GEOLOGY UPDATE AND INTEGRATION

A Report by ODIN Reservoir Consultants

DMIRS/2018/4

December 2017

Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

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Declaration

ODIN Reservoir Consultants was commissioned in 2017 to undertake to provide a reservoir modelling study for the South West Hub CO_2 Sequestration Project on behalf of The Department of Mines, Industry Regulation and Safety, (DMIRS)

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 DMIRS 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 in the industry covering a wide range of environments. Geoff has built geological models and provided geological support to evaluate and generate prospects for a drilling campaign. He has also co-ordinated and completed an FDP (Field Development Plan), including building static models and providing input for development well locations. In addition, he has been responsible for co-ordinating the G&G component of several development projects, which also involved evaluating upside potential near the fields and quality control of Fields, Prospects and Leads.*

1. EXECUTIVE SUMMARY

The Harvey structure, onshore southern Perth Basin, is a north-south elongated fault bounded anticline. The study area for this project within this structure covers 332km^2 and is located approximately 13km northwest of the town of Harvey south of Perth.

ODIN Reservoir Consultants was commissioned by the Department of Mines, Industry Regulation and Safety (DMIRS) to provide a multi-disciplinary group with sub-surface skill sets to:

i. provide modelling and interpretation support to update the existing models by considering additional data such as infill seismic, new core analysis etc. to reduce the uncertainties identified in the Uncertainty Management Plan (UMP) and test the results against defined criteria; and

ii. update the current UMP and provide uncertainty reduction options through new data acquisition.

Several “work-streams” have been defined as the work scope for this phase of the project:

- Work-stream 1: Advanced Seismic Processing (Provided by Curtin University)
- Work-stream 2: Advanced Seismic Interpretation
- Work-stream 3: Log Analysis and integration with Core Data
- Work-stream 4: Geomechanics Update and Integration
- Work-stream 5: Geology Update and Integration
- Work-stream 6: Engineering Update and Integration
- Work-stream 7: Static Modelling
- Work-stream 8: Dynamic Modelling
- Work-stream 9: UMP update, Injectivity and Capacity Expectation Curves

Work-streams 7-9 will proceed upon completion of Phase 1 (Work-streams 1 to 6) which has resulted in building a table of various reservoir and fluid parameters resulting in a probabilistic evaluation of injection rates and capacities and POS computations for injectivity and containment using simulation models and analytical approaches.

The modelling and interpretation work scope builds on previous work and is aimed at integrating all data. Once this integration step has been completed, then an assessment of the Lesueur Formation can be undertaken to determine whether:

- Modelling with a reasonable range of scenarios shows that the required injection rates can be achieved; and
- Modelling of a reasonable range of scenarios and geological data support the residual and dissolution-trapping concept for the SW Hub site.

2. INTRODUCTION

The Harvey structure (Figure 2.1) in the southern Perth Basin, which covers an approximate area of 332km^2, constitutes a potential storage area for CO_2 sequestration. The sandstone rich Wonnerup Member in the Lesueur Formation forms the target injection reservoir, with the containment (based on previous studies) within the same sands of the Wonnerup Member. However, the overlying Yalgorup member, which is represented by the paleosol rich, will be assessed in greater detail to reveal its containment potential should the plume migrate vertically into this member.

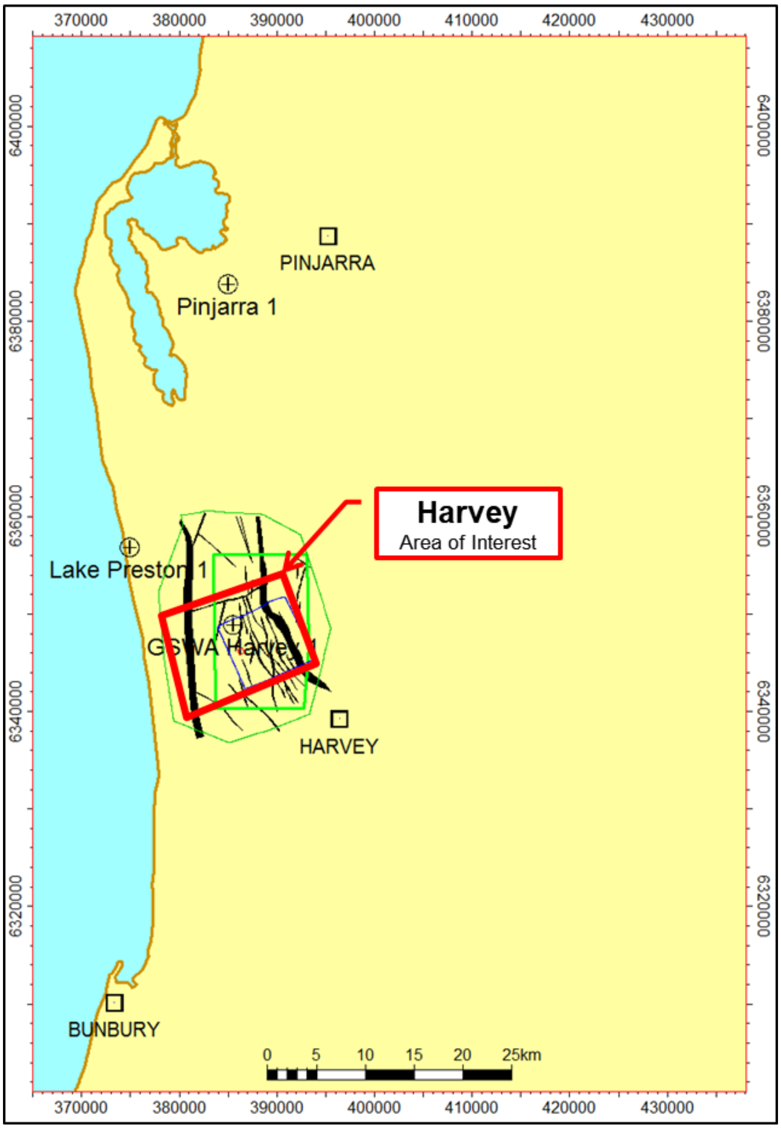


Figure 2.1: Harvey Location Map showing the area of interest

During the first phase of this project a geological report including the general structural geology and sedimentology of the southern Perth basin and the deposition of the Lesueur formation were carried out. Descriptions of the input data their interpretation and use in the building of the 3D static model were also supplied. This report integrates the well and seismic data/interpretations with the knowledge gained from studying analogues in order to define the 3D Geological Model and the distribution of facies/properties (see Figure 2.2).

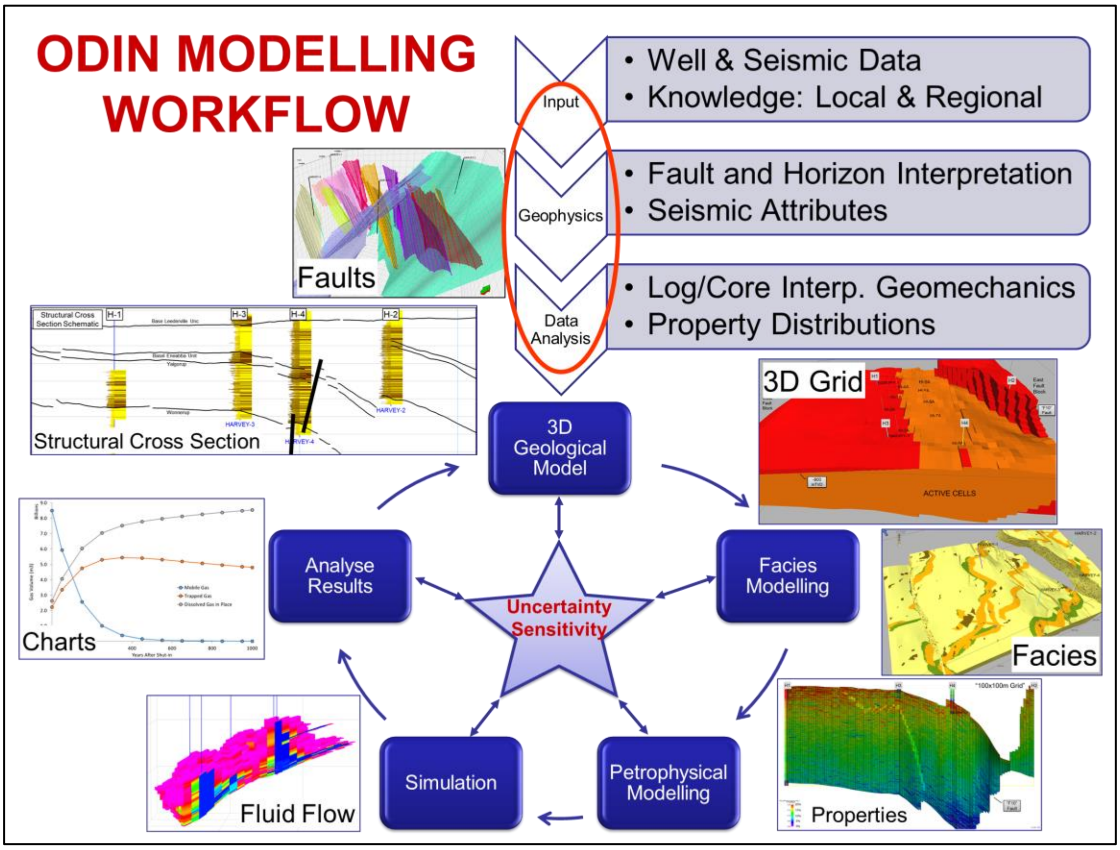


Figure 2.2: ODIN Modelling Workflow

The Lesueur Formation was developed in the Perth Basin during the Late Triassic (Figure 2.3 and Figure 2.5). At the time, the basin was undergoing a phase of thermal subsidence because of an initial stage of rifting in the Gondwana supercontinent. This rifting event took place from the late Permian to the Lower Cretaceous when the final break-up of the continent occurred, and the drifting phase of India/Australia began (Figure 2.3)

During the Late Triassic, the global climate was generally warm; there was no ice at either North or South Poles and warm temperate condition extended to the poles. The Perth Basin region was under a warm temperate regime (Figure 2.4).

The Lesueur formation was deposited in a braided fluvial environment. The paleogeography of the basin indicates an elongated shape roughly running in north-south 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 is likely to come from stable cratons and transitional continents such as Yilgarn craton, Leeuwin complex or Albany-Fraser orogeny, or any combination of these three sources. The main sediment supply direction has been identified as a general West-East trend with a certain west-south-west east-north-east component.

Five main depositional facies spreading from channel fill sands to swampy over bank deposits have been defined. Paleosol//floodplain sediments represent both fluvial environments, braided and meandering, in the Wonnerup and Yalgorup respectively. The two lithostratigraphic members that comprise the Lesueur Formation, 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.

In general, the coarse channel fill sands in the Wonnerup Member are a good reservoir to contain the injected CO_2 and the more clay rich Yalgorup Member dominated by floodplain and paleosols deposits can act as a seal for the reservoir complex. The present analogue used for both fluvial systems in the Wonnerup and Yalgorup Members is the Brahmaputra braided river. This example constitutes a good guide to design the modelling parameters of the reservoir formation.

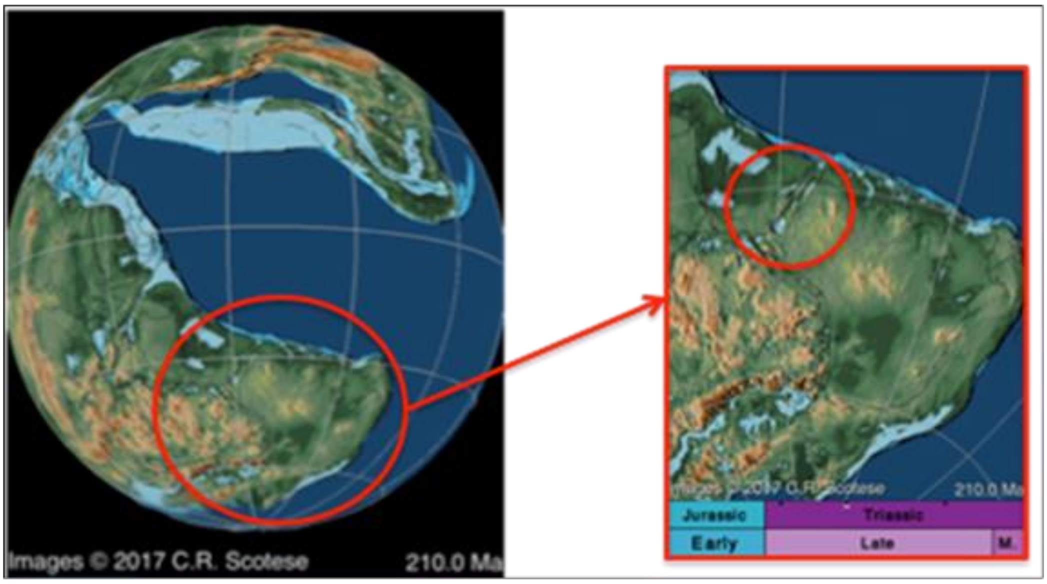


Figure 2.3: “Break-up" Event

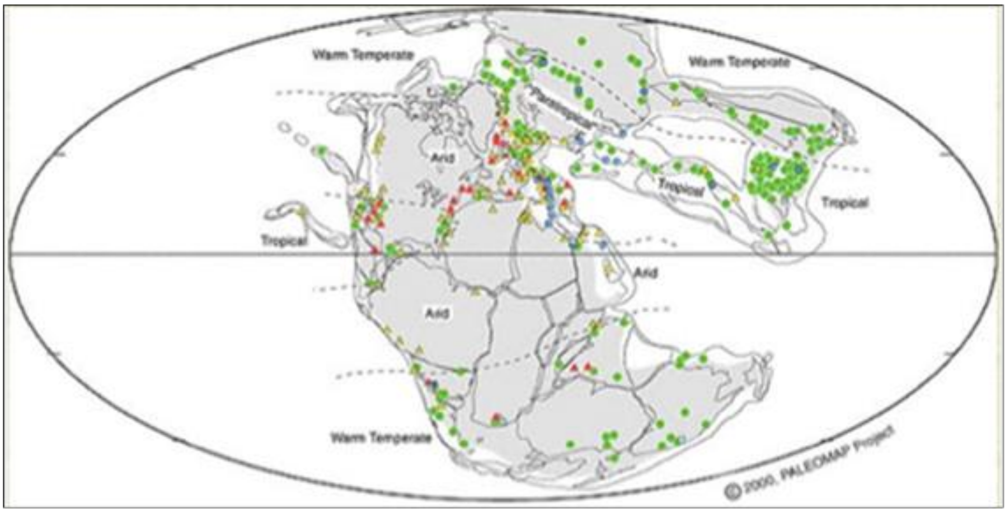


Figure 2.4: Late Triassic Climate (After Reference 3)

