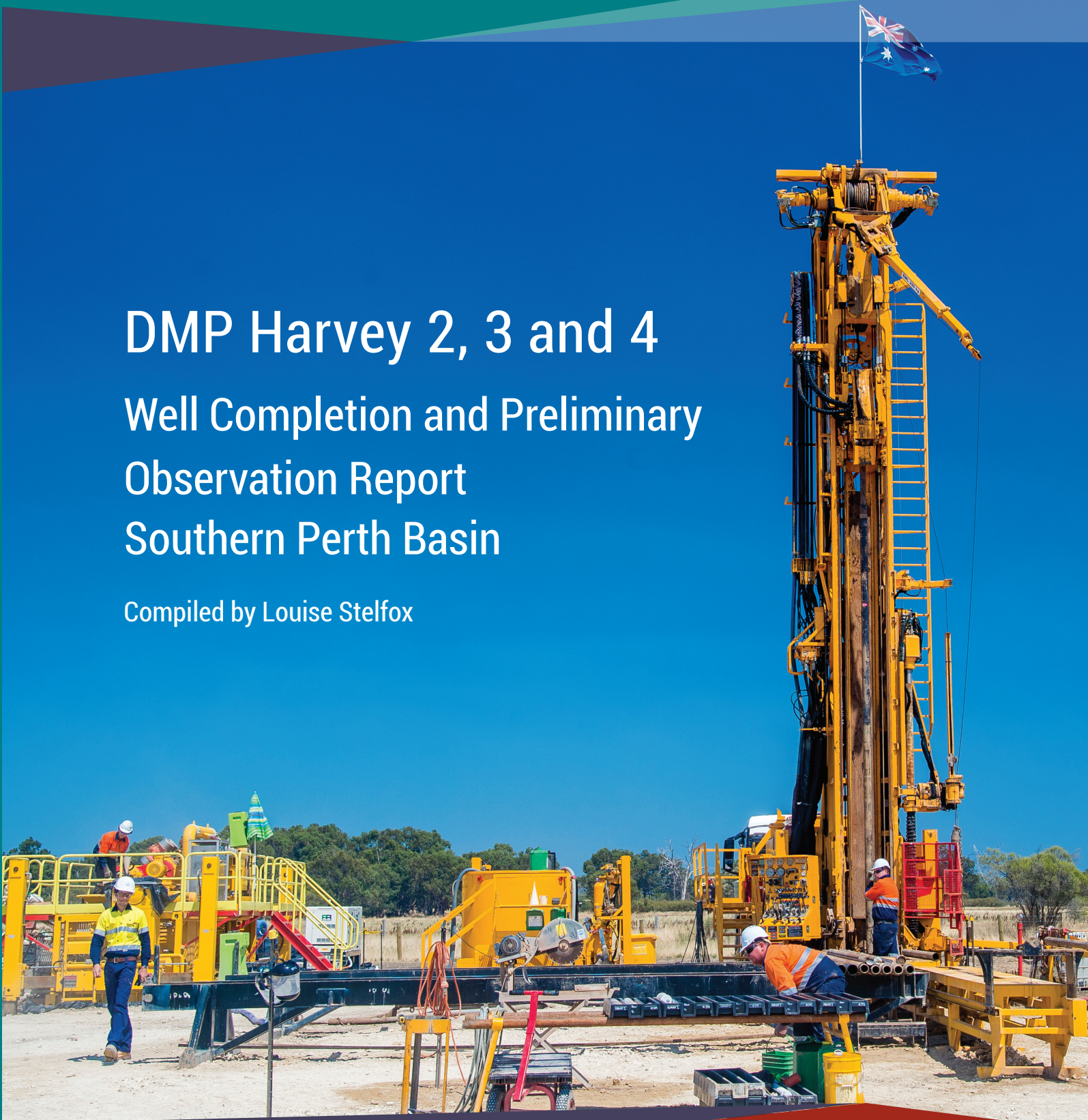




Government of **Western Australia**  
Department of **Mines, Industry Regulation and Safety**

# DMP Harvey 2, 3 and 4 Well Completion and Preliminary Observation Report Southern Perth Basin

Compiled by Louise Stelfox



Department of Mines, Industry Regulation and Safety (DMIRS) was created on July 1, 2017 with the amalgamation of the former Department of Mines and Petroleum (DMP) and parts of the Department of Commerce.

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The DMP Harvey 2, 3 and 4 drilling and evaluation program was made possible by Commonwealth funding through the Department of Industry, Innovation and Science's Carbon Capture and Storage (CCS) Flagship Program.

The recommended reference for this publication is:

Stelfox, L., (compiler) 2017, DMP Harvey 2, 3 and 4 well completion and preliminary observation report, southern Perth Basin: Department of Mines, Industry Regulation and Safety

**National Library of Australia Card Number and ISBN** 978-0-646-97801-7

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

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## Acknowledgements

The work that is the subject of this report was undertaken with the combined input and contributions from the State of Western Australia's Department of Mines, Industry Regulation and Safety (DMIRS) staff, local Harvey community, drilling contractors DDH1 Drilling Pty Ltd and Drilling Contractors of Australia (DCA), KD.1 Pty Ltd, Rockwater Pty Ltd, Halliburton Australia Pty Ltd, ODIN Reservoir Consultants Pty Ltd and the National Geosequestration Laboratory (NGL) research scientists. The latter is a collaboration between the Commonwealth Scientific and Industrial Research Organisation (CSIRO), The University of Western Australia (UWA) and Curtin University.

The South West Hub (SW Hub) carbon capture and storage (CCS) project is financed by the Government of Australia through the Department of Industry, Innovation and Science, and by the State Government of Western Australia through DMIRS.

The Shire of Harvey and the Lesueur Community Consultative Committee (LCCC) are thanked for their community-engagement roles for DMIRS' drilling activities.

Acknowledgment and thanks for their input and assistance is extended to all of the contracted companies, Geological Survey of Western Australia (GSWA, a division of DMIRS), the individual landowners and DMIRS' Carbon Strategy Branch, which includes Dominique Van Gent, Martin Burke, Sandeep Sharma, Kelli Jones, Beth Ferguson, Martin Edmunds and Lisa Crummack. Dr Linda Stalker and the NGL researchers are acknowledged for their contributions in community engagement and with the research and provision of geophysical data. Particular thanks are given to those parties who exceeded their contractual obligations and who partnered with the local community.

Special thanks and acknowledgements to Murray Pollock, Robin Russell, Peter Nims, Alex Aitken, Paul and Phil Curulli, Marjorie Eckersley, Laurie Dimasi, staff at the Amana Inn, Tony Kennaird, James Brown, Ajit Singh, David Lim, Conor Byrne, Geoff Strachan, Jon Roestenburg, Richard O'Brien, Alan Bloore, Allison Hortle, Trevor Iley, Rockwater Pty Ltd's on-site geologists and Fiona Eddison.

Contributors from DMIRS included Alan Millar, Mike Middleton (dec.), Stuart Webster, Arthur Mory, Charmaine Thomas, Alex Zhan, Ted Bowen, Peter Haines, Sarah Martin, Paul Stephenson, Adam Symonds and the team at GSWA's Perth Core Library, including Kris Sando and Lena Hancock.

## Executive summary

This report summarises the drilling program carried out in 2014–15 by the State of Western Australia's (WA); Department of Mines and Petroleum, now Department of Mines, Industry Regulation and Safety (DMIRS). The purpose of the drilling was to acquire pre-competitive data to assess the ability of the Lesueur Sandstone to store and contain supercritical carbon dioxide (CO<sub>2</sub>). The wells were drilled and constructed to the northwest of the Harvey townsite in the South West (SW) Hub study area, which is in the South West region of WA.

Three stratigraphic wells were drilled and investigated, named DMP Harvey 2, DMP Harvey 3 and DMP Harvey 4. This document reports the information and data captured, and analysis and preliminary interpretation of the data. The first section of this report introduces the study area and previous investigations, the second section describes the rationale and the planning of the drilling program and the third section reports on the data and information as required by the Petroleum and Geothermal Energy Resources Act 1967, Petroleum and Geothermal Resources (Resource Management and Administration) Regulations 2015, Schedule 9. The lessons learned from the drilling program, with recommendations for further work, conclude this report.

The wells were drilled within the southern Perth Basin, on the structural feature known as the Harvey Ridge, between December 2014 and June 2015. Seismic data tied to the GSWA Harvey 1 well were used to advise prognosed depths to the targeted strata and to site the wells.

The Lesueur Sandstone comprises the Wonnerup Member (target reservoir) overlain by the Yalgorup Member and, in turn, the Eneabba Formation (containing strata). The Wonnerup Member is a saline aquifer, approximately 1500m thick, that has the potential to act as a CO<sub>2</sub> storage reservoir through mechanisms such as dissolution and residual trapping. The Yalgorup Member and Eneabba Formation contain low-permeability strata with the potential to act as containing units. Importantly, the Yarragadee Formation, which is a significant fresh-groundwater aquifer in the Perth Basin, is absent in the area of interest.

In September 2014, the department contracted DDH1 Drilling Pty Ltd (DDH1 Drilling) to drill the three wells. Wells DMP Harvey 2 and 3 were drilled with a mineral rig. The first sections of each well were open-hole rotary drilled, with wireline core drilling employed to total depth. DMP Harvey 4 was open-hole rotary drilled using a water rig, with interval coring at targeted depths.

The drilling program took longer than anticipated due to abrasive ground conditions, varying lithologies and formation instability. The predicted stratigraphy was intersected, with depths to formation tops and marker horizons generally shallower than prognosed. During drilling, the top of the Wonnerup Member was the only clearly identifiable unit boundary.

Drill chips were collected during rotary drilling and a total of 2136m of core were acquired. Mudstone-rich core samples were selected for preservation. The wells were lithologically logged on site. The core trays were run through the HyLogger spectral scanner upon arrival at DMIRS' Perth Core Library.

All wells were wireline logged for well formation evaluation. Gamma ray, resistivity, dipole sonic and caliper logs were run in the three wells, with the addition of neutron–density logging in DMP Harvey 3 and 4. In addition to the basic logs, DMP Harvey 3 was logged with Halliburton's HSFT™ formation tester, while the XRM1™ image log tool and RDTT™ reservoir description tool were used in DMP Harvey 4. Vertical seismic profiling was carried out at each of the wells.

The three wells were cased with oilfield stainless steel and the well annuli were grouted to surface. Wells DMP Harvey 3 and 4 were completed with chromium steel casing in the lower 330 and 326m, respectively. The wells have been completed with lockable covers and are available for further investigations.

Three hundred and twenty four (324) core samples were scheduled for routine core analysis (RCA), including porosity, permeability and grain density testing. Select core samples were scheduled for special core analysis (SCAL), which included mercury injection capillary pressure (MICP), palynology, X-ray diffraction (XRD) and petrographical examination. Core samples from the Wonnerup Member were tested for geomechanical properties and relative permeability for CO<sub>2</sub> displacing brine.

ODIN Reservoir Consultants Pty Ltd integrated the data from wells with the 3D seismic data to create five depth surfaces. A number of stochastic 3D static geological models were created and used to develop dynamic injection-simulation models. The dynamic modelling assessed the injection potential of the Wonnerup Member. The modelling process was peer reviewed by oil and gas industry modellers. Given the modelling assumptions, the results indicate that 800,000 tonnes per annum of CO<sub>2</sub> could be injected over 30 years in the Wonnerup Member at a depth of 3000m, with the injected CO<sub>2</sub> remaining within the Wonnerup Member beyond 1000 years.

All data and reports resulting from the drilling and investigation of wells DMP Harvey 2, 3 and 4 are presented as appendices to this report. These can also be downloaded free of charge from DMIRS website ([www.dmirs.wa.gov.au/ccs](http://www.dmirs.wa.gov.au/ccs)), or from the Western Australian Petroleum Information Management System (WAPIMS) database ([wapims.dmirs.wa.gov.au/wapims](http://wapims.dmirs.wa.gov.au/wapims)).

**KEYWORDS:** southern Perth Basin, Harvey Ridge, Jurassic, Triassic, paleosols, carbon dioxide, carbon trading, coring, core analysis, core logging, wireline logging, reservoir data, reservoir data, organic petrology, petrography, palynology, geomechanics, permeability, spectral analysis, static modelling, dynamic modelling.

## 1.0 Introduction

The DMP Harvey 2, 3 and 4 wells have been drilled in the southern Perth Basin in Western Australia to ascertain the potential for the Lesueur Sandstone to store and contain injected supercritical carbon dioxide (CO<sub>2</sub>) gas. The drilling has been undertaken as part of the South West Hub (SW Hub) project, Australia's first Carbon Capture and Storage (CCS) Flagship project. The SW Hub project was created as a government and industry partnership, researching an economically and environmentally sustainable low-carbon future in the South West region of Western Australia.

This section describes the targeted audience for this report, location of the study area, activities leading up to the drilling of the wells and the research that is being carried out in the SW Hub study area. Supercritical CO<sub>2</sub> is described in section 1.5.

### 1.1 Target audience

This report has been compiled for those requiring data collected during the drilling and subsequent investigation of wells DMP Harvey 2, 3 and 4.

The key stakeholders of the project are as follows:

- Western Australian State Government through DMIRS
- Commonwealth Government through the Department of Industry, Innovation and Science (DIIS)
- local community in the southwest of Western Australia
- carbon dioxide emitting industry.

### 1.2 Location of study area

The study area is in the South West region of Western Australia, northwest of Harvey townsite as shown in Figure 1. The study area is accessible from the north or south by the Forrest Highway to the west, or the South West Highway to the east. The area is low lying and semi-rural in nature, with the land being typically used for beef and dairy farming, fruit production and tree plantations. A series of drains, tracks and Local Government Authority roads run between the paddocks, connecting properties to the main roads.

The well-sites are on flat, open, grassy areas. Due to the boggy nature of the ground during the winter to early summer months, limestone tracks were constructed prior to drilling.

Riverdale Road provides direct access to the GSWA Harvey 1 and DMP Harvey 2 wells (Figure 1a,b). The DMP Harvey 3 well is located within the Dampier to Bunbury pipeline corridor, which is accessible from Crampton Road (Figure 1c), and the DMP Harvey 4 well is accessed from Gibbs Road (Figure 1d). The details of the properties on which the three wells have been drilled are given in Table 1.

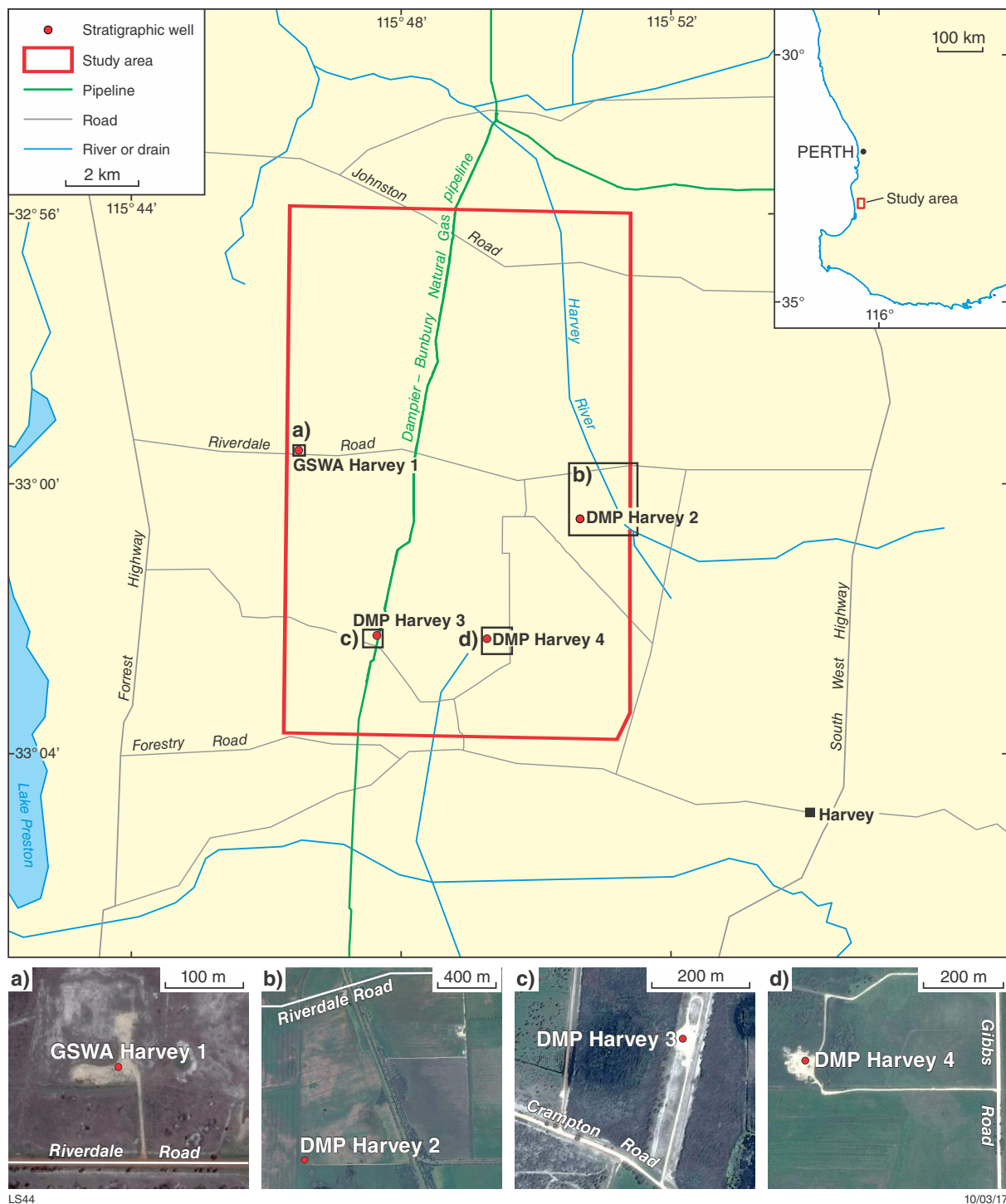


Figure 1: Location of the SW Hub study area, northwest of the Harvey townsite in the South West region of Western Australia. The locations of the four wells drilled by DMIRS between 2011 and 2015 are shown in the study area, with aerial views of the drilling sites shown in the insets.

Table 1: Well-site property details

Well	Lot number	Access-road name
DMP Harvey 2	Lot 2 D41313	Riverdale Road
DMP Harvey 3	Lot 2691 P136890	Crampton Road
DMP Harvey 4	Lot 52 D92136	Gibbs Road

### 1.3 Preliminary investigations

A number of activities were undertaken as part of the SW Hub project prior to the drilling of the DMP Harvey 2, 3 and 4 wells. This work includes preliminary desktop studies, a 2D seismic survey in 2011, a 3D seismic survey in 2015, reservoir modelling and the drilling of well GSWA Harvey 1 in 2012, each of which is summarised herein.

#### 1.3.1 Desktop study

The geological structural feature known as the Harvey Ridge was identified in regional studies as having potential for CO<sub>2</sub> storage in saline aquifers (Varma et al., 2009). The study area was interpreted to contain a significant thickness of a saline aquifer within the sand-rich facies of the lower Lesueur Sandstone (Wonnerup Member), which could act as a target reservoir for injected supercritical CO<sub>2</sub>. This is overlain by variably interbedded mudstones and sandstones of the potential containing strata, the upper Lesueur Sandstone (Yalgorup Member), and the Eneabba Formation.

Importantly, the area does not contain the Yarragadee Formation (Figure 2), a significant fresh groundwater aquifer in the Perth Basin. The Lesueur Sandstone storage complex consists of the lower Lesueur Sandstone (Wonnerup Member) as the injection reservoir, the upper Lesueur Sandstone (Yalgorup Member) as a lower confining layer and the Eneabba Formation, including the 'basal Eneabba unit' (sequence of thick paleosols), as the upper confining layer.

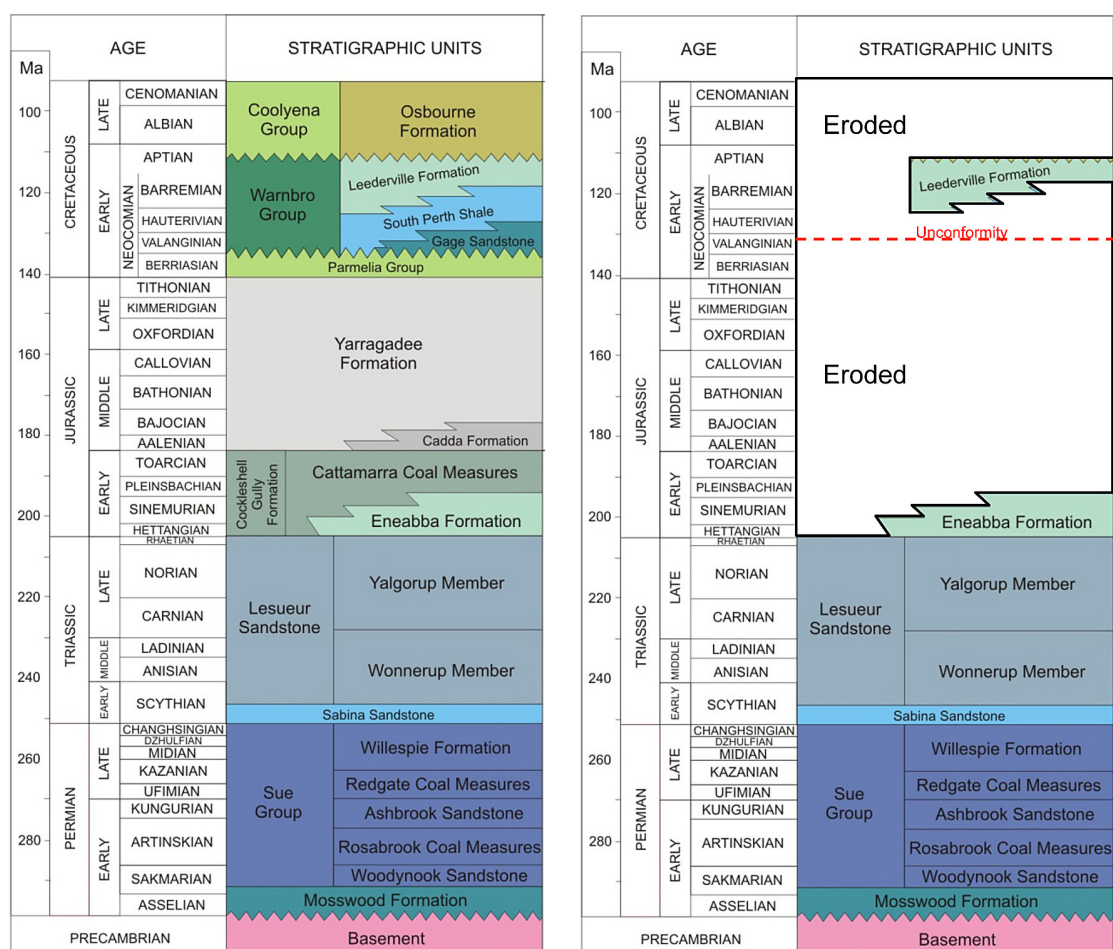


Figure 2: Stratigraphic units of the southern Perth Basin (left). The stratigraphy encountered during the drilling of well GSWA Harvey 1 (right), differed from the remainder of the Basin in that, with the exception of the Eneabba Formation and the Leederville Formation, the Jurassic and Cretaceous strata are absent in the SW Hub study area.

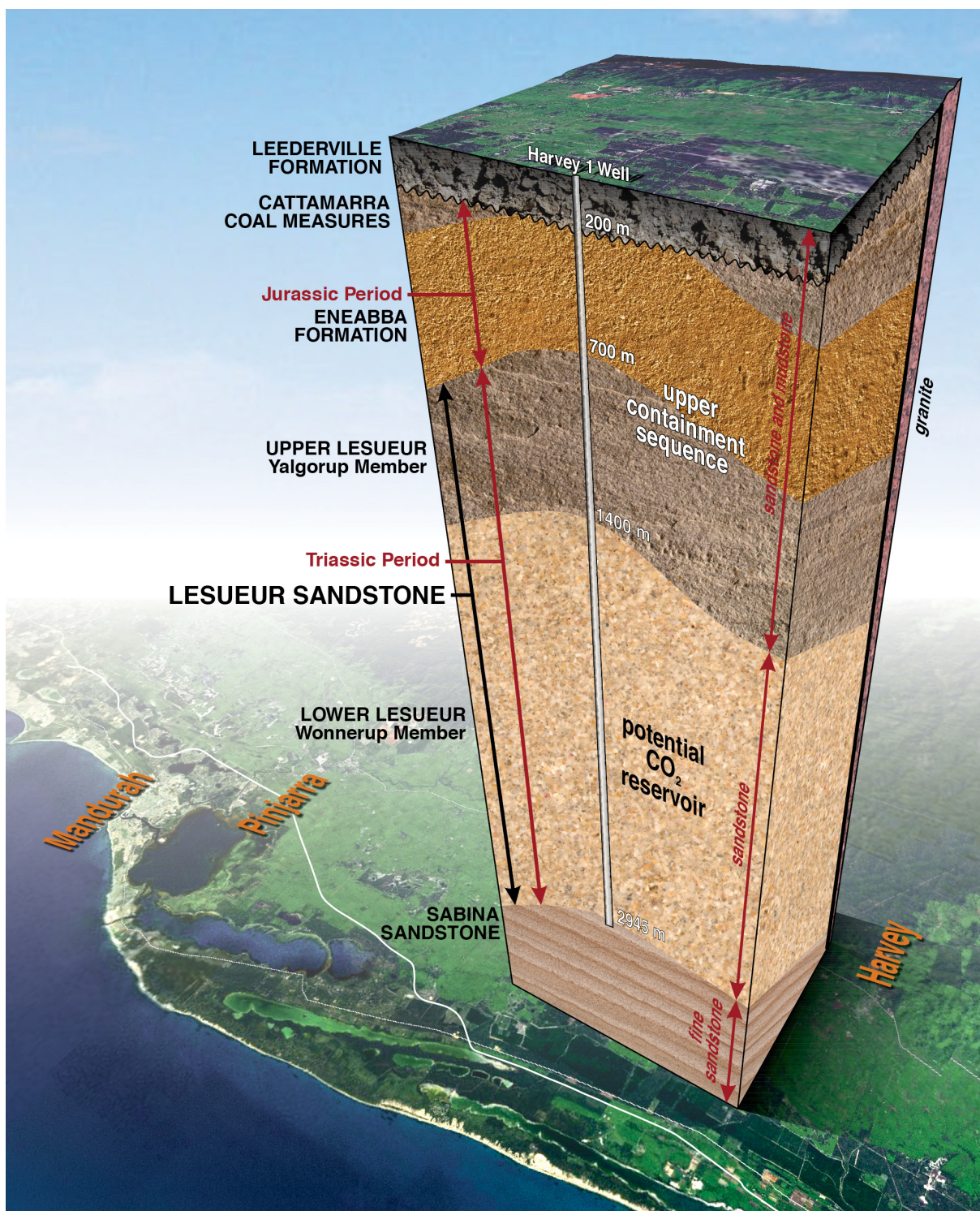


Figure 3: Stratigraphic sketch of the SW Hub study area, as determined from the drilling of GSWA Harvey 1.

### 1.3.2 2D seismic survey

In March 2011 GSWA and Geoscience Australia (GA) completed a 106km 2D seismic survey along shire roads (Figure 1). Data from the 2D seismic survey are available from DMIRS WAPIMS database<sup>1</sup> or the GA website<sup>2</sup>. A preliminary interpretation was undertaken by Fiah and Guiton (2011). The final, published 2D seismic interpretation report (Zhan, 2014) is available from GSWA or the National Library of Australia<sup>3</sup>.

<sup>1</sup> [wapims.dmp.wa.gov.au/wapims](http://wapims.dmp.wa.gov.au/wapims)

<sup>2</sup> [www.ga.gov.au/products/servlet/controller?event=GEOCAT\\_DETAILS&catno=74810](http://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=74810)

<sup>3</sup> [catalogue.nla.gov.au/Record/6578689](http://catalogue.nla.gov.au/Record/6578689)

### 1.3.3 GSWA Harvey 1 well

The results from the 2D seismic survey, together with existing seismic data, were used in planning stratigraphic well GSWA Harvey 1 (Fiah and Guiton, 2011). The objective of drilling GSWA Harvey 1 was to acquire pre-competitive data needed to assist in filling a number of knowledge gaps. Well GSWA Harvey 1 was located on private land (Lot 1326) off Riverdale Road, Cookernup (Figure 1). Following a public tender MB Century was awarded the contract to drill the well using its Rig 7 (Figure 4). The well design and drilling management were completed by Aztech Well Construction Pty Ltd in conjunction with GSWA.



*Figure 4: MB Century Drilling Pty Ltd's petroleum Rig 7 drilling well GSWA Harvey 1 in 2012 (photo courtesy of Mark Mitchell, Aztech Well Construction Pty Ltd).*

In 2012 GSWA Harvey 1 was openhole rotary drilled with targeted interval coring used to cut and recover six cores from four intervals. The resulting core and wireline logging data were analysed, evaluated and recorded. This work, along with preliminary interpretations, has been reported by Millar and Reeve (2014). Well GSWA Harvey 1 was plugged and decommissioned on completion.

The GSWA Harvey 1 well successfully:

- confirmed the presence of the predicted stratigraphy (Figures 2 and 3)
- collected fresh core samples of the Lesueur Sandstone for containment capacity, reservoir characterisation and injectivity testing
- tested the running of a comprehensive suite of modern evaluation logs
- calibrated the 2D seismic data in order to integrate findings into the 3D model for the area
- assisted in the planning and development of the 3D seismic survey and wells DMP Harvey 2, 3 and 4 for further evaluation of the study area.

The GSWA Harvey 1 investigation was unsuccessful in:

- retrieving core from the 'basal Eneabba unit'
- obtaining a full set of formation-fluid samples following the failure of the logging cable and subsequent tool loss.

As a consequence of uncertainties in the seismic horizon picks of formation boundaries, the GSWA Harvey 1 investigation did not evaluate the containment capacity of the 'basal Eneabba unit' and the low-permeability strata overlying the target reservoir (Millar and Reeve, 2014). As such, these were addressed during the drilling of DMP Harvey 2, 3 and 4. A significant amount of new data was obtained from the GSWA Harvey 1 well to address the geological uncertainties, as captured in the modelling report (Fiah and Guiton, 2011).

### 1.3.4 Reservoir model

The data obtained from 2011 2D seismic survey were integrated with existing 2D seismic survey data and data from GSWA Harvey 1 to develop a 3D reservoir model to simulate how injected supercritical CO<sub>2</sub> could migrate through the reservoir from a number of conceptual injection wells (Fiah and Guiton, 2011). This first model was helpful in defining the outstanding data required to define the injection and containment potential of the Lesueur Sandstone. The model focused on the ability of the Wonnerup Member to receive and store injected CO<sub>2</sub>, through residual trapping and solubility mechanisms, and for the Yalgorup Member to provide secondary containment through its many baffles, by preventing or delaying upward movement of CO<sub>2</sub>.

### 1.3.5 3D seismic survey

In 2014 a 3D seismic survey was carried out within the 115km<sup>2</sup> SW Hub study area, within the Shires of Harvey and Waroona (Burke, 2014; Figure 5). This survey is listed as '2013 Harvey Waroona 3D seismic survey' in DMIRS' WAPIMS database.



Figure 5: Vibroseis trucks working in tandem during the Harvey Waroona 3D seismic survey (Geokinetics Pty Ltd, April 2014).

The 3D seismic survey focused on acquiring high-fold seismic reflection data over the Wonnerup Member, from approximately 1500 to 3000m depth. This has resulted in good structural mapping and fault definition in the Wonnerup Member, with lower definition of structure and faults in the Eneabba Formation and the Yalgorup Member.

## 1.4 Research

The principal objectives behind the drilling of the GSWA Harvey 1 and DMP Harvey 2, 3 and 4 stratigraphic wells were to acquire core and geological data to further assess the technical feasibility of storing, and permanently containing, up to 4.6Mt of CO<sub>2</sub> per annum over 30 years in a condition referred to as a 'supercritical' fluid<sup>4</sup> (refer to section 1.5 for details). The Department of Mines, Industry Regulation and

<sup>4</sup> The specified quantity of supercritical CO<sub>2</sub> and the rate of injection were submitted by DMP to the Commonwealth Government CCS Flagship program: Business Case for Collie – South West CO<sub>2</sub> Geosequestration Hub, in 30 June 2010 (Van Gent, 2010).

Safety has coordinated the collection of material and data from the wells and its distribution to institutions and organisations contracted to examine and report on the knowledge acquired from the project. Ongoing studies are being coordinated by DMIRS and ANLEC R&D (Australian National Low Emissions Coal Research and Development). The research studies and investigations are being run by scientists and engineers from Commonwealth Scientific and Industrial Research Organisation (CSIRO), Curtin University, The University of Western Australia (UWA) and other institutions in Australia (Figure 6). Many of these research scientists have been involved with the Otway Carbon Capture and Storage research facility in Victoria<sup>5</sup>.

Research projects were, and continue to be, commissioned to evaluate the data from DMP Harvey 2, 3 and 4. Final research project reports are published separately by ANLEC R&D<sup>6</sup> and these will also be made available on the DMIRS website as they are completed.

The research work is important and valuable, as it augments and enhances DMIRS' work by advancing the storage assessment from a 'pre-competitive' phase to a point where the project could become a viable business opportunity for industry. Research project submissions to ANLEC R&D Committee are discussed with DMIRS before they are finalised and funded. Proposals to date have involved trialling novel data-processing and interpretation techniques, and acquisition of targeted additional data in the SW Hub study area.



*Figure 6: Researchers from ANLEC R&D (Dr Lionel Glendenning, Dr Roman Pevzner and Dr Linda Stalker) reviewing preliminary wireline logging data from wells DMP Harvey 2, 3 and 4 at Australian Resources Research Centre, (ARRC) Kensington, in May 2015 (photo courtesy of National Geosequestration Laboratory (NGL)).*

## **1.5 About supercritical carbon dioxide**

The SW Hub study area is being investigated for the injection and storage of supercritical CO<sub>2</sub>, potentially sourced from power stations or industry, or both, in the South West region of Western Australia. In its natural and preferred state, CO<sub>2</sub> is a gas. When CO<sub>2</sub> is held above its critical temperature of 31°C and above its critical pressure of 7.36MPa (1070psi or 74 bar; Figure 7), it forms a dense phase fluid referred to as supercritical CO<sub>2</sub>. Supercritical CO<sub>2</sub> no longer behaves as a conventional liquid or gas, but has the properties of both a low-viscosity gas and a liquid<sup>7</sup>.

<sup>5</sup> See [www.CO2CRC.com.au/otway-research-facility](http://www.CO2CRC.com.au/otway-research-facility)

<sup>6</sup> See [www.anlecrd.com.au/publications](http://www.anlecrd.com.au/publications)

<sup>7</sup> See [www.CO2CRC.com.au](http://www.CO2CRC.com.au)

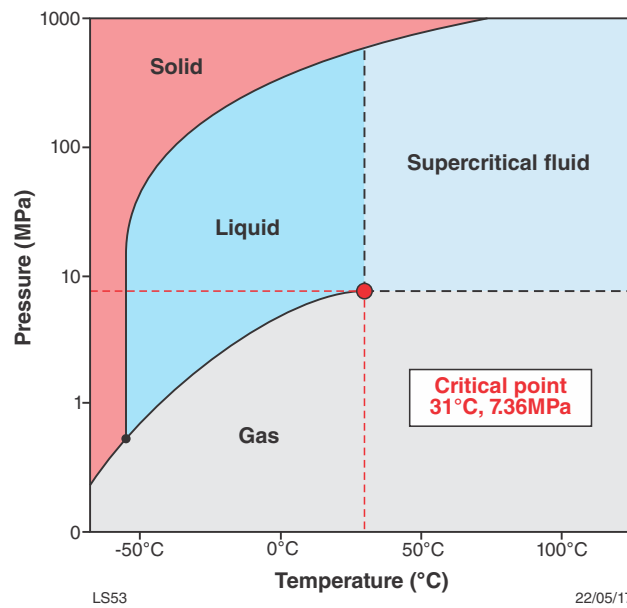


Figure 7: Graph showing the three phases of carbon dioxide, with the critical point corresponding to a temperature of 31°C and pressure of 7.36MPa.

Figure 8 shows how the volume and density of CO<sub>2</sub> vary with depth. Below approximately 800m depth, where in situ pressures are greater than 7.36MPa or 1067psi, CO<sub>2</sub> is a supercritical fluid. Above approximately 800m, a reduction in the confining pressure results in the CO<sub>2</sub> increasing in volume, and decreasing in density, to become a conventional gas.

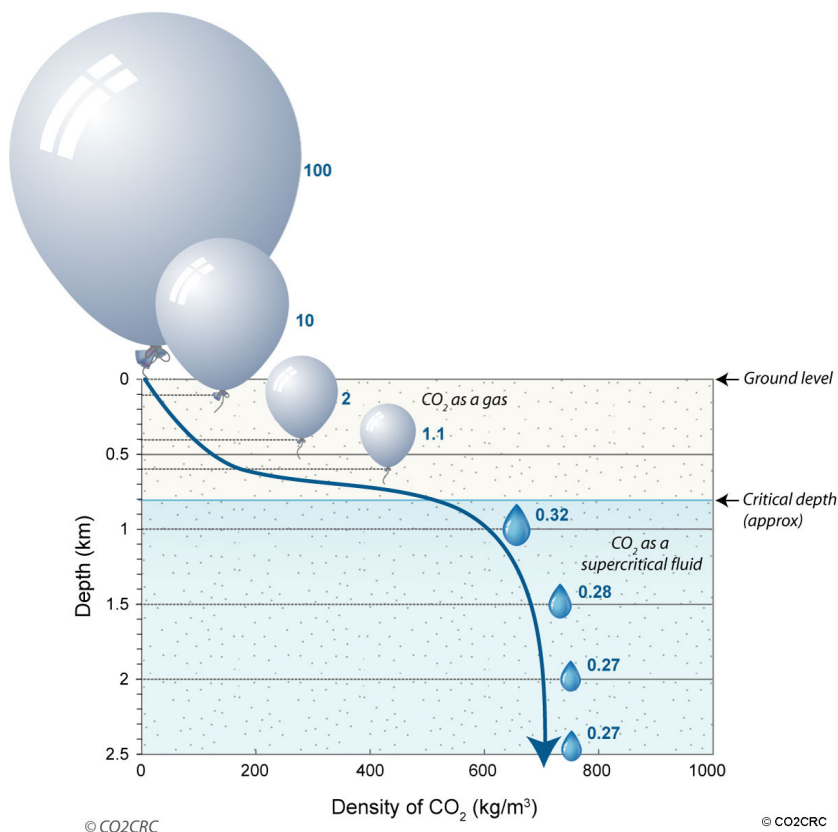


Figure 8: Diagram showing the volumetric and density changes of carbon dioxide with depth. Carbon dioxide (CO<sub>2</sub>) is a supercritical fluid below 800m depth (courtesy of CO2CRC Ltd, <http://www.CO2CRC.com.au>).

