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The Australian South West Hub Project: Developing confidence in Migration Assisted Trapping in a saline aquifer – understanding uncertainty boundaries through scenarios that stress the models.

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Abstract

Carbon Capture and Storage (CCS) is a critical technology to deliver step change de-carbonisation, or reduction of Carbon Dioxide (CO_2), for industrial economies that are implementing climate change mitigation objectives. According to the European Commission Directive "Geological storage of CO_2 in saline aquifers is considered a key option because of their widespread distribution and large theoretical storage capacity" [1].

The South West Hub Project led by the Department of Mines, Industry Regulation and Safety (DMIRS) in Western Australia has been investigating and characterising the Lesueur sandstone as a potential target injection and storage formation since 2007. As expected with an unconfined saline aquifer, the project started with limited data, particularly when compared to sites based in oil and gas field areas. Working with research institutions and private sector expertise the project has judiciously acquired data on a stage gated decision basis. Starting with a 2D seismic over 110 line-km in 2011 and a deep well to 2,945 metres in 2012 the project was able to move through various modelling stages and uncertainty tables, before undertaking a complex 3D seismic over 115km^2 in 2014 and then drilling three "shallow to intermediate depth wells" (1,350m, 1550m and 1,800m) in 2015 that gave good areal coverage, significant core and logging data on targeted critical sub-surface formations. As more information became available, so did the level of sophistication and granularity of the models: 2010: Generation 1 Models - >100 layers -10 million cells; 2013: Generation 2 Models –> 357 layers - 30 million cells; 2016: Generation 3 Models- >1,100 layers - 214 million cells.

The SW Hub is unique insofar as it relies on proving primary containment through "Migration Assisted Trapping" (MAT - sometimes referred to as Migration Assisted Storage or MAS) in the Wonnerup Member of the Lesueur Formation, a 1,500metre thick relatively homogenous sandstone layer. Security of secondary containment is considered through the overlying paleosol packages in the Yalgorup Member, a 800M thick sequence of sand and paleosol deposits.

Project activities are supported by R&D activities conducted under Australian National Low Emissions Coal Research and Development (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. On occasion high resolution seismic, multi-offset VSP's and other data has been acquired over targeted areas to illuminate certain parts of the reservoir. The research work is not the basis of project decision making but supportive to project efforts and complements private sector work through regular information exchange. Both the project activities and the research investigations target geological uncertainties and reduce risk for the project.

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The Generation 3 models provided confidence in the injectivity and containment potential of the Wonnerup Member of the Lesueur Sandstone Formation. The geo-cellular models were very large with the upscaled simulation models requiring significant run times with a compositional simulator. While multiple scenarios were simulated, uncertainties remained and these were addressed in a detailed Uncertainty Management Plan (UMP),

In accordance with the UMP, the Generation 4 model development commenced in late 2017 with further input from re-processed seismic, new core analysis, different analytical techniques and re-interpretation of well log data. The work scope and the key objectives of this model are to: (a) challenge assumptions and conclusions of underlying interpretation work reviewed/performed to date; (b) reduce parametric uncertainties through analog studies and new laboratory test data; (c) develop scenarios and use a range of cases to test storage performance factors and potential limits (injectivity, containment and capacity) going beyond the decision criteria.

Industrial workflows and specific research projects have been converging on the parametric uncertainties. The current models are building on the cumulative body of knowledge developed over the last decade.

This paper reviews the latest uncertainty mapping and the work program developed to extract the maximum information from already collected field data, building on the previous work by different forms of advanced seismic processing and interpretat ion; correlation of log data with previous and new core data; reviewing geo-mechanical stress fields and rock physics in the target reservoir; updating geological and engineering aspects of the data, particularly that of the depositional structures of the paleosols in the overlying Yalgorup Member and; utilising Black Oil as well as Compositional models to improve the efficiency of the dynamic modelling.

However, the major uncertainty remains around the deep reservoir properties and the CO_2 behaviour at the target injection depth up to 3,200m. The strength and robustness of the latest modelling will assist in a decision to drill and test that deeper well. 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.

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

1. Introduction

The Western Australian (WA) Greenhouse Strategy incorporates the technology of carbon capture and storage (CCS) and recognises its potential for greenhouse gas abatement [2]. Under those guidelines the WA State Government Department of Mines, Industrial Regulation and Safety (DMIRS) developed a strategy to identify suitable areas for storage within its jurisdiction which included the South West Hub Project (SW Hub) project area of interest [3].

The area of interest (AOI) is in the Harvey and Waroona Shires near large CO_2 emission sources in the industrial centres of Kwinana and Collie. The study area is located in the onshore part of the southern Perth Basin between the Mandurah Terrace in the North and the Bunbury Trough in the South. It covers an area of 332 km2 and is located approximately 13km northwest of the town of Harvey, approximately 120 km south of Perth (Figure 1).

The SW Hub Project has been managed by the DMIRS Carbon Strategy Branch since 2007, and is continuing to build confidence in the storage potential of the thick unconfined saline aquifers of the Lesueur Formation.

The injection target is the Lower Lesueur sandstone (Wonnerup Member), an approximately 1500 m thick reservoir with varying permeability layers that should support residual and solubility trapping. The storage complex has no regional shale layer and depends on migration assisted trapping (MAT) for primary containment, with the 600-800 m thick 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 SW Hub is in a pre-competitive data acquisition stage aimed at providing technical confidence for acreage gazettal for industrial proponents to consider in the future. Thus, the decision criteria, outlined as under, is to verify the minimum acceptance criteria developed by the Petroleum Division of DMIRS [4].

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

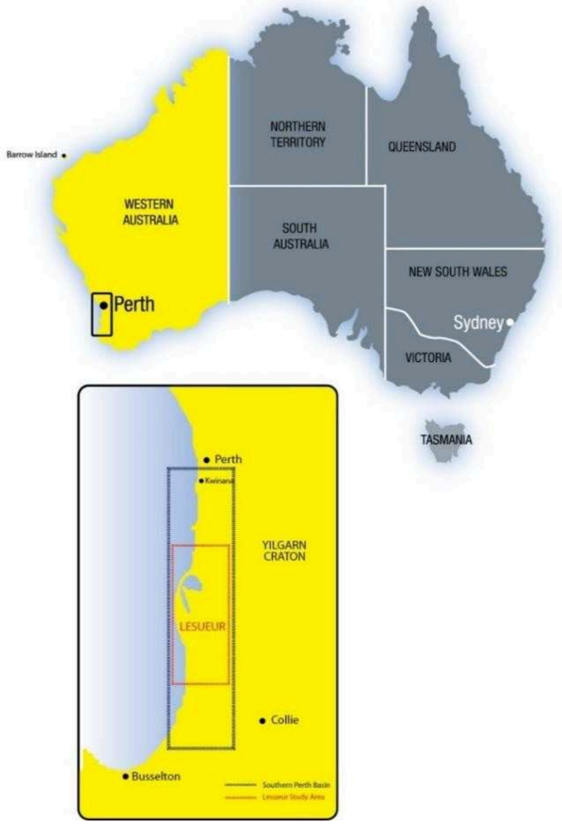

Figure 1: SW Hub Project Location Map

The SW Hub Project has been developed in a stage-gated manner ensuring increased level of technical confidence at each stage. Technical assurance processes include using experienced oil and gas industry professionals to perform the work and an extensive peer assist and review process to ensure that the results are robust. The peer review group has included oil and gas industry professionals, academics and other independent expert practitioners.

2. Geological context and history of investigations

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. Sedimentation in the Perth Basin began in the Late Carboniferous or Early Permian as a result of north-trending regional rifting. This was followed by the full scale rifting of Greater India from Australia and activation of the dominant structural feature of the north-south striking Darling Fault until the Early Cretaceous. The Perth Basin has since been subjected to several extensional and compressional events [5]. The period from the Middle Triassic to Early Jurassic is represented by two key formations: the Middle to Late Triassic Lesueur Sandstone and the Early Jurassic Eneabba Formation. The Lesueur Sandstone is thick (around 2000m from early exploration wells Pinjarra 1 and Lake Preston 1 drilled decades ago) and can be differentiated into the Yalgorup (Upper Lesueur) and Wonnerup (Lower Lesueur) Members in the south and central Perth Basin only. The Yalgorup Member comprises sandstone with subordinate interbeds of finer clastic sediments (mostly siltstone) up to a few metres thick, but it is often difficult to determine the top of the member from the overlying formations using wireline log correlations. The Wonnerup Member is more feldspathic, poorly sorted, coarse and consolidated sandstone, and it conformably overlies the Sabina Sandstone. This fining-up transition, amongst other support, suggests a fluvial environment of deposition [5].

