SOUTH WEST HUB
CARBON CAPTURE STORAGE

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Subsurface Modelling Update

South West Hub Project

November 15, 2012

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Outline

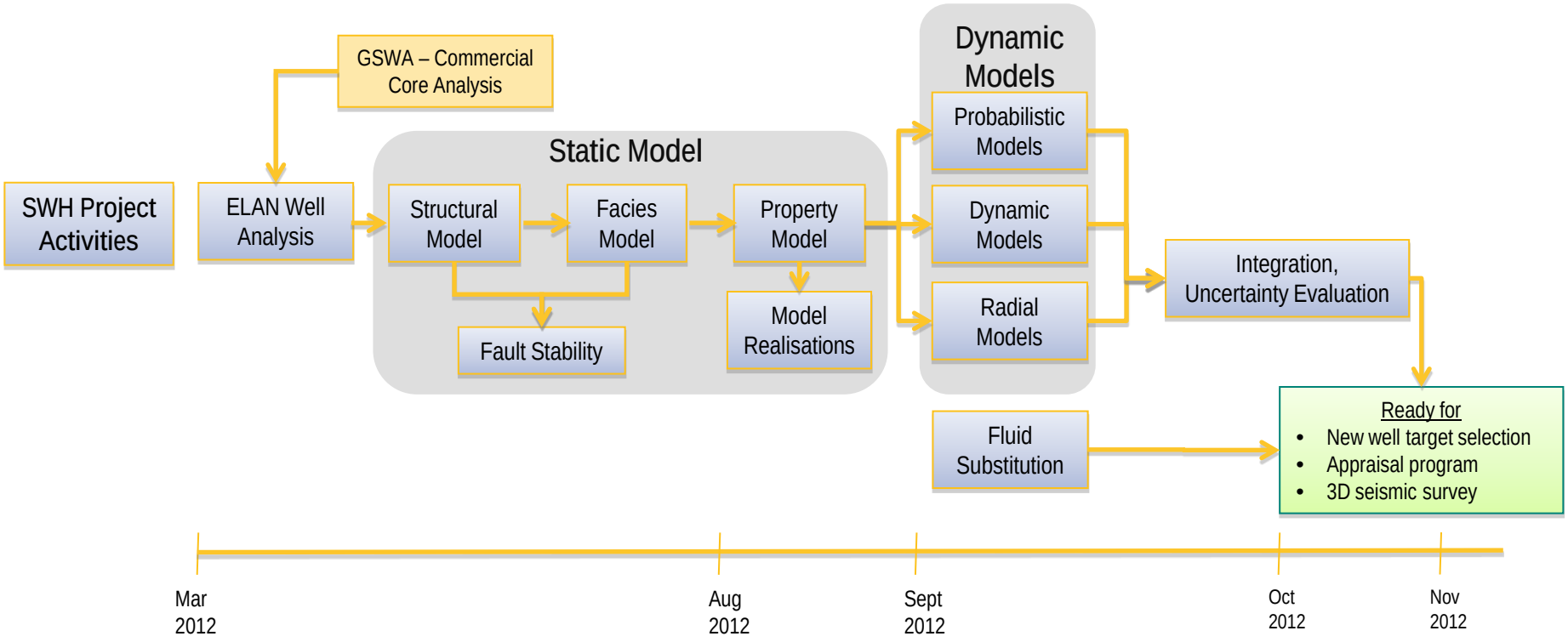
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- Workflow
- Static Model
- Dynamic Models – Radial and Sectoral
- Analytical Probabilistic Computations
- Comparison with previous models
- Appraisal program

Scope of Current Work

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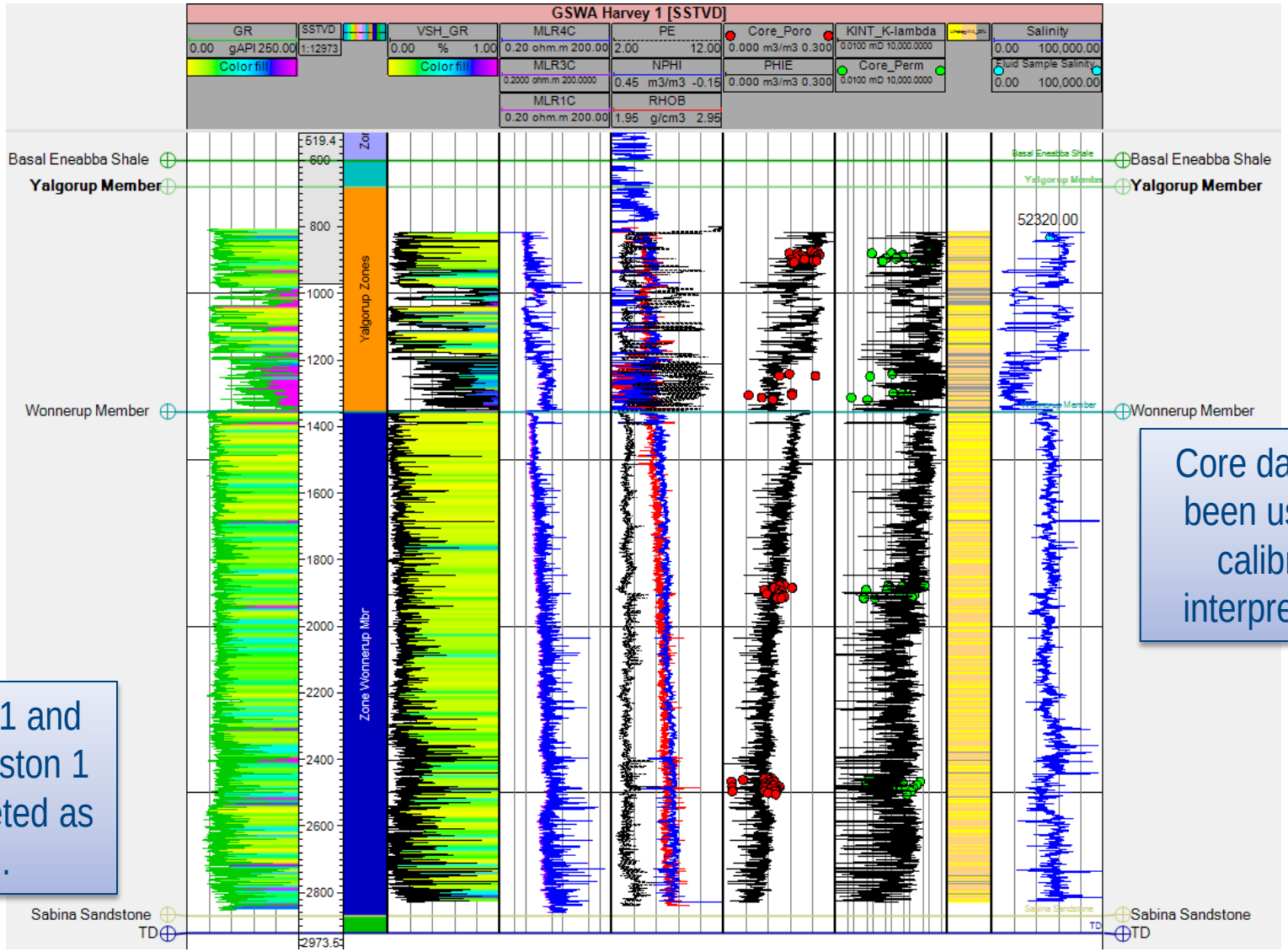
- High level objectives:
  - Update existing models from Stage 1b by integrating newly acquired data
  - Assess how the newly acquired data changes the understanding of the area
  - Identify remaining uncertainties
  - Provide input for the development of a new appraisal program



Static Model

GSWA Harvey 1 Log Interpretation

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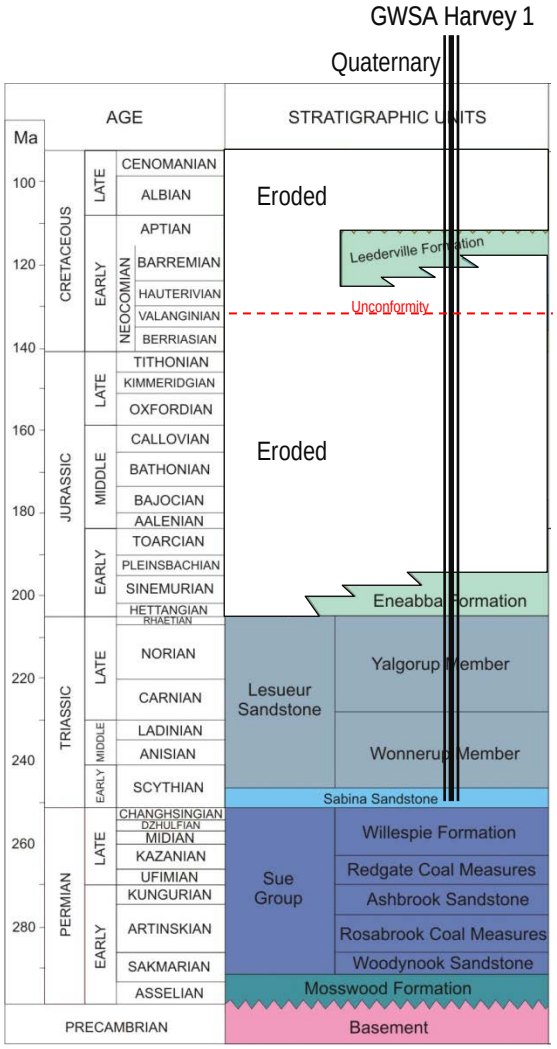


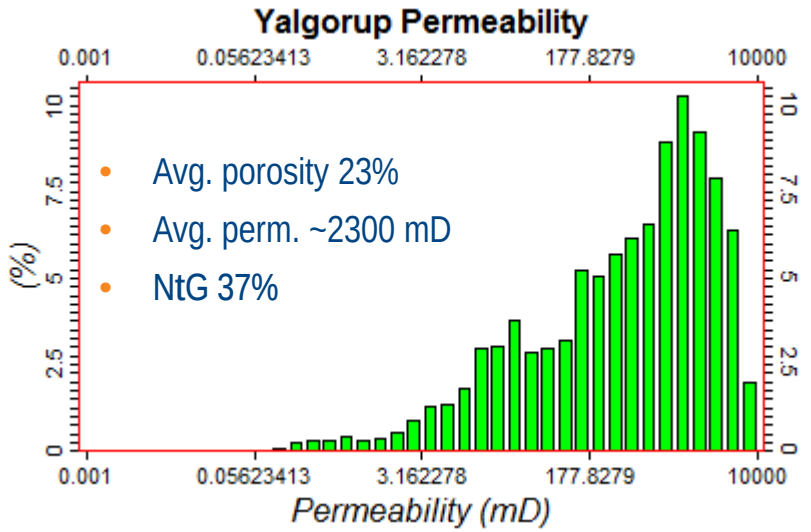
Core data has been used to calibrate interpretation

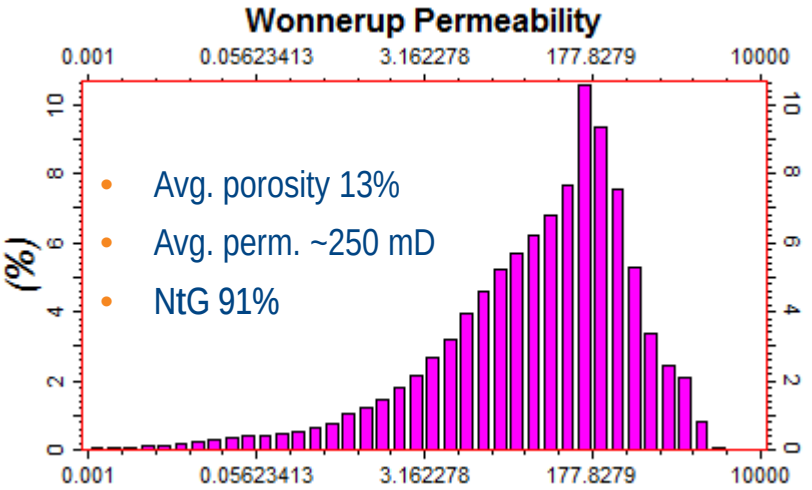
Pinjarra-1 and Lake Preston 1 reinterpreted as well.

GSWA Harvey 1 Petrophysical Results

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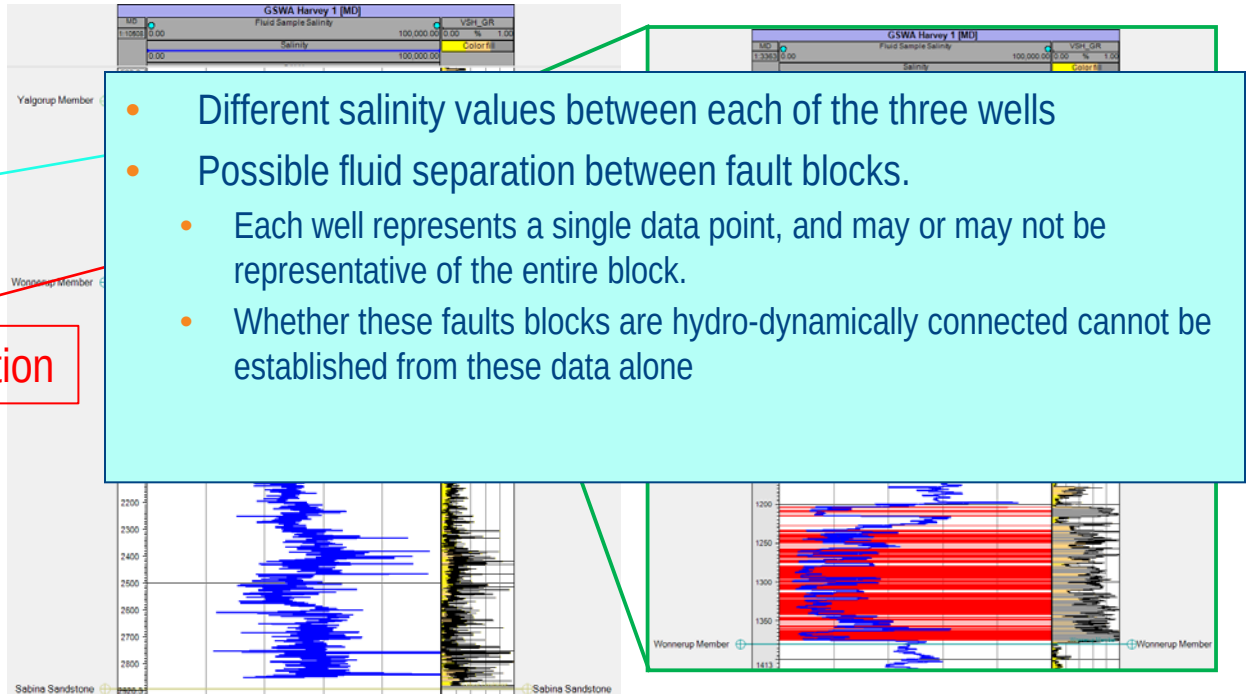




Salinity

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	Leederville Formation	Cattamarra Coal Measures	Eneabba Formation	Yalgorup Member	Wonnerup Member
Pinjarra 1	~1800 ppm	< 400 m, ~1800 ppm > 1050 m, ~30000-42000 ppm	Absent	< 2500 m, ~10000 ppm > 2500 m, ~1800 ppm	~3000-5000 ppm
Lake Preston 1	No data	Absent	< 500 m, ~3000 ppm > 500 m, ~46000 ppm	~40000 ppm	< 2140 m, ~20000 ppm > 2140 m, ~2000 ppm
Harvey 1	No data	No data	No data	~60000 ppm Fluid sample at 856 m: 52230 ppm	~50000 ppm



