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The Australian South West Hub Project: Developing a storage project in unconventional geology.

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Abstract

The South West Hub project, through three generations of modelling based on new 2D and 3D seismic data and core/log information from four new wells is demonstrating that carbon dioxide storage is possible in an environment where there is no regional shale layer acting as a traditional seal. This paper summarises the work that has been undertaken in a collaborative manner into "unconventional geology" exploring migration assisted trapping in an on-shore saline aquifer by Government, private sector contractors and researchers in the south west of Western Australia.

Carbon Capture and Storage (CCS), which involves capturing carbon dioxide that would otherwise be emitted to the atmosphere and injecting it to be stored in deep geological formations, is a potential stepping stone to maintaining energy security while reducing the carbon footprint of Australia's energy sources. CCS is the only technology available to make deep cuts in greenhouse gas emissions while still using the fossil fuels that power much of today's energy infrastructure. At a State level, the Western Australian Greenhouse Strategy incorporates CCS and is helping to address the need for a long-term commitment to climate change and cleaner energy.

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The Western Australia Department of Mines and Petroleum (DMP) started investigating the Lesueur site, near large CO_2 emission sources (the industrial centres of Kwinana and Collie in the South West of Western Australia) in 2007 and developed the South West Hub (SW Hub) project concept in 2010 with the support of local industrial partners. The project was designated an "Australian Flagship" project in 2011 and has received substantial funding and support from the Federal Government, through the Department of Industry Innovation and Science) the Western Australia State Government and industry.

The SW Hub Project is progressing data acquisition and analysis aimed at establishing confidence in storage associated with migration assisted trapping (MAT) in unconfined saline aquifers. The storage complex has no regional shale layer and consists of the Lower Lesueur (Wonnerup Member) as the injection reservoir, the Upper Lesueur (Yalgorup Member) with its numerous paleosol baffles as the lower confining layer and the basal shale part of the Eneabba Formation as the upper confining layer. The injection reservoir is a heterogeneous sandstone that is over 1500 m thick with varying permeability layers that should support residual and solubility trapping.

From the very onset, the SW Hub Project has followed a rigorous stage gated decision making program. The project has been divided into phases and each phase involves targeted data acquisition plans to address technical gaps or uncertainties. These uncertainties have been documented in an Uncertainty Management Plan (UMP) and drive all technical work. "Decision Gates" ensure that, only on increased confidence of success would the project move to the next phase. The project processes are consistent with the DNV CO2QUALSTORE* steps and the workflows defined in the EU Directive 2009/31/EC guidance document.

Under the first phase of the new data acquisition program (2011-12), new geological data was gathered through 100 km of targeted 2D seismic lines and one deep exploration well drilled to 2,945 metres. Multiple modelling scenarios with differing assumptions on the geological properties supported the storage concept and identified no "show stoppers". Notwithstanding, uncertainty planning required additional data to address the gaps identified. Under the next phase of the development program (2013-15), 3D seismic was acquired over 115km^2 and additional wells planned. The area of interest is dominated by farming activity and not all landowners provided consent to acquire the seismic data. As such, while high fold data has been acquired over the deeper Wonnerup Member reservoir sections, the shallower Yalgorup Member was not as well illuminated. The drilling strategy was adapted to maximise geological coverage particularly across the shallower reservoirs. Three wells were drilled using a combination of mineral and water well drilling rigs with a deeper well to be considered following model updates.

Significant technical work has also been done to support this development through a range of research projects launched under the auspices of the Australian National Low Emissions Coal research and development program (ANLEC R&D). These projects are focused on reservoir characterisation and either consider more fundamental physics based questions or delve significantly deeper into specific geology and geophysics domains using laboratory and modelling efforts.

Clear decision criteria to support additional investment in a drilling and testing program have been defined and will be addressed by modelling. The paper will explain the project challenges and the decision making rationale, highlighting the importance of good processes, long term planning, and extensive stakeholder management supported by a robust technical program.

Results to date support MAT and validation of the SW Hub storage concept will substantially increase the number of geologic sites that can be considered for safe storage around the world. There is significant international interest in the project field and research activities.

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* CO2QUALSTORE is a guideline for selection and qualification of geologic storage sites developed by Det Norske Veritas (DNV) as part of an industry driven project in 2009. RPJ-203 are the recommended practices.

Keywords: South West Hub, SWH, CCS, CO_2, Geosequestration, Policy, Legislation, Regulation, Community, Wonnerup; Yalgorup, Lesueur

1. Introduction

The Western Australian (WA) Greenhouse Strategy [1] incorporates the technology of carbon capture and storage (CCS) and recognises its potential for greenhouse gas abatement. Accordingly the WA State Government Department of Mines and Petroleum (DMP) developed a strategy to identify suitable areas for storage within its jurisdiction [2].

The region from Kwinana through to Collie in the south west of Western Australia is one of Australia's major industrial areas generating billions of dollars of domestic and export revenue. The area is also one of the major CO_2 producing regions in Australia. The DMP identified the Lesueur Formation in the Collie-Harvey region as having significant storage potential through a number of targeted studies in the period 2007-2010. The storage concept was based on migration assisted trapping (MAT) in unconfined saline aquifers. The target area has no regional shale layer and consists of the Lower Lesueur (Wonnerup Member) as the injection reservoir, the Upper Lesueur (Yalgorup Member) with its numerous paleosol baffles as the lower confining layer and the basal shale part of the Eneabba Formation as the upper confining layer. The injection reservoir is heterogeneous and over 1500 m thick with varying permeability layers that should support residual and solubility trapping as the primary containment mechanism [3]. This work identified a number of geologic uncertainties for the area. Static and dynamic models were created based on sparse 2D seismic, logs from wells that were drilled in the 60's and 70's and outside the area of interest and core data from an offset well over 30 km away. Many assumptions were made to build these models since there was limited data. The results were promising and on that basis additional 2D seismic was acquired and well GSWA Harvey 1 (Harvey 1) drilled during 2011-12. The new data was interpreted and reservoir models created to evaluate the site potential for storage. The modelling results, whilst promising, identified key uncertainties relating to containment and injectivity [4][5].