Screening studies undertaken by DMIRS had identified the AOI as having a unique structure compared to the rest of Southern Perth Basin. Here the formations had been uplifted and the major fresh water Yarragadee aquifer (source of potable water supply) had been eroded out of the stratigraphy. It was postulated that if CO_2 was injected deep into the Lesueur, the thick and heterogeneous reservoir sequence, the percolation path of CO_2 induced by buoyancy would be convoluted, and that a potentially large pore space could be encountered. Thus despite the absence of a traditional extensive overlying shale layer acting as a primary seal, containment could be secured through dissolution and residual trapping [6].

The initial models were based on sparse data of old 2D seismic and a limited number of offset wells located 30 -60 km away [7]. Since then, new data has been acquired in phases and reservoir models updated at each phase. The project has followed a stage gated development policy wherein financial exposure to acquire new data is only incurred if the modelling results have indicated confidence towards meeting the performance factors.

Phase 1 of the new data acquisition program included a 2D seismic survey (2011) and the drilling of Harvey 1 through the entire sequence (2012). Modelling was updated and a revised set of uncertainties together with recommendations to address these created [8][9]. Subsequently, under Phase 2 of the data acquisition program, new data has been acquired through 3D seismic acquisition (2014) and the drilling of new wells Harvey 2, 3 and 4 (2015) which were spatially distributed but only penetrated the top 150 m of the Wonnerup Member. The next generation of models were built and the uncertainty management plans updated [10]. Table 1 summarises the history of the work performed prior to the stage being discussed in this paper.

Table 1: Data acquisition and modelling timelines

Timeline	Model Complexity	Comments
Generation 1 (Gen 1) Models: 2010	100 layers, 1 million cells	Initial Uncertainty Identification: Coarse screening model based on offset data from region
Generation 2 (Gen 2) Models: 2012	357 layers, 30 million cells	Uncertainty Rationalisation based on new 2D seismic and data from well Harvey 1
Generation 3 (Gen 3) Models: 2016	1100 layers, 214 million cells	Uncertainty Parameterisation based on new 3D seismic and new data from wells Harvey 2, 3 & 4.

As is to be expected, model complexity has increased with data availability and uncertainties better constrained. In Gen 3 models 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 acceptance criteria. Containment security was assessed through a number of reservoir simulation models, which cover a wide range of realisations, including a worst credible case which combines the least favorable containment characteristics and which are consistent with all of the available data and geological setting [10].

The results of all the Gen 3 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 [10]. Notwithstanding, uncertainties do remain primarily associated with the lack of deep reservoir static and dynamic data as only well Harvey 1 penetrates the entire sequence. In addition a substantial amount of laboratory and interpretation work had been done by the research partners which was ready to be used to constrain model parameters [9]. Thus, prior to considering a decision to acquire new data, in accordance to the prudent project approach, a work plan was created to ensure that all available data (including research data)was reviewed, the seismic reprocessed and reinterpreted thereby ensuring that all information from existing data was considered. The work scope and the key objectives of this model are to: (a) challenge assumptions and conclusions of underlying interpretation work reviewed/performed to date; (b) reduce parametric uncertainties through analog studies and new laboratory test data; (c) develop scenarios and use a range of cases to test storage performance factors and potential limits (injectivity, containment and capacity) going beyond the decision criteria. Disciplinary work streams were defined and key aspects are listed in Table 2 below.

Table 2: Input work scope for Generation 4 (Gen 4) models

Subject	Work Proposed	Rationale
Geophysics Work stream 1 and 2	Reprocessing to enhance continuity of reflectors, sequence stratigraphy, rock properties from seismic, fractal studies. Reinterpretation of horizons and faults	Updated fault maps, assist in facies and reservoir property population, identify fault densities
Petrophysics Work stream 3	Integrate all available core-log (NMR) data for analysis of permeability heterogeneity and poro-perm relationships.	Improve the population of permeability in static models.
Geomechanics Work stream 4	Review all image log data, SCAL (rock strength) data and consider past recommendations	Better constrain injection pressures to ensure formation stability
Geology Work stream 5	Review intra formation markers, better constrain paleosol dimensions, regional diagenetic trends	Improve well to well correlations, understand Yalgorup Member containment potential
Engineering Work stream 6	Study grid size effects on solubility, test and tune Black Oil models for more efficient scenario testing	CO_2 dissolution and convective mixing can be over-estimated using large grid blocks leading to numerical dispersion
Core Analysis	Additional relative permeability data for both drainage and imbibition in different facies	Only 1 data point available so more SCAL tests needed. 6 additional samples were selected for steady state and 10 for un-steady state analysis

The reinterpreted data would allow for the static model to be rebuilt (Work stream 7) and specific cases defined for dynamic simulation (Work stream 8). The plan included using a tuned Black Oil simulator to model multiple cases as it would be time efficient. Selected cases would be validated by comparing with full compositional simulation results as well. The final deliverable was to evaluate updated probability of success (POS) for injection rates and capacity while modelling a broad range of scenarios to test containment.

3. Developing the Generation 4 Models

The 3D seismic data originally processed in 2016 was reprocessed by Curtin University using a true amplitude processing workflow, to restore actual intensity of seismic events thereby improving the resolution of the image. Smaller high resolution surface and borehole seismic data sets acquired by Curtin University were integrated into the analysis as well. This resulted in an improvement of the signal to noise ratio at the near-offsets and removal of residual static/velocity errors [11]. The updated cube was interpreted and became the basis for developing the Gen 4 models. Many more faults have been interpreted with the principal alignment being N-S as can be seen in Figure 2 The previously identified E-W fault (towards the North) was not observed on this data set. This is important from a current stress perspective as the N-S faults are not aligned to slip under injection pressure. While well ties were improved, amplitude and coherence extractions were attempted but without any clear patterns [12].

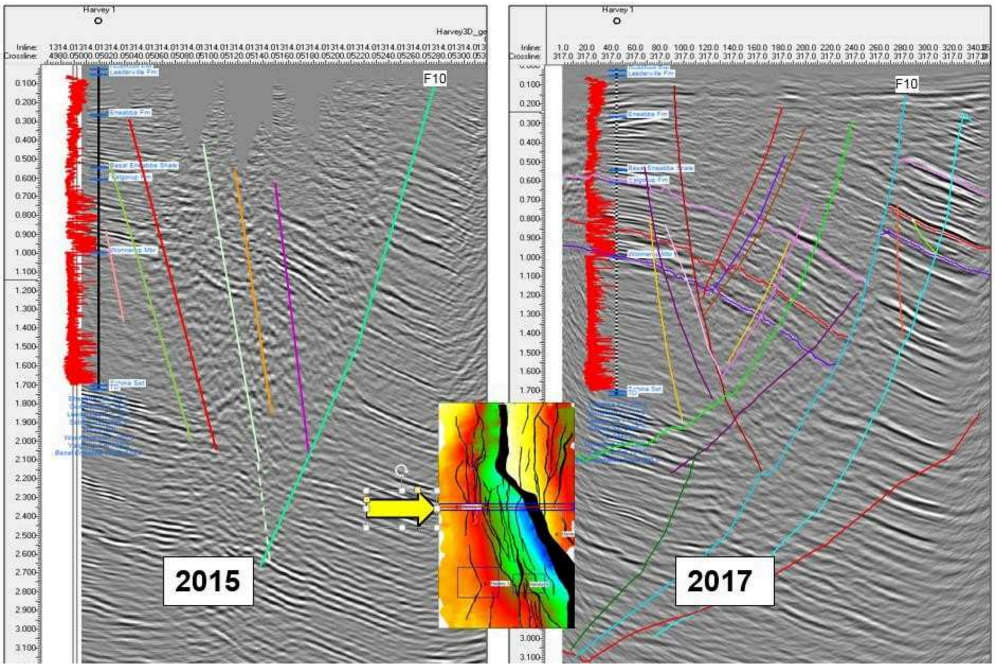

Figure 2: Seismic reprocessing allowed more faults to be picked with confidence

All available petrophysics data (core and logs) was reviewed and poro-perm relationships updated. The Wonnerup Member permeabilities were lower and more conservative than previously computed. Extensive paleosol analog studies were conducted as the dimension of paleosol bodies is key in assessing the containment potential of the Yalgorup Member should the plume migrate up from the Wonnerup Member. The Yalgorup Member with its micro-pores and paleosols should retard any CO_2 movement should it be encountered. The geomechanics work reconfirmed that the faults were not likely to be reactivated but highlighted the lack of information on rock strength and formation stress data so new samples and tests would be required and should be considered as part of any future acquisition campaign [13].

