Static Model of the Harvey Area

A Report by ODIN Reservoir Consultants

For

Department of Mines and Petroleum

DMP/2016/4

ODIN Reservoir Consultants

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Declaration

ODIN Reservoir Consultants has been commissioned to undertake to provide a reservoir modelling study for the South West Hub CO_2 Sequestration Project on behalf of The Department of Minerals and Petroleum, (DMP)

The evaluation of Carbon Capture and Storage is subject to uncertainty because it involves judgments on many variables that cannot be precisely assessed, including CO_2 sequestration rates and capture, the costs associated with storing these volumes, sequestration gas distribution and potential impact of fiscal/regulatory changes.

The statements and opinions attributable to us are given in good faith and in the belief that such statements are neither false nor misleading. In carrying out our tasks, we have considered and relied upon information supplied by the DMP and available in the public domain. Whilst every effort has been made to verify data and resolve apparent inconsistencies, neither ODIN Reservoir Consultants nor its servants accept any liability for its accuracy, nor do we warrant that our enquiries have revealed all of the matters, which an extensive examination should disclose.

We believe our review and conclusions are sound but no warranty of accuracy or reliability is given to our conclusions.

Neither ODIN Reservoir Consultants nor its employees has any pecuniary interest or other interest in the assets evaluated other than to the extent of the professional fees receivable for the preparation of this report

Note:

ODIN has conducted the attached independent technical evaluation with the following internationally recognised specialists:

Geoff Strachan *is a petroleum geologist and specialist geomodeller with over 20 years of experience.*

1. EXECUTIVE SUMMARY

ODIN Reservoir Consultants has been commissioned by the Department of Mines and Petroleum (WA) to provide a multi-disciplinary group with sub-surface skill sets to:

1) Undertake an interpretation of the 3D seismic data;
2) provide support through reservoir model building and updating of the South West Hub Project in the southern Perth Basin; and
3) provide on-going technical support.

As an integral part of the above, ODIN Reservoir Consultants constructed 3D geological stochastic models of the Harvey area to be used in dynamic models to assess the impact of geological uncertainties on the CO_2 storage process which are necessary to establish the suitability of the Harvey structure to act as a CO_2 storage area.

The Harvey structure, onshore Perth Basin, is a N-S elongated fault bounded anticline. The study area for this project within this structure covers 332 km^2 and is located approximately 13km northwest of the town of Harvey south of Perth. The two static models built for this study, cover areas of approximately 54 km^2 and 117 km^2, are the primary input to the dynamic modelling of CO_2 sequestration in the Harvey Area. The static model study provided a reasonable description of the sub-surface in the Harvey area using the interpreted horizon and faults from seismic. This project also included:

1. Log & Petrophysical Property Review.
   - The following evaluations were undertaken:
     - Detailed petrophysics studies for the four available wells. With integration of core data;
     - Geomechanical rock property analyses and considered the rock properties, the stress field and fault orientations. Results were used to define injection pressure constraints for the Dynamic Models;
     - an image log interpretation for determining the facies or geobody orientation that was used in the Static Model;
     - Well correlation panels were prepared for facies, porosity and permeability.

2. Static modelling – structure, facies and properties
    - The static model construction resulted in various realisations guided by known uncertainty (paleosol continuity, fault definition, reservoir connectivity and reservoir quality).

The key uncertainties identified of the static modelling of the Harvey area are:

- How extensive are the individual paleosol geobodies?
- Percentage of sand versus paleosol?
- Permeability range.
- Fault seal.
- Vertical-to-horizontal permeability ratio.

The range of geological uncertainties investigated in the geomodelling study are summarised in the table below (Table 1). Geological models representing these ranges were incorporated into dynamic models investigating the movement of the CO_2 plume during injection of CO_2 and subsequent shut-in.

Table 1: Geological uncertainties investigated

ITEM	RANGE	COMMENTS
Paleosol Geobody Size	500,1500 & 3500m	
Percentage of sand in Wonnerup	50-99%	
Permeability range in the Wonnerup	71 to 372mD Log Mean = 200mD	Average permeability for the Wonnerup.
Fault Seal	0.1 & 1	Open/Closed system
Fault Permeability	x10	Multiply vertical perm near faults by 10
Kv/Kh in the Wonnerup	Mean = 0.3 to >1	3 Methods: Arithmetic & Harmonic averaging in addition to PERMZ=PERMX.
Deterministic Case	Additional paleosols concentrated in the SE section of the model.	Deterministic case used the seismic based trend with higher concentration of paleosols in the Wonnerup.

2. INTRODUCTION

Underground storage of carbon dioxide as a means of reducing atmospheric emissions of CO_2 has been examined both theoretically and practically over the last decade. There is also a large amount of relevant research and field experience in the energy sector, for example, natural gas storage in deep saline formations, carbon dioxide in enhanced oil recovery, and acid gas injection. It is clear from this experience that underground storage of CO_2 is eminently feasible and in fact many companies are currently sequestering tons of CO_2 per year. The learnings from this previous experience and experience has been applied to the study.

In order to assess the suitability of a particular site for storage of carbon dioxide, it is necessary to have an adequate geological model and then to use this as the basis for a numerical simulation which can predict the behaviour of the injected carbon dioxide in the subsurface. Unlike a typical oil-field development, the model needs to be simulated not only during the injection phase but also for up to a thousand years after injection, in order to confirm the storage integrity.

3D geological stochastic models allow the assessment of the different geological uncertainties related to the CO_2 storage process which are necessary to establish the suitability of the Harvey structure to act as a CO_2 storage area. The resulting 3D static geomodel will be the base for the assessment of the reservoir engineering parameters that will control the CO_2 sequestration process and determine the ultimate viability of the project.

The Harvey structure, onshore Perth Basin, is a N-S elongated fault bounded anticline. The study area for this project within this structure covers 332 km^2 and is located approximately 13km northwest of the town of Harvey south of Perth. The two static models built for this study, cover areas of approximately 54 km^2 and 117 km^2.

The main input data used for the 3D geomodel generation has been the result of all the analysis carried out by other disciplines as part of this project. A summary of the analysis of input data used to build the static model has been included in this report.

3. OBJECTIVES

The objective of this study is construct 3D geological stochastic models of the Harvey area to be used in dynamic models to assess the impact of geological uncertainties on the CO_2 storage process to establish the suitability of the Harvey structure to act as a CO_2 storage area.

Firstly, a review of the available literature on the subject at a global scale has been carried out and a number of general geological parameters controlling the process have been established and described within.

Secondly, a 3D static model integrating all geological controlling factors particular to the Harvey area has been built and the uncertainty of such factors evaluated. The 3D model integrates the latest data reviews, interpretations and analysis results carried out by a number of subsurface disciplines as part of the project. These include seismic interpretation, petrophysical interpretation, image log interpretation and a geomechanical study.

Several senarios were built and simulated one at a time to review and adapt the next scenario based on the results. The approach was to create models based on the geological uncertainties in order to gain confidence that the CO_2 could be injected into a defined area and would be contained below -800mAHD.

Through this process a general workflow for the Harvey project has been developed while identifying the key uncertainties and recommended future work to reduce the risk.

4. REGIONAL SETTINGS

4.1 Tectonics

The Perth Basin is a north-south elongated extensional basin stretching along the coastline of Western Australia. It was formed during the separation of Australia and India from the Permian to the Early Cretaceous. 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.

The extension continued until the Jurassic leading to the generation of a graben and half-graben system in the central part of the basin with marine ingression and deposit of marine sediments. The rift system culminated with the breakup of Gondwana in the Late Cretaceous where dextral transtension dominated the northwest of the basin. There was widespread inversion, erosion, strike-slip tectonics and volcanism.

The Perth Basin is bounded by the N-S Darling Fault and Yilgarn Craton to the East and it extends offshore as far as the continent–ocean boundary to the West.
The basin architecture is dominated by listric, extensional, north to north-west trending faults that controlled the distribution of the sediments, compartmentalising the basin into a series of sub-basins. It is considered that sedimentation broadly kept pace with accommodation space during faulting and subsidence.

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. Some studies have suggested that the Harvey Ridge was a result of the northwest–southeast trending transfer movement (Figure 4.1). The "Study Area" marked in Figure 4.1 shows the greater area covered by the Hydrogeological Study; the area for the Static and Dynamic Models is a much smaller area which is described in Section 5.

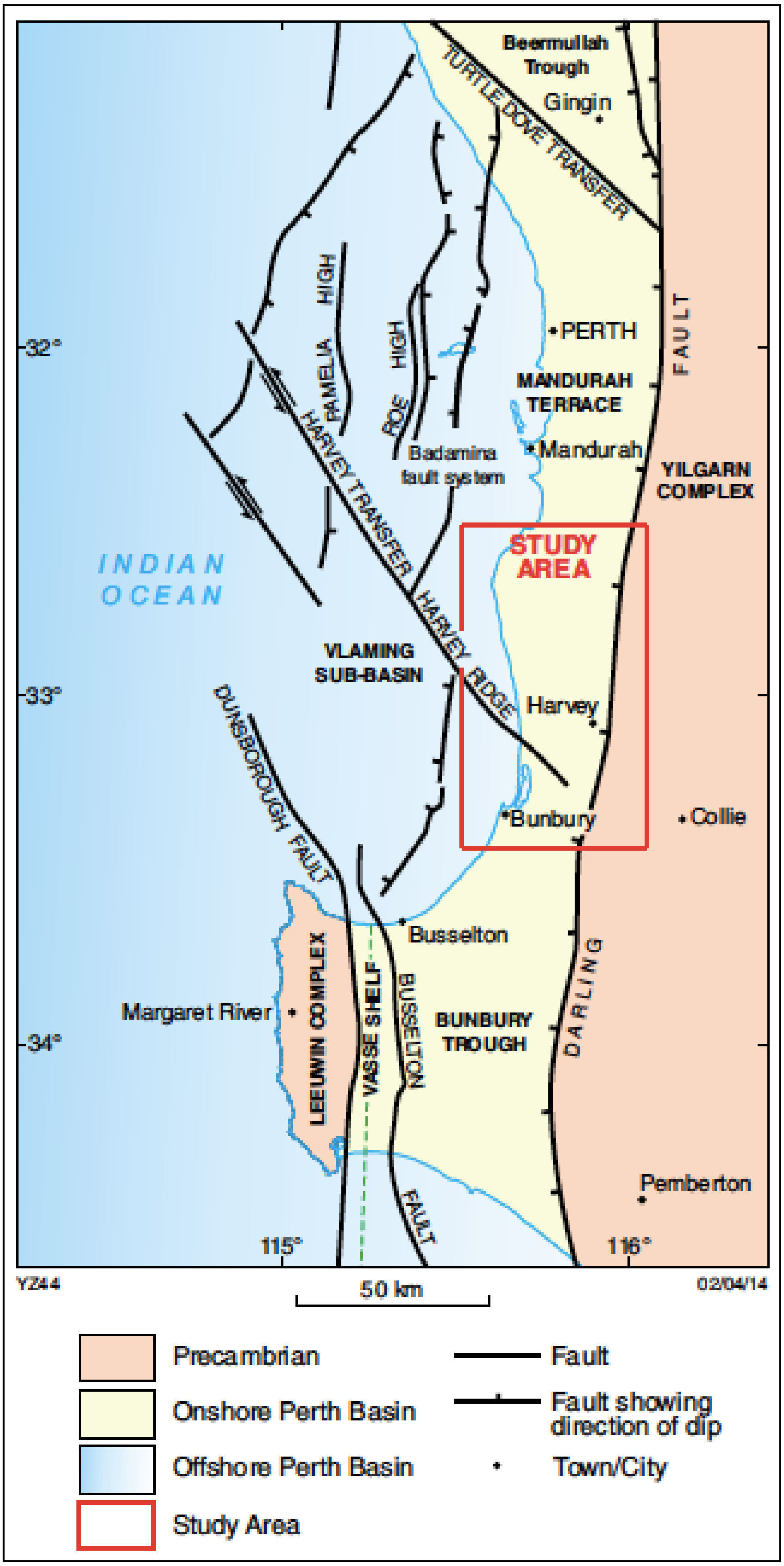

Figure 4.1: Regional Location Map

4.2 Stratigraphy

The stratigraphic succession in the southern Perth Basin ranges from Permian to Quaternary in age (Figure 4.2).

The nomenclature for the Triassic–Jurassic stratigraphic interval has been extrapolated from the northern part of the 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 application of the stratigraphic nomenclature in the southern Perth Basin is tentative as several aspects of the correlations are unsatisfactory such as: the need of a review of the palynology for the Triassic-Jurassic complex; missing sections in wells due to faults not incorporated to the regional correlation; or the fact that the designated type sections for both members of the Lesueur Sandstone, Wonnerup and Yalgorup, are 81 Km apart which introduces uncertainty on their continuity and geometry with respect to each other.

Despite the relative lack of age control and other uncertainties for the fluvial deposits of the Triassic-Jurassic section, a correlation including twelve wells in the area (hydrogeological, oil exploration and stratigraphic) defines the two members of the 'Lesueur Sandstone' as the 'Wonnerup' (lower) and 'Yalgorup' (upper) based on lithological aspects.

The former member consists of over 1 km of homogeneous sandstone showing low-amplitude chaotic reflectors, whereas the latter consists of about 700 m of sandstone interbedded with shale, expressed on seismic data as a series of strong parallel reflectors. The 'Eneabba Formation', overlying the 'Lesueur Sandstone', has a basal unit of over 100 m of pedogenic shale (Millar and Reeve, in prep.), informally referred to herein as the 'basal Eneabba unit.

Within the study area the 'Cattamarra Coal Measures' have been intersected in Pinjarra 1 north of the main study area. The Lower Cretaceous Warnbro Group is relatively extensive, but generally no greater than 250 m thick, and is overlain by a thin Cenozoic section.

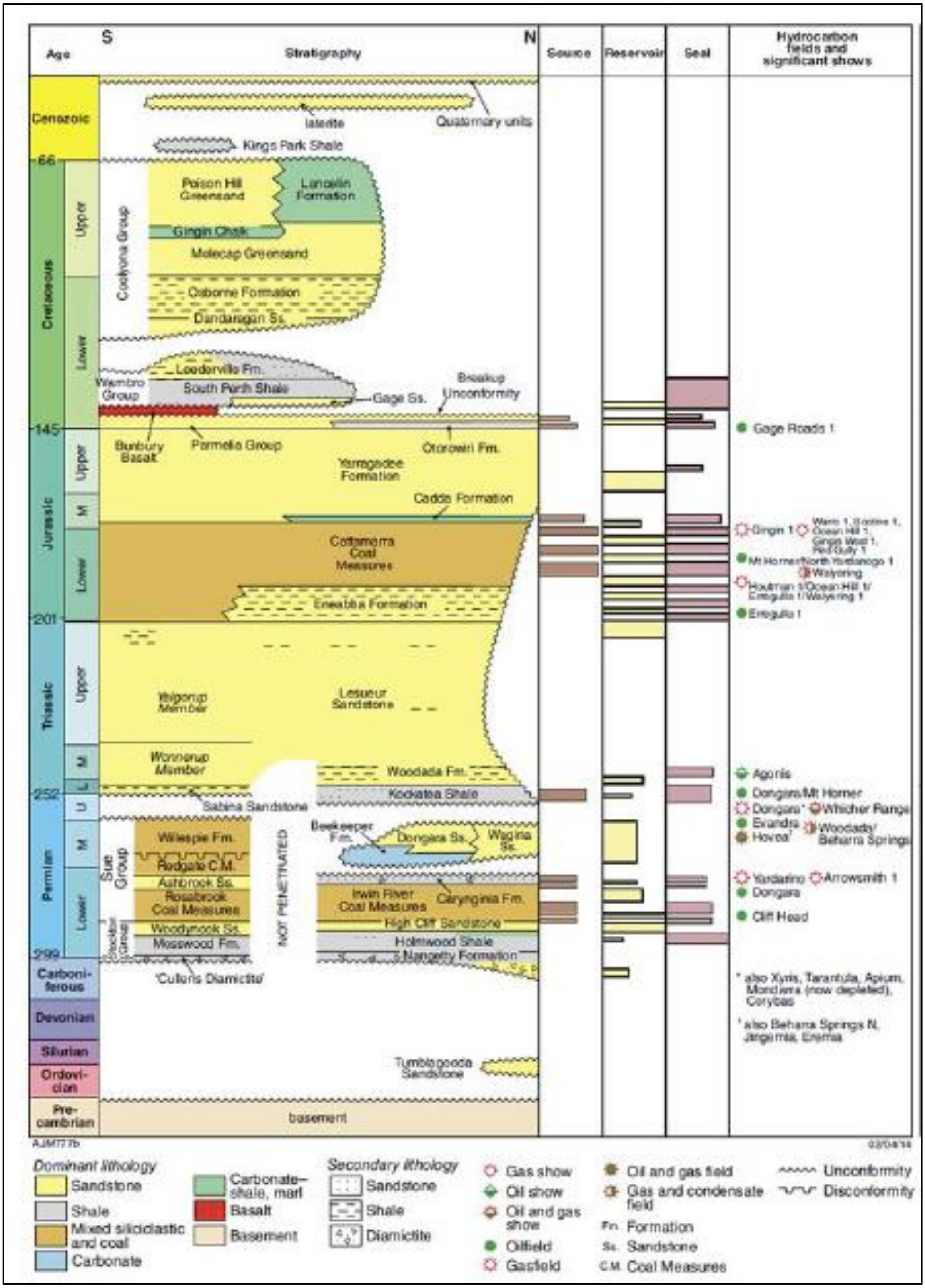

Figure 4.2: Regional Stratigraphy

5. STATIC MODELLING

5.1 Input data

The input data used to generate the 3D model comprises the latest data reviews, interpretations and analysis results carried out by number of subsurface disciplines as part of this project. The location map below (Figure 5.1) outlines the various areas and key elements that will be referenced throughout this report.