An Uncertainty Management Plan (UMP) was created to address these and new data has been acquired through 3D seismic acquisition (2014). The area of interest is dominated by farming activity and not all landowners provided consent to acquire the seismic data. As such, while high fold data has been acquired over the deeper Wonnerup Member reservoir sections, the shallower Yalgorup Member was not as well illuminated. The seismic data was augmented by a targeted high resolution square km seismic (Curtin University 2014). The drilling strategy was adapted to maximise geological coverage particularly across the shallower reservoirs. Three new wells DMP Harvey 2, 3 and 4 (Harvey 2, 3 and 4) were drilled (2015) using a combination of mineral and water well drilling rigs with a deeper well to be considered following model updates. Guided by the UMP, these wells penetrated only the top 100-200+ m of the Wonnerup Member as the DMP's objective for this campaign was to focus on understanding the complex layering of sand paleosol sequences and containment properties of shallower horizons within different fault blocks, prior to investigating injection potential of the target deep reservoir.

Detailed 3D seismic processing and interpretation has been conducted. This together with the log and core data from wells Harvey 1, 2, 3 and 4 have been used to build the next generation of static and dynamic models using industry standard software. Multiple scenarios have been modelled and the technical workflows and results have been peer reviewed. The results and recommendations for future work are reflected in an updated UMP and are tested against an acceptance criteria which has been developed by the Petroleum Division of the DMP considering impending Greenhouse Gas Legislation in Western Australia and requirements for future acreage release for storage. These criteria are listed below:

- Deliver >P50 confidence to inject 800,000 t/a over 30 years;
- Deliver >P50 confidence that "the plume" remains below the basal Eneabba unit or 800m and within the storage complex for 1,000 years;
- Deliver a >P50 level of confidence that injectivity of > 100,000 t/a per well, i.e. no more than 10 wells in total would be required.

Whilst the modelling results are encouraging, it is recognised that there is no dynamic test data and only Harvey 1, the 3D seismic and the understanding of the geology can be used to predict the range of properties in the target injection horizon of the deeper Wonnerup Member. The major uncertainties can only be addressed through additional data acquisition – further wells and a specific test program.

The updated UMP will guide future activities. Initially these will involve further interpretation and modelling using already acquired core, seismic and logging data. Confidence in meeting the decision criteria will warrant additional acquisition through optimising the current well assets and/or the drilling of a deep well Harvey 5.

2. Site Location and geological setting

The stratigraphic sequence of the southern and central Perth Basin largely comprises continental deposits of Permian to Cretaceous age. Much of the sequence is associated with the tectonics of the region during this period from infilling and intracontinental rifting to the breakup of Gondwana and the separation of Australia and India. A rift complex developed in the area due to extension in a south-west direction during the Permian and Early Triassic. During this stage continental clastic deposits were dominant and widespread [6].

The study area is located in the onshore part of the southern Perth Basin, Harvey Ridge, between the Mandurah Terrace in the North and the Bunbury Trough in the South. The Harvey structure, is a N-S elongated fault bounded anticline. It covers an area of 332 km^2 and is located approximately 13km northwest of the town of Harvey south of Perth (Figure 1).

