Figure from Langhi et al, (2013).

The three different relationships between the main geological formations have been investigated as a part of understanding fault behaviour;

- A fault where the Wonnerup member is against another part of the Wonnerup,
- A fault where the Wonnerup Member is against the Yalgorup, and
- A fault where the Wonnerup is against the Eneabba Formation.

The side-by-side position of the different units, geological properties, stress regime, Shale Gouge Ratios (SGR) and other factors are used to calculate likelihood of migration of CO₂ across each fault. These factors indicate that the southern end of the broad area of investigation has a greater likelihood of cross-fault migration than the north.

More work needs to be done when the 3D Seismic Survey is conducted and better models of the subsurface can be developed, with better mapping of faults and more accurate SGRs calculated. Because only limited 2D seismic data has been available so far it is likely that the number of faults has been underestimated, particularly in the case of smaller faults of less than 120m throw (i.e. distance of offset).

Outcomes of the Fault seal integration project

- SGR values on the fault plane suggest an “average to low” likelihood of across-fault migration and the supported CO₂ column before breaching the membrane seal is between 110 and 1100m.
- Some of the faults do have large throw distances (or offset).
- A low density of seismic lines and their relative location results in uncertainties on fault correlations, faults linkage, the definition of low displacement faults and the definition of the slip pattern on fault planes and allows only for the development of a regional first-order geological model able to map faults with displacements of greater than 200m. However this underestimates smaller structures.
- Harvey 1 is the only well in the South West Hub area which is reasonably tied to a seismic line. Knowing where and how thick sandstone versus shale intervals are against the faults to calculate the SGR is important, but the data so far are limited so there is a higher degree of uncertainty in the results. This will be vastly improved after the 3D Seismic Survey and the next data well drilled. However, a good approximation from the

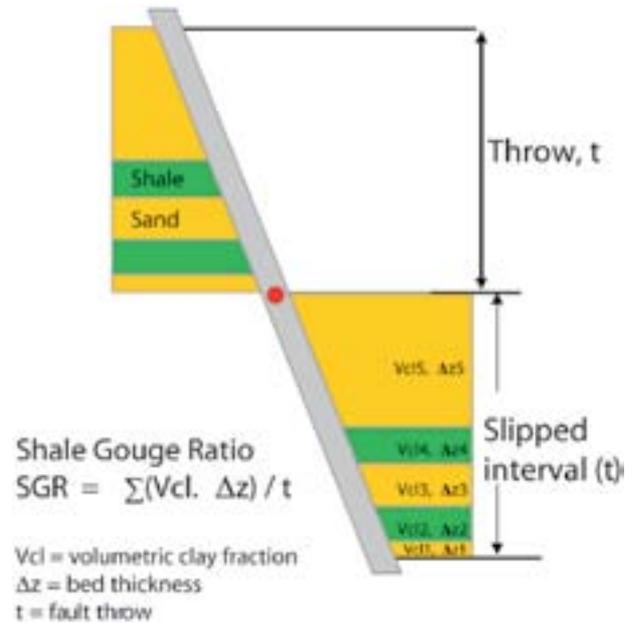


Figure 19 Schematic diagram showing definition of Shale Gouge Ratio (SGR), after Yielding et al. (1997). At any point on the fault surface, the SGR is equal to the net shale (or clay) content of the interval (t) that has slipped past that point. Figure from Langhi et al, (2013).

stratigraphic forward model has aided the analysis but results can only be described as first order.

- There is only limited information on the stresses in the region that will help evaluate any geomechanical fault seal assessment.
- Only 4 cores from Harvey 1 have been geomechanically analysed from the Wonnerup Member. The rock properties for the Yalgorup Member are estimated from velocity data and initially calibrated with data from the Wonnerup Member. This leads to uncertainty in the geomechanical fault seal assessment and the sub-seismic fault prediction. While some cores could be used from the Wonnerup in Harvey 1 to add to our understanding, the shale intervals in the Yalgorup are not able to be tested due to sampling problems.

The outcomes of this particular project are still preliminary. While there are a number of faults in the area, there is no suggestion at this stage that they are an impediment to the project proceeding. A better understanding of their location and behaviour will result from the 3D Seismic Survey and future well data.

Conclusions

The five major research projects conducted on data collected from the Harvey 1 stratigraphic well show there are no barriers to progressing through the feasibility phase up to the point when a commercial decision can be made.

The research conducted during the feasibility phase of the South West Hub project will be scrutinised and peer reviewed in the international scientific arena.

The successful outcome of each stage of the research determines whether the next stage will go ahead. If a stage is not successful the investigation will stop.

The Harvey 1 well research outcomes to date confirm the continuation of the feasibility project investigating CO₂ geosequestration in the Lesueur Sandstone formation in the Harvey Waroona area.

- 1. Facies-Based Rock Properties Distribution Along the Harvey 1 Stratigraphic Well.** Evaluation indicates favourable conditions in the Wonnerup unit for potential storage of CO₂. The presence of inter-layered shale and sands on top of the reservoir may act as a barrier to vertical fluid movement, therefore residual trapping appears to be a realistic containment strategy.
- 2. Geochemical Characterisation of Gases, Fluids and Rocks in the Harvey 1 Data Well.** All the data indicates that the properties of the Lesueur Sandstone make it suitable for CO₂ storage.
- 3. Advanced Geophysical Data Analysis for the South West Hub Harvey 1 Well Site.** Has identified where special focus is required to design an optimal 3D Seismic Survey to obtain the relevant information to better map the subsurface stratigraphy and rock properties, and identify sites for future drilling.
- 4. Stratigraphic Forward Modelling for the Lesueur Sandstone.** New data from Harvey 1 was combined with existing data to build a geological model which has proved reasonably accurate in predicting the geology at the Harvey 1 site.

- 5. Integration of Data from Harvey 1 Well to Support Decisions – Fault Seal.** Preliminary data from the 2D Seismic Survey and the Harvey 1 well was used to develop a map of the fault system in the area and these initial results are not a barrier to continuing the Harvey 1 feasibility study.

The project has obtained geological data through a 2D Seismic Survey and the Harvey 1 stratigraphic well, which has been combined and used to build a 3D model of the area of interest within the southern Perth Basin.

The first model of the Triassic and Early Jurassic sediments in the southern Perth Basin, created using computer generation supports the suitability of the reservoir for CO₂ storage.

While acknowledging that further information is required, the research has confirmed expectations about the area's stratigraphy and hydrology. It has not uncovered anything to indicate that the geosequestration research to evaluate the current area should be re-evaluated or a new area investigated.

Additional information and data will come from the upcoming 3D Seismic Survey, followed by further stratigraphic wells.

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