- Different salinity values between each of the three wells
- Possible fluid separation between fault blocks.
  - Each well represents a single data point, and may or may not be representative of the entire block.
  - Whether these faults blocks are hydro-dynamically connected cannot be established from these data alone

Geo-mechanics: 1D-MEM Results

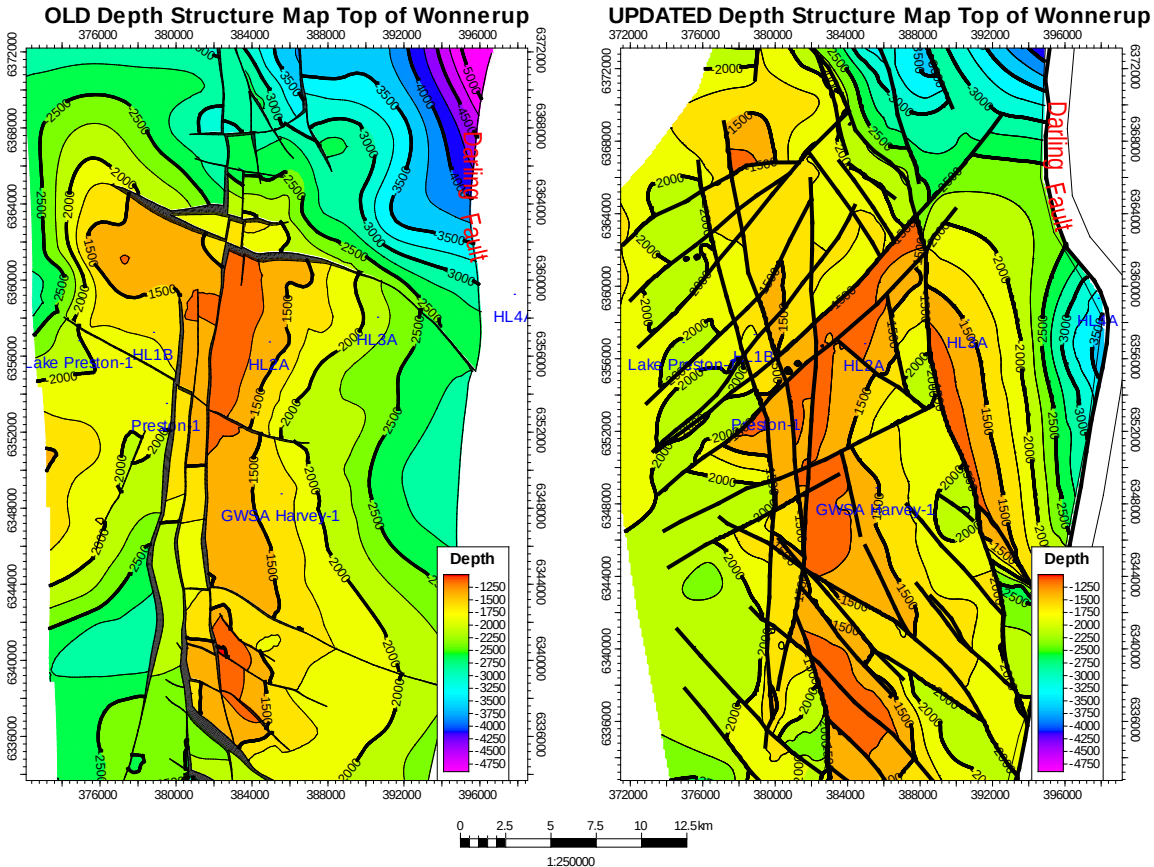
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- Mechanical test data were available from a nearby well
  - Good calibration of the 1D-MEM
  - Predicted breakouts correspond to observed breakouts in borehole images and caliper data
- Maximum bottom hole pressure is found, corresponding to 41.2 MPa, at 2200 mMD.
  - Good design practice might assume injection pressure should not exceed 90% of the maximum calculated value.
- Major uncertainties
  - Validate fracture pressure with LOT
  - Use XLOT or mini-frac to calibrate frac pressure and minimum horizontal stress

Static Model: Structure is more compartmentalised

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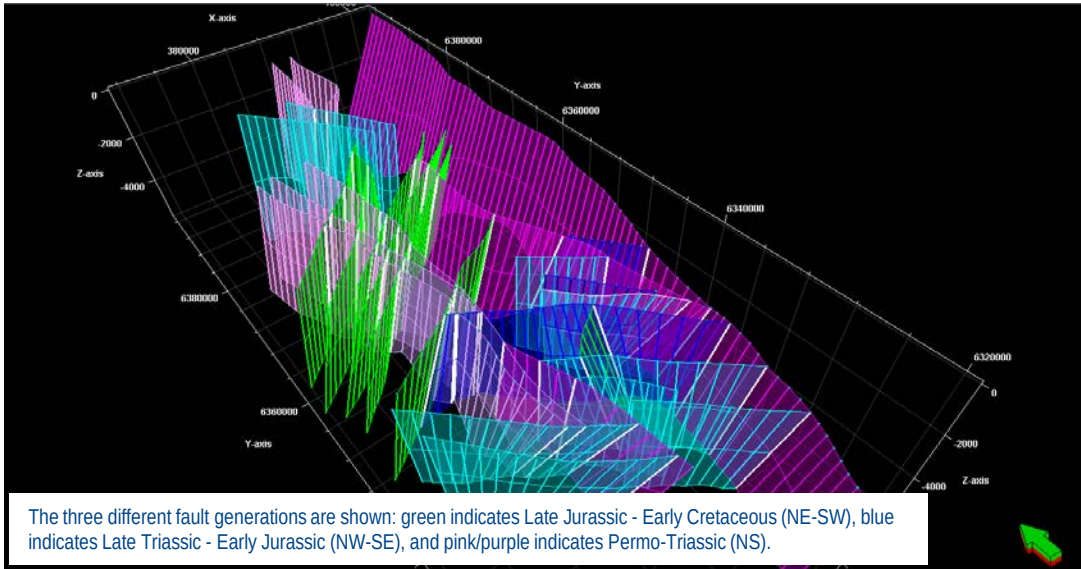
- New seismic changed the understanding of the area around Harvey 1
- New interpretation reconciles the new seismic data with publications on fault orientations in the Perth Basin
- Area is now more faulted



Structural Model – Faults & Horizons

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- Fault truncated according to the chronological sequence of the tectonic events: *younger faults* cut *older faults*
  - Late Jurassic - Early Cretaceous (NE-SW)
  - Late Triassic - Early Jurassic (NW-SE)
  - Permo-Triassic (NS)
- Each family divided into 3 different classes based on uncertainty
  - Class 1: clearly visible on multiple seismic lines
  - Class 2: less defined, lateral extent has some uncertainty
  - Class 3: poorly defined, lateral extent highly uncertain
- Comprised of 50 fault parts (cf 21 faults in Stage 1b model)
- Four horizons modelled
  - Unconformity (Early Cretaceous)
  - top Yalgorup Member
  - top Wonnerup Member
  - base Sabina Sandstone

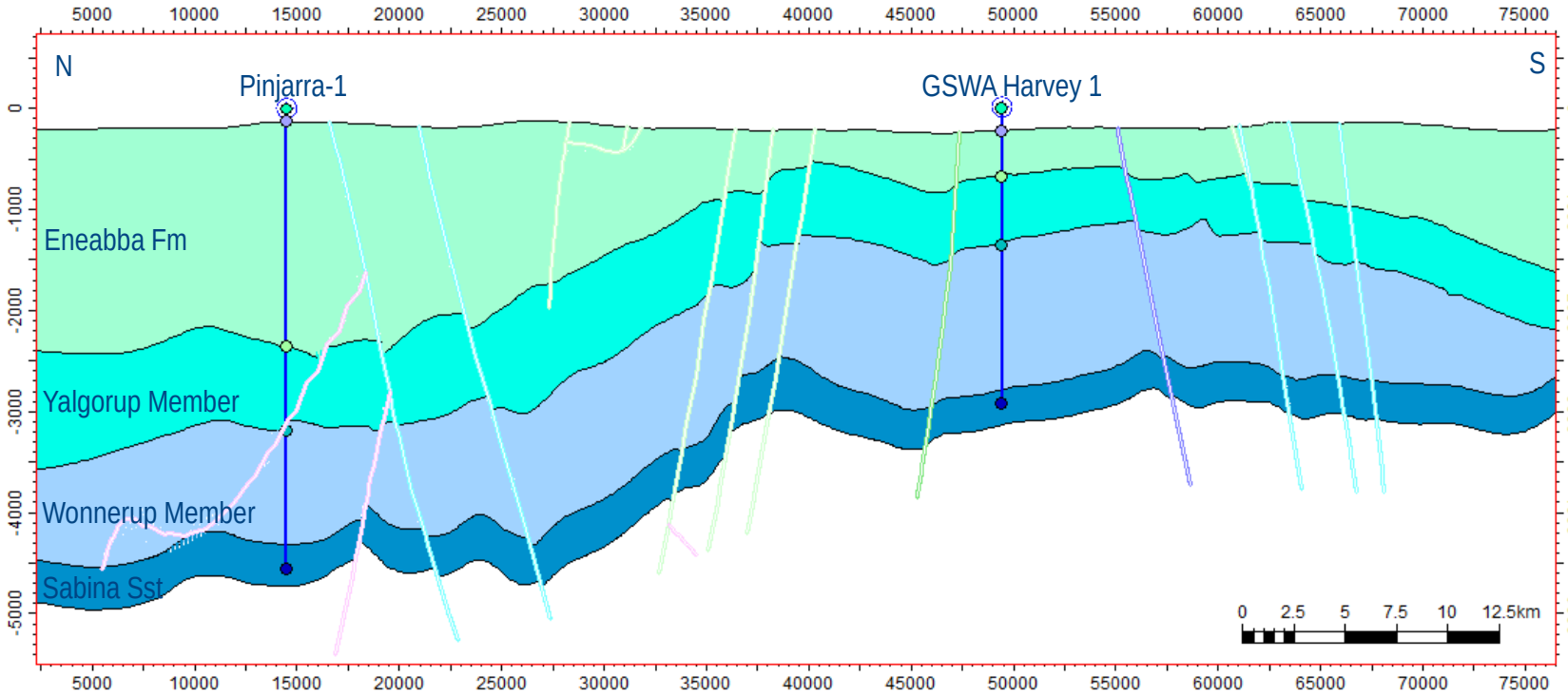


The three different fault generations are shown: green indicates Late Jurassic - Early Cretaceous (NE-SW), blue indicates Late Triassic - Early Jurassic (NW-SE), and pink/purple indicates Permo-Triassic (NS).

Structural Model – Horizons

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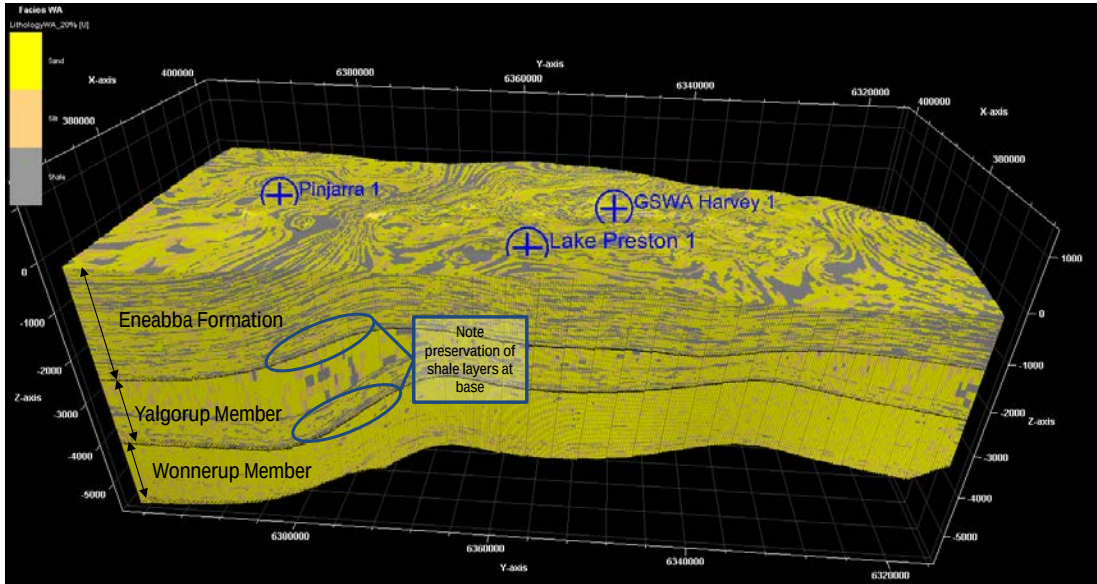
- Four horizons modelled explicitly:
  - Unconformity (Early Cretaceous)
  - top Yalgorup Member
  - top Wonnerup Member
  - base Sabina Sandstone



Facies Modelling

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- Approach replicated from Stage 1b – *object modelling*
  - Uses analog for channel dimensions
  - Orientation from outcrop studies to the north
  - Sand, silt and shale
- Three facies models created
  - Base Case (same cut-offs as Stage 1b)
  - High Silt Case
  - High Shale Case



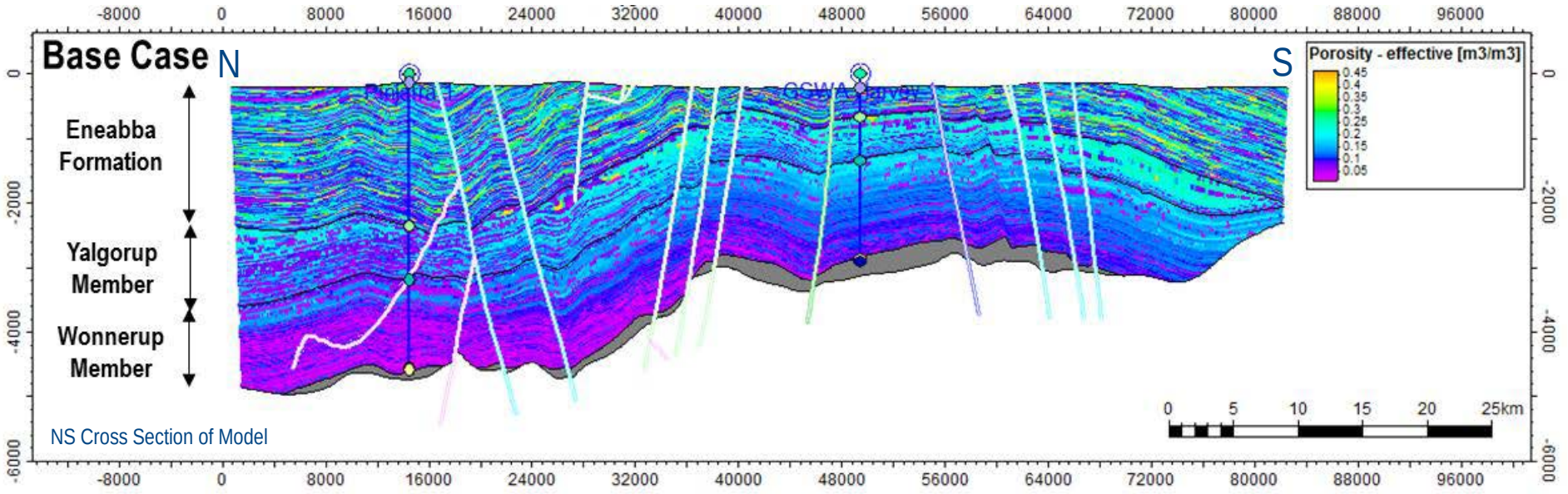
3D perspective of the facies model

Porosity Field

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- *Spatially distribute effective porosity, permeability and net-to-gross*