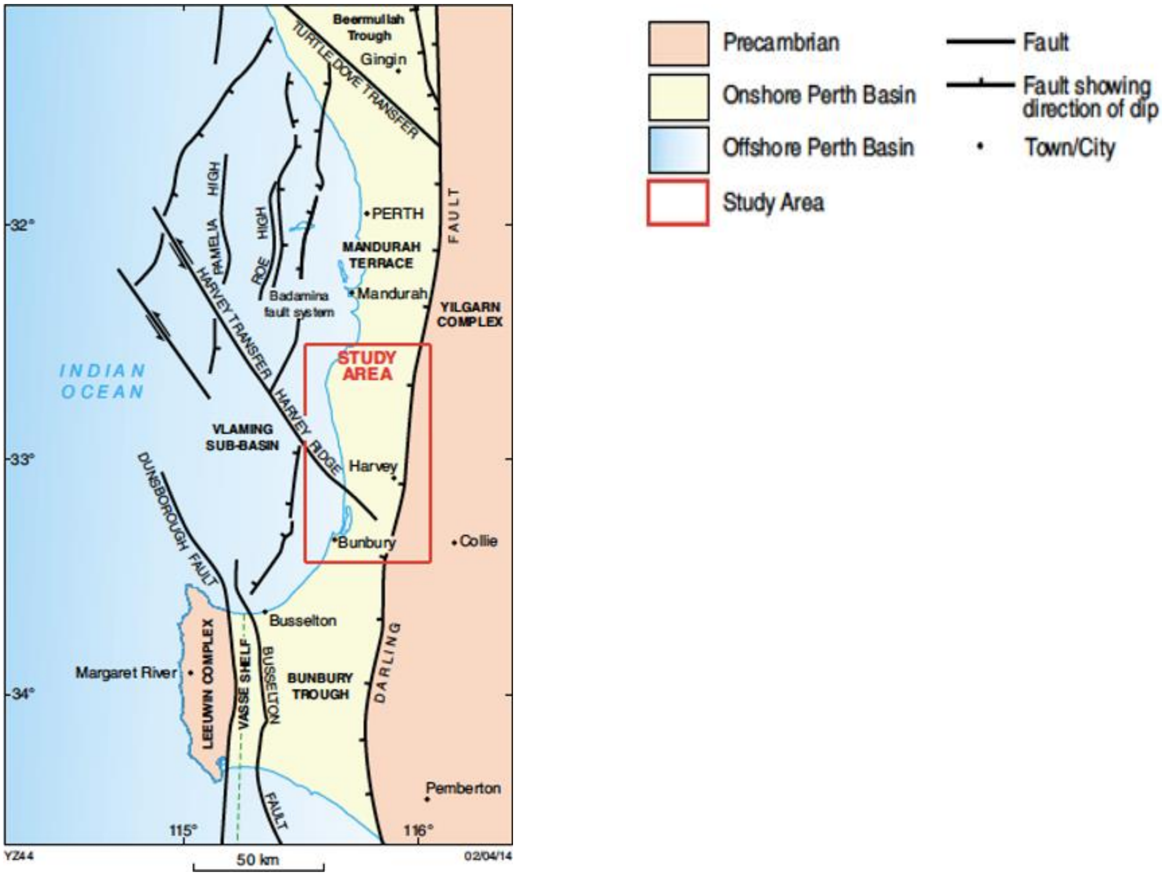


Figure 1: Regional Location Map

The nomenclature for the Triassic–Jurassic stratigraphic interval has been extrapolated from the northern part of the Perth basin, with the exception of the lowermost Triassic Sabina Sandstone, and proposed upper and lower members of the 'Lesueur Sandstone', which are only known in the southern part of the basin. The Lesueur Sandstone is thick (around 2,200 m in well Harvey 1) and can be differentiated into the Yalgorup (Upper Lesueur) and Wonnerup (Lower Lesueur) Members in the south and central Perth Basin only largely based on lithological correlation between 12 wells (water wells, oil and gas exploration and stratigraphic). The Yalgorup Member comprises sandstone with subordinate interbeds of finer clastic sediments likely formed by a fluvial meandering system dominated by point bars, claystone irregular bodies and paleosols. The Wonnerup Member is more sand-rich and formed by a fluvial braided system dominated by linguoid bars. A number of lithofacies ranging from coarse high energy sands to finely laminated mudrocks, derived from well core studies, support this depositional model. The present analogue used for both the Wonnerup and Yalgorup Members is the Brahmaputra River basin in Eastern India [3][5][6].

The study area or area of interest (AOI) was identified as having a unique structure compared to the rest of Southern Perth Basin [3], wherein, the formations were lifted and the major Yarragadee aquifer (potable water supply) and the Cattamarra Coal Measures have been eroded out as shown (Figure 2).

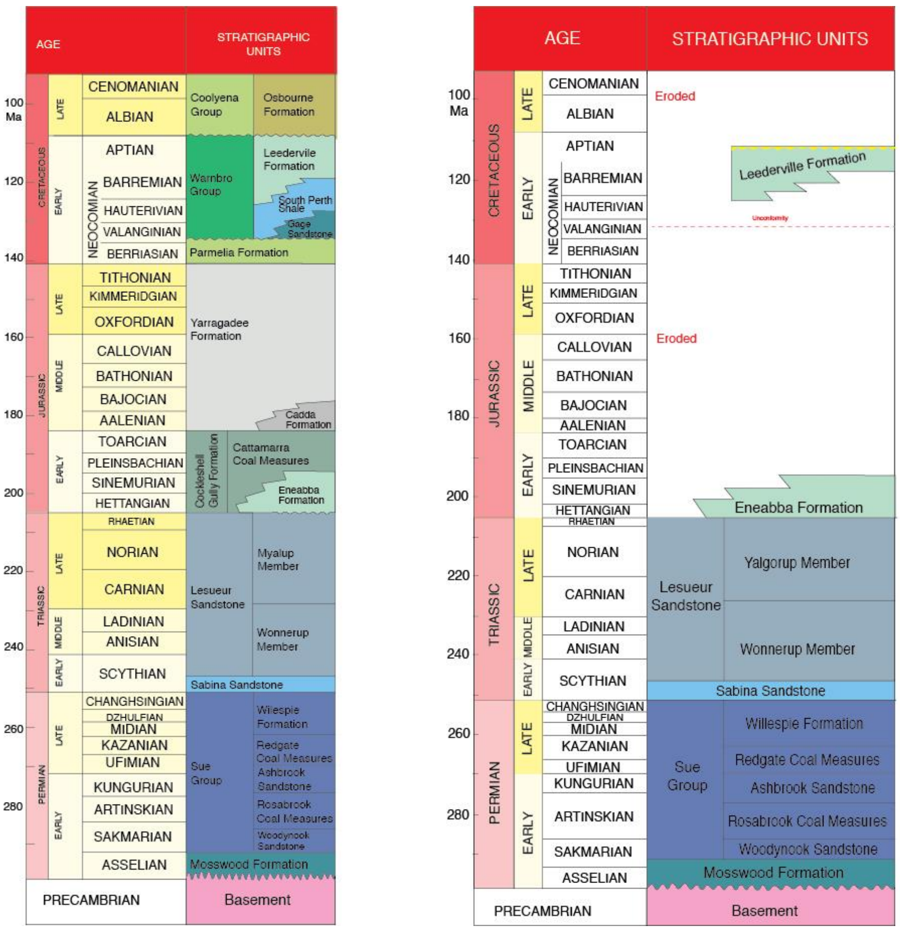


Figure 2: Stratigraphy of the Lesueur in the area of interest (WA Department of Mines and Petroleum, 2012a).