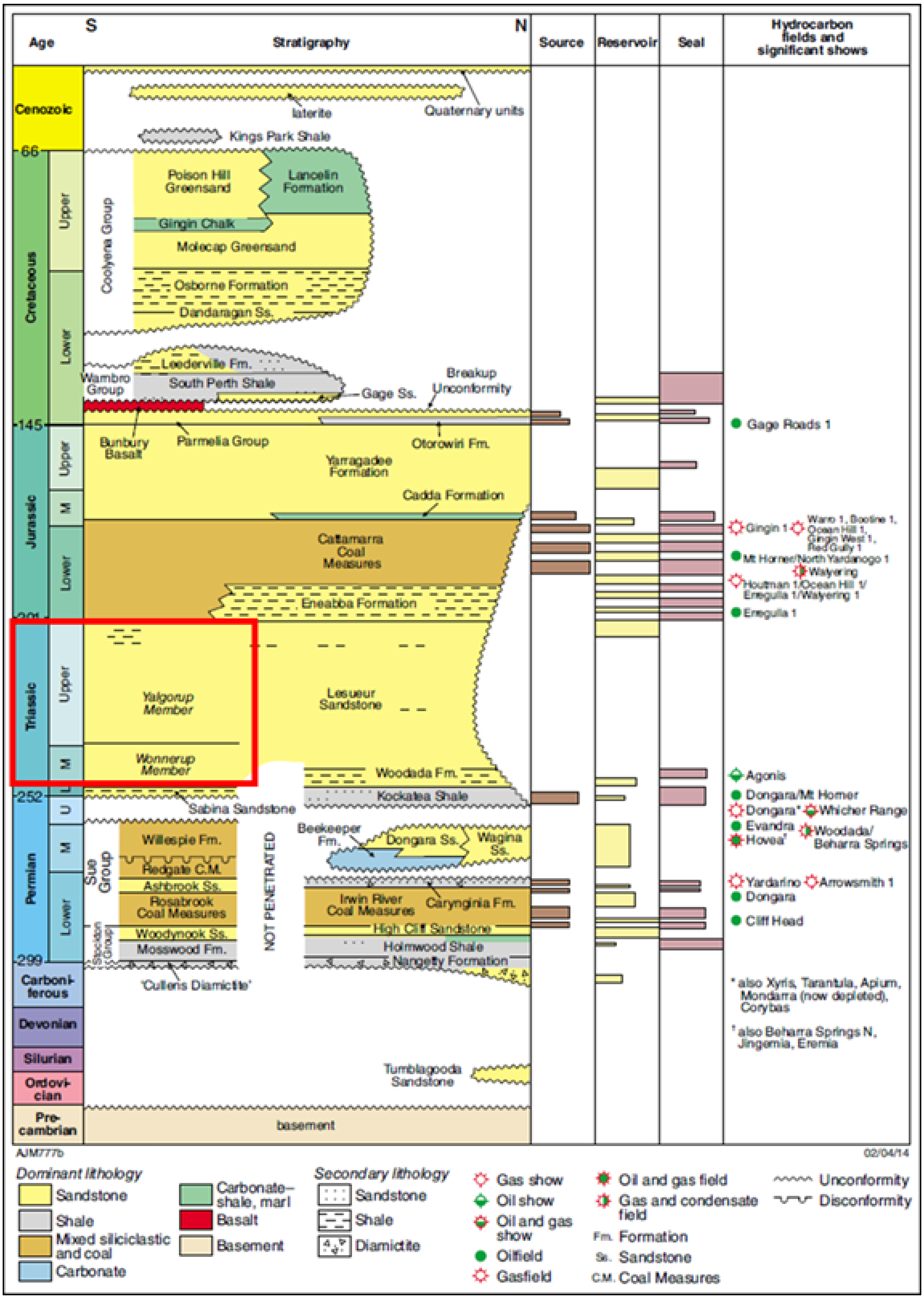


Figure 2.5 Stratigraphy of Perth Basin (Harvey Area within red box)

3. GEOLOGY UPDATE AND INTEGRATION

This part of the work has been built on the current knowledge of the Lesueur Formation to assist in updating the key uncertainty ranges for the Geological Modelling work to follow. The specific uncertainties identified will be documented within the modelling report.

The structural interpretation will be assessed and related to the tectonic setting with integration of the previous image log interpretation. An attempt to define the density of "sub-seismic" faults is also described in this section.

3.1 Structural Review

The scope of work defined for this section is to review the fault/tectonic setting and to integrate the fractures identified using the image logs.

The overall structural/geometric setting is a major north-north-west south-south-east trending fault to the east with a series of en-echelon sub-parallel faults in the downthrown segment of the main fault. This orientation of faulting conforms to the regional understanding of the structural framework and the image log interpretation of fractures at GSWA Harvey 1 (Figure 3.1) confirms this orientation. There are two sets of fractures interpreted in the image logs at DMP Harvey-4, which also aligns with the faults interpreted in that area (Figure 3.1).

The main fault (F10) shows a hinge or knee feature (Figure 3.1: red dashed line) towards the North of the mapped area and the contours to the west show a nose and embayment. This may represent the northern part of a transform zone (Figure 3.2) where a higher density of "accommodating" faults could be expected. Based on our discussions with DMIRS this possible transfer zone is likely and complies with the regional tectonic setting.

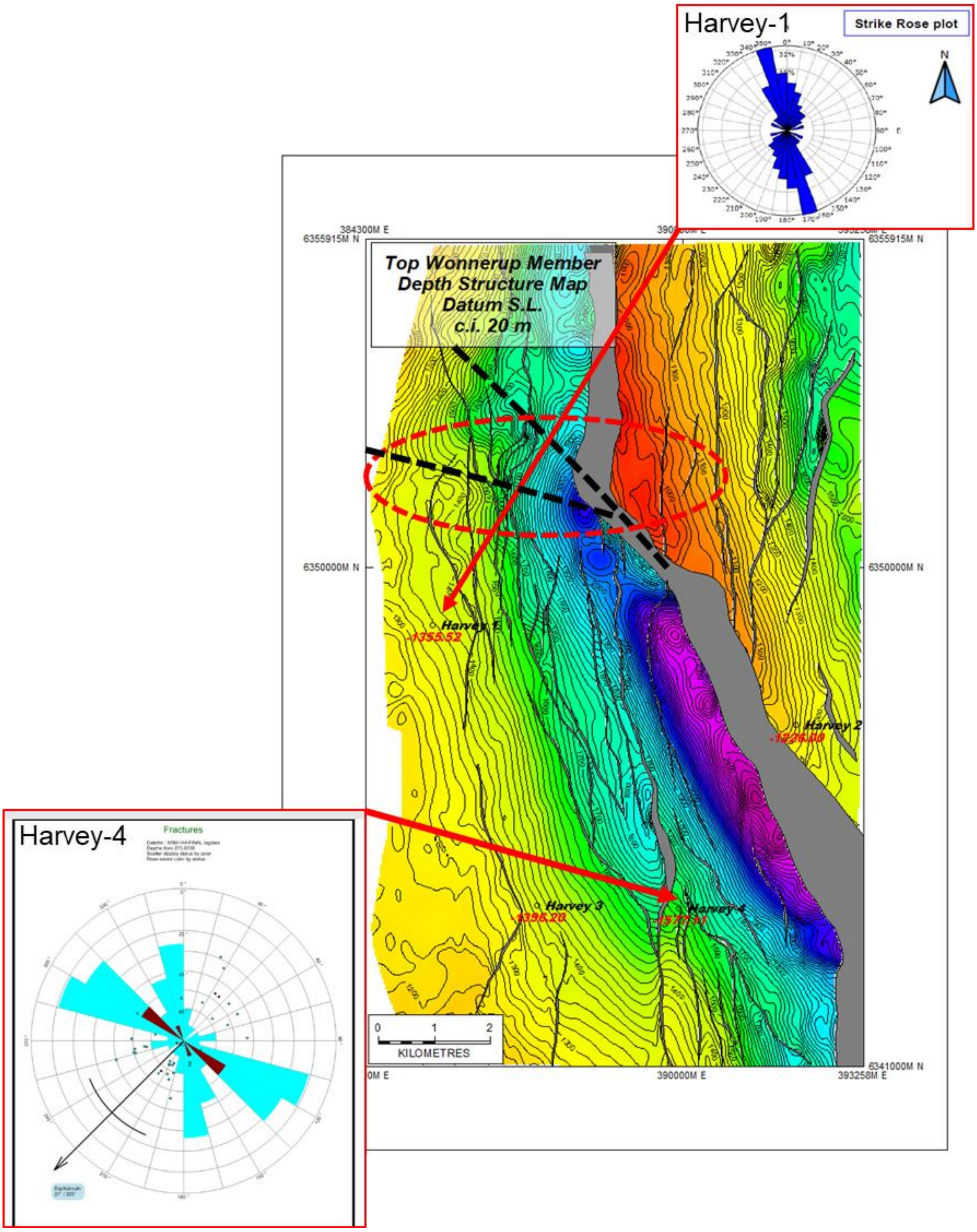


Figure 3.1: Fractures Interpreted from Image Logs Match the Faults Interpreted from Seismic.

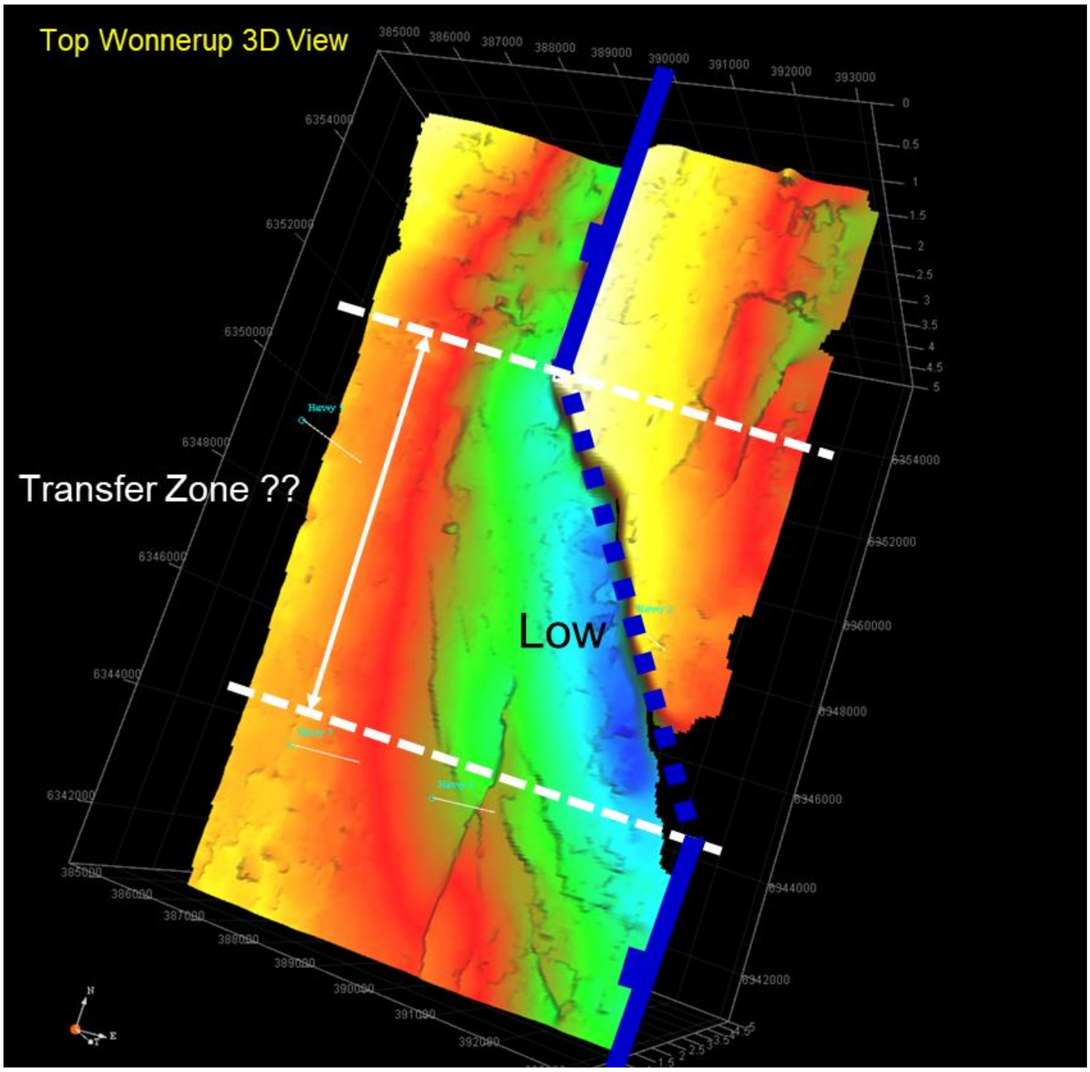


Figure 3.2: Top Wonnerup 3D View Showing Possible Transfer Zone

Although not interpreted, there is a possible northwest southeast or west-east element/lineament (black dotted lines on Figure 3.1). An east-west fault has been previously interpreted in this area. A possible barrier/baffle to the north should still be considered (i.e. limited pressure).

Figure 3.3, below, is a plot of fault throw versus fault length. The plot has four guidelines showing a 1:1 through to a 1:1000 ratio of throw to length. The average Fault Throw versus Length ratio is 0.035, which is similar to the expected average of 0.03 based on literature. This plot is useful to easily spot outliers to the trend; the interpretation of these outliers could then be revisited to confirm the validity of the fault length or the horizons.

The plotted fault length maybe too short as the fault extends beyond the mapped area or extends into a poor data quality area.

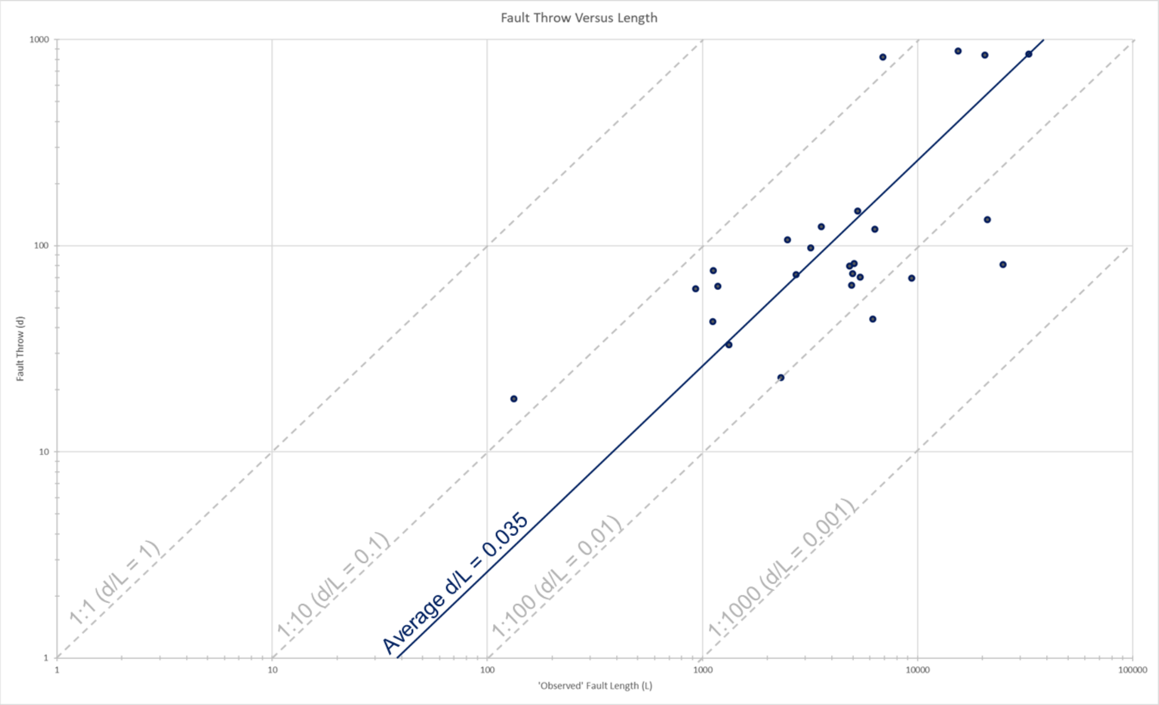


Figure 3.3: Fault Review - Throw versus Length

The expectation is that the interpreted faults within the sand dominated Wonnerup member are not sealing, however, they could create baffles to flow. Therefore, the concept of 'fault compartments' has been assessed and possible compartment sizes have been noted (Figure 3.4). The impact of these potential fault compartments have been modelled during the previous phase of dynamic modelling but given the significant change in fault interpretation the same sensitivity will be repeated.

Should there be an impact based on the modelling of fault compartments then the solution is to selectively place the injection wells in separate fault compartments to minimise the pressure build-up.

The reference case will be one large area with barriers to the east (F10 fault) and 11km to the west (Western fault interpreted on 2D lines) which is open to the north and south. A sensitivity of an east/west barrier to the north maybe considered but this had very little impact when simulated during the last phase of work.