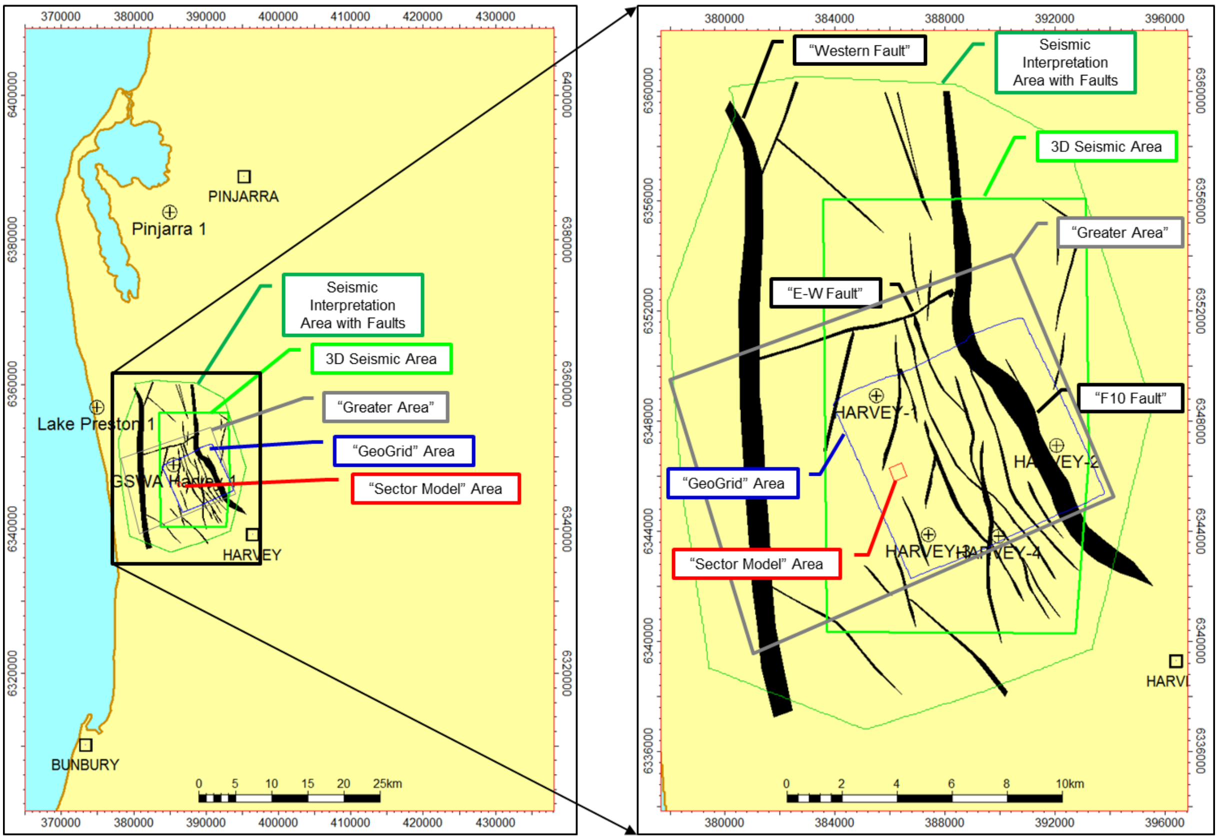

Figure 5.1: Location Map Showing Key Elements and Areas

There are four well penetrations with only one well drilling through all of the Wonnerup, the other three wells drilled between 100-223m into the Wonnerup. A reasonable coverage of wireline data is available for the four wells. There have been several cores acquired and analysed. There is also a 3D seismic survey over most of the study area with some 2D lines to cover the remaining area.

5.1.1 Geophysics and structural concept for the area

The results of the seismic interpretation constitute the structural and stratigraphic framework that have been used to generate the 3D static modelling grid. The data set used comprises a 2D and a 3D survey. The seismic interpretation of this data was carried out over pre-drilling and post-drilling phases, a summary of the interpretation is below with details available in reports Byrne, C., 2016 – DMP/2016/1 and Byrne, C., 2014 – DMP/2014/2.

The first phase tied the 3D seismic to Harvey-1 well to interpret the seismic surfaces and faults for the five horizons: Sabina Sandstone, Wonnerup member, Yalgorup member, basal Eneabba unit and the Break-up Unconformity; and was used to determine the three drilling locations of Harvey-2, -3 and -4. The 2D survey was used to expand the area to cover the “Western Fault” and further to the North (Figure 5.1).

The second phase of the study integrated these three wells (H-2, H-3 & H-4) with an updated seismic interpretation and subsequently depth converted the time interpretation to produce depth surfaces and faults to build a static model.

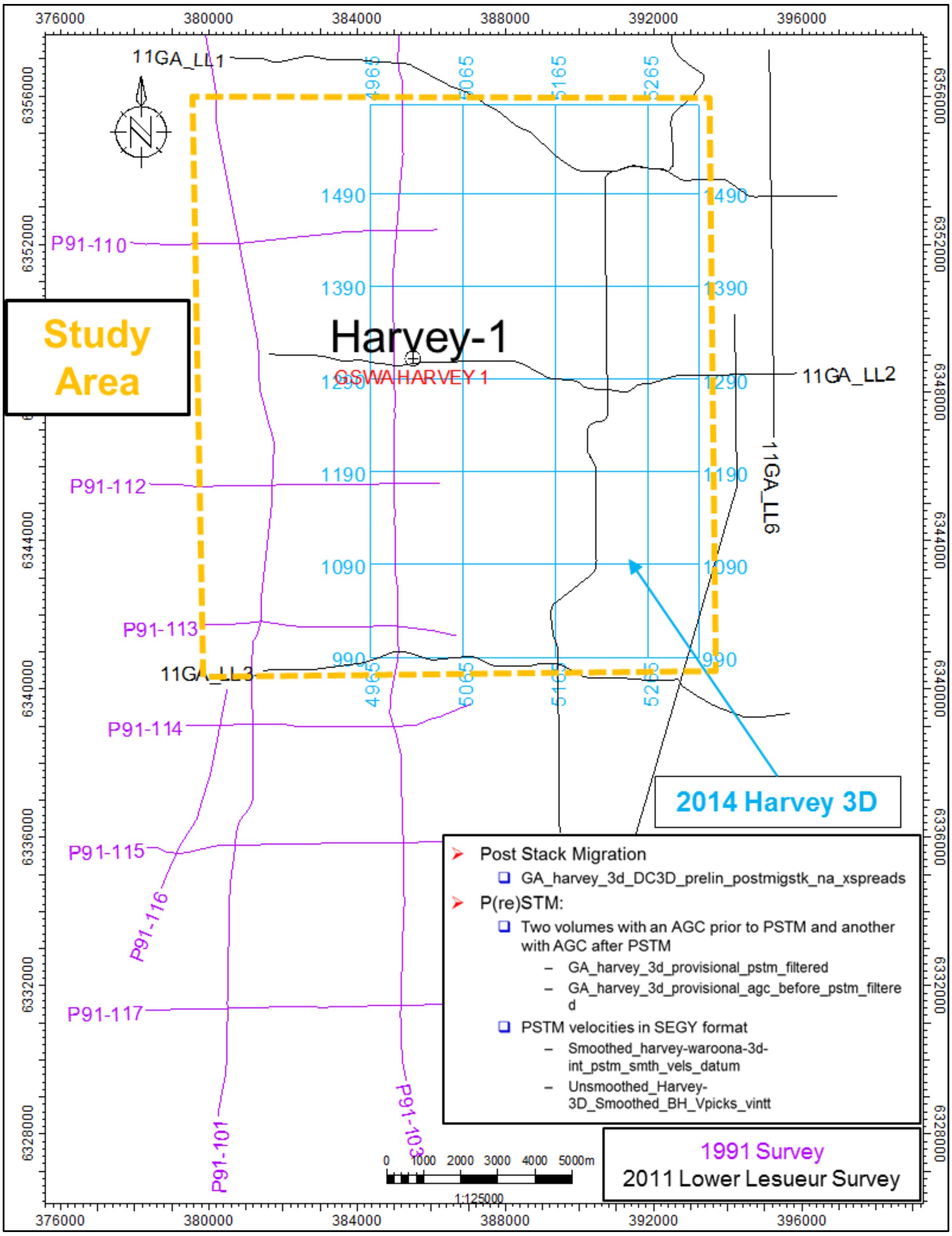

Figure 5.2: Seismic Survey Map

The 3D seismic dataset covers a total of 115 Km^2 but is poor in places due to access constraints (~40% of surface area) when acquiring the data (Figure 5.3). This has greatly influenced data quality below and adjacent to the multiple shallow data holes and its impact is particularly pronounced in the north-western part of the 3D and patchy shallow quality below and adjacent to the multiple shallow data holes. The data quality over the deeper primary zones of interest (i.e.: Yalgorup member, Wonnerup member and fault locations) ranges from poor to good (Figure 5.3).

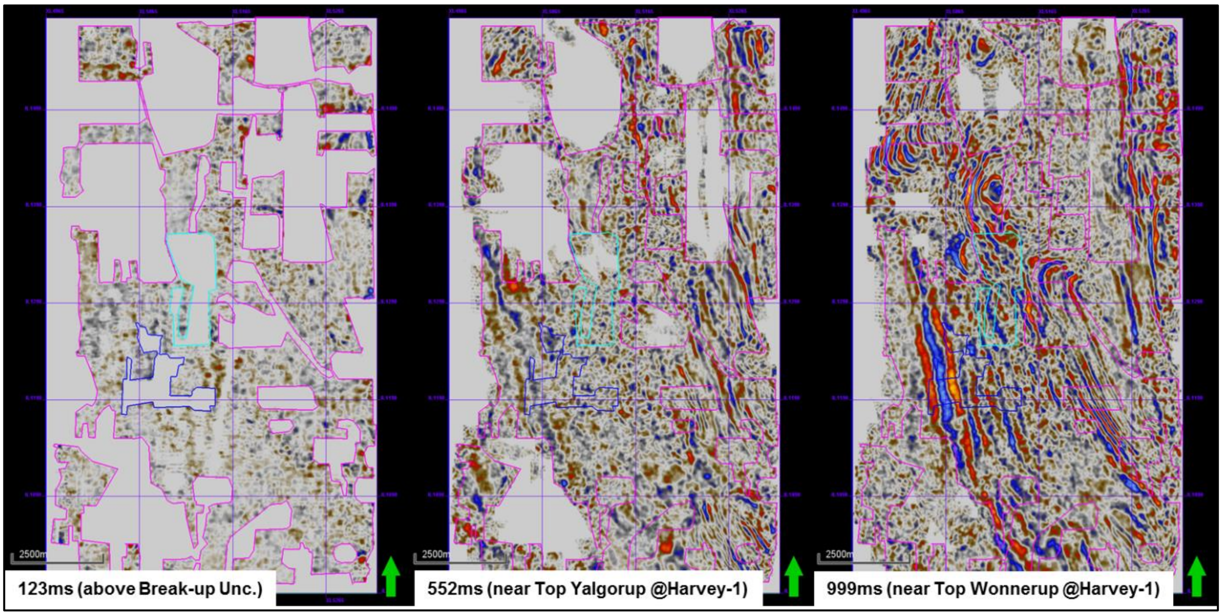

Figure 5.3: Shows Gaps in Seismic due to acquisition constraints

TWT surfaces were created for the Sabina Sandstone, Wonnerup member, Yalgorup member, basal Eneabba unit and the Break-up Unconformity. The main faults interpreted in the study area have been numbered and this numbering was used to describe them in the report. A summary of the main characteristics of each formation is provided below:

The Sabina Sandstone (the deepest formation mapped), is only penetrated in the Harvey-1 well and lies towards the base of a fairly homogenous package of the overlying Wonnerup member. It is not a very strong seismic event (a peak) but it is fairly continuous although it loses character towards the NW. It is the least faulted surface with the exception of the Break-up Unconformity;

The Wonnerup member (Lower Lesueur Formation) corresponds to a unit that is very thick (~1400m at Harvey-1) and typically has a homogenous seismic character that overlies a laterally continuous unit. It is overlain by a high amplitude laterally discontinuous package. All four wells penetrate the top Wonnerup, however only Harvey-1 penetrates the whole formation. It is the most faulted unit of the studied surfaces and exhibits typically antithetic with some conjugate faulting style from the main faults (F7 and F10) that are linked in a series of en-echelon faults that converge and show a relaying style.

The Yalgorup member is the claystone rich/mudstone upper unit of the Lesueur Formation and has a strong seismic amplitude character that corresponds to the potential 'containment' unit overlying the Wonnerup member. The Yalgorup member presents in general the strongest amplitudes of all the mapped units. Nevertheless, the amplitudes in this unit come and go making the mapping of individual units/packages across the 3D difficult. There were various regions where this unit could not be imaged due to poor seismic coverage gaps. The faulting style at this level shares many of the same features as that of the Wonnerup member, however some crossing conjugate normal faulting is present.

The basal Eneabba unit appears immediately overlying the Yalgorup member. It is not a very thick unit, approximately 80 m at GSWA Harvey-1 well. As with the underlying Yalgorup unit there were various regions that were unable to be imaged as it shares the same poor seismic coverage gaps that are present on the eastern side of the F10 fault block, the southwest and the north-east corner.

The Break-up Unconformity is a strong angular unconformity in all regions of the study area, particularly above the footwall block of the F10 fault. It is a regional unconformity that occurred during the Early Cretaceous associated with the separation of Australia from Greater India. The seismic coverage at this level is very patchy due to the influence of the many gaps in the seismic data, particularly the NW. However, where the seismic is present, this event is of very good quality. It is the least faulted of all the five surfaces mapped and the only faults that penetrate this surface are typically reactivation of the larger main faults (F10, F7, F15, F16).

The five TWT mapped surfaces were converted to depth after evaluating various methods to minimize the depth error at the wells. The lowest depth error method was the Interval velocity SEGY cube provided by Velseis, which was converted to Average Velocity and used in the TWT surfaces depth conversion. The three depth structure maps used as inputs for the modelling are Sabina Sandstone (Figure 5.4), Wonnerup member (Figure 5.5) and Yalgorup member (Figure 5.6).