- Porosity field distributed by Sequential Gaussian Simulation
  - Constrained by same variogram as Stage 1b (from analogue)



NS Cross Section of Model

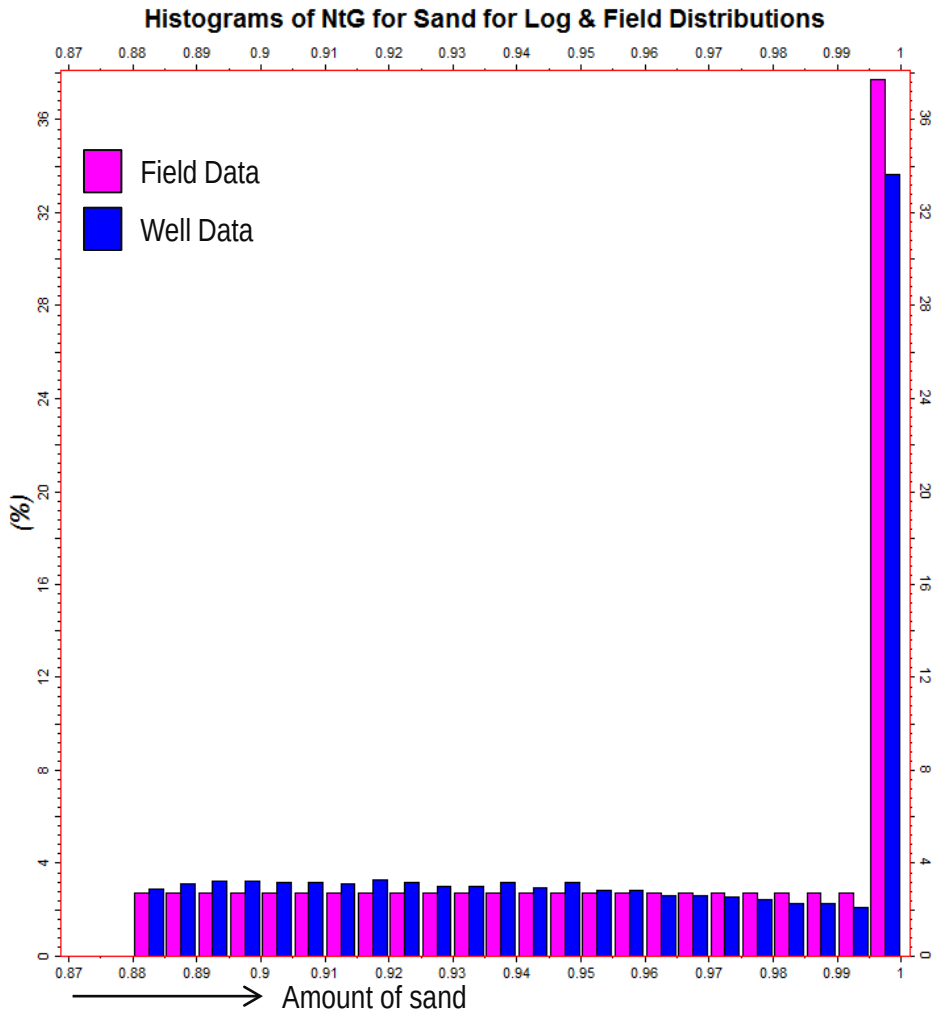
Permeability

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- Permeability fields were generated using logs from the petrophysical interpretation
- Permeability was distributed using Gaussian random function simulation
- Distribution is trended to porosity and guided by variogram
- Borehole quality affects permeability, and will therefore affect the property field
- Core data is used where sections of log are washed out

Confidence in Net-to-Gross

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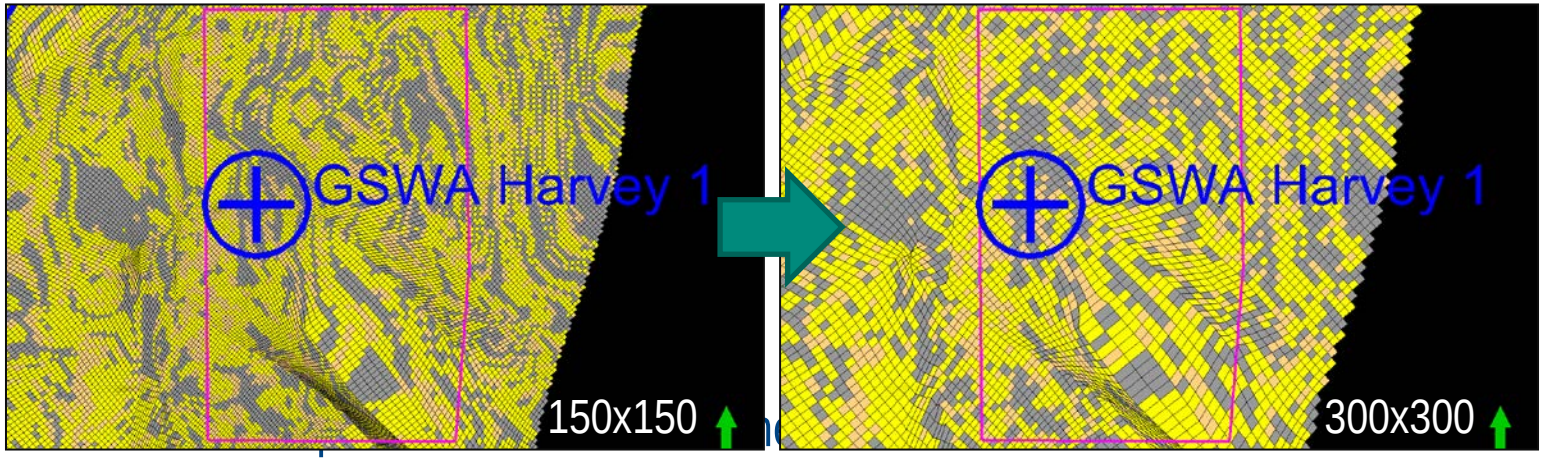


Well data matches field data, giving us confidence that we are replicating observed data

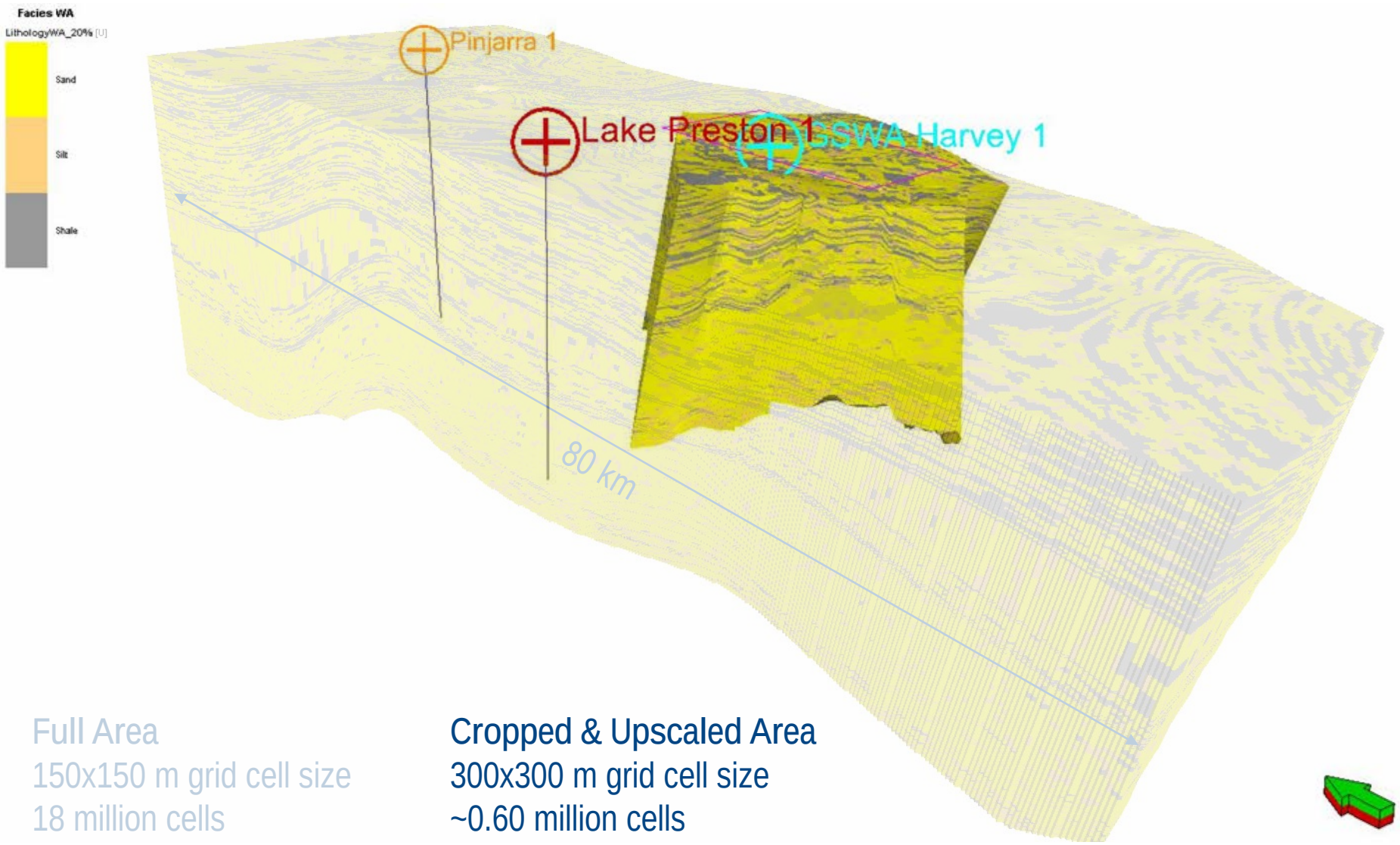
Simulation Grid

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- Grid size of the entire model is ~18 million cells
  - Too large for simulation
- How do we reduce the number of cells?
  - Common practice in O&G to **upscale the geological model**
  - Change the size of the grid cells or the number of layers
    - For this work, we want to keep the fine layer detail, **so we change the grid size**

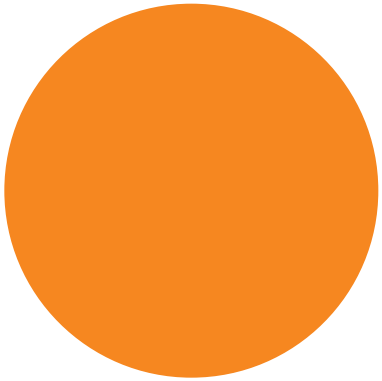


- Focus the simulation grid **around the planned 3D seismic area** and takes into consideration faults



Full Area
150x150 m grid cell size
18 million cells

Cropped & Upscaled Area
300x300 m grid cell size
~0.60 million cells

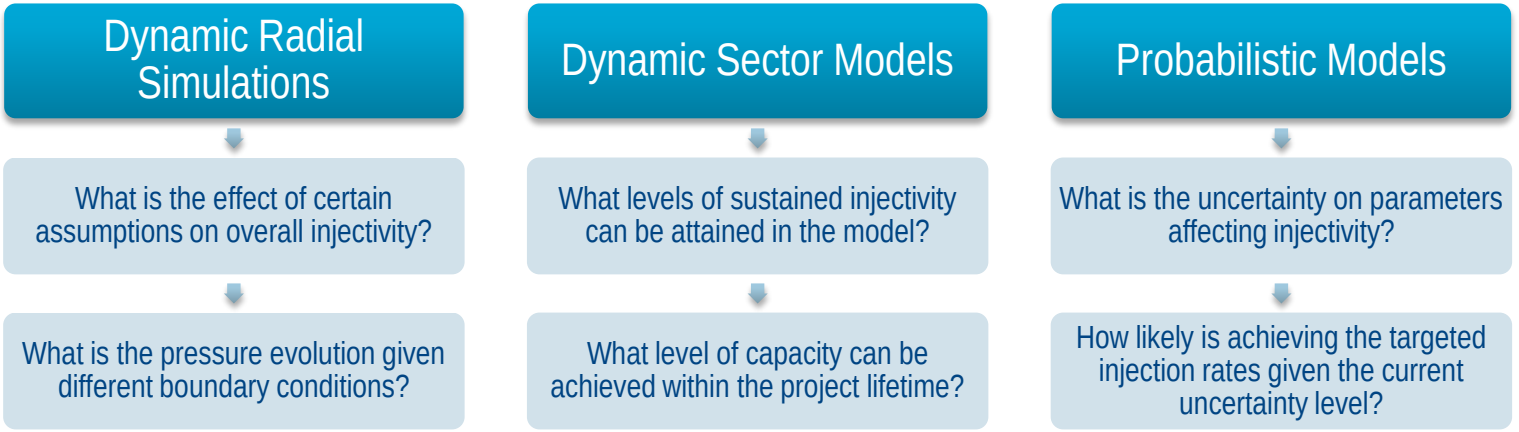


Dynamic Models

Introduction

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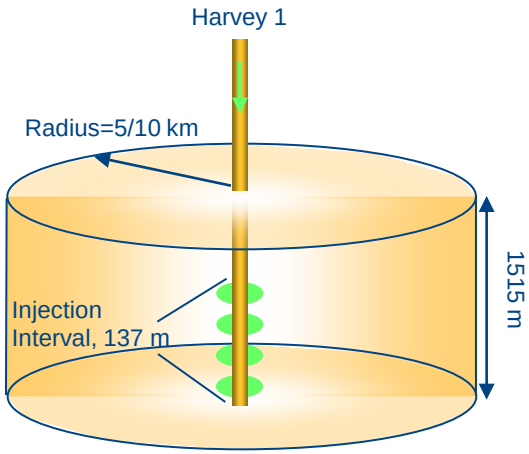
- Three types of modelling are used to assess the CO_2 storage potential.
- Each of these types of models is used to assess certain questions or aspects.
- The types of modelling are:



Dynamic Radial Models

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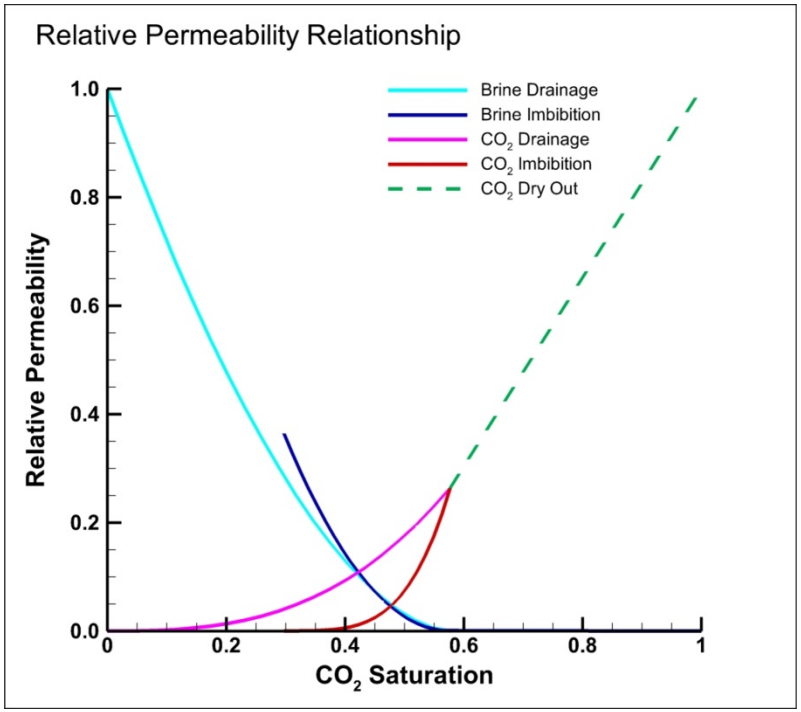
- *Dynamic radial models* are used to qualitatively explore the impact of certain assumptions on injectivity.
- Radial model is built from the Wonnerup Member portion of the Harvey 1 well.
- The assumptions and assessment parameters chosen for particular reasons are:
  1. Compartment size, i.e. distance to no-flow boundary
  2. Permeability upscaling approach
  3. Grid layer thickness
  4. Relative permeability end-point.