The storage concept postulates that injection at the bottom end of such a thick reservoir sequence (circa 3000 m) will promote residual trapping by providing a convoluted percolation path of CO_2 induced by buoyancy leading to safe containment even in the absence of a conventional structural sealing layer. The absence of the Yarragadee aquifer and lack of conflict with other resources provide additional support to examining the potential of the Lesueur for CO_2 storage.

3. Geological (Static) Modelling

The 3D seismic dataset covers a total of 115 Km^2 but is not optimal in places due to access constraints (~40% of surface area) when acquiring the data. The data quality in the shallow areas is consequently impacted but reasonable fold is achieved over the deeper Lesueur Formation (Figure 3).

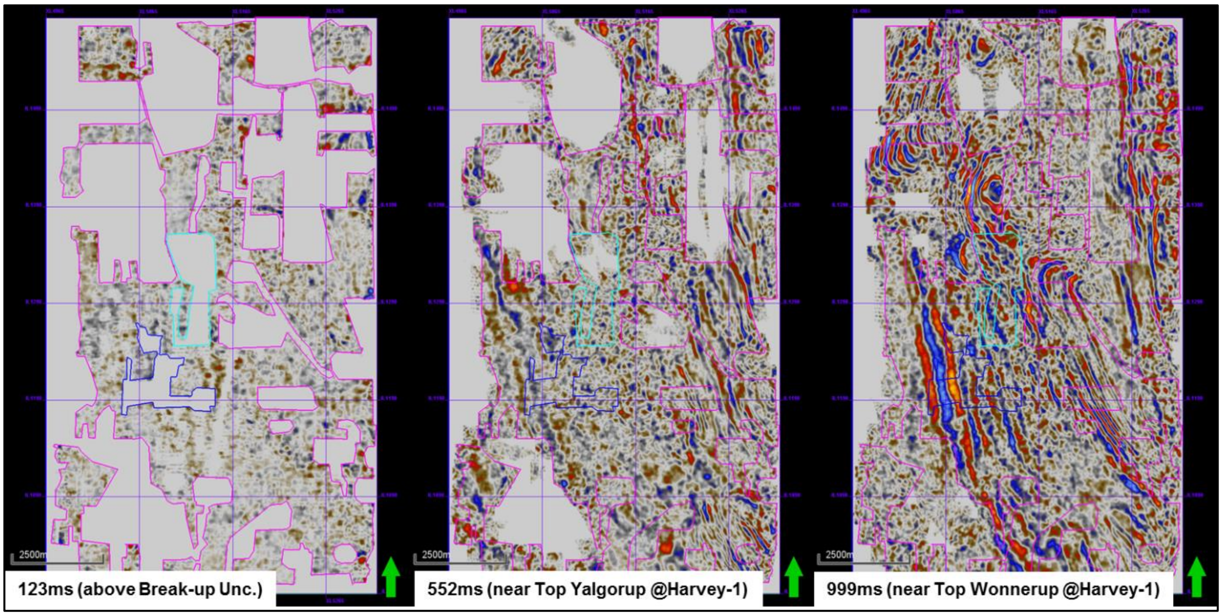


Figure 3: Gaps in Seismic due to acquisition constraints impact quality in the shallower depth sections (depth in Milliseconds)

The 3D seismic interpretation was used to develop the structural and stratigraphic framework. Five horizons were mapped, the Sabina Sandstone, Wonnerup Member, Yalgorup Member, basal Eneabba unit and the Break-up Unconformity. The existing 2D survey was used to expand the area to cover the "Western Fault" and further to the North. Using Harvey 1 for a well tie, the initial interpretation was used to select locations for wells Harvey 2, 3 and 4. These wells were extensively logged and cored. Subsequently, the interpretation was updated to include the 3 new wells and the depth surfaces and faults used to build the static model [7].

The static model workflow included building various 3D grids, facies modelling, property distributions and fault seal analysis. A log correlation panel was built using the available offset wells around the area of interest. In the fluvial depositional environment it proved difficult to correlate locally from well to well. The top Wonnerup Member and the Break-up Unconformity can be clearly mapped on the seismic, but not so the Yalgorup Member and the Eneabba Formation tops [8].

Five main depositional facies spreading from channel fill sands to swampy overbank deposits and paleosol/floodplain sediments have been defined, based on the core data, to represent both fluvial environments, braided and meandering, in the Wonnerup and Yalgorup Members respectively. The coarse channel fill sands in the Wonnerup Member represent a good reservoir (high energy facies) while the Yalgorup Member is dominated by floodplain and paleosol deposits (low energy facies) which can potentially act as baffles to any upward flow of CO_2. For modelling these were simplified into four main facies groups: high and low energy fluvial, paleosols with some overbank facies in the Yalgorup Member. Three separate grids (Figure 4) were built and made available for the simulation modelling: (i) **Greater Area Grid:** this is the very large area (~117km^2) which extends from the East-West fault located 2.4km north of Harvey-1 and south of the Harvey-4 well for 9.2km. This large model was built in order to monitor the extent of the plume movement following injection on the Eastern edge of the model (west of the "F10" fault). The plume would migrate both vertically and updip towards the West, thus the model was built to cover the entire area up to the major North-South orientated "Western" fault. This grid was built at the fine scale (25x25m) and upscaled (250x250m) in order to produce a total number of cells that could be simulated; (ii) **GeoGrid:** The area of the GeoGrid was approximately 54km^2 (7km x 7.7km) and covered all wells to create the various distributions. All scenarios were built at this scale in the GeoGrid (25x25x1m) in order to honour the available well data; (iii) **Sector Model Grid:** this was a 500x500m grid extracted from the GeoGrid and exported at various vertical scales (1, 2 & 4m layers) with the properties from the various scenarios built for upscaling and injectivity sensitivity analyses [8].