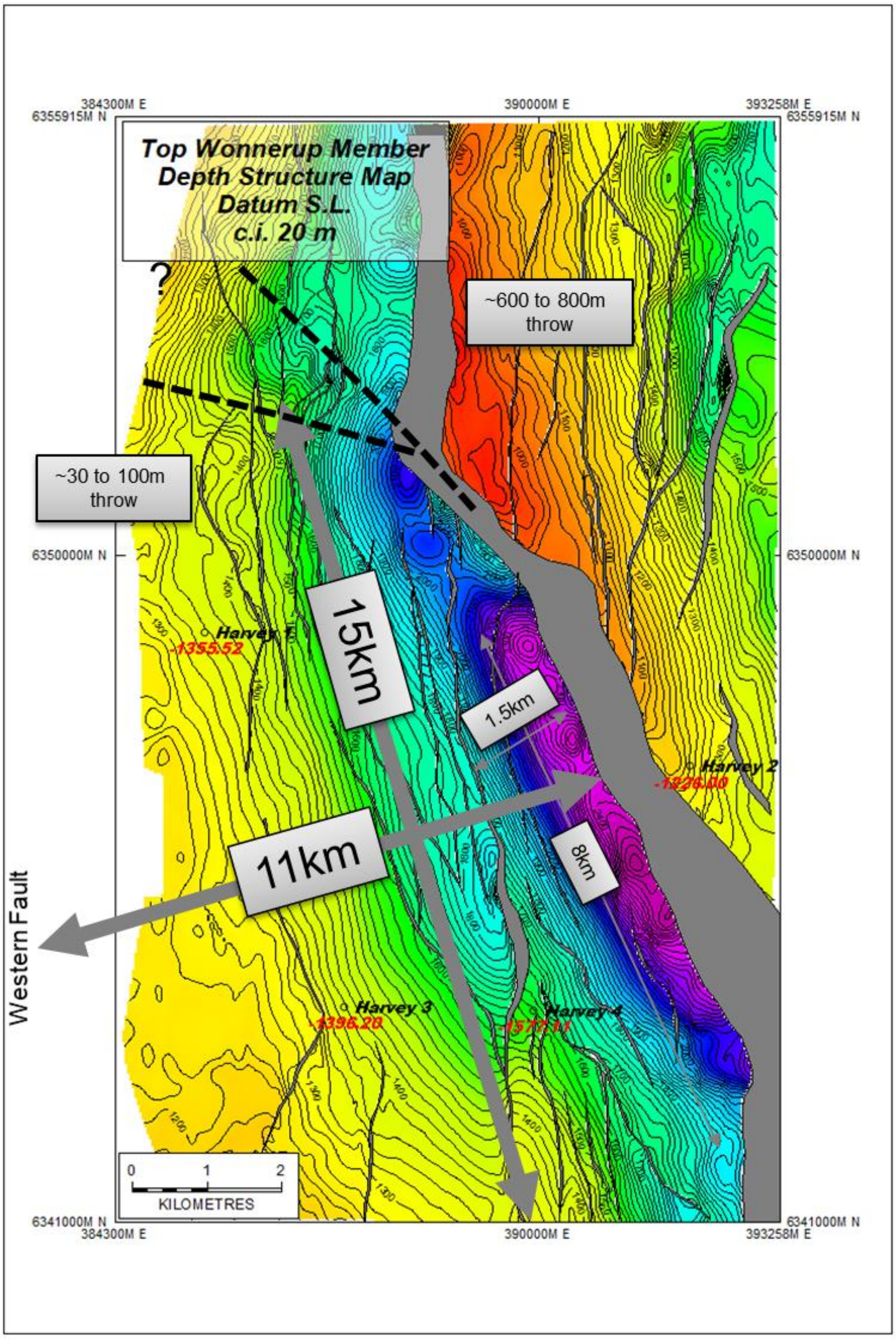


Figure 3.4: Potential Fault Compartments

3.2 Seismic data conditioning and automatic fault extraction

The process of conditioning seismic data followed by automatic fault extraction falls under a workflow called “Ant Tracking” in Petrel (Figure 3.5). “Ant Tracking” in Petrel is an algorithm which is part of a workflow that starts with seismic conditioning. Seismic conditioning is applying filters and/or smoothing to the seismic cube. In this case, “Structural Smoothing” provided the best results.

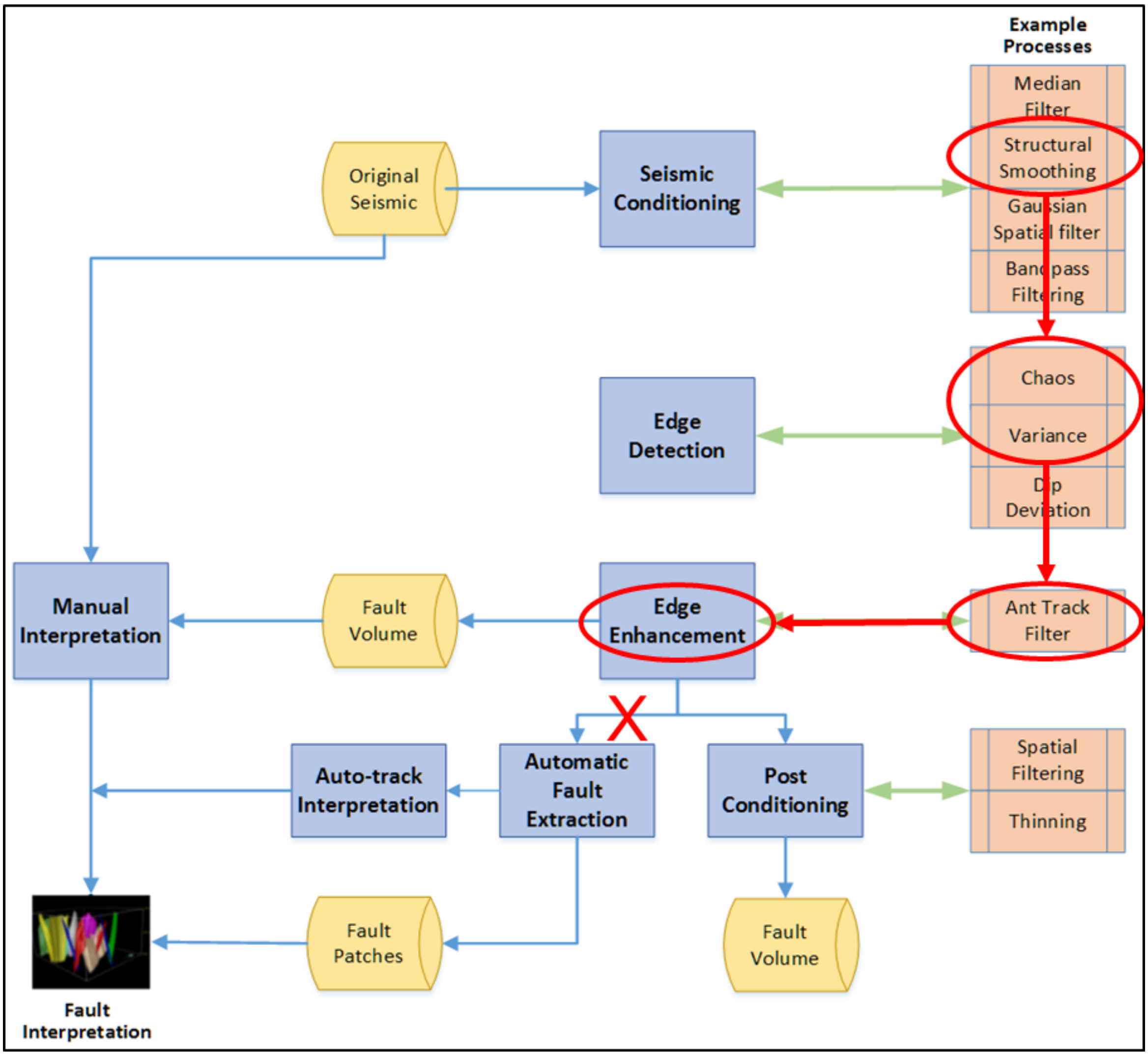


Figure 3.5: Schlumberger’s Petrel ANT Tracking Workflow

The next stage is to create seismic volume highlighting edges (“Edge Detection”); an Ant Track filter is then applied to enhance the edges. This results in “Fault Volume”, which can be manually either interpreted for faults or passed through an “Automatic Fault

Extraction" process to create Fault Patches. These "Fault Patches" would then be QC'd and filtered to be used as input for a fault interpretation.

Unfortunately, the "Fault Volume" created was not useful for creating "Fault Patches'. The High Resolution seismic volumes were also run through the same Ant Tracking workflow; however, it did not provide the necessary detail to extract faults/fractures (see Figure 3.6).

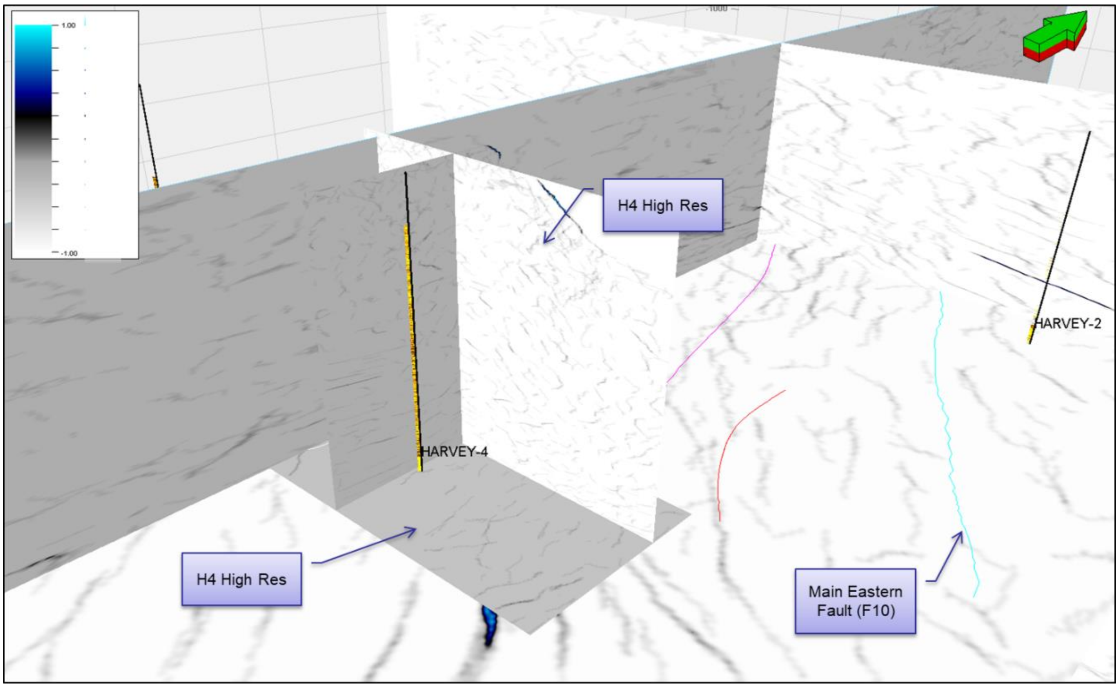


Figure 3.6: Schlumberger Petrel ANT Tracking Product

3.3 Fault Analysis & Fractal Studies

Fault analysis by fault strike with a projection to sub-seismic scales using power law assumptions help to populate the geological model stochastically. Faults can be interpreted from seismic but they have a limit due to the seismic resolution. The displacement of these interpreted faults can be plotted by a cumulative number per kilometre (see Figure 3 to Figure 3.8). If any fractures/faults have been interpreted from, core/image logs (with displacement), these can also be plotted and the gap between the two data sets can be predicted.

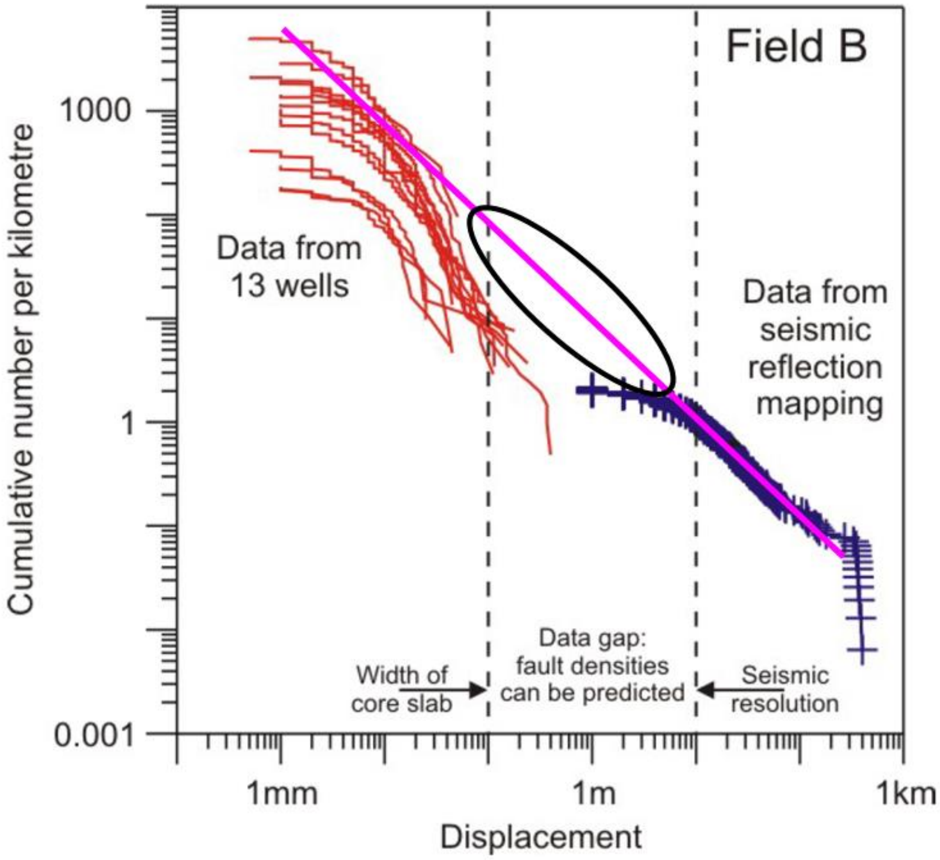


Figure 3-7: Fractal Analysis

If the two sets of data are available then a line can be drawn between to reduce the uncertainty. However, the Harvey area does not have any displacements available for the core/image logs so we are relying on the projection from the seismic data set only. Unfortunately, if the seismic does not have a high resolution then the tangent drawn through the seismic data set can result in a large uncertainty (Figure 3.7).

Figure 3.8 shows the results of drawing the tangent through the seismic data in the Harvey area, this has resulted in a large range for predicting the density "sub-seismic" faults expected. This plot can only be used as a reality check for any fault density values assumed for the Harvey area.