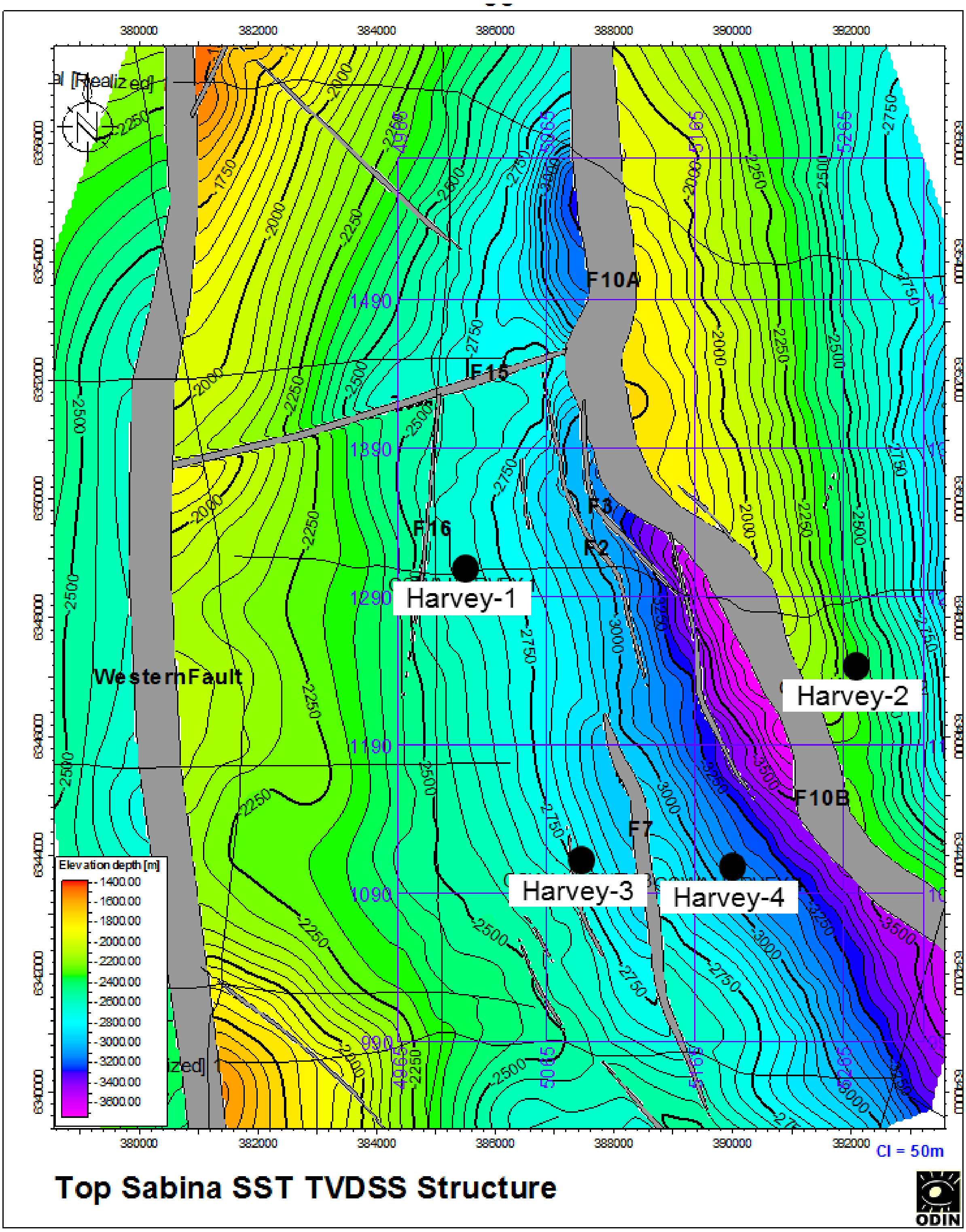

Figure 5.4: Sabina Sandstone Depth Structure Map

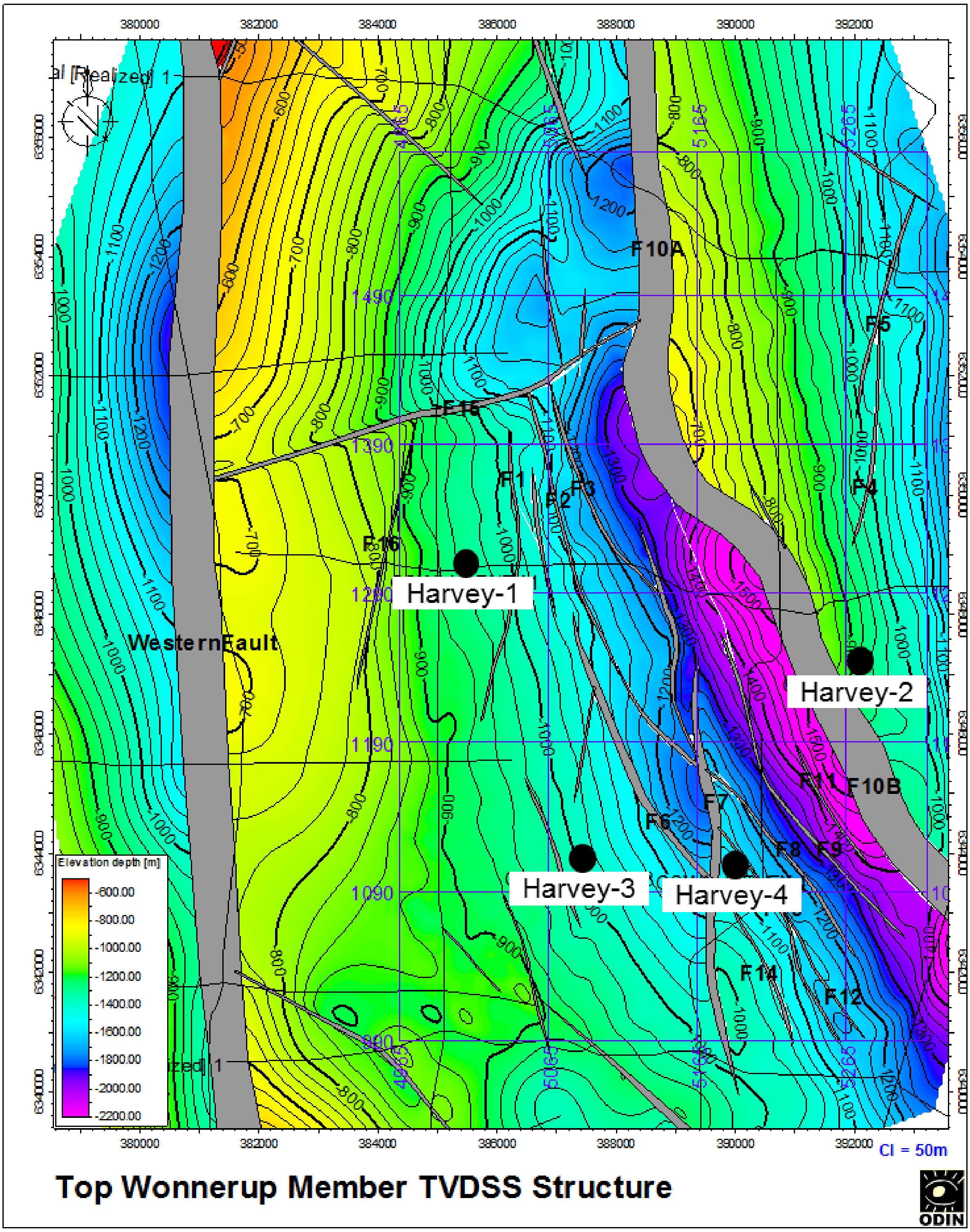

Figure 5.5: Wonnerup Member Depth Structure Map

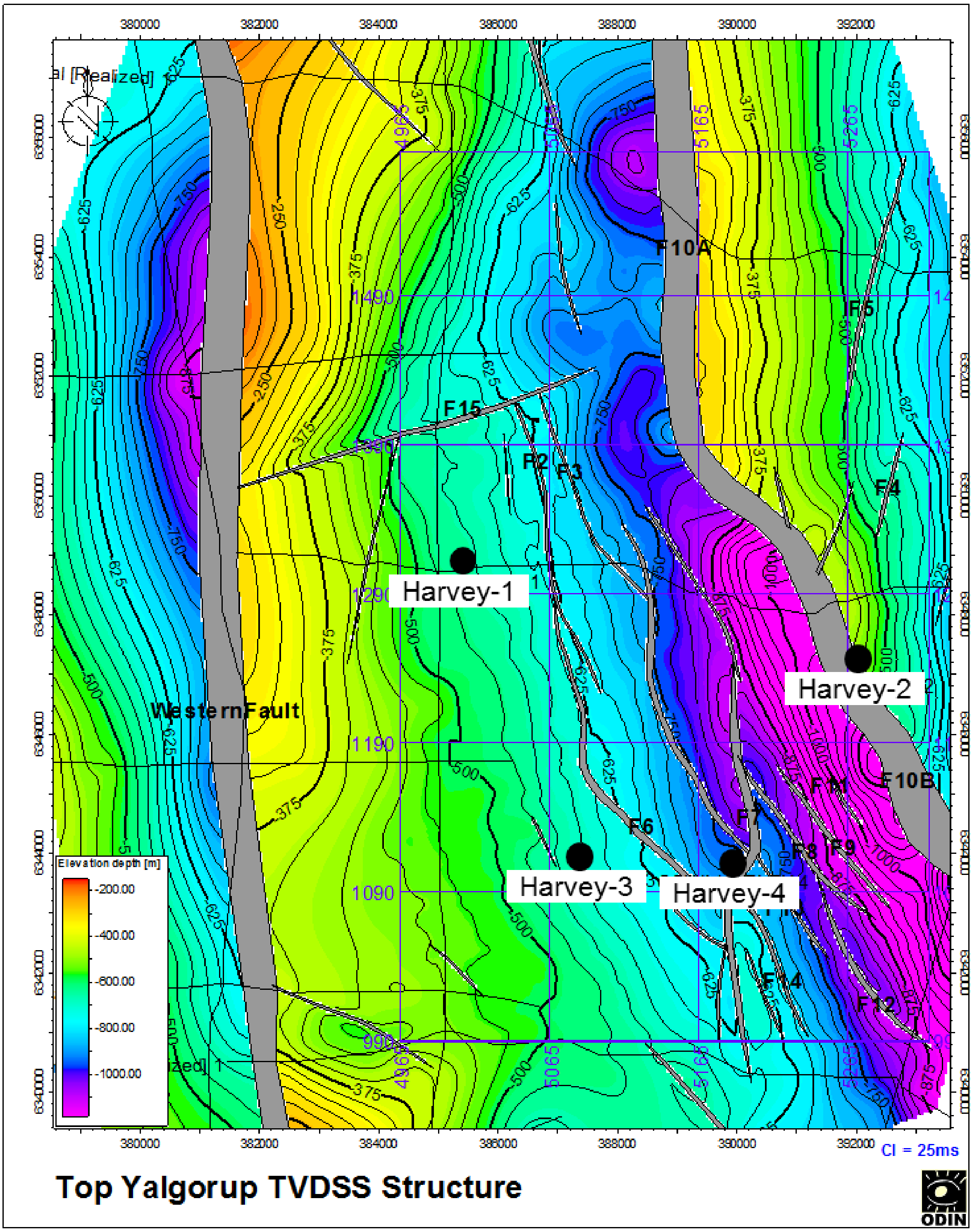

Figure 5.6: Yalgorup Member Depth Structure Map

The model commenced with the Velseis processing. During the course of the development of the static model, Curtin University processed the 3D data as part of an ANLEC R&D research project (the final report is notpublished as yet). Using novel and innovative techniques, the Curtin reprocessing of the Harvey 3D is of better quality than the Velseis processing as it is more laterally continuous and also maintains amplitude continuity with less 'blotchy' amplitudes (Figure 5.7). It is higher frequency; and the shallow gaps from the acquisition problem are less pronounced and it images better underneath the gaps. In particular, the paleosols within the Yalgorup unit and the main reservoir unit (Wonnerup member) show more lateral continuity. The Curtin processing was used to QC the modelling as it was not available at the start of the model construction.

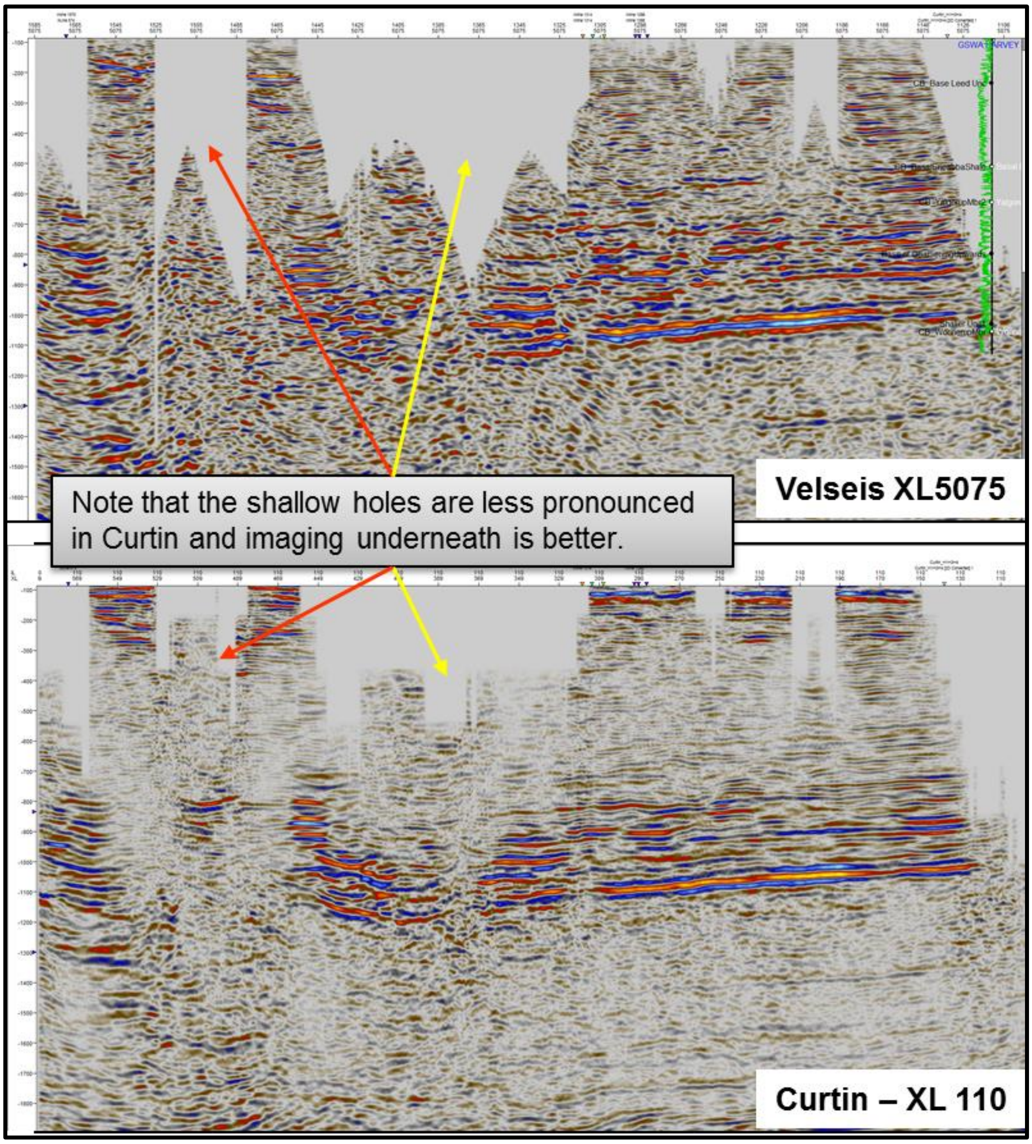

Figure 5.7: Comparison between Velseis and Curtin data

5.1.2 Stratigraphy and well correlation

A regional correlation based on twelve wells drilled over the southern Perth Basin has been the basis for the correlations of the four Harvey wells that will be the main control points during the 3D static modelling process.

This correlation has been mainly based on wireline data such as gamma ray log (GR), see Figure 5.8. Due to the non-marine nature of the deposits there is a lack of paleontological control for the Triassic-Jurassic section in this zone that results in an uncertain correlation in some areas.

In addition, the lack of associated acoustic logs and sufficient palynological data has also resulted in difficulties to differentiate stratigraphic units in some wells, particularly in separating the Eneabba Formation from the underlying Yalgorup member of the Lesueur Sandstone. Thus there has been uncertainty in correlating the strata in Harvey-1 with the other wells.

Also, the fluvial depositional environment is extremely difficult to correlate locally from well to well, particularly the individual sands and as we do not expect them to be extensive enough to be penetrated by more than one well. There is more confidence of correlating packages, however, due to the number of possible outcomes these markers have not been used to divide the model into sub-zones.

The seismic has been used to assist with the correlation which does help with a mid-Yalgorup marker but it was not very useful in the Wonnerup. Although there is uncertainty surrounding the geometry of the Wonnerup and Yalgorup members due to the large distance between the two type sections that define them, this has been accepted as a conformable stratigraphic relationship. Likewise, the Eneabba Formation appears conformably overlaying both members of the Lesueur Sandstone.

The most consistent correlatable marker is the Top Wonnerup, which is characterised by a sharp decrease of the GR. This is the best seismic event mapped.
The Break-up Unconformity is the second most consistent marker and is defined as an abrupt change overlain by a shalier unit. Again this is a good seismic marker when the seismic is present (i.e. it has been imaged and is not in a shallow muted zone).

The uncertainty in the well correlation mainly lies on the Eneabba-Yalgorup interval due to lack of consistent packages and/or events to correlate the wells. It is noted that this interval changes into a lower energy facies towards the south-east (i.e. from Harvey-1 to Harvey-4);

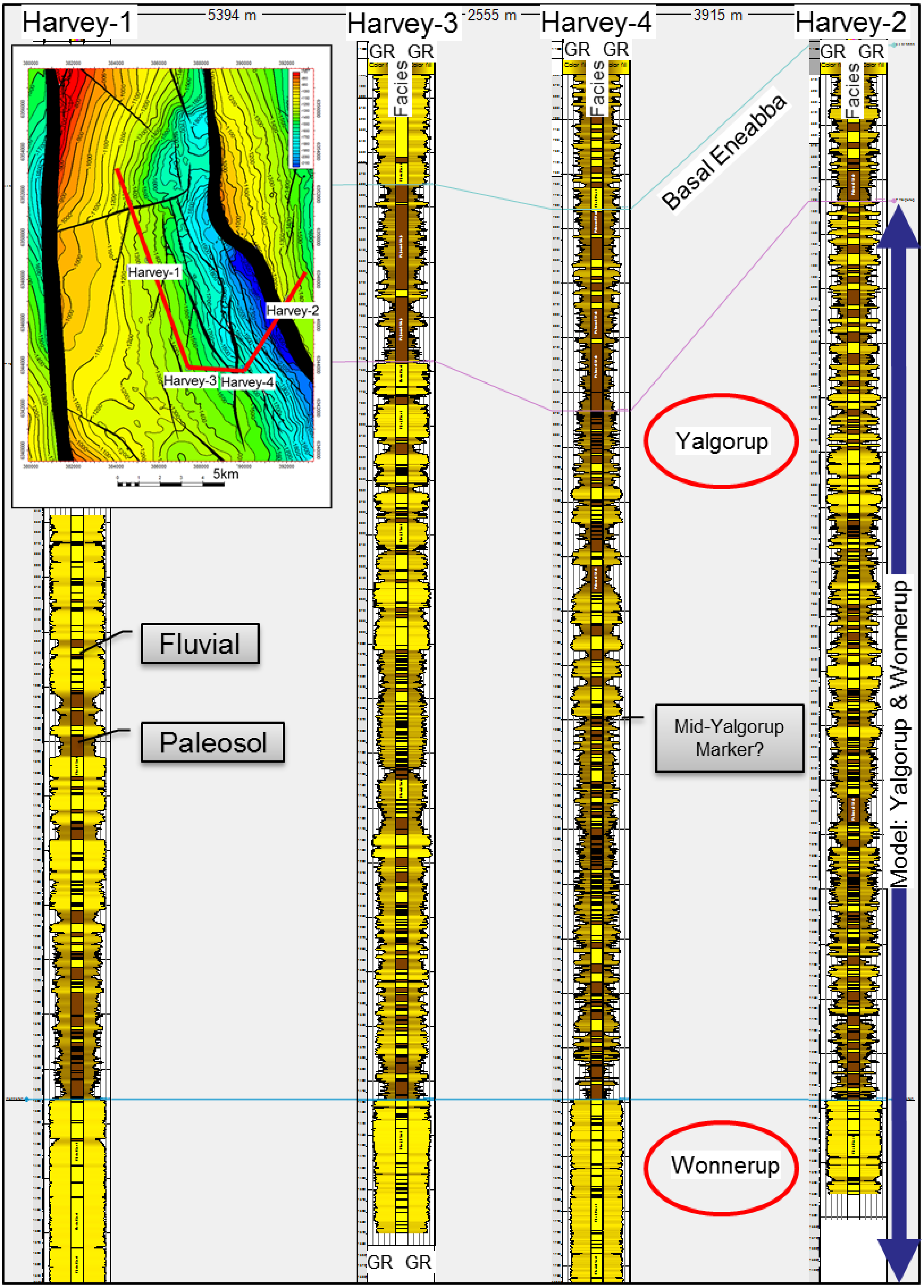

Figure 5.8: Correlation Panel

5.1.3 Sedimentology, analogues and conceptual depositional model

The Lesueur Sandstone was deposited during the Triassic in a braided fluvial environment within the Perth Basin. The paleogeography of the basin indicates an elongated shape roughly running in a N-S direction and bounded by stable cratons which constitute the sediment source.

The exact provenance of the Perth Basin sediments is still an open question but according to mineralogical analysis it is likely to come from stable cratons and transitional continents such as Yilgarn craton, Leeuwin complex or Albany-Fraser orogen, or any combination of these three sources. The main sediment supply direction has been identified as a general W-E trend with a WSW-ENE component.

The two lithostratigraphic members that comprise the Lesueur Sandstone, Wonnerup member and Yalgorup member present some depositional differences. The Wonnerup member is formed by a fluvial braided system dominated by linguoid bars whereas the Yalgorup member is formed by a fluvial meandering system dominated by point bars, claystone irregular bodies and paleosols. A number of lithofacies ranging from coarse high energy sands to finely laminated mudrocks, derived from well core studies, support this depositional model.

Five main depositional facies spreading from channel fill sands to swampy overbank deposits and paleosol/floodplain sediments have been defined to represent both fluvial environments, braided and meandering, in the Wonnerup and Yalgorup respectively. The present analogue used for both the Wonnerup and Yalgorup members is the Brahmaputra River (Figure 5.9).

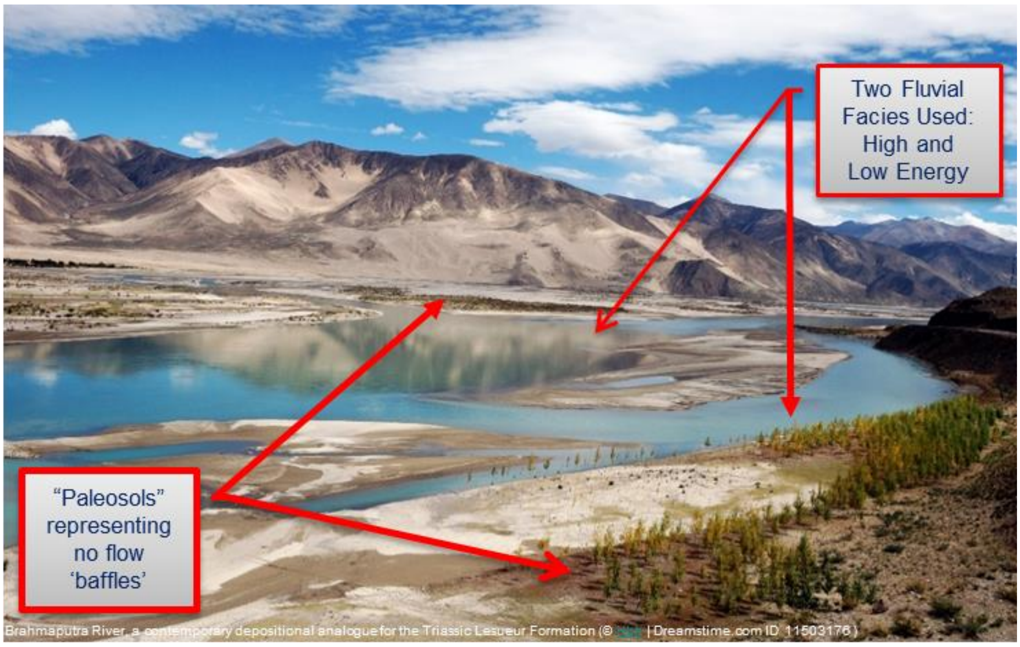

Figure 5.9: Brahmaputra River as an analogue for the Lesueur Sandstone

In general, the coarse channel fill sands in the Wonnerup member are a good reservoir to contain the injected CO_2 and the more paleosol rich Yalgorup member dominated by floodplain and paleosol deposits can act as a baffle to flow for the reservoir complex. However, what makes these lithostratigraphic units a suitable target for CO_2 sequestration is the high frequency sand/paleosol alternation and the tortuous path that this generates for the gas to flow through. In other words, it is the low Kv/Kh ratio of this formation is what will benefit the sequestration process by increasing the gas migration time to surface.

In order to design and build a facies model within the generation of a full and integrated 3D static model, more detailed characteristics about geometries, dimensions, lateral extend and relationship between facies are needed. The paleosols in particular, have been a special challenge in this project as their dimensions and lateral extend are not well known.

Thus, other possible analogues for fluvial environments with paleosols development have also been reviewed during this study. For example, the Hawkesbury Formation in Eastern Australia and the Durkand Group in the Triassic deposits of USA.