The experience from the Gen 3 compositional models was that tuned Black Oil models could be more efficient in modeling multiple scenarios. This was tested and a “Reference Case” Black oil model developed. Here all faults were assumed to be non-sealing and the Wonnerup and Yalgorup Members in communication. As this model is isothermal, a temperature of 55° C which is the reservoir temperature at a mid-point of the pore volume of the model (depth of about 1600 mTVDss) was selected. All other injection related parametrs were consistent with the Gen 3 compositional model [10].

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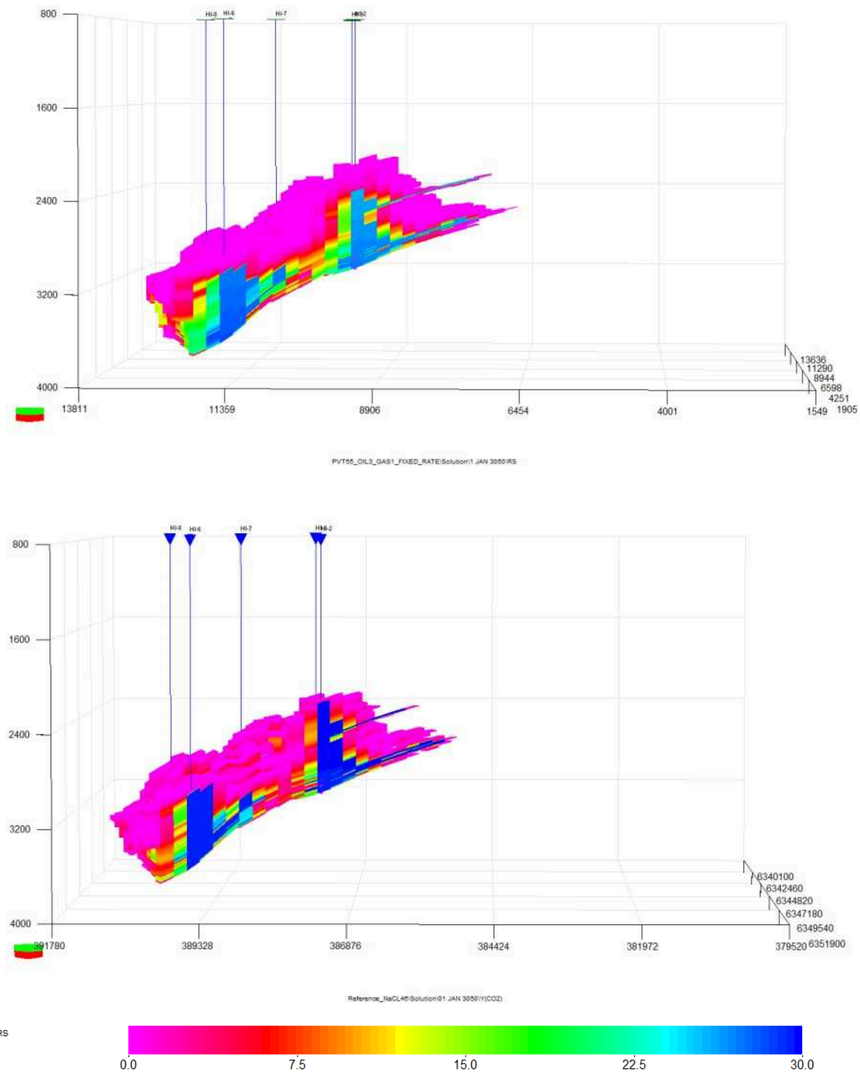

Black Oil Model

1000 years after injection

Mole fraction of CO2 in the water phase.

Material Balance:

- Dissolved CO2 73%
- Trapped CO2 26%

Compositional Model

1000 years after injection

Mole fraction of CO2 in the water phase

Material Balance:

- Dissolved CO2 56%
- Trapped CO2 44%

Figure 3: Tuned Black Oil Model results compared to a fully Compositional Model (Generation 3).

The results (Figure 3) show that Black Oil modelling is a suitable alternative to compositional modelling. The predicted shape and CO_2 plume movement are similar, however, the Black Oil model is optimistic as it predicts more

CO_2 dissolution in the liquid phase than the compositional model. The use of this approach, would allow reservoir uncertainties and development sensitivities to be evaluated relatively quickly compared to compositional modelling. Nevertheless, selected cases would be tested against a fully compositional model

Grid sensitivity studies in the Gen 3 model had determined 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 [10]. The objective here was to test the sensitivity of the grid sizes to solubility a key trapping parameter determining containment. Grid sizes as small as 50mX50m were tested and it was determined that grid blocks affect the shape of the plume but have an impact of only around 10% on the estimates of gas in the supercritical state or dissolved in the liquid phase. It was concluded the 250X250m full field model would be suitable for estimating the volume of supercritical gas and the volume of gas dissolved in the liquid phase [14].

4. Generation 4 Static Models

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. However, 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 [13]. The modelled area is shown in Figure 4.

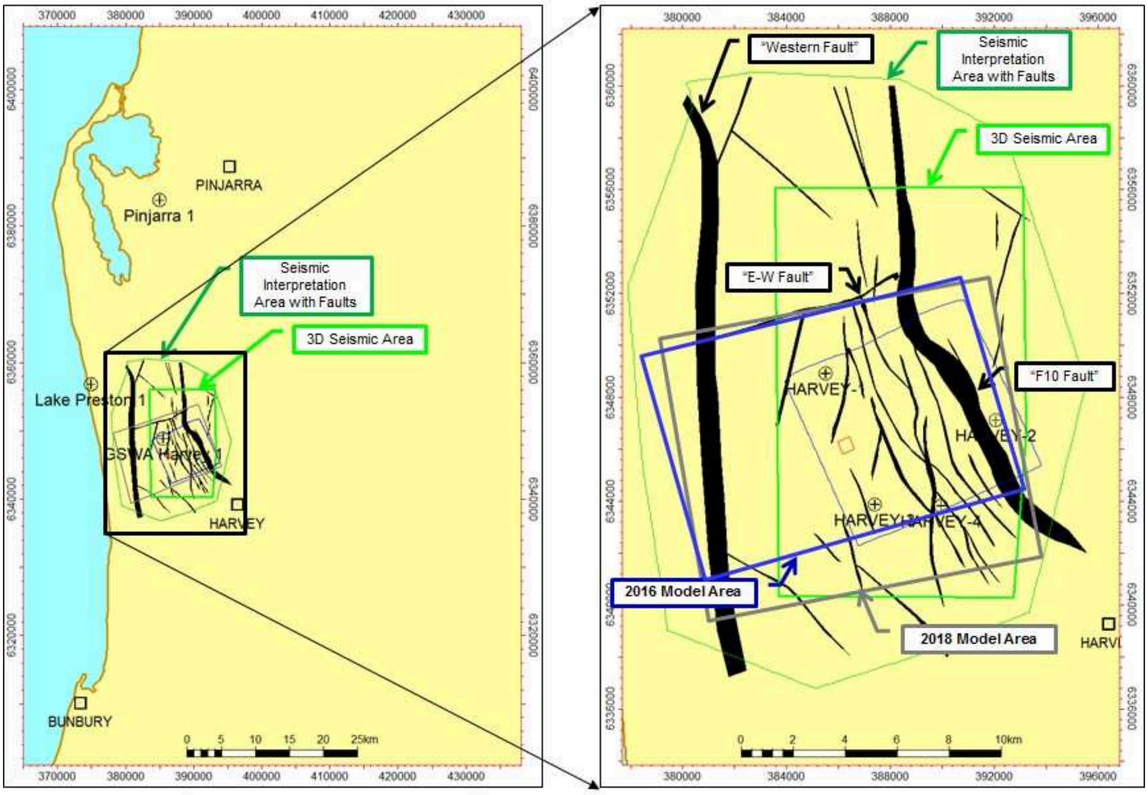

Figure 4: Modelled Area for the Gen 4 Model (2018)

There is high confidence in the understanding of the fluvial depositional environment, braided and meandering, in the Wonnerup and Yalgorup Members respectively. Consistent with Gen 3 models, 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 [10].