Any proposal for storage of CO<sub>2</sub> in the SW Hub study area would be to inject supercritical CO<sub>2</sub> into the Wonnerup Member reservoir at depth and to retain the CO<sub>2</sub> in the storage complex below 800m.

## 2.0 Drilling program

This section reports on DMIRS scoping, planning and selection of the drilling regime, the drilling objectives and the procurement and contractual arrangements that resulted in the successful completion of the wells.

### 2.1 Rationale for drilling

Department of Mines, Industry Regulation and Safety's rationale for drilling DMP Harvey 2, 3 and 4 followed earlier investigations. The on-ground activities were carried out to obtain pre-competitive data to prove up the containment and injection potential of the Lesueur Sandstone.

#### 2.1.1 Decision framework for addressing uncertainties

To address the areas of uncertainty regarding the ability of the Lesueur Sandstone to receive and contain the required volumes of supercritical CO<sub>2</sub>, DMIRS operated a value-for-money, stage-gated decision framework in the sequence shown in Table 2.

Table 2: Stage-gated decision framework to address uncertainty prior to drilling the DMP Harvey 2, 3 and 4 wells

Stage gate	Uncertainty	Activity	Uncertainty addressed
1	Is there a reservoir and containment potential?	2D seismic survey (2011) and GSWA Harvey 1 well (2012)	Progress made and models improved
2	What is the 3D structure of the study area?	3D seismic survey (2014)	Geological structure and stratigraphy illuminated, with GSWA Harvey 1 used as a well tie
3	Are the baffles and reservoir laterally extensive across the study area? Is there containment potential?	'Shallow' drilling program, notionally 50m into the top of the Wonnerup Member	To be clarified by spatial drilling using wireline coring
4	What is the injection potential?	A deep well, or well couplet, drilled into the top of the Sabina Sandstone (notionally 'DMP Harvey 5')	To be assessed pending resolution of containment in Stage gate 3

As each area of uncertainty was addressed, DMIRS proceeded with investigations to address and reduce these uncertainties in the next stage of data acquisition, eventually leading to the planning and execution of the drilling of 'shallow wells' DMP Harvey 2, 3 and 4. Each stage of DMIRS investigations is summarised below.

##### 2.1.1.1 Stage gate 1

The GSWA Harvey 1 well was the first deep stratigraphic well to be drilled within the SW Hub study area. The stratigraphy and depth to the formation tops was estimated using available offset well data and the preliminary interpretation of the 2D seismic survey data (Fiah and Guiton, 2011). The planning and design formulated for GSWA Harvey 1 were made on this basis. The final interpretation of the 2D seismic survey is reported by Zhan (2014).

Well GSWA Harvey 1 verified the stratigraphy and the formation tops at the well location and significant reservoir information was obtained via wireline logs and core data. The basal Eneabba unit and top of the Yalgorup Member were intersected at shallower depths than prognosed in the openhole section of the GSWA Harvey 1 well, and so these strata were not cored (Millar and Reeve, 2014).

Reservoir models were built and simulation scenarios were run to track the migration of CO<sub>2</sub> plumes from conceptual injection wells. The results were encouraging. However, the character and lateral extent of the baffles, or containing strata, overlying the Wonnerup Member sandstones and the property distributions through the reservoir remained poorly constrained due to being based on data from one well. Therefore, a shallow drilling program was recommended over a geographic spread to obtain core from the basal Eneabba unit and Yalgorup Member in order to characterise the CO<sub>2</sub> containing capacity of the baffles within these stratigraphic units. The acquisition of additional seismic data was also recommended in order to provide structural and stratigraphic controls.

### 2.1.1.2 Stage gate 2

A 3D seismic survey was carried out in early 2014 within the 115km<sup>2</sup> SW Hub study area. Department of Mines, Industry Regulation and Safety contracted Geokinetics Pty Ltd to collect the seismic reflection data and the resulting data were processed by Velseis Pty Ltd.

Unfortunately, restricted access applied to approximately 34 per cent of the surveyed area, including some private properties, sensitive environmental zones, areas planted to forestry and infrastructure corridors (Figure 10; Burke, 2014; Byrne, 2016). These inaccessible areas resulted in gaps, or 'holes', in the dataset that had an impact on the seismic coverage and data quality, as shown in Figures 9 and 11. The holes in the dataset decrease with increasing depth, as shown in Figure 12. At a depth of approximately 2000m below ground level the survey 'fold' parameter was almost double the contract specifications.

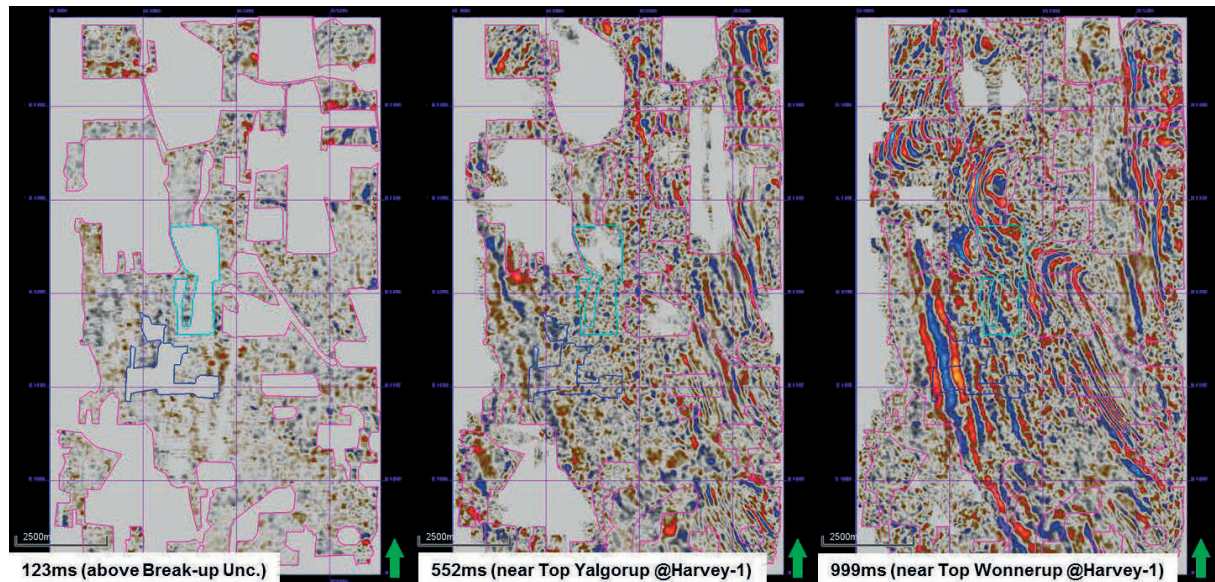


Figure 9: Interpreted 3D seismic survey data: shallow and deeper time slices showing seismic coverage (Byrne, 2016).

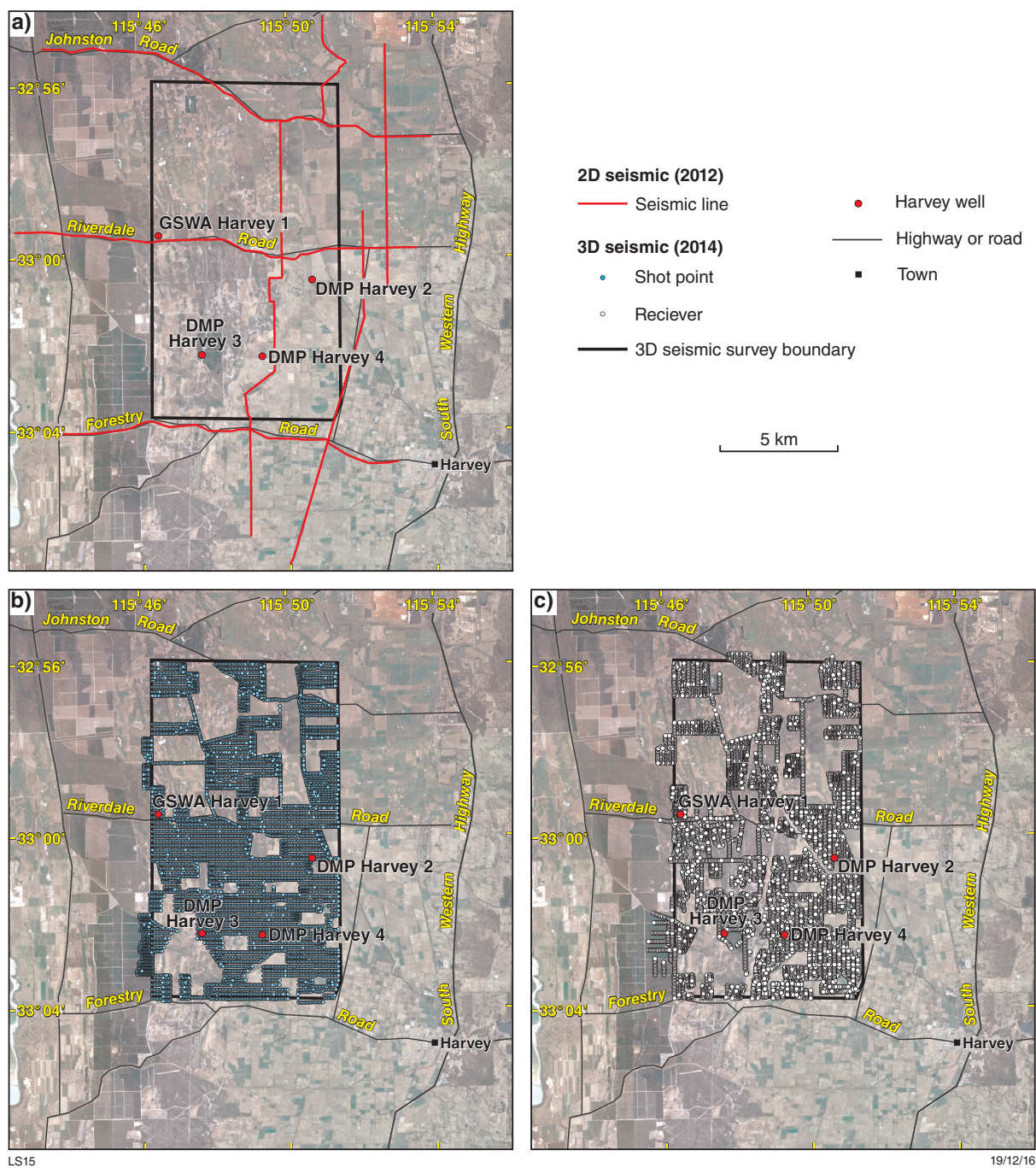


Figure 10: Location of wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4, and the 2D and 3D seismic surveys of 2012 and 2014, respectively.

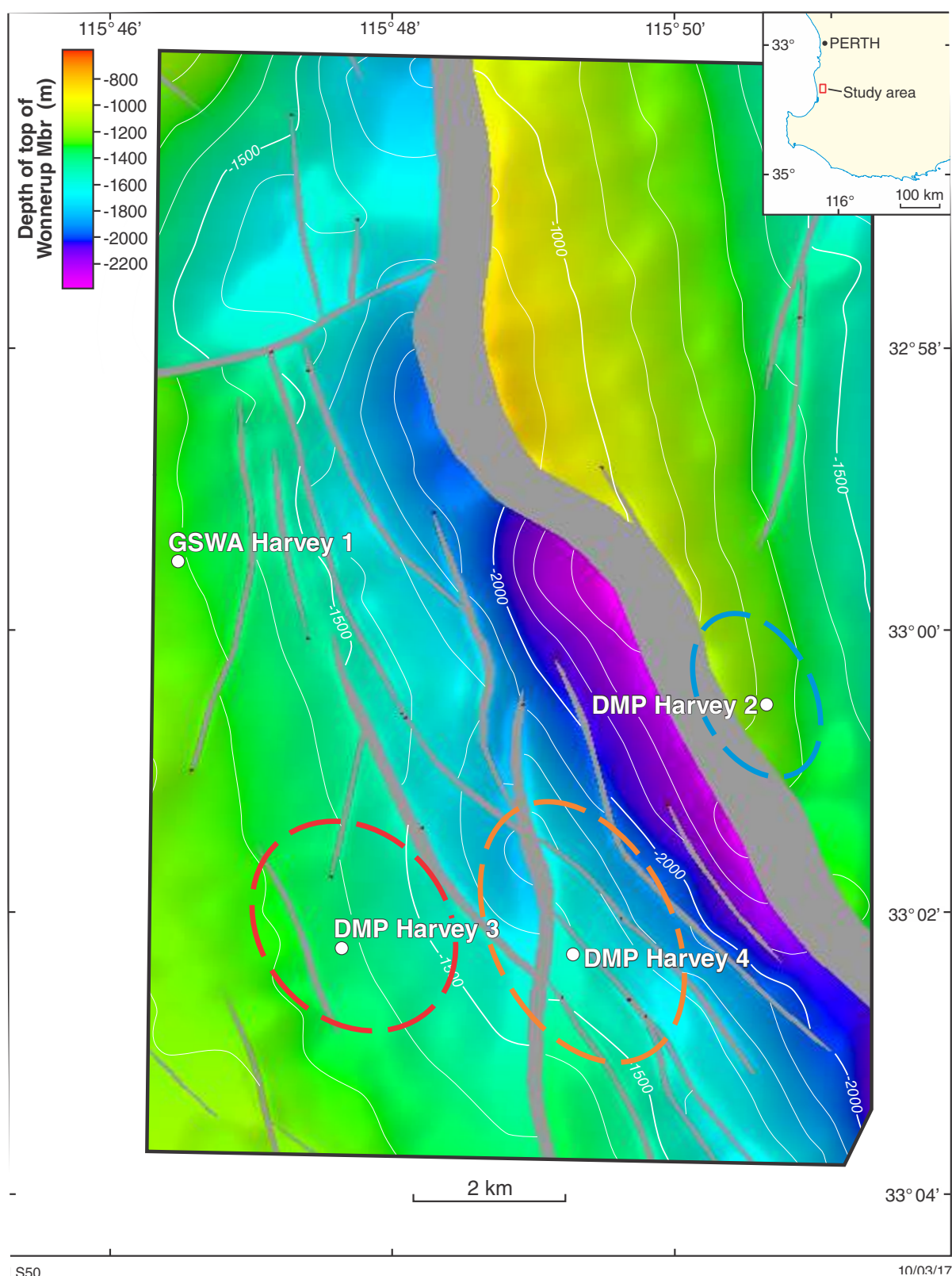


Figure 11: Contoured depth surface for the Wonnerup Member as interpreted by ODIN from the 3D seismic data, measured from ground level. The three outlined areas (shown as dashed lines) are the targeted areas for wells. The red and orange, into yellow and green colours indicate depth to the Wonnerup Member horizon of less than 1500m; the blues and purples indicate depth to the Wonnerup Member of more than 1500m. Faults and fault zones are shown in grey. The F10 Fault has the largest heave, or throw, depicted as the thickest grey line.

The processed 3D seismic data provided better coverage than the 2D seismic data, allowing better lateral resolution of the horizons and faults. The interpreted formation tops intersected in GSWA Harvey 1 were used as a well–seismic tie for calibrating the 3D seismic data.

The interpreted 3D seismic survey data indicates that the stratigraphy intersected in well GSWA Harvey 1 is laterally persistent across the study area. However, the character of the baffles remained poorly defined. Further drilling was required to obtain core to adequately characterise these baffles and to assess reservoir properties.

### **2.1.1.3 Stage gate 3**

Department of Mines, Industry Regulation and Safety's decision to drill three shallow wells was made in May 2014 following the preliminary interpretation of the 3D seismic survey. Three wells drilled approximately 100m into the Wonnerup Member were considered an optimal requirement to reduce uncertainties in the containment potential of the Lesueur Sandstone and the overlying Eneabba Formation within the available budget. The shallow wells were required to satisfy two purposes:

- validate the depth interpretation from the 3D seismic survey across the SW Hub study area at distances far from the seismic well-tie provided by GSWA Harvey 1.
- obtain core from the Eneabba Formation and Yalgorup Member (Figure 3), which overlie the Wonnerup Member reservoir, to characterise the properties of the containing strata. Core was also obtained from the Wonnerup Member to characterise the properties of the potential injection zone.

## **2.2 Objectives**

The planning of the DMP Harvey 2, 3 and 4 wells was based on satisfying prioritised objectives, including reducing the uncertainties identified in earlier investigations in the SW Hub study area.

### **2.2.1 Primary objective**

The primary objective behind the drilling of DMP Harvey 2, 3 and 4 was to ascertain the stratigraphy and containment potential of the shallower horizons in the Lesueur Sandstone and the Eneabba Formation, specifically to:

- ascertain the lateral continuity of the low-permeability horizons determined in the GSWA Harvey 1 well
- retrieve core from the 'basal Eneabba unit'
- retrieve core across the boundary between the Yalgorup and Wonnerup Members of the Lesueur Sandstone.

The containment potential of the upper Lesueur Sandstone and the Eneabba Formation was to be addressed through two relatively shallow wells in the area of interest drilled 50–100m into the top of the Wonnerup Member. In addition to providing the required core data, the wells could also be used as platforms for intrawell and interwell tests across the potential sealing layers

### **2.2.2 Secondary objectives**

The secondary objectives of the 'shallow' drilling program were to:

- validate the 3D seismic data and determine the 3D structure of the geology across the study area
- determine any porosity and permeability variation with depth within the top sections of the Wonnerup Member

- ascertain the optimal location for an injection test well, notionally 'DMP Harvey 5'
- test the stratigraphic correlations and displacement across the F10 Fault (Figure 11).

### 2.2.3 Key uncertainties

The key uncertainties identified following the drilling and investigation of GSWA Harvey 1 and the 3D seismic interpretation are summarised in Table 3. In order to secure the required technical data, a targeted acquisition plan was developed and scoped by DMIRS (Table 3). The scoping exercise created the specifications within the tendered service contracts.

Table 3: Key uncertainties and possible areas of investigation recognised prior to drilling

	Uncertainty	Activity to address uncertainty	Data required	Project focus
Containment	Faults (location, reactivation pressures and juxtaposition effects)	3D seismic survey, geomechanical information and modelling, log data	Interpreted seismic data, images, logs; fault and fracture locations and orientations	3D seismic acquisition and processing
	Fracture gradient	Drilling, core tests, well logs	Leak-off tests, rock strength, stress tests	Wells
	Quality and continuity of the basal Eneabba seal. Yalgorup paleosols extent and ability to act as baffles laterally and vertically.	Cores, well logs, single well and multi-well tests, 3D seismic	Interpreted well ties and correlations, well-test interpretations	Wells and cores
	Capillary entry pressures	Laboratory core analysis	Mercury injection capillary pressure (MICP) and other measurements	Special core analysis (SCAL)
Injectivity	Permeability anisotropy ( $K_v/K_h$ ratios; injection horizons and overlying formations)	Coring, well tests	Laboratory-derived permeability measurements, Formation Tester tool data interpretation	SCAL
	Absolute permeability	Logs, cores, well tests	Nuclear magnetic resonance (NMR), Formation Tester tool measurements, core-flood data, pressure interpretation	SCAL
	Relative permeability	Coring	Core-flood data, relative permeability end points	–
	Initial pore pressures	Well logs, well tests	Formation Tester tool measurements, test pressure data	Wireline logging
	Reservoir fluid salinity, reactive flow and transport effects	Coring, well logs, fluid samples, reactive transport modelling	Core floods and sample analysis (SEM), Formation Tester tool samples and analysis	–

Uncertainty		Activity to address uncertainty	Data required	Project focus
Capacity	Location of faults, compartmentalisation	3D seismic survey, logs, interference tests	Interpreted seismic data, pressure interference data	Model update
	Gross thickness of reservoir	Well logs, seismic inversion	Lithology data, quantitative processing	Model update

## 2.3 Scoping study for drilling rig selection

The drilling program was considered and selected by DMIRS following a preliminary scoping exercise, several workshops and discussions inside and outside of DMIRS. During the drilling planning stage, DMIRS staff made enquiries regarding drilling rig capacities and capabilities and the issues encountered during the drilling and investigation of the GSWA Harvey 1 well. The discussions shared ideas and experiences to formulate the optimal drilling program to address the key uncertainties in order to prove up the Lesueur Sandstone for CO<sub>2</sub> injection and storage. The scoping of the drilling regime considered the following:

- required well designs, such as diameters and depths
- drilling operations, such as rigs, locations, water requirements, land access and environmental considerations such as impact of operations on flora and fauna, noise and visual impact on the landowners and community
- sequencing of wells
- required investigation of the wells, such as core requirements, wireline logging and analytical techniques
- well completions to allow for any future monitoring and water flow testing
- component and potential total cost estimates.

Consideration was given to the strengths and weaknesses of the three rig types available in selecting the optimal well types for achieving the key outcomes (see section 2.9.1). For example, it was determined that, while a large oilfield drilling rig could efficiently and effectively drill to the Wonnerup Member at approximately 1500m depth, the cost to drill several wells with such a rig to ascertain the lateral extent and spatial character of the containing strata would be cost prohibitive.

Equally, mineral rigs were determined as capable of obtaining core for characterisation studies. However, uncertainties remained regarding the ability of these rigs to comfortably drill to 1500m, and whether the resulting hole diameters could accommodate specialised wireline logging tools and well-completion standards as used in the petroleum industry to evaluate the formation.

### 2.3.1 Drilling scenario

Given the key uncertainties and overall constraints, DMIRS' drilling program scenario is detailed below.

#### 2.3.1.1 Four-well program

A four-well program consisting of different rig and well types was developed to reduce the uncertainties associated with the shallower horizons, while getting incrementally more information about the Wonnerup Member with each well. The proposed program included the following wells:

- Stratigraphic wells DMP Harvey 2 and 3 to be drilled with a mineral drilling rig to get core data, validate the depositional environment and continuity of the target formations in the secondary confining layers of the Eneabba Formation and Yalgorup Member and also the top of the Wonnerup Member.
- DMP Harvey 4 to be drilled with a rotary water drilling rig, focusing on the Eneabba Formation, the Yalgorup Member and the top of the Wonnerup Member to establish the heterogeneity and retardation potential of the aquitards in the stratified formation layers. Select cores to be taken, modern logs recorded and well tests performed with water to investigate hydraulic connectivity. The well will also be completed as a baseline and ongoing monitoring well collecting reservoir data over several years.
- Deeper well DMP Harvey 5 to be drilled with an oilfield-style rotary drilling rig at the conclusion of the program.

Targeted drilling locations considered by DMIRS as permissible within land-access constraints are shown in Figure 12. The potential drilling areas focused on locations where depths to the top of the Wonnerup Member were less than 1500m. The target areas are discussed below:

- Well DMP Harvey 2 to be sited at the shallowest depth to the top of the Wonnerup Member and to the east of the F10 Fault (ie. within the footwall of the F10 Fault).
- Well DMP Harvey 3 to target the Wonnerup Member surface in the southeast of the CCS study area, where it will be slightly deeper than at the site of GSWA Harvey 1, and closer to the CO<sub>2</sub> plume fairway as modelled by Fiah and Guiton (2011).
- Well DMP Harvey 4 to target a deeper Wonnerup Member depth contour, maintaining a safety margin with respect to the rig's capability. If this well is sited in a different fault block, then reservoir data in this well in another fault block could be compared with reservoir data from well DMP Harvey 3.

Wells DMP Harvey 2 and 3 can provide flexibility as monitoring wells in the future if left cased with well caps, specifically for the following activities:

- DMP Harvey 2 primarily for monitoring any microseismic activities associated with the F10 Fault.
- DMP Harvey 3 and 4 to provide options to support testing in any deep well, notionally DMP Harvey 5.

The combination of DMP Harvey 3 and DMP Harvey 4 would be used to de-risk the deeper and more expensive DMP Harvey 5 well and to locate it in a reasonable location to test the potential for injectivity and residual trapping. Using the depth prognoses shown in Figure 13, DMIRS carried out a qualitative assessment for the proposed drilling scenario (Table 4).

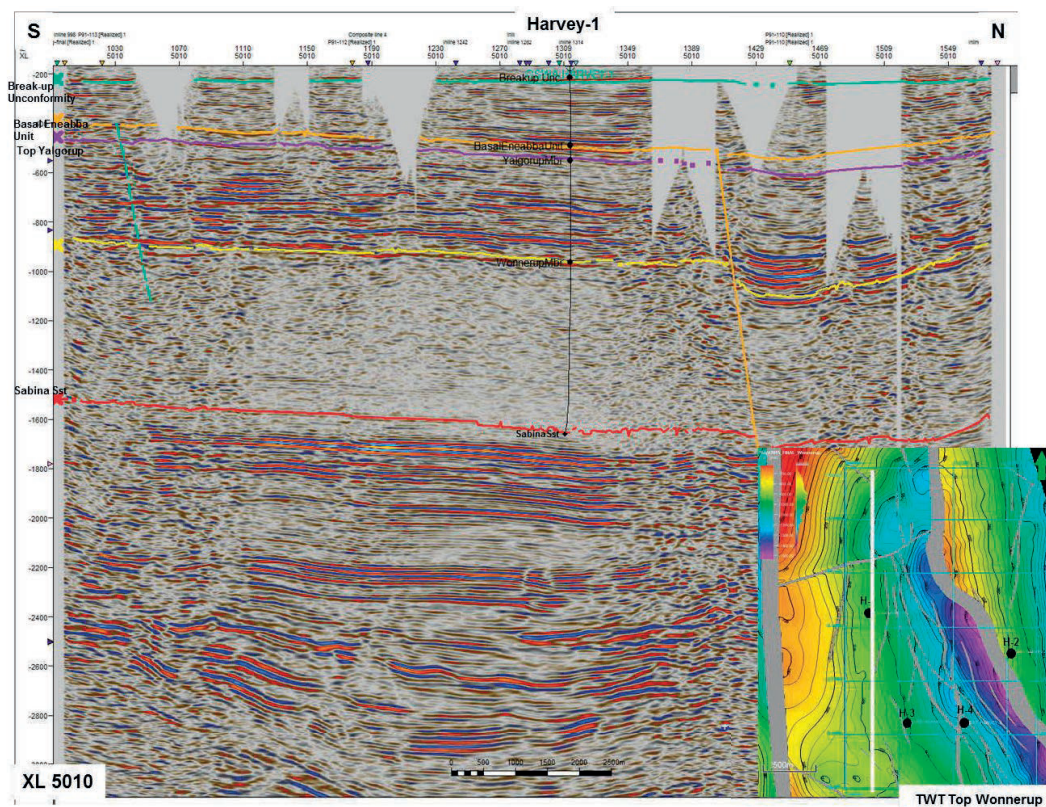


Figure 12: Section showing the interpreted 3D seismic data tied to GSWA Harvey 1 along Cross-line 5010. This well-tie, with the velocity survey data, was used to extrapolate the formation tops in GSWA Harvey 1 to create 3D surfaces for the depths to the formations and marker horizons across the SW Hub study area (Byrne, 2016).

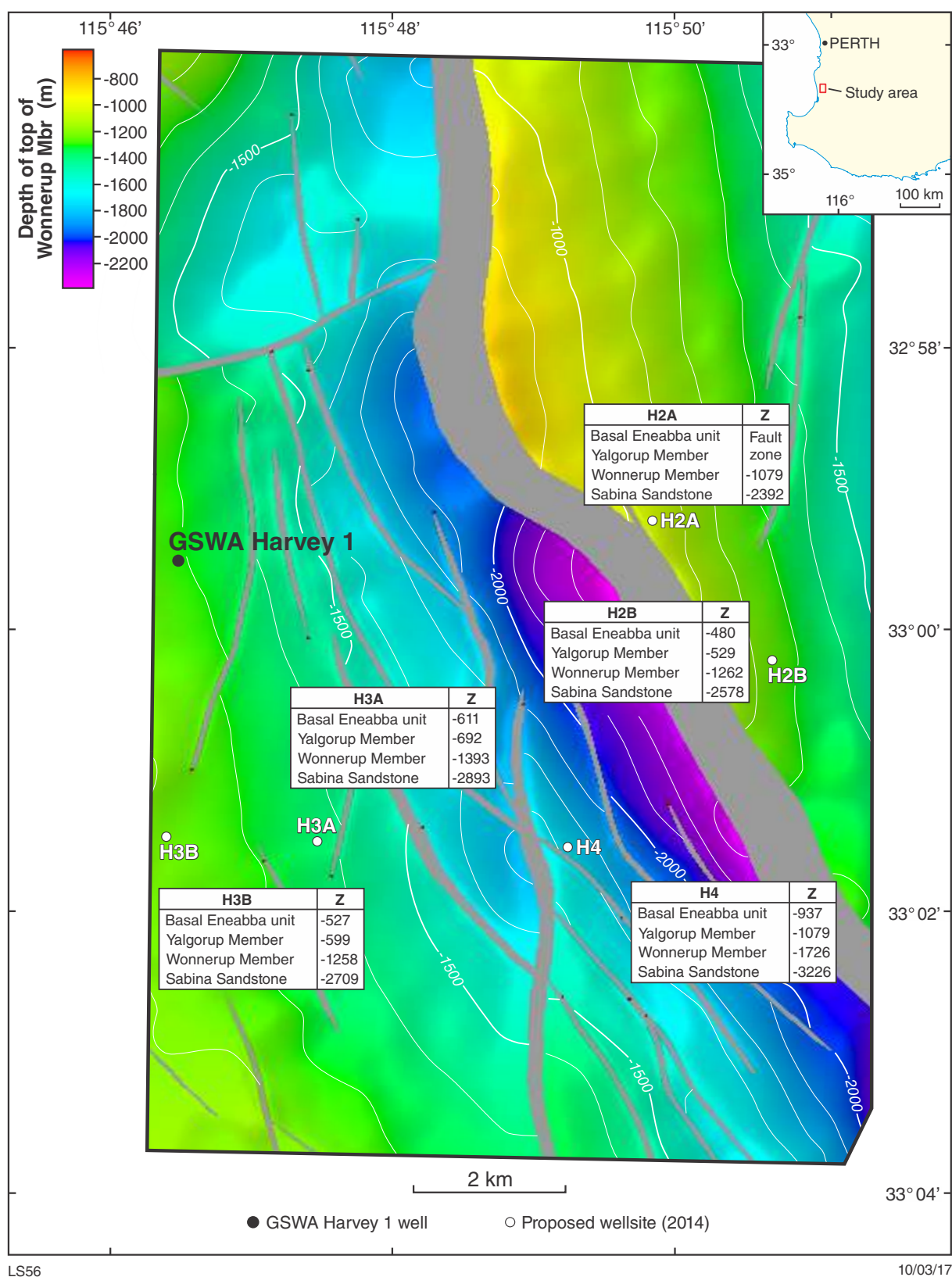


Figure 13: Prognosed depth to formation and marker horizons at notional well locations shown on a background image of the contoured Wonnerup Member depth-surface (Byrne, 2016). Faults and fault zones are shown in grey. The F10 Fault has the largest heave, or throw, depicted as the thickest grey line.

Table 4: Drilling-program rationalisation: qualitative assessment for the proposed scenario

Criteria	Remarks
Improved geological coverage	Three wells
Characterisation of the Yalgorup Member	Three wells
Characterisation of the upper Wonnerup Member	Three wells
Characterisation of the full Wonnerup Member	Would require deep wells to 3000m
Better de-risk target selection of deep well by investigating different fault blocks with wells DMP Harvey 3 and 4	–
Conduct single-well CO <sub>2</sub> residual saturation test in the high porosity and permeability facies (using GSWA Harvey 1 as a guide)	–
Conduct multi-well CO <sub>2</sub> injection test in the more-permeable facies	Only if DMP Harvey 5 was to be drilled adjacent to an existing well
Cost impacts	Three wells could be drilled for the cost of one deep well
Schedule impacts	–

### 2.3.1.2 Rig and well types

Different drilling rigs and well depth, diameter and location scenarios were appraised by DMIRS to gather pre-competitive data in the Lesueur Sandstone to facilitate CCS development. Provision for water flow tests was made in the design of these wells.

The use of a combination of mineral drilling and water drilling rigs was considered to be an optimal way to proceed with the program. The design of well DMP Harvey 4 is predicated on a large hole size to acquire specialised wireline logs to equip the wells for monitoring temporal baseline conditions and for any flow testing. As a contingency, flexibility is retained in the well design of DMP Harvey 3, albeit with some constraints due to its reduced diameter.

A strength, weakness, opportunity and threat (SWOT) analysis for different rig types was carried out by DMIRS employees and ANLEC R&D researchers based on the drilling scenario. The results are summarised in Table 5.

Table 5: Strength, weakness, opportunity and threat analysis of rig and well types

Rig type	Strengths	Limitations
Mineral	<ul style="list-style-type: none"> <li>• Full coring provides more-representative samples for lab testing</li> <li>• Lower cost</li> <li>• Speed?</li> <li>• Rigs available</li> </ul>	<ul style="list-style-type: none"> <li>• Smaller hole size (PQ/HQ)</li> <li>• Smaller cores</li> <li>• Slimline logs</li> <li>• Limited testing ability in soft formations (no fluid samples)</li> <li>• Limited hole depths (1400m should be alright in PQ/HQ size)</li> </ul>
Water	<ul style="list-style-type: none"> <li>• Larger hole sizes possible (7–8½in.)</li> <li>• Standard casings and completions possible</li> <li>• Fluid sampling, special logs</li> <li>• Speed?</li> <li>• Rigs available</li> </ul>	<ul style="list-style-type: none"> <li>• Higher costs from day rates, time for coring</li> <li>• Interval coring compared to full coring</li> <li>• Larger footprint</li> </ul>

### 2.3.1.3 Summarised decision

From the SWOT analysis, it was determined that a mineral rig could be used to drill DMP Harvey 2 to the east of the F10 Fault and to drill DMP Harvey 3 to the southeast of well GSWA Harvey 1. A rig capable of producing a rotary water well was selected to drill DMP Harvey 4 in another fault block, to greater depth in the southeast of the SW Hub study area and to the east of DMP Harvey 3 (Figure 13). The mineral rig and the water-well rotary drilling rig were favoured over the oilfield rotary rig because the latter was deemed non-optimal with respect to:

- acquiring core for stratigraphic property characterisation
- schedule
- cost.

Given DMIRS objective to gather pre-competitive data in the Lesueur Sandstone to facilitate CCS development, considerable thought has been given to which water-based flow tests might be conducted in these wells.

While not detailed here, the design of DMP Harvey 4 is focused on this. As a contingency measure, flexibility is retained in DMP Harvey 3 also, albeit with some constraints due to the smaller hole size. Using a combination of mineral drilling and water drilling rigs was the optimal way to proceed with the program.

### 2.3.2 Drill-site selection

Geophysicists from ODIN used the 3D seismic data tied to the GSWA Harvey 1 well to create contoured depth surfaces to the formation tops and bench-marker horizons, with an estimated depth accuracy of  $\pm 5$  per cent. These contoured surfaces were used to advise DMIRS on potential drilling sites for DMP Harvey 2, 3 and 4 (Figure 11).

In Figure 12 the data holes (light grey) due to restricted access are visible to the west (left) and east (right) of GSWA Harvey 1. The two-way travel time (TWT) contour plot for the Wonnerup Member horizon is shown in the small colourful figure to the right. Cross-line 5010 is shown in white and the positions and orientations of the faults, with their heave, are shown in grey. The F10 Fault has the largest heave, or throw, depicted as the thickest grey line in the small image.

After correlating the formation tops and marker horizons in GSWA Harvey 1 to the seismic data, the following seismic horizons were interpreted (Figures 14 and 15):

- the Cretaceous or 'break-up' unconformity
- top of basal Eneabba unit
- top of Yalgorup Member
- top of Wonnerup Member
- top of Sabina Sandstone.