Input Data and Constraints

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- Reservoir Properties (Permeability, NTG, porosity) from ELAN, kv-kh ratio of 0.1
- Simulation restricted to Wonnerup Member
- E300 CO2Store (compositional)
- Boundary conditions
  - Injection rate is limited by an imposed fracture gradient (0.149 bar/m), otherwise freely
  - Injection interval: 2283 – 2410 MD – criterion: relatively deep and thick sand package
    - Fine grid: 135 m (27 cells @ 5m)
    - Coarse grid: 100 m (2 cells @ 50m)
  - 30 years of injection
  - Injection into a saline aquifer (60000 ppm) – mean out of ELAN analysis
  - Initially in hydrostatic equilibrium (190 bar @ 1913 m) – RCI tool
  - Temperature vs. Depth as measured – RCI tool
  - Relative Permeability: Viking (Bachu)



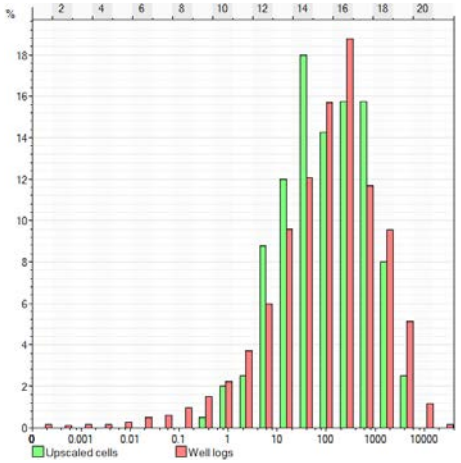
Upscaling Results - Permeability

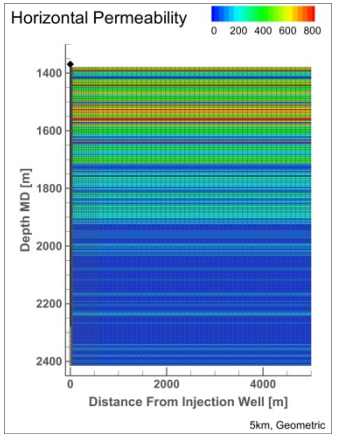
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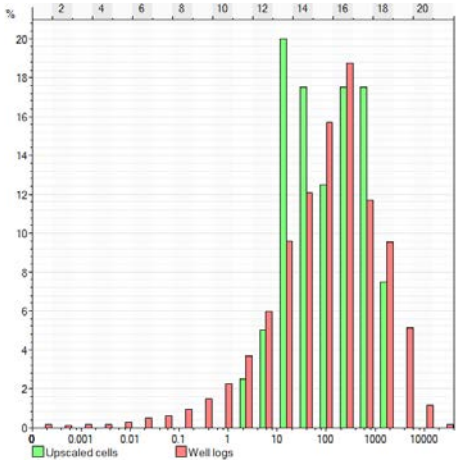
Fine Layering