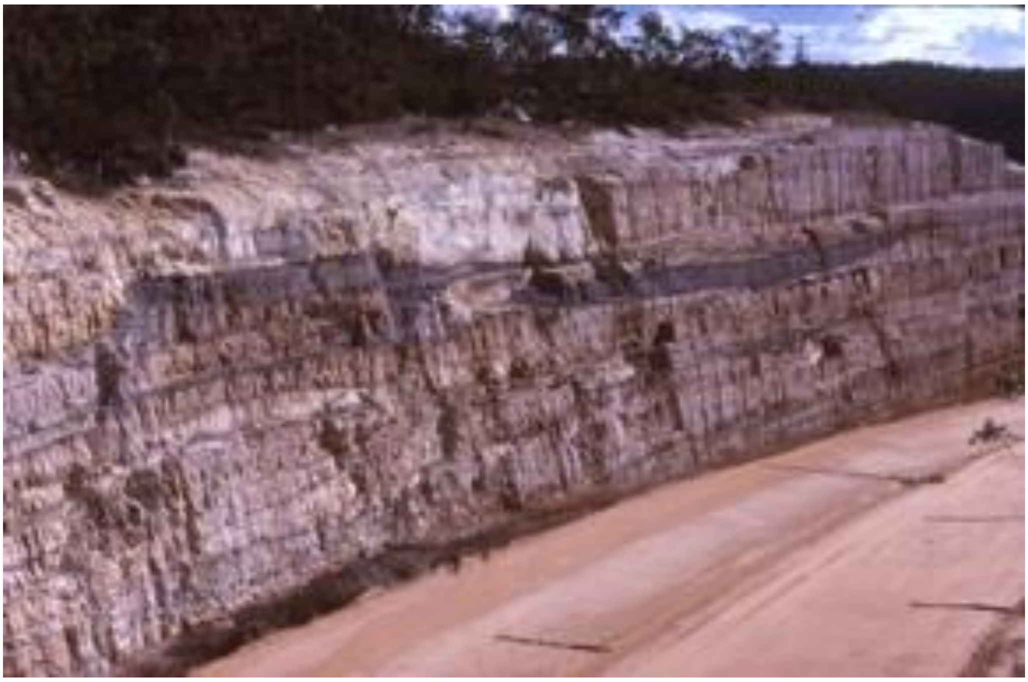

Figure 5.10: Pacific Hwy cutting near Gosford through Triassic Hawkesbury Sandstone. Photo courtesy of J Roestenburg.

5.1.4 **Paleosol geometry and lateral continuity**

Cores 2 to 4 (between 1266 and 1344 m) in well Harvey-1, representing the Yalgorup member, mainly consist of paleosols facies (vertisols) represented by a mottled interval with the following characteristics: variegated colouring, churned appearance, abundant pedogenic slickensides and crumb-like aggregations of minerals, vertical desiccation mud cracks (up to 40 cm deep) and more unusually pipe-like structures (up to 70 cm vertically).

The slickenside marks are clearly not associated to tectonic activity as they are randomly oriented (as opposed to regional stress oriented), have a strongly curved relief and are formed in shallow depths.

All these characteristics point out to a vertisol development typically formed in a warm subhumid or semi-arid climate that comprises alternating long dry and wet periods and where the vegetation is predominantly savannah, open forest or desert shrub.

Although these soils are formed through an autocyclic process in a fluvial system (ie.: channel avulsion) the thick accumulation of stacked paleosol horizons deposited over a long period of time (enough to generate >500 m of section in Yalgorup), indicates that an allocyclic process must have been the main cause for this large development.

The external allocyclic process could have been a tectonic event or climate change that affected the entire basin. For example, a shift from a wetter climate to a drier climate reducing the size of rivers and therefore the amount of sediment supplied to a sedimentary basin. Likewise, a quiet tectonic phase with slower rates of sedimentation and a higher percentage of finer sediment during this period of quiescence could provide the stable conditions needed for a large paleosol development. An uplift of part of the source area may also deflect river systems away from sedimentary basins, starving them of sedimentation for extended periods of time and favouring paleosol development.

In summary, the great thickness (~600 m) of the paleosol dominated interval probably implies stability during long periods of time of the allocyclic factors that could intervene in their development, such as climate or tectonic movements. According to modern analogues these paleosols are dependent on several factors that will condition their development, distribution and extend: Climate, vegetation, relief or topography and time.

Climate is one of the most important amongst these factors and although vertisols at present are formed in most types of climate, an alternation of wet-dry periods is needed to create this type of soils. In addition to that a long enough interval of time where that particular climate operates is needed to develop the large paleosol extensions.

Topography or relief is also important, with most vertisols being formed in gentle slopes (no more than 5%) or level ground. When the soils are formed in broad level ground the drainage network can become very poor allowing water ponding that could develop into swamps and marshlands. (which are facies E and G, as described in Harvey-1 – see on page 30).

Another important factor is that vertisols can be autoctonous, formed by the degradation of a substrate (parent material) or alloctonous, formed by the degradation of sedimentary materials that have been transported to an area. The latter (Harvey area case) are geographically more extensive than the former and occupy the low lands where they are distributed. These paleosols, normally found on interfluves, distal floodplain, backswamps and marsh can extend in present times for many tens or hundreds of km2.

Everything seems to indicate that when vertisols develop they are very large and extensive and their dimension depends (apart from climate, time and vegetation which have to be suitable) on the peleogeography/paleotopography of the basin. Obviously they cannot be infinite and sometimes they concatenate with another type of soil when the relief changes (with different physical and chemical properties).

In the work of Cecil, C.B., (1990) 'paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks', the "incompatibility" of silisiclastic supply in a basin and the formation of soils (mainly by pedogenic processes involving chemical precipitation) are stated. When supply of siliciclastics is reactivated in the basin the paleosols get eroded. This also supports the concept of a long period of stable climate and tectonic quiescence where fluvial channels are very reduced or maybe shifted to another part of the basin allowing the development of large extensions of vertisols.

Nevertheless, although allocyclic processes such as tectonic quiescence and a certain type of climate or even the paleo landscape are the main causes for the development of the soils, autocyclic process of these sedimentary environments are still taking place and need to be taken into consideration. For instance, the partial erosion of the soil by channelized bodies at certain times could break up the paleosol continuity. Likewise, the sand filled cracks formed by desiccation processes during dry periods, reaching up to 0.5 m in depth in the Harvey area, will also have an impact on the continuity of the paleosol petrophysical properties.

In fact, an article on the sedimentology of the Monongahela and Dunkard Groups (USA, Upper Pennsylvanian to Lower Permian) mentions up to nine different facies within a paleosol interval with thicknesses between 150 and 335 m and a total areal extension of 78,000 Km2. (Daniel I. Hembree, et. al 2014)

However, despite these facies variations other works by the same authors suggest their possible utility as stratigraphic markers due to their extensive nature and consistent physical properties across several hundreds of meters in different directions.

Finally, another case study that has been used as an analogue for the Yalgorup paleosol interval is the Triassic Hawkesbury sandstone in the Sydney Basin (B.R. Rust et al.

1986). In their paper, mudrock beds with a typical thickness of 1-2 m are described. The most common facies in this mudrock beds are ripple-cross-laminated, fine sandstone to siltstone and horizontally laminated ("pin-stripe") fine sandstone to siltstone to shale. These facies being intergradational and representing relatively long-term sedimentation on a portion of the floodplain remote from active channels. Common abandoned channel fill intersecting the mudrock beds in some outcrops are also described.

These facies can sometimes reach thicknesses up to 9-12 m (Standard,1969) or even 35m (Herbert and Uren, 1972), and extend laterally for 2.5 Km in a coastal outcrop near Sydney.

In summary, paleosol facies are by nature extensive and irregular in shape which have a small average thickness and present rather continuous petrophysical properties. Given enough time under stable climate and tectonic conditions these facies can develop to form thicker and more extensive packages over a basin. Although dimension rules for these geobodies have not been defined, it seems fair to assume that they extend for many hundreds of meters.

Nevertheless, some variations within the paleosols are to be expected due to their allocyclic nature. For instance, presence of intersecting abandoned channel fill or sand filled desiccation cracks. These facies variations will have an impact on the petrophysical anisotropy of the paleosol bodies that has to be captured in the static model as it will impact in particular the Kv/Kh ratio and the CO_2 migration pathway.

5.1.4 Core facies analysis

Nine different lithofacies have been defined (Payne et al,2013) over the cored section of Harvey-1 which comprise both the Yalgorup and the Wonnerup members. The core study has been carried out on the 6 cores taken for the well: cores 1 to 4 represent Yalgorup member, whereas cores 5 and 6 belong to the Wonnerup member.

These nine facies (Ai, Aii, Aiii, B, C, D, E, F, G) have different characteristics in terms of lithology, colour, texture, grain size, sorting, etc. and roughly represent different depositional facies.

Ai – High energy channel fill, commonly cross bedded, gravelly to very coarse sandstone (Figure 5.11).

Aii – High energy fluvial channel barforms, medium to very coarse cross bedded sandstone with significant grain size variation between beds (Figure 5.11).

Aiii – Fluidized fluvial barforms, massive, coarse sandstone (Figure 5.11).

B – Moderate energy fluvial barforms, massive, medium sandstone with flaser cross lamination (Figure 5.11).

C – Moderate to low energy stacked rippleforms, fine to medium cross laminated sandstone, with common organic fragments and flaser-drapes (Figure 5.11).

D – Floodplain palaeosols (often vertisols), fine to medium homogenized sandstone with rootlets, dessication cracks and slickensides (Figure 5.11).

E – Swampy/lagoonal deposits, under waterlogged conditions, muddy bioturbated sandstone with slumps and dewatering structures (Figure 5.11).

F – Crevasse splays and overbank deposits, interbedded silty fine sandstone and siltstone with trough cross lamination.

G – Swampy/ overbank deposits, muddy laminated silt with plant fragments and thin laminated fine sandstone.

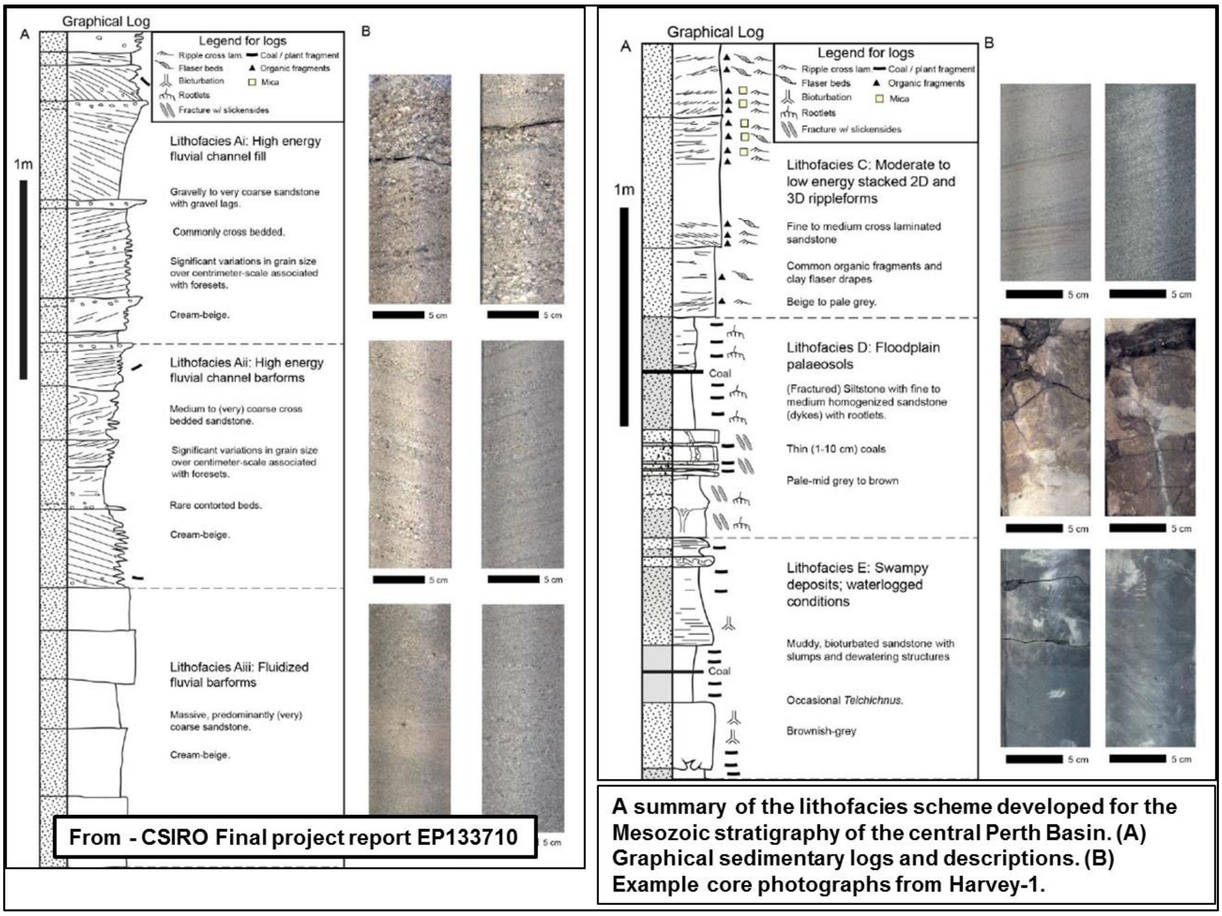

Figure 5.11: Example of core facies in Harvey-1

The upper part of the **Yalgorup** (core 1) is formed by mixed high energy sandstone (Ai to Aiii), moderate energy sandstones (B) and low energy ripple marked sandstone (C). A mudstone bed up to 2 m thick is also present intercalated with the sands.

The middle and lower parts of this member (cores 2 to 4) consists mainly of siltstones and sandstones representing paleosols (D). Vertisols, more precisely, which are soils with high expanding clay content, in ephemeral fluvial systems, expanding clay minerals expand during wet winter seasons, and contract during dry, summer seasons. This causes vertical desiccation cracks during the drying of clay minerals. During the dry season, surface sediment fills these cracks through channel flow by flash flooding of poorly sorted, medium-grained to gravelly sands.

Towards the middle of core 2 the sandstones proportion increases in an interval of about 3 m thick. Core 3 and 4 are again dominated a mudstone/siltstone lithology.

Vertical to sub-vertical, trans-bedform fractures are pervasive in mudstones; they are typically planar to irregular, and can extend from 5 cm to several meters. These fractures are typically filled with medium-grained sandstone and occasionally very coarse grained sandstone, creating sub-vertical sandstone 'dykes', which could act as permeable pathways through otherwise relatively impermeable mudstone.

So, the Yalgorup consists of a rapidly-switching, in the order of 1m, mixed lithofacies, with the exception of extensive floodplain palaeosols in the lower Yalgorup. However, even within this soil profile there is rapid switching in the sandstone dykes, between high energy channel fill and moderate energy channel barforms, indicated by the variation in grain size.

The **Wonnerup** represented by cores 5 and 6, mainly consists of continuous high energy sandstone. (Ai to Aii) that may be occasionally punctuated by medium energy sandstone (B) or low energy ripple forms (C) and very rare punctuations of siltstone/mudstone beds. When they occur they are mainly overbank type of deposits (G) and occasionally finely interbedded indicating crevasse-splay deposition (F) or swampy lagoonal environments (E). These appear in core 6, so in the lower part of the Wonnerup member.

The Wonnerup member is more homogeneous in terms of lithofacies development. However, within a lithofacies unit, there is still rapid-switching between crossbeds and foresets, indicated by 1-10cm beds of alternating grain-size sandstones. These are primarily high energy channel fill and barforms, with rare lower energy rippleforms and swampy/lagoonal deposits.

Both continuous and cumulative facies thickness have been analysed. The first one supplies information about the average thickness of the facies bodies which will lead in turn to deriving other dimensions like width and length. The second indicates the proportion of each facies in total lithostratigraphic unit accumulation.

The Lesueur Sandstone contains over 60% of high energy channel fill and barforms (facies Ai-Aiii). Its two lithostratigraphic members, the Yalgorup and Wonnerup contain approximately 35% and 85% of facies Ai-Aiii, respectively.

The Yalgorup member is dominated by floodplain palaeosols (facies D) in cores 2-4, consisting of between 5- 15% of the other facies. The Wonnerup member is dominated by facies Ai and Aii, with 1-10% of all other facies.

The continuous thicknesses of facies in the Lesueur Sandstone average about 1-2 meters. The Yalgorup member is relatively evenly distributed, with the mean varying between 0.7 m and 1.5 m, with the exception of facies D and E, where the mean is between 2.5-3 m, and facies G, where the mean is less than 0.1 m.

The Wonnerup member has thick continuous intervals of facies Ai to Aiii, with 50% of the thicknesses falling within 1-2 m

5.1.5 Petrophysical analysis

The log interpretation confirms the Lesueur Sandstone consists of interbedded sands and paleosols. The porosities of the sands in the Yalgorup member are of the order of 25-30% and in the Wonnerup they fall from 25% near the top of the member to 20% at TD in Harvey-4 (1740m). However, in Harvey-1 porosities fall to as low as 10% at the base of the Wonnerup (2840m).

In summary, good reservoir properties are recorded in the homogeneous Wonnerup member (1380-2895m depth). In contrast, the overlying Yalgorup (704-1380m) is far more heterogeneous with excellent porosities noted in the sand intervals. Full details are available in the ODIN report Kennedy, M., 2015 – DMP/2015/3 with a brief summary of section below.

5.1.5.1 Gamma ray response

Core gamma measurements were compared to the interpreted facies scheme. High to moderate energy, clean, channel fill and barforms (facies Ai to B) typically exhibit the lowest gamma response; facies C to D are intermediate, and facies E to G have higher gamma response.

However, there are overlaps in the gamma response from different facies types: The probability of **facies Ai-Aiii** is more likely to occur at gamma ray values between 10-50 counts per second. Facies B to D typically have intermediate values between 50 and 90 counts per second. For facies E to G, gamma ray values are most commonly in the range of 70 to 90 counts per second.

Using gamma ray alone to infer lithofacies types in non-cored intervals leads to a reasonable ‘rule-of-thumb’, but not a unique interpretation. A GR cut-off of 80 gApi to discriminate between sands and paloesols was used as a guide but manual picking and interpretation of the facies types was undertaken in this project.

5.1.5.2 Shale volume

Total shale thickness for the Yalgorup member is about 145m, based on a shale cut-off value of 50%. This thickness of shale is about 21% of the total thickness of the Yalgorup member, which is about 676m. However, for the Wonnerup member, with a total thickness of 1501m, the shale thickness is approximately 25m, less than 2% of the total thickness of this member.

5.1.5.3 Porosity

Neutron, density and sonic log data were used to estimate total, effective and secondary porosities. Secondary porosity is calculated from the difference between neutron-density porosity and sonic porosity. Secondary porosity that may result from feldspar dissolution and other lithic grains, increases with increasing depth from near to zero to about 8%.

A comparison between core and log porosity shows an acceptable match. The best correlation is between the effective density porosity and core porosity with a coefficient of determination of about 72%.

5.1.5.4 Permeability

There is a strong relation between the bulk density and the permeability. The other log data appear to have less correlation with the permeability

$$\log k = 22.4 - 9.36\,ZDNC - 6.52\,CNC + 0.0481\,DT - 0.270\,PE + 0.0307\,MLR4C$$

This equation was used to calculate permeability over the whole thickness of the Wonnerup and Yalgorup members This shows a clear trend in the permeability reduction with depth. Permeability reduces from more than 4000mD to less than 10mD for the Wonnerup member. For the Yalgorup member bad hole flag intervals and shale layers

were removed before conducting the permeability calculation. For this member, the permeability of sand intervals range from more than 10,000mD to 4mD.
There is a good correlation between the core permeability and the calculated permeability.

Similarly, there is a reasonable match between core porosity and core permeability. However, this match improves when the samples are plotted separately for each facies. Therefore, a new porosity to permeability transformation was created for each facies using the Geo2Flow software. The resultant relationship was then used to create a permeability curve for each well.