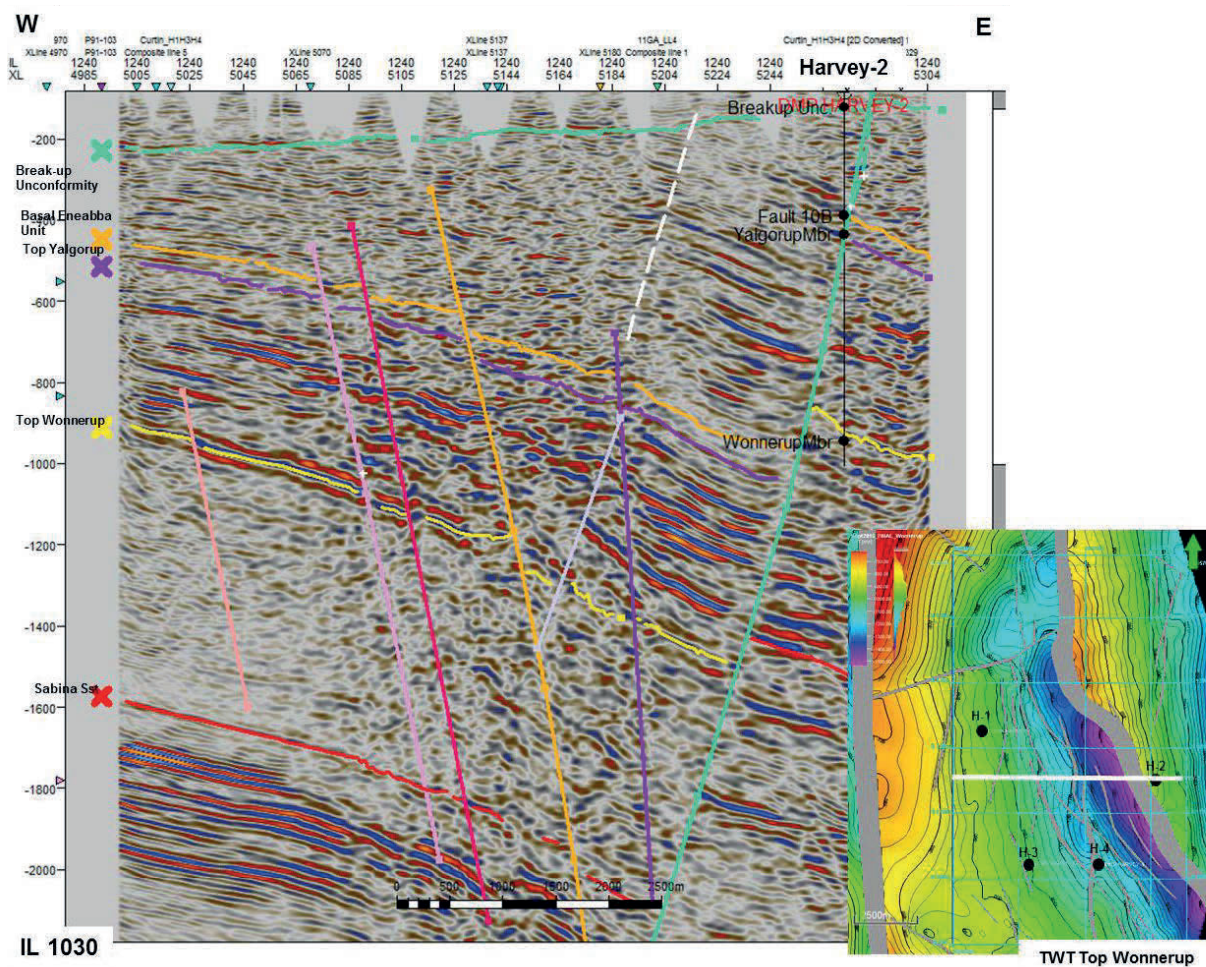


Figure 14: DMP Harvey 2: In-line 1240 two-way travel time (TWT) section with ODIN's interpreted horizons and faults. The well DMP Harvey 2 is shown to intersect the F10 Fault (light green) between 400 and 500ms. A map of the TWT contoured surface of the top of the Wonnerup Member is shown in the small figure to the right. The location of In-line 1240 is shown in white; the fault polygons are shown in grey (Byrne, 2016).

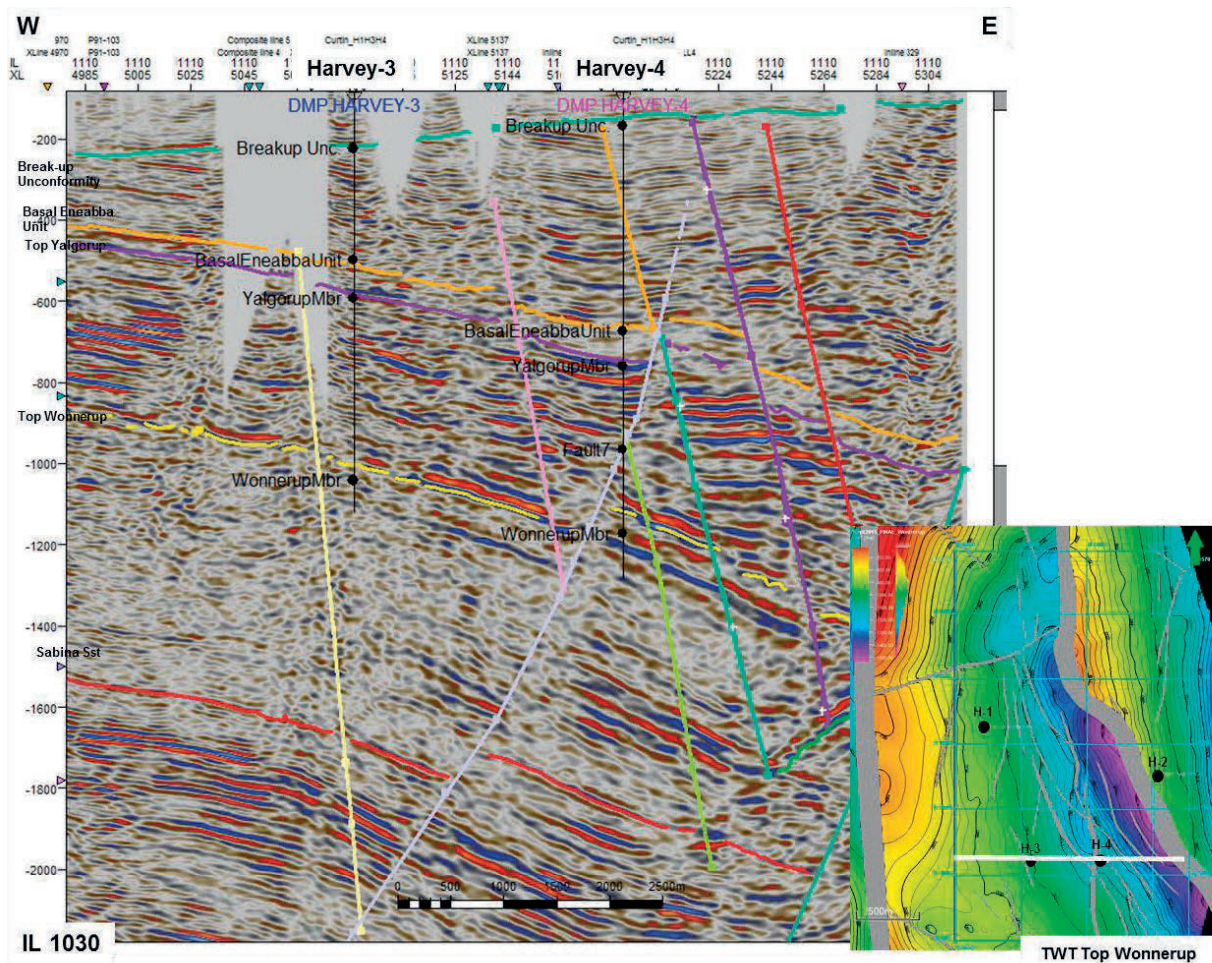


Figure 15: DMP Harvey 3 and 4: In-line 1110 TWT section with ODIN's interpreted horizons and faults (Byrne, 2016). A map of (TWT) contoured surface of the top of the Wonnerup Member is shown in the small figure to the right. In-line 1110 is shown in white; the faults are shown in grey.

Using ODIN's interpreted depth to the top of the Wonnerup Member, nine to ten potential properties in three broad locations across the SW Hub study area were assessed for their potential as drill sites in a scoping exercise. The properties were selected based on the following criteria:

- property owners accepting DMIRS access requirements for drilling and subsequent monitoring investigations
- the prognosed top of the targeted Wonnerup Member being less than or equal to 1500m below ground surface
- no sensitive environmental or heritage features
- to the east or southeast of GSWA Harvey 1 in different fault blocks
- safe vehicular ingress and egress
- acceptable distance from any occupied property to minimise noise disturbance
- proximity of water supply for drilling
- minimal visual disturbance
- minimum of 500m from a geological fault
- minimum of 500m from a residence.

The proposed drilling areas were narrowed down to individual land ownership holdings in accordance with a qualitative risk assessment as shown in Table 6.

Table 6: Traffic-light risk assessment matrix developed following site visits in the proposed drilling areas for wells DMP Harvey 2, 3 and 4

		Depth to Wonnerup Member and distance from faults	Environmental issues	Access and safety	Water availability
DMP Harvey 2	Site A				
	Site B				
DMP Harvey 3	Site C				
	Site D				
DMP Harvey 4	Site E				
	Site F				
	Site G				
	Site H				
	Site I				
	Site J				
	Site K				

NOTE: Matrix developed following site visits in the proposed drilling areas for wells DMP Harvey 2, 3 and 4. Green signifies no difficulties; orange signifies issues to be overcome and red signifies unresolvable issues.

Land access contractor KD.1 Pty Ltd liaised with landowners and negotiated access to the optimal drill sites on behalf of DMIRS. Leases were signed with the three freehold land owners in late 2015. These leases gave DMIRS three years' access to each well site, from late 2015 to 2018 inclusive, with the option of a further year's extension.

### 2.3.3 Well design

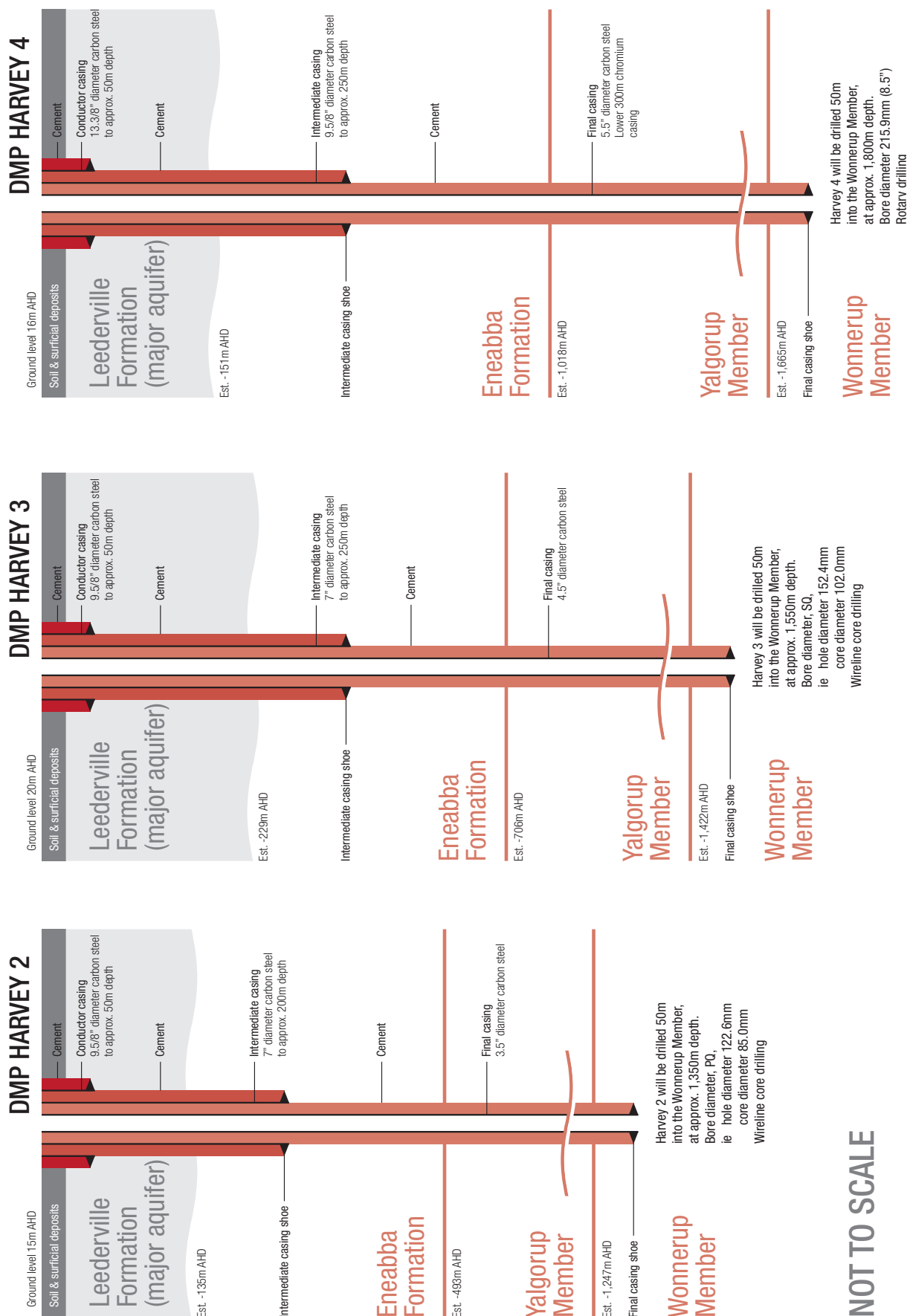
The three stratigraphic wells were designed to acquire the data required to meet the objectives of the drilling program, in a safe manner and with regard to well integrity. The wells as designed are shown in Figure 16.

#### 2.3.3.1 Specification for construction

The specifications for the surface, intermediate and final sections of each well as requested by DMIRS are summarised in Table 7.

Table 7: Construction specifications for wells DMP Harvey 2, 3 and 4

Well	Depth (m)	Diameter	Rotary drill	Diamond coring size	Casing diameter	Casing material
<b>Surface hole</b>						
DMP Harvey 2	50	12¼in. (311mm)	Yes	–	9⅝in. (245mm)	Carbon steel
DMP Harvey 3	50	12¼in. (311mm)	Yes	–	9⅝in. (245mm)	Carbon steel
DMP Harvey 4	50	17½in. (445mm)	Yes	–	13⅜in. (340mm)	Carbon steel
<b>Intermediate hole</b>						
DMP Harvey 2	200	8⅞in. (218mm)	Yes	–	7in. (178mm)	Carbon steel
DMP Harvey 3	250	9⅝in. (245mm)	Yes	–	7in. (178mm)	Carbon steel
DMP Harvey 4	250	12¼in. (311mm)	Yes	–	9⅝in. (245mm)	Carbon steel
<b>Final hole</b>						
DMP Harvey 2	1350	4□in. (122.6mm)	No	PQ	3½in.(89mm)	Carbon steel
DMP Harvey 3	1550	6in. (152.4mm)	No	SQ	4½in. (144.3mm)	Carbon steel with lower 300m chromium steel
DMP Harvey 4	1800	8½in. (216mm)	Yes, with interval coring	SQ	5½in.(140mm)	Carbon steel with lower 300m chromium steel



**NOT TO SCALE**

Figure 16: Schematic of conceptual well designs for DMP Harvey 2, 3 and 4.

### **2.3.3.2 Well construction**

The conceptual well designs for DMP Harvey 2, 3 and 4 are shown in Figure 16. Final well construction and completion details are reported in section 2.9.3.1.

Local field investigations and earlier drilling at the GSWA Harvey 1 well site. (Millar and Reeve, 2014) determined that the strata were highly unlikely to be overpressured or to yield hydrocarbon flows. However, as a precautionary measure, DMIRS specified the use of diverters for well control. Details are reported in section 2.9.3.3.

### **2.3.3.3 Well integrity**

Department of Mines, Industry Regulation and Safety recognises the importance of well integrity to ensure there are no preferential pathways for fluids or gases, such as water or CO<sub>2</sub> or both, to move from the injection reservoir into overlying aquifers or to the surface. Conceptually, such pathways could be via the well annuli, or via any transmissive (permeable) fault systems linking the target CO<sub>2</sub> reservoir, the Wonnerup Member, with overlying aquifers. The installation of multiple layers of steel and cement during any well construction create a protective barrier between the well and the groundwater.

Well integrity of the three Harvey wells was ensured during the well-design phase, and during the construction of the wells. This was enacted by careful management during the installation of casing and cementing, and was validated by pressure testing after cementing. Further details are provided in section 4.3 and in the final well reports provided by DDH1 Drilling (Appendix A).

## **2.4 Approval to drill**

### **2.4.1 Legislation**

Given the purpose of drilling of wells DMP Harvey 2, 3 and 4 was to determine the nature of the stratigraphy, DMIRS gained approval from the Director of GSWA to drill under the Western Australia Mining Act 1978, Section 115 (Appendix B). The project team chose to seek approvals under the Petroleum and Geothermal Energy Resources Act 1967 (PGERA) and to report on the drilling and investigative activities in accordance with the Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015. The approvals and reporting are consistent with those for the first well, GSWA Harvey 1, and will be continued for potential future activities.

An Environment Plan was prepared by KD.1 Pty Ltd on behalf of DMIRS (Wells, 2014), and DMIRS subsequently liaised with WA Department of Parks and Wildlife (DPaW) and followed all clearing regulations in the establishment of the drill sites. No clearing was required, as the drill sites for DMP Harvey 2 and 4 are on cleared land (Figure 1) and the DMP Harvey 3 site was is the cleared corridor of the Dampier to Bunbury natural gas pipeline (Figure 1).

### **2.4.2 Community engagement**

Community consultation was managed by DMIRS Carbon Strategy Branch. The Lesueur Community Consultative Committee (LCCC) was established in 2011 to assist with stakeholder engagement and consultation for:

- the proposed drilling of GSWA Harvey 1
- presentation of the drilling data from GSWA Harvey 1
- planning and carrying out of the 3D seismic survey conducted in 2014 (Burke, 2014).

## 2.5 Procurement of contracts

A procurement strategy was developed by DMIRS under which certain contracts were bundled together. This approach was designed to simplify administration by limiting the number of contracts and interfaces. Tenders were developed after a risk assessment exercise.

Tenders were advertised in April 2014, for the drilling of the DMP Harvey 2, 3 and 4 wells, and for the provision of associated services. Additional procurement was required for surveying, land-access negotiations, well insurance during drilling and subsequent monitoring, wireline logging, core analysis of samples from the cored sections of the wells, and static and dynamic modelling. Service contracts were awarded by DMIRS to the parties shown in Table 8.

Following the WA Department of Finance guidelines, quotations were requested where the value of services was assessed as being less than \$50,000 excluding GST.

Table 8: Service contracts awarded by Department of Mines, Industry Regulation and Safety

Tender title	Tender release date	Tender award date	Successful respondent
DMP110214 Provision of geological and geophysical interpretation and modelling support	17/03/2014	08/05/2014	ODIN Reservoir Consultants Pty Ltd
DMP201309356 and DMP201409187 Land access	20/08/2013	02/07/2014	KD.1 Pty Ltd
DMP710714* Surveying	Quotes were requested	November 2014	BCE Surveying Pty Ltd
DMP120214 Provision of drilling rig services	17/04/2014	29/08/2014	DDH1 Drilling Pty Ltd
DMP700714 Well insurance	26/09/2014	17/10/2014	ToleHouse Risk Services Pty Ltd
DMP680714 Provision of core analysis services	01/08/2014	14/11/2014	Core Laboratories Pty Ltd
DMP400514 Provision of wireline logging services	01/10/2014	23/12/2014	Halliburton Australia Pty Ltd

NOTE: \* The wells were surveyed in November 2014, and again in April 2015.

## **2.6 Contractual arrangements for drilling**

In late 2014, DDH1 Drilling Pty Ltd (DDH1 Drilling), in conjunction with Drilling Contractors of Australia (DCA) and Rockwater Pty Ltd (Rockwater), were awarded a contract by DMIRS to drill and geologically log three wells in the SW Hub study area. The lead contractor role, including overall site responsibility, was appointed to DDH1 Drilling. Direct responsibility for drilling wells DMP Harvey 2 and 3 was retained by DDH1 Drilling, with these wells to be continuously cored to estimated total depths of 1350 and 1550m, respectively. Drilling Contractors of Australia was subcontracted by DDH1 Drilling to drill DMP Harvey 4 to an estimated total depth of 1800m, the bulk of which was to be drilled openhole with interval coring in zones of specific interest.

Rockwater was subcontracted to provide on-site hydrogeological logging services and geological supervision for all three wells and Australian Mud Company (AMC) was engaged to provide mud engineering services for the entire drilling program.

## **2.7 Risk management**

Risk was managed by DMIRS throughout the drilling process, from the planning stage through to the operational stage.

Insurance broker ToleHouse Risk Services Pty Ltd was contracted by DMIRS to provide insurance cover for the three wells during the drilling operations and flow testing and subsequent monitoring.

During the tendering process, the drilling companies were required to provide a risk management procedure and risk matrix. Each was reviewed as part of DMIRS tender evaluation process. A further risk assessment was developed by DDH1 Drilling for the project's scope of works. The assessment was subject to review and acceptance processes with DMIRS following the award of the contract, and prior to the commencement of works.

A risk register was compiled by DMIRS prior to the procurement of the drilling program. This document was reviewed and updated after the drilling contract had been awarded, and again during the drilling operations.

## **2.8 Prognosed and actual drill depths**

ODIN interpreted the 3D seismic data and determined prognosed depths to the top of the formation tops and marker horizons (Table 9). The prognosed depths were reported with an error margin of  $\pm 5$  per cent, giving a potential depth range for the top of the formation tops and marker horizons as recorded in Table 9. The predicted stratigraphy was intersected, with depths to formation tops and marker horizons generally shallower than prognosed from the interpreted 3D seismic survey (Table 9).

Table 9: Prognosed depths to formation tops and marker horizons as interpreted from the 3D seismic survey data, and actual depths and depth uncertainties (Byrne, 2016)

Well	Formation top or bench marker name	Rig table elevation (m AHD)	Total depth (TD) (m)	Prognosed					Actual		Difference between actual and prognosed depth (m)	Calculated accuracy (%) of the prognosed depth
				Depth (MDRT)	Depth (m AHD)	Accuracy $\pm 5\%$ (m)	Minimum depth (m)	Maximum depth (m)	Depth (MDRT)	Depth (m AHD)		
DMP Harvey 2	–	16.0	-1351.2	–	–	–	–	–	–	–	–	–
	Cretaceous unconformity	–	–	-161.0	-145.0	7.3	-137.8	-152.3	–	–	–	–
	Basal Eneabba unit	–	–	-441.0	-425.0	21.3	-403.8	-446.3	-408.0	-392.0	33.0	-8
	Yalgorup Member	–	–	-507.0	-491.0	24.6	-466.5	-515.6	-549.0	-533.0	-42.0	9
	Wonnerup Member	–	–	-1253.0	-1237.0	61.9	-1175.2	-1298.9	-1242.0	-1226.0	11.0	-1
	Total well depth (TD)	–	–	–	–	–	–	–	-1350.2	-1334.0	–	–
DMP Harvey 3	–	20.8	-1550.2	–	–	–	–	–	–	–	–	–
	Cretaceous unconformity	–	–	-246.8	-226.0	11.3	-214.7	-237.3	–	–	–	–
	Basal Eneabba unit	–	–	-648.8	-628.0	31.4	-596.6	-659.4	-581.0	-560.0	68.0	-11
	Yalgorup Member	–	–	-733.8	-713.0	35.7	-677.4	-748.7	-743.0	-722.0	-9.0	1
	Wonnerup Member	–	–	-1446.8	-1426.0	71.3	-1354.7	-1497.3	-1417.0	-1396.0	30.0	-2
	Total well depth (TD)	–	–	–	–	–	–	–	-1550.0	-1529.0	–	–
DMP Harvey 4	–	19.9	-1802.0	–	–	–	–	–	–	–	–	–
	Cretaceous unconformity	–	–	-173.9	-154.0	7.7	-146.3	-161.7	–	–	–	–
	Basal Eneabba unit	–	–	-856.9	-837.0	41.9	-795.2	-878.9	-872.0	-852.0	-15.0	2
	Yalgorup Member	–	–	-1035.9	-1016.0	50.8	-965.2	-1066.8	-1014.0	-994.0	22.0	-2
	Wonnerup Member	–	–	-1684.9	-1665.0	83.3	-1581.8	-1748.3	-1597.0	-1577.0	88.0	-5
	Total well depth (TD)	–	–	–	–	–	–	–	-1802.6	-1782.0	–	–

One in four of the actual depths to the top of the formation tops and marker horizons were within the prognosed potential depth ranges. The exceptions included the Cretaceous unconformity in DMP Harvey 2, which was 19 per cent shallower than the prognosed depth, and the basal Eneabba unit in DMP Harvey 3, which was 11 per cent shallower than the prognosed depth.

## 2.9 Drilling activities

This section reports on the data and information collected by DMIRS during the operational drilling of wells DMP Harvey 2, 3 and 4.

### 2.9.1 Drilling rigs

Department of Mines, Industry Regulation and Safety contracted DDH1 Drilling to drill DMP Harvey 2, 3 and 4. DDH1 Drilling drilled DMP Harvey 2 and 3 with the company's Rig 16 (Figure 17). Rig 16 is an Evolution 3000 rig, with a pullback of 70,000lb.



Figure 17: DDH1 Drilling Pty Ltd's Evolution 3000 rig (Rig 16) drilling DMP Harvey 3 (Henderson Photographics for DMP).

Drilling Contractors of Australia Pty Ltd (DCA) drilled well DMP Harvey 4, under subcontract to DDH1 Drilling, using DCA's ADS 1500 rotary rig (Figure 18).

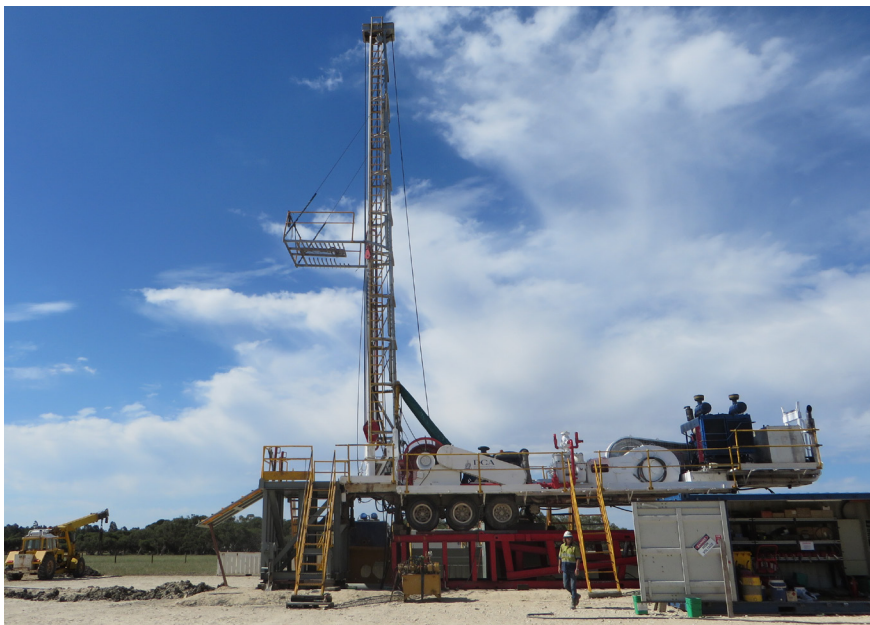


Figure 18: Drilling Contractors of Australia Pty Ltd's rotary ADS 1500 drilling rig, drilling DMP Harvey 4 in February 2015.

## 2.9.2 Subsidiary contracts

Subsidiary contracts for the drilling program are summarised below:

- Earthworks: the drill pads were constructed from locally sourced limestone supplied by Carbone Bros Pty Ltd. The preparation of the drilling pads was subcontracted by DDH1 Drilling to P. & T. Curulli.
- Cementing: the drillers carried out the cementing operations, this being DDH1 Drilling for wells DMP Harvey 2 and 3 and DCA for DMP Harvey 4.
- Mud logging: a specialised mud-logging company was not employed. However, Rockwater was subcontracted to DDH1 Drilling to provide well-site geologists. These geologists described the chip samples and bagged rock chips every three metres during the rotary-drilled sections of DMP Harvey 2, 3 and 4. During the coring operations, Rockwater's geologists described the lithology of the core as it was brought to the surface.
- Wireline logging: Halliburton Pty Ltd.
- Local suppliers: DDH1 Drilling sourced raw materials and services from local suppliers when possible.

## 2.9.3 Well construction

This section reports on well-construction schematics, drilling methods, issues encountered during drilling, and well control.

### 2.9.3.1 Well construction schematics

The full details regarding the construction and completion of the casing for the three wells are reported in the final well reports (Appendix A). Each well has been completed as shown in Figures 19 to 21. Table 10 summarises the wells as constructed and completed.

# DMP HARVEY 2

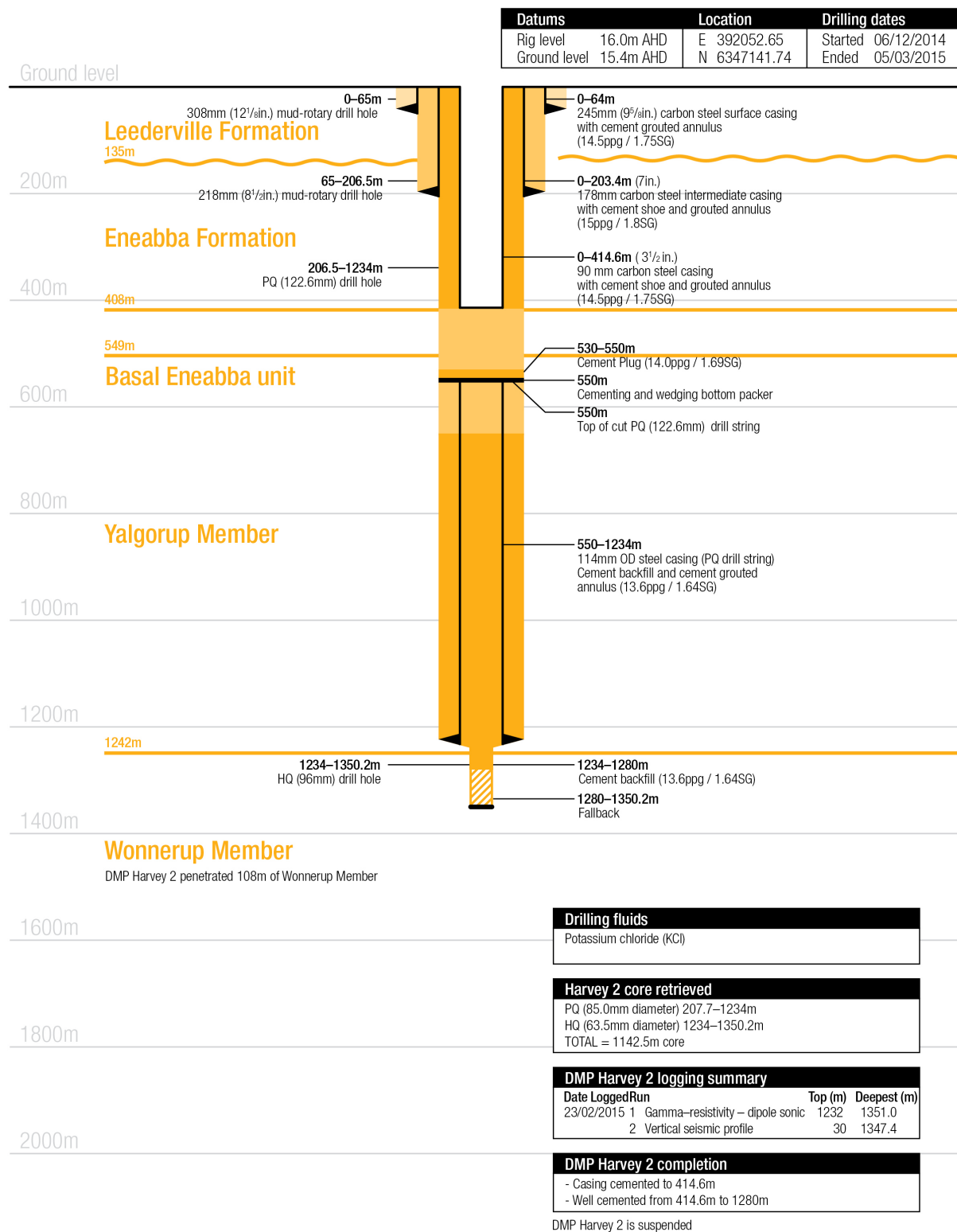


Figure 19: DMP Harvey 2: well completion schematic.

# DMP HARVEY 3

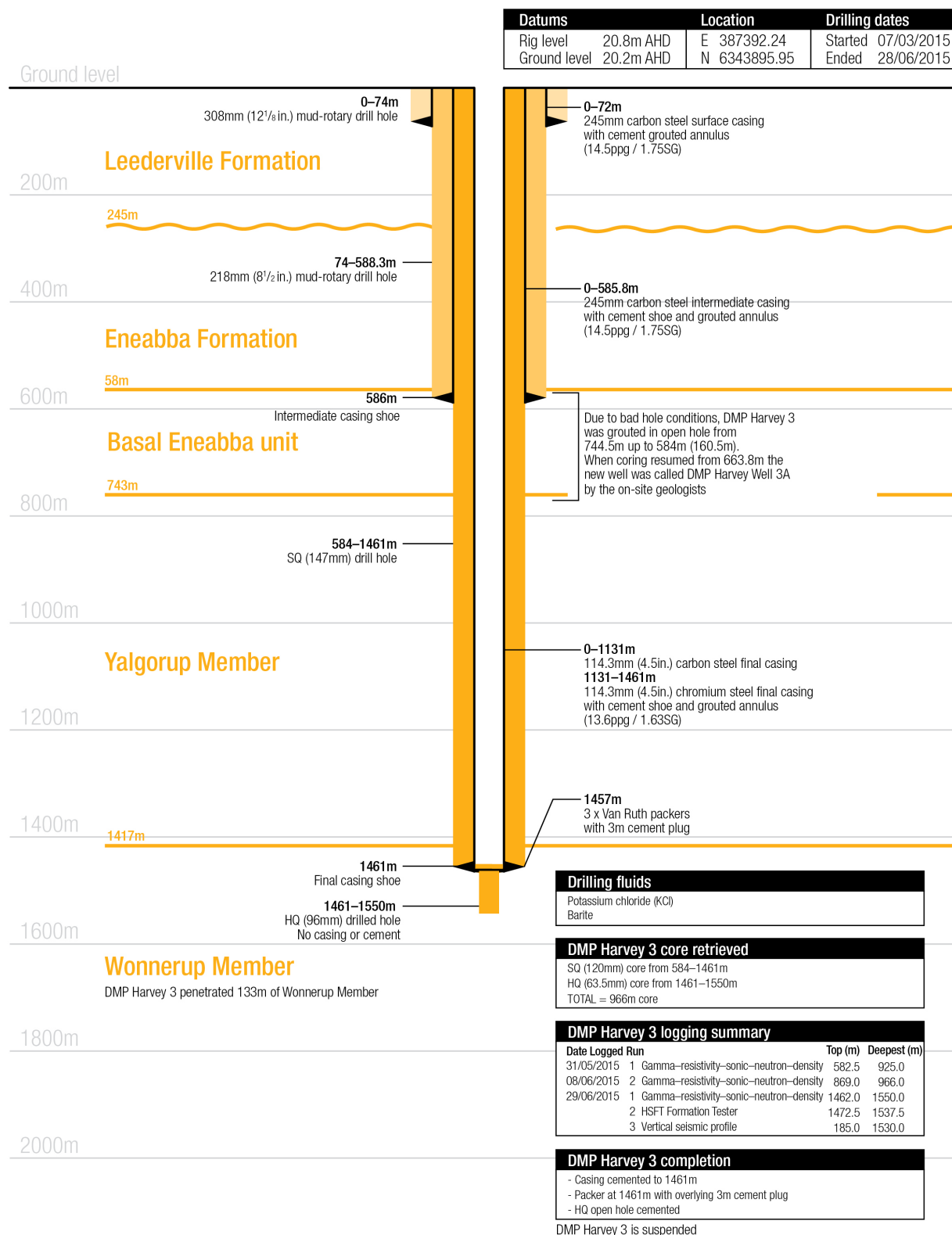


Figure 20: DMP Harvey 3: well completion schematic.

# DMP HARVEY 4

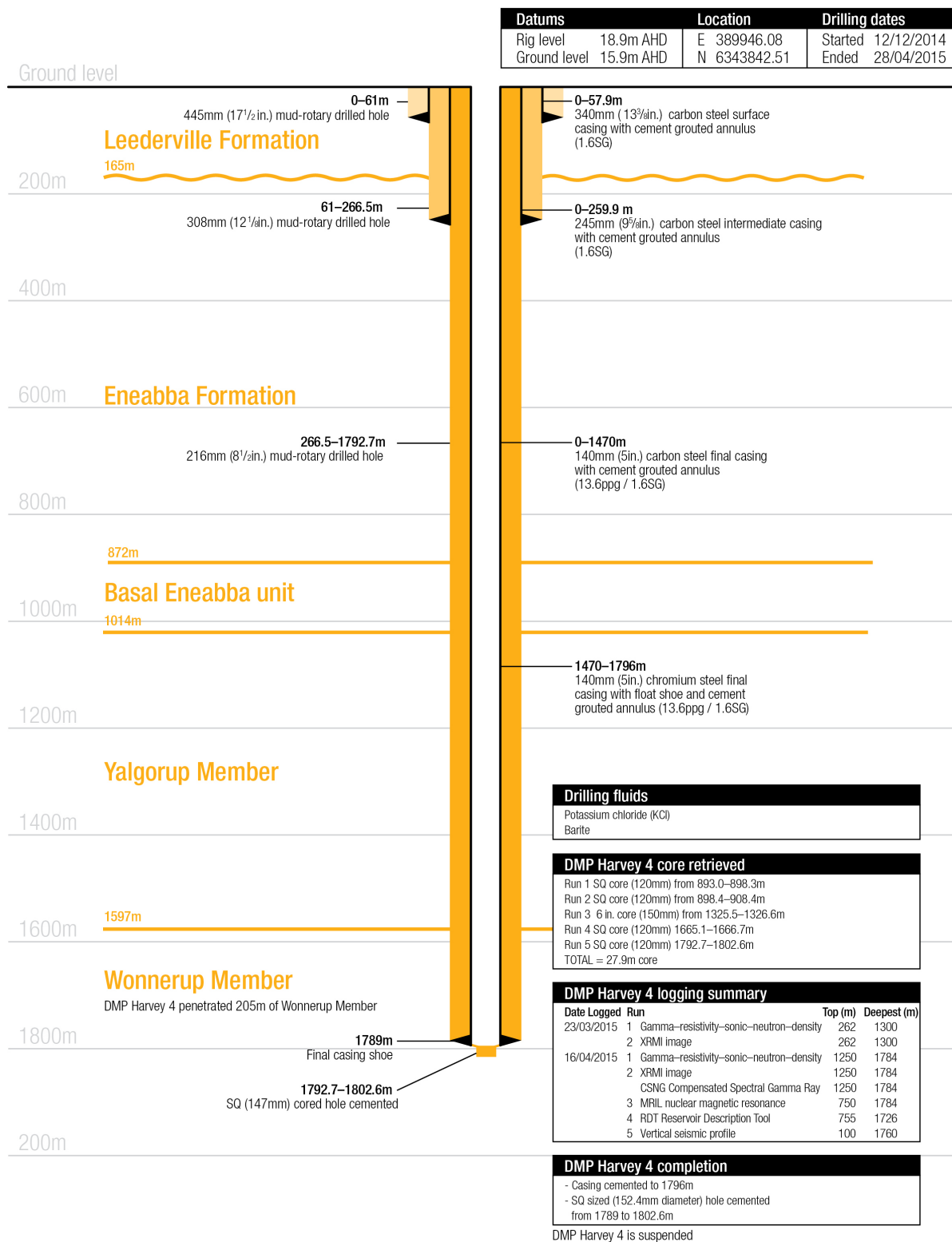


Figure 21: DMP Harvey 4: well completion schematic.