The new static model has been developed to be consistent with the updated structural interpretation. It has been built in RMS^{TM} and has 1050 layers (Yalgorup Member 1-700 and Wonnerup Member 701-1050). Cell sizes were reduced to 100m by 100m to test sensitivities in the Wonnerup only (2.9 million cells) and 250mX250m in the combined Wonnerup-Yalgorup Member model (2 million cells). Based on the new seismic interpretation the reference case model is more heterogeneous and thus more characteristic of the Harvey 4 area. To allow representing a Harvey 1 type reservoir, a "Homogeneous Reservoir" model has been built for simulation as well. Paleosol extants and geobody sizes were constrained based on the extensive review of analogue data. Geological models representing these ranges are incorporated into dynamic models investigating the movement of the CO_2 plume during injection and subsequent shut-in.

The static model includes all the interpreted faults. A more stringent porosity-depth trend has been considered and permeabilities are lower reflecting greater heterogeneity. Seismic attributes coherency and fractal studies for "sub-seismic" fault assessment have been considered but no definitive correlations found. Subsurface uncertainties modelled are listed in Table 3.

Table 3: Mapping geologic uncertainties

Parameter	Range (Gen 3 Models)	Range (Gen 4 Models)	Comments
Paleosol dimensions (extant)	500-1500-3500m	300-3000-10000m	New range based on extensive analogue work. 3000m has been used in the reference Case. Thickness is from the logs around 2.5m.
Permeability range in the Wonnerup Member	71 to 372mD Mean = 200mD	0 to 900 mD Mean = 110mD. High Perm Case = 1.4 times.	Significantly reduced permeability based on the porosity versus depth trend used.
Fault Seal Multiplier	0.1 & 1	0.01 & 1	Open/partially closed system for internal faults
Fault Permeability Multiplier	x10	x10	Multiply vertical perm near faults by 10
Kv/Kh in the Wonnerup Member	X 0.3 to 1 Kh	X 0.1 to 0.8 Kh	Multipliers to Kh
Deterministic Case based on Seismic trend	Additional paleosols modelled	Reference Case	Deterministic case used the seismic based trend with higher concentration of paleosols in the Wonnerup Member. This has become the Reference Case for the Gen 4 models
Homogeneous Case		Homogeneous Reservoir	Lower percentage of paleosols in the Wonnerup member as evidenced in Harvey 1.

5. Generation 4 Dynamic Models: Scenarios and Results

The seismic data has not been able to predict properties and as no new well based information was available, the peer review process determined that the injectivity POS work need not be repeated. The initial exercise had considered sector models and performed numerous sensitivity studies varying permeability, relative permeability, compartment volumes and BHP constraints. Combinations of the above parameters were used to create a cumulative probability distribution function of injection volumes per well over 30 years in line with the minimum acceptance criteria. Results indicated that under the current set of assumptions and sensitivity ranges tested, there is confidence that we can inject at least 2.4 million tonnes of CO_2 per well (Figure 5) [10].

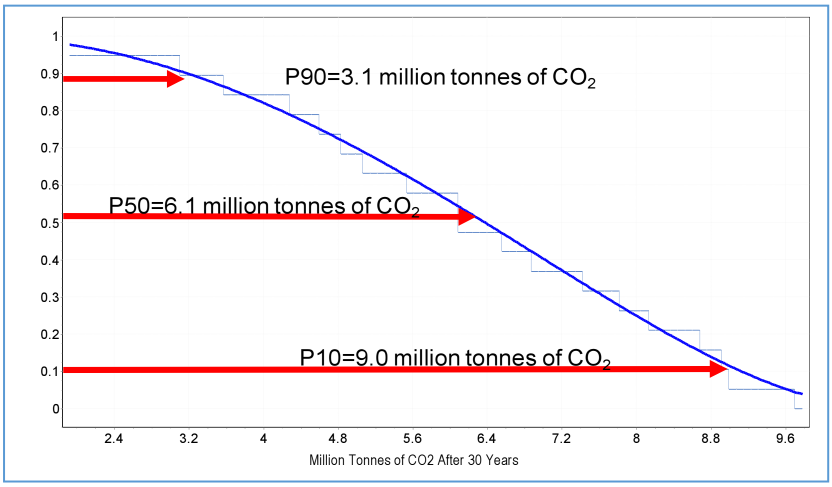

Figure 5: Single well injection volumes: probabilistic estimates for injected volumes of CO_2.

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. 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 initial simulations were done using tuned Black Oil models as these had been deemed to be a suitable alternative to fully compositional models in the Harvey area. Grid sensitivity studies had indicated that grid block sizes of 250mX250m in the full field model were suitable for estimating the volume of supercritical gas and the volume of gas dissolved in the liquid phase. Vertical resolutions of 4m in the Wonnerup Member and 1m in the Yalgorup Member were retained as the Yalgorup Member is finely layered and very heterogeneous [10].

The dynamic models were built in Eclipse^{TM} format and simulated using the Black Oil engine of the tNavigator^{TM} Simulator. The Reference Case is as below:

- Reservoir: All faults are assumed to be not sealing and the Wonnerup and Yalgorup Members are assumed to be in communication.
- PVT Properties: Oil properties calculated using a salinity of 46 g/L H_2O, Temperature of 55 C.
- Hysteresis assumed for the gas phase and none for the water phase as evidenced from the data.
- Injection: Dry gas ("CO_2") is injected at rate of 1.2 million m3/day.
- Bottom hole pressure constraint = 360 bars @ mid-point injection depth of 3250 m (34 bars above pore pressure). This is even more conservative than the constraint for the Gen 3 models.

The conceptual development plan for the Harvey area envisages injection of 800,000 tonnes of CO_2 per year for 30 years. At the end of the 30 year injection period, the wells are shut-in and the CO_2 is allowed to dissipate through the aquifer for 1000 years.

The number of wells were reduced from nine (9), one at a time, keeping the BHP constraint to test the minimum number needed to inject the required volumes. The well locations are a random selection from the staggered in line placement of nine wells in the previous model. No optimisation has been attempted, which is appropriate for this stage of the project. While the required volume could be injected through two wells, in keeping with a sparing philosophy of n+1, three wells have been considered for the cases.

All of the wells are completed in the bottom 250 metres of the Wonnerup Member at a depth of over 3000 mTVDss (Figure 6).