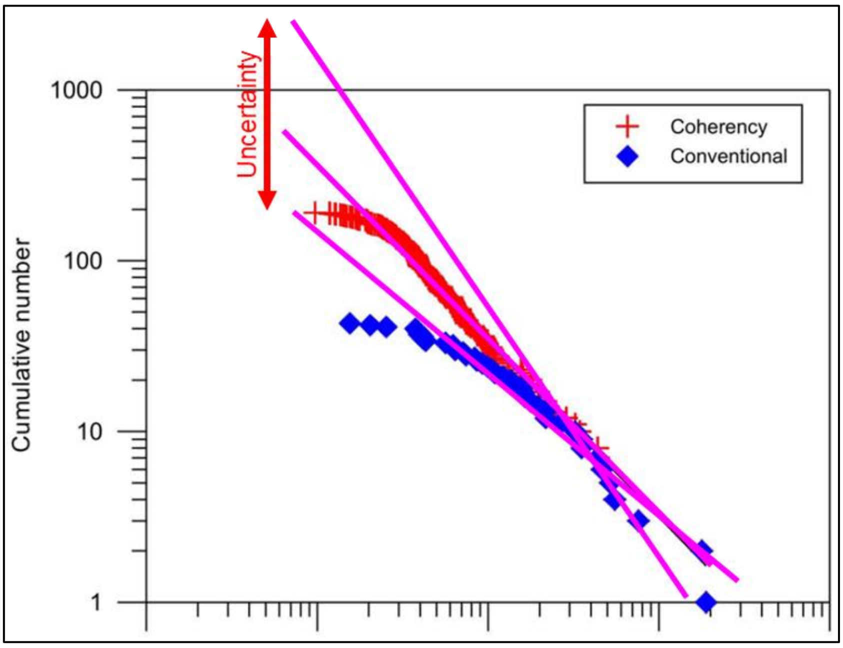


Figure 3.7: Comparison of Impact of Seismic Quality/Resolution

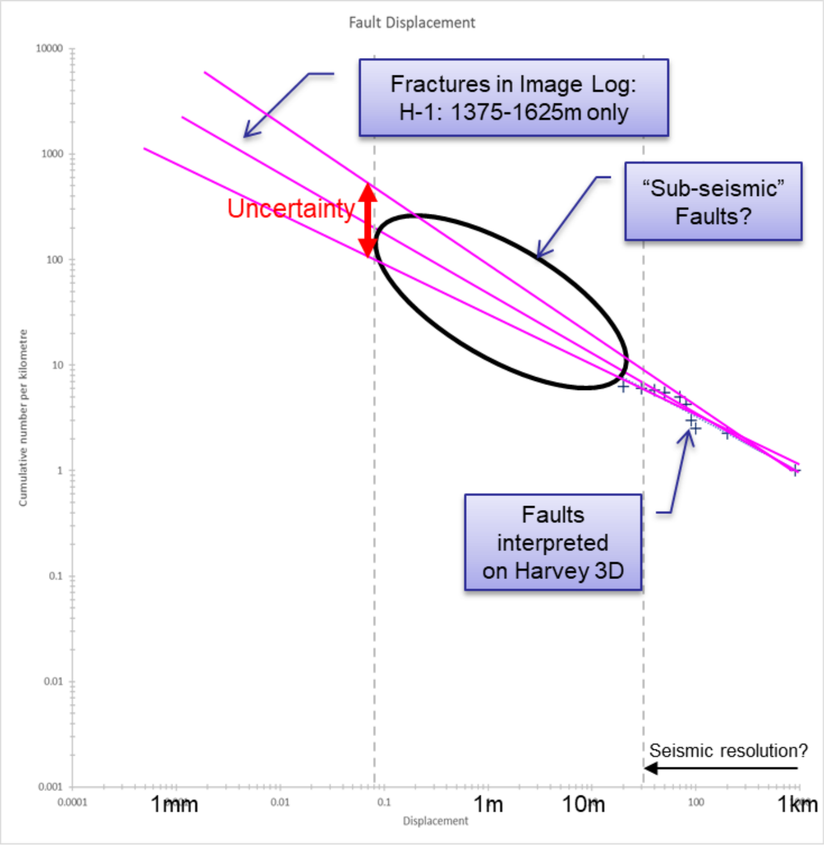


Figure 3.8: Fractal Analysis using Harvey Fault Data

4. REVIEW OF AVAILABLE INFORMATION AND ANALOGUES FOR PALEOSOLS

4.1 Lesueur Formation

The Lesueur Formation developed in the Perth Basin during the Late Triassic (Figure 4.1). At that time, the basin was undergoing a phase of thermal subsidence as a result of an initial stage of rifting in the Gondwana supercontinent. This rifting event took place from the late Permian to the Lower Cretaceous when the final break-up of the continent occurred and the drifting phase of India/Australia began.

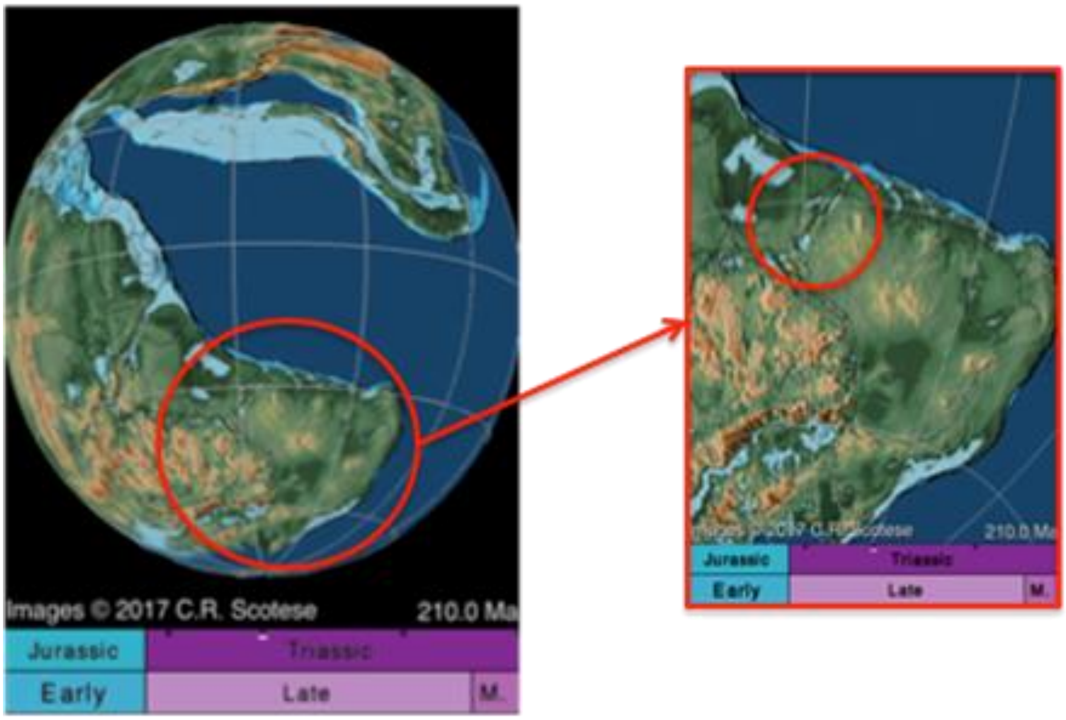


Figure 4.1: Image of the Earth during the Late Triassic (Scotese Ancient Earth Atlas 2017)

During the Late Triassic, the global climate was generally warm; there was no ice at either North or South Poles and warm temperate condition extended to the poles. The Perth Basin region was under a warm temperate regime (Figure 4.2).

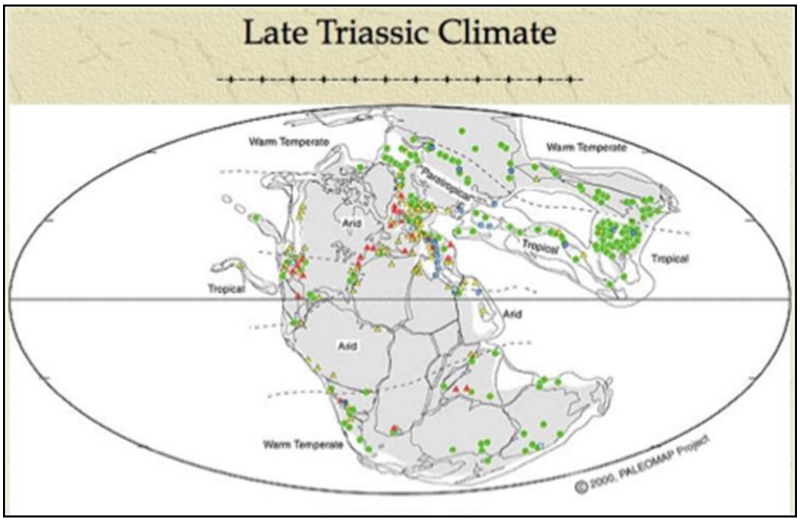


Figure 4.2: Late Triassic Climate

The Lesueur formation was deposited in a braided fluvial environment. The paleogeography of the basin indicates an elongated shape roughly running in a North-S direction and bounded by stable cratons, which constitute the sediment source.

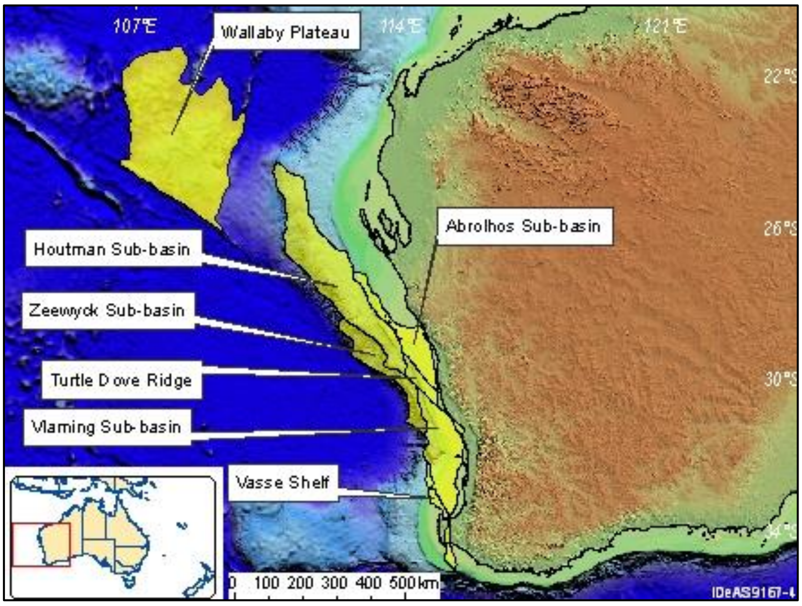


Figure 4.3: Perth Basin, Geoscience Australia. Australian Government

General information about the geological settings of the Perth Basin at the time of the Lesueur formation deposition (which were sustained for a long period of time) are:

- Tectonic stability

- Warm temperate climate

The Lesueur Formation in the Harvey area comprises two lithostratigraphic units (Figure 4.4); Wonnerup Member at the base and Yalgorup Member at the top. The Wonnerup represents a fluvial braided system dominated by linguoid bars whereas the latter is formed by a fluvial meandering system dominated by point bars, claystone irregular bodies and paleosols.

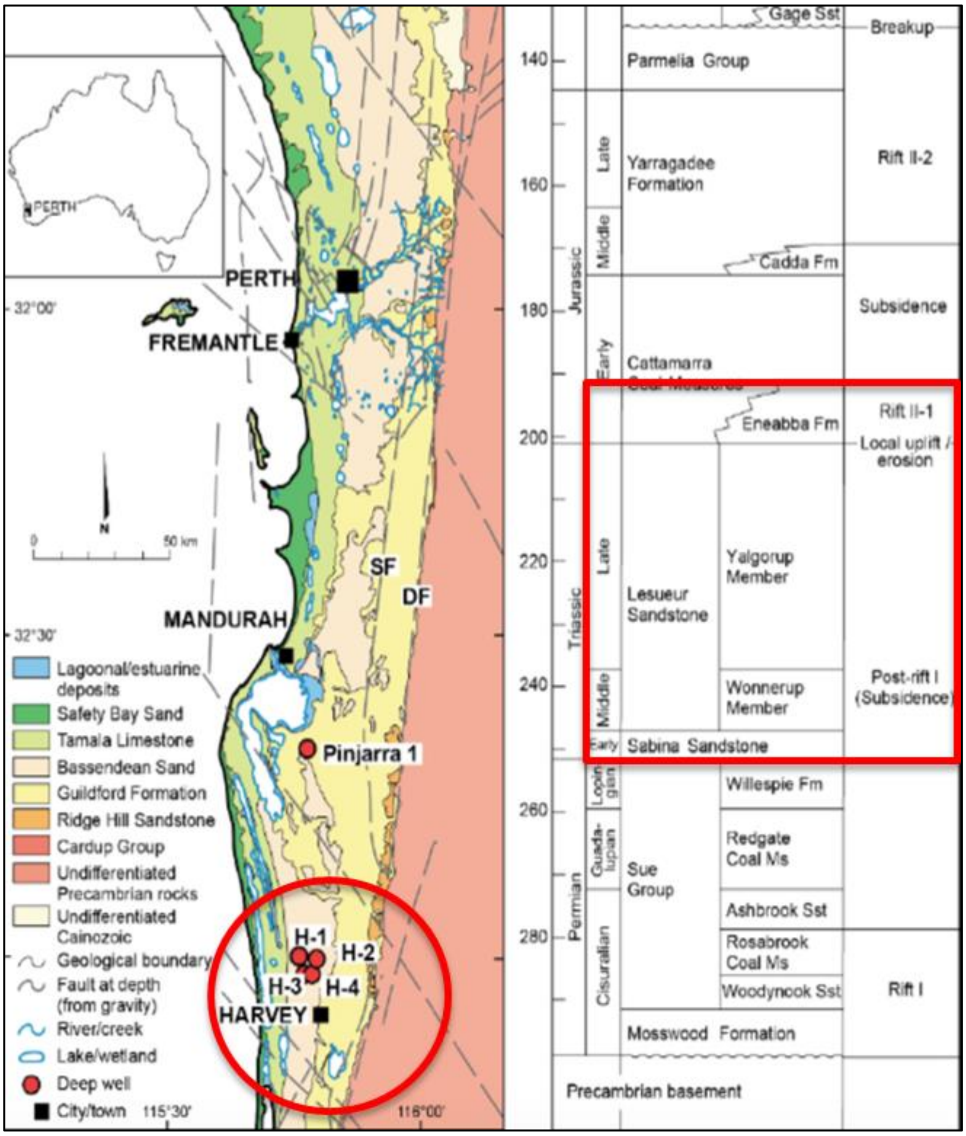


Figure 4.4: Lithostratigraphy and location of the Harvey Area (Ref: CSIRO, 2013)

Five main depositional facies spreading from channel fill sands to swampy deposits and paleosol/floodplain sediments have been defined to represent both fluvial environments (Figure 4.5). However, coarse channel fill sands dominate the Wonnerup Member and shaly floodplain and paleosols deposits dominate the Yalgorup Member.

Many different analogues can be found to guide the modelling parameters of the fluvial reservoir formation, however modelling the paleosol facies can be a challenge as their dimensions and lateral extend are not well known.

Figure 4.5 is a representation of the depositional environment and facies distribution that characterises the Lesueur Formation during the Late Triassic in the Harvey area.

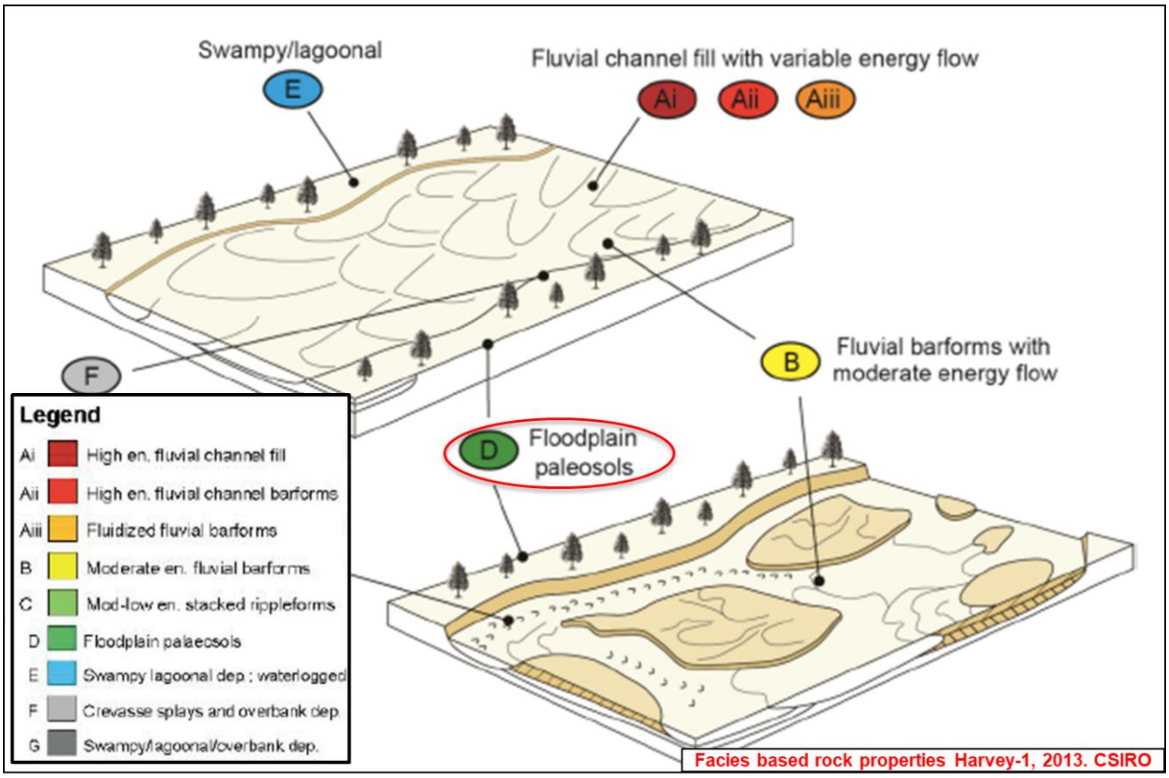


Figure 4.5: Facies Model based on GSWA Harvey 1 Core Interpretation by CSIRO

4.2 Soils

There is a large amount of information regarding present soils: their taxonomy, specific characteristics, conditioning factors of their development processes, management and uses and their impact on economy/society. To identify, understand, and manage soils, scientists have developed a soil classification or taxonomy system. The most general level of classification is the ***soil order,*** of which there are 12 according to the **FAO (Food and Agricultural Organization of the United Nations):**