Table 10: Final well construction and completion details

Well	Drilled depth (m)	Drilled diameter	Rotary drill	Diamond coring size	Completed depth (m)	Casing diameter	Casing material
<b>Surface hole</b>							
DMP Harvey 2	65	12¼in. (311mm)	Yes	—	—	9⅝in. (245mm)	Carbon steel
DMP Harvey 3	74	12¼in. (311mm)	Yes	—	—	9⅝in. (245mm)	Carbon steel
DMP Harvey 4	61	17½in. (445mm)	Yes	—	—	13⅜in. (340mm)	Carbon steel
<b>Intermediate hole</b>							
DMP Harvey 2	206.5	8⅞in. (218mm)	Yes	—	—	7in. (178mm)	Carbon steel
DMP Harvey 3	584.0	9⅝in. (245mm)	Yes	—	—	7in. (178mm)	Carbon steel
DMP Harvey 4	266.5	12¼in. (311mm)	Yes	—	—	9⅝in. (245mm)	Carbon steel
<b>Final hole</b>							
DMP Harvey 2	1350.2	4⅝in. (122.6mm)	No	PQ and HQ	414.6	3½in. (89mm)	Carbon steel
DMP Harvey 3	1550.2	6in. (152mm)	No	SQ and HQ	1461.0	4½in. (114.3mm)	Carbon steel with lower 330m* chromium steel
DMP Harvey 4	1802.0	8½in. (216mm)	Yes, with interval coring	Interval cored with SQ barrel	1792.7	5½in. (140mm)	Carbon steel with lower 326m* chromium steel

NOTE: \* Minor change to final carbon steel casing length due to availability of additional casing.

Due to difficulties experienced during the drilling of well DMP Harvey 2 (refer to the final well report for DMP Harvey 2 in Appendix A), the annulus of this well was cement grouted and the cut PQ drill string was backfilled with cement (refer to Table 10 and Figure 19).

All of the casing installed in the wells during construction and the wells' completion is of oilfield standard. As an added precaution in the event of any future CO<sub>2</sub> injection close to wells DMP Harvey 3 and 4, the lower 330m and 326m portions, respectively, have been cased with Cr13 steel corrosion-resistant alloy (13 per cent Cr), which has greater resistance to CO<sub>2</sub> than standard steel casing (Figures 20 and 21; Meyer, 2007).

Pending a decision on the future use of the wells, all three have been suspended. Each well has been installed with a lockable well cover. At the date of publication of this report, no equipment has been installed in wells DMP Harvey 2, 3 or 4.

### **2.9.3.2 Drilling details and issues**

The drilling details and issues experienced for each well are reported in full in the final well reports (Appendix A) and are summarised below.

The final well construction and completion details for the three wells are shown in Figure 19 for DMP Harvey 2, Figure 20 for DMP Harvey 3 and Figure 21 for DMP Harvey 4. The dimensions of the drilled and completed wells are summarised in Table 10. The wells as drilled and completed can be compared with the wells as designed (Figure 16). Construction specifications are summarised in Table 7.

#### **DMP Harvey 2**

Well DMP Harvey 2 was spudded on 6 December 2014. The well was rotary drilled to 206.5m, PQ-cored to 1233.4m and HQ-cored to the end of the well at 1350.2m (Table 10). In February 2015 the drilling rod line was jammed in the lower section of the well, resulting in the coring of this well being reduced from PQ diameter (122.6mm, 4<sup>7</sup>/<sub>8</sub>in.) to HQ diameter (96.0mm, 3<sup>6</sup>/<sub>8</sub>in.) for the interval starting from 1233.7m to total depth (TD). The well was plugged with cement up to 414.6m, and 90mm (3<sup>1</sup>/<sub>2</sub>in.) steel casing was installed from surface to 414.6m depth. The space behind this completion casing was fully grouted with cement. The rig was released on 5 March 2015 and moved to the DMP Harvey 3 drill site. Well DMP Harvey 2 was capped with a lockable cover.

#### **DMP Harvey 3**

Upper formation instability was experienced during the drilling of DMP Harvey 2. As a consequence DMP Harvey 3 was rotary drilled to 588m. The well was then cored using an SQ-sized core barrel (hole diameter 147.0mm or 5<sup>5</sup>/<sub>8</sub>in.) to 1462m depth, and an HQ-sized core barrel (hole diameter 96.0mm or 3<sup>6</sup>/<sub>8</sub>in.) to the end of the well at 1550m (Table 10).

After flow testing the lower two metres of the Wonnerup Member on 27 June 2015, the 88m length of HQ openhole was filled with cement and 1462m (114.3mm or 4<sup>1</sup>/<sub>2</sub>in. diameter) steel completion casing was installed. The lower 331m of this completion casing was chromium steel. The annulus of the completion casing was grouted with cement to surface. Well DMP Harvey 3 was capped with a lockable cover.

#### **DMP Harvey 4**

Well DMP Harvey 4 was the largest hole of the three wells, with a diameter of 216mm (8<sup>1</sup>/<sub>2</sub>in.) through the Lesueur Sandstone. The well was rotary drilled, with three separate, targeted interval coring runs with a SQ core barrel, to 1793m (Table 10). From 31 March 2015 bottom-hole clearing with an eight-inch outer diameter mineral core barrel resulted in a fourth cored interval being attained between 1323 and 1326m depth.

The condition of the hole deteriorated during drilling. When drilling reached 1303m the well was wireline logged. At 1793m the second suite of wireline logs was run before the final SQ-sized cored interval was drilled, from 1793m to the end of the well at 1802m. A cement float shoe of 156mm (6<sup>1</sup>/<sub>8</sub>in.) diameter was installed at the bottom of the hole, and steel casing of 140mm (5<sup>1</sup>/<sub>2</sub>in.) diameter was installed to 1789m. The lower 326m of this completion casing was high-chromium steel. The openhole section, from 1789 to 1802.6m (TD), and the annular space behind the casing were fully grouted with cement. The well was capped with a lockable cover.

### **2.9.3.3 Well control**

During the drilling of GSWA Harvey 1, no petroleum product or natural gases were encountered. Given this experience and the improved geological understanding of the study area (Millar and Reeve, 2014), the presence of petroleum products was not anticipated during the planning and drilling stages of wells DMP Harvey 2, 3 and 4 and so the installation of a blowout preventer (BOP) was not required in the specification of works. As a precaution DMIRS required diverters to be installed on wells Harvey 2, 3 and 4 to control and manage any pressurised water encountered during drilling.

Following the installation and cementing of the intermediate casing in each of the three wells, DDH1 Drilling installed annular diverters. All three wells used annular diverters with hydraulic actuators and pressure-rated casing heads were also used to allow the introduction of kill mud into the annulus below a closed-in annular diverter. Typically a triple stack will include a diverter and a set of rams to close around drill pipe, and another set to shear pipe. During the SW Hub shallow drilling program, all items were provided, with the exception of the rams. The well head, annular diverter, plumbing and actuator used for the DMP Harvey 2, 3 and 4 wells made up what DDH1 Drilling refers to as the BOP system (M. Pollock [DDH1 Drilling Pty Ltd] 2016, pers. comm., 4 April). The final well reports for Harvey 2, 3 and 4 confirm the installation of a BOP system in each well (refer to Summary of Drilling Operations, in DDH1 Drilling's final well reports in Appendix A).

Function and pressure tests to verify the integrity of the installed BOP system were carried out by DDH1 Drilling. Leak-off tests (LOT) were conducted on each well and are summarised in section 4.3. These are reported in full in the final well reports in Appendix A.

#### **2.9.3.4 Bit records**

Summaries of the bits used during the drilling of wells DMP Harvey 2, 3 and 4 are given in Tables 11, 12 and 13, respectively, and each well is discussed below.

#### **DMP Harvey 2**

In the DMP Harvey 2 well, bit changes were frequent at the start of the coring program while the drillers attempted to identify the optimal bits for drilling progress and maximum core recovery. Bit changes were frequent when difficulties were encountered trying to cut particularly hard and abrasive formations or when formations were varying rapidly. Maximum cutting performance and core recovery were achieved using surface-set internal discharge step bits with large protruding diamonds (Russell and Pollock, 2015). A diamond-impregnated core bit was used in the drilling of the HQ-sized Wonnerup Member sections of DMP Harvey 2 and 3 (Figure 22).



*Figure 22: HQ3-sized diamond-impregnated core bit used in the drilling of the HQ-sized Wonnerup Member sections of DMP Harvey 2 and 3, December 2014.*

Lithologies encountered in the Wonnerup and Yalgorup Members were harder and more abrasive than DDH1 Drilling and DCA anticipated based on previous drilling experience in the Perth Basin. The hard and abrasive lithologies are considered to result from the presence of plutonic lithic fragments and garnets identified in the sandstones of the Yalgorup and Wonnerup Members during petrographic analysis (Nelis, 2015). Locally intense ferruginisation effects throughout the majority of the core from DMP Harvey 2 may have contributed to variability in downhole competency as well as bit wear (Russell and Pollock, 2015).

Table 11: Bit record for DMP Harvey 2 (Nims and Pollock, 2015)

Date	From (m)	To (m)	Interval *(m)	Size	Type	Style	Serial No.	Brand	Formation (downhole interval)
6/12/2014	0.0	7.4	7.4	8½in.	Tricone	TCI	710170/8	Not reported	Leederville Formation (0–135m)
6/12/2014	0.0	7.4	7.4	14in.	Blade	4 wing	24111978	Not reported	
7/12/2014	7.4	65.0	57.6	8½in.	Tricone	TCI	710170/8	Not reported	
7/12/2014	7.4	65.0	57.6	12½in.	Tricone	Mill tooth	10925336	Not reported	
9/12/2014	65.0	206.5	141.5	8½in.	Tricone	Mill tooth	3210321	Not reported	
6/01/2015	206.5	207.7	1.2	4⅞in.	Tricone	Mill tooth	F209013	AMS	Eneabba Formation (135–419m)
6/01/2015	207.7	208.4	0.7	PQ3 core	Impreg	HA9	31591/05	Hayden	
6/01/2015	208.4	210.8	2.4	PQ3 core	PCD	TSP	1A9015	Dimatec	
7/01/2015	210.8	214.7	3.9	PQ3 core	Impreg	8:10	133886	Hardcore	
7/01/2015	214.7	231.4	16.7	PQ3 core	PCD	TSP	1A9015	Dimatec	
7/01/2015	231.4	234.4	3.0	PQ3 core	PCD	Not reported	139152	Hardcore	
8/01/2015	234.4	246.1	11.7	PQ3 core	Surf Set	Not reported	HD0264/3	Hayden	
8/01/2015	246.1	403.7	151.3	PQ3 core	Surf Set	15/25	101-01	AMS	
12/01/2015	403.7	409.1	5.4	PQ3 core	PCD	TSP	1A9015	Dimatec	

Date	From (m)	To (m)	Interval *(m)	Size	Type	Style	Serial No.	Brand	Formation (downhole interval)
13/01/2015	409.1	458.3	49.2	PQ3 core	Surf Set	Not reported	1132737	Asahi	Yalgorup Member (419–1245m)
14/01/2015	458.3	489.6	31.3	PQ3 core	Surf Set	Not reported	1369173	Asahi	
15/01/2015	489.6	491.5	1.9	PQ3 core	PCD	Not reported	139154	Hardcore	
16/01/2015	491.5	548.4	57.7	PQ3 core	Surf Set	Not reported	HD0264.3	Hayden	
17/01/2015	548.4	600.4	52.0	PQ3 core	Surf Set	Not reported	1416107	Asahi	
19/01/2015	600.4	663.1	62.7	PQ3 core	Surf Set	Carbarna	2B2463	HMI	
23/01/2015	663.1	678.1	15.0	PQ3 core	Surf Set	Not reported	1010962	Asahi	
24/01/2015	678.1	919.1	241.0	PQ3 core	Surf Set	Carbarna	2B2462	HMI	
1/02/2015	919.1	971.9	52.8	PQ3 core	Surf Set	Carbarna	2B2463	HMI	
4/02/2015	971.9	1233.9	262.0	PQ3 core	Surf Set	Carbarna	2B2460	HMI	
12/02/2015	1233.9	1234.0	0.1	PQ3 core	Surf Set	Carbarna	2B2463	HMI	
16/02/2015	1234.0	1242.3	8.3	HQ core	Impreg	HA9	32104/03	Hayden	
17/02/2015	1242.3	1244.4	2.1	HQ3 core	Surf Set	Not reported	51313.2	SDS	
17/02/2015	1244.4	1276.2	31.8	HQ3 core	Impreg	SC10.3	1094834	Craelius	Wonnerup Member (1245–1351.2m)
19/02/2015	1276.2	1351.2	75.0	HQ3 core	Impreg	4:06	36847/1	Hayden	

\* Bit-interval colour code:

0–5m	5–10m	10–25m	25–50m	>50m
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### DMP Harvey 3

A summary of bit usage throughout the DMP Harvey 3 hole is provided in Table 12. Analysis of the data and comparison of the bit records for DMP Harvey 3 relative to DMP Harvey 2 (Russell and Pollock, 2015) show the following:

- The bit designs that performed best in DMP Harvey 2 did not provide the same performance differential in DMP Harvey 3. This could be due to formation differences between the two sites or, as bit design seemed almost irrelevant to rate of penetration (ROP), perhaps mud weight or viscosity was an overriding influence on penetration rates in DMP Harvey 3.
- In attempting to determine the optimal bits for drilling progress in DMP Harvey 3, bit changes were more frequent than ideal.
- Fourteen core bits were used in DMP Harvey 3 compared to 23 core bits in DMP Harvey 2 for a similar length of core drilling. Not all bits were completely worn at the end of their run as several bit changes were made in a bid to determine the optimal design to increase the ROP.

Table 12: Bit record for DMP Harvey 3 (Nims and Pollock, 2015)

Date	From (m)	To (m)	Interval* (m)	Size	Type	Style	Serial No.	Brand	Formation (downhole interval)
06/03/2015	0.0	6.5	6.5	8½in.	Tricone	Mill tooth	710170/8	AMS	Leederville Formation (0–245m)
06/03/2015	0.0	6.5	6.5	16in.	Blade	4 wing	24111978	Not reported	
07/03/2015	6.5	74.0	67.5	8½in.	Tricone	TCI	710170/8	AMS	
08/03/2015	6.5	74.0	67.5	12½in.	Tricone	Mill tooth	10925336	AMS	
10/03/2015	74.0	312.5	238.5	8½in.	Tricone	Mill tooth	3210321	Not reported	
14/03/2015	312.5	585.5	273.0	8½in.	Tricone	Mill tooth	8.450140.3	Not reported	Eneabba Formation (245–741m)
17/03/2015	585.5	588.3	2.8	8½in.	Tricone	Mill tooth	57718-02	Not reported	
24/03/2015	583.4	591.7	8.3	5½in.	Tricone	Mill tooth	F212813	AMS	
25/03/2015	591.7	679.2	87.5	SQ3 core	Surf Set	Not reported	1	Atlas Copco	
29/03/2015	679.2	703.4	24.2	SQ3 core	SS TC	Not reported	8372092505	Atlas Copco	
31/03/2015	703.4	744.5	41.1	SQ3 core	Surf Set	Not reported	1	Atlas Copco	
02/04/2015	544.4	668.3	123.9	5½in.	Tricone	Not reported	PH3609	Focus	
18/03/2015	668.3	845.1	176.8	SQ3 core	Surf Set	Not reported	1	Atlas Copco	
12/04/2015	845.1	884.5	39.4	SQ3 core	Surf Set	Not reported	8451/16	Atlas Copco	
16/04/2015	884.5	913.5	29.0	SQ3 core	Impreg	S6	402201	Atlas Copco	Yalgorup Member (741–1418 m)
18/04/2015	913.5	933.9	20.4	SQ3 core	Impreg	9M	139212	HMI	
02/04/2015	933.9	1064.9	131.0	SQ3 core	Surf Set	Not reported	5B 3864	ADT	
27/04/2015	1064.9	1184.9	120.0	SQ3 core	Surf Set	SKL-146	5B 3865	ADT	
05/05/2015	1184.9	1303.6	118.7	SQ3 core	Surf Set	SKL-146	5B 3863	ADT	
14/05/2015	1303.6	1423.9	120.3	SQ3 core	Surf Set	SKL-146	5B 3864	ADT	
22/05/2015	1423.9	1462.3	38.4	SQ3 core	Impreg	S6	139207	Hardcore	Wonnerup Member (1418–1550.2 m)
31/05/2015	1462.3	1462.7	0.4	SQ3 core	Impreg	9M	139212	Hardcore	
19/06/2015	1462.7	1550.2	87.5	HQ3 core	Impreg	HA9	HA34660-02	Hayden	

\* Bit-interval colour code:

0–5m	5–10m	10–25m	25–50m	>50m
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## DMP Harvey 4

A summary of bit usage throughout the drilling of DMP Harvey 4 is provided in Table 13. In attempting to determine the optimal bits for drilling progress and bit life, change-outs were frequent. A total of 17 rotary bits and three coring bits were used.

Table 13: Bit record for DMP Harvey 4 (Russell and Iley, 2015)

Date	From (m)	To (m)	Interval* (m)	Size	Type	Style	Formation (downhole interval)
13/12/2014	0.0	61	61	17½in.	Tricone	TCi	Leederville Formation (0–165m)
15/1/2015	61	266.5	205.5	12¼in.	Tricone	TCi	
28/01/2015	266.5	336	70	8½in.	PCD	Not reported	Eneabba Formation (165–1020m)
31/01/2015	336	474	138	8½in.	PCD	HF	
3/02/2015	474	655	181	8½in.	Tricone	TCi	
7/02/2015	655	661	6	8½in.	PCD	Not reported	
9/02/2015	661	662	1	8½in.	Tricone	HF	
12/02/2015	662	810	148	8½in.	Tricone	Milltooth	
14/02/2015	810	815	5	8½in.	PCD	Not reported	
15/02/2015	815	893	78	8½in.	Tricone	Milltooth	
17/02/2015	893	908	15	SQ3 core	Diamond	Impreg	
20/02/2015	908	912	4	8½in.	Tricone	TCi	
21/02/2015	912	921	9	8½in.	PCD	Not reported	
23/02/2015	921	1121	200	8½in.	Tricone	Milltooth	
1/03/2015	1121	1303	182	8½in.	Tricone	TCi	Yalgorup Member (1020–1579m)
20/03/2015	1303	1303.7	0.7	7⅞in.	Junk	Basket	
24/03/2015	1303.7	1308	4.3	8½in.	Tricone	TCi	
28/03/2015	1308	1323	15	8½in.	Tricone	TCi	
31/03/2015	1323	1326	3	8in. core	Diamond	Impreg	
4/04/2015	1326	1665	339	8½in.	PCD	4 wing HF	
11/04/2015	1665	1666.7	1.7	SQ3 core	Diamond	Impreg	Wonnerup Member 1579–1802.6m
12/04/2015	1666.7	1792.7	126	8½in.	PCD	4 Wing HF	
20/04/2015	1792.7	1802.6	9.9	SQ3 core	Diamond	Impreg	

\* Bit-interval colour code:

0–5m	5–10m	10–25m	25–50m	>50m
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The formations were assessed by the driller as ‘hard early in the drilling’; however, the use of tungsten carbide insert bits specifically designed for these types of conditions seemed to provide no real advantage compared with mill tooth bits.

Optimal performance was achieved from a four-blade, hard-formation, polycrystalline diamond composite (PCD) drill bit, which completed a total of 465m in the Wonnerup Member at the fastest progress rates achieved (up to 40m per 12-hour shift) throughout the DMP Harvey 4 well.

Most rotary bits were expended at the end of their runs and metal left in the hole from previous bits exacerbated subsequent bit wear. Shortening of scheduled in-hole bit life is recommended in any future drilling campaign (Russell and Iley, 2015).

### **2.9.3.5 Drilling fluids used**

The drilling fluids employed during the drilling of DMP Harvey 2, 3 and 4 are reported in detail in DDH1 Drilling's final well reports in Appendix A. Refer to the 'Mud Program' section and Appendix 2: AMC drilling fluid summary report in each report.

Australian Mud Company (AMC) was contracted by DDH1 Drilling to provide technical support, on-going mud supplies for DMP Harvey 2, 3 and 4 and to review the effectiveness of the various mud programs used during the drilling program.

Pre-drill testing and analysis work was carried out by AMC on 11 drill chip samples from well GSWA Harvey 1 to design and cost appropriate drilling fluids for DMP Harvey 2, 3 and 4. The testing showed that the clays in GSWA Harvey 1 were more dispersive than swelling in nature. To ensure well integrity during drilling, AMC's inhibitive fluid using CoreWell™ was proposed as an encapsulating agent, with potassium chloride (KCl) as a weighting agent. As DMP Harvey 2 was the first well to be drilled, the lessons learned from the drilling fluids used in this well were subsequently incorporated into a revised drilling fluids proposal for the remaining wells.

For wells DMP Harvey 2, 3 and 4, AMC proposed to use a PAC-R™ KCl-based mud, but greater KCl concentrations were required to maintain adequate mud weight and inhibition<sup>8</sup> to reduce formation squeezing and to stabilise the wells. The formation in DMP Harvey 4 was squeezing into the well from an early stage; resulting in high torque while drilling, over-pull when pulling drill pipe and excessive reaming when changing bits. Despite increasing the KCl concentrations to a weight of approximately 10.2ppg by 1250m depth, a caliper run indicated numerous washout zones between approximately 260 and 960m.

The mud weight was increased to 11.0ppg by the addition of barite to assist in controlling further washouts. This was similar to the mud weight used during the drilling of GSWA Harvey 1 (Millar and Reeve, 2014). The mud weight was increased again to 11.3ppg at 1793m depth, with the addition of further barite (Russell and Iley, 2015). The use of barite facilitated with drilling rates and hole stability.

During the drilling of DMP Harvey 4, the extended drilling time resulted in increased circulation time with fluid shear stress and polymer breakdown (Russell and Iley, 2015). The result was the requirement for increased drilling-fluid products and increased costs of the drilling fluids in DMP Harvey 4.

Given the similar down-hole conditions to DMP Harvey 4 in any future SW Hub drilling, the new well proposals could reasonably include higher concentrations of KCl and barite and increased use of lost circulation materials (LCM; Russell and Iley, 2015).

The drilling fluids used at varying depth intervals in the wells are summarised in Table 14.

<sup>8</sup> Inhibition in this context refers to the control that potassium cations at sufficient concentrations in water-based drilling fluids can have, effectively reducing the swelling and dispersive tendencies of clay-containing strata. Such strata frequently result in well instability that can be exacerbated when the well remains open for a long duration; from in situ stresses and adverse formation characteristics, and from the mechanical and erosive action of drilling.

Table 14: Drilling-fluid usage

Well		Depth (m)	Drilling method	Drilling fluids	Mud weight (ppg)	Recorded fluid loss depths (m)	Use of LCM*	Fluid gains
Yalgorup Member	DMP Harvey 2	0–64	Mud rotary	ShaleHib/CoreWell system with bentonite-based mud	8.7–8.9			Ingress of fresh groundwater
		64–206.5	Mud rotary	ShaleHib/CoreWell system with bentonite-based mud	9.2–9.5			
		206.5–255	PQ3 coring	Experimentation with mud viscosity to control core loss	8.4–8.6			
		255–410.4	PQ3 coring	Changed to a more conventional system (KCl/PAC-R) at 409m	8.6–9.2			
		410.4–603.4	PQ3 coring	Conventional system (KCl/PAC-R). Mud weight was increased with the use of KCl	9.2–9.3			
		603.4–666.4	PQ3 coring					
		666.4–922	PQ3 coring		9.3–9.6	At coarser sandstone horizons encountered at the interface of interbedded sandstones and mudstones	Yes	
		922–1233.7	PQ3 coring		9.6–10.2			Verbal advice from DDH1 Drilling's on-site drillers, drilling fluids observed to flow from the annulus at the transition between the Yalgorup and Wonnerup Members
		1233.7–1350.2	HQ coring					

Well	Depth (m)	Drilling method	Drilling fluids	Mud weight (ppg)	Recorded fluid loss depths (m)	Use of LCM*	Fluid gains
Valgorup Member and the Valgorup-Wonnerup Member transition	0–74	Mud rotary	Conventional gel/polymer mix				
	74–588	Mud rotary	Weighted KCl/PAC-R polymer mud system	9.8–10.2			
	588–900	SQ3 coring		10.2			
	900–1462	SQ3 coring	From 1337 to 1430m the mud weight was reduced to 9.2ppg to control mud losses	10–9.2	Increasing fluid losses observed, notably at 946, 1053, 1083 and 1418m. Losses were approx. 1500 to 7000L per 12-hour shift. At 1430m fluid losses were 8000L per 12-hour shift.	Yes	
	at 1462	SQ3 coring	Mud weight reduced to free differentially stuck drill pipe	8.5			
Valgorup Member and fractures within the Wonnerup Member	1462–1550	HQ coring	Mud weight lifted	10.2			
	0–266.5	Mud rotary	KCl PAC-R based mud	8.5			
	266.5–893	Mud rotary	Mud weight was increased with the use of KCl	8.5–9			
	893–908	SQ3 coring					
	908–1303	Mud rotary	Mud weight was increased to 10.2ppg, with KCl, from 1222 to 1250m	9–10.4			
	1303–1326	Mud rotary	Barite was used to lift the mud weight to 11ppg	11			
	1326–1665	Mud rotary	Additional barite was used to lift the mud weight to 11.3ppg at approx. 1665m	11–11.3	Notable mud loss at approx. 1661m	Yes	
	1665–1802	SQ3 coring, mud rotary and coring	Continued use of PAC-R mud with KCl and barite to maintain the mud weight	11–11.3			

NOTE: \* LCM: lost-core materials.

## Lessons learned

The lessons learned from the drilling fluids used in DMP Harvey 2, 3 and 4 include the following:

- The PAC-R KCl drilling fluid was successful and allowed drilling-fluid density to be controlled without the addition of contained solids.
- In any future drilling in the SW Hub area, the new well proposals should consider higher concentrations of KCl, barite and increased use of lost circulation materials (LCM; Russell and Iley, 2015).
- Consideration should be given to running the intermediate casing to a greater depth, perhaps 500–700m, to counteract formation squeezing in the upper, fragile-hole section.
- High mud weights were required to maintain hole stability.
- Seepage losses require monitoring, including correlating with changes in mud weight.
- Continuous presence on-site by an oilfield mud engineer is recommended for future drilling in the SW Hub area.

## Preliminary interpretation

During the drilling of GSWA Harvey 1 the focus was on the pressure-based system, with inadequate appreciation of the dispersive formations. In wells DMP Harvey 2, 3 and 4 AMC's primary focus was on a dispersive system, with the use of an inhibitor and an encapsulator. The focus changed as drilling continued into DMP Harvey 2, to incorporate the pressurised formations. Future drilling in the SW Hub area will need to consider dispersive and pressurised formations in the planning of an optimal drilling fluid.

Barite was required in DMP Harvey 4 and not in DMP Harvey 2 or 3 due to the latter holes being slimline drilled. In slimline drilling the high rotation speeds can cause centrifugal forces to take effect, resulting in 'spin out'. The high rotation speeds would ultimately deplete barite from the fluid system.

### 2.9.3.6 Drilling fluid losses and gains

This section discusses drilling fluid losses and gains, as reported during drilling in the final well reports for wells DMP Harvey 2, 3 and 4 in Appendix A and as summarised in Table 14.

## Drill fluid losses

All three wells experienced fluctuating drilling fluid losses, which were treated with LCM. In DMP Harvey 4, notable mud loss occurred at about 1660.6m (Russell and Iley, 2015). The final well reports and daily drilling records (Appendix A) were reviewed against the composite well logs (Appendix C) to determine down-well geological features that could have caused the loss of drilling fluids and the water gains that were observed in wells DMP Harvey 2, 3 and 4.

In DMP Harvey 2, fluid losses were reported and LCM was used to seal the well between 666.4 and 922m depth. Fluid losses were associated with coarser sandstones interfacing with mudstones and claystones (Russell and Pollock, 2015) within the Yalgorup Member.

During the SQ-coring of DMP Harvey 3, fluid losses were experienced between 900 and 1337m depth, with significant losses noted from 942 to 946m, and at 1053m and 1083m (Nims and Pollock, 2015). These depths correspond to coarse-grained sandstone and conglomerate interfacing with siltstones in the Yalgorup Member, as described by the lithological log for DMP Harvey 3 (Appendix C).

Relative to DMP Harvey 2 and 3, drilling fluid losses in DMP Harvey 4 were minimal. According to DDH1 Drilling, the larger annulus and lower annular dynamic pressures during rotary drilling in DMP Harvey 4 could have resulted in the lower fluid losses. The increased viscosity (60 seconds) and the LCM may have served to seal fractures caused by the hydrostatic head of 11ppg drilling fluid below 1300m, when barite was introduced to the drilling fluid (Russell and Iley, 2015).

In DMP Harvey 4, notable mud loss occurred around 1660.6m (Russell and Iley, 2015) in the Yalgorup Member. The lithology at this depth is reported as weakly cemented, coarse-grained sandstone (Appendix D). A thin gamma-ray spike at this depth indicates the presence of a thin mudstone bed at 1661m depth.

### **Preliminary interpretation**

The notable fluid losses in the three wells are considered to be associated with more-permeable horizons (poorly sorted, coarse-grained sandstones and conglomerates) interfacing with siltstone, mudstone and claystone-dominant strata in the middle to lower sections of the Yalgorup Member, and within fractured, potentially highly permeable horizons within the Wonnerup Member.

### **Fluid gains**

#### **DMP Harvey 2**

Fresh water entered the annulus of DMP Harvey 2 during the cementation of the surface casing at 64m (refer to DMP Harvey 2 final well report and daily drilling report of 8 December 2015, in Appendix B). This ingress is considered to be groundwater flowing into the well either from the sands beneath the clays within the surficial sediments or from sandstone within the Leederville Formation (lithological log in Appendix C).

On 16 February 2015, the drilling fluid in the well annulus of DMP Harvey 2 flowed at the surface (Appendix A, DMP Harvey 2 final well report and daily drilling reports). Fluid gain was observed by the drillers while drilling the transition zone between the Yalgorup and Wonnerup Members. It is suggested that the fluid gain could have resulted from pressurised groundwater flowing into the well. The lithology log infers that drilling had penetrated sandy mudstone horizons overlying fine-grained to granular sandstones (Appendix D, DMP Harvey 2 composite log). The fluid flow from the annulus is reported as clear water flowing to surface of a density of 8.6ppg and a viscosity of 32 seconds. The drilling mud at this time had a density of 9.7ppg and a viscosity of 41 seconds (Appendix A, DMP Harvey 2 daily drilling report, 16 February 2015). Unfortunately the flowing water and the drilling mud used at this time were not sampled for chemical analysis.

The top of the Wonnerup Member is likely to have been subject to erosion and weathering. It is suggested that any weathering of the upper Wonnerup Member could have resulted in a higher porosity and permeability zone, which would facilitate the flow of groundwater from the upper part of the Wonnerup Member into the DMP Harvey 2 well.

#### **DMP Harvey 3 and 4**

No groundwater inflows were reported in the final well reports for DMP Harvey 3 and 4. However, the driller verbally reported groundwater inflow into the well annulus during the rotary drilling of the shallow (upper) section of DMP Harvey 3. After the flow test in DMP Harvey 3 on 27 June 2015, DDH1 Drilling allowed the water level to recover and stabilise before completing the well. The water level stabilised at 20m below ground level (Bolton, 2015).

## Preliminary interpretation and recommendation

Fluid gains were recorded by the drillers during the drilling of DMP Harvey 2 and 3. These are considered to be related to groundwater flowing via permeable horizons into the wells' annuli and to be driven by piezometric heads.

In any further drilling in the area, the use of naturally occurring radioisotopes are recommended to clarify the ages of the formation fluids in the stratigraphy in order to refine the conceptual hydrogeological model for the SW Hub study area.

### 2.9.3.7 Cementing operations

The importance of cement placement is recognised in the provision of an effective barrier to any upward migration of CO<sub>2</sub> in the annular space between the well wall and the well casing. The wells have been completed with cemented casing to the standard required by the water-well drilling industry (National Uniform Drillers Licensing Committee, 2012) to ensure that there is no risk of hydraulic continuity between the aquiferous horizons, and such that perforation or equipping of the wells for monitoring can take place.

The cementing operations are detailed in the final well reports (Appendix A) and are as shown in the well completion schematics (Figures 19 to 21).

After the installation of the conductor, intermediate and final casing, and respective casing shoes, cementitious grout was pumped into the well annulus between the casing and the formation to ensure well integrity. In all cases the cementitious grout was supplied by Holcim Concrete, or mixed on-site, and injected into each well annulus at a minimum slurry density of 13.6ppg or 1.63SG (Figures 19 to 21).

The volumes of cementitious grout required for injection into the annular space behind each cased section were calculated. Formation squeezing and formation fall back were experienced in all three wells during drilling and reaming of the wells' walls. The wells had a larger diameter in the friable sections and a smaller diameter in the 'tight', mudstone-rich sections, as noted in the caliper logs. Cementitious grout of 120 per cent of the calculated annular space was injected into each cased section. The increased volumes of grout were pumped into the annular spaces of each well, until grout return was observed exiting the annulus at ground surface. The exception was during the construction of DMP Harvey 3. During the cementation of the final casing in DMP Harvey 3, return of cementitious grout was not observed at the well surface. DMIRS proposes to verify the well integrity of the three wells as part of a future well workover program by running a downhole cement-bond logging tool in each well.

Wells DMP Harvey 2, 3 and 4 have not been decommissioned, but have been suspended pending a decision regarding further testing, or plugging and decommissioning. The cement distribution in each well will be evaluated during a future workover phase.

## 3.0 Well details

The approval to drill the wells was issued by GSWA under Section 115 of the Western Australian Mining Act 1978 (see section 2.4, above), but DMIRS has reported under the Western Australian *Petroleum and Geothermal Energy Resources Act 1967* (PGERA) for the purposes of full transparency and consistency with the reporting of GSWA Harvey 1.

This section reports on the details of the three wells as required by, and in accordance with, Schedule 9 of the Petroleum and Geothermal Resources (Resource Management and Administration) Regulations 2015. Section 4.0 of this report documents drilling details and section 5.0 discusses the core analysis.

### 3.1 Name and numbers of wells

Three wells were drilled: DMP Harvey 2, DMP Harvey 3 and DMP Harvey 4. The wells were drilled by DMIRS following the drilling and investigation of the GSWA Harvey 1 well in 2012 (Millar and Reeve, 2014).

### 3.2 Cost of the wells

The cost of access works and preparation of the drilling pads, geological services, drilling, drilling fluids, completion and transportation of core to the Perth Core Library for each of the three wells, exclusive and inclusive of GST, are reported in Table 15. The tabulated costs do not include costs incurred from wireline logging and processing, core analysis and reservoir modelling.

Table 15: Cost of drilling and completing the wells

Well	Cost excluding GST	Cost including GST
DMP Harvey 2	\$1,598,369	\$1,758,206
DMP Harvey 3	\$1,869,682	\$2,056,650
DMP Harvey 4	\$2,415,958	\$2,657,553
Total	\$5,892,704	\$6,481,974

### 3.3 Name of instrument holder

There is no instrument holder<sup>9</sup> as DMP Harvey 2, 3 and 4 were drilled under the Western Australian Mining Act 1978 (Appendix B). An instrument holder is specified when a well is drilled under Petroleum and Geothermal Energy Resources Act 1967. The SW Hub project activities, including the shallow well drilling program, were managed by DMIRS Bunbury office, with Dominique Van Gent as Principal.

### 3.4 Name of instrument area in which the wells are located

There is no instrument area relating to wells DMP Harvey 2, 3 and 4.

### 3.5 Purpose of the well activity

The principal objective of the drilling of DMP Harvey 2, 3 and 4 was to determine the nature of the stratigraphy to ascertain the CO<sub>2</sub> containment potential of the upper Lesueur Sandstone (Yalgorup Member).

The secondary objectives of the 'shallow' drilling program were as follows:

- Validate the 3D seismic data and determine the 3D structure of the geology across the study area.
- Ascertain the lateral continuity of the low-permeability horizons (baffles to CO<sub>2</sub>) determined in the Eneabba Formation and Yalgorup Member in well GSWA Harvey 1.
- Retrieve core from the 'basal Eneabba unit'.
- Retrieve core from the contact of the Yalgorup and Wonnerup Members of the Lesueur Sandstone.
- Determine any porosity and permeability variation between the wells within the top 50m or so of the Wonnerup Member.
- Ascertain the optimal location of any injection testing well. Notionally this well is referred to as 'DMP Harvey 5'.

<sup>9</sup> An instrument holder is defined and required by the Western Australian Petroleum and Geothermal Energy Resources Act 1967, when the purpose of drilling is to investigate petroleum potential or geothermal energy potential at a given site.

### 3.6 Well status

The wells DMP Harvey 2, 3 and 4 have not been perforated. The wells have been completed and suspended pending future activities, which, at the time of printing, are yet to be determined.

### 3.7 Locations of the wells

The locations of the wells are shown in Figure 1.

#### 3.7.1 Elevation, latitude and longitude

The locations of the proposed sites for wells DMP Harvey 2, 3 and 4 were surveyed by BCE Surveying Pty Ltd in November 2014, and again in April 2015 once the well positions had been finalised.