In summary, the Lesueur Sandstone has the potential to be the target reservoir for CO_2 sequestration. The formation has reasonable porosity and permeability based on a petrophysical evaluation. The shale volume interpretation highlighted shale intervals of varying thickness (maximum 30m) in the Yalgorup member. The Wonnerup member on the other hand is composed of thick sand intervals with a lack of major shale breaks.

In general, both members show a distinct porosity and permeability depth trend. Total porosity reduces from 26% to less 10% and permeability reduces from more than 4000mD to less than 10mD within the Wonnerup.

Impact of diagenesis on petrophysical properties can be translated into two opposite porosity trends. On the one hand there is significant compaction and cementation (primarily kaolinite, and to a lesser extent illite, smectite and chlorite cement) in all samples, increasing with depth. However, the sub-hedral nature and size of clay-occluded pores suggests that secondary porosity was created through weathering of feldspars.

5.1.6 Log image interpretation and facies definition

The data set studied comprises the cored intervals of two wells: Harvey-1, which had previously been interpreted, and the more recently acquired Harvey-4. For consistency purposes both wells have been interpreted again using the same methodology. Full details are available in Roestenburg, J., 2016 – DMP/2016/2 with a summary below.

Harvey-4 core covers an interval from 250 to 1784 m and Harvey-1 cored interval ranges from 1285 to 2723 m. These intervals cover both lithostratigraphic members, Wonnerup member and Yalgorup member. The main objective of this analysis has been the identification of the depositional facies orientation as they will control the facies objects that will be populated in the 3D static and dynamic models.

There is considerable post-depositional structuring in the area (faulting and tilting) that will have interfered with the original depositional bedding orientation and dip. This structural print has been identified using preserved claystone bedding and truncation surfaces and then removed (palynspastic rotation) to avoid interference with the original depositional bearings. In the Wonnerup member, this structural dip is about 10^o at a 22^o azimuth, and in the Yalgorup member is about 7^o at a 35^o azimuth.

After removing the structural dips and identifying other post-sedimentary features such as compaction, diagenesis and fracturing, all the images are classified into dip sets and displayed along the well trajectory together with other log curves (GR, litholog, etc), dipmeter data, core and interpreted depositional facies. This allows for the identification of the main depositional facies and their orientation.

Sandbody or geobody orientation is defined by the internal architecture, mainly the spatial orientation of sedimentary structures and bedding. Primary sedimentary structures are related to the depositional processes that have generated them and the energy involved, which is usually indicated by the bedding dip magnitude.

The main sedimentary features seen on the image logs were planar parallel and tangential cross bedding. In the Wonnerup member these correspond to cross-bed strata and cosets separated by truncation surfaces and paleosol horizons. In the Yalgorup member however the sedimentary features represent thalweg oriented planar crossbedding separated by paleosols.

In the Wonnerup member, dominated by transverse or linguoid bars typical of braided systems, the bars orientation is oblique to the downstream elongation direction of the braided plain. The bars show an orientation between $35\text{-}45^o$ from this direction. In the Yalgorup member, dominated by point bars typical of meandering systems, the bars orientation is perpendicular to the internal dip direction.

Three groups or azimuthal classes have been defined: E-NE, NE-N and N-NW (Figure 5.12). The E-NE class is the dominant direction of the geobodies in both stratigraphic units, with a NE-N subdominant component. There are also a few occurrences of gebodies oriented in a N-NW direction. These are associated with local changes on the depositional direction probably due to faulting and tilting.

In summary, the Harvey data sets show that the direction of the planar and tangential cross bedding is the most definitive sedimentary structure capable of defining reservoir orientation. In both lithostratigraphic units studied the predominant bar orientation (elongation direction) is E-NE, indicating a provenance from West or Southwest sources.

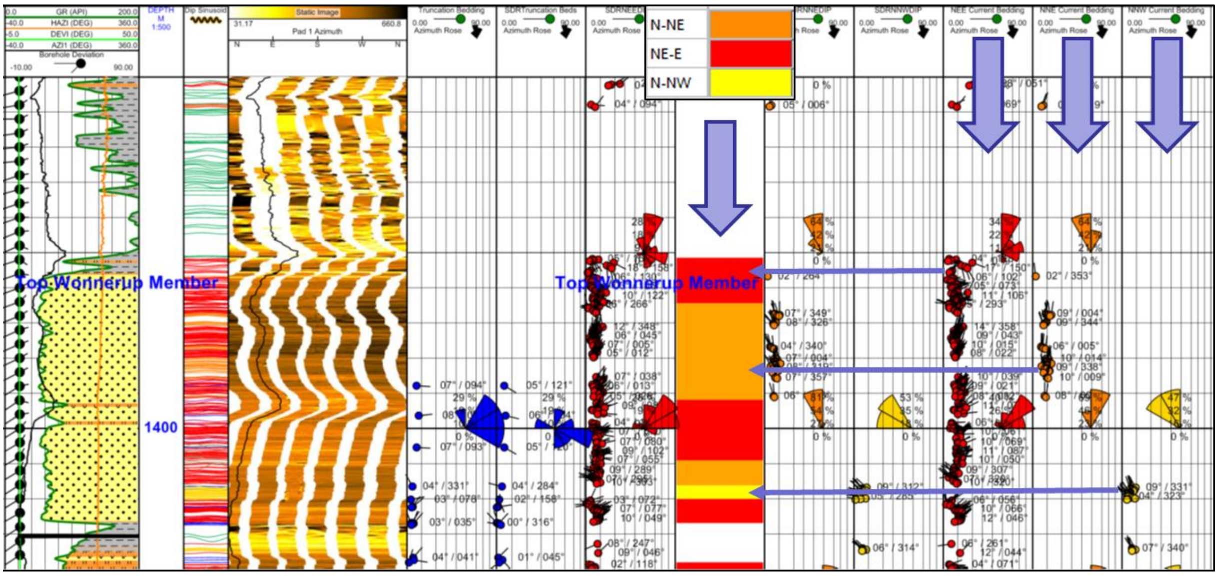

Figure 5.12: Azimuthal Classes for Geobodies.

5.1.7 Sand/Shale distribution

Thick sand intervals with high NTG are the obvious reservoirs to inject the CO_2. However, the NTG and sand shale distribution will control the Kv/Kh ratio or tortuosity of the pathway during CO_2 migration. Longer shale bodies will create longer pathways for the gas to migrate upwards but will also reduce contact between gas and formation water reducing the amount of CO_2 that will dissolve in water and leaving a larger amount of CO_2 to migrate upwards. Shorter shale bodies will have the opposite effect.

High NTG may also be indicative of the existence of an open aquifer as lateral fault seals would be unlikely and this will improve the injectivity capacity in the structure.

Unfortunately, in a fault bounded structure like the Harvey, where a 4 way dip closure cannot be defined, the high NTG may be a critical issue (cross fault breach) should the plume migrate near towards major faults (such as the Western fault) in the area.

5.1.8 Geomechanics

A geomechanical evaluation has been carried out based on a wealth of drilling data that has been collected in the four available wells, Harvey-1, -2, -3, and -4 in the Harvey area. The primary objective of constructing a geomechanical model for this project is to estimate the critical injection pressures that would induce shear failure along faults.

The Harvey-1 well provided the most information for better understanding the present-day stress state in the Harvey region. Unfortunately, a data set documenting the least principal stress S_{hmin} was never collected in any of the Harvey wells. However, in the absence of information, observations of wellbore failure were exploited in order to identify a range of permissible stress states that might be operative in the Harvey area.

On the other hand, fine-scale detection of wellbore breakouts in the ultrasonic image data (CBIL), detailed drilling summaries in Harvey-1 well, and the petrophysical data in this well used for estimating rock strength, were all used to place preliminary bounds on absolute stress magnitudes.

The resultant range of permissible stress (500-2800 psia) was used to identify preliminary critical injection pressures along a characteristic sample set of faults in the Harvey area. In the worst-case scenario, some faults in the Harvey area are prone to experience shear failure and could become conduits for subsurface fluid flow. Although these critical injection pressures may be as low as 500 psi for a small set of optimally-oriented faults, avoiding shear failure on these faults could be achieved by optimising well placement and/or regulating injection pressures.

Nevertheless, the identification of the critical injection-induced pressures are not well constrained and a more refined assessment would be required to more robustly identify the critical injection-induced pressure for reactivating faults and/or natural fractures. Further details are available in Costello D., - DMP/2015/2.

5.2 Static model

Static modelling was carried out in Schlumberger's Petrel software package initially using version 2014.3 and finalising the model using the 2016.1 version. A permeability curve was created using the Geo2Flow software. Depths were referenced to AHD (Australian Height Datum) across the area. The Petrel project containing the input data and key models have been made available.

The subsections below describe the construction of the reference case static models for the injection and plume migration phases of the project. Additional alternate scenarios used similar methodology with adjustments to input data and/or parameters. The uncertainties investigated with alternate senarios are dimensions of the individual paleosol geobodies, percentage of sand, permeability range and fault seal. Harvey-1 was the only well to penetrate the full Wonnerup section, therefore a deterministic case based on the seismic response was also created.

5.2.1 Data base

The Petrel project database has been loaded with all the available depth structure maps for the area with fault sticks and fault polygons. All of the wireline and petrophysical interpretation logs have been loaded. The resultant curves from the Hylogger survey are also available in the project.

5.2.2 Main phases of model building

There were 2 main phases of model building during this project:

A. Injectivity Model; Various scenarios were created to test injectivity of the reservoir. Also, cell thickness was evaluated using this model prior to building the larger plume migration model.
B. Plume Migration Model; several scenarios were built to evaluate the movement of the plume within the greater Harvey area.

5.2.3 Structural modelling

The initial fault model was built from the top Yalgorup to 400m into the Wonnerup using the pillar gridding method. This was a challenging fault model to build and some minor faults were removed but the final result was a reasonably regular grid. Faults were gridded as planar features (i.e. “linear’ in Petrel terminology), with zig-zag geometry. The resulting 3D grid was smooth with no twisted or negative cells. The relatively simple fault structure allowed good cell orthogonality to be achieved with minimal use of trends. An illustration of the input fault sticks is shown in Figure 5.13.

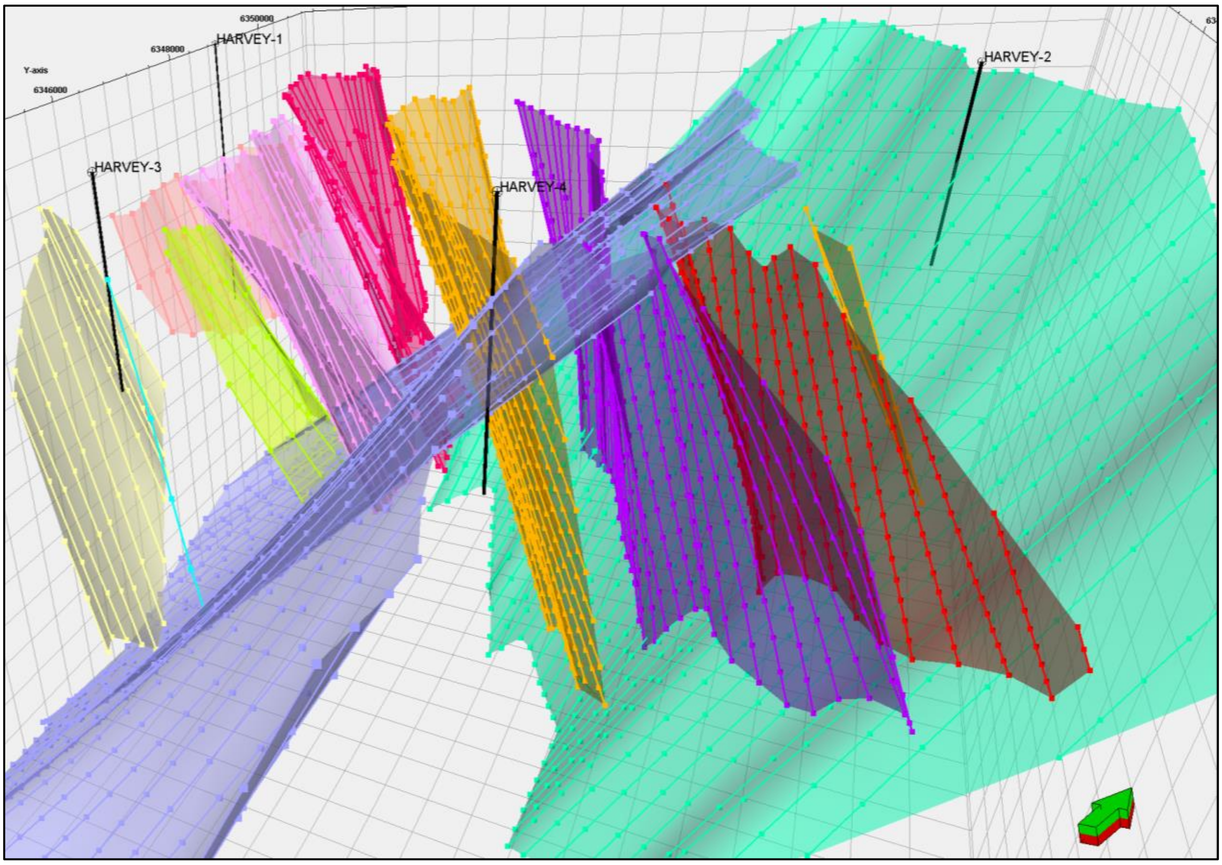

Figure 5.13: Fault sticks/planes.

However, the model interval was subsequently extended to the base of the Wonnerup (top Sabina) which significantly increased the structural complexity of the model. Therefore, it was necessary to rebuild the fault model using the “Structural Framework” module.

The fault planes were edited and cleaned up prior to being used in the structural framework process. The resultant fault framework was then used to build the structural model via horizon modelling from the top of the Yalgorup to the base of the Wonnerup members (Figure 5.14).

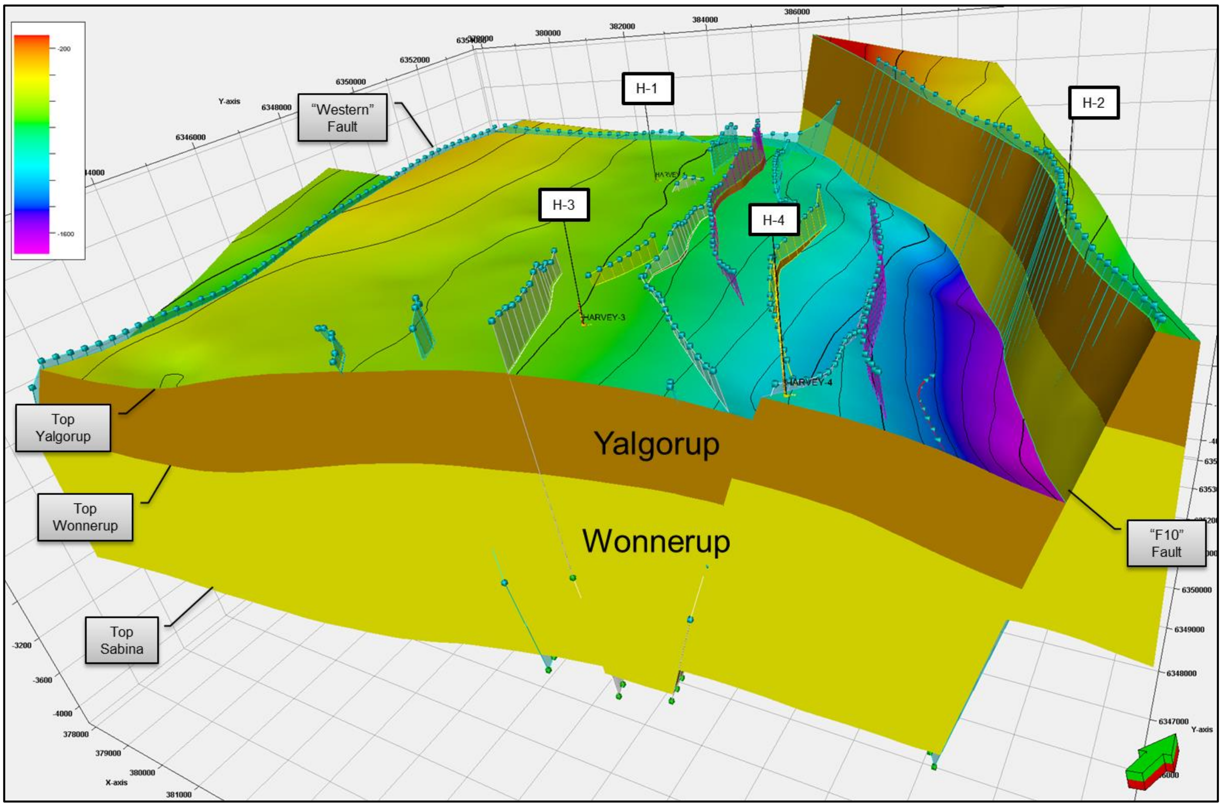

Figure 5.14: Structural Model with cleaned up Fault Sticks/Planes

5.2.4 3D gridding

The two main zones (Yalgorup and Wonnerup members) have been incorporated in the model. There were 3 grids built and made available for the simulation modelling:

GeoGrid: This covered just enough area to incorporate all the well data points to ensure all available data was utilised to create the various distributions. The area of the GeoGrid was approximately 54km^2 (7km x 7.7km). Due to the size of the cells (25x25x1m), there were too many cells to be able to simulate, particularly when simulating a number of scenarios. However, all scenarios were built at this scale in the GeoGrid in order to honour the available well data in the Harvey area.

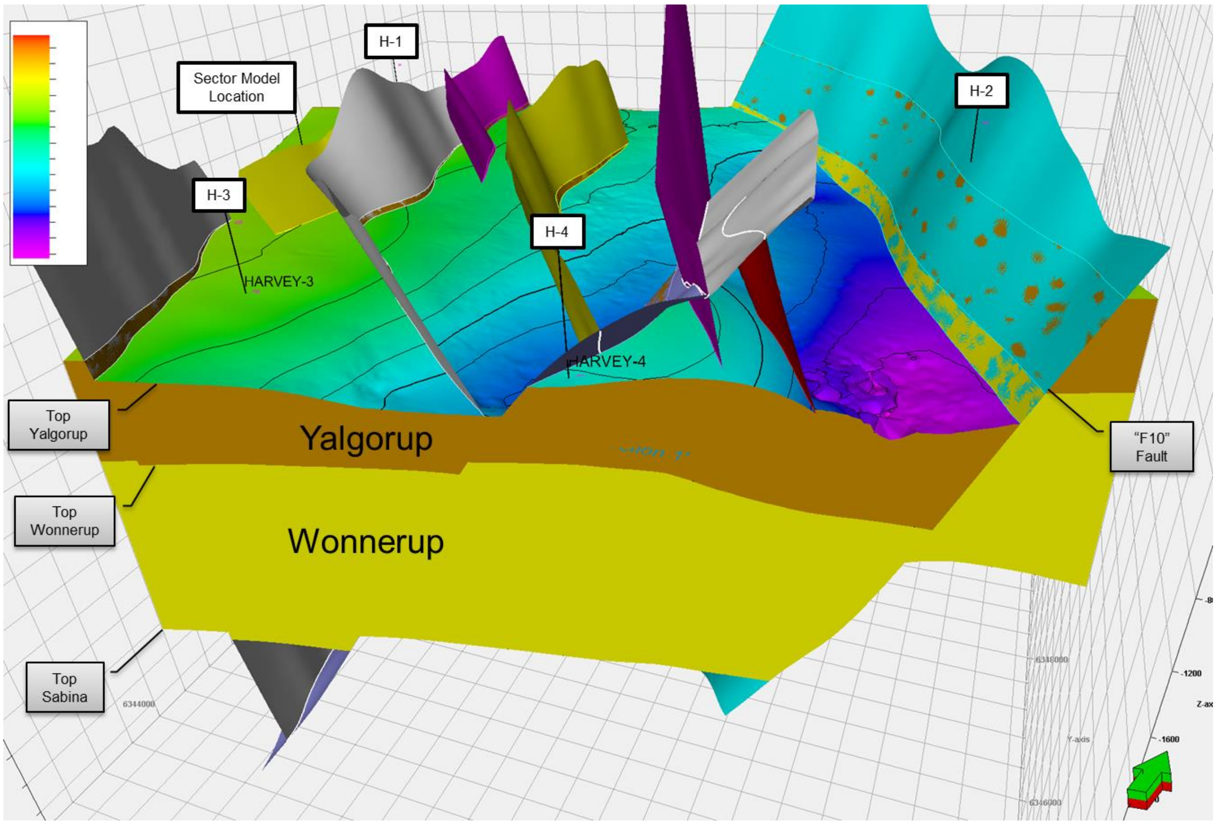

Figure 5.15: Location of GeoGrid.