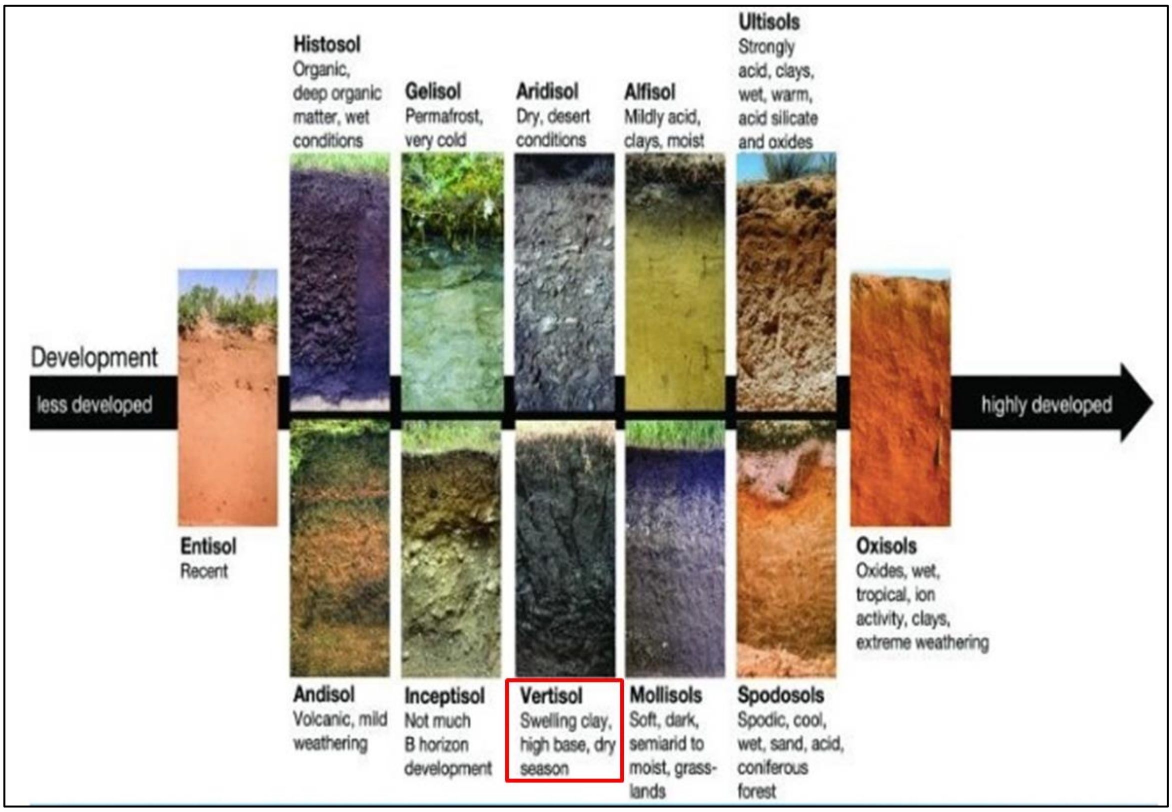


Figure 4.6: The twelve orders of soil taxonomy. United States Department of Agriculture

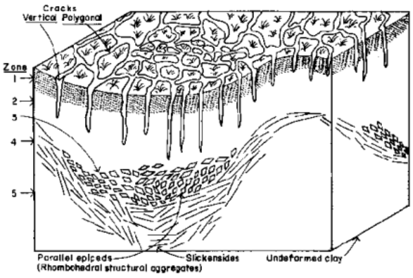
The **Paleosols** of the Harvey area are interpreted to be originally **Vertisols,** which are soils with high expanding clay content, usually developed in ephemeral fluvial systems. The expanding clay minerals swell during wet winter seasons, and contract during dry, summer seasons. This causes vertical desiccation cracks by 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.

Figure 4.7: Example of a Vertisol ("The twelve order of soil taxonomy." United States Department of Agriculture.)

The four Vertisol suborders (*Xererts, Torrerts, Uderts and Usterts*), which are defined precisely in Soil Taxonomy, are based on the length of time the cracks remain open or closed during the year, which requires field observations for several years.

The definition of Vertisols in Soil Taxonomy is based on **four obligatory properties**.

1. Do not have a lithic or paralithic contact, petrocalcic horizon, or duripan within 50cm of the surface.
2. Have 30% or more clay in all sub-horizons to a depth of 50cm or more after the soil has been mixed to a depth of 18cm.
3. Have, at some time in most years unless irrigated or cultivated, open cracks at a depth of 50cm that are at least 1cm wide and extend upward to the surface or to the base of a plough layer or surface crust.
4. Have one or more of the following:
    a. gilgai
    b. slickensides close enough to intersect at some depth between 25cm and 1m
    c. Wedge-shaped natural structural aggregates that have their long axis tilted 10-60° from the horizontal at some depth between 25cm and 1m.



In the GSWA Harvey 1 well, the Yalgorup Member (704-1380m) is quite heterogeneous. It consists of a rapidly switching, on the order of 1m, mixed lithofacies, with the exception of extensive floodplain paleosols in the lower part of the Yalgorup. The cored section of this member comprises cores 1 to 4.

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

The middle and lower parts of this member (cores 2 to 4, between 1266 and 1344m) consists mainly of siltstones and sandstones representing paleosols (D). These are 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 40cm deep) and more unusually pipe-like structures (up to 70cm 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. The pipe-like structures resemble bioturbation features created by a freshwater crayfish (Camborygma) typical of vertisols.

However, when it comes to their dimensions, the only information given for present soils is usually the total area in km^2 that they occupy.

For this reason, the information about present soils could be interesting to understand the internal structure of soils, their heterogeneity and their vertical and horizontal anisotropy at a small scale, but regarding dimensions and geometries at basin scale, paleosol case studies will be more useful.

4.2.1 Information and Analogues for Paleosols

Most of the research work on paleosols promotes these sedimentary bodies as tools to reconstruct ancient landscapes and as indicators of paleoclimates. In fact, it is the paleosol dimensions observed on outcrops (and extrapolated to the rest of the basin through correlations) is important to infer the paleoclimate and paleorelief.

For the Harvey area, subsurface information is scarce and correlations between wells difficult, analysing paleoclimate and landscape at the time in the region could give us a clue about the potential extension of the paleosols.

There are fewer papers found on specific case studies, being most of them from the Appalachian Basin in USA during the Late Carboniferous-Early Permian, although some other examples from Canada (McCarthy et al., 1998), (Ufnar et al. 2005) or Russia (Kovda et al. 2003) have also been located. It is important to bear in mind that these examples correspond to ages other than the Late Triassic (Yalgorup Member and the Eneabba Formation) and that the climate during those ages could have been very different (climate being one of the main factors conditioning the vertisols development) as well as the depositional environment in which the paleosols were developed.

Parts of Australia is still, at present a good area for vertisol development; (Viscarra, 2011), and (Knight, 1980), presents a case study on gilgai analysis in South Australia. Likewise, there are a few examples of paleosol case studies in South Australia (Parachilna, Billy Creek, Moodlatana, Balcoracana, Pantapinna and Grindstone Range Formations in the central Flinders Ranges) (Retallack, 2008), but they were developed during the Cambrian mainly in alluvial-coastal environments and can be assigned to more than one type of soil other than vertisol.

The Late Carboniferous-Early Permian Dunkard Group deposits of the Appalachian basin have often been mentioned as a main analogue for the Yalgorup Member and Basal Eneabba Formation (Beerbower 1961 & 1969; Cecil et al. 1990 & 1991; Fedorko et al., 2011; Hebree et al., 2011; Martin et al. 1969; Martin 1998). However, it is important to note that climate regime during the deposition of the Dunkard group was different to the climate that conditioned the development of the paleosols of the Yalgorup/Eneabba complex. The Yalgorup/Eneabba was a warm temperate regime whereas the Dunkard Group was arid. In addition, there are some differences in the depositional environment such as the Dunkard Group lacustrine limestones do not have any similar facies in the Yalgorup Member and Basal Eneabba Formation.

The paleosols of the Dunkard group represent in the vertical section a change in climate from arid in the upper alluvial plain to more humid regime in the basin centre. Two modern low-gradient alluvial fan complexes appear to approximate the dry and humid end-member climatic conditions that prevailed during deposition of the Dunkard Group.

The Okavango Fan at the northern edge of the Kalahari Desert in Botswana (Milzow et al.,2009), southern Africa, appears to represent the dry climate end member condition and the alluvial fan complex along the eastern edge of the Pantanal in southern Brazil (Assine and Soares, 2004; Assine, 2005) is a likely candidate for the more humid climatic Dunkard conditions.

These analogues do not correspond exactly with the development conditions assigned to the Yalgorup/Eneabba.

However, the vertisols present in the underlying Conemaugh Gp (stratigraphically) below the Dunkard Gp. and Monongahela Fm) represent paleosol facies that could be a closer analogue to the Yalgorup/Eneabba vertisols (Sturgeon, 1958; Catena & Hembree, 2012). Furthermore, the Wichita and Bowie Groups developed in the Midland basin show a very similar depositional environment to that of the Yalgorup/Eneabba complex (Tabor et al., 2004).

In Section 6, a summary of the most significant papers amongst the consulted bibliography has been included for your reference.

4.3 Review of Regional Diagenetic Information

Chemical and mineralogical changes associated with burial diagenesis of the paleo-vertisol include:

- Oxidation of organic carbon (OC)
- Illitization of smectites
- Dehydration and recrystallisation of Fe–Mn oxyhydroxides, and
- Dolomitisation of pedogenic calcite.

4.3.1 Summary of the Most Significant Papers On Diagenetic Features

Driese *et al.*, 2000, stated that vertisols tend to show retention of primary pedochemical patterns, suggesting that they constitute nearly closed systems during burial diagenesis and therefore keep the original signal of the sedimentary conditions in which they were deposited/developed.

Nord *et al*., 2011, studied a paleo-vertisol example which, was buried to depths of less 2km and not subjected to substantive diagenetic processes such as illitisation. → burial history of the Harvey area suggests an approximate burial 1.5km

Sheldon *et al*., 2009 stated that compaction rates of paleosols during burial are variable. Soils and their associated sediments are compactable because they include some porosity between the individual constituent grains. How compactable a given soil or sediment type will be is a function of their solidity.

4.3.2 Diagenetic Features/Processes of Paleosols

The mineral analysis (core Pinjarra 1) indicates that paleosol facies show high abundance of Illite relative to mixed-layer Illite - Smectite, with presence of Kaolinite and micas, in the Basal Eneabba Formation, and high content of Illite and mixed-layer Illite - Smectite with lesser amounts of Kaolinite and Chlorite in the Yalgorup Member.

GSWA Harvey 1 inter-grown Kaolinite is the main diagenetic clay mineral, which typically occurs as microcrystalline coatings on detrital grains and as heterogeneously distributed pore-occluding clots. Illite is a secondary diagenetic mineral, which typically occurs as pore-occluding clots. Smectite forms are inter-grown with illite in pore-occluding clots in floodplain paleosols (facies D) of cores 2-4.

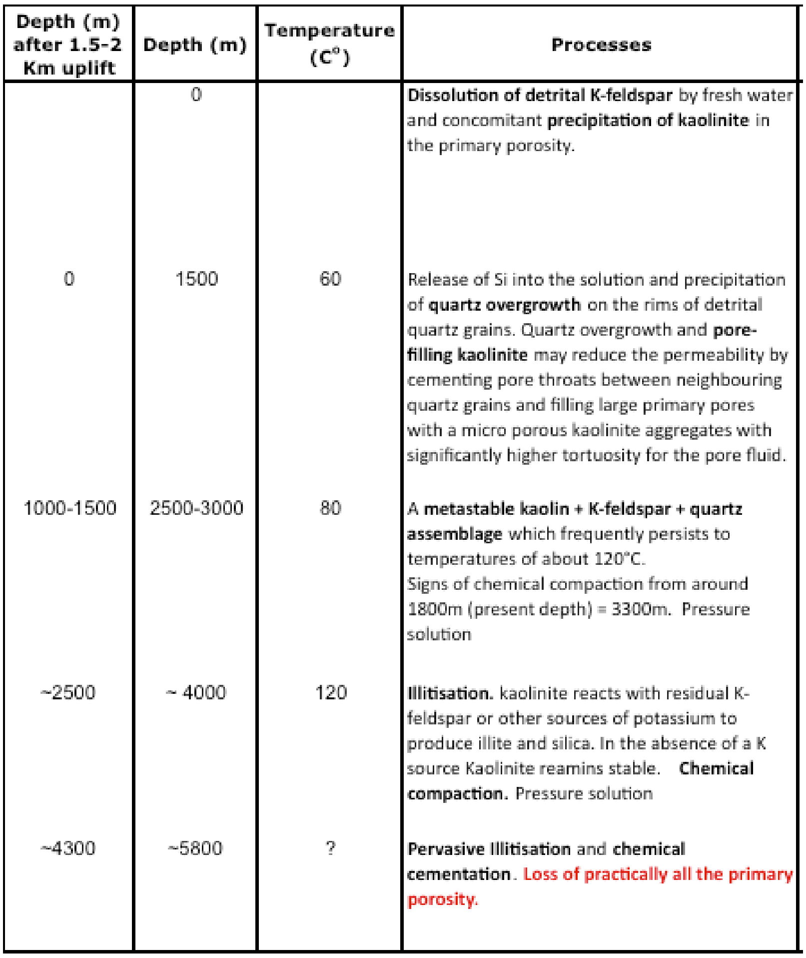
The mineralogical analysis suggests that the main diagenetic reaction on the clay minerals has been illitisation. This has been possible through potassium release to the system caused by dissolution of K-feldspar and plagioclase.

The mineral transformations that take place during this process do not increase porosity, as they do not involve a change on mineral volume (original and final product are similar in volume). Furthermore, some authors state that paleosols are rather closed systems that preserve the primary features of deposition during diagenesis. In addition, clay minerals do not react with CO_2.

Therefore, the impact of diagenesis on the sealing capacity of the paleosols is not negative. However, the sandy sections may be affected as it would have induced kaolinite and Illite generation between grains, occluding porosity.

Also, the overall reservoir quality in the relatively homogeneous, sandstone-dominated Wonnerup Member of the Lesueur Sandstone deteriorates with increasing depth (and temperature) due to diverse diagenetic modifications. Three major diagenetic processes are contributing to the general loss of pore volume during burial:

- Mechanical compaction
- Cementation
- Chemical compaction



Depth (m) after 1.5-2 Km uplift	Depth (m)	Temperature (C°)	Processes
	0		**Dissolution of detrital K-feldspar** by fresh water and concomitant **precipitation of kaolinite** in the primary porosity.
0	1500	60	Release of Si into the solution and precipitation of **quartz overgrowth** on the rims of detrital quartz grains. Quartz overgrowth and **pore-filling kaolinite** may reduce the permeability by cementing pore throats between neighbouring quartz grains and filling large primary pores with a micro porous kaolinite aggregates with significantly higher tortuosity for the pore fluid.
1000-1500	2500-3000	80	A **metastable kaolin + K-feldspar + quartz assemblage** which frequently persists to temperatures of about 120°C. Signs of chemical compaction from around 1800m (present depth) = 3300m. Pressure solution
~2500	~ 4000	120	**Illitisation.** kaolinite reacts with residual K-feldspar or other sources of potassium to produce illite and silica. In the absence of a K source Kaolinite reamins stable. **Chemical compaction.** Pressure solution
~4300	~5800	?	**Pervasive Illitisation** and **chemical cementation**. Loss of practically all the primary porosity.