The elevation and location information for wells DMP Harvey 2, 3 and 4 are given in Table 16, with the locations also shown in Figure 1. The photographs and drawings from the April 2015 survey are in Appendix E.

Table 16: Surveyed locations of the wells

Well	Ground elevation (m AHD)	Latitude and longitude (GDA94)		Projected coordinates (MGA94, Zone 50)	
		Latitude	Longitude	Easting (m)	Northing (m)
DMP Harvey 2	15.40	115°50'42.108"	33°00'30.591"	392052.65	6347141.74
DMP Harvey 3	20.20	115°47'43.35"	33°02'08.402"	387392.24	6343895.95
DMP Harvey 4	15.89	115°49'24.533"	33°02'18.521"	389946.08	6343842.51

#### 3.7.2 Basin and sub-basin

Wells DMP Harvey 2, 3 and 4 correspond to the Phanerozoic onshore southern Perth Basin, specifically on the Harvey Ridge of the Mandurah Terrace as shown in Figure 23.



### 3.7.3 Map sheet and graticular block

The three wells are located within the Pinjarra (SI50-02) 1:250,000 and Pinjarra (2032) 1:100,000 map sheet areas (Figure 23). In terms of DMIRS tenement-administration graticular blocks, DMP Harvey 3 and 4 are located within graticular block 5886 of the Albany SI50 1:1 million sheet and DMP Harvey 2 is within graticular block 5887 (Figure 23).

### 3.7.4 Geophysical-survey location identifier

The wells are located within the Harvey 3D seismic study area of 2014 (Burke, 2014). The closest in-line and cross-line of this survey to wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4 are given in Table 17.

Table 17: Locations of the wells relative to the 3D seismic survey lines

Well	In-line	Cross-line
GSWA Harvey 1	1313	5010
DMP Harvey 2	1241	5273
DMP Harvey 3	1111	5086
DMP Harvey 4	1109	5188

The locations of the seismic lines from the 2011 2D seismic survey are shown in Figure 9a, with the shot points and the receiver locations of the 2014 3D seismic survey shown in Figure 9b and Figure 9c, respectively.

## 3.8 Results of check survey

Surveys of the drill site were carried out by BCE Surveying Pty Ltd, in November 2014 before the wells were spudded, and again in April 2015, after the wells were drilled. The locations of the wells in April 2015, were at the same points as surveyed in November 2014. The projected well locations relating to the GDA94 geodetic datum are given in Table 16.

## 3.9 Spud date

The spud dates for the three wells are as shown in Table 18.

Table 18: Dates of spudding, total depth and rig release

Well	Spud date	Date total depth was reached	Rig release date
DMP Harvey 2	06/12/2014	22/02/2015	05/03/2015
DMP Harvey 3	06/03/2015	24/06/2015	30/06/2015
DMP Harvey 4	13/12/2014	22/04/2015	14/05/2015

## 3.10 Rig release date

The rig release dates are as given in Table 18. The information is derived from the final well reports for DMP Harvey 2, 3 and 4, which are in Appendix A. These reports include the daily drilling reports (Appendix 1) and the drilling fluid summary report (Appendix 2) for each well.

Actual versus predicted time–depth curves for wells DMP Harvey 2, 3 and 4 are shown in Figures 24 to 26. Drilling delays were encountered for each of the wells.

Drilling delays in DMP Harvey 2 were incurred as a consequence of drilling difficulties on the following days:

- day 30 at 800m depth.
- day 40 at 1100m depth.
- day 48 at 1233m depth.

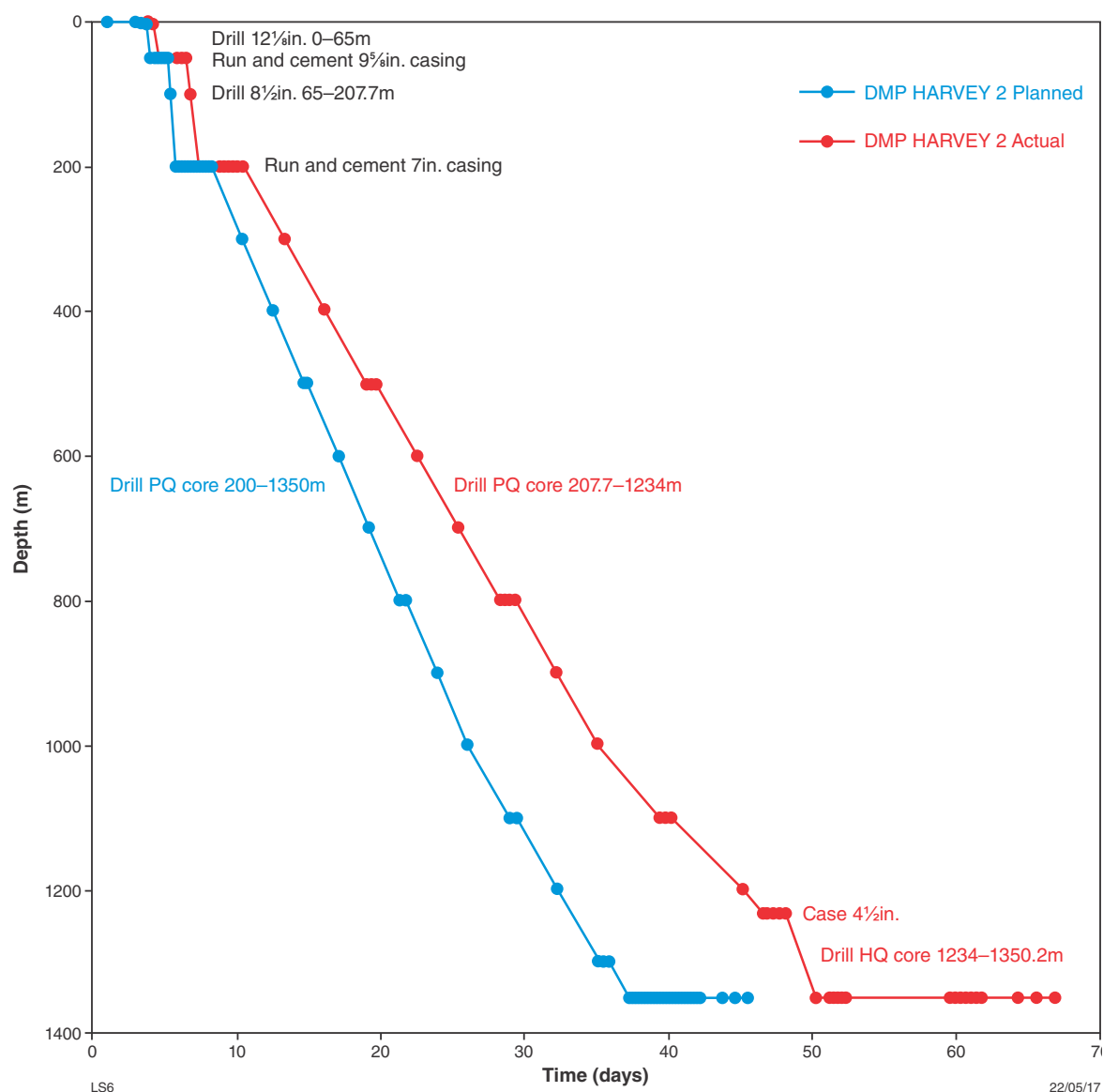


Figure 24: DMP Harvey 2 drilling time–depth curve: predicted versus actual.

Drilling delays in DMP Harvey 3 were incurred as a consequence of the following:

- Placement and cementing of intermediate casing (7in.) at 585.8m depth. Following DDH1 Drilling's experiences during the drilling of well DMP Harvey 2, the depth of the intermediate casing in DMP Harvey 3 was increased from that specified in the scope of works (250m depth) to improve well stability.

- Well instability from 588 to 744m, while drilling mudstone-rich interbedded strata of the lower Eneabba Formation and the upper part of the Yalgorup Member. Delays were incurred during cementing operations and redrilling of the well between 588 and 744m depth.
- During contract negotiation with DDH1 Drilling, DMIRS changed the specified core size in DMP Harvey 3 from PQ to SQ. The larger SQ-sized core barrel (147mm diameter drill hole) resulted in a slower than predicted ROP.
- Differential sticking of the rod line at 1462m, remediated by a reduction in mud weight to 8.9ppg.
- Several wiper trips to condition the open hole between 588 and 1462m prior to a wireline logging attempt that was aborted due to obstacles in the hole.
- Reaming runs to recondition the hole, followed by a further wireline logging run and running and cementing of the final casing.
- HQ coring of the hole to 1550m (TD) and a final wireline logging run.

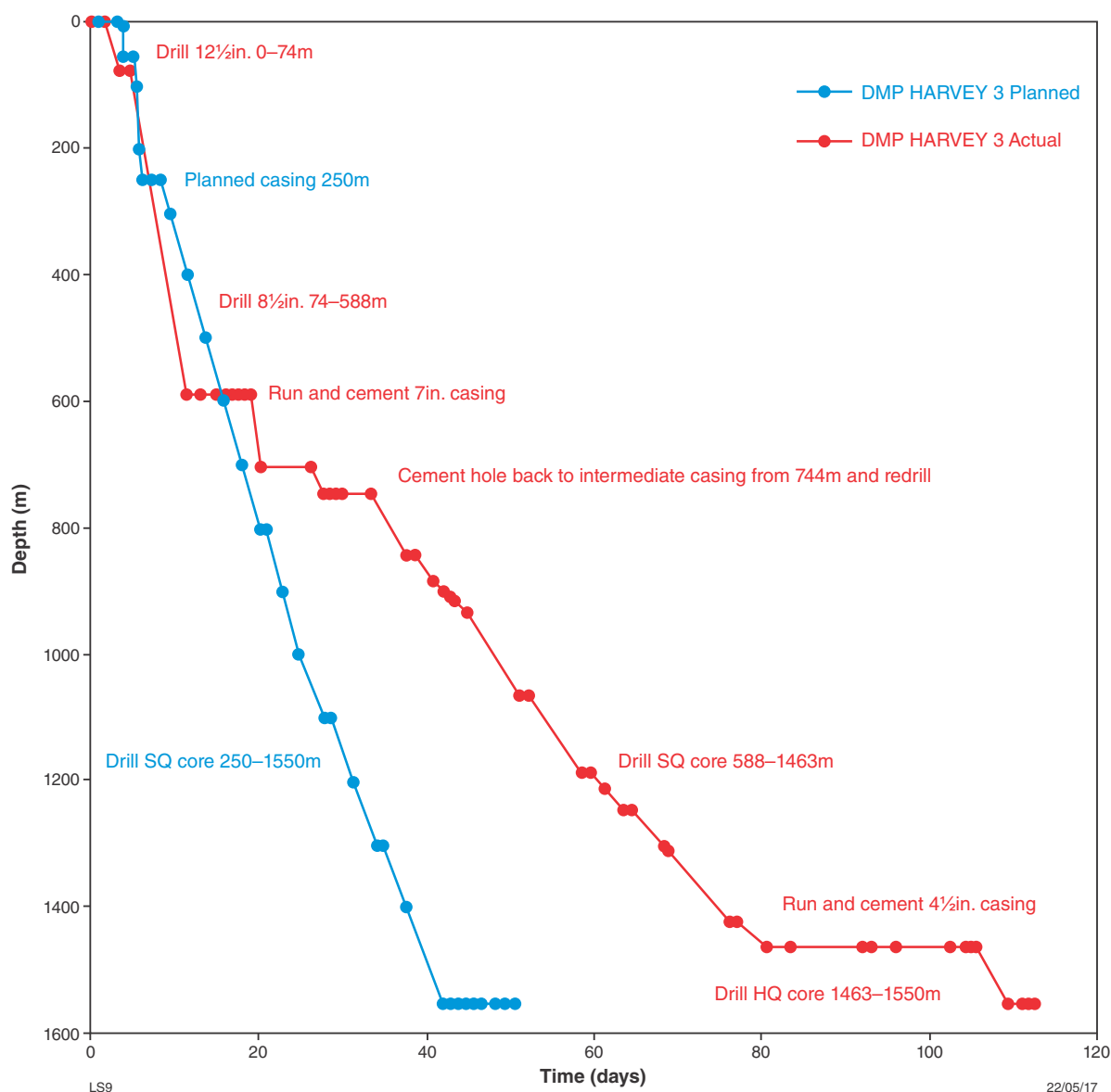


Figure 25: DMP Harvey 3 drilling time–depth curve: predicted versus actual.

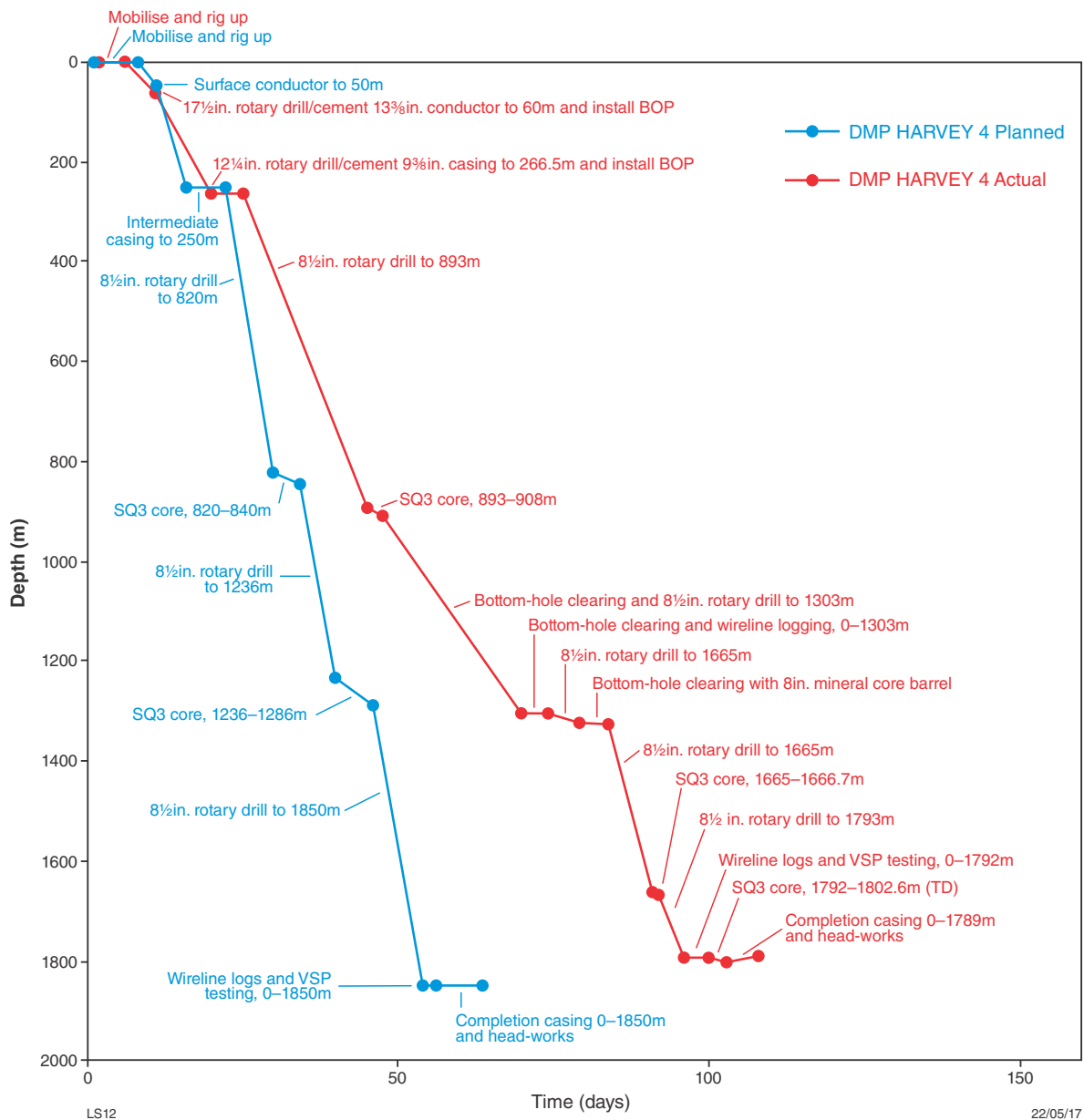


Figure 26: DMP Harvey 4 drilling time–depth curve: predicted versus actual.

### 3.11 Depth reference for the wells

DDH1 Drilling recorded drilling depth relative to the rig floor for DMP Harvey 2 and 3 (0.60m above ground elevation for Rig 16). For DMP Harvey 4, DCA's rig's floor was 4.00m above ground level; however, DCA recorded drilling depth with respect to ground elevation. The ground elevation, rig-table datum and driller's datum for DMP Harvey 2, 3 and 4 are in Table 19. The land survey details are given in Appendix E.

Table 19: Ground elevation, rig table datum and driller's datum for the wells

Well	Ground elevation (m AHD)	Rig-table datum (m AHD)	Driller's datum (m AHD)
DMP Harvey 2	15.40	16.00	16.00
DMP Harvey 3	20.20	20.80	20.80
DMP Harvey 4	15.89	19.89	15.89

### 3.13 Ground depth at the well

The ground depth beneath the drilling table, or ground elevation, at the wells is given in Table 19.

### 3.14 Measured and true vertical depths of the wells

The total depth (TD) of the wells as measured by the drillers is assumed to be the true vertical depth (TVD), as reported in Table 20. The measured depth is from ground level. The depth of the wells relative to Australian Height Datum (m AHD) is also reported.

Table 20: Well depths

Well	Well surveyed?	Well depth from ground level (m AHD)	Drilled depth (m)	True vertical depth (m)	Depth difference (m)	True vertical depth (m AHD)
DMP Harvey 2	Yes	-1335	1351.2	1351.07	0.13	-1335.7
DMP Harvey 3	Yes	-1530	1500.2	1499.96	0.60	-1479.8
DMP Harvey 4	No	-1786	1802.0	1802.0	Not measured	-1786.1*

NOTE: \* As the drilled path of DMP Harvey 4 was not surveyed during drilling, the true vertical depth of DMP Harvey 4 is assumed to be the same as the drilled depth.

Due to the friable nature of some of the strata drilled, some fall back may have occurred during the installation of the completion casing. Therefore, the depths of the completed wells may be shallower than the reported drilled depths.

### 3.15 Depth to formation tops and marker horizons

The measured depths and TVD to the formation tops and marker horizons for DMP Harvey 2, 3 and 4 are in Table 21. These depths were determined by ODIN using seismic picks in the interpreted 3D seismic data (Byrne, 2016)<sup>10</sup>.

<sup>10</sup> The formation tops and bench marker horizons are preliminary, contingent upon confirmation from GSWA, following their review of the stratigraphy in the southern Perth Basin.

Table 21: Measured and true vertical depths of formation tops and marker horizons (Byrne, 2016)

Well	Formation or marker horizon	Easting (m; MGA94, Zone 50)	Northing (m; MGA94, Zone 50)	Interpreted depth (m AHD)	Interpreted depth (m MDRT)	True vertical depth (m MDRT)
DMP Harvey 2	Cretaceous unconformity	392052.68	6347141.89	-118	134	134.0
	Basal Eneabba unit	392053.03	6347143.62	-392	408	408.0
	Yalgorup Member	392053.44	6347144.36	-533	549	549.0
	Wonnerup Member	392061.60	6347140.18	-1226	1242	1241.9
DMP Harvey 3	Cretaceous unconformity	387391.70	6343896.36	-210	231	230.8
	Basal Eneabba unit	387388.80	6343898.24	-560	581	580.7
	Yalgorup Member	387385.41	6343899.51	-722	743	742.7
	Wonnerup Member	387370.64	6343897.01	-1396	1417	1415.8
DMP Harvey 4	Cretaceous unconformity	389946.08	6343842.51	-142	162	Not measured
	Basal Eneabba unit	389946.08	6343842.51	-852	872	Not measured
	Yalgorup Member	389946.08	6343842.51	-994	1014	Not measured
	Wonnerup Member	389946.08	6343842.51	-1577	1597	Not measured

A well survey was not carried out in DMP Harvey 4, so it has been assumed that TVD to the formation tops and marker horizons is the same as the measured depth in that instance.

### 3.16 Depth of perforation in the carbon-storage reservoir

The wells DMP Harvey 2, 3 and 4 have not been perforated. The wells have been completed, as shown in Figures 19 to 21 and as recorded in Table 10, and have been suspended pending a decision regarding future monitoring or decommissioning. Any future installation, testing or monitoring of wells DMP Harvey 2, 3 and 4 will require permission from the regulator, the Petroleum Division of DMIRS.

### 3.17 The date on which the total depth was reached

The dates when TD was reached in DMP Harvey 2, 3 and 4 are in Table 18.

### 3.18 The surveyed path of the wells

DDH1 Drilling Pty Ltd used a Ranger Discoverer™ to survey, followed by Halliburton Compass™ software, the drilled paths of DMP Harvey 2 and 3. The tabulated well-survey data for DMP Harvey 2 and 3, including the coordinates for the bottom of the wells, are in Figure 27. As no well survey was run for DMP Harvey 4, this well is assumed to have been vertically drilled, with the bottom-hole coordinates assumed to be the same as the well's ground surface coordinates.

<sup>10</sup> The formation tops and bench marker horizons are preliminary, contingent upon confirmation from GSWA, following their review of the stratigraphy in the southern Perth Basin.

The two wells average approximately one degree off vertical, with DMP Harvey 3 dropping back towards vertical after kicking off the cement plug inserted for formation stability between 744.5 and 584m depth, at approximately 670m. The driller aimed to achieve a total vertical depth within half a metre of the drilled depth (Murray Pollock [DDH1 Drilling Pty Ltd] 2016, pers. comm., 22 February). The sidetrack well was named DMP Harvey 3A.

The inclination and azimuth of wells DMP Harvey 2 and 3 are shown in Figure 27 and the surveyed paths are shown in Figure 28.

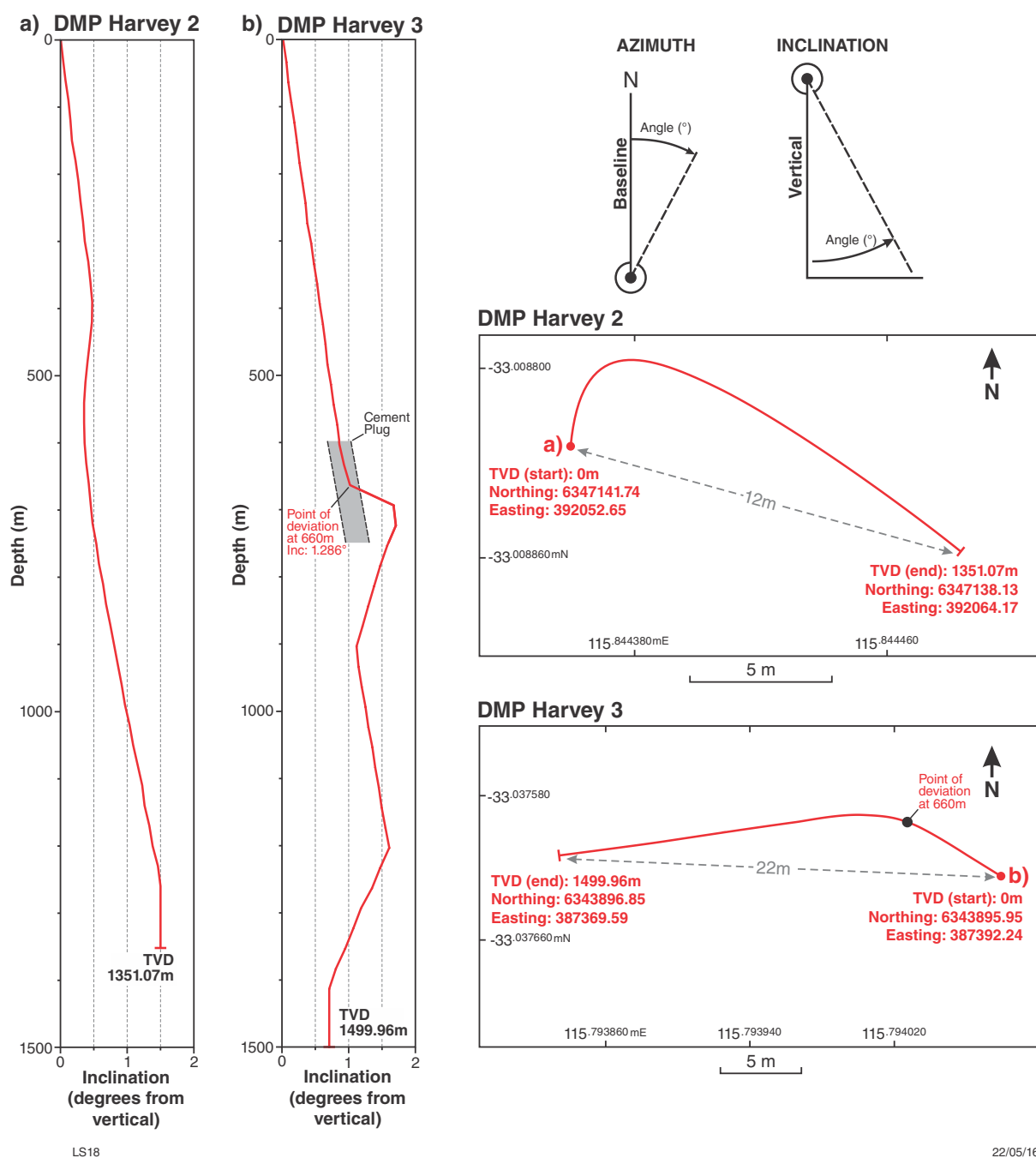


Figure 27: DMP Harvey 2 and 3 inclination and azimuth surveys.

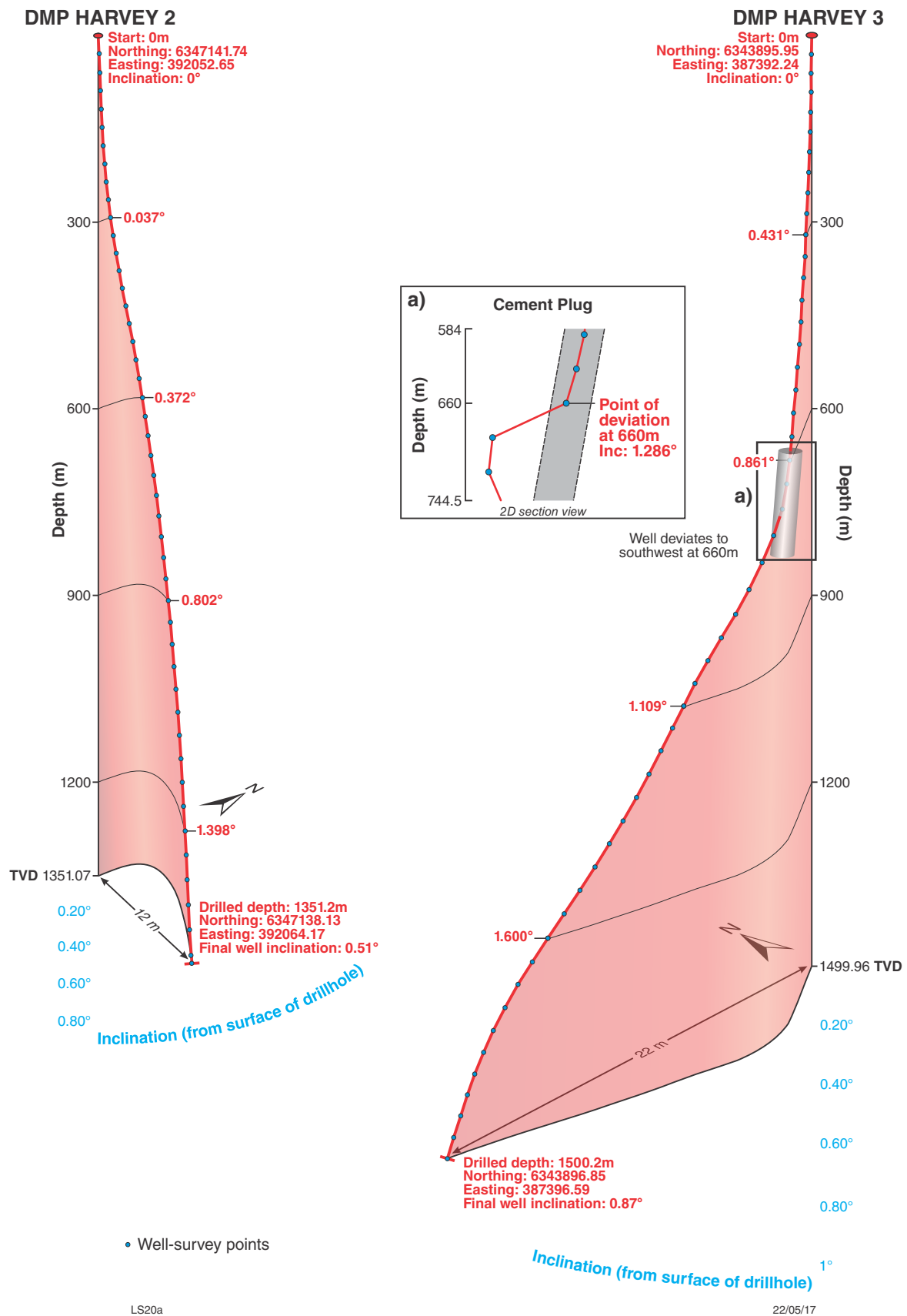


Figure 28: The surveyed paths of DMP Harvey 2 and DMP Harvey 3, as drilled.

### **3.19 DMP Harvey 3A sidetrack well**

Technically DMP Harvey 3A is a sidetrack well. However, as there was only a short section of repeat drilling of the same stratigraphy, DMP Harvey 3A is considered to be a continuation of DMP Harvey 3 from approximately 660m down-hole depth, when the drill bit deviated off the cement plug shown in Figures 27 and 28.

## **4.0 Wireline logging and well tests**

Wireline logging and pressure and flow tests were conducted in DMP Harvey 2, 3 and 4. The testing and results are discussed below.

### **4.1 List of log runs for wireline logging and velocity surveys**

The wireline logs run by Halliburton Australia Pty Ltd are summarised in Table 22. Well instability due to the formation squeezing in or collapsing prevented logging wells DMP Harvey 3 and 4 in their entirety in single runs. Instead, wells were logged over different depth intervals on separate occasions, and the resulting logs were merged, or 'spliced', to give one continuous log of the well, albeit some of the logging is in casing, as described in section 2.9.3.1. Details regarding the wireline log runs are in Table 22.

#### **4.1.1 DMP Harvey 2**

From 22 to 23 February 2015, DMP Harvey 2 was logged to 1350m, including the HQ-sized section. However, the Yalgorup Member was not logged as openhole due to the PQ drill string being stuck. Logging in openhole was from 1347 to 1232m. Above 1232m logging was within the PQ drill string, which acted as casing.

#### **4.1.2 DMP Harvey 3**

In DMP Harvey 3, formation instability meant that logging undertaken on 25 June 2015, was through casing for the 900–1462m. This resulted in the loss of approximately 500m of openhole logging for much of the Yalgorup Member and some of the uppermost Wonnerup Member. For the interval 1550–1462m logging was within an openhole section.

#### **4.1.3 DMP Harvey 4**

In DMP Harvey 4, logging was carried out on two occasions: from 0 to 1303m on 23 March 2015, and from 0 to 1793m during 16–18 April 2015. There is complete logging coverage of the Yalgorup Member. Due to deteriorating hole conditions, DMP Harvey 4 was logged before the last coring run progressed drilling from 1793m to the end of the well at 1802m TD (Russell and Iley, 2015).

### **4.2 Processed wireline logging data**

Halliburton processed the sonic logs recorded behind casing from DMP Harvey 2 and DMP Harvey 3. Image logs from DMP Harvey 4 were processed by ODIN and those from GSWA Harvey 1 were reprocessed by Baker Hughes. Curtin University's Department of Exploration Geophysics processed the vertical seismic profile (VSP) logs. The raw and processed wireline logging data are available for download from DMIRS WAPIMS database. The raw (unprocessed) wireline logging data is in Appendix G. The wireline formation analysis and processing results are summarised in section 6.0. The cement evaluation logs have not been run at this stage. It is proposed that these logs will be carried out as part of a future workover program.

Table 22: Wireline logging runs undertaken by Halliburton Australia Pty Ltd

Well	Suite	Date logged	Run	Services	Relating files	Log also run in casing	Length of tool string (m)	Top Gamma (m)	Top Sonic (m)	Top of main log (m)	Deepest (m)
DMP Harvey 2	1	23/02/2015	1	Gamma, resistivity, dipole sonic	LAS, PDF, EMF, TIF, DLIS	Yes	29.49	12	30	1232	1347
			2	Vertical seismic profile	Seismic raw data and field report (PDF)	Yes	18.66	30		30	1347.4
DMP Harvey 3	S1R1*			Processed sonic	–	–	–	–	–	–	–
	1	31/05/2015	1	Gamma, resistivity, dipole sonic, neutron, density	LAS, PDF, EMF, TIF, DLIS	Yes	48.22	21	582.5	582.5	911
			2	Gamma, resistivity, sonic, neutron, density	LAS, PDF, EMF, TIF, DLIS	No	44.9	869	869	869	966
	2	25/06/2015	1	Gamma, resistivity, sonic	LAS, PDF, EMF, TIF, DLIS	Yes	27.58	900	900	1462	1550
			2	Gamma, neutron, density	LAS, PDF, EMF, TIF, DLIS	Yes	16.61	900		1462	1550
			3	Formation tester (HSFT)	PDF, EMF, TIF, DLIS	No	17.12	1465		1472.5	1537.5
			4	Vertical seismic profile	Seismic raw data and field report (PDF)	Yes	18.66	185		185	1530
	S1R1&S1R2&S2R1*			Processed sonic	LAS, PDF, EMF, TIF, DLIS	Yes	–	44	76	76	1535
	S1R1&S1R2*			Spliced quad-combo	LAS, PDF, EMF, TIF, DLIS	Yes	–	44	582	582	966
	S1R1&S1R2&S2R1&S2R2*			Spliced quad-combo	LAS, PDF, EMF, TIF, DLIS	Yes	–	44	75	582	1548

Well	Suite	Date logged	Run	Services	Relating files	Log also run in casing	Length of tool string (m)	Top Gamma (m)	Top Sonic (m)	Top of main log (m)	Deepest (m)
DMP Harvey 4	1	23/03/2015	1	Gamma, resistivity, dipole sonic, neutron, density	LAS, PDF, EMF, TIF, DLIS	Yes	41.32	13	13	262	1298
			2	Image tool (XRMI)	DLIS, LAS, PDF	No	15.6	260		262	1298
	2	16/04/2015	1	Gamma, resistivity, dipole sonic, neutron, density	LAS, PDF, EMF, TIF, DLIS	No	41.32	1250	1250	1250	1775
			2	Image tool (XRMI)	DLIS, LAS, PDF	No	18.09	1250	–	1250	1776
				Compensated Spectral Gamma Ray tool (CSNG)	LAS, PDF, EMF, TIF, DLIS	No	18.09	250	–	250	1769
			3	Nuclear magnetic resonance (MRIL)	LAS, PDF, EMF, TIF, DLIS	No	24.1	750	–	750	1772
			4	Reservoir Description Tool (RDT)	PDF, EMF, TIF, DLIS	No	29.47	744	–	742	1726
			5	Vertical seismic profile	Seismic raw data and field report (PDF)	Yes	18.66	100	–	100	1760
	S1R1&S2R1*			Processed sonic	LAS, PDF, EMF, TIF, DLIS	Yes	–	13	13	13	1765
	S1R1&S2R1*			Spliced quad-combo	LAS, PDF, EMF, TIF, DLIS	No	–	250	250	262	1775
	S1R2&S2R2*			Spliced XRMI image	LAS, PDF, EMF, TIF, DLIS	No	–	250	–	250	1776
	S1R2&S2R2*			Spliced caliper – borehole volume	LAS, PDF, EMF, TIF, DLIS	No	–	250	–	250	1776

NOTE: \* Two or more logging runs over different sections of the well, joined to make one log over the whole logged interval.

## 4.3 Formation testing

Formation testing comprising in situ temperature and pressure measurements, and formation-fluid sampling, were carried out in the three wells, as discussed below.

### 4.3.1 In situ pressures and temperatures

Downhole in situ temperatures were measured in DMP Harvey 2, 3 and 4, and pressures were measured in DMP Harvey 3 and 4, as outlined herein. Formation-fluid sampling within DMP Harvey 4 is discussed in section 4.2.2, below.

#### 4.3.1.1 Procedure

##### DMP Harvey 2

Temperature was measured in DMP Harvey 2 at TD using the standard wireline-logging tools.

##### DMP Harvey 3 — formation testing tool

Pressure and temperature were measured in DMP Harvey 3 using Halliburton's slimline HSFT™ formation testing tool at four depths in the Wonnerup Member.

##### DMP Harvey 4 — reservoir description tool

Halliburton's reservoir description tool (RDT™) tool was deployed in DMP Harvey 4 for the purpose of formation testing, under the supervision of DMIRS. This tool is designed to:

- measure downhole in situ reservoir pressures
- measure downhole in situ reservoir temperatures
- sample formation fluids
- perform formation stress tests using a dual-packer module.

The RDT was used at multiple depths in DMP Harvey 4 in preference to the HSFT due to its capacity to pump out fluids. The tests were successfully carried out, with the exception of the formation stress tests, which were not performed due to deteriorating hole conditions and the risk of equipment becoming stuck in the well.

Pressure measurements were taken as the tool was lowered down DMP Harvey 4 to minimise any errors due to the tool and reservoir temperatures not being in equilibrium. As the tool was held stationary at specified depths, it was 'set', meaning a probe was triggered to enter the formation and extract a small volume of fluid amounting to approximately 10cm<sup>3</sup>. The pressure in the fluid was allowed to stabilise to equal the reservoir pressure before taking an in situ pressure measurement. An in situ temperature measurement was taken concurrently. Reservoir 'fluid mobility' was calculated at the same time.