Sector Model: this was a 500x500m grid that was extracted from the GeoGrid (Figure 5.16). So, the scenarios and properties within this grid are the same as the ones populated into the GeoGrid using the well control. The centre of the Sector Model is located approximately 3.2km to the south of Harvey-1 and 2.3km to the north-northwest of Harvey-3. This Sector Model grid was then exported at various vertical scales (1, 2 & 4m layers) with the properties from the various scenarios built. Details of the scenarios and upscaling results are available in the report by Lim, D., - DMP/2016/5.

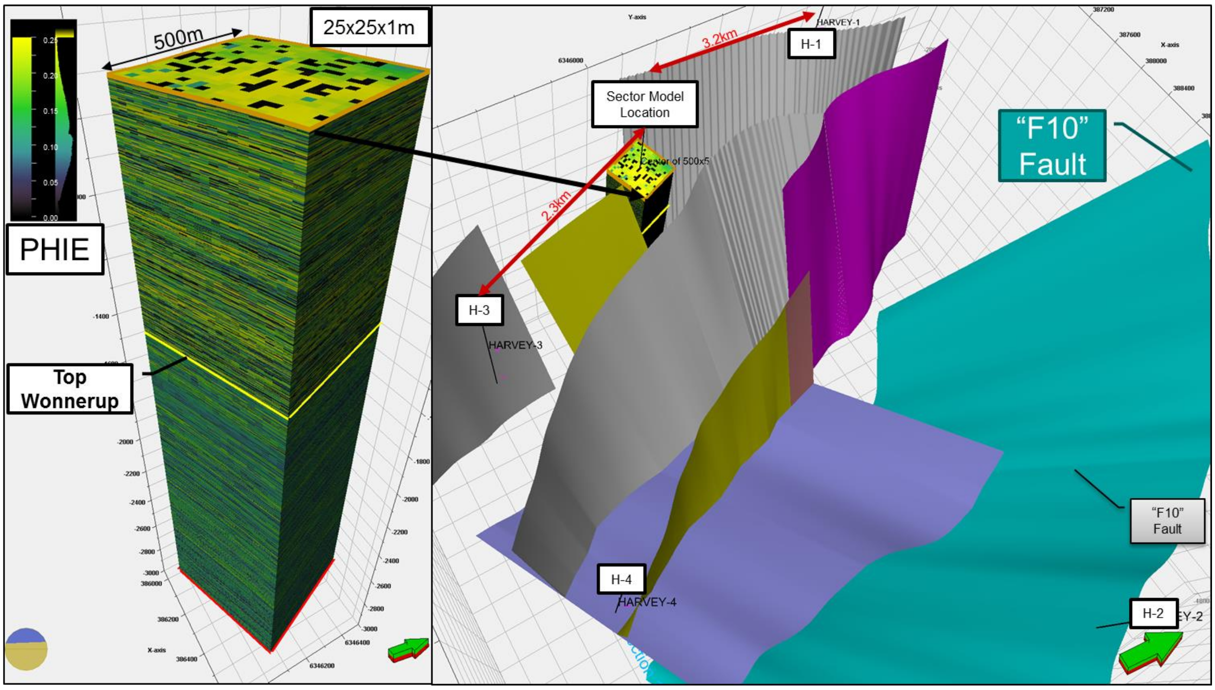

Figure 5.16: Location of Sector Model.

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 (Figure 5.14). This large model was built in order to monitor the extent of the plume movement. The plan was to inject into wells located on the Eastern edge of the model (west of the "F10" fault) and it was expected that the plume would migrate both vertically and updip towards the West. The distance of the migration to the West was unknown, so the model was built to cover the entire area up to the major North-South orientated fault called the "Western" fault which is 12.7km from East to West. 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. Details of the scenarios and upscaling results are available in the report by Lim, D., - DMP/2016/5.

5.2.5 Facies modelling

The facies used in the modelling process was based on the core facies but simplified into 3 main facies groups: High and Low Energy Fluvial and Paleosols with some Overbank facies in the Yalgorup (Figure 5.17).

The reference case facies model was built by populating the high energy channels and paleosol objects into the background which is the low energy facies (Figure 5.18). This enabled preferential flow in the high perm facies and creates local barriers or baffles with the paleosol objects. The facies were populated using estimated horizontal variograms due to the insufficient number of wells to generate meaningful values. There was also vertical proportion applied bases on the well data in order to ensure the packages of paleosols were replicated as seen in the wells (Figure 5.19).

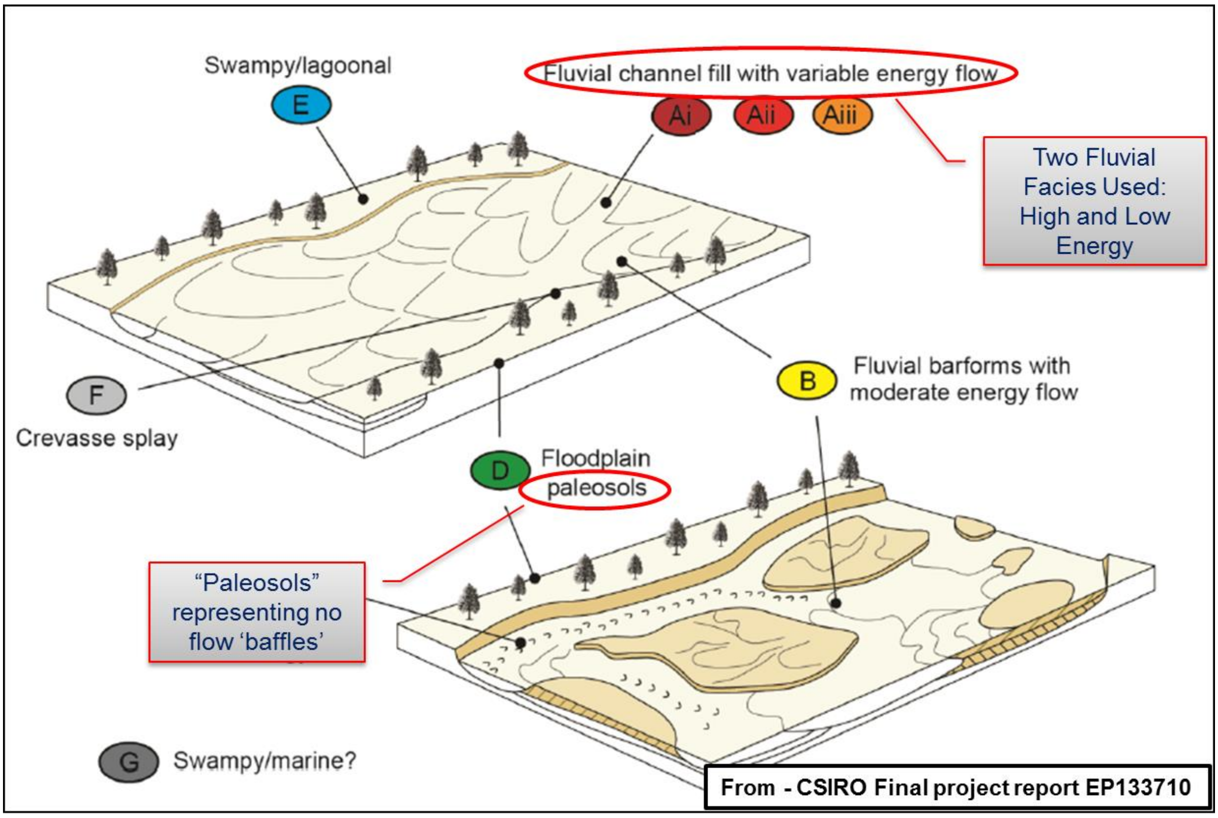

Figure 5.17: Simplified Facies types used in Model

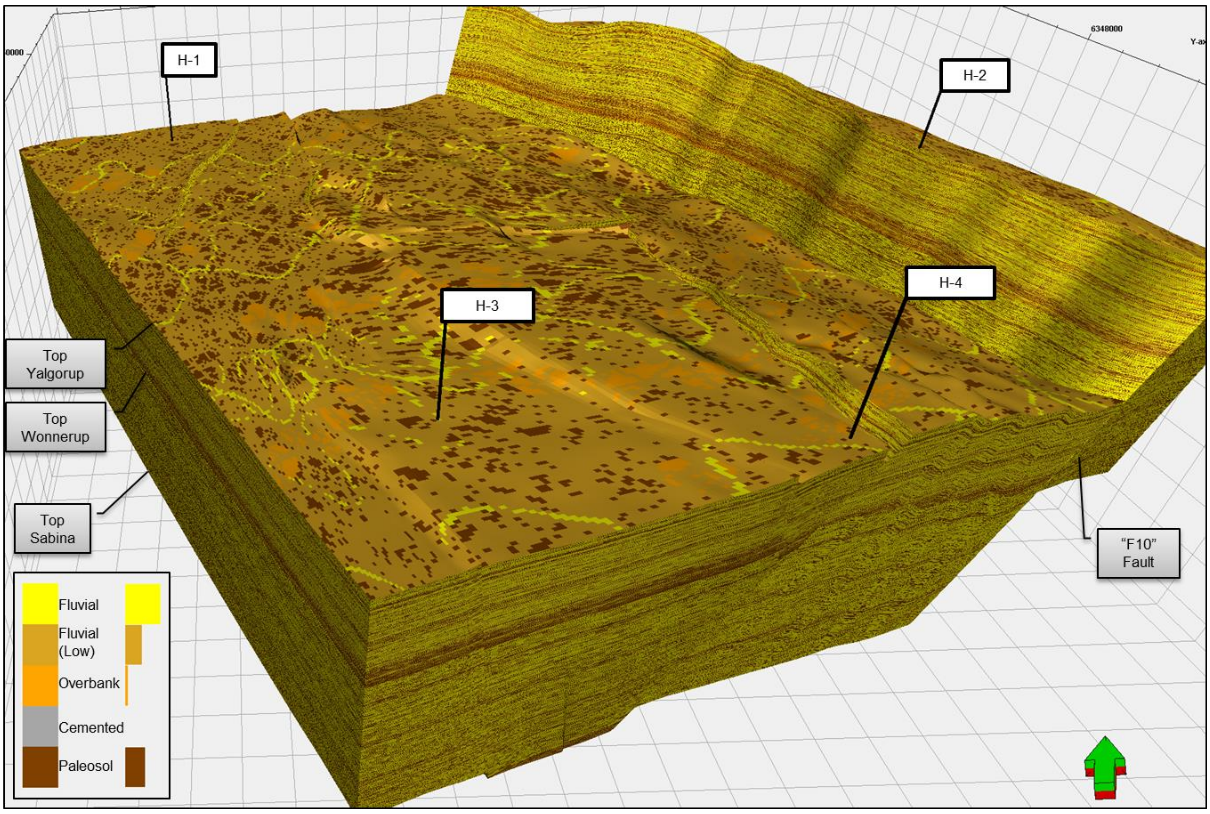

Figure 5.18: Facies Model

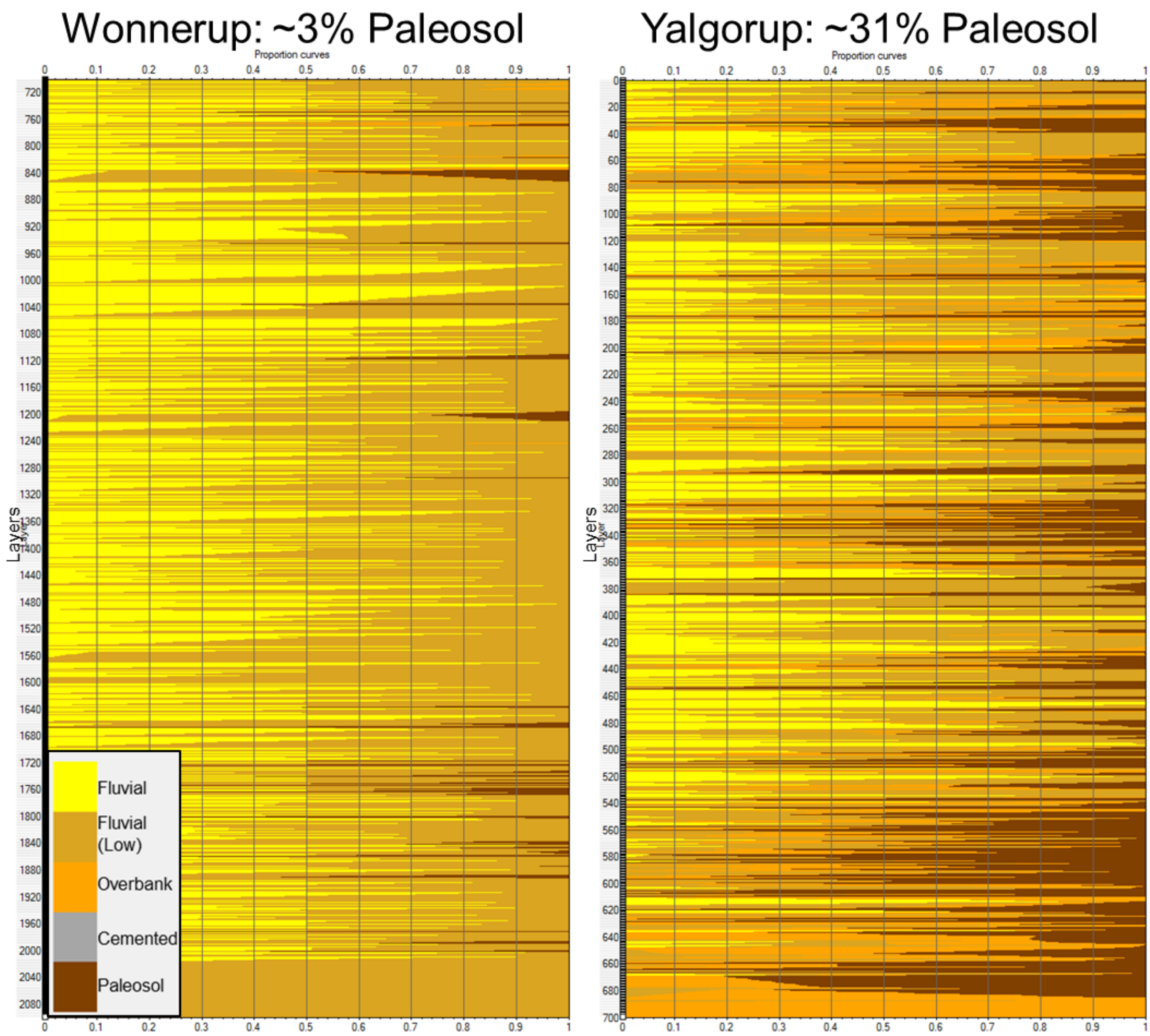

Figure 5.19: Vertical Proportions for Facies

An alternate facies model was built using the seismic response as a guide or trend. The seismic response in the Wonnerup for the majority of the study area is bland and devoid of reflectors. Harvey-1 drilled through this entire section and encountered a massive sandstone with a very small amount of thin paleosol beds. This lithology supports the seismic response in the area (Figure 5.20).

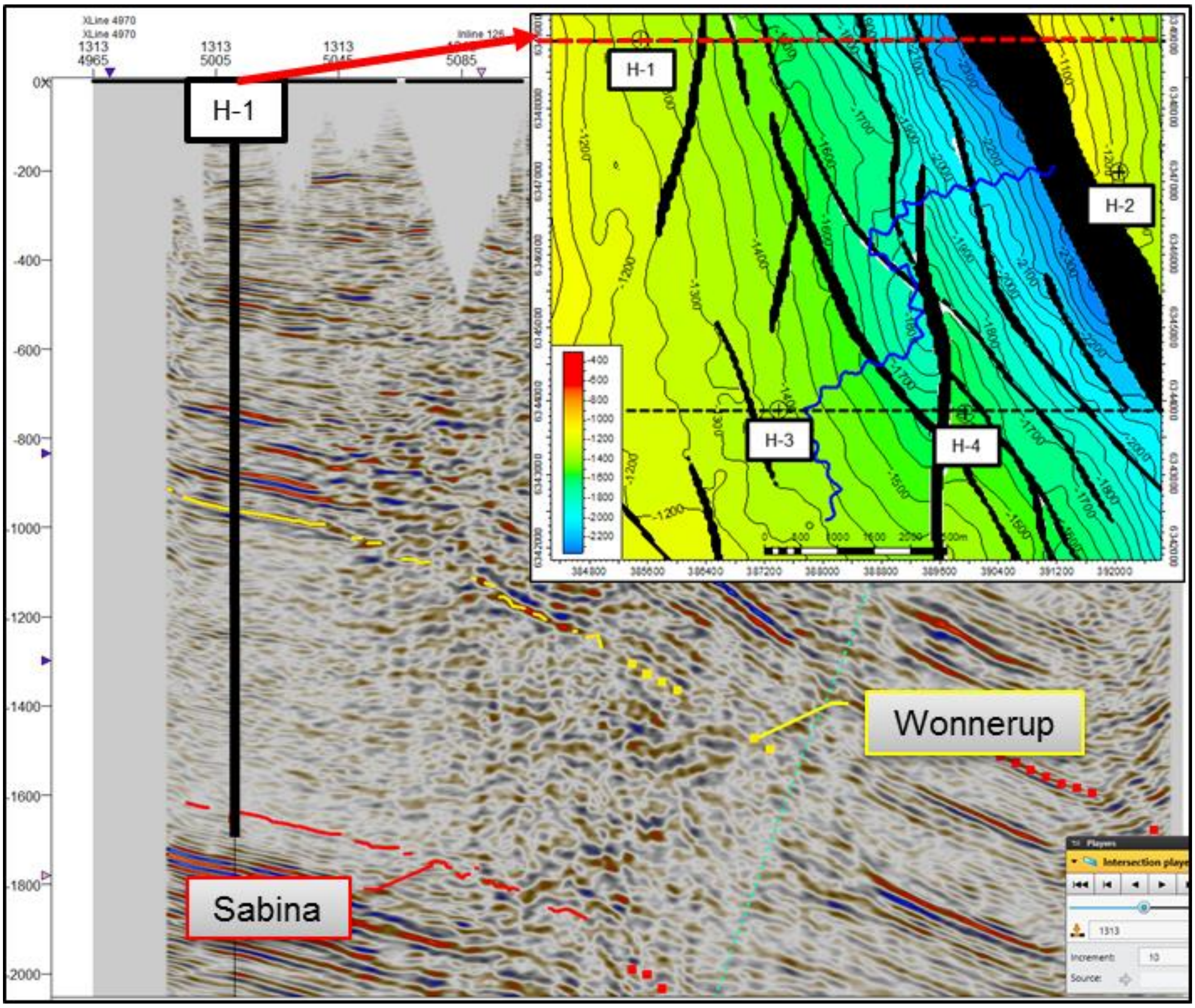

Figure 5.20: Seismic line through H-1 showing bland seismic character

However, further to the South East (below the Harvey-4 well) the seismic response changes and more seismic character is observed in the Wonnerup section. This is interpreted to represent an area with more paleosol development. Therefore, the area with a higher concentration of seismic reflectors has been defined and delineated with a trend map produced. This trend map was then used to preferential populate into the facies model with a higher percentage of paleosol objects.