Figure 4.8: Summary of diagenetic processes with depth

The Wonnerup Member of the South West Hub shows a clear pattern of diagenetic alteration leading to reduction of pore space. Microstructural observations indicate that this diagenetic pattern is repeated in samples from the available core material from the four Harvey wells (CSIRO Draft Report). This is interpreted as evidence that the Wonnerup Member of the Lesueur Sandstone underwent a similar degree of alteration at the four wells locations before these were affected by faulting and tectonic movement.

5. DISCUSSION ABOUT PALEOSOLS AND RECOMMENDATIONS FOR PALEOSOL FACIES MODELLING.

There are two types of mechanism that act in the generation of a paleosol: autocyclic and allocyclic (Beerbower 1961, Fedorko et al. 2011). The first type of mechanism is inherent to the processes that take place in a particular sedimentary environment. For instance, in a fluvial system, the partial erosion of the paleosol by channelized bodies, variations on topography affecting the water-table depth, changes in the alluvial/fluvial system (channel avulsion), or differential erosion and/or compaction. Autocyclic pedogenic sequences are very difficult to correlate, as they are highly dependent on local basin factors and have reduced lateral continuity.

The allocyclic mechanisms however correspond to the operation of large scale controlling factors such as tectonic or climate regime. In contrast, allocyclic pedogenic sequences are much more continuous laterally and generally became good correlation markers.

For example, in 1993 Wright and Marriot, presented a model of pedogenic development in a fluvial system related to sea-level cycle, Figure 5.1. In this model low see level periods (LST) produce strongly developed and well-drained paleosols cut by channel incisions whereas high sea level periods (TST) result in development of hydromorphic paleosols (waterlogged) with channel overlap due to initial low accommodation space. As the sea level rises and accommodation space increases rapid sediment accumulation takes place preventing soil development. In the final stage of high sea level (HST) low accommodation space is predominant in the fluvial basin allowing the development of soils again.

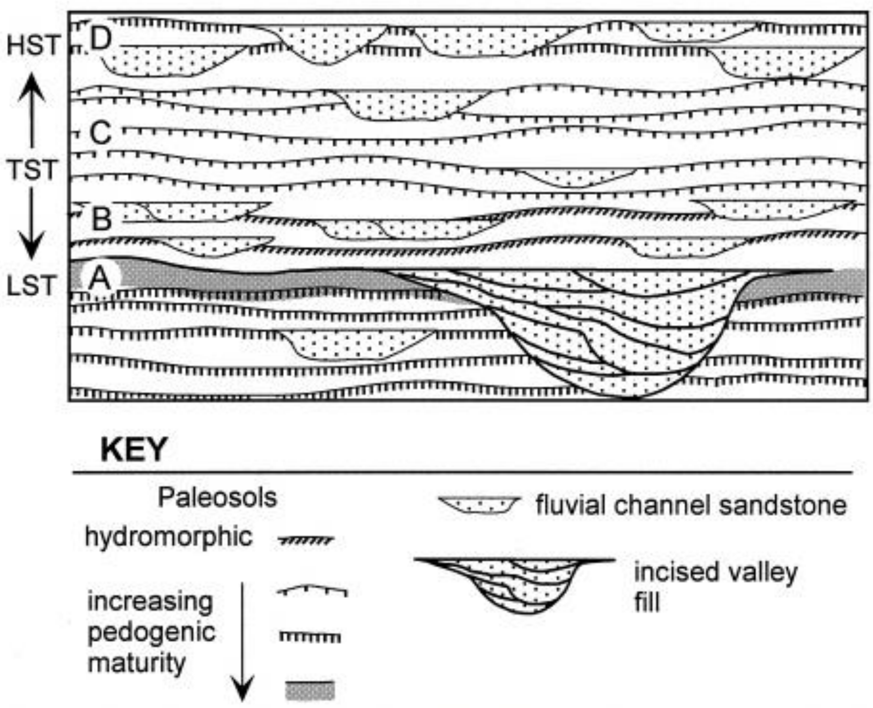


Figure 5.1: Pedogenic development in a fluvial system related to sea-level cycle (Wright & Marriot 1993 in Kraus 1999)

According to modern analogues, soils are dependent on several of allocyclic 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 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.

Thus, although soils are formed through autocyclic processes, in a fluvial system the thick accumulation of stacked paleosols horizons deposited over a long period of time (for instance, enough time 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 affecting the Harvey area paleosols 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, especially coarser sediment, supplied to the 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 paleosols development.

In summary, the great thickness (~150m) of the paleosol dominated interval and the total thickness of the Yalgorup Member. (>500m), probably imply stability during a long period of time of the allocyclic factors that could have intervened in the paleosols development.

Stable tectonic and climatic conditions in the Perth Basin during the Late Triassic would have potentially allowed extensive development of vertisols in the area. Large and irregular shaped paleosol bodies can be expected covering tens or even hundreds of Km^2.

In addition, the Harvey area vertisols were developed in a fluvial floodplain as the core facies analysis shows. This allochtonous character (formed by the degradation of sedimentary materials that have been transported to an area) grants them a priori a large extension according to modern analogues. Present autochtonous vertisols formed by the degradation of a substrate or parent material are geographically less extensive than present allochtonous vertisols developed in the low lands of alluvial or fluvial floodplains, where they are usually distributed. These paleosols, normally found on interfluves, distal floodplain, backswamps and marsh can extend in present times for many tens or hundreds of km_2.

Although allocyclic processes are probably the main cause for the development of such a thick paleosol interval in the Harvey area, autocyclic process have still taken place and need to be taken into consideration. For instance, the partial erosion of paleosols by channelized bodies at certain times breaks up the paleosol continuity. Differential erosion and/or compaction, variations on topography affecting the water-table depth, or changes in the alluvial/fluvial system (channel avulsion) will affect the lateral continuity of the paleosol at a smaller scale. This facies variability has a direct impact on the petrophysical characteristics of the paleosol unit and needs to be captured in the model, as it will affect the Kv/Kh ratio, and the tortuosity of the plume migration pathways.

J M. Kraus, 1999 presents a diagram (Figure 5.2) showing the range of paleosols that can form in a thick vertical section depending on whether sediment accumulation was steady or discontinuous. This diagram shows three different cases corresponding to different sedimentation rates associated to different small-scale basin conditions.

The lower part of the section (A) corresponds to a thick and strongly weathered paleosol formed on an unconformable surface due to a lengthy period of landscape stability and soil development (higher topography). The middle part of the section (B) represents a thick sequence of multiple stacked paleosols formed on floodplain deposits because erosion was insignificant in the area and sedimentation steady (lower topography). The upper part of the section (C) shows a moderately long pause in sedimentation related to valley incision that resulted in a paleosol more strongly developed than the underlying multiple paleosols although not as intensely weathered as the paleosol at the unconformity (channel avulsion).

This conceptual section could easily represent the Yalgorup Member stratigraphic architecture.

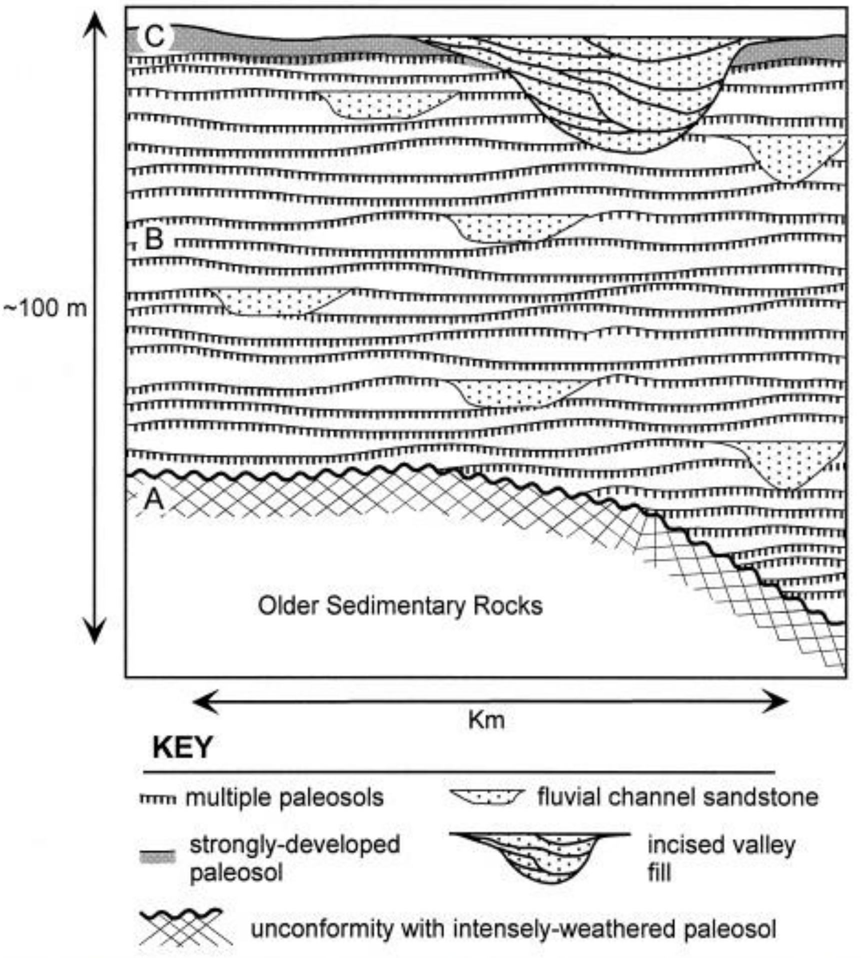


Figure 5.2: Different sedimentation rates associated to different small-scale basin conditions

Recognising and analysing paleosol variability at different spatial and temporal scales is important for evaluating how landscapes evolved over time and for assessing the relative significance of autogenic and allogenic controls on landscape evolution. In the Harvey case study such reasoning could be reversed in order to make an attempt on deducting the paleosols spatial variability through the analysis of the paleorelief and evidence of paleoclimatic conditions.

The primarily terrestrial deposits of the Bowie and Wichita Groups on the north-eastern portion of the Eastern shelf constitute a good analogue for the paleosols of the Yalgorup Member and Basal Eneabba Formation. These series reach a thickness of up to 530m in the east of the basin and thin westward towards marine-dominated strata. Three terrestrial facies are recognized: (1) sand- and gravel-rich channel-bar facies; (2) point-bar facies; and (3) floodplain facies. Sand and gravel rich, channel-bar facies were deposited by braided stream systems fringing the north-eastern highlands, whereas the point-bar facies record penecontemporaneous meandering stream systems that developed on the Eastern shelf to the south and west of the braided stream system. These depositional environments are very similar to those recognised in the Harvey area.

Several types of paleosols have been identified, amongst them paleosols classified as vertisols based on abundant and well-developed vertic features, their clay content (28–39%) with a significant percentage of smectite and the presence of deep V-shaped cracks developed within the upper horizons (Soil Survey Staff, 1998). The relatively low kaolinite content and preservation of expandable 2:1 layer-lattice clays (smectite) in these paleosols coupled with the occurrence of clastic dykes indicate periods of drying that were sufficiently long to preserve expandable clay minerals and to allow for significant shrinkage of the clay rich matrix. However, the presence of grey matrix colours and common to abundant redox depletions requires that periods of paleosol moisture deficiency in these paleosols were temporally limited. Based on their stratigraphic association with overbank mudstones as well as the morphological and chemical characteristics of these paleovertisols, they are interpreted as having formed in interfluve muds on the Late Pennsylvanian upper coastal plain and piedmont.

There are two different types of vertisols that can be defined; The first one with abundant redoximorphic features but morphological evidence for periods of drying (e.g. clastic dykes in the upper portions of profiles) make up an important component of latest Pennsylvanian mature paleosols. These paleosols are interpreted as recording intermediate soil moisture conditions and the initiation of a drying trend during the transition at the Pennsylvanian–Permian boundary interval.

The second one, interpreted as vertisols based on their well-developed vertic features, their smectite dominated clay composition and the presence of V-shaped cracks developed to significant profile depths, exhibit two major differences from the first type of vertisols: (1) accumulation of pedogenic carbonate; and (2) a paucity of redoximorphic features. The lack of redoximorphic features indicates that these well-drained profiles formed well above the paleowater table. Furthermore, the significant carbonate accumulation, including carbonate horizons in the profiles, and the presence of deeply penetrating V-shaped clastic filled dykes require prolonged periods of drying of the profiles and prolonged duration of pedogenesis.

The role of autocyclic and basin-scale allocyclic processes other than climate in determining the development of the pedotypes above described and their observed spatial distribution has been assessed.

Small scale patterns in pedotype distribution defined by paleosols within thin stratigraphic intervals (metres to a few tens metres in the vertical section) has been observed. Lateral variations in pedotype distribution, degree of maturity of paleosol and stratigraphic relationships between paleosols, have been followed between age-equivalent deposits located hundreds of metres to tens of kilometres apart

Reconstruction of paleocatenas (e.g. fluvial channels and their associated floodplains) was limited to a few laterally continuous outcrops in the scale of hundreds of metres to 1-2 kilometres long.

These references to fluvial plain paleosol dimensions could be useful to define the geometry of the Yalgorup/Eneabba paleosols complex. Although the lateral variability derived from outcrops in the Midland Basin is large, it can be assumed that for thicknesses in the scale of a few meters, the paleosols could extend for hundreds of meters to several kilometres.

Furthermore, the observed topography coupled with paleocatenary relationships inferred from meter scale vertical stacking patterns of pedotypes in this analogue basin, indicates that geomorphic position on the aggrading floodplain influenced soil development through differences in topographically controlled drainage and sediment accumulation provided by channel-margin deposits and shallow floodplain scours.

Nevertheless, longer term stratigraphic trends due to climate variation and sea level changes, overprinted the autocyclic sequences described above. Larger scale lateral variations (kilometres to tens of kilometres) are defined by differences in the stratigraphic distribution of pedotypes observed within time-equivalent mudstone-dominated intervals bracketed by laterally correlatable, major sand bodies.

Overall, these inferred meso- and macroscale paleosol–landscape associations indicate that differences in sediment accumulation rates and topographically (or parent material) controlled drainage clearly influenced soil development on the Eastern shelf alluvial basin. In turn, the imprint of landscape variability is recorded in the vertical stacking patterns of pedotypes at the meter to tens of meter vertical scale and accounts for the stratigraphic ‘noise’ observed in the longer-term trend. Larger vertical scale (tens to hundreds of metres) stratigraphic variations in the Permo-Pennsylvanian paleosols define a long-term trend upon which the aforementioned smaller-scaled variations are superimposed.

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 1-2m 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 are intergradational and represent 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, which description fits well with the Yalgorup paleosol facies can sometimes reach bigger thicknesses up to 9-12m (Standard,1969) or even 35m (Herbert and Uren, 1972), and extend laterally for 2.5km in a coastal outcrop near Sydney.

In conclusion, paleosol facies are by nature extensive and irregular in shape bodies 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 bodies have not been defined, it seems fair to assume that they extend for many hundreds of meters. That is, paleosols are essentially extensive facies bodies. Their dimension associated to their simultaneous autocyclic nature and their allocyclic origin. In both cases, paleovertisols extend in the range of hundreds to tens of hundreds of meters.

The Yalgorup materials were deposited over a period of about 27 my reaching a total thickness over 500m. The analogues found through the bibliography research show that the origin of such thick intervals has been controlled by large scale allocyclic processes like tectonic and climate.

In the Perth Basin at the time of sedimentation of the Yalgorup/Eneabba paleosol complex there was tectonic stability dominated by thermal subsidence and a suitable warm temperate climate, alternating dry and wet periods, sustained during enough time to have allowed the development of extensive vertisol formations at basin scale.