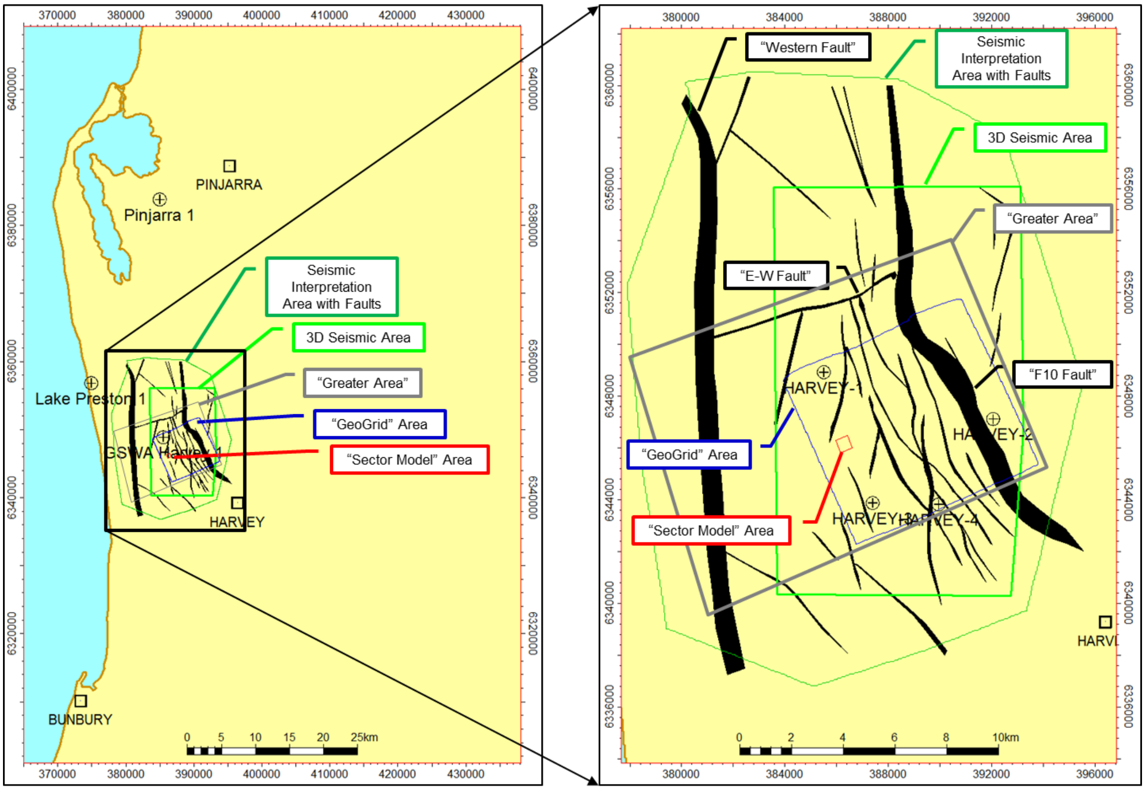


Figure 4: Area of Interest map showing key elements

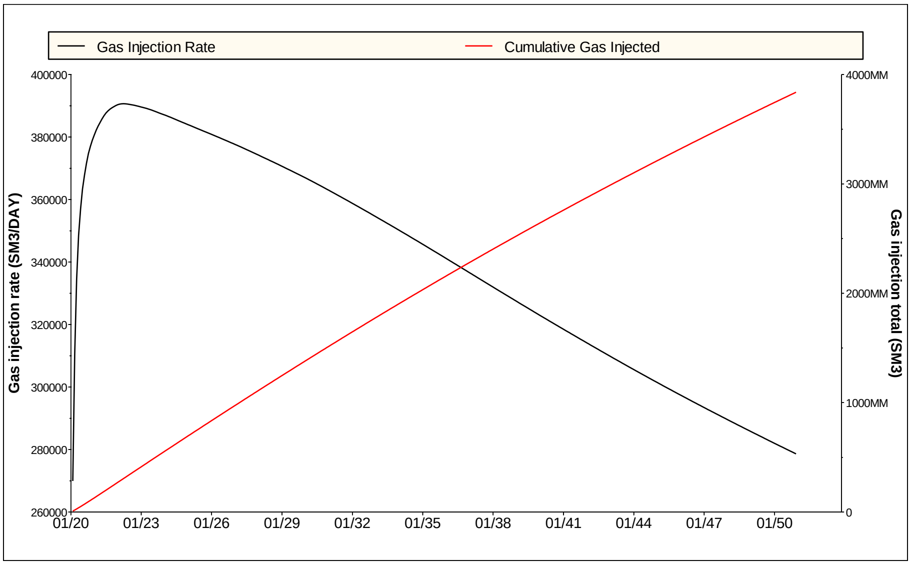
Petrophysical analyses (log and core data) was performed, shale volumes computed and porosity-permeability variograms developed. Properties vary significantly depending on the facies, with total porosity ranges from less than 10% to 26% and permeability from less than 10mD to more than 4000mD within the Wonnerup Member. Permeability of sand intervals for the Yalgorup Member range from 4mD to more than 10,000mD. Image logs were examined to study the sedimentary deposition, the bedding planes and formation dips in support of the depositional environment. The geomechanical analysis focused on estimating the critical injection pressures that could induce shear failure along faults/fractures. Due to remaining uncertainties (especially Shmin) three geomechanical models were constructed to define the possible ranges in the area. The three models were used to estimate the injection-induced pressures that could reactivate the identified faults. In total, eight Static Models were built to investigate the effectiveness to contain the injected CO_2 including a deterministic case using the seismic response to populate the palaeosols in areas outside of well control.