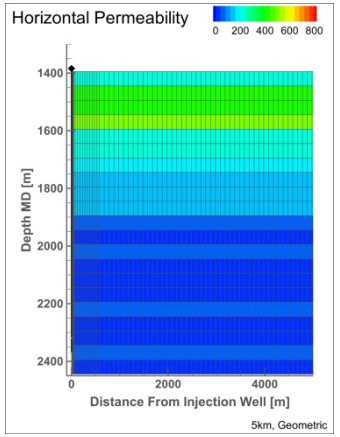
Coarse Layering

Geometric Upscaling

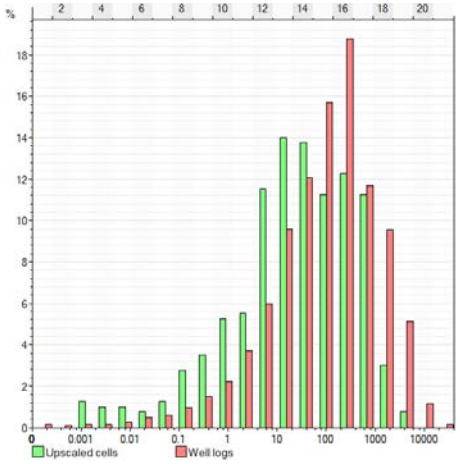


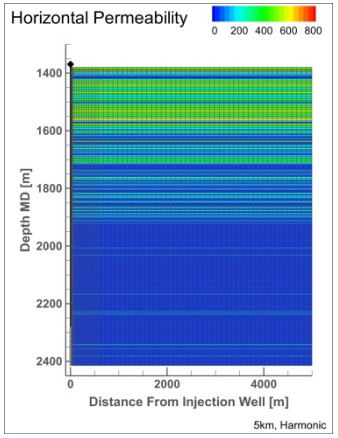


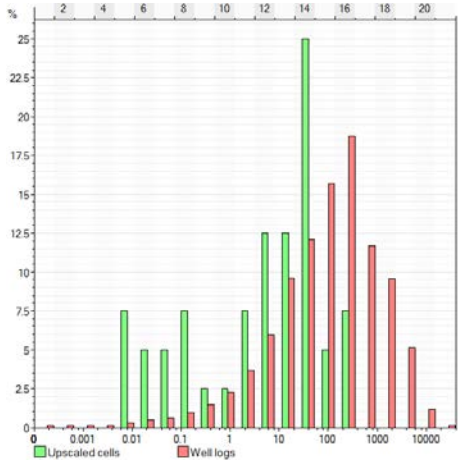


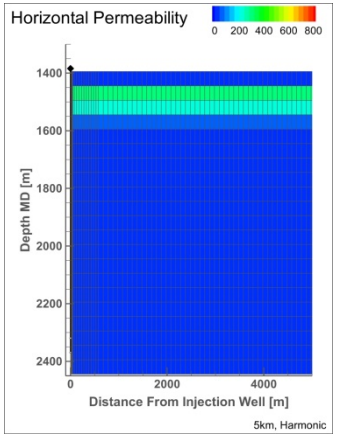


Harmonic Upscaling



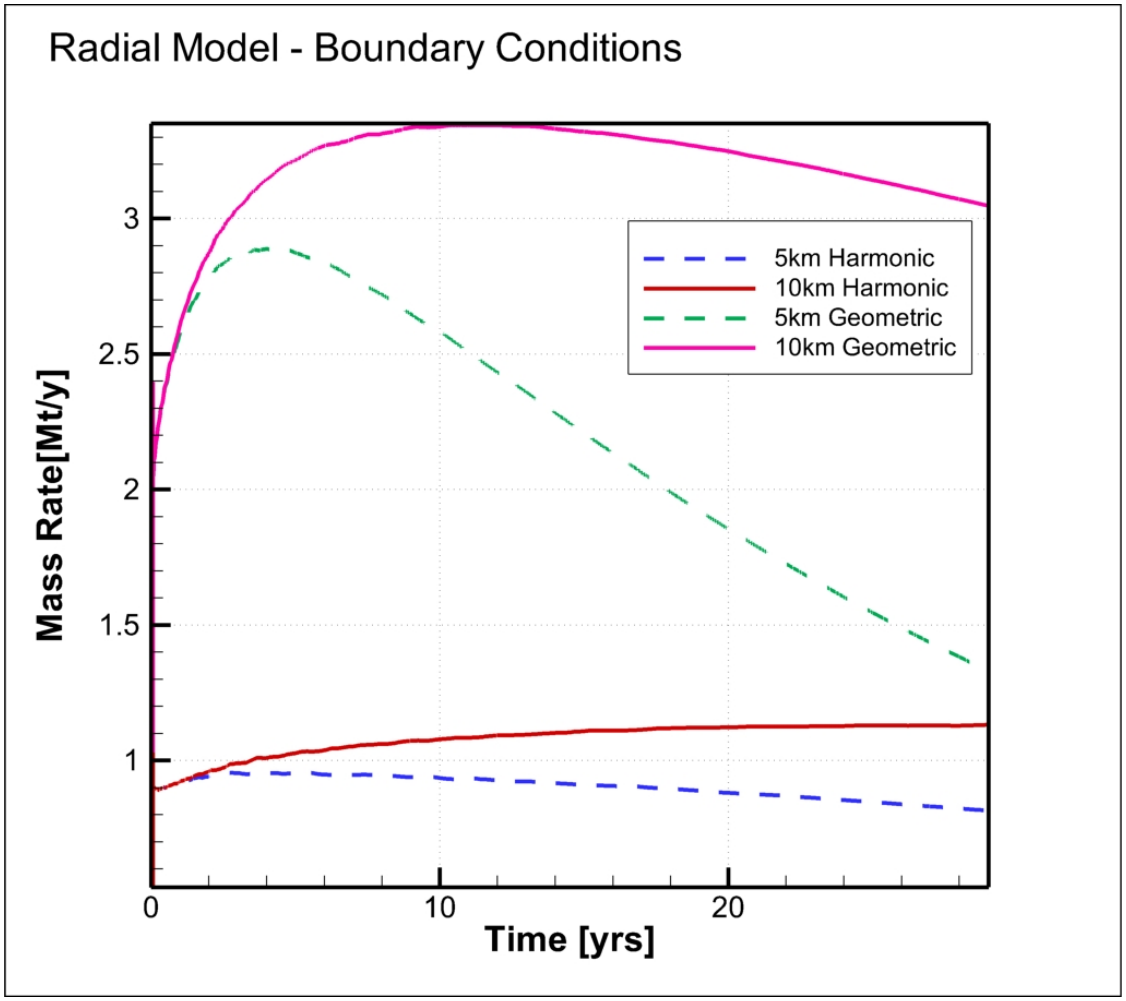






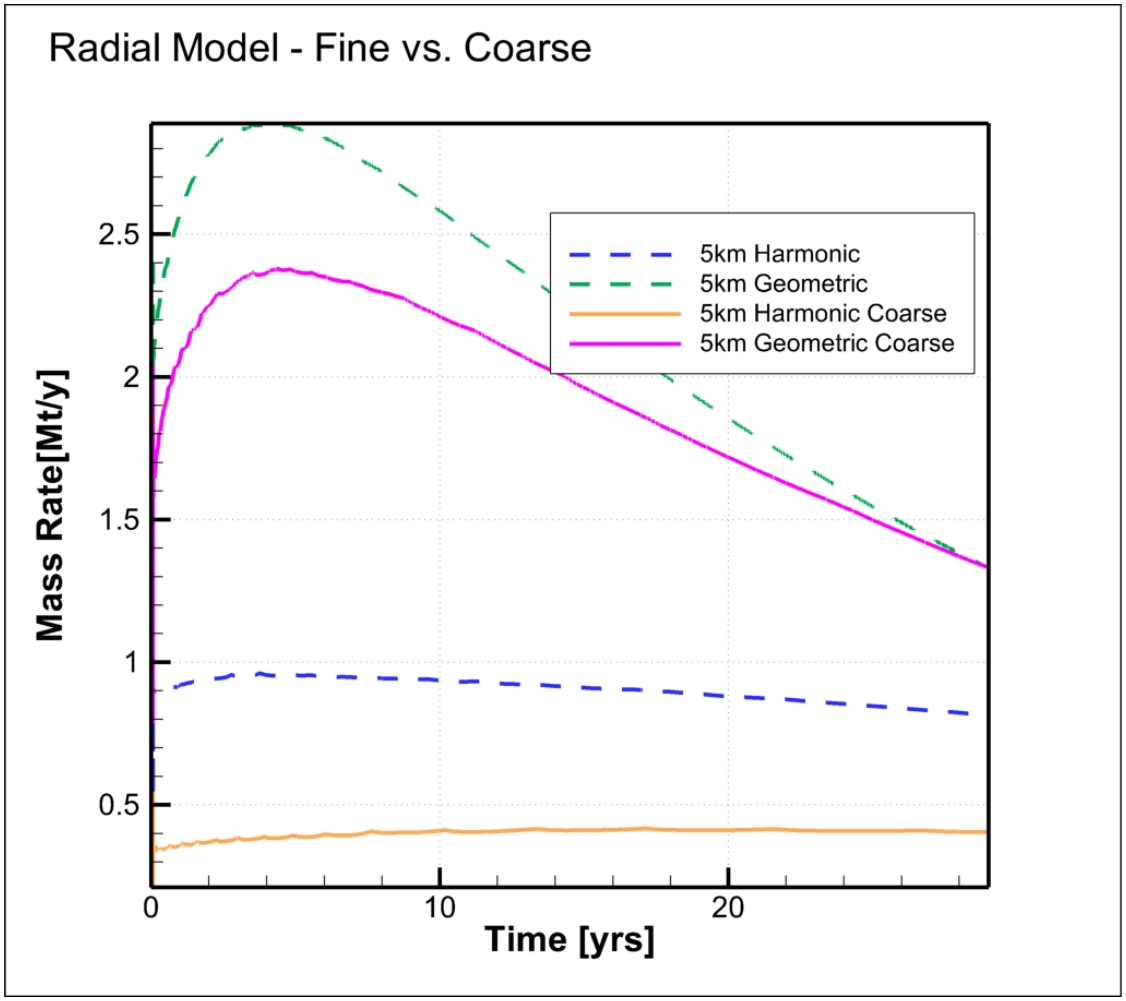
Injection Profiles – Tank Size

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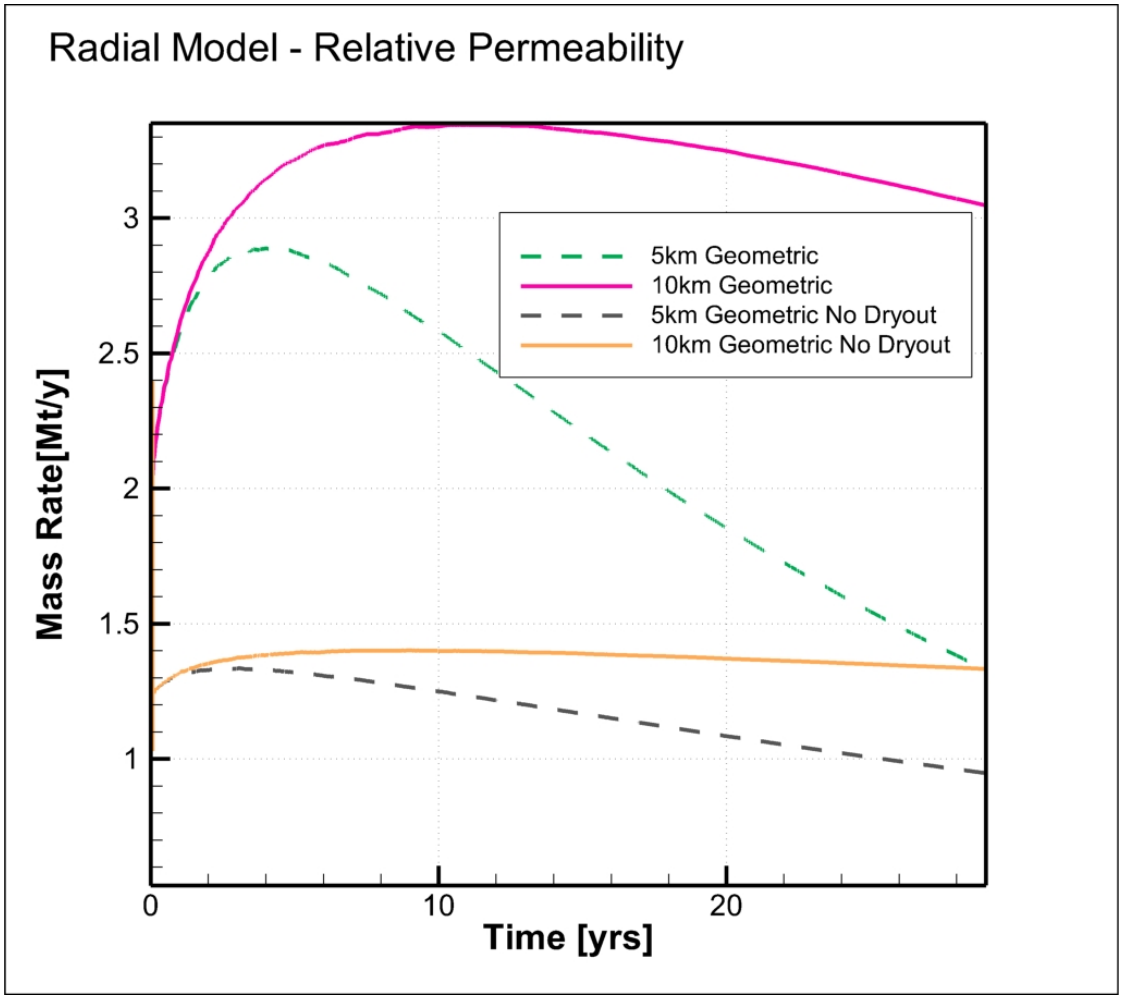
Injection Profiles – Layer Thickness

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Injection Profile – Relative Permeability

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Discussion

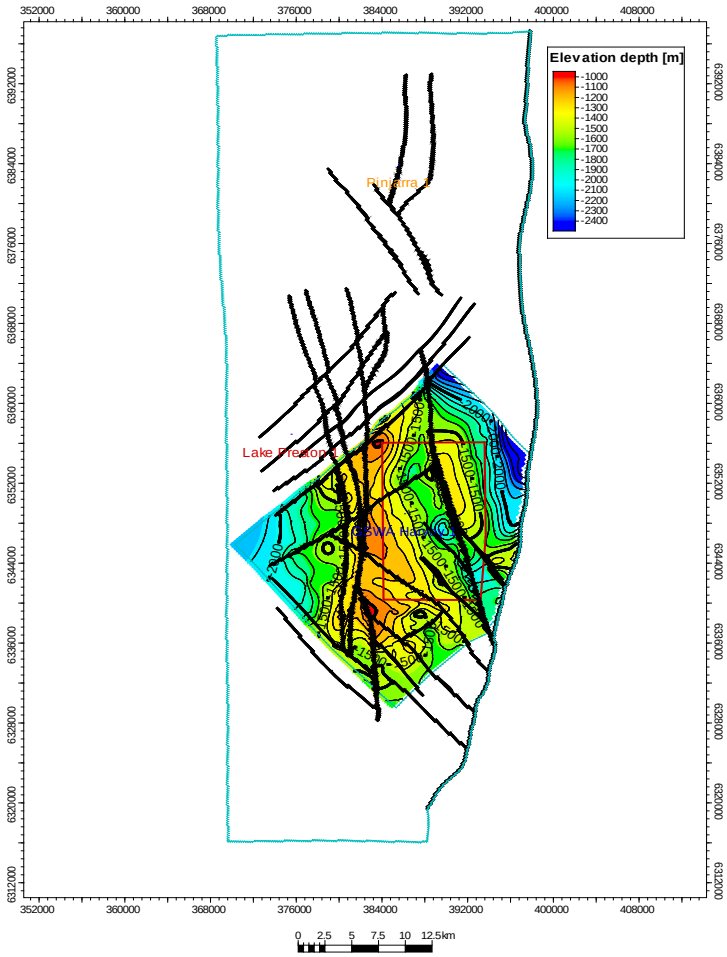
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- Boundary conditions
  - *Compartmentalisation expected to be a major factor on injectivity.*
- Upscaling approach
  - *Geometric better represents the data in this area*
- Grid cell layer thickness 5 m and 50 m
  - *Use finer grid sizes in areas of interest*
- Relative permeability end-point
  - *For the dynamic sector model, the dry-out addition should be allowed, as it expected to happen in the near well-bore.*
- Using Harvey 1 data as representative single well data, given the different boundary conditions, the results indicate that ~1-3 Mt/a of CO2 could be injected.

Dynamic Sector Models

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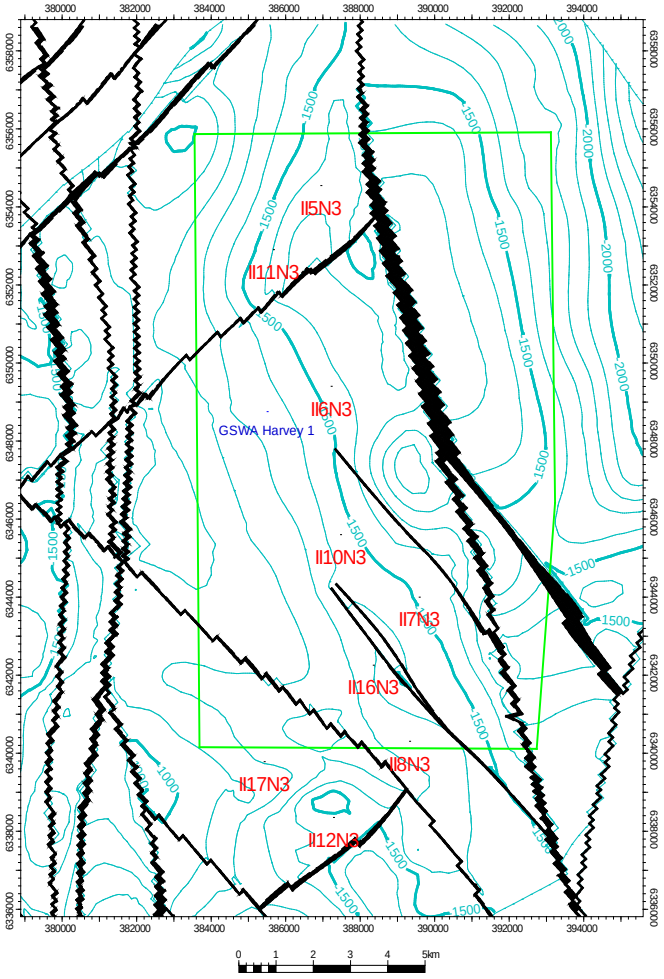
- Modeling Area
  - East Boundary: Darling fault
  - Minimum Size: Seismic Survey Area
  - 2000 m Isochore of Top Wonnerup
- Numerical Model
  - Cell size: 300x300 meter
  - 591776 active cells



Injection Well Location and Perforation

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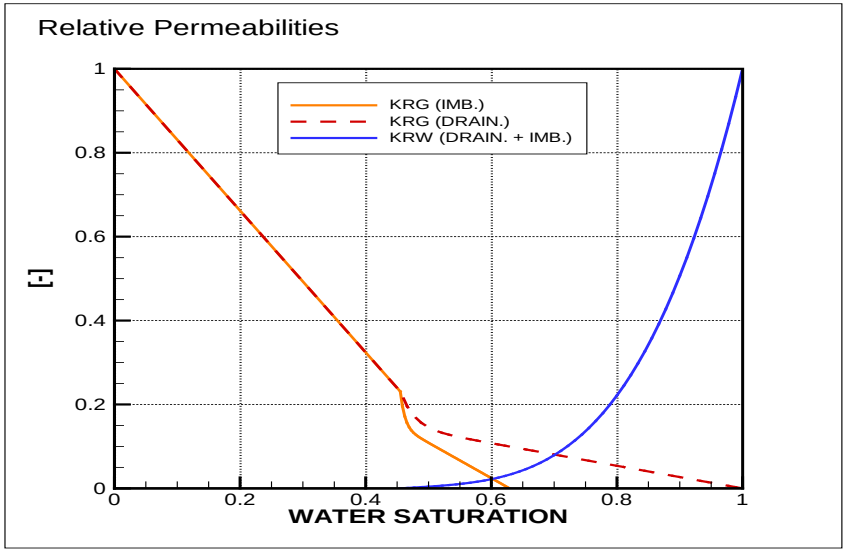
- Placement Criteria
  - At least 9 wells
  - Quite down-dip
  - Distant from Faults
  - Placed in main fault compartments
- Perforations
  - Maximize KH
  - Lower Wonnerup Member
  - Roughly 700 m per well

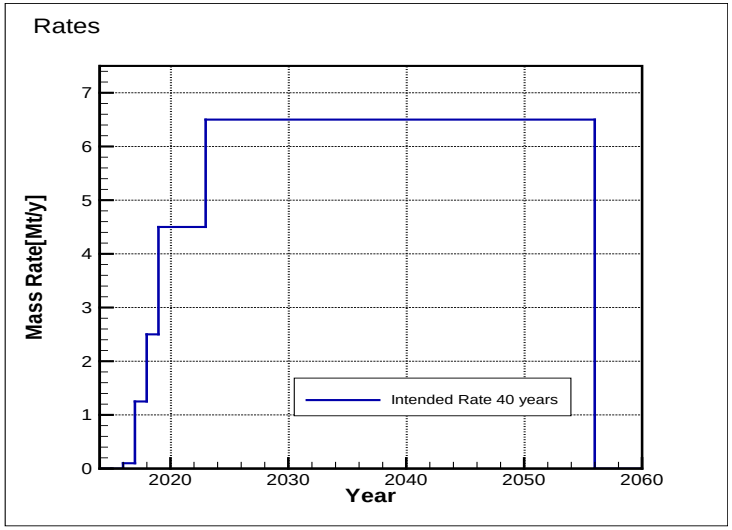


Boundary and Initial Conditions

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- Rel.Perm curves after Ali Saeedi
  - Imbibition curve created by normalization of drainage curve
- Salinity: 60,000 ppm
- Carter Tracy aquifer on 3 edges
- Constant pressure aquifer on top
- Hydrostatic equilibrium
- Injection
  - Target Field rate of SWPH imposed
  - BHP constraint (90 of frac-pressure)





Simulation Scenarios

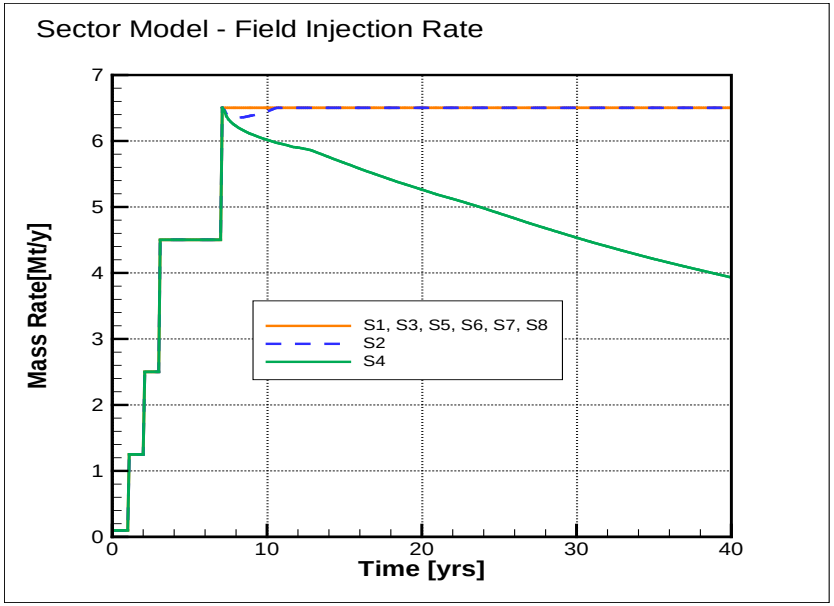
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Scenario No.	Property Field	Wells	Faults	Boundary	Top Aquifer	Transmissibility Multiplier
S1	Base Case	9	Open	Open	Open	NTG^2
S2		8				
S3		9		Closed		
S4			Closed	Open		
S5			Open		Closed	
S6					Open	-
S7	Shale Case	9	Open	Open		NTG^2
S8	Silt Case					
S9	Base Case	9 with Drilling Priority				

Results: Injectivity

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Scenario No.	Total injected mass [Mt]
S1	236.4
S2	236.0
S3	236.4
S4	188.1
S5	236.4
S6	236.4
S7	236.4
S8	236.4
S9	236.4



- All scenarios apart from S2 and S4 can achieve the target rate
- Effect of closed boundaries apparent