Nevertheless, some variations within the paleosols are to be expected due to the autocyclic nature of paleosols developed in a fluvial plain. For instance, presence of intersecting abandoned channel fill or sand filled desiccation cracks. The average paleosol facies thickness observed on core data from GSWA Harvey 1 well, indicate that individual paleosol bodies are between 2.5 to 3m thick. From the literature explored during this phase of the project it can be assumed that series in the order of a few meters in the vertical scale can extend laterally for several hundreds of meters.

Reconstructing paleocatenas (i.e.: fluvial channels and their associated floodplains) by analysing the lateral relationship between neighbour facies, could supply some information on the extension and geometry of the paleosol bodies.

Making a mineralogical study of the Harvey cores as detailed as that of the Pinjarra 1 well could be a good recommendation. The mineralogy of the paleosols can throw some light on the controlling factors of their development, which has a direct impact on their lateral extension. Furthermore, it could supply information on small-scale variations of the paleotopgraphy that could have constrained their extension.

On the other hand, any information regarding the paleogeography of the basin at the time of deposition would be most helpful. The Harvey area represents only a small portion of the Perth Basin so perhaps it would be possible to perform a small-scale paleogeographic reconstruction by flattening the seismic horizons available to derive roughly the distribution and extension of the flat/low slope areas. This together with the information derived from the log image data about the orientation and distribution of the channel facies could result in a fair reconstruction.

These small-scale facies variations are important because they 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.

Nonetheless, these variations on paleosol properties do not have to be detrimental to the CO_2 sequestration objective. What makes these lithostratigraphic units a suitable target for CO_2 sequestration is the high frequency sand/shale alternation and the tortuous path that this generates for the gas to flow through. In conclusion, it is the low Kv/Kh ratio of this formation what will benefit the sequestration process by increasing the gas migration time to surface.

6. SUMMARY OF THE MOST SIGNIFICANT PAPERS ON PALEOSOLS

In the following paragraphs, a summary of the most significant papers amongst the consulted bibliography has been included.

(Beerbower, 1961 & 1969)

A simple model of the alluvial plain environment includes six distinct elements: - channel, crevasse channel, levee, crevasse distributary, abandoned channel, and floodplain. Because of internal energy gradients and vectors, these elements are redistributed progressively across the plain.

If subsidence removes some of the lower energy deposits from the zone of reworking by high energy environments, this redistribution will produce alternation of sedimentary types, (cyclothemic sequence). Such autocyclic sequences are characterised by their restriction to a single alluvial plain, by their limited extent, and by their shape.

Allocyclic sequences are those generated outside the sedimentary system by changes in discharge, load, and slope. They differ from autocyclic alternations in their lateral extension across the alluvial plain.

Unequal subsidence, differential compaction, depositional topography, and substrate modify the effects of the various cyclic mechanisms and may obscure them altogether, exaggerate some at the expense of others, or produce megacyclothems or cyclothem bundles. Because of internal restrictions the dominant cyclothems on one portion of an alluvial plain may have quite a different origin than those on another part.

(Fedorko et al. 2011)

Describes the rock types commonly found in the Dunkard Group arranged in a typical cycle or cyclothem. Smaller cycles can occur within the larger cycle. Variance from the typical cyclothem is evident from difference in position within the basin-scale depositional system and to differences induced locally by depositional environments.

The paleosols, where developed in the fine material at the top of waning fluvial deposits, are barely discernible in the lake deposits of the north. The paleosol beneath the Washington coal complex is one of the better developed and thickest soil profiles of the

Dunkard Group, but in places in the lake environment of the north, it is very thin and weakly developed.

The (Figure 6-1) below shows the facies distribution of the underlying Monongahela Formation and the Dunkard Group. Arkle (1969 and 1974) interpreted the grey facies as the lacustrine swamp facies and the red facies as the alluvial facies. Martin (1998) identified these facies provinces (south to north) as upper fluvial plain, lower fluvial plain, and fluvial-lacustrine deltaic plain. Current indicators in sandstones and the arrangement of facies of the Dunkard Group indicate a north to northwest paleoslope with sediment source in the southeast with some evidence on the northeastern margin for subordinate sediment input from a northern, cratonic source (Martin, 1998).

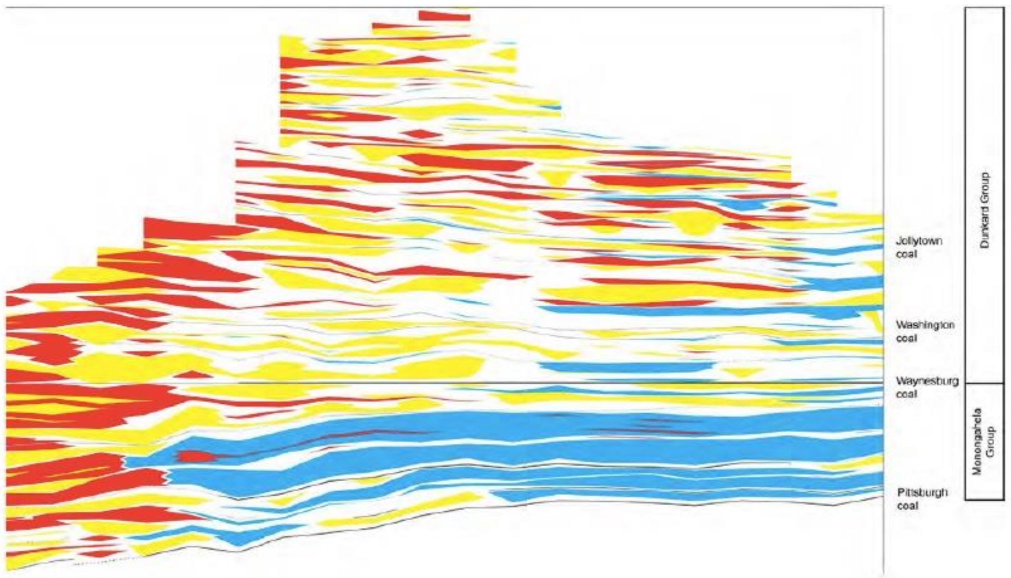


Figure 15. Distribution of facies in the Monongahela and Dunkard groups taken from cross section A-A'. Coal beds are black lines, limestone is blue, sandstone is yellow, redbeds are red, and white is shale.

Figure 6.1: Facies distribution of the underlying Monongahela Formation and the Dunkard Group

(Cecil, C.B., 1990)

In his work of '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 are 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.

Cecil et al. (2011)

An extensive variety of paleosols occurs in the Dunkard Group ranging from Inceptisols to petrocalcic-paleo-Vertisols.

Inceptisols are common in aggrading alluvial plain sequences. Hydromorphic Histosols include coal beds and certain dark shales. Plant fossils in the dark shales are indicative of waterlogged conditions and a clastic swamp. Vertisols with petrocalcic horizons and nodules are common, especially in the upper half of the Dunkard Group. A paleosol within the Waynesburg Fm. is apparently the oldest petrocalcic-Vertisol in the Dunkard. The regional distribution of the petrocalcic-Vertisol under the Waynesburg A coal is indicative of landscape topography and a paleosol catena where a paleosol developed on topographic highs and lacustrine carbonate developed in topographic lows.

Two sedimentary environments, corresponding to the upper alluvial plain and the basin centre seem to have controlled the deposition of the Dunkard Gp. paleosols. Lacustrine systems developed under a more humid climate characterized the basin centre. Well drained paleosols with red beds (oxidation) developed in the upper alluvial plain under dry conditions. It appears that autocyclic processes dominated alluvial plain sedimentation whereas allocyclic climate changes, ranging from humid to dry sub-humid and perhaps even semiarid dominated the lacustrine systems.

The period-scale trend in climate drying represented in the approximately 366m (1,200ft) of Dunkard strata probably lasted for at least 10 million years and at least some, if not most, of the Dunkard is Permian (Asselian to Kungurian; see Lucas, 2011). If so, then Dunkard deposition was coeval with the transition between the humid Late Carboniferous and the arid late Permian (Kungurian in Russia) (summarized by Wardlaw et al., 2004).

(Catena et al, 2012)

In this case the vertisols appear concatenated with inceptisols; both developed in alluvial swamps with semi-arid climate. This type of environment is similar to that described for the Yalgorup Member during core interpretation.

Although the alluvial swamp is formed by a very low slope surface, small changes in topography result in the simultaneous development of inceptisols in lower waterlogged areas dominated by reduction conditions with a high water table, and vertisols formed in higher better drained areas with a much deeper water table, characterised by oxidizing conditions.

The vertical and lateral variability of these two types of soils is large as it depends on topography, hydrology, and changes in the alluvial system and small-scale climate.

For this analogue, vertisols average thickness ranges between 2 and 3.5m and their lateral extension is estimated on several meters lenses which are about 1.2m wide, making correlation of different sections throughout the basin very difficult.

(Chumakov et al, 2002)

This work was accessed for the information about climatic condition during the Permian. The Permian was marked by transition from the glacioera to the thermoera. This global climatic reorganization followed the significant paleogeographic changes related to Pangea formation and preceded the major reorganization in the Earth’s biota that occurred in the terminal Permian-initial Triassic.

(Donaldson et al. 1985)

Central Appalachian Basin; Late Pennsylvanian. Redbeds, calcium carbonate concretions and gilgai paleosol structures of Late Mississippian and Late Pennsylvanian rocks suggest seasonally dry tropical climate whereas the lithologies of the earlier Pennsylvanian rocks are indications of ever-wet tropical climates with their quartz-rich fluvial sandstones, high quality coals and aluminum-rich clay deposits. Streams change from predominantly bedload to suspended load generally from Early to Late Pennsylvanian, in response to changes in paleoslope gradient, distance from source area, unvegetated highland, and change from ever-wet to intermittently dry tropical climate. Greater dryness is suggested for increased alkaline conditions observed in paleosols, carbonates, and coal beds of Late Pennsylvanian time but sufficiently wet to prevent evaporite deposition.

(Driese et al., 2005)

Crooked Fork Group (Lower Pennsylvanian, Atokan, Langsettian). Climate changes (possibly Milankovitch-driven) resulted in evolution of soil landscapes from well-drained, seasonally wet floodplains and delta plains dominated by vertic (Vertisol-like) paleosols, to very poorly drained, ever-wet swamps dominated by sideritic gley paleosols. Pedogenic slickensides and angular blocky ped structures, in conjunction with illuviated clay pore fillings and sepic-plasmic microfabric, indicate an initial better-drained phase of paleosol development. Gley overprinting, characterized by drab, low-chroma paleosol colours (Fe reduction) in upper portions of paleosols, sideritic rhizocretions, sphaerosiderite and pyrite nodules, extensive leaching and translocation of alkali and alkaline earth elements, and kaolinitization of smectites and hydroxy-interlayer vermiculite, indicate a later poorly drained stage of paleosol development characterized by saturated conditions.

(Driese et al., 2000).

Houston Black series, Central Texas. Modern vertisol, which can be directly compared with an Upper Mississippian paleo-Vertisol from the Appalachian basin.

Retention of primary pedochemical patterns suggests that Vertisols constitute nearly closed systems during burial diagenesis. Chemical and mineralogical changes associated with burial diagenesis of the paleo-Vertisol include oxidation of organic carbon (OC), illitization of smectites, dehydration and recrystallization of Fe–Mn oxyhydroxides, and dolomitization of pedogenic calcite.

(Hembree, et. al 2014)

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 335m and a total areal extension of 78,000km^2.

(Hembree, 2011).

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.

(Joeckel, 1995)

Conemaugh Group (Upper Pennsylvanian) in the Appalachian Basin. A Vertisol-like paleosol complex, ranging from 3 to > 10m thick, is developed below the Ames marine interval containing the following pedogenic features: very large slickensides, microsparitic calcite nodules, nodules or coatings of radial calcite spar, preserved soil microstructure, soil-compatible birefringence fabrics, and prominent mottling.

The stratigraphy of the Ames-Harlem Coal interval, the regional distribution and thickness of the Harlem Coal, and features of the sub-Ames paleosol show that the pre-Ames landscape had significant local relief (in the form of shallow paleovalleys with broad interfluves) along the western to northern margin of the Appalachian Basin (Ohio, southwestern Pennsylvania). The stratigraphic relationships of sub-Ames paleosols, the Harlem Coal-Ames marine unit interval, and the Ames marine unit itself are compatible with a significant effect of eustatic sea-level rise in this area. Greater regional tectonic subsidence was probably the strongest control on sub-Ames sedimentation and pedogenesis along the eastern to southern margin (south-central Pennsylvania, West Virginia, northeasternmost Kentucky), where there appears to have been very little relief.

(Knight, 1990)

Gilgai microrelief. The microrelief is situated on a gently dipping regional slope. It is characterised by large cracks on the ground surface have an orientational relationship with the strike and dip of the regional slope and by a lenticular gravel layer of sedimentary origin folded into a series of anticlines and synclines beneath the microrelief surface.

The mechanism proposed to explain the surface and subsurface structures involves moisture concentrations that focus near, and below pre-gilgai surface cracks and a gravel lens. Differences between lateral and vertical stresses due to swelling pressures and overburden loads are sufficient to cause small, inclined shear displacements in definable depth zones.

Accumulations of vertical movement components arising from the shear displacements, and vertical sliding of blocky non-sheared units nearer the ground surface, cause the gilgai microrelief and fold-like deformations in the soil profile. Zones of possible downward movement are located at the margins of mounds.

(Kovda et al., 2003)

North Caucasus, South Russia. Gilgai microrelief. Microrelief with an amplitude about 30cm resulted in a wetter environment with stronger leaching in the microlow and a drier pedoenvironment with carbonate accumulation in the microhigh.

Carbonate nodules represent early pedogenic products that were initiated before gilgai formation. Modern hydrology resulted in variability of dissolution/recrystallization of the nodules along the gilgai microtopography. The variability in degree of impregnation, aggregation into pellets, and presence of hard nodular cores reflects several generations of soft masses.

(Kraus, 1999)

Soil development, due to the episodic nature of sediment accumulation, is a normal part of the continental sedimentary regime and that many ancient continental deposits contain vertically stacked or multistorey paleosols. Because many ancient soil profiles are easily recognized, exposed over broad areas, and formed almost instantaneously in terms of geologic time (in the range of 2000–30,000 years), they offer a nearly ideal method of correlating deposits in the continental realm, both at a local and at a regional or basinal scale.

Paleosol–landscape analysis can produce a clearer, more complete picture of the environmental conditions and processes operating in ancient continental basins. Specifically, recognizing and analysing paleosol variability at different spatial and temporal scales is important for evaluating how landscapes evolved over time and for assessing the relative significance of autogenic and allogenic controls on landscape evolution.

(Mack et al., 2010)

Abo Member, south-central New Mexico. Lower Permian. Comparing interfluve and fluvial-terrace paleosols with paleosols that developed within lowstand-fluvial deposits. Interfluve and fluvial-terrace paleosols consist of primary pedogenic features, including vertical root traces, vertic structures, pedogenic calcite and translocated clay (argillans), which are cross-cut or replaced by low-aluminium goethite, grey colour mottling, sparry calcite veins and ankerite. In contrast, lowstand-fluvial sediment that filled incised valleys contains only rooted and vertic paleosols, whose immaturity resulted from high aggradation rates.

(McCarthy et al., 1998)

Interfluve paleosols can be most reliably identified using a combination of (1) stratigraphic position; (2) field observations such as thickness, structure, colour, and degree of rooting; and (3) micromorphological features such as bioturbation fabric, clay coatings, ferruginous features, and siderite and barite. Only micromorphology permits recognition of temporal changes in drainage, surface stability, and protracted pauses in sedimentation that typify these surfaces. These changes are consistent with regional changes in base level and accommodation, supporting a sequence boundary interpretation.

(Nord et al., 2011).

Study on two paleosols to test the validity of MAP (mean annual precipitation) estimates from the proposed weathering indexes. These paleosols were selected as representative examples because they are classified as Vertisols on the basis of high clay content and slickensides, they have available elemental oxide data within range of the modern climosequence, and one is calcareous and one noncalcareous. Further, the morphology of both of these paleosols expresses a level of weathering maturity similar to those in the modern Vertisol climosequence. Rocks at both settings were buried to depths of <2km and not subjected to substantive diagenetic processes such as illitisation.