4. Dynamic Modelling

The input data for modelling included the reservoir pressure and temperature information (well logs), fluid properties (samples), geomechanics (SCAL tests) and relative permeability data (SCAL tests).

Grid sensitivity studies were performed using the 'Sector Model" and it was found that cell sizes of 250X250X4m could be used in the Wonnerup Member whereas vertical resolution of 1m (250X250X1m) had to be retained in the Yalgorup Member.

Injectivity studies were performed on the Wonnerup Member to create a cumulative probability distribution function to test whether it is possible to inject at least 2.4 million tonnes of CO_2 in a well over 30 years as per the decision criteria (Figure 5).



Reference Case parameters

- Bottom hole pressure constraint = 360 bars @ 2948 m [Pore Pressure + 0.9*69 bar]
- Average kv/kh = 0.75 derived from static model
- No damage skin.
- Well is completed in the bottom 250 metres for kh=20330 mD-m.
- Arbitrary start date of 1/1/2020

Figure 5: Single well injection volumes for 'reference case" indicate that 6.9Million tonnes can be injected over 30 years.

A range of sensitivity studies were conducted varying permeability, relative permeability, compartment volumes and BHP constraints. Table 1 lists these parameters in appropriate units.

Table 1: Parameters considered for sensitivity studies.

Scenario	Million Tonnes of CO2 Injected Over 30 Years
Low Krg	3.1
Small Compartment	3.6
Low BHP Constraint	4.3
Low Krw	4.6
Low Permeability	5.1
Low Vertical Permeability	6.6
Reference Case	6.9
Large Compartment	7.4
High Krw	7.8
High Permeability	9.0
High BHP Constraint	9.3
High Krg	9.8

In addition, combinations of the above parameters were used to create a probability density function of injection volumes from a single well and probabilistic estimates computed (Figure 6) [9].

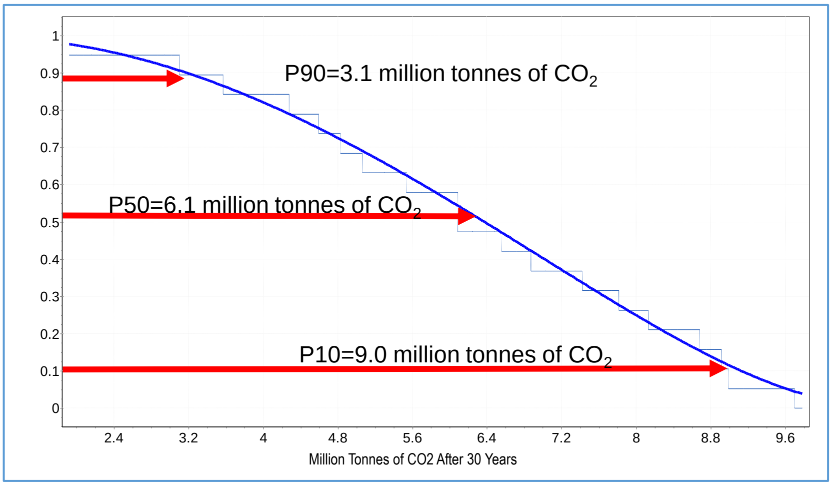


Figure 6: Single well injection volumes: probabilistic estimates for injected volumes of CO_2.

The modelling shows that under the current set of assumptions and sensitivity ranges tested, there is confidence that the injectivity criteria can be met in the Wonnerup Member.

The full field model was built to integrate all of the available subsurface information into a dynamic reservoir model that represents and describes the fluid flow processes in the reservoir. The model was upscaled from the "Greater Area' model based on the grid sensitivity studies. To further reduce the number of cells, all cells with a depth shallower than 800 mTVDss was made void as migration of CO_2 shallower than 800 mTVDss would be considered to be a breach of the containment criteria.

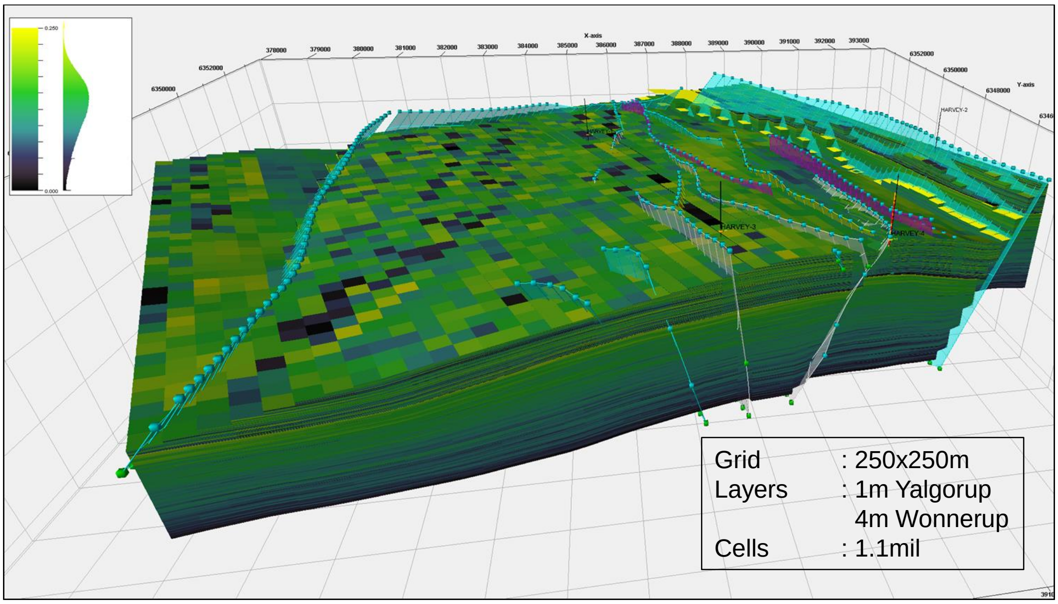


Figure 7: Coarse Scale Model showing porosity distribution within the Lesueur Sandstone.