Plume migration and Distribution of CO_2

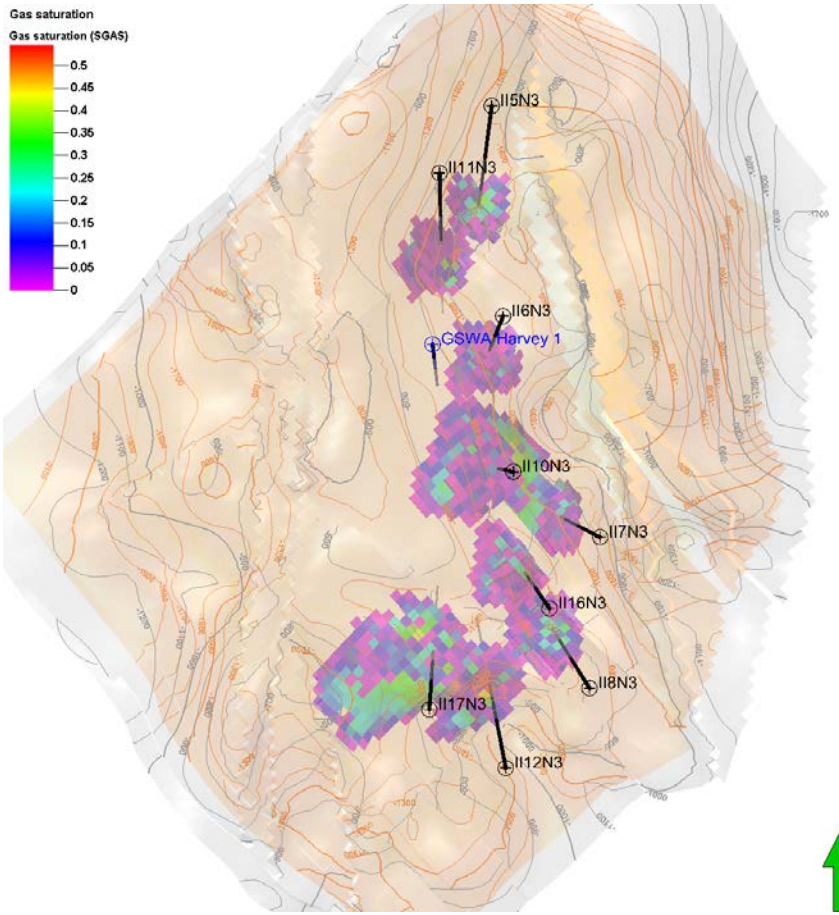
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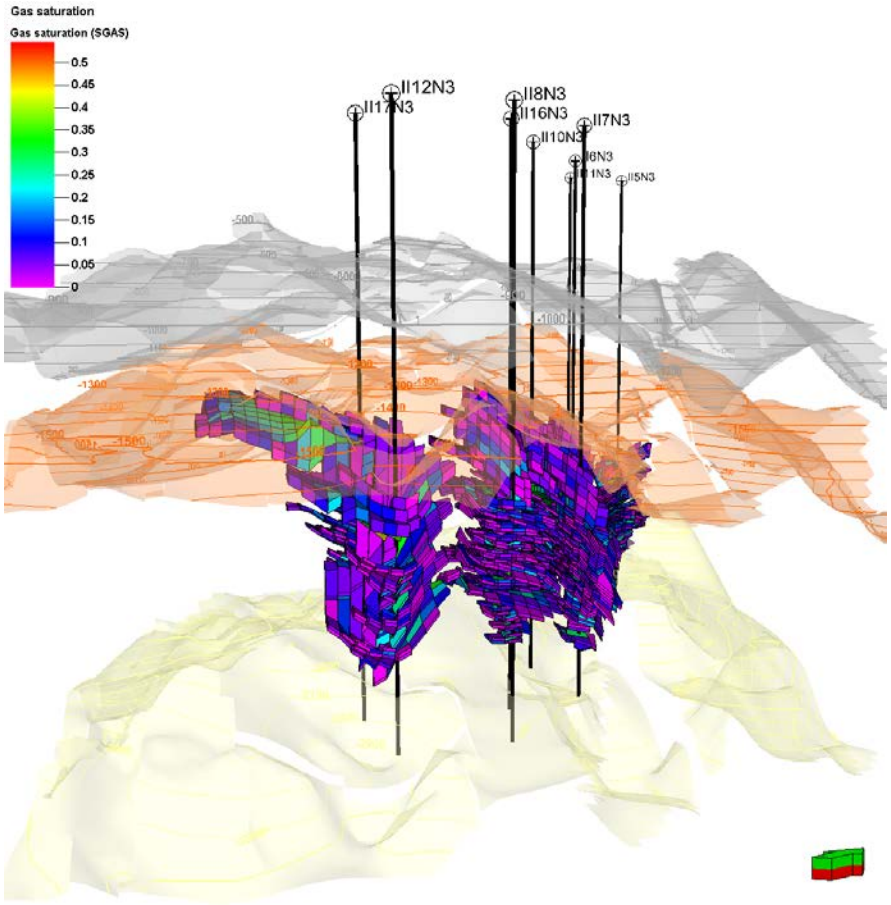
- Observations 250 years after injection stop
  - Extent is strongly dependent on the property field
  - The plume enters the Yalgorup Member

Scenario No.	Formation	Total injected mass [Mt]	Dissolved	Immobile	Mobile
			[mass % of total CO_2]		
S1	Yalgorup	236.4	<0.1	<0.1	<0.1
	Wonnerup		39	55	6
S4	Yalgorup	188.6	<0.01	<0.01	<0.01
	Wonnerup		41	52	6
S7 (Shale Case)	Yalgorup	236.4	1	1	1
	Wonnerup		43	47	7
S8 (Silt Case)	Yalgorup	236.4	5	6	3
	Wonnerup		40	43	2

At Shut-In (Base Case S1)

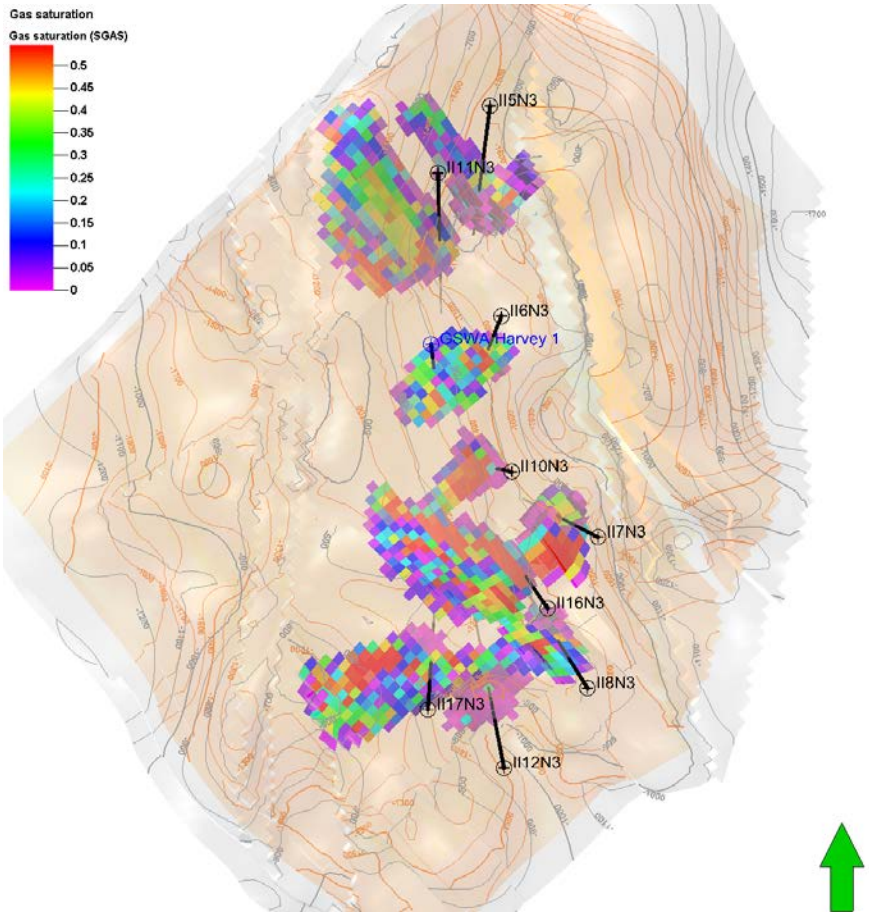
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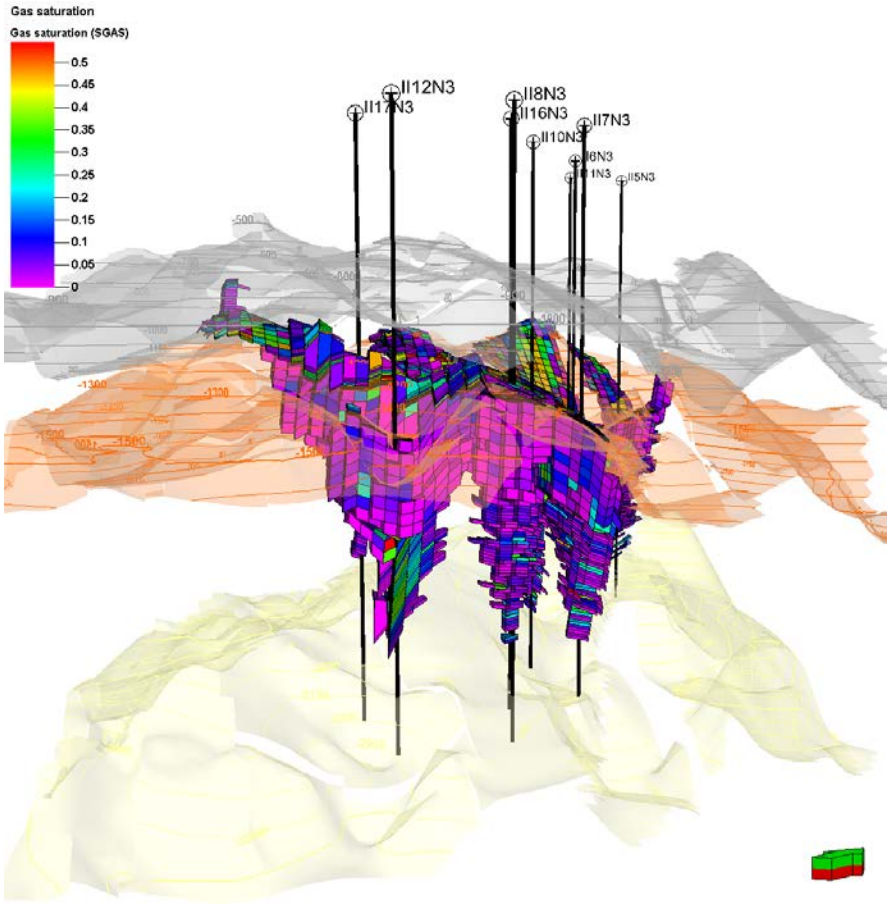




At Shut-In (Silt Case S8)

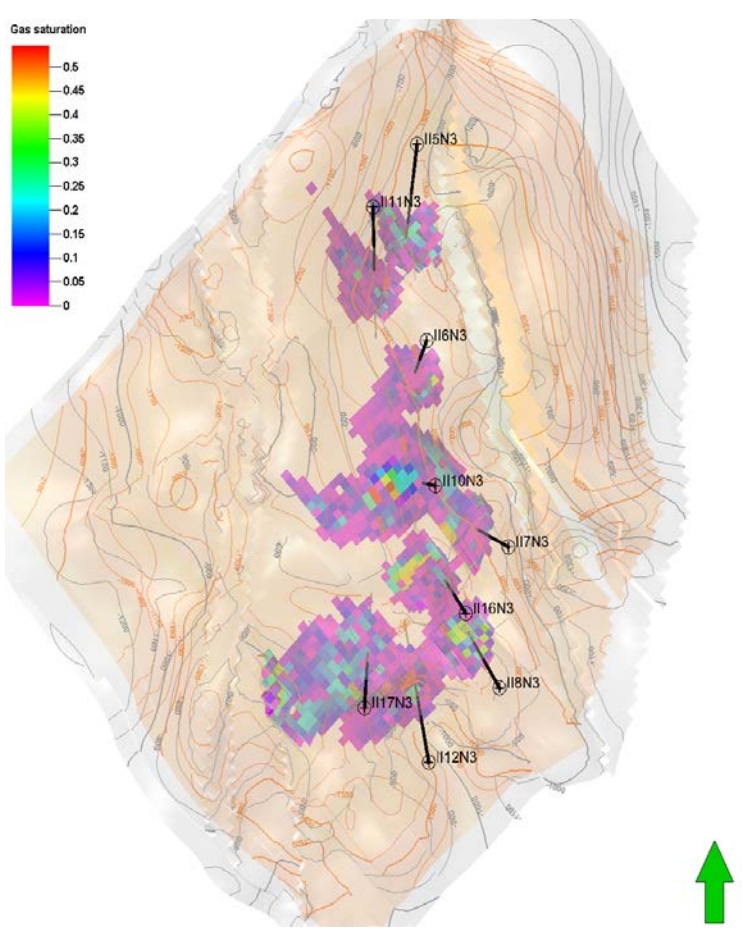
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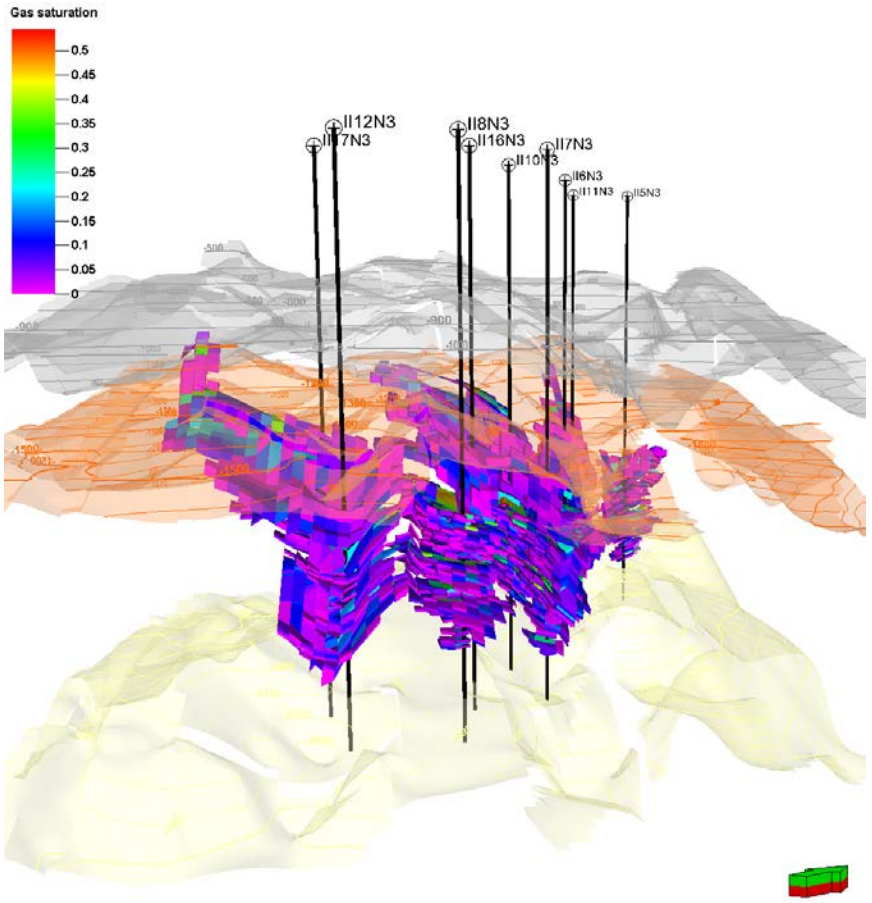