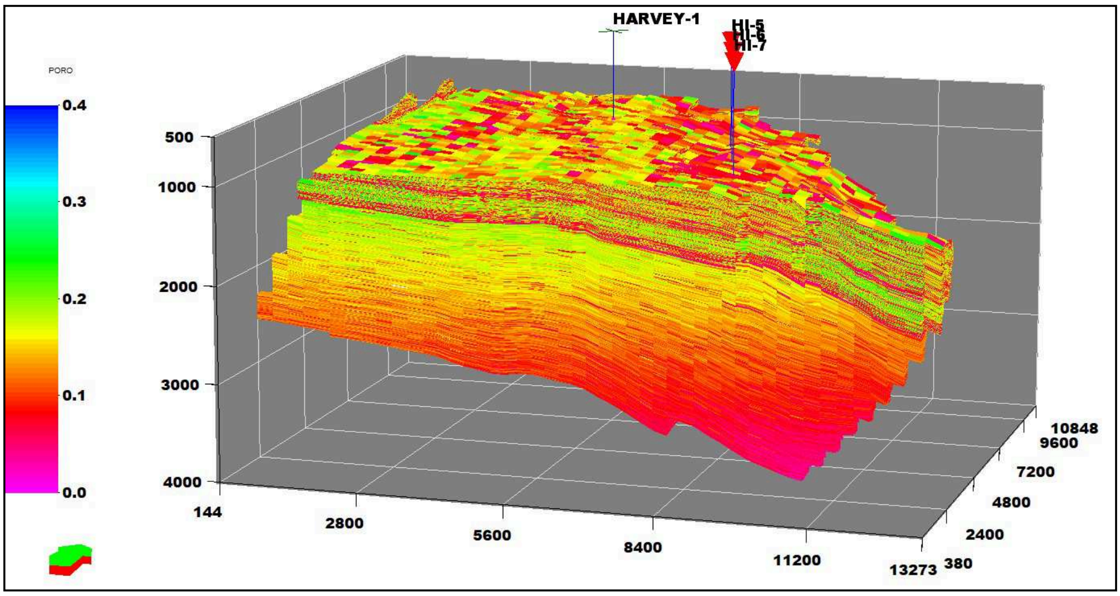

Figure 6: Porosity Grid Showing Well Locations in the Model

A number of models of the Harvey area were constructed to investigate the effects of the reservoir uncertainties on containment failure and the location of the CO_2 plume. The models were tested with a number of subsurface parameters and combinations of these parameters to assess the robustness of the development concept. The intent of the uncertainty modelling is to "break" the model and identify the mechanism or subsurface parameters that are responsible for the failure. Action can then be undertaken to reduce or eliminate the uncertainties responsible for the failure of containment. **Error! Reference source not found.** provides a summary of the reservoir uncertainties investigated and the parameters used in the investigations.

In each of the 13 cases, the plume remained within the storage complex over 1000 years. In the "holey faults" cases (10, 11, and 12), wherein the permeability in the damaged zone near the faults is assumed to have enhanced permeability (multiplier of 10 applied), does a small percentage of the plume injected (< 2%) enter the Yalgorup Member (Figure 7).

Table 4: Geological Uncertainty Modelling Scenarios

Case	Geological Model	Description
Ref.	Reference	Reference case representing the best technical case. 800,000 tpa. Brine salinity=45600 ppm (NaCl Equivalent) SgT based on Land Correlation C=1.95
1	Reference	No capillary or drainage pressure curves considered to gauge the impact of these on the plume movement.
2	Reference	Enhancing the lateral and vertical movement of CO_2 in the reservoir by increasing the non-wetting phase end point relative permeability to 0.25.
3	Wonnerup Member is homogeneous	While the seismic indicates more heterogeneity, this case was created using the results of the GSWA Harvey 1 well to test the effects of a more "bland" Wonnerup Member.
4	Permeability X 1.4	The “High Permeability” realisation was created to test the impact of a significant increase in permeability in all directions.
5	Reference	The Land Correlation with C=3.2 was used to generate pessimistic trapped gas saturation for the range of permeabilities in the model to test reduced residual trapping.
6	Reference	The model assumed a brine salinity of 200 g/L H_2O NaCl Equivalent to reduce the volume of CO_2 dissolved in the liquid phase
7	Kv=0.8*K Horizontal	Thi s case was run to to examine the impact of a uniformly high kv/kh ratio on the vertical migration of CO_2.
8	Kv=0.1*K Horizontal	This scenario was created to examine the impact of a low kv/kh in the Wonnerup Member on the lateral migration of the CO_2
9	Fault Transmissibility X 0.01	This case considered these compartmentalisation effects of cataclastic processes (lower lateral transmissibility) which would result in the injected CO_2 preferentially flowing vertically.
10	Cells adjacent to faults have X10 Kv	The areas near the faults may have enhanced vertical permeability due to fractures. These fracture zones are modelled as areas of enhanced vertical permeability to test impact on vertical migration. Wonnerup and Yalgorup Members in communication only through the faults.
11	Cells adjacent to faults have X10 Kv	A variation of the above case assuming that the Wonnerup and Yalgorup Members are in communication vertically through sand on sand contact and the faults.
12	Cells adjacent to faults have X10 Kv	No communication whatsoever between the Wonnerup and Yalgorup Members. This implies that there is no secondary containment unit; and any gas that reaches the top Wonnerup Member would be forced to move towards the “E-W” fault and risk containment failure.

In addition to the above, 2 ‘stress’ cases were simulated combining the effects of uncertainties. In Case 13, the damaged zone permeability (holey faults) was enhanced and combined with a low solubility case by assuming higher fluid salinity as in Case 6. Case 14, combined the realisation where the faults are baffles to the lateral flow of fluids (as in Case 9) and higher vertical permeability conduits close to the faults. In these cases as well, the results indicated that the plume remained within the storage complex.

The results of all the modelled scenarios considering a wide range of geological uncertainties indicate the injected CO_2 remains within the Lesueur Formation and below 800mSS even after 1000 years.

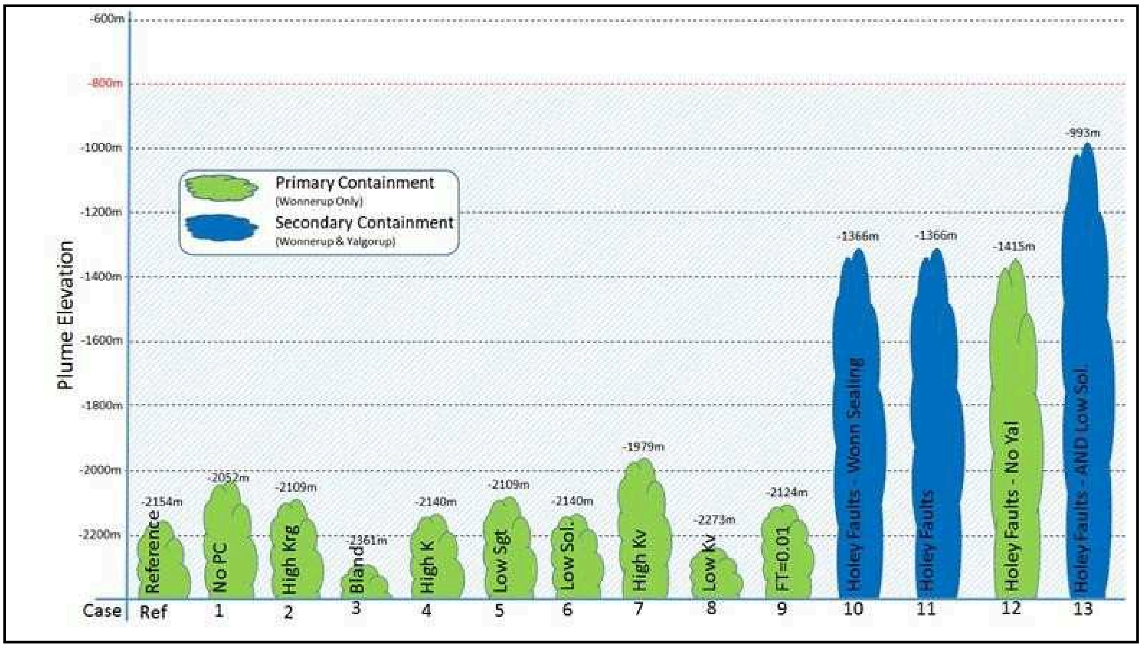

Figure 7: Vertical Plume Migration. The shaded area marks the storage complex.

The plume spread does not vary much between the cases and the plume remains contained within a 3.5kmX6.5km area. As an illustration (**Error! Reference source not found.**) the plume outline (after 1000 years) of the Reference Case is overlain on the profile of Case 8, one in which we would expect to see a higher spatial spread due to reduced vertical permeability.

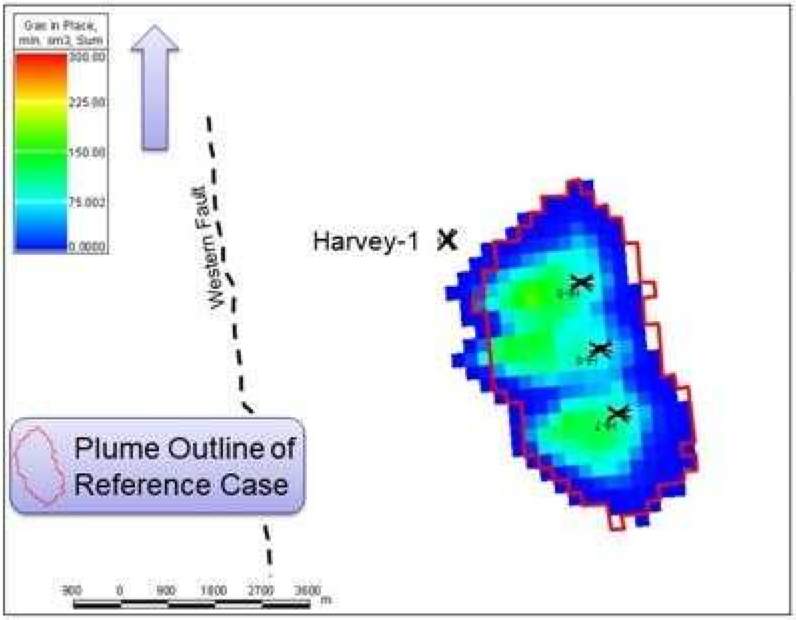

Figure 8: Plume Outline for Case 8 compared to Reference Case

The following development scenarios were also modelled to test the variability of the development concept.