This is considered to be a more deterministic case with interpretation that the change in seismic character represents an area of greater paleosol development. However, there is no well control in this interval to confirm the interpretation. A recommendation would be to expand on the seismic attribute analysis in order to confirm this interpretation and to better delineate the extent of the paleosol deposition both in aerially and vertically (at least to be able to locate the paleosol packages.

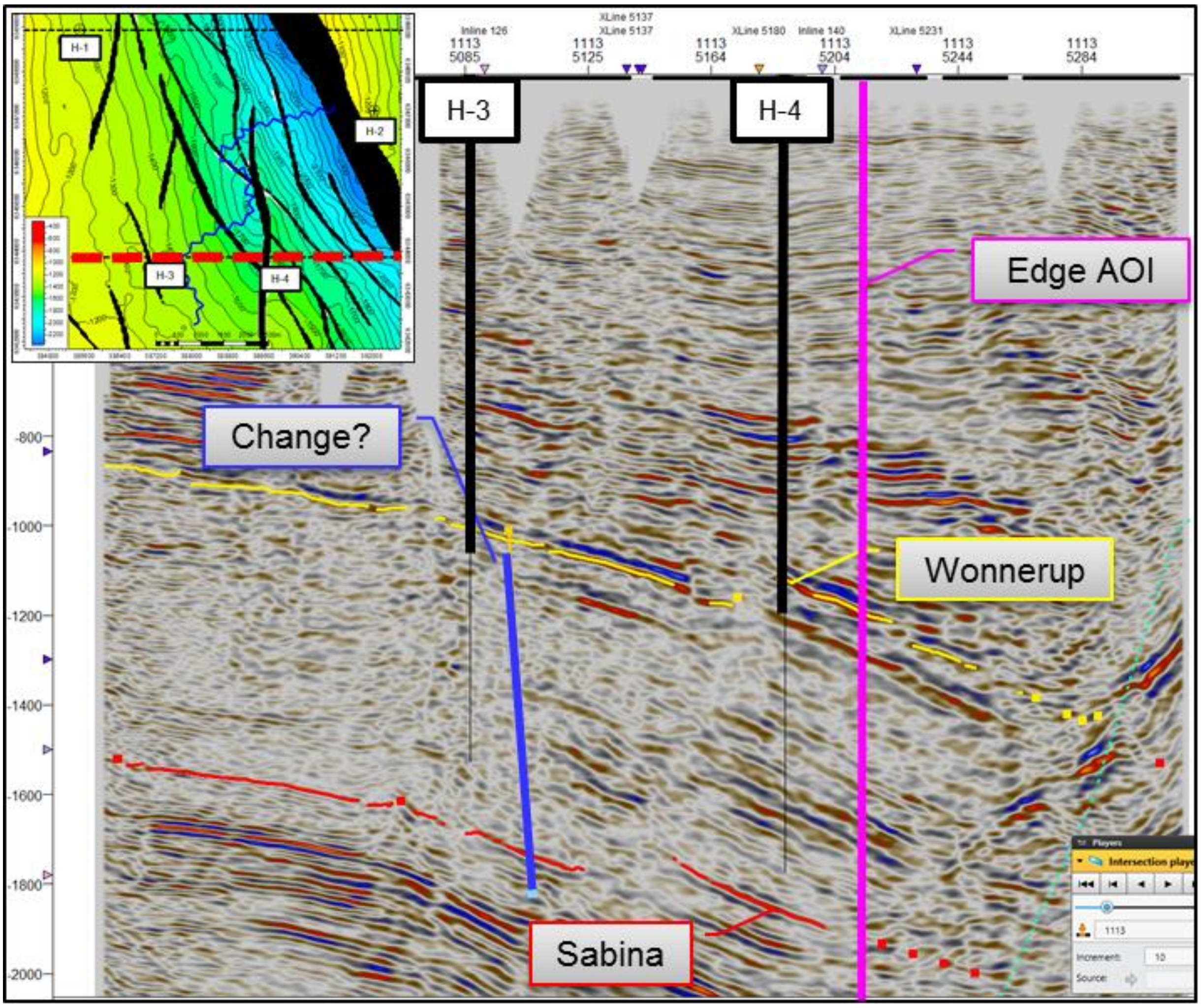

Figure 5.21: Seismic line through H-3 & H-4 showing change in seismic character

5.2.6 Petrophysical modelling

In data analysis the logs were conditioned to the facies described in the previous section. Each portion of the facies curve as per corresponding facies was analysed and a best fit curve to describe the distribution assigned.

Porosity logs were scaled up into the 3D grid using arithmetic averaging. Some manual manipulation of the porosity distributions for each facies was undertaken using Data Analysis in Petrel. Porosity was then modelled across the grid using Sequential Gaussian Simulation algorithm conditioned to the property with an additional vertical trend applied (porosity depth trend shown in Figure 5.22). There are insufficient number of wells to generate meaningful sample horizontal variograms directly from the input data. Therefore, estimated anisotrophic variograms were used to distribute porosity.

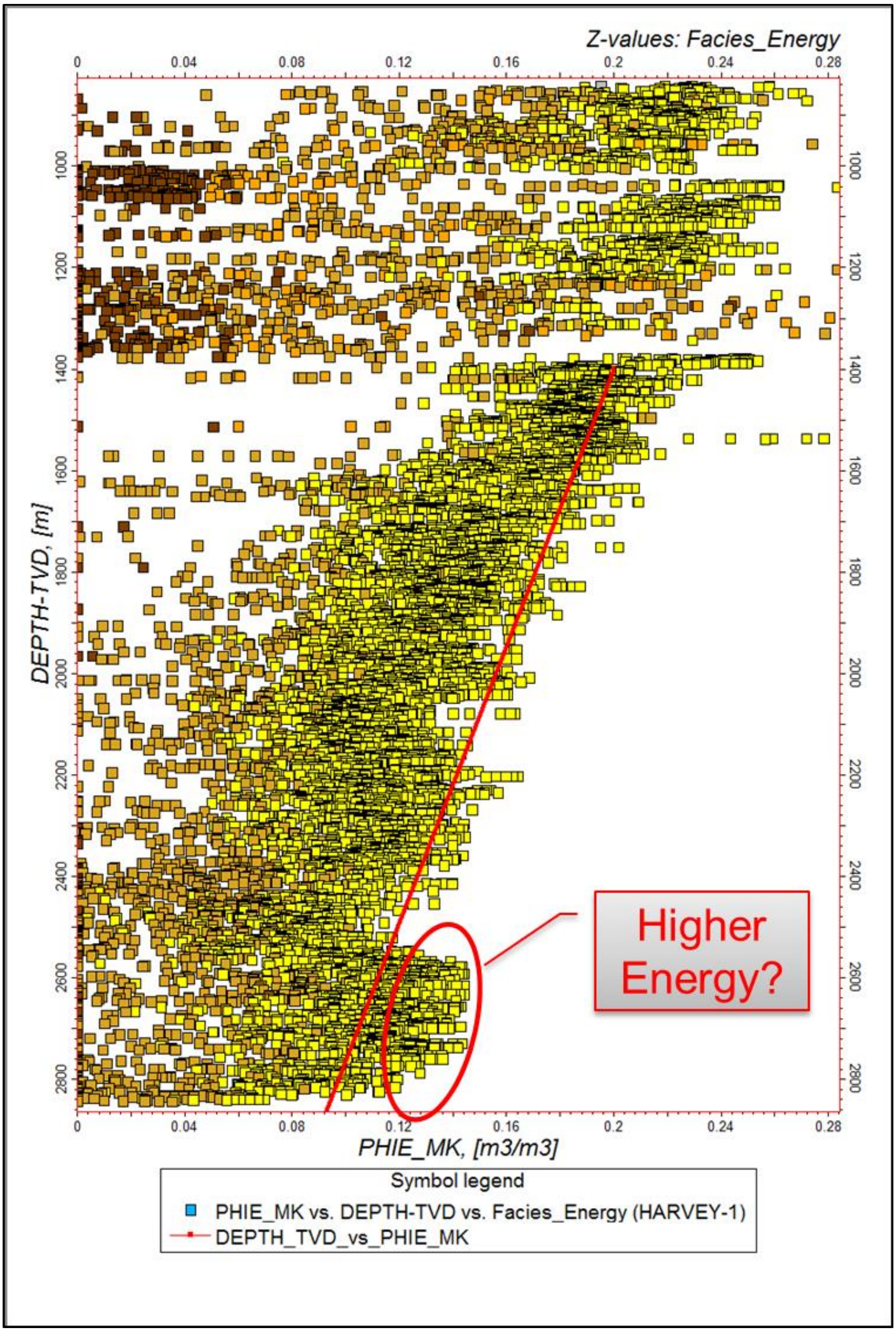

Figure 5.22: Porosity Depth Trend.

The interval from 2600 to 2800m in Harvey-1 was noted to have a package of higher porosity values (Figure 5.22). This feature was also noticed in an offset well outside of the Harvey study area and maybe a zone where higher energy deposition may have occurred. This may need further investigation in follow up studies if this interval is targeted for injection.

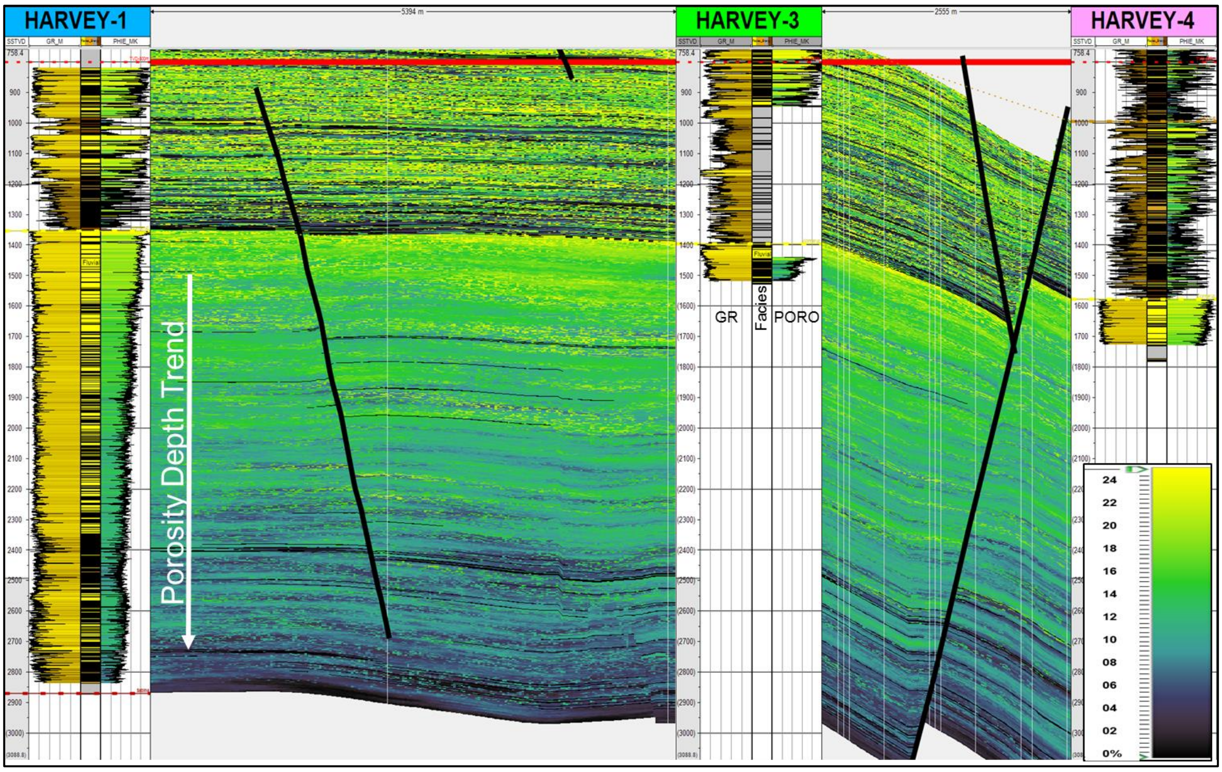

Figure 5.23: Well Section showing porosity distribution.

Permeability curves were generated by using the transform per facies created using the Geo2Flow software (Figure 5.24 to Figure 5.26). Subsequently each permeability curve was sampled into the grid via upscaling using geometric averaging as the sampling methodology. Some manual manipulation of the permeability distributions based on facies classification was performed in Data Analysis in Petrel.

Logarithmic transformations were tested and applied to the data distributions. Permeability was then modelled using Sequential Gaussian Simulation conditioned to the facies model with collocated co-kriging to porosity as the secondary variable. The permeability modelling used identical variograms to those used for porosity modelling.

The Low/Med Energy Fluvial facies may require further evaluation with a suggestion that this facies could be divided into 2 or possibly 3 facies.