Some tests were 'tight' and a couple exhibited 'supercharging', which is an effect wherein the gauges in these tools measure a pressure higher than the reservoir pressure. These outcomes commonly result from the tool being set across a mudstone or low-permeability zone in a heterogeneous formation. The pressure-test mobility measurements were used as indicators to select the formation fluid sampling points.

### 4.3.1.2 Results

The data retrieved by Halliburton's RDT in DMP Harvey 4 are given in Table 23.

Table 23: Downhole formation testing for DMP Harvey 4, including pressure and temperature

Test number	Depth (m)	Total mud and formation fluid pressure (psia)	Equivalent mud weight (lb/gal)	Formation fluid pressure (psia)	Temperature (°C)	Remarks
1.1	755.01	1437.04	11.16	1099.63	41.11	Good test
2.1	833.96	1586.80	11.15	1201.43	42.39	Good test
3.1	868.01	1651.89	11.15	1369.93	43.06	Supercharged
4.1	868.49	1652.85	11.16	1377.18	42.94	Supercharged
5.1	1043.50	1987.01	11.16	1497.83	45.39	Good test
6.1	1160.00	2210.23	11.17	1668.05	47.50	Good test
7.1	1231.10	2346.17	11.17	1772.28	49.00	Good test
8.1	1313.00	2503.81	11.18	1906.88	50.72	Good test
9.1	1419.48	2707.24	11.18	2058.91	52.94	Good test
10.1	1486.49	2836.15	11.18	2191.89	54.50	Good test
11.1	1504.00	2869.85	11.18	2190.23	55.22	Good test
12.1	1610.49	3073.83	11.19	2327.68	57.89	Good test
13.1	1674.09	3196.22	11.19	2419.83	59.50	Good test
14.1	1706.99	3260.06	11.20	2467.52	60.28	Good test
15.1	1726.00	3297.47	11.20	2495.24	60.78	Good test
16.1	1632.00	3117.06	11.19	2359.55	58.44	Good test
17.1	1527.03	2915.14	11.19	2260.49	56.22	Tight test
18.1	1486.49	2837.61	11.19	2192.56	55.28	Tight test
19.1	1486.50	2836.82	11.19	2180.10	55.72	Tight test
20.1	1270.00	2422.57	11.18	1855.34	50.39	Fluid sample 2
21.1	742.05	1412.03	11.15	1075.16	41.06	Fluid sample 3

### Pressure gradients

The pressure and temperature data from the HSFT in DMP Harvey 3 and 4 are shown in Figures 29 and 30. The lines on the left side of the pressure versus depth plots (blue squares) are consistent with the formation fluid being water. The lines on the right side of the figures (red squares) refer to the mud pressures and the gradients of these lines are the average mud densities in the two wells.

The formation-fluid pressure gradients in DMP Harvey 3 and 4 correlate. The total-pressure gradient for each well reflects the density of the drilling muds and fluids used in each well.

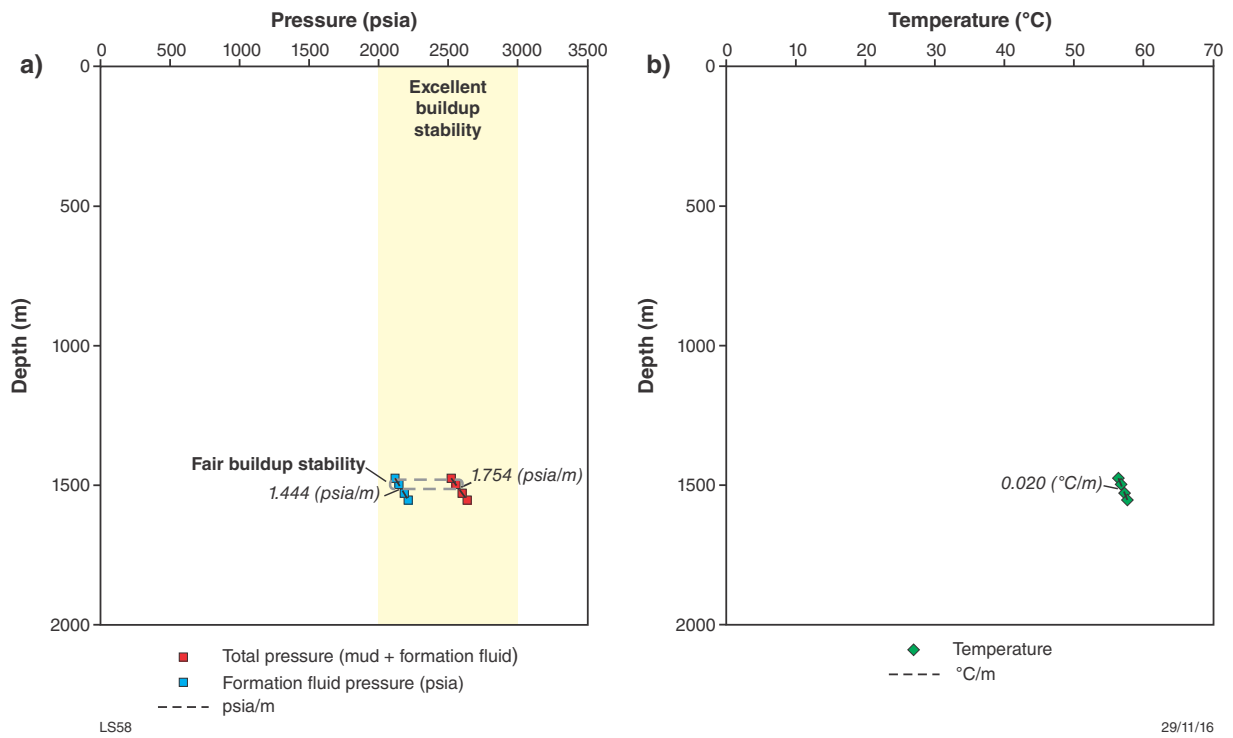


Figure 29: DMP Harvey 3: formation fluid, mud pressure and temperature readings, as measured by the HSFT tool, plotted against sampling depth.

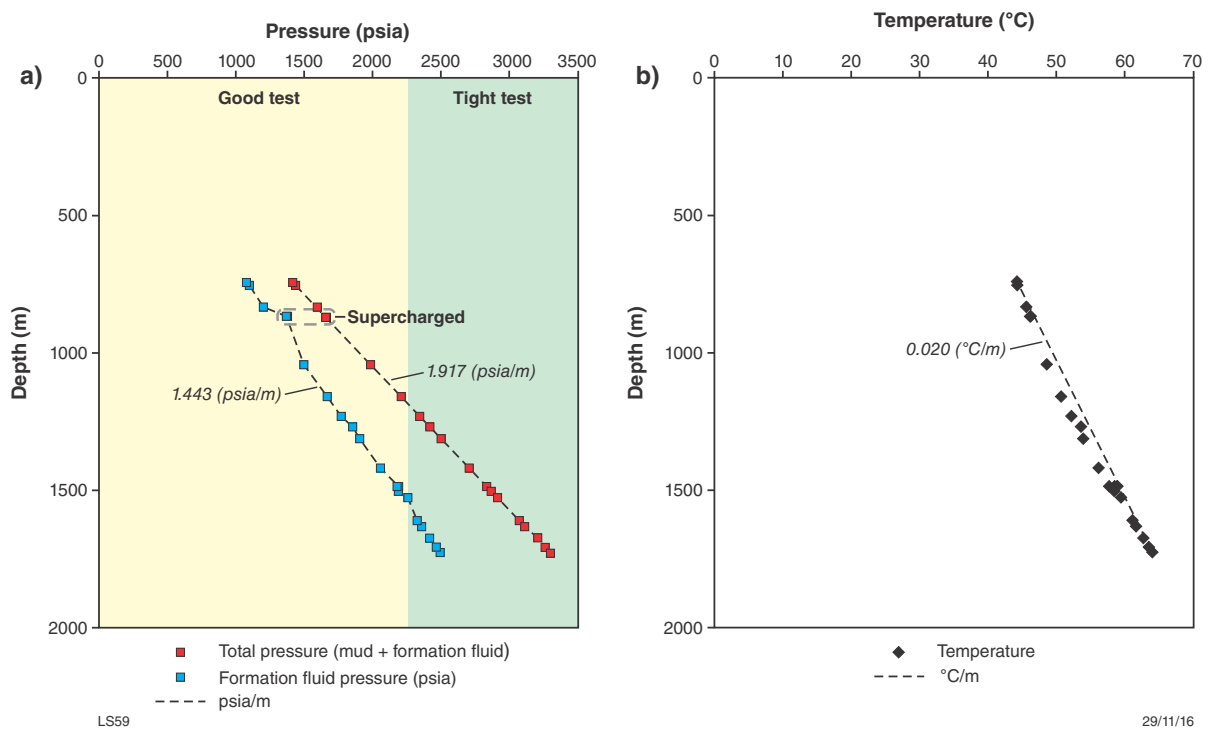


Figure 30: DMP Harvey 4: formation fluid, mud pressure and temperature readings, as measured by the RDT tool, plotted against sampling depth.

## Temperature gradient

The in situ, or downhole, temperatures measured in DMP Harvey 2, 3 and 4 are shown with the in situ temperatures measured in GSWA Harvey 1 in Figure 31. There is a difference in the temperature gradients calculated from the GSWA Harvey 1 and DMP Harvey 4 temperature with depth data as shown in Figures 29 to 31. The temperature gradients from DMP Harvey 3 and 4 are  $0.020^{\circ}\text{C}/\text{m}$ , whereas the temperature gradient for GSWA Harvey 1 is  $0.015^{\circ}\text{C}/\text{m}$  ( $1.5^{\circ}\text{C}/\text{km}$ ).

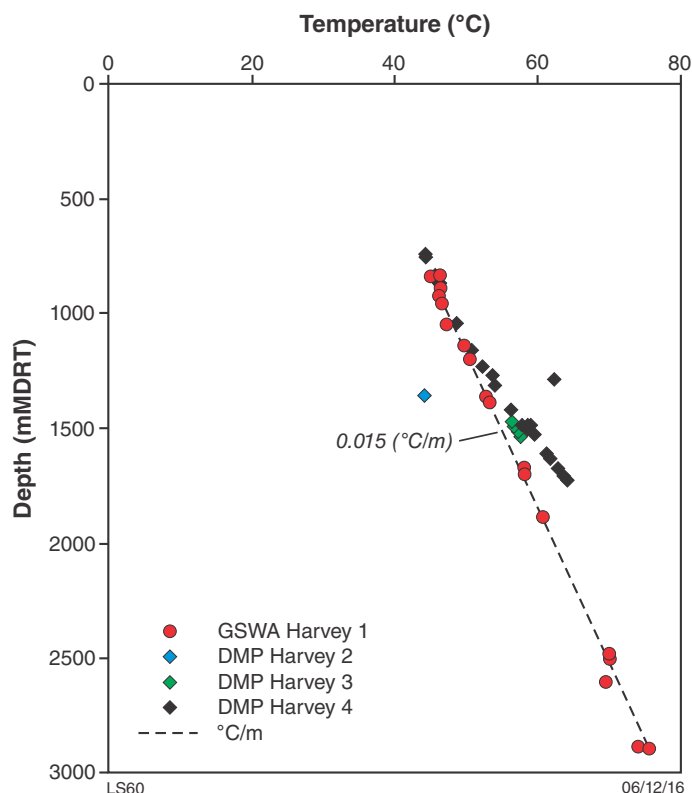


Figure 31: In situ temperatures measured in the four SW Hub wells by Halliburton's and Baker Hughes' downhole reservoir description tools.

## Preliminary interpretation

The downhole temperature gradients for wells DMP Harvey 3 and 4 differ from the temperature gradient generated from data from Baker Hughes' Reservoir Characterisation Instrument (RCI™) logging tool run in GSWA Harvey 1 (Millar and Reeve, 2012).

It is noted that wells GSWA Harvey 1 and DMP Harvey 4 are in different fault blocks, but it is not clear what geological factors, if any, may have contributed to the difference in temperature gradients. The differences in the computed temperature gradients may relate to the different tools used by Halliburton and Baker Hughes and associated calibration error. It is recommended that the difference in temperature gradients is investigated during any future logging work in the Harvey wells.

### 4.3.2 Formation-fluid sampling

During the drilling program, attempts were made to secure representative formation-fluid samples for chemical analysis. The first attempts were with Halliburton's RDT in DMP Harvey 4. Additional sampling was conducted during a flow test of the Wonnerup Member in DMP Harvey 3, as discussed in section 4.3.2. Sampling techniques and results for the samples collected using the RDT are summarised below.

#### **4.3.2.1 Procedure**

The RDT formation pressure and reservoir fluid sampling tool is commonly run from depth towards the top of the well. While the tool was taking pressure measurements, it was set in the well and the probe ‘fired’ to extract a formation-fluid sample. As the near-well area represents an ‘invaded zone’, the initial fluid drawn is significantly contaminated with drilling mud filtrate. Samples contaminated with drilling fluids are ‘pumped out’ back into the well and the process is continued until the tool’s sensors indicate that the fluid’s characteristics have stabilised. Such a qualitative process is not a precise indicator for pristine formation fluid being drawn. As the tool is stationary during the sampling process, the risk of tool sticking increases with time and a well-site decision is needed to instruct the cessation of pumping and the collection of a sample.

Three samples were collected: the first from the Wonnerup Member, the second from the Yalgorup Member and the third from the Eneabba Formation. The samples were analysed by CoreLab in Aberdeen, Scotland, as detailed in CoreLab’s report (Appendix H). The sampling protocol is discussed below.

#### **Wonnerup Member, 1632m**

The tool was lowered to approximately 20m below the top of the Wonnerup Member. At 1632m depth, the first formation-fluid sample was collected. Elevated and changing fluid densities are qualitative indicators that contamination of the formation fluid is still present, so the tool was attached to the well wall and the sampling chamber was pumped until the fluid density decreased. The first sample was taken when the fluid density had stabilised and the sample was estimated to be less than 5 per cent contaminated by drilling fluid, which was after 46 minutes of pumping.

#### **Yalgorup Member, 1270m**

The sampling tool was raised to 1270m in order to sample the Yalgorup Member. This depth corresponds to approximately 256m below the top of the Yalgorup Member and 327m above the top of the Wonnerup Member. A sample was extracted after 32 minutes of pumping, following the third pumping session. Despite reasonable indications of mobility during the pre-test, the horizon was difficult to sample due to the absence of any appreciable volumes of flow. Possible causes for diminishing volumes of flow of the formation fluid with successive emptying of the sampling chamber and pumping include fines plugging the probe and a lack of permeable sands due to significant heterogeneity of the sampled strata.

#### **Eneabba Formation, 742m**

The sampling tool was raised to 742m to sample the formation fluid from the Eneabba Formation. This depth is approximately 272m above the top of the Yalgorup Member. After 16 minutes of pumping, a formation-fluid sample was captured. The fluid density and percentage contamination with time qualitatively indicated that this sample was contaminated with drilling fluid.

#### **4.3.2.2 Results**

The formation-fluid chemistry was analysed, along with drilling fluids and muds sampled from equivalent depths. The summarised formation-fluid chemistries are given in Table 24. For the Wonnerup Member target injection reservoir, the fluid chemistry showed total dissolved solids (TDS) of 45,230mg/L, of which 4680mg/L was potassium, indicating contamination by mud filtrate. It is important to note that the values are not a true representation of the formation-water salinities, as the samples are contaminated with drilling fluid. Full analytical data for the three formation fluid chemistry samples are reported by CoreLab in a water analysis report dated 23 June 2015 (Appendix H).

Table 24: Summarised fluid chemistries for the three depths sampled in DMP Harvey 4

Sample	Formation	Depth (m)	Total dissolved solids (mg/L), evaporation at 105°C	Density (g/cm <sup>3</sup> ) at 15.6°C	pH at 20°C	Resistivity (ohm-m) at 25°C
1	Wonnerup Member	1632	45,230	1.0314	6.8	0.172
2	Yalgorup Member	1270	156,960	1.0991	7.9	0.043
3	Eneabba Formation	742	70,500	1.0466	7.7	0.102

#### 4.3.2.3 Preliminary interpretation

For the three formation fluids sampled at the three depths, efforts were made to reduce contamination by using the fluid-density sensor readings in the sampling tool to decide when to stop sampling. Despite the curves flattening out, laboratory analysis later identified the presence of mud filtrate in the extracted fluids. As such, there is no clear understanding of the formation-water salinities in the SW Hub study area.

## 4.4 Production and pressure test results

Flow or leak-off tests were conducted in wells DMP Harvey 2, 3 and 4. The test types, dates and formation tested in each well are summarised in Table 25.

Table 25: Production and pressure leak-off tests carried out

Well	Flow test	Leak-off test	Date	Hole depth (m MDRT)	Stratigraphic unit
DMP Harvey 2	No	Yes	06/01/2015	209	Eneabba Formation
DMP Harvey 3	No	Yes, shallow	25/03/2015	584	Eneabba Formation
DMP Harvey 3	No	Yes, deep	20/06/2015	1461	Wonnerup Member
DMP Harvey 3	Yes, deep	No	27/06/2015	1550	Wonnerup Member
DMP Harvey 4	No	Yes	29/01/2015	267	Eneabba Formation

### 4.4.1 Leak-off tests

#### 4.4.1.1 DMP Harvey 2

In well DMP Harvey 2, a single leak-off test was conducted at 209m depth after setting the surface 178mm (7in.) casing at 203.4m. The mud weight was 1.0g/cm<sup>3</sup> (8.5ppg). The test was conducted in the Eneabba Formation, which started taking pressure at 375psi during the test (Figure 32).

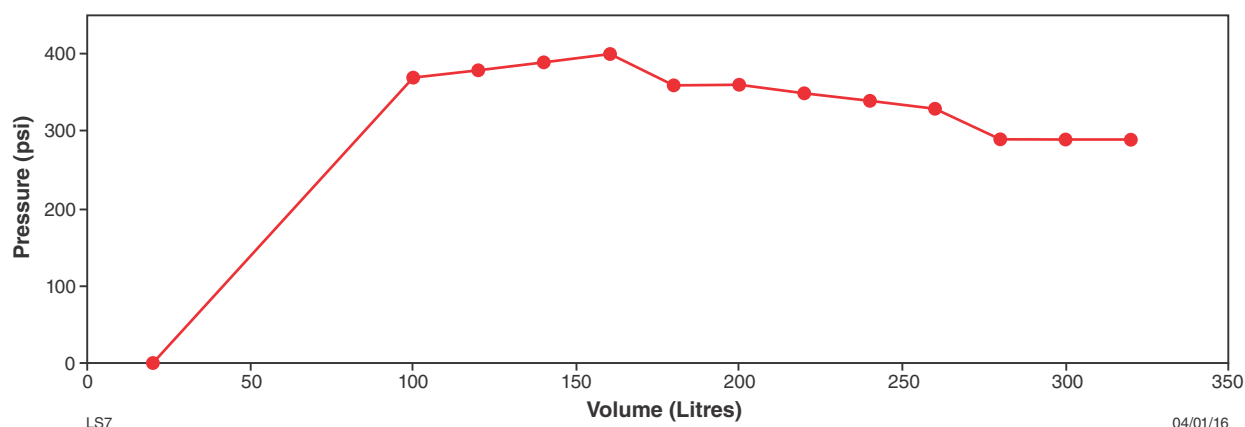


Figure 32: DMP Harvey 2 leak-off test data.

#### 4.4.1.2 DMP Harvey 3

Two leak-off tests were carried out in DMP Harvey 3. The first test was at a shallow depth of 591.7m after the intermediate 178mm (7in.) casing had been set at 584m. The corresponding volume is shown plotted against pump pressure in Figure 33. The mud weight was 1.2g/cm<sup>3</sup> (10ppg).

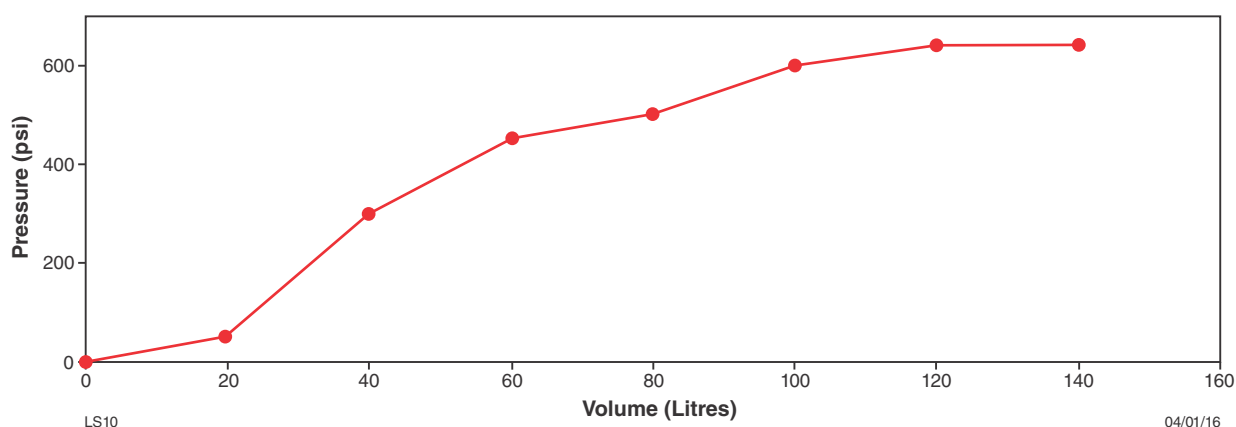


Figure 33: DMP Harvey 3 shallow leak-off test results.

A second, deeper leak-off test was carried out at 1467m depth in the Wonnerup Member. The final casing 114.3mm (4.5in.) shoe was at 1461m and the mud weight was 1.2g/cm<sup>3</sup> (10ppg). The pump and relief valve achieved a maximum pressure of 1725.5psi, the limit of their capability. No leak off was observed at this pressure at 1467m, when surface pressure and mud pressure together were 4259psi or 29.4MPa. The data from this leak-off test were not recorded.

#### 4.4.1.3 DMP Harvey 4

A shallow leak-off test was carried out in DMP Harvey 4 when the intermediate 245mm (9 $\frac{5}{8}$ in.) casing had been installed and cemented at 259.9m depth. The casing shoe was at 267m depth and the mud weight was 1.0g/cm<sup>3</sup> (8.5ppg). The formation started taking pressure at 214psi. The data from this leak-off test were not recorded.

#### **4.4.1.4 Preliminary interpretation**

The leak-off test data do not adequately constrain the minimum horizontal stress. Testing for the minimal horizontal stress is recommended during the drilling of any additional wells in the SW Hub study area.

### **4.4.2 DMP Harvey 3 flow test**

Upon the completion of drilling of well DMP Harvey 3, and prior to the pack-up and demobilisation of the rig, a flow test was carried out on 27 June 2015. The full report (Bolton, 2015), including the setup, objectives, final resting water level, test limitations and recommendations for future flow tests are in Appendix H (Bolton, 2015).

#### **4.4.2.1 Objectives**

The objectives of the flow test were to sample the formation fluid in the Wonnerup Member, and to assess an approximate hydraulic conductivity (permeability) for the top of the Wonnerup Member.

#### **4.4.2.2 Flow-test procedure**

A submersible pump was lowered down the well and pumped for 315 minutes. The saline water produced from the well was collected by tanker and treated off-site. After three to four hours, the majority of the drilling fluid had been removed from the drill rods, which resulted in a mixture of drilling fluids and formation water flowing from the top of the drill rods at the well head. The flow rate, colour, pH, temperature and electrical conductivity (EC) of the flowing water were recorded at 15-minute intervals. After five hours of pumping the orange discoloration was no longer visible in the flowing water. After five hours and 15 minutes of the well flowing, samples of the formation fluid were collected and the test was terminated following a stabilisation of the EC measurements.

#### **4.4.2.3 Results**

Over the five-hour period of well DMP Harvey 3 being pumped, the pH of the fluid discharging from the wellhead decreased from approximately 8 to 7, the temperature increased from 28 to 38°C and the electrical conductivity of the fluid decreased from 120 to 72mS/cm. After 315 minutes of pumping at 70L/min (approximately 1.2L/s), fluid samples were collected from the flowing well into one-litre glass jars and sealed. These were refrigerated and analysed by ALS Laboratories Pty Ltd. The analytical methods are discussed in Rockwater's report (Bolton, 2015) in Appendix H.

The analyses reported a TDS of 59,900mg/L (determined by evaporation of the sample at 180°C), 9830mg/L potassium, 9960mg/L sodium, 1960mg/L calcium, 28,400mg/L chloride and 3.58mg/L iron (Bolton, 2015).

The water samples acquired at the end of the DMP Harvey 3 flow test were left to stand in a refrigerator. A thick, fine, orange-brown precipitate settled at the bottom of the sample bottles. The precipitate is likely to be drilling fluid filtrate, and possibly iron oxide formed as the water sample came into contact with air in the sample jars. Filtering and 'chemical fixing' of any future fresh formation-fluid samples is recommended at the time of sampling.

Assessment of the water quality and water-level monitoring results from the formation-fluid sampling programme at DMP Harvey 3 indicates that the well was not fully developed prior to sample collection. Hence, no representative water sample from the aquifer was obtained, and aquifer coefficients could not be determined. The pumping was sustained throughout the test at a rate of 1.2L/s. It is considered that higher yields could be obtained from a greater thickness of the aquifer and a greater annular clearance (Bolton, 2015).

Monitoring of water-level data during recovery indicated that the potentiometric surface for the Wonnerup Member of the Lesueur Sandstone lies at about 20m below ground surface at DMP Harvey 3.

#### **4.4.2.4 Preliminary interpretation**

The formation fluid from the Wonnerup Member is considered to have a TDS of less than 59,900mg/L, possibly in the range of approximately 40,000–45,000mg/L. The collection of a pristine sample is required during a longer future flow test.

It is recommended that the lessons learned and the recommendations made following the DMP Harvey 3 flow test are considered in any further well flow testing to obtain representative fluid chemistry and to determine the permeability of the formation.

#### **4.4.2.5 Lessons learned**

A well-planned flow test can provide valuable information about the permeability of the formation and formation fluid quality. A step test is recommended before any longer-duration, single flow test to determine the maximum achievable pumping rate. Given the time required to measure resting water levels, equip a well with a pump and to install water level monitoring pressure transducers (loggers), and with associated fluid disposal and rig time costs, the scoping and costing of a flow test is recommended at the earliest planning stage of any drilling program.

To ensure an uncontaminated formation fluid sample is attained, any sample should be free from contamination by drilling fluids. On-site continuous chemical monitoring of the pumped water with a sophisticated and calibrated EC, pH, temperature, redox potential (Eh) and dissolved oxygen (DO) meter is recommended to assist with planning when to take a sample. The latest guidance on how to sample and preserve groundwater samples (eg. glass jars, filtering, acidisation, refrigeration, maximum time window before analysis) is provided by Geoscience Australia and the relevant jurisdiction's water regulator.

## **5.0 Core, drill chips and core analysis**

This section documents the core and chip samples collected and the analytical techniques conducted on these samples, in addition to the results and the preliminary interpretation.

The core and rock chips from DMP Harvey 2, 3 and 4 are available for inspection at the Perth Core Library in Carlisle. Requests to view the core and rock chips may be emailed to DMIRS core library at [corelibrary.requests@dmirs.wa.gov.au](mailto:corelibrary.requests@dmirs.wa.gov.au).

### **5.1 Core storage**

A total of 2136m of core of various sizing were retrieved from the three wells, including HQ (63.5mm), PQ (83.0mm) and SQ (102.0mm) sizing.

#### **5.1.1 Core stored in trays**

The non-preserved core was laid in labelled core trays, lithologically logged by Rockwater's on-site geologists and photographed in DDH1 Drilling's on-site photo booth. Core trays were then placed on pallets, wrapped in plastic and transported by the drilling contractor to DMIRS Perth Core Library in Carlisle (Figure 34). The first delivery of core trays was on 28 January 2015. Table 26 lists the downhole intervals for which core was obtained and sent to the Perth Core Library in core trays.



Figure 34: Core trays containing core from DMP Harvey 3 stored and wrapped on a pallet at the Perth Core Library.

Table 26: Depth intervals and diameter of core stored in core trays for the three wells

Well	Depth (m)	Core size	Core diameter	Core-tray number
DMP Harvey 2	207.7–1234.0	PQ3	3¼in. (83.0mm)	1–369
	1234.0–1351.2	HQ	2½in. (63.5mm)	370–400
DMP Harvey 3	591.7–1466.3	SQ3	4in. (102mm)	1–429
	1466.35–1550.2	HQ	2½in. (63.5mm)	430–451
DMP Harvey 4	896.3–909.35	SQ3	4in. (102mm)	1
	1325.5–1326.6	From core barrel; 8in. outer diameter and 6in. inner diameter	6in. (152mm)	1
	1665.05–1666.65	SQ3	4in. (102mm)	1
	1792.7–1802.55	SQ3	4in. (102mm)	2–6

Each segment of core is up to one metre in length. The cored strata in Figures 35 and 36 comprise interbedded sandstones, mudstones and siltstones of the Yalgorup Member. These are well consolidated, mostly oxidised, bioturbated (burrows or root structures, or both) with common sand dykes and some slickensides throughout (Appendix C).



Figure 35: DMP Harvey 3: SQ3-sized core (102mm) between 1078.55 and 1080.40m, in core tray 224. These are considered to be paleosols within the Yalgorup Member.



Figure 36: DMP Harvey 3: slickensides (shiny surface) within the paleosols in core from the base of the Yalgorup Member, above the boundary between the Wonnerup and Yalgorup Members.

### 5.1.2 Core preserved in wax

Some of the core gained from the drilling of well DMP Harvey 4 has been preserved in wax for long-term preservation. These intervals are listed and described in Table 27.

Table 27: DMP Harvey 4: core samples preserved in wax

Depth (m)	Lithology
1795.10–1795.60	Sandstone; light brown, light grey, white, bedding sets of fine to coarse grained, mostly coarse grained, well to moderately sorted, grading fine grained to pebble size, very poorly sorted, sub-angular to rounded. Moderately to well consolidated, some oxidation? Quartz (clear, grey, yellow and orange tint), weathered feldspar forming cement around quartz grains, garnet, some heavy minerals in laminations. Crude 0–20° bedding. Bedding sets are 0.75 to 0.80m thick. Some porosity.
1797.60–1798.10	As above
1800.65–1801.15	Sandstone; light brown to light grey, fine grained to pebble size, very poorly sorted, sub-angular to rounded. Well consolidated, minor oxidation. Quartz (clear, grey, frosted, light brown tint, orange), weathered feldspar forming cement (kaolinised), trace of garnet, minor heavy mineral (and/or carbonaceous) laminations. Small cross-beddings of finer and coarser sand (0–30°).

### 5.1.3 Core preserved in mineral oil

During the wireline coring of DMP Harvey 2 and 3, Rockwater's on-site geologists selected mudstone–claystone core from the interpreted paleosol intervals for sampling, without removing the drilling mud in order to reduce exposure to oxidation and desiccation of the core.

During the rotary drilling of DMP Harvey 4, DMIRS specified interval coring depths and intervals. Retrieving core from the basal Eneabba unit was a specific interval coring target in DMP Harvey 4. The well was cored between 896.3–909.35m depth. When DDH1 Drilling's SQ-sized core barrel was brought to surface (Figure 37), a grey, cemented, brittle mudstone from an interpreted paleosol in the basal Eneabba unit was identified (Figure 38). The identification of the mudstones in the freshly cored sample indicated that the DMIRS targeted coring run had been successful.



*Figure 37: DMP Harvey 4: SQ-sized (120mm diameter) inner core barrel containing freshly cut core retrieved during interval coring of the Yalgorup Member. The core is contained within a plastic sleeve within the inner core barrel.*



*Figure 38: DMP Harvey 4: grey, cemented, brittle mudstone from an interpreted paleosol in the Yalgorup Member, retrieved overnight during interval coring between 893.00 and 899.30m depth. The identification of the mudstones in the freshly cored sample indicated that DMIRS' targeted coring run had been successful.*

Under the on-site direction of the on-site geologist short lengths of core approximating 0.35m were cut by the drillers for quick preservation. Figure 37 shows a polystyrene insert within the SQ-sized core barrel from which a mudstone-rich core sample was extracted for preserving in mineral oil at the drill site. Mudstone-rich core lengths, still within the plastic liner, were carefully lowered into heavy-duty PVC tubes that were flooded with mineral oil (Figure 39). The preservation of these samples in mineral oil helps prevent desiccation and reaction with oxygen in the air, which could otherwise have an impact on the results of the analyses of the core's structure, composition and properties. Core intervals preserved in mineral oil are listed in Table 28.



Figure 39: DMP Harvey 4: mudstone-rich facies (paleosols) preserved in mineral oil filled PVC tubing, at the drill site on 19 February 2015, prior to transportation to CoreLab's premises in Kewdale.

Table 28: Depth ranges for core samples preserved in mineral oil

Well	Immersion date		Depth (m)		Core size	Stratigraphy
	Start	End	Start	End		
DMP Harvey 2	12/01/2015	12/02/2015	402.20	1231.25	PQ	Eneabba Formation, basal Eneabba unit, Yalgorup Member
DMP Harvey 3	27/03/2015	08/05/2015	604.25	1416.85	SQ	Basal Eneabba unit, Yalgorup Member
DMP Harvey 4	19/02/2015	23/04/2015	893.00	908.05	SQ	Basal Eneabba unit

## 5.2 Drill-chip sampling

Drill chips were collected in drill chip trays (Figure 40) and bulk sample bags by the on-site geologists. Sampling of rock chips was every three metres during the rotary drilling of the upper sections of DMP's Harvey 2 and 3 and throughout the rotary drilled sections of DMP Harvey 4. The rock chips shown in Figure 40 are considered as representative of the superficial sediments and Leederville Formation. Segments of wells sampled using discrete and bulk rock-chip sampling methods are listed in Tables 29 and 30, respectively.



Figure 40: DMP Harvey 2: drill chip trays from the openhole rotary drilling of the superficial sediments and Leederville Formation.

Table 29: Depth ranges for discrete drill-chip sampling for the three wells

Well	Depth (m)	
	Start	End
DMP Harvey 2	0	205.5
DMP Harvey 3	0	591.0
DMP Harvey 4	0	1794.0

Table 30: Depth ranges for bulk drill-chip sampling for the three wells

Well	Depth (m)	
	Start	End
DMP Harvey 2	0	205.5
DMP Harvey 3	0	591.0
DMP Harvey 4	0	1794.0

### 5.3 Core sampling

Following a review of all available geological data; including daily drilling reports, the on-site geologists' lithological logs, wireline logging data, HyLogger data and visual inspection of the core laid out at the Perth Core Library; the core sampling depths were selected by DMIRS in consultation with core sampling specialists from CoreLab. Figure 41 shows GSWA geologists inspecting core from DMP Harvey 3 in conjunction with gamma-ray logs from wells Lake Preston 1, GSWA Harvey 1 and DMP Harvey 2, 3 and 4.



Figure 41: GSWA geologists Alan Millar, Charmaine Thomas and Sarah Martin examining SQ-sized core from DMP Harvey 3 at the Perth Core Library in conjunction with wireline logging gamma ray data – depth plots.

The objective of sampling was to select depths to cut plugs from the core from the DMP Harvey 2, 3 and 4 wells to adequately capture the spatial (3D) properties of the strata within the SW Hub study area. Permission to view and sample core for core analysis was requested and granted by the GSWA under Approval G32745.

### 5.3.1 Selection of core sampling depths

Core depths were selected to sample the baffles (siltstone, claystone and mudstone-rich facies of the Yalgorup Member and the basal Eneabba unit) and the target reservoir (sandstone-rich facies of the Wonnerup Member). The intent of sampling and subsequent core analysis was to populate the static geological model and dynamic CO<sub>2</sub> injection simulation dynamic model with property data representative of the lateral and spatial variability of the stratigraphy within the study area.

### 5.3.2 Sampling methodology

Sampling depths for each well were selected following a review of the wireline logging data and visual inspection of the core at the Perth Core Library. The associated core trays were transported to CoreLab's premises in Kewdale for sampling. CoreLab cut plugs from the core at depths specified by DMIRS. Where samples could not be achieved at the specified depths, CoreLab consulted with DMIRS and samples were cut in similar lithologies, close to the specified depths.

The lower cored sections of DMP Harvey 2 and DMP Harvey 3 are HQ-sized (63.5mm), which is too narrow to permit the cutting of large plugs. Cylindrical plugs 2.54cm (1in.) wide and just less than 5cm (2in.) long were cut from the HQ-sized core. Cylindrical plugs 3.81cm (1.5in.) wide and 5.0cm (2in.) long were cut from the SQ-sized and PQ-sized core (Table 26). Some plugs were cut perpendicular to the bedding plane (vertical plugs), but the majority were cut parallel to the bedding plane (horizontal plugs).

Plugs from the sandstones within the Wonnerup and Yalgorup Members were cut relatively easily using two per cent KCl as the bit lubricant, and were placed in labelled plastic bags (Figure 42). These sandstone-rich samples were numbered chronologically (#1, #2, etc.).



*Figure 42: Cut and labelled sandstone-rich plugs cut from the Wonnerup Member in DMP Harvey 2, 3 and 4, at CoreLab's premises, Kewdale.*

Those core lengths preserved in mineral oil at the drill sites (Figure 39) were carefully removed from their protective plastic tubes. Samples were cut from the siltstone-, claystone- and mudstone-dominant<sup>11</sup> core using mineral oil as the bit lubricant (Figures 43 and 44).



*Figure 43: CoreLab's technician cutting a horizontally orientated, 1.5-inch diameter plug from a mineral oil-preserved interpreted paleosol at 697m depth in DMP Harvey 3.*

<sup>11</sup> In this report, the terms 'mudstone' or 'mudstone rich' describes the grouping of siltstone, claystone and mudstone lithologies.



Figure 44: Cutting plug samples from core preserved in mineral oil at CoreLab's premises in August 2015. The photograph shows red iron staining of a core sample taken from paleosol mudstones within the Yalgorup Member of DMP Harvey 3.

The mudstone-rich samples were preserved in plastic wrap, aluminium foil or sealed plastic bags, and then refrigerated. Samples prefixed with 'PS' were preserved samples; 'H' denotes samples cut horizontally, or perpendicular to the length of core (labelled 'PSH1, PSVH2', etc.); and 'V' denotes vertically cut samples, or plugs parallel to the length of core (labelled 'PSV1, PSV2', etc.).