Full field simulations were performed to model the movement of the CO_2 plume after 30 years of injection at 800,000 tonnes per annum and 1000 years of shut-in. The simulation model assumed nine CO_2 injectors in a staggered line drive configuration, all completed in the bottom 250 metres of the Wonnerup Member.

The "Reference Case" assumed the interpreted and measured parameters for reservoir fluid salinity, trapped gas saturation, BHP constraints from the geomechanics and relative permeability from special core analysis (SCAL) data. All faults in the Wonnerup Member were assumed to be non-sealing as they have sand juxtaposed on sand.

The results show that the plume has a limited spread of 7 x7km and remains well within the Wonnerup Member.

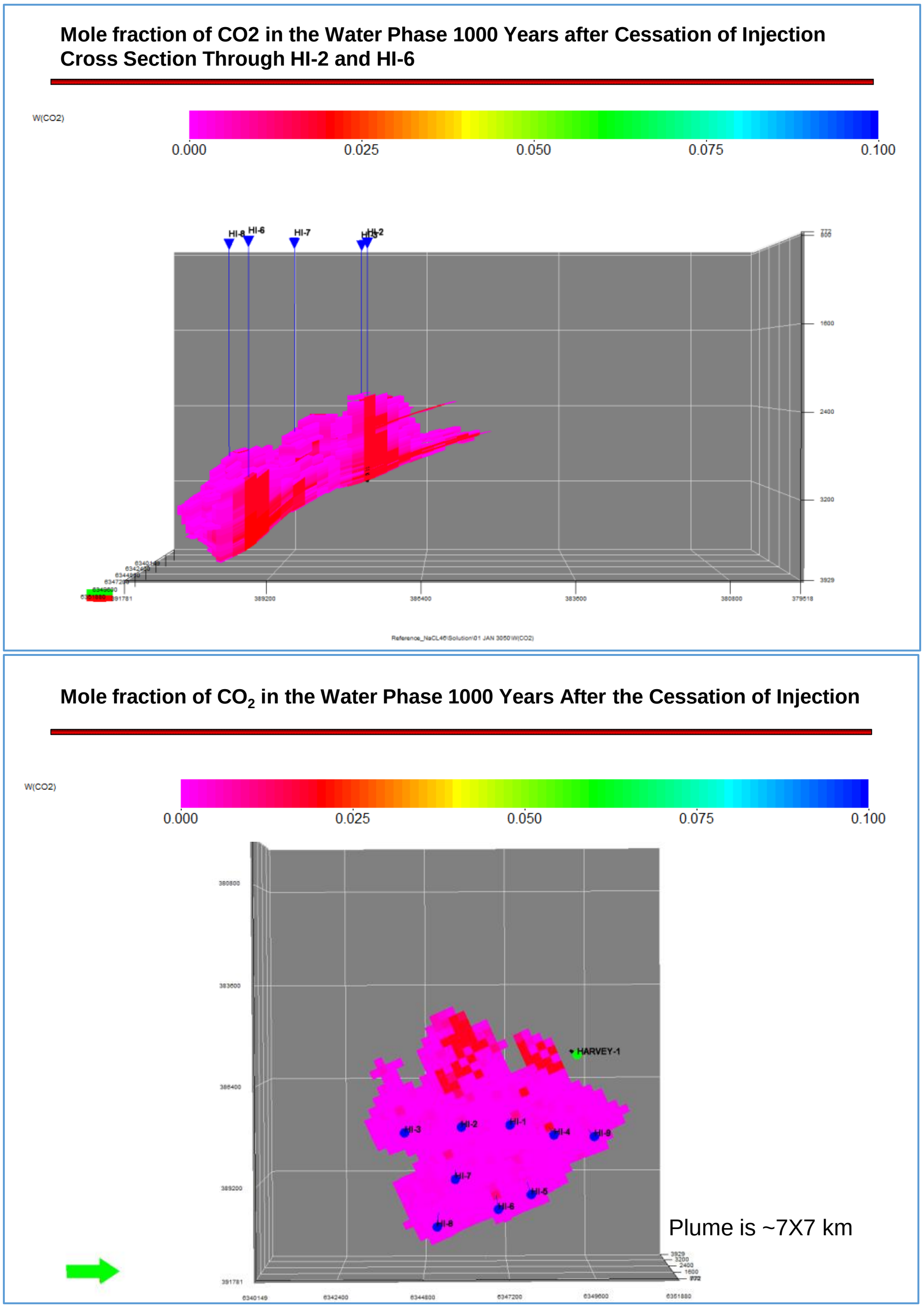


Figure 8: Cross –sectional and Plan view of the "reference case" CO_2 distribution 1000 years after injection

Eight scenarios were considered in addition to the reference case to test against the decision criteria [9].

Table 2: Simulation scenarios.