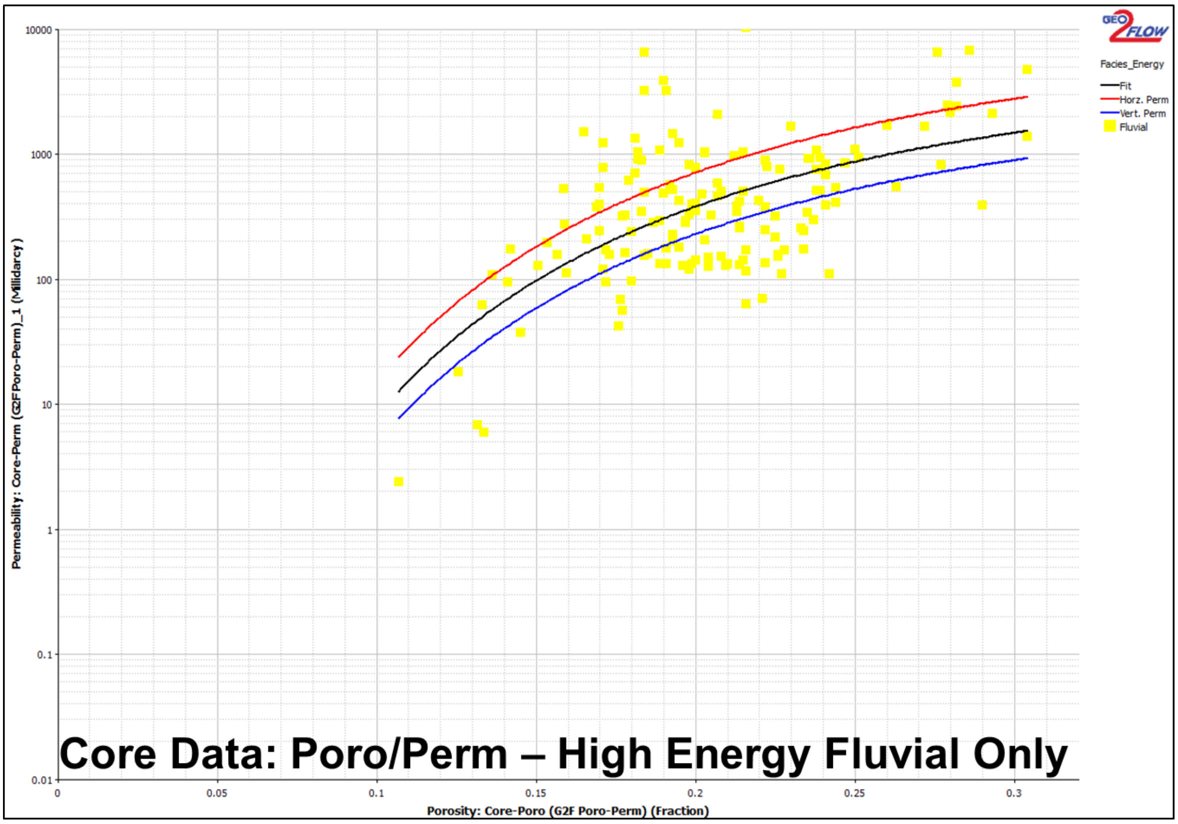

Figure 5.24: Porosity/Permeability for High Energy Fluvial

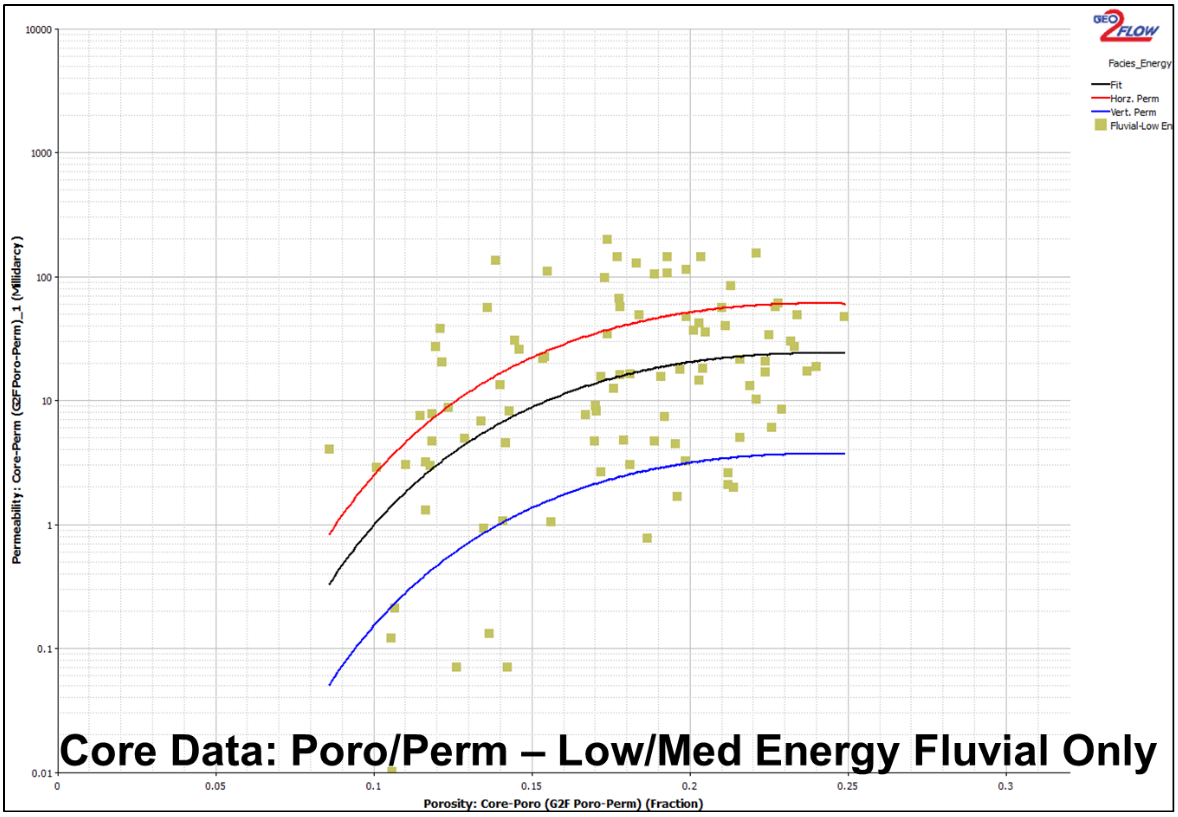

Figure 5.25: Porosity/Permeability for Low/Med Energy Fluvial

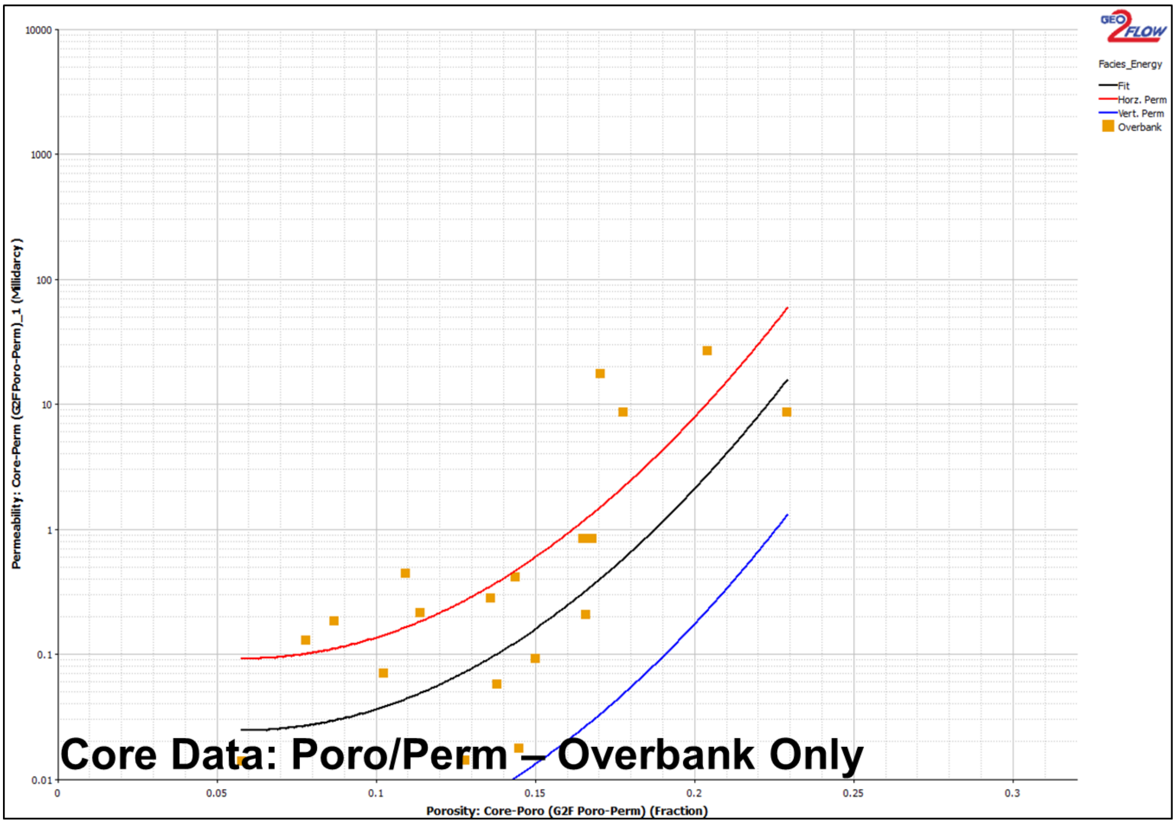

Figure 5.26: Porosity/Permeability for Overbank

The alternate "Seismic Trend" facies model was also populated with porosity (Figure 5.27) and permeability (Figure 5.28) and exported for simulation. The results are discussed in Lim, D., 2016 – DMP/2016/5.

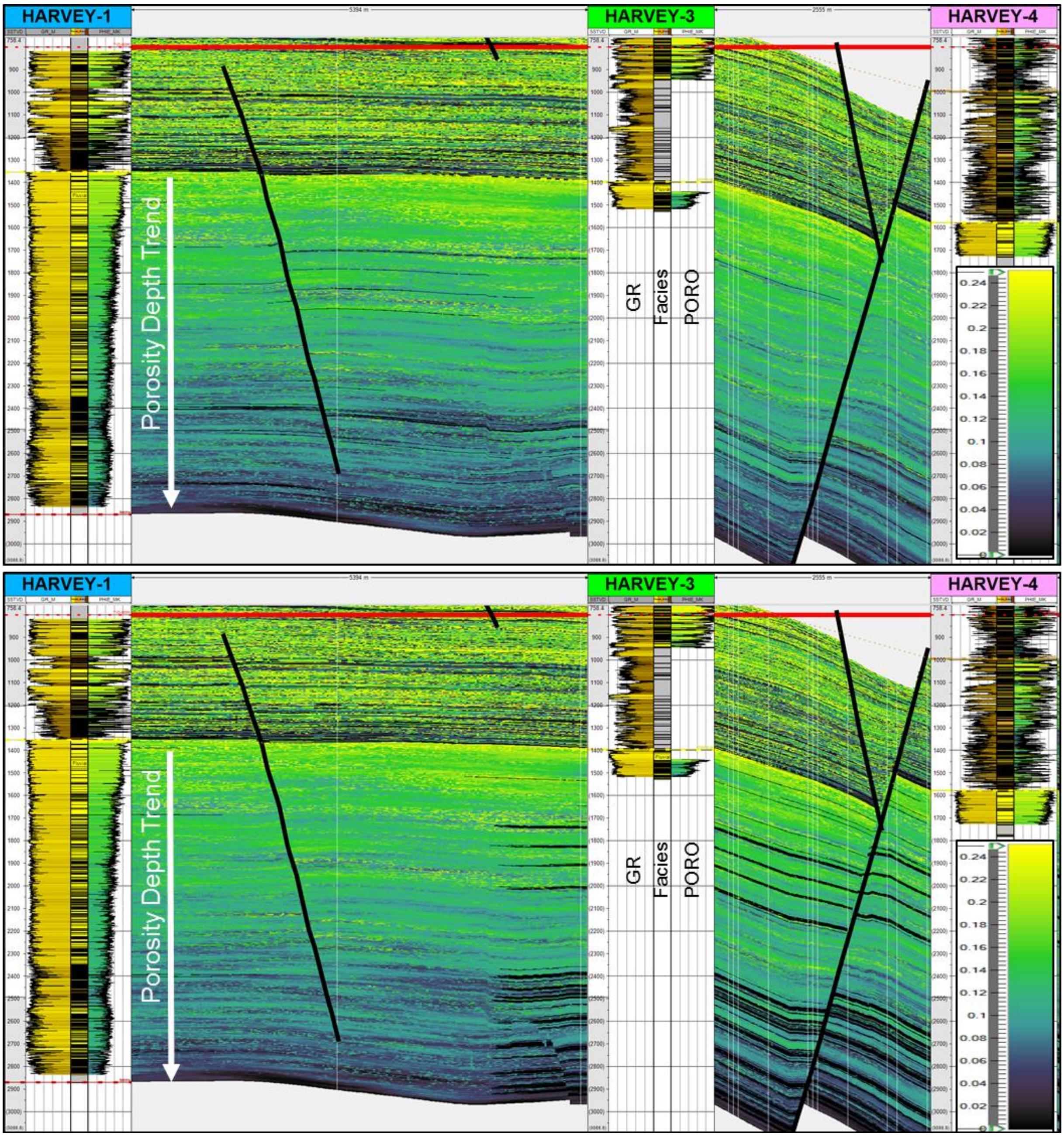

Figure 5.27: Porosity comparison between "Reference Case" and "Seismic Trend" (note the low porosity layers in the lower section between H-3 & H-4).

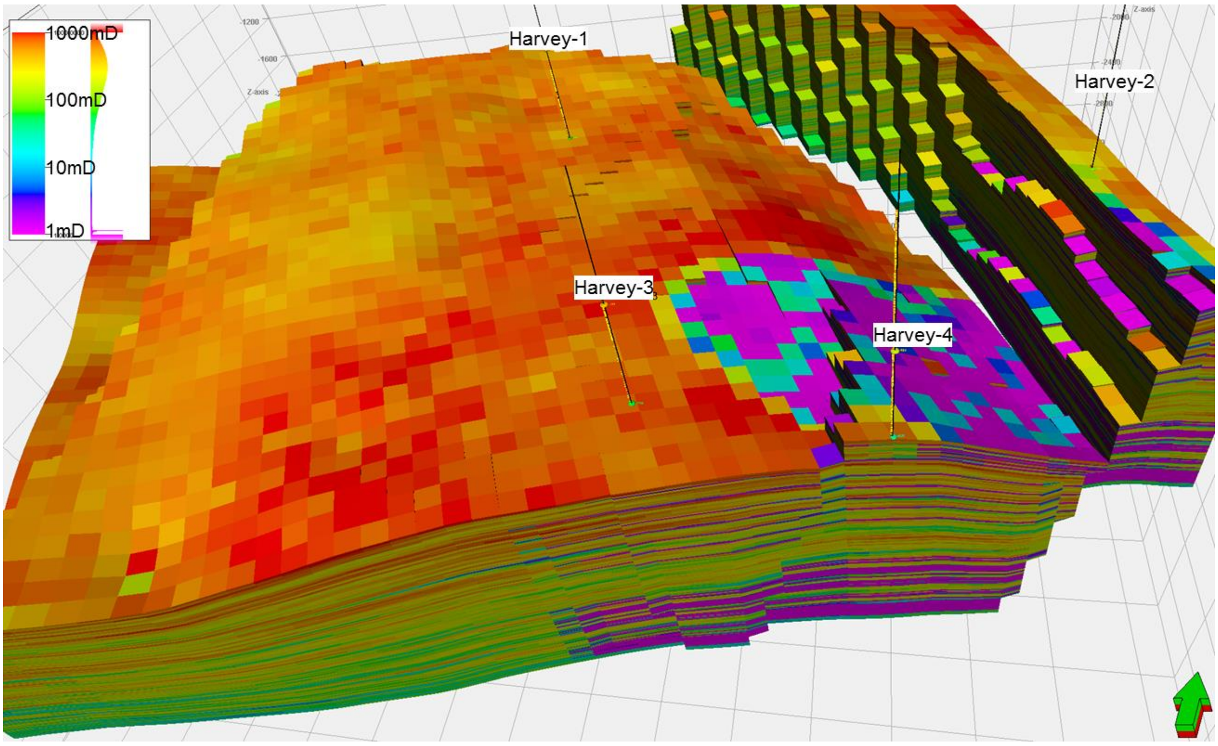

Figure 5.28: Permeability distribution using "Seismic Trend" Facies Model

5.2.7 Fault Seal Analysis

Petrel's "Fault Seal Analysis" workflow (Figure 5.29) was followed in order to produce a transmissibility property for the faults in the model. This involved creating a VShale property which was populated in the grid by using Sequential Gaussian Simulation conditioned to the facies model with collocated co-kriging to porosity as the secondary variable. The VShale modelling used identical variograms to those used for porosity modelling.

The VShale property was used to determine the clay content on the faults based on the fault throws. Fault permeabilities and fault thickness were then calculated. These properties were then used as the inputs to compute the transmissibility multipliers for the faults.

As can be seen in the histogram (Figure 5.29), the transmissibility multipliers were very high – almost 1. However, for the simulation study a multiplier of 0.1 was used to test the sensitivity of fault seal on the plume movement.

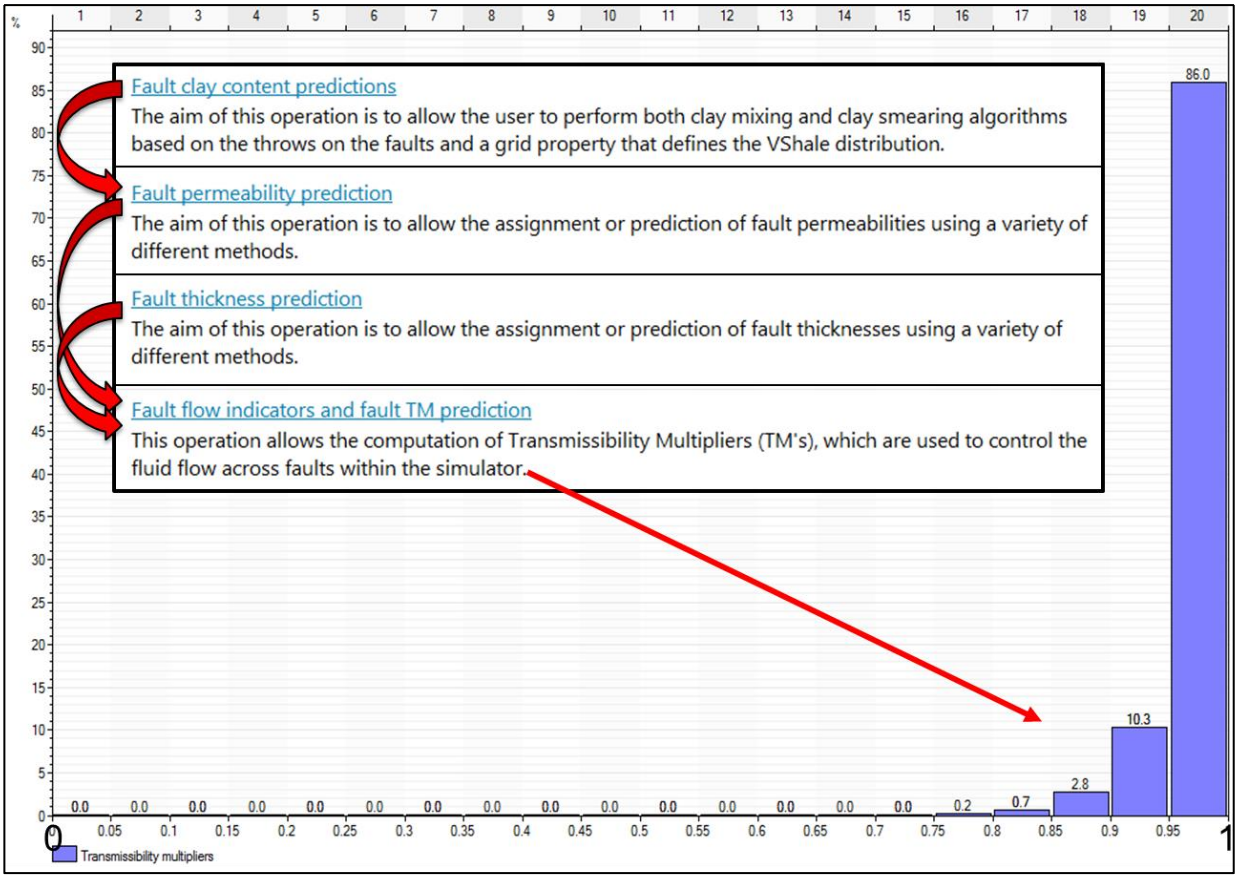

Figure 5.29: Fault Seal Analysis Workflow and Resultant Transmissibility Multipliers

5.2.8 Sensitivity and uncertainty analysis

A number of subsurface uncertainties are discussed in this section and the impact of these uncertainty have been assessed during the model building process.

The key uncertainties identified of the static modelling are:

- How extensive are the individual paleosol geobodies?
- Percentage of sand versus paleosol?
- Permeability range. The mean permeability for the Wonnerup based on the log data is 200mD.
- Fault Seal Analysis was conducted, the results indicated very low chance of fault seal. However, a fault transmissibility of 0.1 was applied to access the impact of partially sealing faults.
- Kv/Kh will influence the flow of CO_2 in the reservoir. It is scale dependent, so care was taken during upscaling permeability, however, further sensitivity to varying Kv/Kh was also investigated during simulation.

- Impact of upscaling cells for simulation has been accessed.

The range of geological uncertainties investigated in the geomodelling study are summarised in Table 2. Geological models representing these ranges were incorporated into dynamic models investigating the movement of the CO_2 plume during injection of CO_2 and subsequent shut-in.

Table 2: Summary of ranges/scenarios for injection and/or plume migration.

ITEM	RANGE	COMMENTS
Paleosol Geobody Size	500,1500 & 3500m	
Percentage of sand in Wonnerup	50-99%	
Permeability range in the Wonnerup	71 to 372mD Log Mean = 200mD	Average permeability for the Wonnerup.
Fault Seal	0.1 & 1	Open/Closed system
Fault Permeability	x10	Multiply vertical perm near faults by 10
Kv/Kh in the Wonnerup	Mean = 0.3 to >1	3 Methods: Arithmetic & Harmonic averaging in addition to PERMZ=PERMX.
Deterministic Case	Additional paleosols concentrated in the SE section of the model.	Deterministic case used the seismic based trend with higher concentration of paleosols in the Wonnerup.

6. CONCLUSION AND RECOMMENDATIONS

The Harvey structure, onshore Perth Basin, is a N-S elongated fault bounded anticline. The study area for this project within this structure covers 332 km^2 and is located approximately 13km northwest of the town of Harvey south of Perth. The two static models built for this study, cover areas of approximately 54 km^2 and 117 km^2.

The static model study provided a reasonable description of the sub-surface in the Harvey area using the interpreted horizon and faults from seismic. This project also included:

1) Log & Petrophysical Property Review.
   - The following evaluations were undertaken:
     - Detailed petrophysics studies for the four available wells. With integration of core data;
     - Geomechanical rock property analyses and considered the rock properties, the stress field and fault orientations. Results were used to define injection pressure constraints for the dynamic models;
     - Discretisation of individual flow units;
     - Well correlation panels were prepared for facies, porosity and permeability.
2) Static modelling – structure, facies and properties
   - The static model construction resulted in various realisations guided by known uncertainty (paleosol continuity, fault definition, reservoir connectivity and reservoir quality).

Some of the recommendations for future possible work are:

A. Building on the seismic attribute analysis conducted in this study. There may be a requirement to either run an inversion on the current seismic volumes and/or reprocess the seismic to better image the reservoir. The objective would be to ascertain the necessity to drill a deep Harvey-5 well that may contradict or support the reservoir properties intersected at Harvey-1. This is a very large area with only one control point (H-1) defining the properties used for this injectivity and plume migration study.

B. There was some evidence during the simulation study that indicated the "High Energy Fluvial" facies may influence the extent of the plume migration by preferentially flowing in these higher permeability streaks. The current study only observed a small affect but if a higher permeability contrast was invoked then a larger effect may be evident. A facies analysis/interpretation of the image logs may highlight that the "Low/Med Energy Fluvial" facies could be further divided thus the potential for a greater contrast may exist.

C. The interval from 2600 to 2800m in Harvey-1 was noted to have a package of higher porosity values (Figure 5.22). This feature was also noticed in an offset well outside of the Harvey study area and maybe a zone where higher energy deposition may have occurred. This may need further investigation in follow up studies if this interval is targeted for injection.

D. Further work could also be carried out to calculate the possible fault seal in the area. This may involve a more detailed geomechanical study.

E. Perhaps this study could be expanded to determine if interference type tests could be designed to test the vertical permeability and/or communication across faults.

F. The fractures identified during the image log interpretation should be reviewed further and if required, they should be incorporated in the model as either potential conduits for flow or baffles to flow.

G. The identification of the critical injection-induced pressures are not well constrained and a more refined assessment would be required to more robustly identify the critical injection-induced pressure for reactivating faults and/or natural fractures.

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