Plume Migration (Base Case S1) 250 years post Shut-In

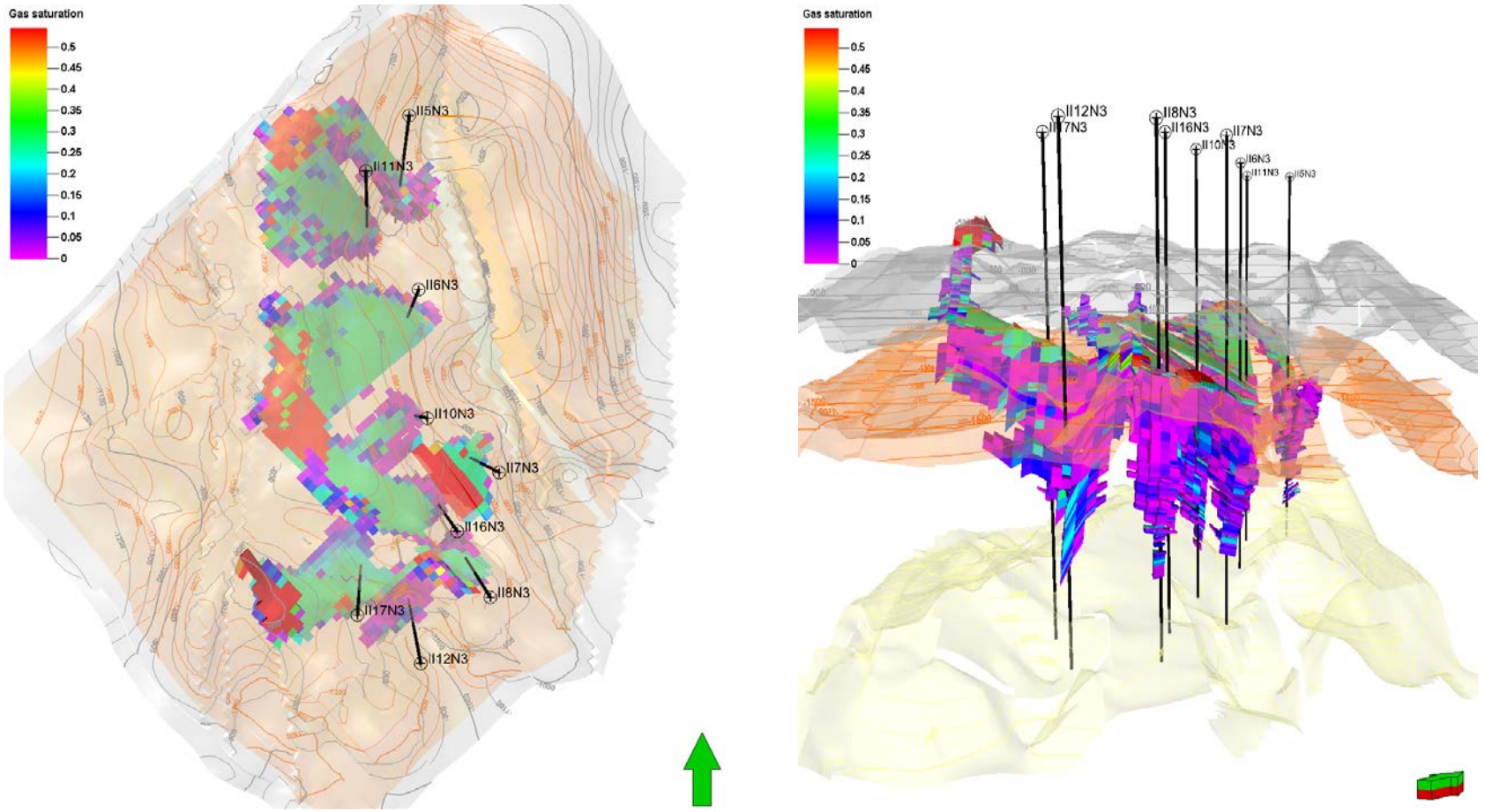
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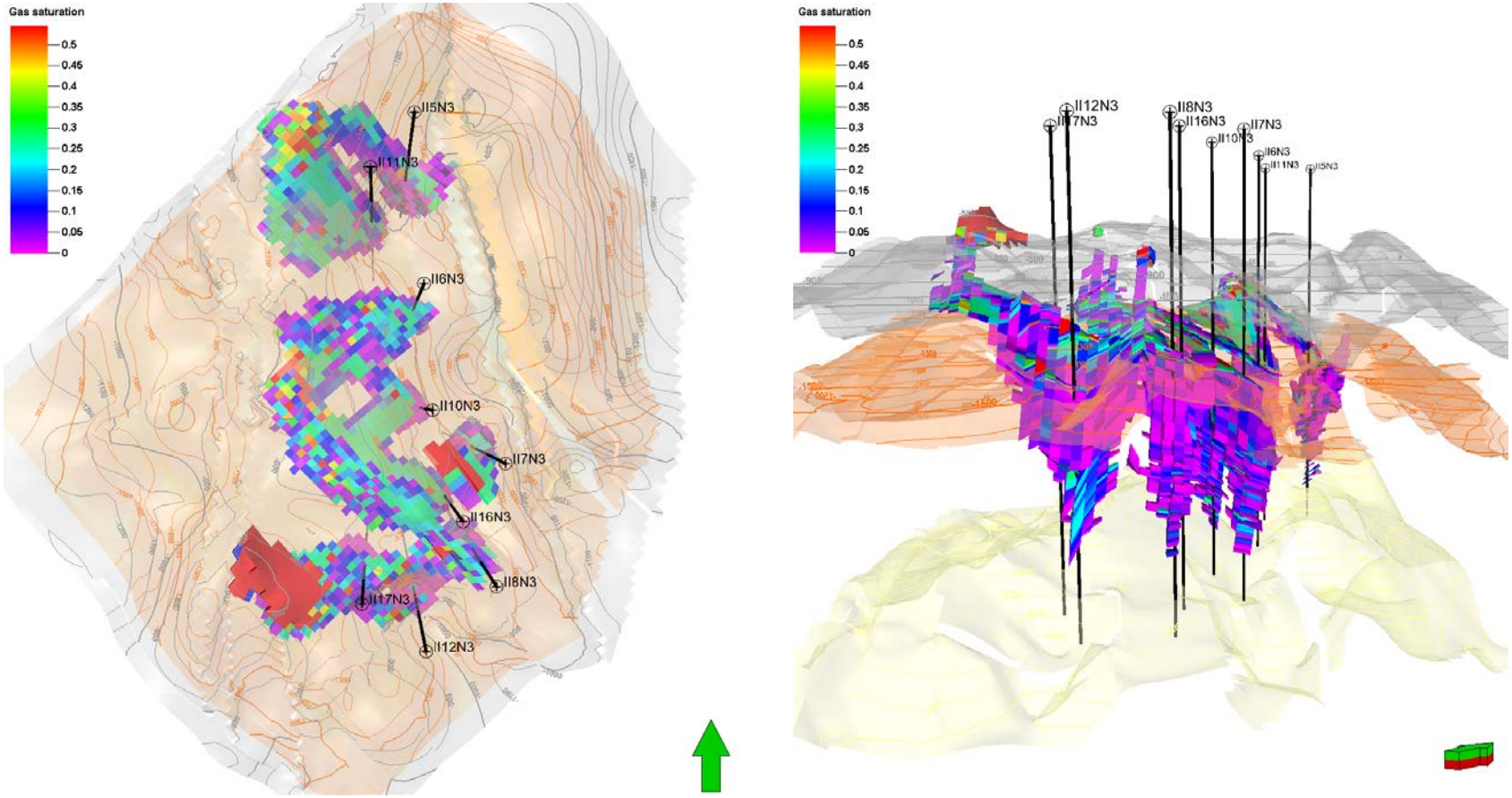
Plume Migration (Shale Case S7) 250 years post Shut-In

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Plume Migration (Silt Case S8) 250 years post Shut-In

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Summary of Simulations

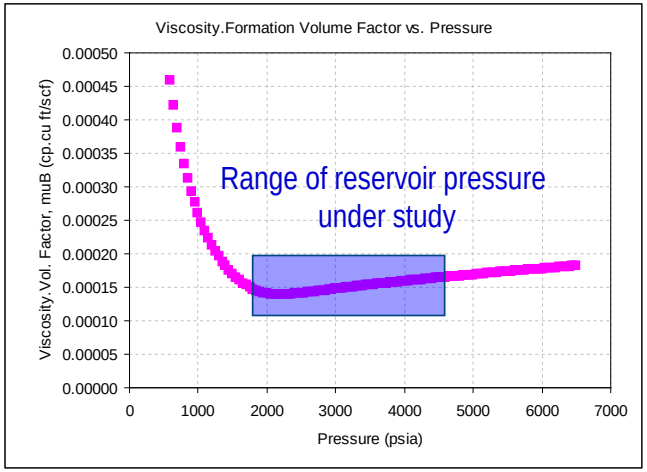
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- Only under the consideration of fully sealing faults, the total amount of CO_2 injected could not meet the project target.
- At least 8 wells with quite long perforations are necessary
- Higher effective permeability (relative permeability times absolute permeability) in combination with some pressure relief wells might meet the project requirements even under the consideration of sealing faults
- CO_2 generally stays in the Wonnerup Member, and only a small amount entering the Yalgorup Member

Probabilistic Modeling of Storage Injectivity

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- Analytical Model
  - Injection rate per individual play
  - Injection rate per well
  - Injection rate per basin development
- Darcy law approximation for high pressure compressible fluid flow: valid if μB ~ constant (pressure > 2000 psi)
- CO_2 viscosity and formation volume factor, ρ_{CO2} and B_{CO2}, evaluated at an average pressure (between P_{res} and P_{inj})



$$q_{CO_2} = \frac{k_{absolute} k_{rCO_2} h_{gross} NTG \left(p_{inj} - p_{res}\right)}{25.15 \overline{\mu}_{CO_2} \overline{B}_{CO_2} \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + S \right]}$$

8 Variables for Monte Carlo

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1. Gross thickness (based on static model of the Lower Wonnerup)
2. Net-to-gross thickness ratio (based on static model of the Lower Wonnerup)
3. Middle reservoir depth (based on static model of the Lower Wonnerup)
4. Permeability (based on static model of the Lower Wonnerup)
5. Fracture gradient (1D-MEM)
6. Initial pore pressure gradient (based on measurement)
7. CO_2 relative permeability (from technical literature)
8. Wellbore skin (oil and gas practices)

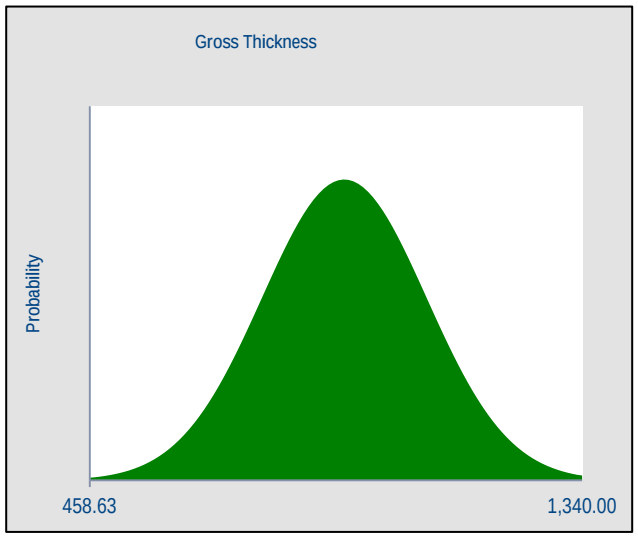
PDFs used for probabilistic modelling

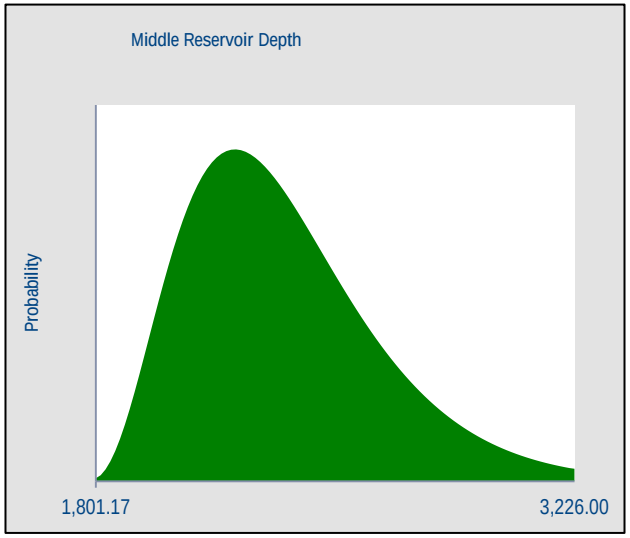
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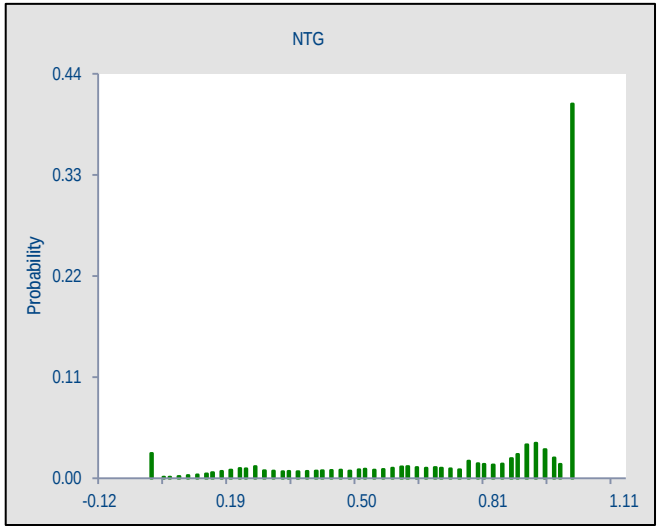
Number	Property	Unit	Probability Distribution	Mean or Likeliest	Standard Deviation	Truncation Limits
1	Gross Thickness	m	Normal	913	147	459 - 1340
2	Net-to-Gross	adimensional	Custom	0.77		0 - 1
3	Middle Reservoir Depth	m	Gamma	2349		1794 - 3220
4	Permeability	mD	Gamma	48.7		0 - 700
5	Fracture Gradient	psi/ft	Normal	0.826	0.082	0.75 – 0.9
6	Initial Pore Pressure Gradient	bar/m	Normal	0.1	0.01	0.09 – 0.11
7	CO_2 Relative Permeability	adimensional	Uniform	0.25		0.1 – 0.4
8	Skin	adimensional	Normal	4	2	-2 to 10

Examples of PDFs used for probabilistic modelling

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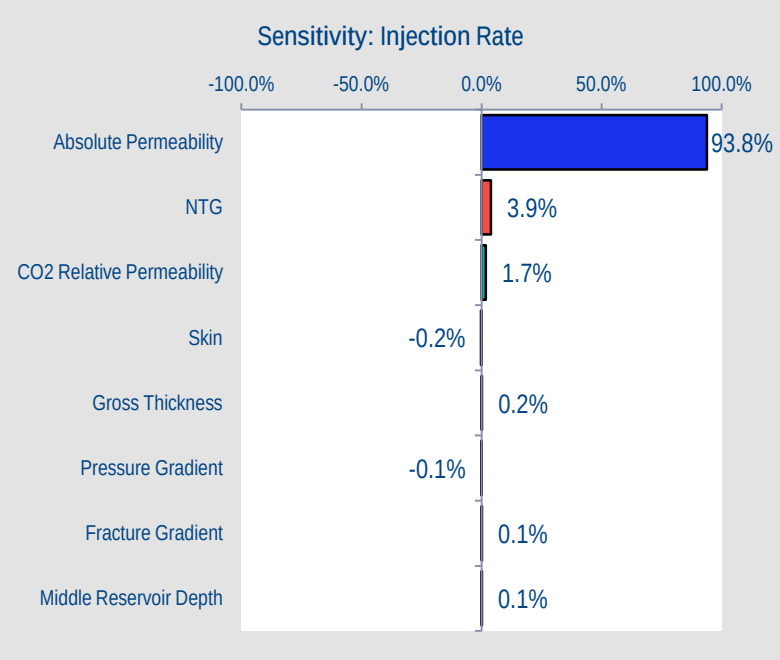