Core samples cut from dominantly mud-rich strata were difficult to cut, particularly those samples at shallow depth, as the samples fractured easily. Therefore, the success rate for cutting the sandstone samples was greater than that for the cutting of the mudstone-rich samples, as recorded in Table 31.

Table 31: CoreLab's core-plug cutting record for the three wells

Well	Routine plugs attempted	Failed routine plugs	Preserved plugs attempted	Failed preserved plugs
DMP Harvey 2	52	7	24	16
DMP Harvey 3	195	1	48	6
DMP Harvey 4	15	1	15	0

For the three wells, core-plug samples were taken between the depths shown in Table 32. A full listing of samples taken (plugs cut), with their depths and intervals is provided in Appendix J.

Table 32: Depth ranges for core sampling for the three wells

Well	Core sampling depth	
	Start (m)	End (m)
DMP Harvey 2	213.9	1348.25
DMP Harvey 3	604.6	1424.6
DMP Harvey 4	893	1802

## 5.4 Core analysis

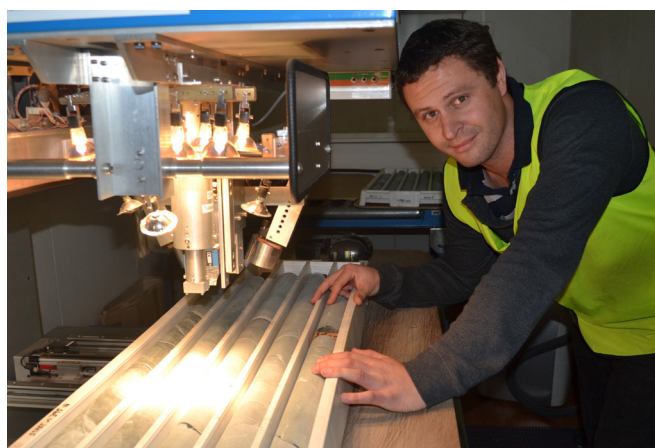
A number of tests were carried out on core samples from the DMP Harvey 2, 3 and 4 wells, as listed below:

- HyLogger spectral analysis and portable X-ray diffraction (pXRD).
- Routine Core Analysis (RCA)
  - grain volume and grain density
  - porosity and permeability
  - permeability to brine
  - threshold pressure to CO<sub>2</sub>
  - petrographic analysis.
- Special Core Analysis (SCAL)
  - flow studies
  - mercury-injection analysis
  - geomechanical analysis.

### 5.4.1 HyLogger spectral analysis

The Perth Core Library houses the HyLogger spectral scanner (Figure 45). This is a rapid spectroscopic logging and imaging system that uses continuous visible and infrared spectroscopy and digital imaging to non-destructively examine drillcore. The HyLogger scans the surface of the core, captures and condenses the data at a resolution of 8mm.

All core retrieved from the DMP Harvey 2, 3 and 4 wells was scanned by the HyLogger to obtain high-resolution digital images and spectral data, which can inform the mineralogical content of the core, and how the composition of the core varies with depth. An example of the spectral imagery provided by the HyLogger is shown in Figure 46.



*Figure 45: Core being scanned by the GSWA HyLogger, at the Perth Core Library in Carlisle, WA, 29 June 2015, by Geoscience Support Officer Kris Sando.*



Figure 46: HyLogger screen image for DMP Harvey 2 core from 1231.3 to 1234.0m depth. Images of each one-metre length of core and the shortwave infrared (red and salmon pink) and thermal infrared (pink and brown) spectrometer images can be seen, providing the mineralogical composition. In this screen image the dominant minerals are kaolinite and quartz, from the interbedded sandstones and mudstones at the base of the Yalgorup Member.

#### 5.4.1.1 HyLogger scanned imagery

The images of each core tray as scanned by the HyLogger (Figures 47 to 51) show the condition of the core soon after its retrieval from the drilling sites, within approximately one week of its receipt at the Perth Core Library.

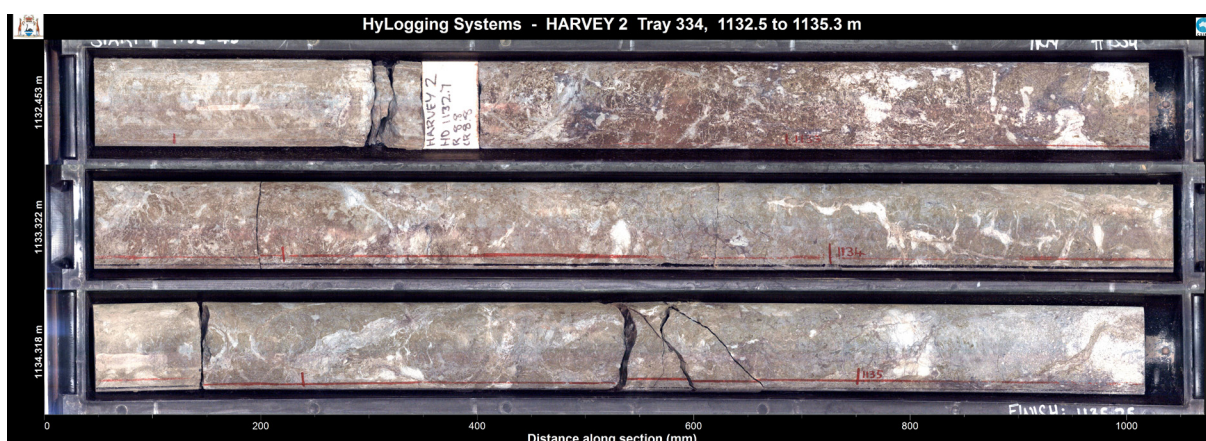


Figure 47: HyLogger scanned image of core from the Yalgorup Member paleosols from well DMP Harvey 2, between 1132.5 and 1135.3m.

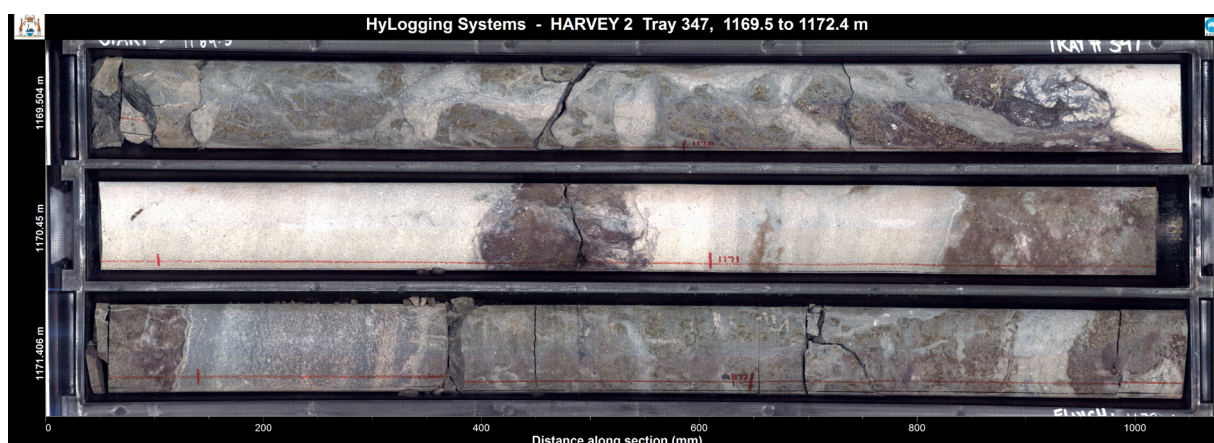


Figure 48: HyLogger scanned image of core from the Yalgorup Member paleosols from DMP Harvey 2, between 1169.5 and 1172.4m. Sandstone bioturbations or dykes, considered to be root zones, can be seen in the upper one-metre core length.

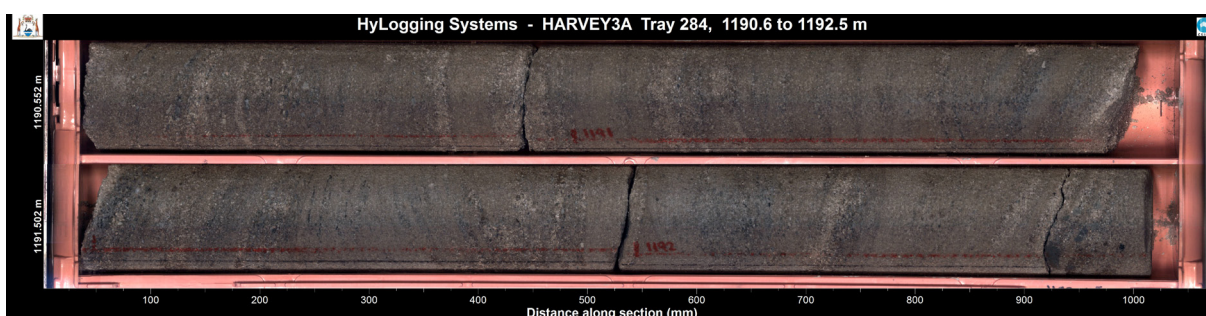


Figure 49: HyLogger scanned image of core of sandstone and minor siltstone from the Yalgorup Member, from well DMP Harvey 3, between 1190.6 and 1192.5m.

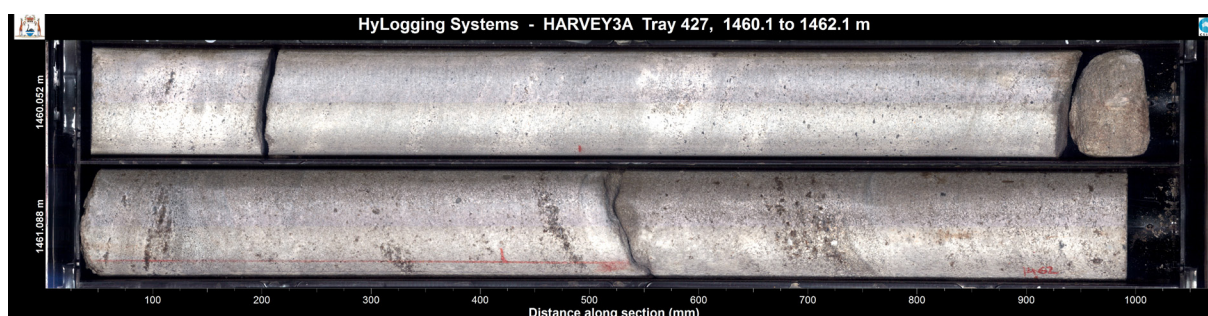


Figure 50: HyLogger scanned image of core from the Wonnerup Member sandstone from well DMP Harvey 3, between 1460.1 and 1462.1m. Crystal-filled vugs can be seen in the lower one-metre core length.

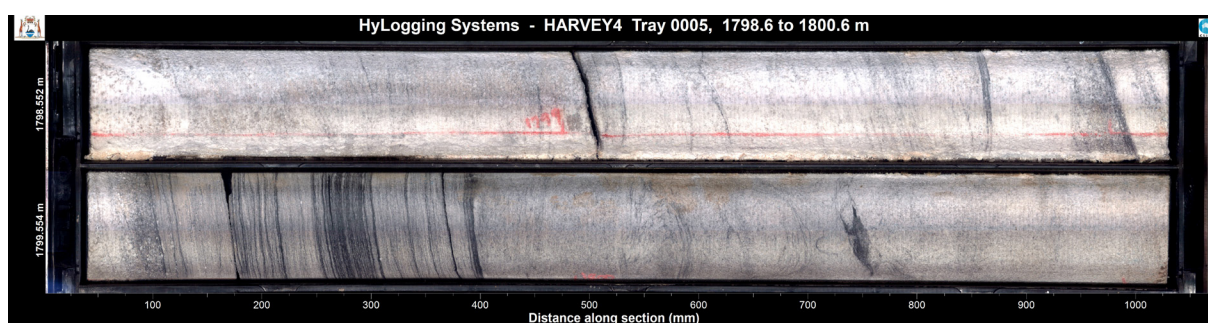


Figure 51: HyLogger scanned image of core from the Wonnerup Member from DMP Harvey 4, between 1798.6 and 1800.6m. The dip of the sandstones and laminae of organic material can be seen in the image.

It was important to run the core through the HyLogger spectral scanner as soon as the core trays were received at the Perth Core Library, before any deterioration of the core that can be caused by desiccation, reaction to air, and precipitation of drilling salts on the core's surface. The core was observed to deteriorate with time, on successive displays of the core trays. Due to the removal of the core from the in situ well pressures and exposure of the core to air, those sections of core rich in claystone, mudstone and siltstone were observed to fracture into smaller pieces. During coring, drilling fluid invades the formation and permeates into the outer surface of the core. With time an outer layer of core from the claystones and mudstones within the core trays was observed to break away from the inner core, as a thick peel or skin. In addition, white salt crystallised on the surface of the core as the drilling fluid, which was rich in potassium chloride (approximately 20 per cent by composition), evaporated from the core's surface (Figures 52 and 53).



Figure 52: DMP Harvey 3 well: SQ3-sized core from the Wonnerup Member at approximately 1500m depth, in tray 406, showing the locations of core plugs 11 and 12.



Figure 53: DMP Harvey 3: a close-up of the Wonnerup Member core shown in Figure 52. The white crystals on the core's surface are sylvite, a potassium chloride (KCl) evaporitic salt; the drilling fluid invaded the formation and subsequently evaporated at the core's surface.

#### 5.4.1.2 HyLogger spectral data

The HyLogger spectral scanner contains three spectrometers, covering shortwave infrared, thermal infrared and visible to near infrared wavelengths, which can identify different minerals by their diagnostic absorption and reflection features at differing wavelengths when used conjunctively (Hancock et al., 2013). As the visible to near infrared spectrometer is mainly used for iron-oxide minerals, only data from the shortwave infrared and thermal infrared spectrometers are reported here.

The raw HyLogger spectral data were processed and interpreted within the 'The Spectral Geologist' (TSG™) software created by Commonwealth Scientific and Industrial Research Organisation (CSIRO), in order to create images and define mineralogy. The semi-quantitative spectral data are available in Microsoft® Excel® spreadsheets, along with accompanying tray by tray, high-definition imagery<sup>12</sup>, from DMIRS WAPIMS database and in Appendix K. Figures 54 to 56 show the mineralogical spectra data with depth for wells DMP Harvey 2, 3 and 4.

#### DMP Harvey 2

For DMP Harvey 2, the HyLogger spectra (Figure 54) show that the core is rich in quartz (pink in the lower image) and well-ordered and crystalline kaolinite (kaolinite-WX) and poorly ordered and crystalline kaolinite (kaolinite-PX) in red and salmon pink, respectively, in the upper image. Other minerals present are albite, microcline, muscovite, illite and montmorillonite.

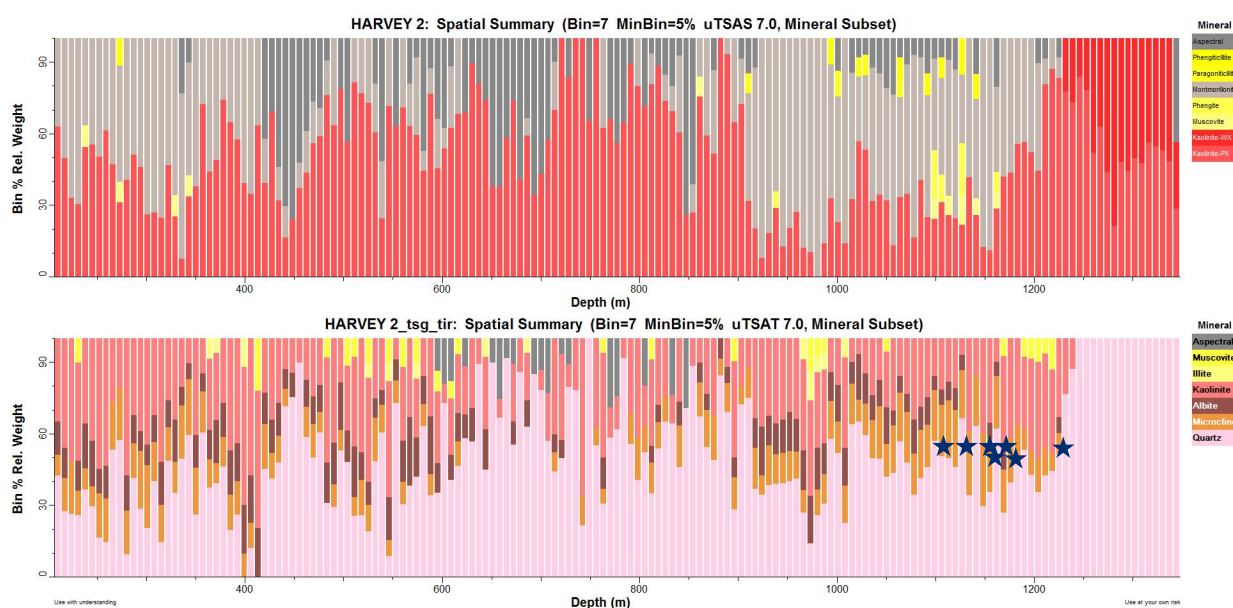


Figure 54: Spectral summary data for mineralogy of core from well DMP Harvey 2. The upper image is from the shortwave infrared; the bottom image is from the thermal infrared spectrometer. The pink represents quartz and the reds represent kaolinite. The 'spot' sampling at discrete depths for analysis by the portable XRD machine are shown as blue stars, as explained in section 5.4.2.

<sup>12</sup> HyLogger spectral scanner images are available via GeoView's HyLogger layer: [wapims.dmp.wa.gov.au/GeoView/Viewer.html?Viewer=GeoVIEW](http://wapims.dmp.wa.gov.au/GeoView/Viewer.html?Viewer=GeoVIEW). Spectral information, images and downloadable datasets are available from AuScope's Discovery portal: <http://portal.auscope.org/portal/gmap.html>.

### DMP Harvey 3

The spectral summary data for DMP Harvey 3 (Figure 55) show that kaolinite (red and salmon pink in the upper image) is the clay mineral present when the quartz (pink in the lower image) content is high and total clay is low. Between approximately 1000 and 1360m depth the quartz content is low, and the total clay content is high with illite–smectite as the dominant clay species, with montmorillonite, albite and microcline, reflecting the origin of these lithologies as soils.

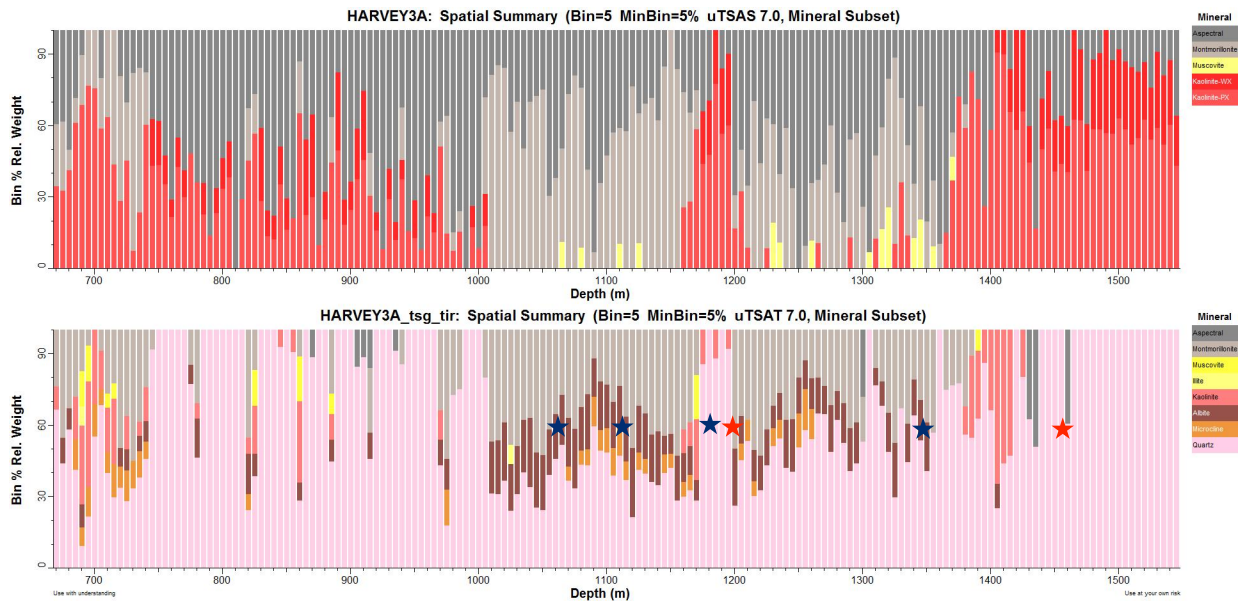


Figure 55: TSG spectral summary data for mineralogy of core from well DMP Harvey 3. The upper image is from the shortwave infrared spectrometer; the lower image is from the thermal infrared spectrometer. The 'spot' sampling depths for analysis by the portable XRD machine are shown as blue stars, as explained in section 5.4.2. The red stars denote where the KCl-rich drilling mud, detected as the mineral sylvite, has a strong influence on spectral resolution.

### DMP Harvey 4

For DMP Harvey 4, the core retrieved from the basal Eneabba unit (1665.05–1666.65m depth, Figure 56), is rich in quartz, kaolinite and muscovite. The core from the Wonnerup Member (1792.7–1802.55m depth, Figure 56), is also rich in quartz and kaolinite, with undefined minerals within the 'aspectral' category (coloured dark grey in Figure 56). These strata are rich in sands.

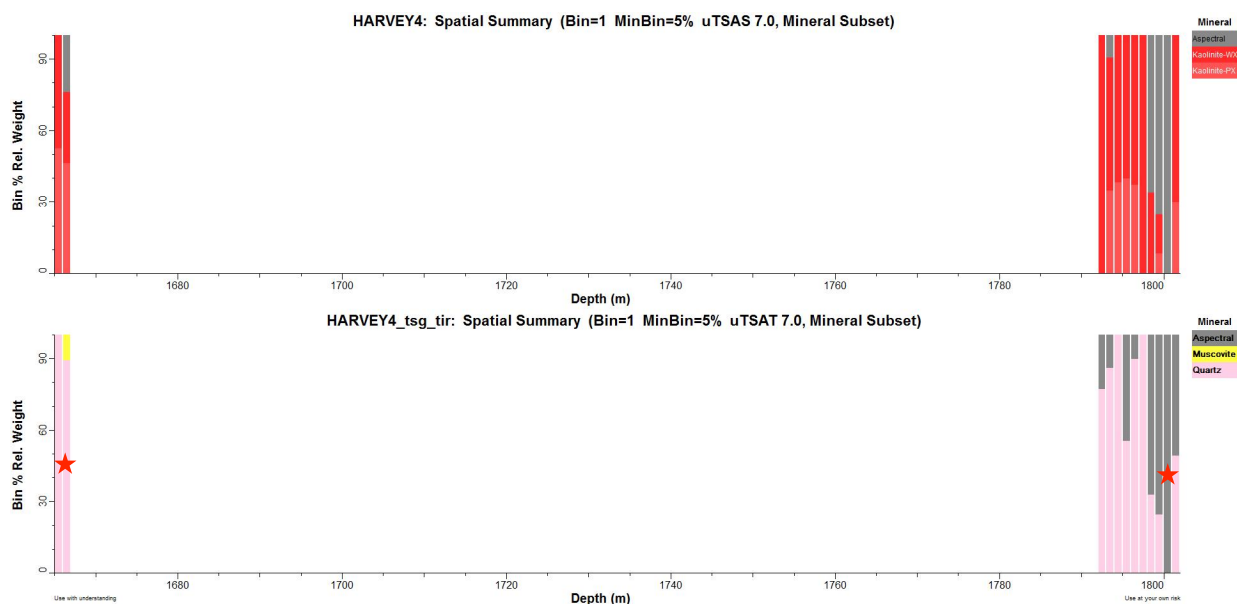


Figure 56: Spectral summary data for mineralogy of core from well DMP Harvey 4. Note that, as DMP Harvey 4 was interval cored, limited core lengths are available for core analysis. The upper image is from the shortwave infrared spectrometer, kaolinite is shown in red; the lower image is from the thermal infrared spectrometer, quartz being shown in pink and aspectral data in grey. The 'spot' sampling depths for analysis by the portable XRD machine are shown as red stars. The KCl-rich drilling mud, detected as the mineral sylvite, has a strong influence on the spectral resolution.

## F10 Fault zone

During the drilling of DMP Harvey 2, well-site lithological logging suggested the absence of a thick paleosol sequence in the basal Eneabba unit, as was anticipated from the correlation of the shallow-depth geological strata with the strata determined in GSWA Harvey 1. A review of ODIN's early interpretation of the 3D seismic data (Byrne, 2016) suggested that the well had drilled through the F10 Fault.

Early visual inspection of the core from DMP Harvey 2 did not reveal any obvious brecciated features indicative of faulting. The gamma-ray log for this well has elevated gamma-ray responses at discrete depths, which could be associated with clay-rich fault gouge. Mineral investigation staff at GSWA reviewed the HyLogger data from DMP Harvey 2 core and identified elevated concentrations of the mineral sylvite at depths of approximately 450–900m and at 1260m, which is associated with KCl in the drilling fluid (Figure 57).

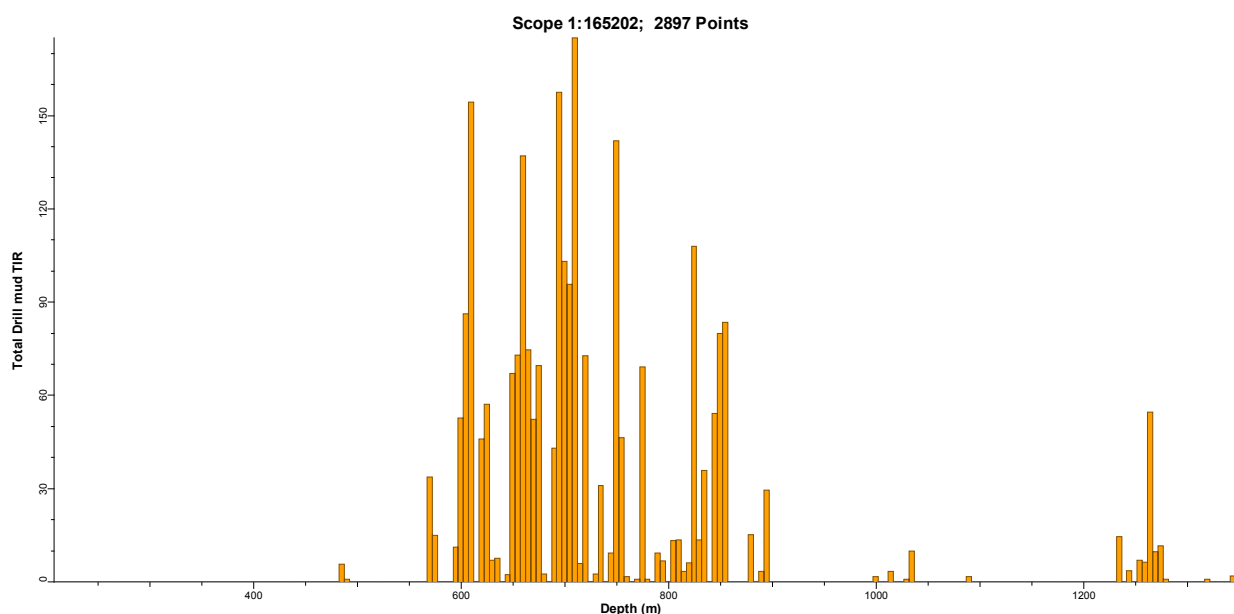


Figure 57: HyLogger spectral scan of the DMP Harvey 2 core showing the depths at which the mineral sylvite (KCl) was identified in the core.

As shown in Figure 58, a mineral group identifying as 'sulphate' was identified in the core from DMP Harvey 2 from 421 to 857m depth, and at 1270m depth. The spectral data presenting as sulphate were investigated further by GSWA's mineral investigation staff. The 'gypsum' response was identified as water, indicating 'wet core', between approximately 347 and 700m depth (Figure 59).

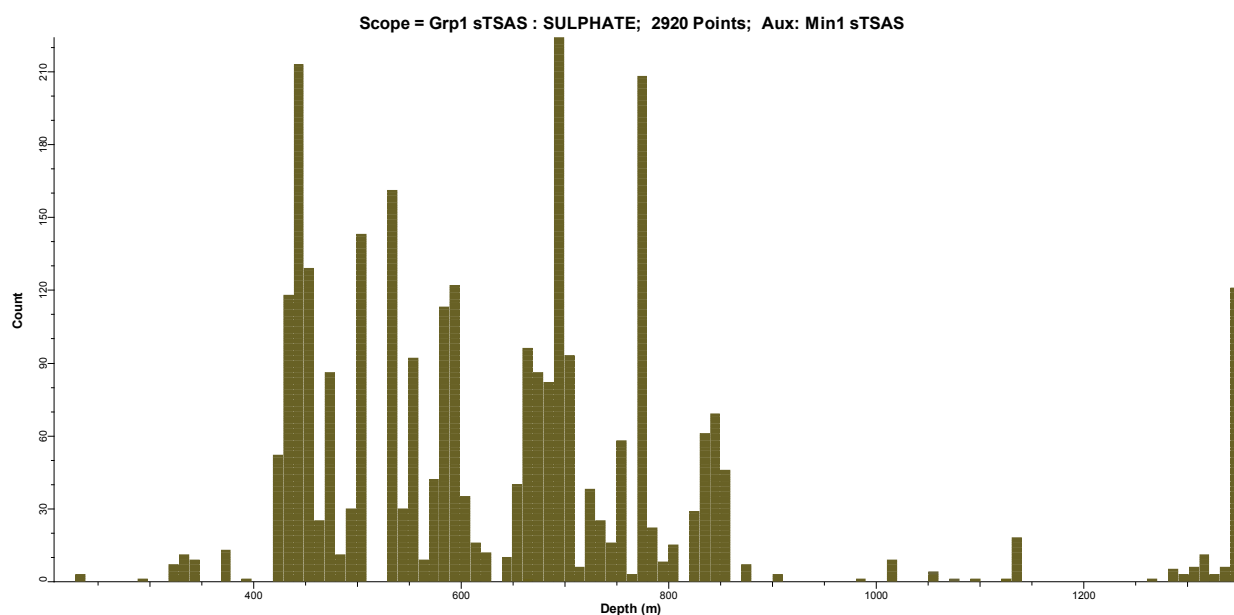


Figure 58: HyLogger spectral data from the DMP Harvey 2 core, identifying 'sulphate' with depth.

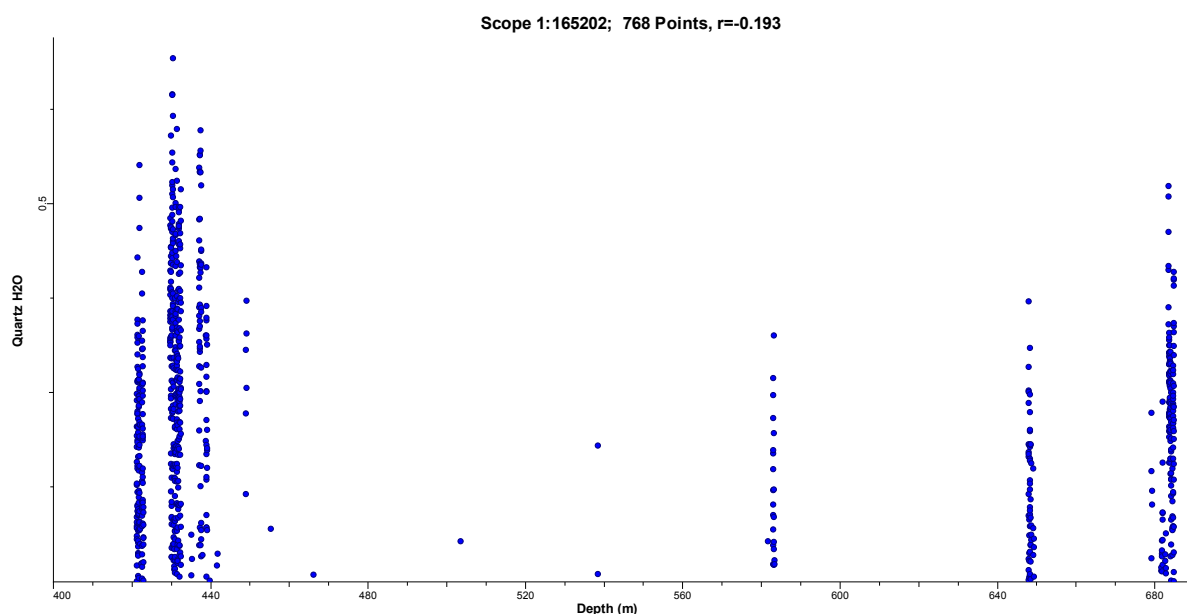


Figure 59: HyLogger spectral data showing 'water' (absorption wavelength of 1900nm) in the DMP Harvey 2 core, soon after the core's arrival at the Perth Core Library.

The core from DMP Harvey 2 was rescanned by the HyLogger three months after the core's arrival at the Perth Core Library. The resulting spectral data were compared with those from the first scan (Figure 59). The 'water signature' remained at depths of 430, 439 and 683m (Figure 60).

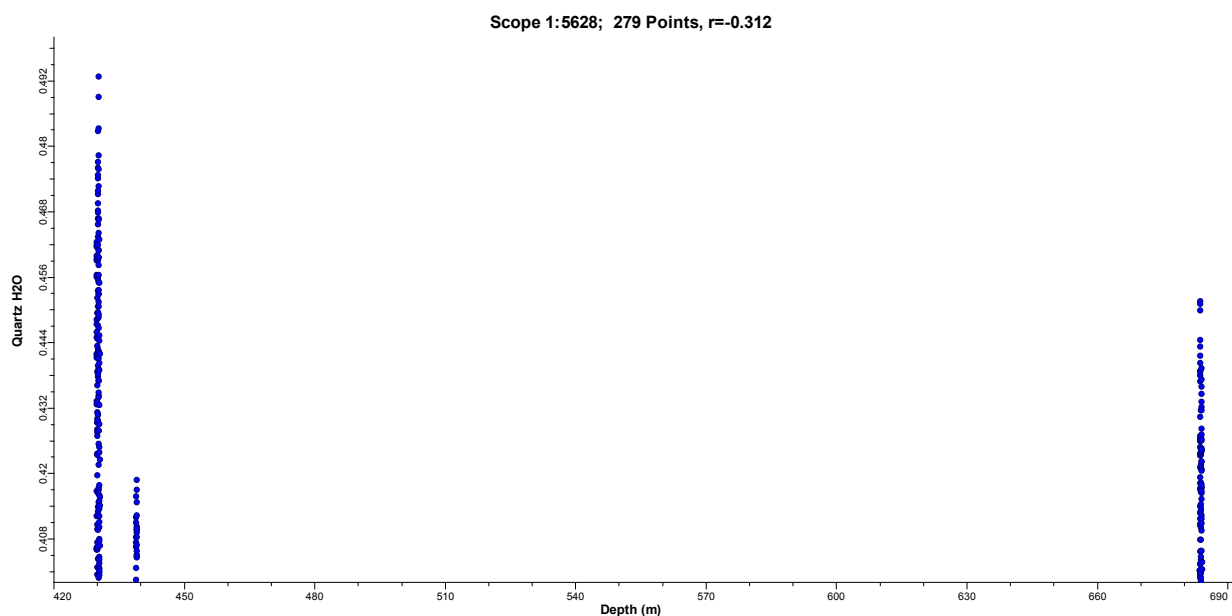


Figure 60: HyLogger spectral data from DMP Harvey 2 core, three months after the arrival of the core at the Perth Core Library. The figure shows the depths at which water remained in the core.

It was suggested that water was 'locked' within the core. As shown in Figure 61, elevated amorphous silica content was identified in the spectral data, between 347 and 376m depth.

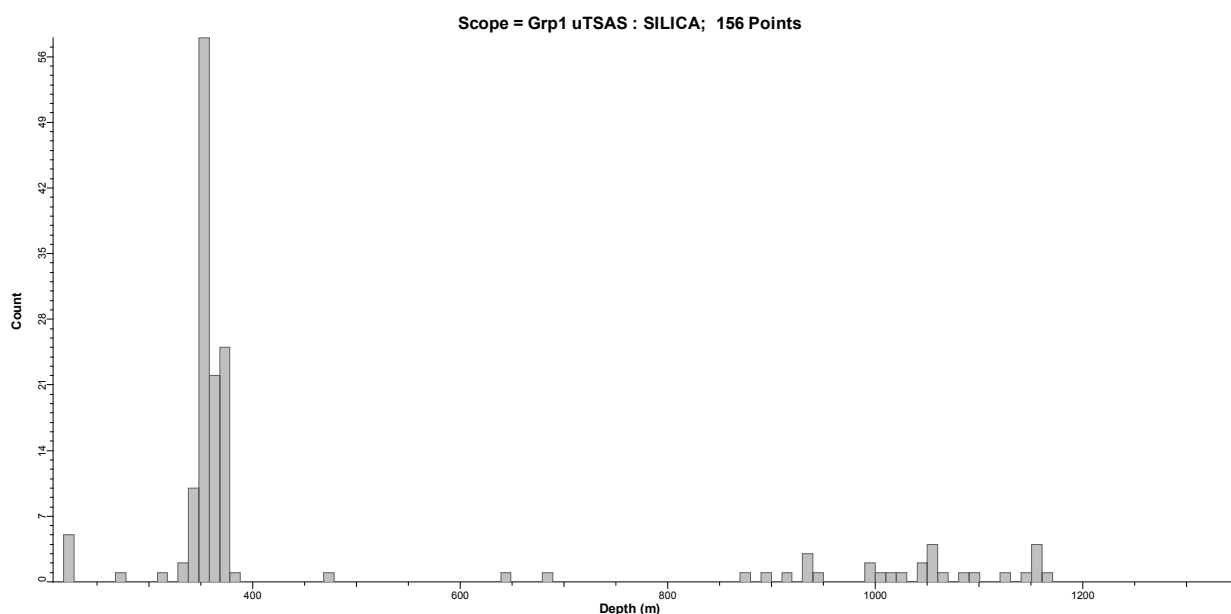


Figure 61: HyLogger spectral scan data of the DMP Harvey 2 core showing depths of core containing amorphous silica.