(Opdyke et al., 1994)

This work was accessed for the information about climatic condition during the Carboniferous. A large-scale climatic change is recorded in Carboniferous and Permian rocks of North America. The middle Mississippian to Early Pennsylvanian sediments of central and eastern North America are characterised by a dry, oxidizing climate reflected in an abundance of red beds. The climate turned wet in the Pennsylvanian, evidenced by a lack of red beds and an abundance of coal. Iron is mostly held in the reduced forms, largely siderite. Dry conditions returned in the latest Pennsylvanian and into the Permian as shown by the return of red beds and reduction of coals, particularly domed peat types. One of the primary factors influencing climate was the paleolatitude of ancient sedimentary environments. Paleomagnetic data compiled from North America may be used to determine the expected paleolatitude of any site on the continent.

(Phillips et al., 1984)

Influence of paleoclimate on the sedimentation of the Dunkard basin. The climate during Early Pennsylvanian time was moderately wet and the median in moisture availability. Early Middle Pennsylvanian was drier, probably seasonally dry-wet; late Middle Pennsylvanian was the wettest in the Midcontinent; early Late Pennsylvanian was the driest; and Late Pennsylvanian was probably the wettest in the Dunkard Basin. Regional differences in basinal geology and climate were significant variables, that affected sedimentation but the synchronous control of paleoclimate was of primary importance.

(Retallack, 2008)

A broader view of Cambrian landscapes and soilscapes now comes from paleosols of alluvial coastal plains of the Cambrian (to Ordovician?) Parachilna, Billy Creek, Moodlatana, Balcoracana, Pantapinna and Grindstone Range Formations in the central Flinders Ranges of South Australia. Paleosols are recognised by soil structures such as calcareous nodules (caliche) and cracked ridges (mukkara). They also show gradational changes down-profile in minerals, grainsize and chemical composition comparable with soils. Some of these Cambrian paleosols are thick (>1 m) and well developed (large caliche nodules). They indicate stable alluvial and coastal landscapes of quartzo-feldspathic and locally tuffaceous sediments. Paleoclimates were generally semiarid, although several intervals of subhumid paleoclimate coincide with local marine transgression.

Cambrian paleosols of the Flinders Ranges are assignable to the modern soil orders Vertisol, Aridisol, Inceptisol and Entisol.

(Sheldon et al., 2009)

This paper was accessed for information on compaction rates on paleosols during burial. Soils and their associated sediments are compactable because they include some porosity between the individual constituent grains. How compactable a given soil or sediment type will be is a function of their solidity.

(Soil Survey Staff, 2014)

This paper was accessed for information on soil taxonomy and characteristics of different types of soils. Present vertisols specific attributes and the mechanisms that control their development.

(Sturgeon, 1958)

This work was accessed for the information about the Conemaugh Group geology.

(Tabor et al., 2004 &2008)

Wichita and Bowie Groups, Midland Basin, North-Central Texas, Permo-Pennsylvanian. Paleosols of the Eastern shelf of the Midland basin exhibit stratigraphic trends in the distribution of soil horizons, structure, rooting density, clay mineralogy and colour that record long-term changes in soil-forming conditions driven by both local processes and regional climate. Paleosols similar to modern vertisols, all bearing morphological, mineralogical and chemical characteristics consistent with a tropical, humid climate, represent the Late Pennsylvanian suite of paleosol orders. Paleosols similar to modern vertisols, preserve characteristics indicative of a drier and seasonal tropical climate throughout the Lower Permian strata.

The analysis of stacked paleosols document the influence of paleolandscape position on pedogenesis in aggradational depositional settings. This study evaluates the influence of local- to regional-scale autogenic and larger scale allogenic processes on the stratigraphic distribution of paleosol morphologies and compositions.

(Ufnar et al., 2005)

Paddy Member of the Peace River Formation. Western Canada Foreland Basin, Late Albian. This work exhibits detailed description of several micromorphologies associated to paleosols developed under “well-drained conditions.

The thickness and abundance of clay coatings indicate that the soil was well drained for a long period of time. The deformation and reworking of clay coatings into the matrix suggests prolonged landscape stability.

The prevalent birefringent fabrics and assimilation of the clay coatings into the matrix may have resulted from shrink–swell reorganization of the soil materials during wetting–drying cycles. The compound clay coatings with ferruginous hypocoatings may also reflect cyclic wetting and drying, and some fluctuations in redoximorphic conditions.

The Paddy Member paleosols exhibit a polygenetic history of pedogenic development characterized by an earlier well-drained history of pedogenesis followed by late-stage hydromorphism. The changes in drainage conditions may be related to base-level changes associated with parasequence-scale relative sea-level change. However, the soil development in each location is related to paleo-slope position.

Although the paleosols are genetically linked by the base-level (sea-level) changes, but each paleosol developed at different rates and times along the ancient landscape surface.

(Viscarra, 2011)

This paper provides spatially explicit clay mineralogy information for Australia that will help to improve our understanding of soils and their role in the functioning of landscapes and ecosystems. The abundances of kaolinite, illite and smectite in Australian soils have been measured for several soils in different locations and the results show that climate, parent, material and soil type exert the largest influence on the abundance and spatial distribution of the clay minerals whereas relief and vegetation have more local effects. Some present analogues for vertisols in Australia are mentioned

(Wilkinson et al., 2009)

This paper describes the impact of bioturbation on the soil properties at small-scale. The primary effects of bioturbation, include soil production from saprolite, the formation of surface mounds, soil burial, and downslope transport. Rates of bioturbation can be as rapid as sustained maximum rates of tectonic uplift. In connection with surface geomorphic processes, bioturbation alters fundamental properties of soil, including particle-size distribution and porosity.

(Wilson, 1999)

There are three principal processes to account for the genesis of clay minerals. These processes are: (a) detrital inheritance whereby, for soils, clay minerals are inherited from pre-existing parent rock or weathered materials; (b) transformation where the essential silicate structure of the clay mineral is maintained to a large extent, but with major change in the interlayer region of the structure; and (c) neoformation, where the clay mineral forms through crystallization of gels or solutions.

Regarding neoformation, two mineral weathering processes have been distinguished in the formation of clay minerals in soils: Hydrolysis and acidolysis. The first occurs through dilute solution with high pH (5-9.6). Total hydrolysis leads to precipitation of gibbsite and kaolinite minerals whereas partial hydrolysis, under different conditions, leads to the formation of smectite minerals. The second process operates when the soil pH is <5 and leads to the generation of layer silicates.

In general, acydolysis is associated with cold temperate climates whereas hydrolysis is dominant in warm humid tropics and warm temperate zones.

Thus, kaolinite is typical of freely drained, acid and base-depleted tropical environments, where an abundant supply of water ensures the required silica and alumina. Montmorillonite is more typical of a poorly drained or hydromorphic soils under alkaline conditions, rich in Mg and Ca ions and where Si, A1 and commonly Fe tend to accumulate. Smectite minerals originate in low-lying topography, poor drainage and base-rich parent material.

Vertisols are dominated by smectite originating through inheritance or neoformation. Vertisols may have formed on alluvial plains where inherited smectite is of detrital origin such as in Sudan (Wilson & Mitchell, 1979), Turkey (0zkan & Ross,1979; Gfizel & Wilson, 1981) and northern Uruguay (Rossignol, 1983). In these instances, the smectites are all Fe-rich with a high tetrahedral charge. Similar smectites are found in Vertisols developed upon basic igneous rocks, such as found in Kenya (Kantor & Schwertmann, 1974), Israel (Singer, 1971) and Jordan (Shadfan, 1983) where the clay mineral has a neoformational origin. Smectites originating by transformation of micas have not been conclusively demonstrated to occur in Vertisols although Badroui & Bloom (1990) and Graham & Southard (1983) have suggested the possibility. However, it would be surprising if a mica-to-smectite conversion is able to occur in the poorly drained conditions characteristic of Vertisols.

In other words, the smectites are largely pedogenic, forming by a combination of transformation and neoformation but in vertisols a neoformation origin seem to be the main genetic process.

7. CONCLUSIONS

The dimension of paleosol bodies in the Yalgorup member is key to assess the containment potential of this unit should the plume migrate up from the Wonnerup member.

Generally speaking the paleosol facies are by nature extensive and irregular in shape, which have a small average thickness and present rather continuous petrophysical properties that do not suffer a great impact during diagenesis. However, dimension rules for these bodies have not yet been defined and this presents a challenge during the facies modelling stage. Based on bibliography research of paleosol case studies, these bodies usually extend for hundreds of meters to tens of hundreds of meters. Their dimension is associated to their simultaneous autocyclic nature (small scale processes inherent to the sedimentary environment) and their allocyclic origin (global or basin scale control factors).

Amongst the first type of processes are differential erosion and/or compaction, partial erosion of paleosols by channelized bodies, variations on topography affecting the water-table depth or channel avulsion. Amongst the second type, tectonic and climate conditions are the most relevant.

In order to model these sedimentary bodies, it is important to deduct their spatial variability from the analysis of the basin paleorelief, tectonic and paleoclimatic conditions so a regional extension of the bodies can be assessed. Also observing the lateral variations in pedotype distribution, degree of maturity of paleosol and lateral relationship between neighbour facies will give an idea of dimensions and internal variability of individual paleosols.

In the particular case of the Harvey area, the Yalgorup materials were deposited over a period of about Twenty Seven million years reaching a total thickness over 500m. In the Perth Basin during that time there was tectonic stability dominated by thermal subsidence and a suitable warm temperate climate, alternating dry and wet periods, sustained during enough time to have allowed the development of extensive vertisol formations at basin scale.

On the other hand, the average paleosol facies thickness observed on core data from GSWA Harvey 1 well, indicate that individual paleosol bodies are between 2.5 to 3m thick, which is an indication of lateral extensions up to several hundreds of meters.

According to core analysis the paleosol facies of the Yalgorup and basal Eneabba present a high percentage of claystone with abundant Kaolinite, Illite and Smectite as main diagenetic clay minerals present. However, even within this continuous soil profile rapid facies switching can be observed, i.e.: sandstone dykes, high energy channel fill or moderate energy channel barforms, indicated by the variation in grain size and petrophysical properties.

Subsequently the high content in clay minerals and widespread continuity, gives theses facies a large potential as containment unit for CO_2 injection in the Harvey area. The internal variations on paleosol properties observed on these bodies are not considered detrimental to the CO_2 sequestration objective. In fact, the small-scale facies variations (high frequency sand/shale alternation) and the tortuous migration pathway that this generates give a low Kv/Kh ratio to these lithostratigraphic units which makes them a suitable target for CO_2 sequestration by increasing the gas migration time to surface.

8. DEFINITIONS

Gelisols (from the Latin *gelare – to freeze**)** are soils that are permanently frozen (contain “permafrost”) or contain evidence of permafrost near the soil surface. Gelisols are found in the Arctic and Antarctic, as well as at extremely high elevations. Permafrost influences land use through its effect on the downward movement of water and freeze-thaw activity (cryoturbation) such as frost heaves. Permafrost can also restrict the rooting depth of plants. Gelisols make up about 9% of the world’s glacier-free land surface.*

Histosols (from the Greek *histos – tissue) are dominantly composed of organic material in their upper portion. The Histosol order mainly contains soils commonly called bogs, moors, peat lands, muskegs, fens, or peats and mucks. These soils form when organic matter, such as leaves, mosses, or grasses, decomposes more slowly than it accumulates due to a decrease in microbial decay rates. This most often occurs in extremely wet areas or underwater; thus, most of these soils are saturated year-round. Histosols can be highly productive farmland when drained; however, drained Histosols can decompose rapidly and subside dramatically. They are also not stable for foundations or roadways, and may be highly acidic. Histosols make up about 1% of the world’s glacier-free land surface.*

Spodosols (from the Greek *spodos – wood ash) are among the most attractive soils. They often have a dark surface underlain by an ashy gray layer, which is subsequently underlain by a reddish, rusty, coffee-colored, or black subsoil horizon. These soils form as rainfall interacts with acidic vegetative litter, such as the needles of conifers, to form organic acids. These acids dissolve iron, aluminum, and organic matter in the topsoil and ashy gray (eluvial) horizons. The dissolved materials then move (illuviate) to the colorful subsoil horizons. Spodosols most often develop in coarsely textured soils (sands and loamy sands) under coniferous vegetation in humid regions of the world. They tend to be acidic, and have low fertility and low clay content. Spodosols occupy about 4% of the world’s glacier-free land surface.*

Andisols (from the Japanese *ando – black soil) typically form from the weathering of volcanic materials such as ash, resulting in minerals in the soil with poor crystal structure. These minerals have an unusually high capacity to hold both nutrients and water, making these soils very productive and fertile. Andisols include weakly weathered soils with* *much volcanic glass, as well as more strongly weathered soils. They typically occur in areas with moderate to high rainfall and cool temperatures. They also tend to be highly erodible when on slopes. These soils make up about 1% of the glacier-free land surface.*

Oxisols (from the French *oxide – oxide) are soils of tropical and subtropical regions, which are dominated by iron oxides, quartz, and highly weathered clay minerals such as kaolinite. These soils are typically found on gently sloping land surfaces of great age that have been stable for a long time. For the most part, they are nearly featureless soils without clearly marked layers, or horizons. Because they are highly weathered, they have low natural fertility, but can be made productive through wise use of fertilizers and lime. Oxisols are found over about 8% of the glacier-free land surface.*

Vertisols (from the Latin *verto – turn) are clay-rich soils that contain a type of "expansive" clay that shrinks and swells dramatically. These soils therefore shrink as they dry and swell when they become wet. When dry, vertisols form large cracks that may be more than one meter (three feet) deep and several centimeters, or inches, wide. The movement of these soils can crack building foundations and buckle roads. Vertisols are highly fertile due to their high clay content; however, water tends to pool on their surfaces when they become wet. Vertisols are located in areas where the underlying parent materials allow for the formation of expansive clay minerals. They occupy about 2% of the glacier-free land surface.*

Aridisols (from the Latin *aridus – dry) are soils that occur in climates that are too dry for "mesophytic" plants—plants adapted to neither too wet nor too dry environments—to survive. The climate in which Aridisols occur also restricts soil weathering processes. Aridisols often contain accumulations of salt, gypsum, or carbonates, and are found in hot and cold deserts worldwide. They occupy about 12% of the Earth's glacier-free land area, including some of the dry valleys of Antarctica.*

Ultisols (from the Latin *ultimus – last) are soils that have formed in humid areas and are intensely weathered. They typically contain a subsoil horizon that has an appreciable amount of translocated clay, and are relatively acidic. Most nutrients are held in the upper centimeters of Ultisol soils, and these soils are generally of low fertility although they can become productive with additions of fertilizer and lime. Ultisols make up about 8% of the glacier-free land surface.*

Mollisols (from the Latin *mollis – soft) are prairie or grassland soils that have a dark colored surface horizon, are highly fertile, and are rich in chemical "bases" such as calcium and magnesium. The dark surface horizon comes from the yearly addition of organic matter to the soil from the roots of prairie plants. Mollisols are often found in climates with pronounced dry seasons. They make up approximately 7% of the glacier-free land surface.*

Alfisols (from the soil science term *Pedalfer – aluminum and iron) are similar to Ultisols but are less intensively weathered and less acidic. They tend to be more inherently fertile than Ultisols and are located in similar climatic regions, typically under forest vegetation. They are also more common than Ultisols, occupying about 10% of the glacier-free land surface.*

Inceptisols (from the Latin *inceptum – beginning) exhibit a moderate degree of soil development, lacking significant clay accumulation in the subsoil. They occur over a wide range of parent materials and climatic conditions, and thus have a wide range of characteristics. They are extensive, occupying approximately 17% of the earth's glacier-free surface.*

Entisols (from *recent – new) are the last order in soil taxonomy and exhibit little to no soil development other than the presence of an identifiable topsoil horizon. These soils occur in areas of recently deposited sediments, often in places where deposition is faster than the rate of soil development. Some typical landforms where Entisols are located include: active flood plains, dunes, landslide areas, and behind retreating glaciers. They are common in all environments. Entisols make up the second largest group of soils after Inceptisols, occupying about 16% of the Earth's surface.*

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