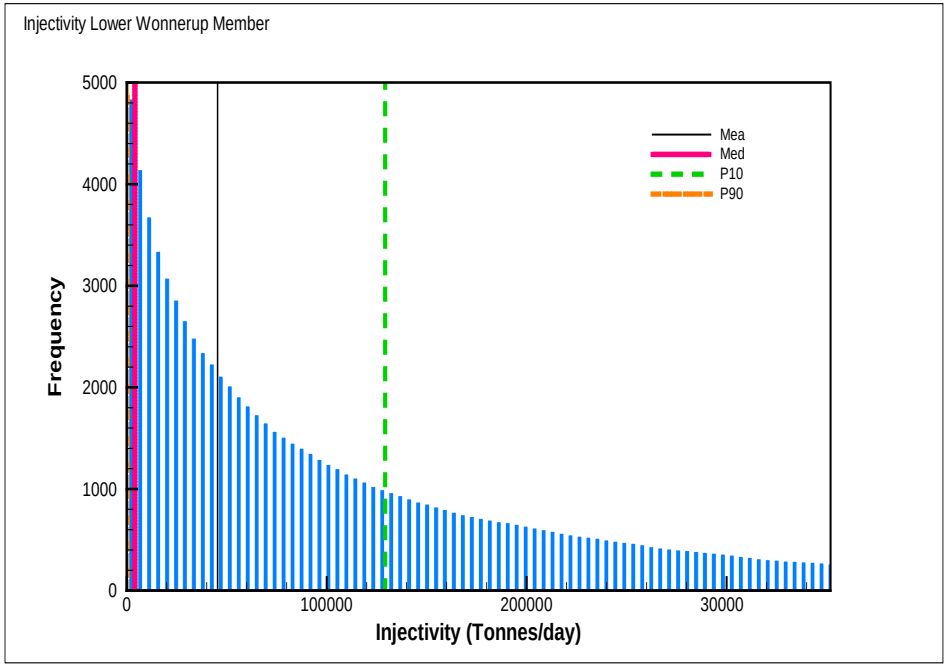




Results of Probabilistic Study

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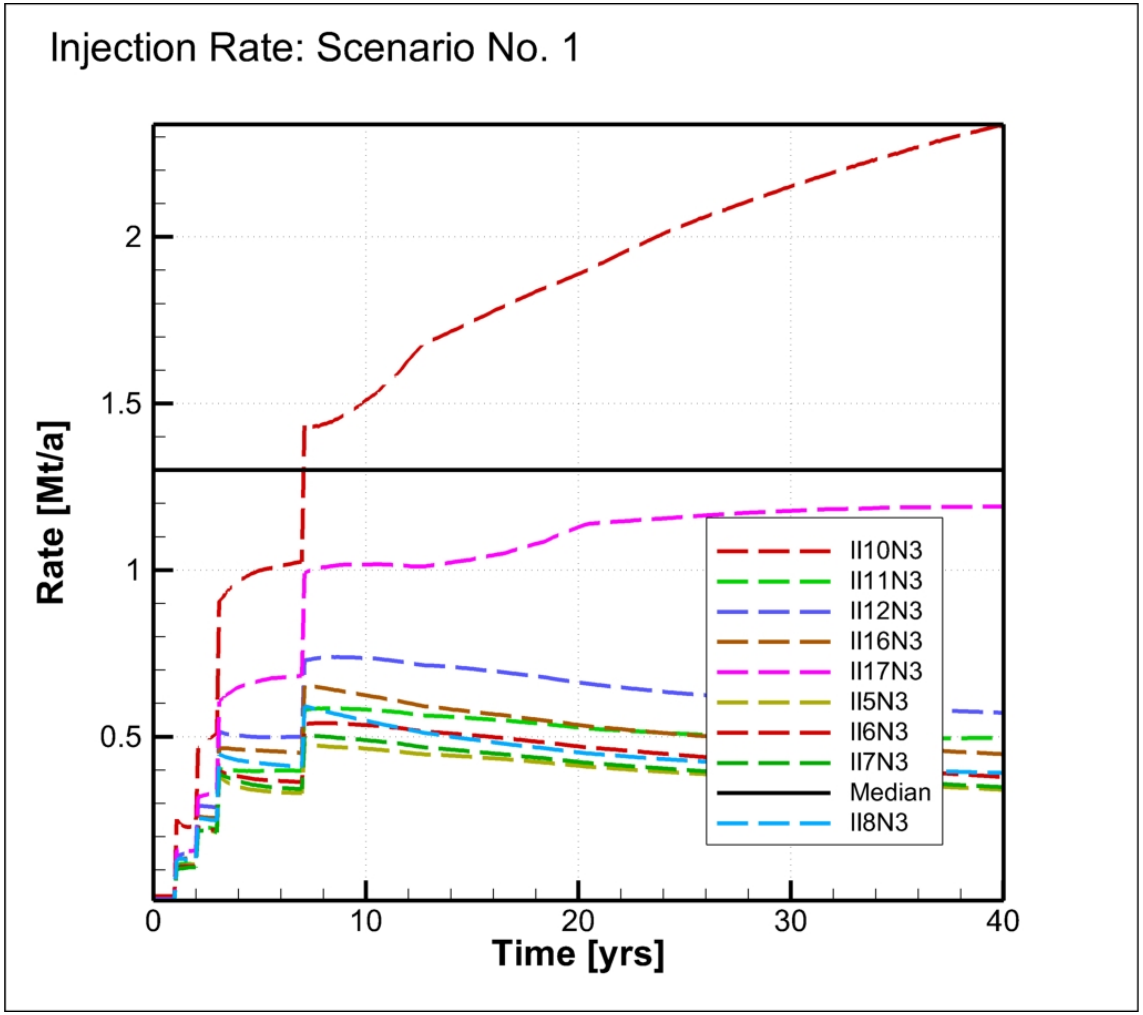




	Injection Rate [t/d]	Injection Rate [Mt/a]
Median (P50)	3784	1.3
P90	0.4	0.000146
P10	141000	51.5

Comparison with Numerical Simulation

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Comparisons with previous work

Overview

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- In this Section, the present work will be compared and contrasted with the previous Stage 1a/1b work to record progress in understanding of the area of interest and to discuss uncertainty reduction.
  - New and old petrophysical interpretation, and how Harvey 1 changes the reservoir properties
  - New and old structural models
  - New and old dynamic sector and probabilistic models
- This work contains several new pieces of work, such as fluid substitution and dynamic radial models, that cannot be compared to previous work.

Petrophysical Interpretation

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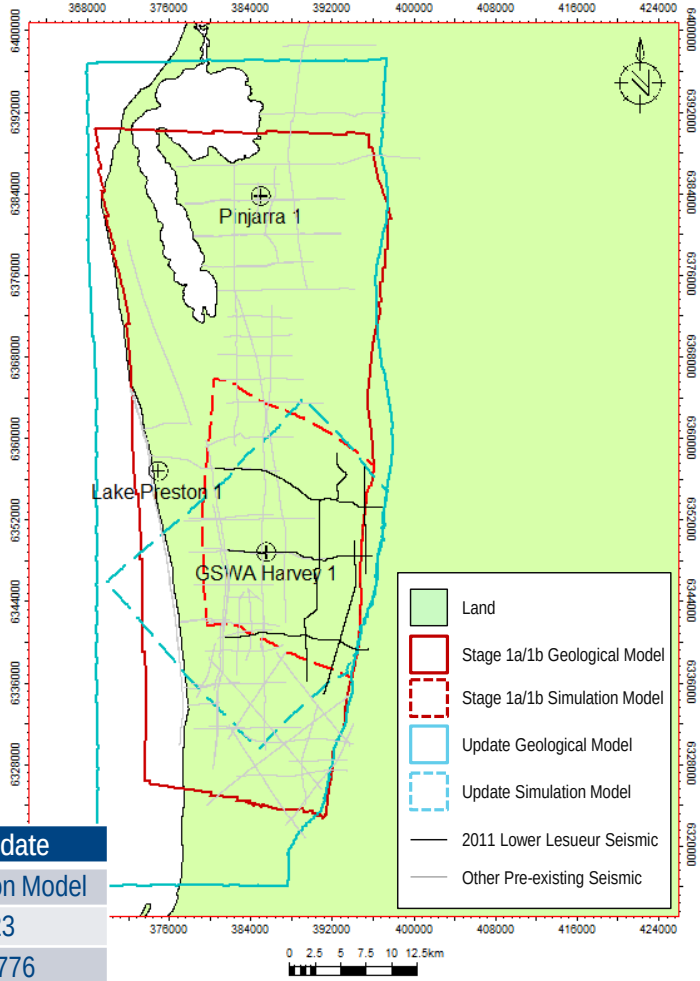
- Pinjarra 1 and Lake Preston 1 were reinterpreted in addition to Harvey 1
- There are various methodology differences between to the interpretations.
- Average porosity is higher in the new study by as much as 6 porosity units in Lake Preston 1 Yalgorup Member (Table 10-1).
- In other wells and formations, the difference between the old and new values is not as large.

Yalgorup Member				
	Stage 1a/1b		Subsurface Modelling Update	
Well	Avg. PHIE [%]	NtG	Avg. PHIE [%]	NtG
Lake Preston 1	13.2	0.68	19.5	0.781
Pinjarra 1	8.0	0.335	10.2	0.336
Wonnerup Member				
	Stage 1a/1b		Subsurface Modelling Update	
Well	Avg. PHIE [%]	NtG	Avg. PHIE [%]	NtG
Lake Preston 1	8.2	0.441	12.8	0.756
Pinjarra 1	5.2	0.056	9.9	0.09

Static Model

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- The differences between the Stage 1a/1b and current models in terms of number of cells, grid size, layers and area do not necessarily imply that one model is more correct than the other
- Indicate the parameters chosen by the modeller to represent the data.
- Biggest difference – number of faults in the Area of Interest
  - Structure is considerably more complex than previously thought
  - Largely attributed to the previous lack of seismic control in the simulation area.
- Model areas are roughly similar and overlap closely



	Stage 1a/1b		Subsurface Modelling Update	
	Geological Model	Simulation Model	Geological Model	Simulation Model
Area [km²]	1505	357	2300	423
Cells	4.5 million	287280	18.6 million	591776
Grid Size [m]	300x300	400x400	150x150	300x300
Layers	3223	135	347	187
Number of Fault Segments	21	6	50	26

Static Model

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- New seismic data and interpretation changed the understanding of the Area of Interest significantly
- No considerable change in formation thickness
  - 3% difference for the Yalgorup Member
  - 8% difference for the Wonnerup Member
- Depths of each formation are significantly changed
  - Overall, the members are 300-350 m shallower than previously thought
- There are more dip angles >10°, implying steeper horizons

	Stage 1a/1b						Subsurface Modelling Update					
	Yalgorup Member			Wonnerup Member			Yalgorup Member			Wonnerup Member		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Depth [m]	-670	-2160	-1240	-1005	-2990	-1900	-395	-1730	-905	-945	-2495	-1535
Thickness [m]	20	1020	655	360	1965	1335	50	1095	635	490	1865	1445
Dip [deg]	85% < 10°			73% < 10°			76% < 10°			70% < 10°		

Remaining Uncertainty

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- Structure built from 2D seismic only – not complete picture
- Velocity model – additional well data can resolve issues
- Can Harvey 1 be considered ‘representative’
  - Excellent reservoir properties
  - High net-to-gross
  - Need to keep in mind that Harvey 1 could be conservative or optimistic

Dynamic Models

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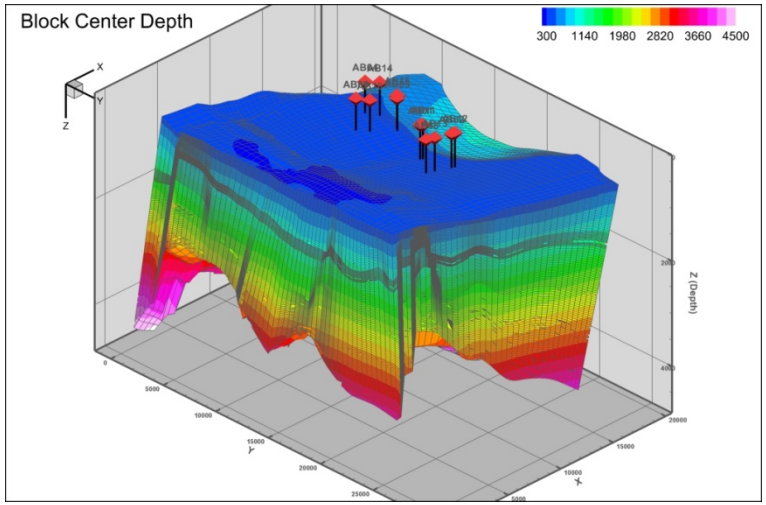
- Overall, the settings and general conditions for the dynamic modelling of the previous and current model align with each other.
- Differences include
  - Gridding
  - Fault properties
  - Relative permeabilities, endpoints and capillary effects
  - Well control and injection intervals

Gridding

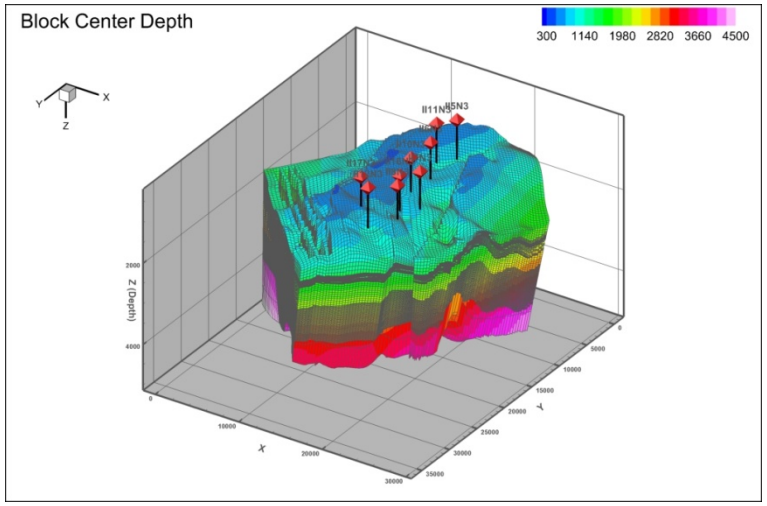
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- Grid orientation is different
- Greater vertical resolution in new grid
- Larger extent in new grid, less boundary condition effects
- More faults in new grid

Stage 1a/1b



Subsurface Modelling Update



Appraisal Program

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- Three broad areas of investigation
  1. Overall permeability of geological system
  2. Degree of reservoir and pressure continuity across faults and strata
  3. Containment assurance without a conventional caprock
- At least two wells are needed
  1. Conduct water injection testing in the main fault block of the Area of Interest, that is in the **same fault block as the Harvey 1 well**, but in a structurally deeper position.
  2. Appraise the **adjacent fault block to the north or south** to verify the degree of hydraulic and stratigraphic continuity and to confirm injectivity in the Area of Interest.

New Wells

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- The wells should:
  - Be located within the area of the 3D seismic survey. VSP data are required for optimal well-to-seismic tie.
  - Be close enough to a significant fault to gauge response to injection test
  - Collect vertical pressure interference data during injection test

- Additionally, they should
  - Allow sufficient core data collection
  - Measure pressure gradients and pore fluid sampling
  - Allow characterization through well loggings across formations of interest

New Wells

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- New well could consider
  - An optional, small scale CO_2 injection test, followed by repeat logging
  - Drilling companion monitoring well nearby to directly measure injection test performance

- Several key appraisal points should be addressed in addition to routine model updates
  - Calibrate geomechanics study with XLOT
  - In depth stratigraphic and sedimentological study on size and quality of beds of sand, silt, and shale
  - Geochemistry of reservoir rocks and interaction with CO_2 saturated pore fluid
  - Consider other monitoring approaches for Area of Interest

Concluding Remarks

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- Although data are still limited, no technical showstoppers can be identified.
- Several sections of this study are favourable to CO_2 injection
  - Good reservoir properties
  - High fracture gradient
  - Stable faults
  - Preliminary area-specific relative permeability curves suggesting higher residual trapping potential than in the previous study
- No new indicators that would suggest postponing or cancelling additional appraisal data acquisition plans
- Still critical uncertainties related to structure and trapping potential that need to be address before any final investment decision is made.