- A two well case which has similar but slightly more compact plumes compared to the reference 3 well case;
- A three well shallow case wherein the perforations were moved from the bottom of the Wonnerup Member to the middle i.e. around 700m from the base of the Wonnerup Member. Here the plume rises through into the Yalgorup Member but stabilises at 1137m and does not reach the bounding fault on the West side. In this case if the Yalgorup and Wonnerup are not in communication the plume does just reach the Western fault;
- A high rate case wherein 3 million t/a are injected through 8 wells. The plume rises into the Yalgorup Member but stabilises around 1300m.

The results of the Black Oil modelling show that it could be feasible to inject 800,000 t/a of CO_2 over 30 years in the Wonnerup Member of the Lesueur Formation and that all of the injected volume remains in the defined storage complex. The main factors controlling plume migration are: (i) the solubility of CO_2 in brine and (ii) the combination of the transmissibility of fluids across the faults, and high vertical permeability fracture zones close to faults.

As per the modelling strategy select cases of the Black Oil modelled results are tested by running them using the compositional GEM^{TM} simulator. The cases to be validated were agreed through discussion with the project peer review group and are (i) the Reference Case, (ii) Stress Case 13 (“holey faults” with low solubility) and (iii) Stress Case 14 (“holey faults” with low transmissibility faults).

The Reference Case results are shown in Figures 9 and 10.

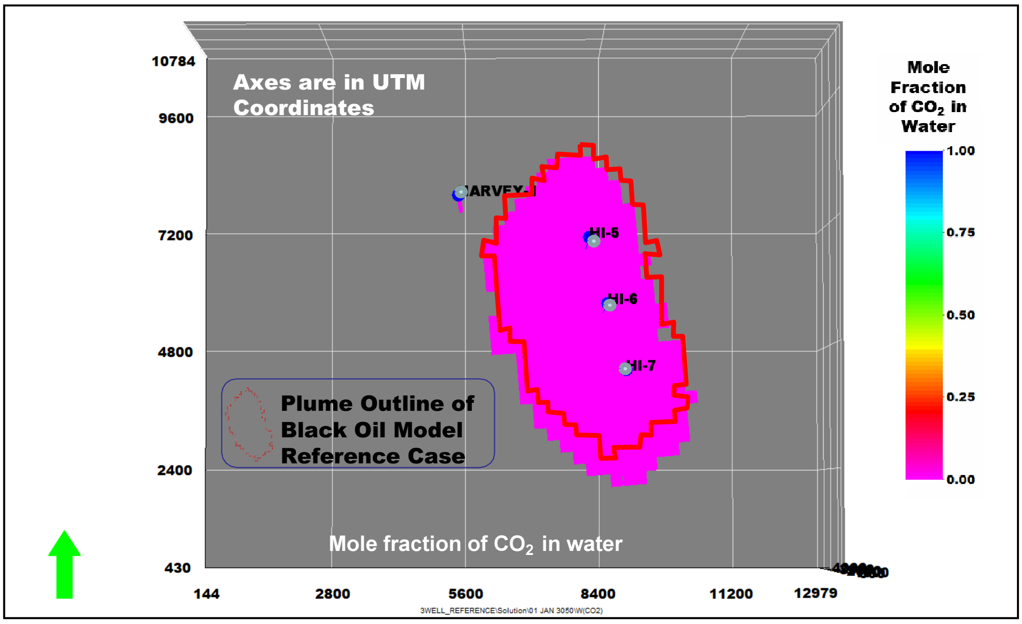

Figure **Error! No text of specified style in document.**- Top View Comparison of CO_2 Plume @ 1000 years – Reference Case (Black Oil and Compositional)

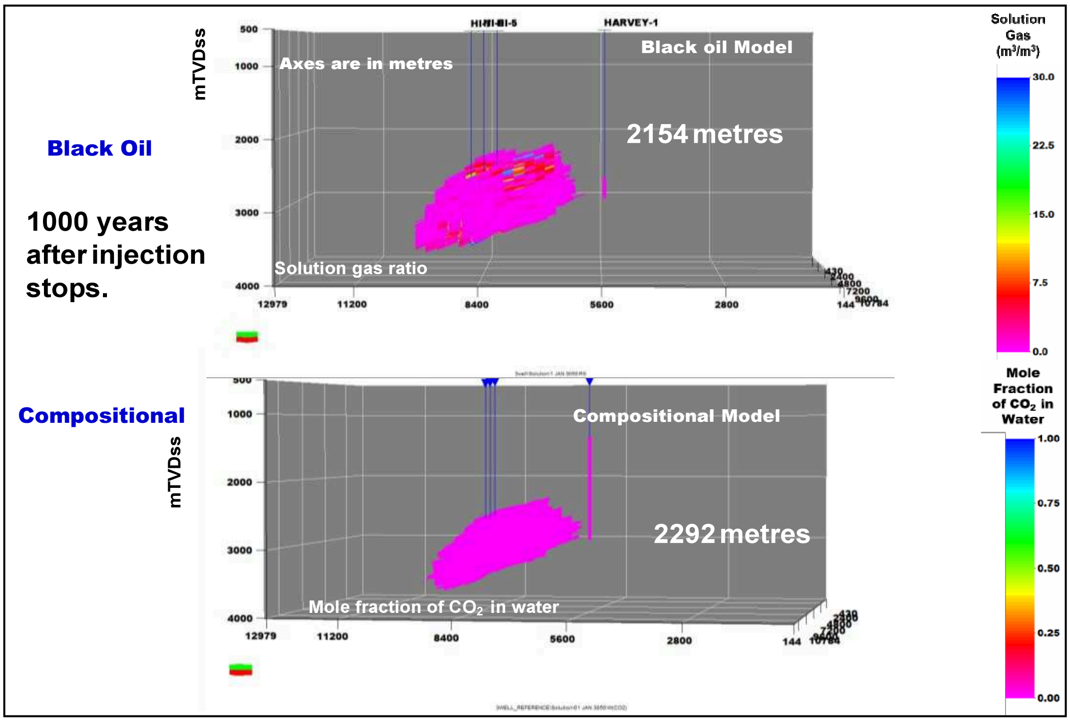

Figure 10: Looking South Comparison of CO_2 Plume – Reference Case (Black Oil and Compositional)

Table 5 lists the material balance accounting of the various components of the free and trapped CO2 after 1000 years using both the simulation technqiues.

Table 5: Material Balance Accounting – Reference Case (Black Oil and Compositional Model)

Reference Case : Black Oil Model				
	Supercritical CO_2			
	Trapped CO_2 (Sm3)	Mobile CO_2 (Sm3)	Total Dissolcved CO_2 (Sm3)	Total CO_2 (Sm3)
Gas Material Balance	5.4E+09	2.0E+07	7.7E+09	1.3E+10
% Injected	40.9%	0.2%	59%	100%

Reference Case : Compositional Model				
	Trapped CO_2 (moles)	Mobile CO_2 (moles)	Total Dissolcved CO_2 (moles)	Total CO_2 (moles)
Gas Material Balance	3.45E+11	2.37E+08	2.13E+11	5.68E+11
% Injected	62.4%	0.0%	37.5%	100%

The modelling shows that the description of the CO_2 plume in the compositional models are similar to those predicted using the Black Oil models. These results confirm that the Black Oil formulation can effectively model CO_2 sequestration in the Harvey area and indicate that it could be feasible to inject 800,000 t/a of CO_2 over 30 years in the Wonnerup Member of the Lesueur Formation and that all of the injected volume remains in the defined storage complex.