Case	Model Name	Geological Model	Trapped Gas Saturation	Brine Salinity (g/L NaCl Eq.)	Internal Faults	End Point Gas Relative Permeability
Reference	Reference	Reference	0.19	45600	Not sealing	0.12
1	Holey Faults	*Vertical permeability of cells adjacent to faults is increased by 10 times.*	0.19	45600	Not sealing	0.12
2	HighKrg	Reference	0.19	45600	Not sealing	0.23
3	LoHyst	Reference	*0.10*	45600	Not sealing	0.12
4	HighPerm	*Proportion of High Energy Facies in Wonnerup Increased to 90%.*	0.19	45600	Not sealing	0.12
5	Hikvkh	*Vertical and horizontal permeability are equal.*	0.19	45600	Not sealing	0.12
6	Seismic_Trend	*Used Seismic Trend (Deterministic Case) to populate Paleosols in the Wonnerup.*	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

Two additional "stress" scenarios were tested to examine the impact of "extreme" assumptions on plume migration. These were: (i) low trapped gas saturation and low solubility to force more CO_2 upwards and (ii) a significantly higher of injection (3 million t/a). The motivation for testing the larger volumes is that it equates to the emissions of a 500MW thermal power station.

The results of all the modelled scenarios are consistent with the injection of 800,000 t/a of CO_2 over 30 years in the Wonnerup Member with nine wells. The injected CO_2 remains within the Wonnerup Member even after 1000 years. Notwithstanding, uncertainties do remain and the UMP will be used to address these.

5. Technical Assurance and Uncertainty Management

Technical assurance and robustness has been maintained through a panel of "peer assist" and peer review" members, who are domain experts. There has been a regular interchange of ideas and approaches between the project team and the broader research community working on projects under the auspices of the Australian National Low Emissions Coal research and development program (ANLEC R&D). These projects are focused on reservoir characterization and either consider more fundamental physics based questions or delve significantly deeper into specific geology and geophysics domains using laboratory and modelling efforts.

The project UMP is being updated to address the key technical uncertainties. Principal among these are: vertical flow uncertainty within the Wonnerup Member, properties in the deeper sections as currently only one data point exists (Harvey 1), compartmentalisation effects of faults both seismic and sub-seismic, short range horizontal and vertical heterogeneities, paleosol extant and baffling effects in the Yalgorup Member and reservoir fluid geochemistry.

Future work plans are being developed. Some of the elements under consideration are: extracting more information from existing seismic data (spatial property maps, inversion to guide facies, FRACTAL studies to support incorporation of sub-seismic faults in reservoir scenario modelling), fault seal studies and additional SCAL. The models will then be updated and additional scenarios considered to justify further investment.

6. Stakeholder Engagement

This program has been running successfully for several years. A Stakeholder Consultative Group formed with members coming from the project, relevant land owners, Local Government representatives and other interested parties has been engaged and meetings are held on a regular basis. Educational program conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Education (‘CarbonKids‘) continues to be active [4]. With the revocation of the Carbon price legislation, industry interest had flagged but effort is being made to engage with them again.

7. Legislation

The injection and permanent storage of greenhouse gases in underground geological formations is currently not regulated in Western Australia other than for the Gorgon Greenhouse Gas Storage Project which is regulated via the Barrow Island Act 2003 State Agreement. The *Petroleum and Geothermal Energy Legislation Amendment Bill, 2013* is being considered by the State Parliament to amend the *Petroleum and Geothermal Energy Resources Act 1967* for onshore geological storage of greenhouse gases (mainly carbon-dioxide). The Bill will provide property rights for greenhouse gas storage formations, acreage release provisions, exploration, retention and injection licences and address injection site closure and long-term liability issues. The Bill also amends the *Petroleum Pipelines Act 1969* to provide for the transport of greenhouse gas substances via pipelines. When passed, this Bill will provide the framework to enable onshore carbon capture and storage projects to proceed with legal certainty.

In the interim the project activities are being pursued by the DMP under various State instruments, principally under the existing Mining and Petroleum Acts.

8. Concluding comments

The SW Hub Project proponents have a high degree of confidence in the project and are aiming to demonstrate feasibility of the storage concept based on MAT as the primary containment mechanism in the absence of a regional seal. In Australia, the reservoir characteristics of the Gippsland Basin, the onshore Otway Basin and the Surat Basin, the focus areas for Flagship and other CCS projects, are more conventional high permeability saline aquifers. Unconventional containment concepts pose unique challenges in the form of a higher degree of technical scrutiny as all stakeholders are justifiably cautious.

The SW Hub project has proceeded with care and managed its risk judiciously. Success in validating the storage concept will potentially open up areas around the world, several of which may have been prematurely screened out on “risk of containment” grounds due to the absence of a traditional seal in the form of a regional shale. The project thus has the potential of driving a major mindset change and have a significant impact in lowering storage costs in areas of similar geology.

Strong process and governance structures have allowed the project activities to progress safely with community/stakeholder support without any significant budgetary impacts. Planning for the next phase of desk-top work is underway and will determine future field drilling and testing activities.

The area of interest is relatively unencumbered with very limited, if any overlaps with other resources. This together with proximity to the industrial hubs of Kwinana, Kemerton and Collie, will aid in establishing commerciality once the national/international position on greenhouse gas mitigation becomes clear.

9. Acknowledgements

The project is supported through the Australian Commonwealth Government Flagship Program through the Department of Industry, Innovation and Science (DOIIS); the West Australian State Government through the Department of Mines and Petroleum; the Australian National Low Emissions Coal R&D Program and the local community in the south west of Western Australia.

10. Information sources

Project information - www.dmp.wa.gov.au/ccs

Technical data – www.dmp.wa.gov.au /wapims

Research projects – www.anlecrd.com.au

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