6. Uncertainty Evolution and Uncertainty Management Recommendations

As is to be expected the impact level of the uncertainties on the project success factors have varied as new information has become available and resulted in an iteration of the geological and simulation models. This evolution over four generations of models is illustrated qualitatively in Figure 11. It is clear that significant progress has been made in understanding the uncertainties and identifying the ones that have maximum impacts on the project objectives.

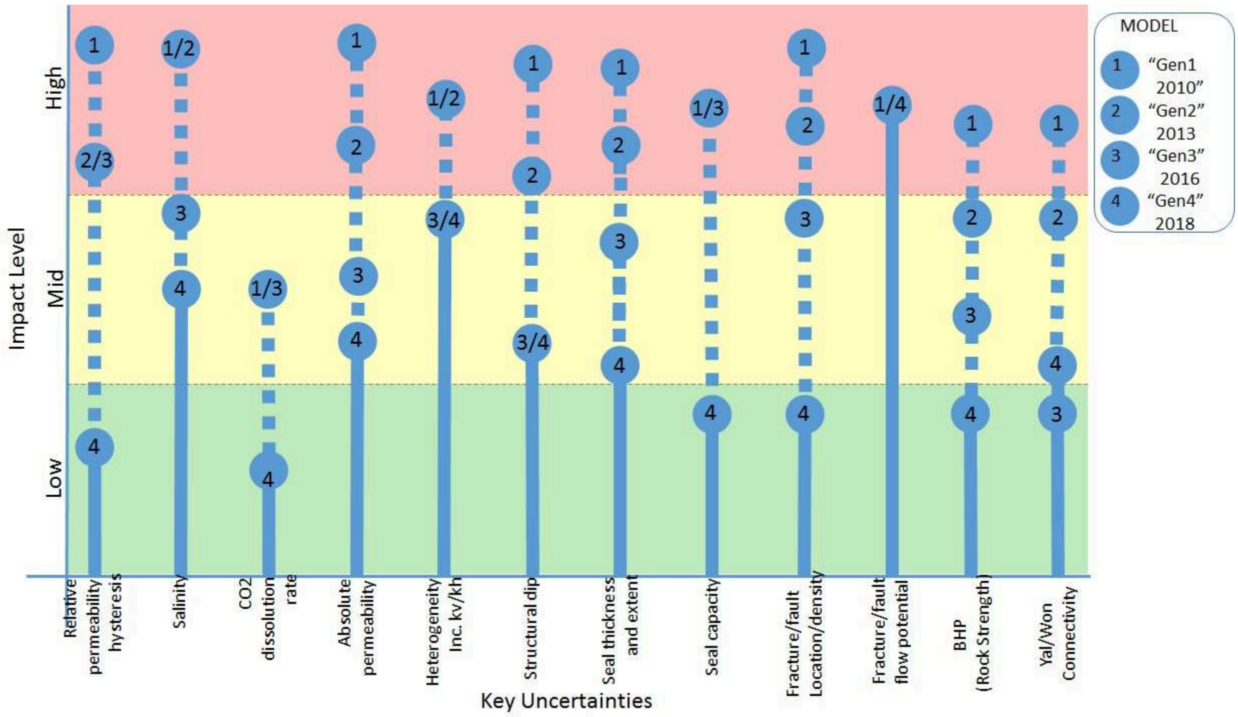

Figure 11: Mapping the impact levels through four generations of project models.

The current UMP is based on the 4th generation models and the key remaining uncertainties are as categorized in Figure 12. All information that can be extracted from existing data has been extracted and new data will be needed to address the remaining high impact uncertainties. This would have to include assessing deep reservoir properties and assessing dynamic reservoir performance based on flow and well tests.

Multiple options were considered for new data acquisition targeted at the defined uncertainties. These included deep wells and well pairs to facilitate interference testing which could potentially understand fault based compartmentalisation and also evaluate vertical plume migration.

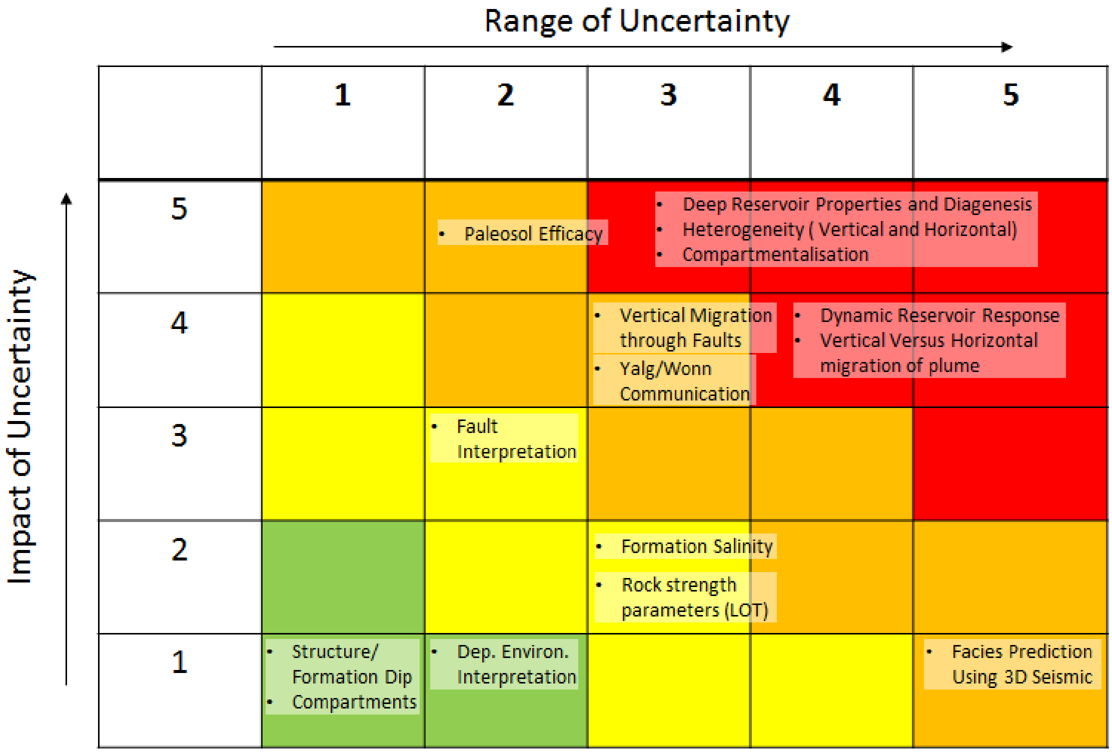

Figure 12: SW Hub Project uncertainty matrix

A prioritisation scheme was developed to assess and rank the new data acquisition options. The priority for the each uncertainty were was considered for its impact and assigned a value as indicated in Table 6:

Table 6: Prioritising the Uncertainties

Score	Technical Gap Impact	Comments
5	High	Highest level of risk to the project objectives and should be targeted by the additional work.
3	Medium	Moderate risk to the project objectives and should be targeted by the additional work;
1	Low	Current understanding is fit-for-purpose to support the targeted project objectives and no further work is required at this time;

The technical solutions in the form of data acquisition options were assigned weights as well. These options each have individual logistical, regulatory, technical and cost strengths and weaknesses. Thus only permissible sites were considered wherein landowners were amenable and no environmentally sensitive areas would be encountered. A priority score for each option reflecting its technical ability to address the identified gaps is considered through a six-grade ranking system as shown in Table 7. A qualitative financial screen would then be used to formalize the final recommendation.

Table 7: Scoring the technical data acquisition options

Score	Description	Data Acquisition Option Efficacy
5	One of the Best Options	Capable, by itself, of entirely resolving the Gap
4	Good	Probably capable of entirely resolving the Gap
3	Fair	With other supporting data, capable of resolving the Gap
2	Not Good	May complement other data to resolve the Gap
1	Poor	Of little use in understanding the data Gap
0	Bad	Entirely inapplicable to the data Gap

The options for new data acquisition considered are listed below from A-H:

- Option A: Additional Acquisition in well H3.
- Option B: New shallow well using H3 as monitoring well.
- Option C: A new deep well (near H3) and using H3 as monitoring well.
- Option D: One deep, one shallow (near H3) and using H3 as monitoring well.
- Option E: A deep well (near H4) and using H3 as monitoring well.
- Option F: One deep well and one shallow well near H4.
- Option G: One deep well and two shallow wells near H4.
- Option H: Two deep wells and a shallow well near H4.

Figure 13 shows the various options considered and Figure 14 the results of the ranking methodology. A qualitative finance screen was considered to make the final recommendation, which included the drilling of two wells in specific locations with a detailed test plan (Figure 15).

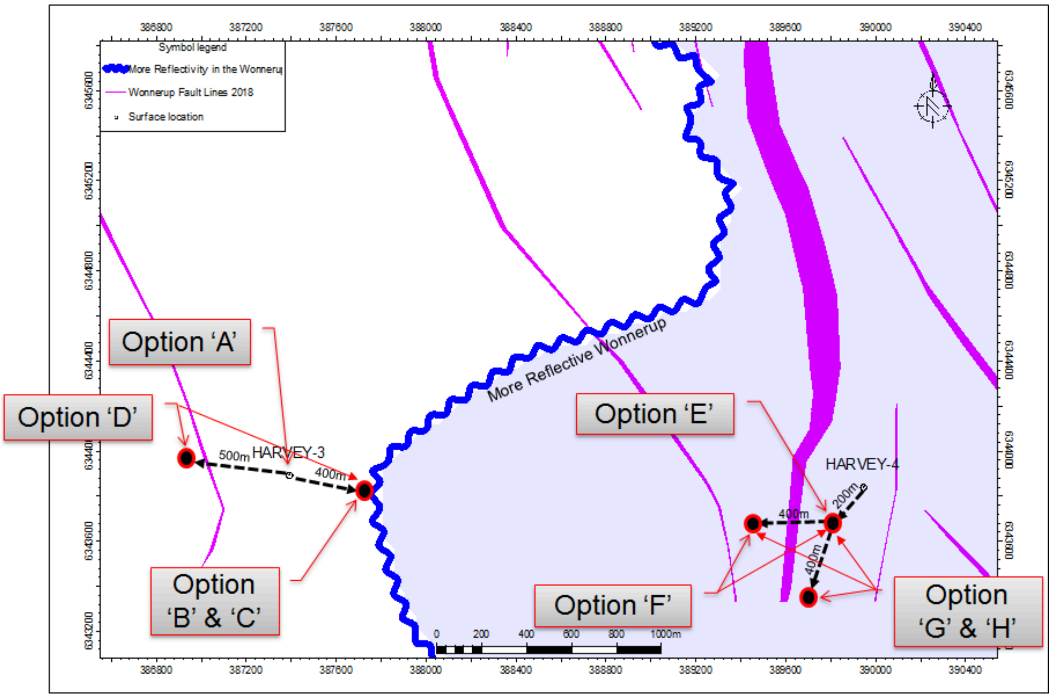

Figure 13: New data acquisition options considered

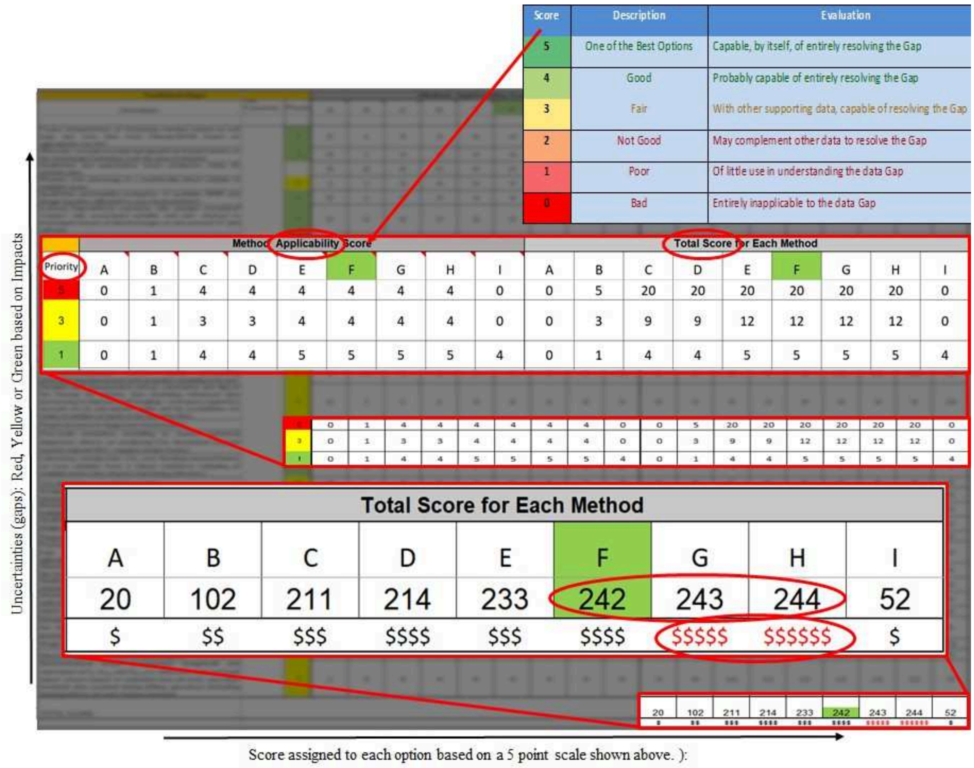

Figure 14: Prioritisation scheme for all options

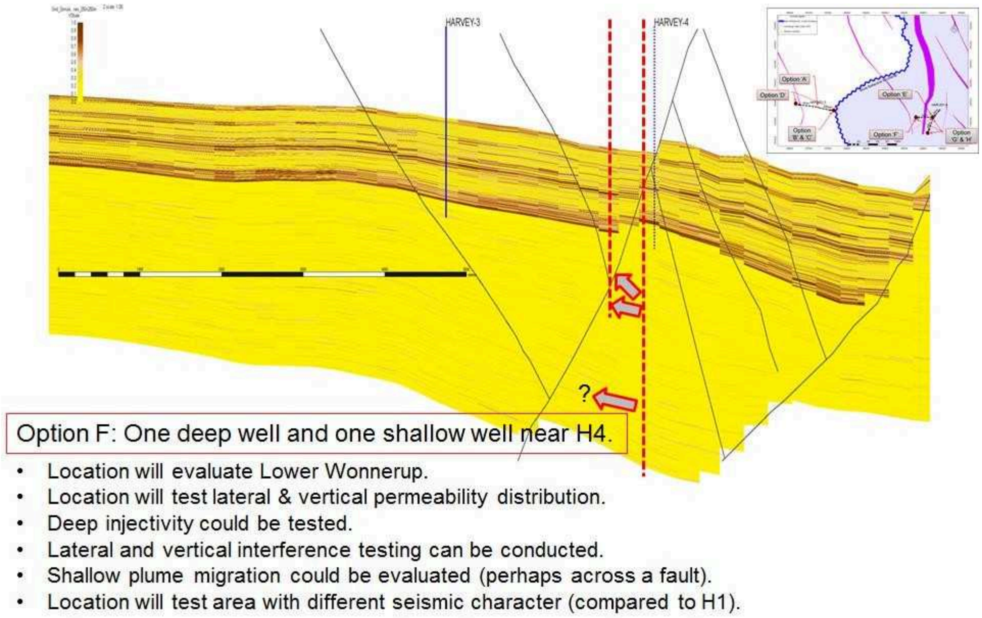

Figure 15: Recommended new data acquisition option

7. 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‘) was used as a means of educating school going children [15]. With the revocation of the Australian carbon price legislation, industry interest had flagged but efforts are being made to engage with them again as storage remains a viable option to consider for Australia to meet its commitment made at the Paris meetings in December 2015.

8. Concluding comments

The modelling results have concluded that it could be feasible to meet the success criteria and inject at least 800,000 t/a of CO_2 over 30 years in the Wonnerup Member of the Lesueur Formation. The models have been determined to be robust and the multiple scenarios considered, including the “stress” cases attempting to break the storage concept. The results have bolstered the confidence of the SW Hub Project proponents in the potential of the area for storage.

Additional drilling and suitable test programs could be used to demonstrate feasibility of the storage concept based on MAT as the primary containment mechanism in the absence of a regional seal. 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.

Funding options are currently being explored to proceed with the identified data acquisition option to reduce the uncertainties further.

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, Industry Regulation and Safety (DMIRS); 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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