The above data (Figures 57 to 61) may suggest that the F10 fault zone in DMP Harvey 2 is between 347 and 870m. This fits with ODIN's interpreted F10 Fault intersect in well DMP Harvey 2 at 531m.

#### 5.4.2 Portable X-ray diffraction

The HyLogger spectral data are semi-quantitative. With these data there are ambiguities that arise with the HyLogger's spectral mineral-matching algorithms due to scanned sample points being composites of a number of minerals as opposed to any discrete mineral. Semi-quantitative XRD analysis using GSWA's pXRD machine (Figure 62), can validate the minerals reported by the HyLogger to gain an improved understanding of the mineralogical composition of the core.



Figure 62: GSWA's portable X-ray diffraction (pXRD) machine.

#### 5.4.2.1 Sampling

The pXRD machine was used at 15 points along the cores from wells DMP Harvey 2, 3 and 4 to verify minerals detected by the HyLogger. Mineral investigation staff at GSWA discretely, or 'spot', sampled the core trays from wells at the depths shown in Table 33 and as denoted by red stars in Figures 54 and 56.

Table 33: Details of discrete core-sampling depths in wells sampled by GSWA for portable X-ray diffraction analyses

Well	Sample number	Core-tray number	Depth (m)
DMP Harvey 2	1	324	1104.00
	2	334	1133.08
	3	340	1152.27
	4	343	1160.57
	5	347	1172.00
	6	352	1185.20
DMP Harvey 3	7	370	1234.46
	8	210	1054.30
	9	240	1109.85
	10	281	1186.20
	11	284	1191.25
	12	368	1349.80
	13	427	1461.60
DMP Harvey 4	14	1	1666.15
	15	5	1799.93

NOTE: Each spot sample has a nominal weight of 10 g.

#### 5.4.2.2 Portable X-ray diffraction analyses

Each pXRD sample resulted in approximately 10g of powder, which was collected and analysed by the Perth Core Library mineral investigation personnel using GSWA's pXRD machine. These data were subsequently interpreted using the pXRD's software, XPowder.

The pXRD data were used to validate GSWA's HyLogger data. Minerals identified by XRD, but not immediately in HyLogger data, were extracted using scalars within the TSG software. The analysed pXRD data show that the KCl-rich drilling fluid used by DDH1 Drilling to drill wells DMP Harvey 2, 3 and 4 had a strong overprint on the HyLogger spectral data, appearing as the mineral sylvite in the spectra from the more-permeable core samples. Some minerals picked up by the thermal infrared spectrometer, but not found in the pXRD sample, were turned off in TSG, resulting in the mineral matching algorithm 'the spectral assistant', finding the subsequent best fit of minerals.

The semi-quantitative pXRD analyses are shown in Table 34. The pXRD data show the mineralogical composition of the core at the spot depths sampled.

Table 34: Dominant mineralogy throughout the stratigraphy as determined by the pXRD-validated HyLogger spectral data for the three wells

Well	Sample number	Depth from (m)	Stratigraphic unit	Minerals identified
DMP Harvey 2	1	1104.00	Yalgorup Member	Quartz (major), muscovite (major), albite (major), microcline (major), kaolinite (minor, 7%), montmorillonite (minor, 1%), hematite (trace)
	2	1133.08	Yalgorup Member	Quartz (major), albite (major), microcline (major), muscovite (minor, 9.5%), kaolinite (minor, 2.9%), montmorillonite (trace)
	3	1152.27	Yalgorup Member	Quartz (major), albite (major), microcline (major), muscovite (major), calcite (minor, 4%), kaolinite (minor, 3%), montmorillonite (trace)
	4	1160.57	Yalgorup Member	Quartz (major), microcline (major), chamosite (major), albite (major, 12%)
	5	1172.00	Yalgorup Member	Quartz (major), albite (major), microcline (major), muscovite (major), kaolinite (minor, 7%), dolomite (minor, 1.8%), montmorillonite (minor/trace 1%)
	6	1185.20	Yalgorup Member	Quartz (major), microcline (major), muscovite (major), kaolinite (minor, 7%), montmorillonite (minor/trace, 1%)
DMP Harvey 3	7	1234.46	Yalgorup Member	Quartz (major), microcline (major), kaolinite (minor, 9.4%)
	8	1054.30	Yalgorup Member	Quartz (major), albite (major), microcline (major), montmorillonite (trace)
	9	1109.85	Yalgorup Member	Quartz (major), albite (major), microcline (major)
	10	1186.20	Yalgorup Member	Quartz (major), chamosite (major), microcline (major)
	11	1191.25	Yalgorup Member	Quartz (major), microcline (major), kaolinite (minor, 9%), sylvite (9%)
	12	1349.80	Yalgorup Member	Quartz (major), albite (major), microcline (major), illite-muscovite (major), kaolinite (minor, 2%), montmorillonite (trace)
DMP Harvey 4	13	1461.60	Wonnerup Member	Quartz (major), sylvite (major), microcline (major), illite-muscovite (major), kaolinite (minor, 7%), dolomite (minor, 2%)
	14	1666.15	Wonnerup Member	Quartz (major), microcline (major), kaolinite (major, 11%), sylvite (minor, 6.4%)
	15	1799.93	Wonnerup Member	Quartz (major), microcline (major), kaolinite (major, 14%), sylvite (minor, 3%)

The mineralogical composition, or petrography, of core from wells DMP Harvey 2, 3 and 4 is discussed further in section 5.4.3.2, below.

### **5.4.3 Analyses by Core Laboratories Pty Ltd**

Core Laboratories Pty Ltd (CoreLab) was contracted by DMIRS to provide core-analyses services. These services included:

- Cutting and preparation of core samples for analysis.
- Routine core analysis (RCA)
  - grain volume and grain density
  - porosity and permeability
  - permeability to brine
  - threshold pressure to CO<sub>2</sub>
  - petrographic analysis.
- Special core analysis (SCAL)
  - flow studies
  - mercury injection analysis
  - geomechanical analysis.

The routine core analysis and special core analysis are discussed below. The datasets are in Appendices J and D, respectively.

#### ***5.4.3.1 Simulation of in situ pressures and temperatures***

In order to simulate in situ pressures (commonly referred to as net overburden pressure, or NOBP) and temperatures, core depth samples were tested at pressures and temperatures as determined by wireline logging, as shown in the pressure and temperature depth plots (Figures 29 and 30).

#### ***5.4.3.2 Routine core analysis***

As shown in the analytical program and sample summary (Table 35), 34 samples were scheduled for porosity, permeability and grain density testing, XRD analysis, thin-section petrography and scanning electron microscopy (SEM). The methods and results for the RCA tests on selected samples cut from the core from the DMP Harvey 2, 3 and 4 wells are detailed in (Appendix J) and discussed below.

Table 35: Petrographical analyses, analytical program and sample summary (Brown, 2015, 2016a,b; Nelis, 2015)

Well	Stratigraphic unit	Depth (m)	Sample number	Thin section plate number*	SEM	XRD	Porosity (%)	Permeability(md)	Grain density (g/cm <sup>3</sup> )	Lithology
DMP Harvey 2	Yalgorup Member	511.04	PSH 8	1	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	790.68	PSH 11	2	Yes	Yes	–	–	–	Sandy claystone
DMP Harvey 3	Basal Eneabba unit	725.44	PSH 7	3	Yes	Yes	–	–	–	Sandy hemattic mudstone
	Basal Eneabba unit	740.70	PSH 9	4	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	760.15	142	5	Yes	Yes	29.7	4420.0	2.64	Sandstone
	Yalgorup Member	863.00	147	6	Yes	Yes	23.4	18.9	2.64	Kaolin-rich sandstone
	Yalgorup Member	919.00	152	7	Yes	Yes	28.3	6610.0	2.63	Sandstone
	Yalgorup Member	965.64	PSH 11	8	Yes	Yes	–	–	–	Slightly sandy claystone
	Yalgorup Member	1079.85	163	9	Yes	Yes	9.6	2.2	2.66	Argillaceous sandstone
	Yalgorup Member	1179.70	168	10	Yes	Yes	27.5	928.0	2.65	Kaolin-rich sandstone
	Yalgorup Member	1226.38	PSH 15	11	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	1258.05	175	12	Yes	Yes	5.8	0.0	2.65	Calcite-cemented sandstone
	Yalgorup Member	1291.61	PSH 18	13	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	1335.50	183	14	Yes	Yes	20.2	36.4	2.62	Sandstone
	Yalgorup Member	1353.81	PSH 24	15	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	1394.30	187	16	Yes	Yes	18.1	17.8	2.63	Sandstone
DMP Harvey 4	Yalgorup Member	1395.70	186	17	Yes	Yes	20.5	333.0	2.64	Sandstone
	Yalgorup Member	1406.33	PSH 28	18	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	1414.00	4	19	Yes	Yes	21.4	21.2	2.64	Sandstone
	Yalgorup Member	1416.65	PSH 30	20	Yes	Yes	–	–	–	Slightly silty claystone
	Wonnerup Member	1420.00	11	21	Yes	Yes	23.2	35.1	2.64	Sandstone
	Wonnerup Member	1444.00	35	22	Yes	Yes	18.0	582.0	2.63	Sandstone
	Wonnerup Member	1462.00	53	23	Yes	Yes	19.8	1030.0	2.63	Sandstone
	Wonnerup Member	1479.00	70	24	Yes	Yes	18.5	309.0	2.64	Sandstone
	Wonnerup Member	1500.00	91	25	Yes	Yes	20.3	18.2	2.65	Sandstone
	Wonnerup Member	1519.00	110	26	Yes	Yes	17.9	2070.0	2.63	Sandstone
	Wonnerup Member	1544.00	135	27	Yes	Yes	18.4	633.0	2.64	Sandstone
	Wonnerup Member	1549.00	140	28	Yes	Yes	18.5	3700.0	2.68	Sandstone
	Basal Eneabba unit	893.04	PSH 1	29	Yes	Yes	–	–	–	Sandstone
	Basal Eneabba unit	899.12	PSH 5	30	Yes	Yes	–	–	–	Slightly sandy claystone
DMP Harvey 4	Basal Eneabba unit	902.78	PSH 7	31	Yes	Yes	–	–	–	Sandy claystone
	Basal Eneabba unit	906.33	PSH 10	32	Yes	Yes	–	–	–	Sandy claystone
	Yalgorup Member	1326.25	1A	33	Yes	Yes	20.0	371.0	2.63	Sandstone
	Wonnerup Member	1793.00	4	34	Yes	Yes	21.1	2230.0	2.64	Sandstone

NOTE: \* Refers to figures in CoreLab report.

## Porosity, permeability, grain density and threshold pressure to CO<sub>2</sub>

A CMS-300 permeameter was used to determine unsteady-state gas permeability at varying confining stress values to mimic reservoir conditions. Refer to CoreLab's routine core analysis reports in Appendix J for CoreLab's laboratory procedures.

Analyses performed on selected plug samples included:

- Porosity, permeability in air and grain density at net overburden pressure (NOBP) on sand-rich facies samples from the Yalgorup and Wonnerup Members. At the maximum NOBP of 1700psi, the Klinkenberg permeability<sup>13</sup> ( $K_{inf}$ ) was determined.
- Permeability to brine ( $k_w$ ) at NOBP on sandstone-rich samples from the Yalgorup and Wonnerup Members. The Yalgorup samples were tested at 800psi and 1250psi. The Wonnerup samples were tested at 800psi and 1700psi.
- Permeability to brine ( $k_w$ ) and threshold injection pressure to CO<sub>2</sub> at NOBP on low permeability mudstone-rich samples from the basal Eneabba unit (at 800psi) and the Yalgorup Member (at 1250psi).

### Samples tested

For each well, the number of samples from sand-rich facies scheduled for porosity and permeability measurements at the specified NOBP are shown in Table 36. Grain density was measured on all samples. More samples were scheduled for porosity, permeability and grain density testing for DMP Harvey 3 (183 samples), than for DMP Harvey 2 and DMP Harvey 4 (45 and 10 samples, respectively; (Table 36). Low-permeability samples were tested for permeability to brine ( $k_w$ ) and threshold pressure to CO<sub>2</sub> at NOBP.

Table 36: Tally of sand-rich samples scheduled for porosity, permeability and grain-density measurements at specified net overburden pressure (Brown, 2015, 2016a,b)

Well	Stratigraphic unit	Total number of samples	First NOBP* (psi)	No of measurements for first NOBP* test	Second NOBP* (psi)	Number of measurements for second NOBP* test
DMP Harvey 2	Yalgorup Member	25	800	5	1250	25
	Wonnerup Member	20	800	5	1700	20
DMP Harvey 3	Yalgorup Member	50	800	13	1250	50
	Wonnerup Member	133	800	27	1700	133
DMP Harvey 4	Yalgorup Member	2	800	1	1250	2
	Wonnerup Member	8	800	27	1700	8
Totals		238		78		238

NOTE: \* Net overburden pressure.

<sup>13</sup> Gas is used in conventional core analysis for laboratory determination of permeability. The permeability of a gas in a core is dependent on the composition of the gas and the mean pressure in the strata. As the confining pressure (NOBP) increases, the permeability of the gas decreases. The extrapolation of a plot of the inverse of pressure versus permeability of the gas gives the Klinkenberg permeability, which is the equivalent permeability of a non-reactive fluid in the core.

## Results and discussion

CoreLab's full RCA reports for each of the DMP Harvey 2, 3 and 4 wells, including the laboratory procedures and data and its graphic representation, are available in Appendix J. The results are summarised below.

### DMP Harvey 2

The porosity, permeability and grain density analysis for DMP Harvey 2 core samples are given in Table 37.

Table 37: DMP Harvey 2: summarised routine core analysis (RCA) data (Brown, 2016a)

	Minimum	Maximum
<b><i>Yalgorup Member (sand-rich facies)</i></b>		
Net confining pressure of 800psi		
Porosity (%)	8.8	28.6
Permeability, Horizontal $K_{inf}$ (md)	0.347	2560
Grain density (g/cm <sup>3</sup> )	2.608	2.766
Net confining pressure of 1250psi		
Porosity (%)	7.8	30.4
Permeability, horizontal, $K_{inf}$ (md)	0.212	6460
<b><i>Yalgorup Member (clay-rich facies)</i></b>		
Permeability to brine (md)	No flow	—
Threshold pressure to CO <sub>2</sub> (psi)	No injection	
<b><i>Wonnerup Member (sand-rich facies)</i></b>		
Net confining pressure of 800psi		
Porosity (%)	21.4	24.6
Permeability, horizontal $K_{inf}$ (md)	2.79	759
Grain density (g/cm <sup>3</sup> )	2.597	2.701
Net confining pressure of 1750psi		
Porosity (%)	13.6	24.6
Permeability, horizontal, $K_{inf}$ (md)	0.278	750

None of the preserved mudstone-rich samples tested for permeability to brine and threshold pressure to CO<sub>2</sub> at NOBP resulted in any flow or injection to CO<sub>2</sub>.

### DMP Harvey 3

The porosity, permeability and grain density analysis for DMP Harvey 3 core samples are given in Table 38.

All of the analysed porosity and permeability data for DMP Harvey 3 are graphically represented in Figure 63, which shows that the range of measured porosities and permeabilities from the Yalgorup Member samples is greater than those from the Wonnerup Member samples.

Table 38: DMP Harvey 3: summarised routine core analysis (RCA) data (Brown, 2015)

	Minimum	Maximum
<b><i>Yalgorup Member (sand-rich facies)</i></b>		
<b>Net confining pressure of 800psi</b>		
Porosity (%)	10.1	30.4
Permeability, horizontal $K_{inf}$ (md)	0.004	6730
Grain density (g/cm <sup>3</sup> )	2.592	2.842
<b>Net confining pressure of 1250psi</b>		
Porosity (%)	5.8	30.4
Permeability, horizontal, $K_{inf}$ (md)	0.002	23900
Permeability to brine (md)	0.0001	4180
<b><i>Basal Eneabba unit and Yalgorup Member (clay-rich facies)</i></b>		
Permeability to brine (md)	<0.00001	0.00003
Threshold pressure to CO <sub>2</sub> (psi)	850	4500
<b><i>Wonnerup Member (sand-rich facies)</i></b>		
<b>Net confining pressure of 800psi</b>		
Porosity (%)	17.1	24.1
Permeability, horizontal $K_{inf}$ (md)	2.39	6810
Grain density (g/cm <sup>3</sup> )	2.624	2.897
<b>Net confining pressure of 1750psi</b>		
Porosity (%)	12.9	24.9
Permeability, horizontal, $K_{inf}$ (md)	0.003	10800
Permeability to brine (md)	0.929	5247

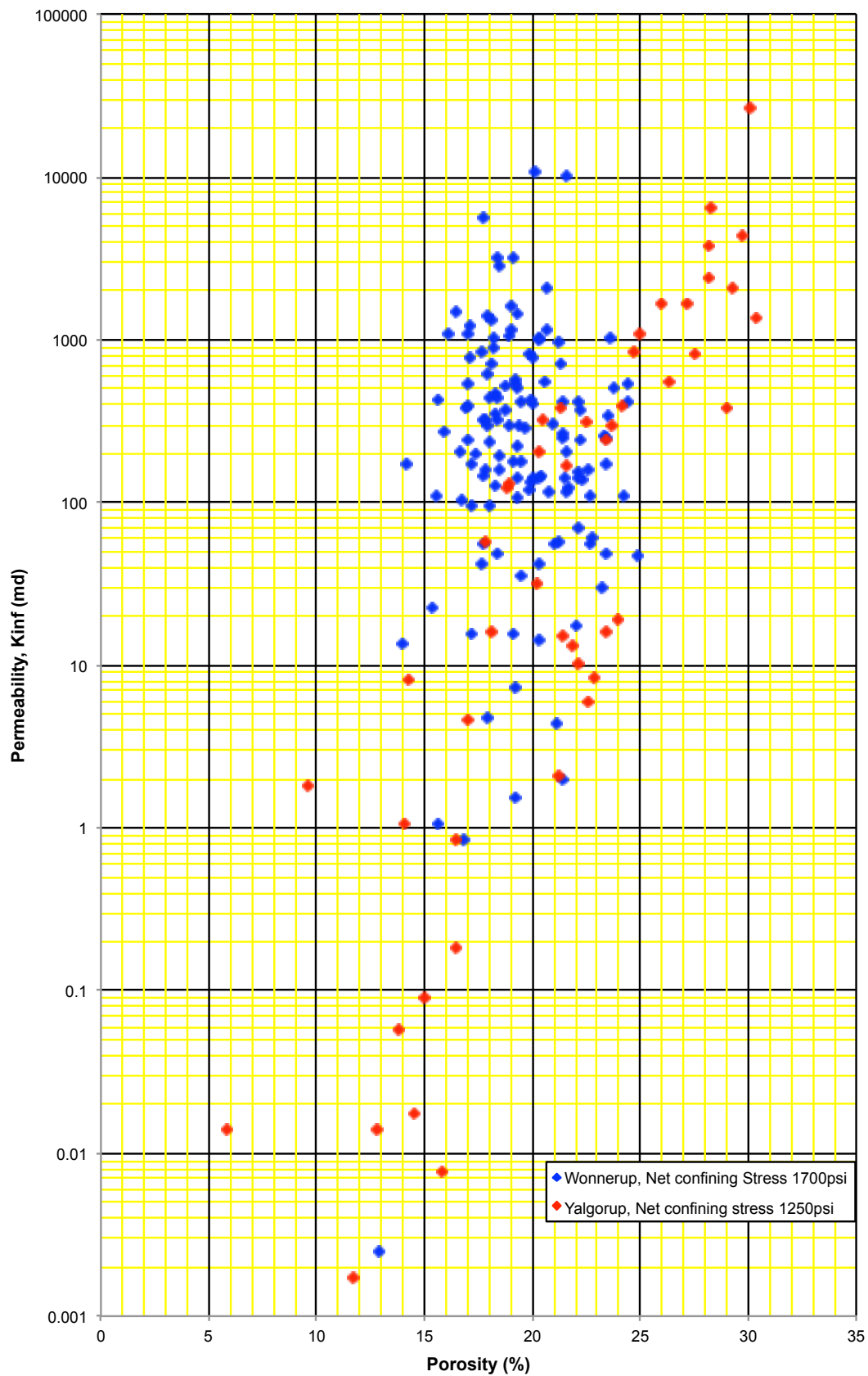


Figure 63: DMP Harvey 3: porosity versus permeability ( $K_{inf}$ ) at net confining stress for the Wonnerup and Yalgorup Members (Brown, 2016).

For DMP Harvey 3 samples from the basal Eneabba unit and Yalgorup Member gave very low permeabilities to brine ( $<0.00001$  to  $0.00003$ md) at 1250psi NOBP, whereas the Wonnerup Member samples gave permeabilities to brine ranging from 0.929md (1419.10m depth) to 5247md (1474.00m depth). Those preserved mudstone-rich samples resulting in permeabilities to brine and giving CO<sub>2</sub> threshold pressure results were horizontally orientated core samples (ie. those samples cut in the same direction as the assumed orientation of the bedding planes).

#### DMP Harvey 4

The porosity, permeability and grain density analyses for DMP Harvey 4 core samples are given in Table 39.

Table 39: DMP Harvey 4: summarised routine core analysis (RCA) data (Brown, 2016b)

	Minimum	Maximum
<b><i>Yalgorup Member (sand-rich facies)</i></b>		
Net confining pressure of 800psi		
Porosity (%)	20.4	
Permeability, horizontal K <sub>inf</sub> (md)	371	
Grain density (g/cm <sup>3</sup> )	2.622	2.626
Net confining pressure of 1250psi		
Porosity (%)	20	23.0
Permeability, horizontal, K <sub>inf</sub> (md)	350	1670
<b><i>Basal Eneabba unit</i></b>		
Permeability to brine (md)	$<0.00001$	0.101
Threshold pressure to CO <sub>2</sub> (psi)	17	No injection
<b><i>Wonnerup Member (sand-rich facies)</i></b>		
Net confining pressure of 800psi		
Porosity (%)	17.1	17.6
Permeability, horizontal K <sub>inf</sub> (md)	8.58	33.1
Grain density (g/cm <sup>3</sup> )	2.632	2.651
Net confining pressure of 1700psi		
Porosity (%)	16.7	22.5
Permeability, horizontal, K <sub>inf</sub> (md)	7.65	1750
Permeability to brine (md)	2.24	7.47

For DMP Harvey 4, two sand-rich Yalgorup Member samples were tested; hence, the paucity of analyses in Table 39. The Klinkenberg permeability (k<sub>inf</sub>) and porosity decreased slightly for the one Yalgorup Member sample tested as the NOBP was increased from 800 to 1250psi (Appendix D).

All bar two of the preserved mudstone-rich samples tested for permeability to brine and threshold pressure to CO<sub>2</sub> at NOBP resulted in flow and injection to CO<sub>2</sub>. The two samples not resulting in flow or injection results were from 899.00 and 899.12m depth. For two of the three paired samples, cut from core at the same depths (PSH#2 at 893.10m and PSV#1 at 893.17m, PSH#8 at 902.86m and PSV#3 at 902.88m) the vertically orientated samples resulted in lower flows and higher CO<sub>2</sub> threshold pressures than the horizontally orientated samples.

### ***Preliminary interpretation***

A significant range of porosity and permeability data are reported for the non-preserved sandstone-rich and preserved mudstone-rich samples, as would be expected for variable lithologies in stratified formations. The increased spread of porosities and permeabilities in the Eneabba Formation and Yalgorup Member samples relates to more varied facies being present in these formations (silt, clay, mud and sand rich) than in the Wonnerup Member (predominantly sand-rich facies). The porosities and permeabilities of same depth samples decreased as the NOBP increased.

The analyses from the mudstone-rich preserved samples indicate that the paleosols or baffle horizons can withstand permeability to brine and gaseous CO<sub>2</sub> flow. The permeability to brine and threshold pressure to CO<sub>2</sub> at NOBP test results for samples from DMP Harvey 3 and 4 suggest that flow to brine and CO<sub>2</sub> is less impeded in horizontally cut core samples where the flow test direction is aligned with the bedding plane orientation as compared with the vertically cut plugs, where the flow testing direction is assumed to be perpendicular to the bedding plane orientation.

### **Petrography**

Inorganic petrographical analysis of the Harvey core samples was contracted to CoreLab, who examined 34 thin sections, as outlined in Table 35. The inorganic chemistry, structure, composition and properties of the rocks that were the subject of thin-section examination are summarised below. CoreLab's petrographical report is in Appendix M.

### **X-ray diffraction (XRD) analysis**

The XRD results are presented as whole-rock mineralogy and relative clay mineralogy in Table 34.

### **Whole-rock mineralogy**

Figure 64 summarises the whole-rock mineralogy as determined by XRD for each of the 34 mineral samples analysed. The quartz proportion is shown in blue and the clay group is shown in brown. The plug offcuts from well DMP Harvey 2 are both sandy claystones. The 26 samples from well DMP Harvey 3 comprise 17 sandstones and nine mudstones, and the six samples from DMP Harvey 4 comprise three claystones and three sandstones.

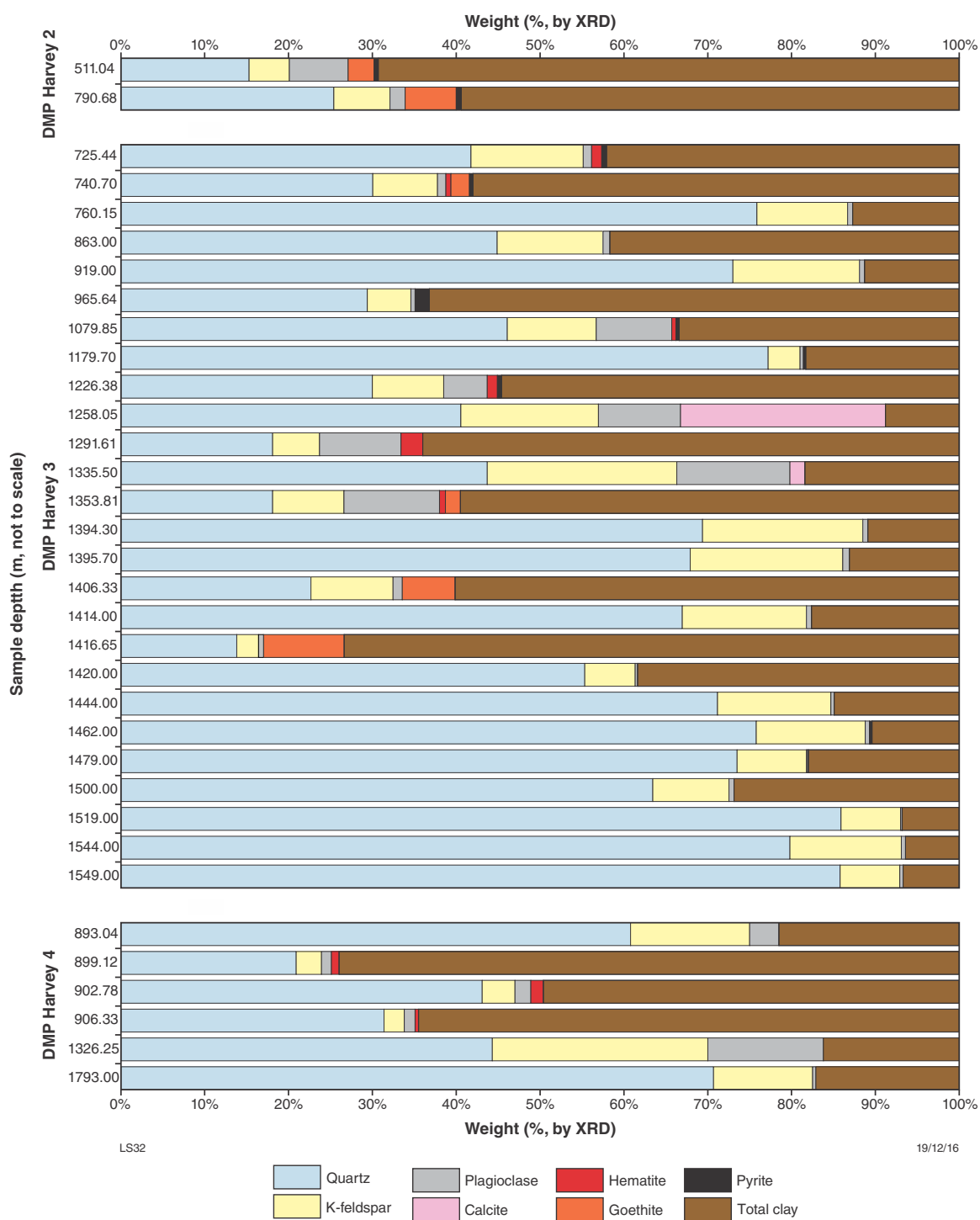


Figure 64: DMP Harvey 2, 3 and 4: whole-rock mineralogy determined by X-ray diffraction (Nelis, 2015).

### Relative clay mineralogy

The semi-quantitative percentage weight of the different clay minerals as a proportion of the total clay content as determined by XRD is displayed in Figure 65.

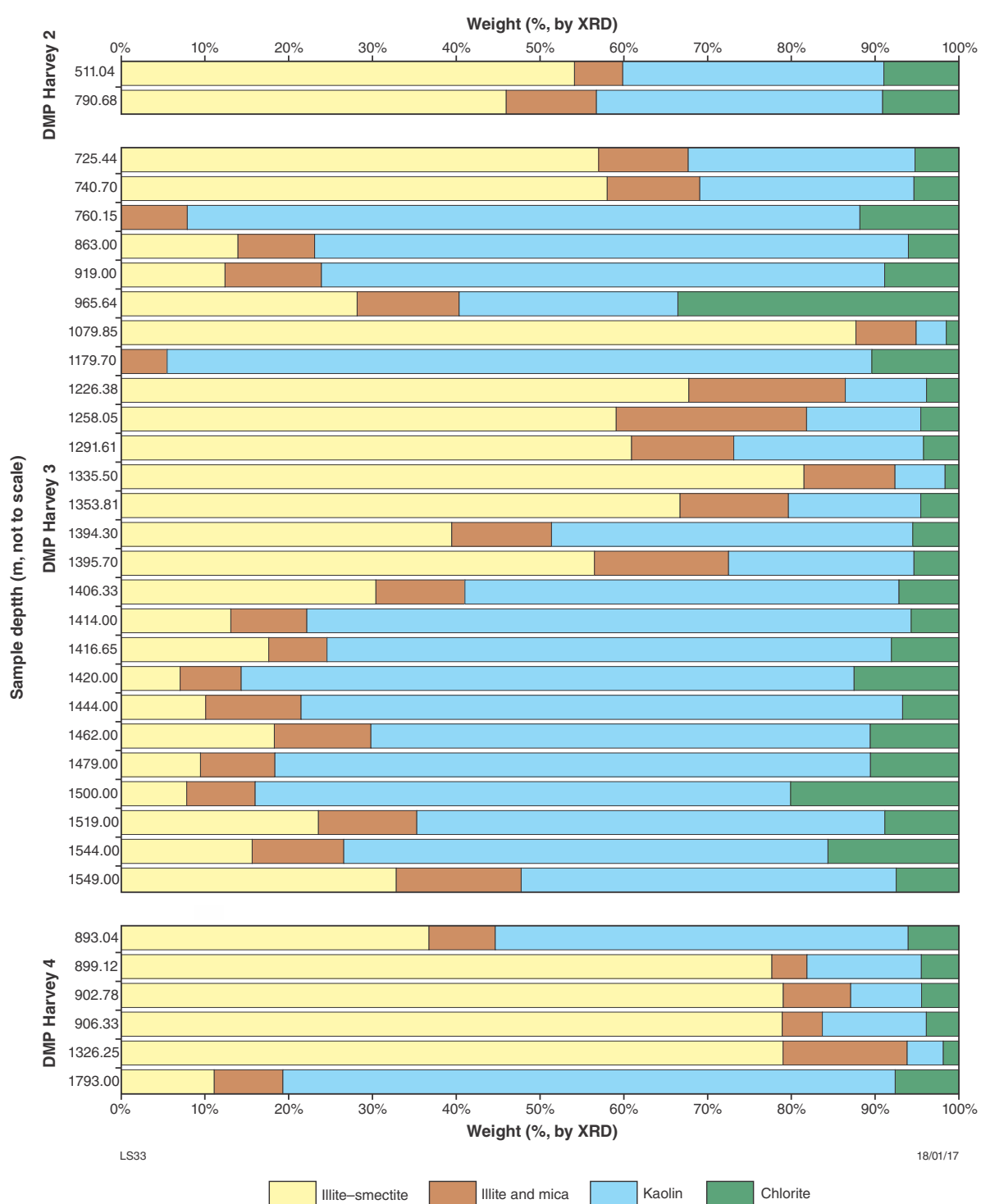


Figure 65: DMP Harvey 2, 3 and 4: summarised relative clay mineralogy, as determined by X-ray diffraction (Nelis, 2015).

### Thin section petrography and scanning electron microscopy

Plates of each core sample as thin sections viewed through a standard microscope and a scanning electron microscope, with varying magnification, are in CoreLab's petrography report (Appendix M). The structure, framework grains, accessory grains, matrix, cements and pore types are summarised for each of the 34 core samples (Nelis, 2015). A summary of the inorganic petrography for each well is discussed below.

## DMP Harvey 2

### *Yalgorup Member*

Figure 66 features an illite–smectite structure that consists of well-aligned pure-clay platelets, which could represent infiltrated clay or a root zone (Nelis, 2015). The illite is detrital, along with mica and chlorite. The remains of plant fragments are identifiable. The quartz and feldspar identified in XRD form scattered, silt to very fine sand-size grains. The fractures in the sample, which appear blue in Figure 66 due to being filled by epoxy resin, opened during sample preparation.

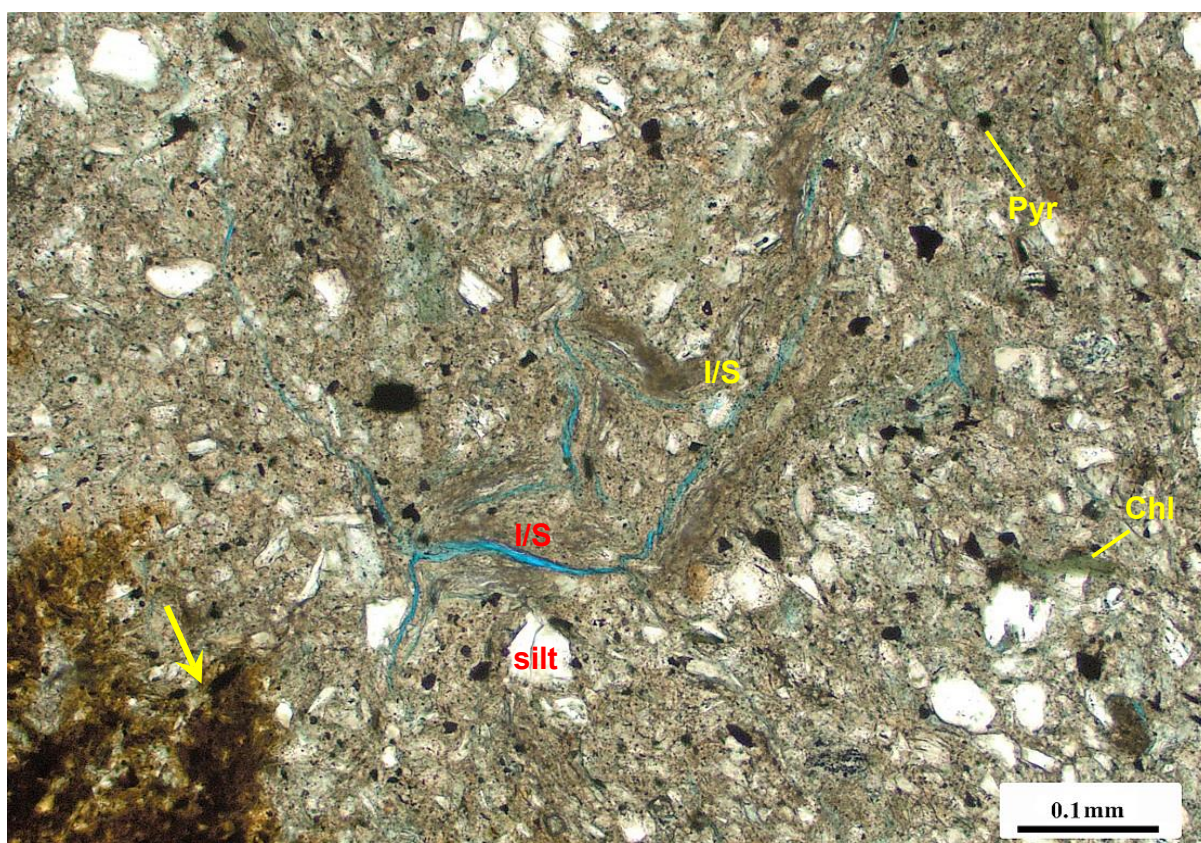


Figure 66: Thin section photomicrograph of a sandy claystone from the Yalgorup Member at 790.68m depth in DMP Harvey 2 (Nelis, 2015) with evenly dispersed silt to very fine sand grains (silt). Minor detrital chlorite (Chl) and authigenic pyrite as dispersed framboids (Pyr) are present. Areas show mottled hematite staining (yellow arrows). Illite–smectite (I/S) structure consisting of well-aligned, pure clay platelets (no detrital silt) may represent an infiltrated clay or a root zone. The epoxy-filled fractures (blue) are a consequence of the smectite-rich clay.

## DMP Harvey 3

### *Eneabba Formation*

The two basal Eneabba samples from DMP Harvey 3 are from 725.44 and 740.70m depth. These samples have a yellow-brown, iron-stained (yellow-brown) illite–smectite matrix with quartz (left side of Figure 67) and potassium-feldspar (K-feldspar) grains. Some grains have been replaced by kaolin-group minerals (kaolinite and dickite). Figure 67 shows kaolinite platelets (right side of the image) with minor intercrystalline micropores.

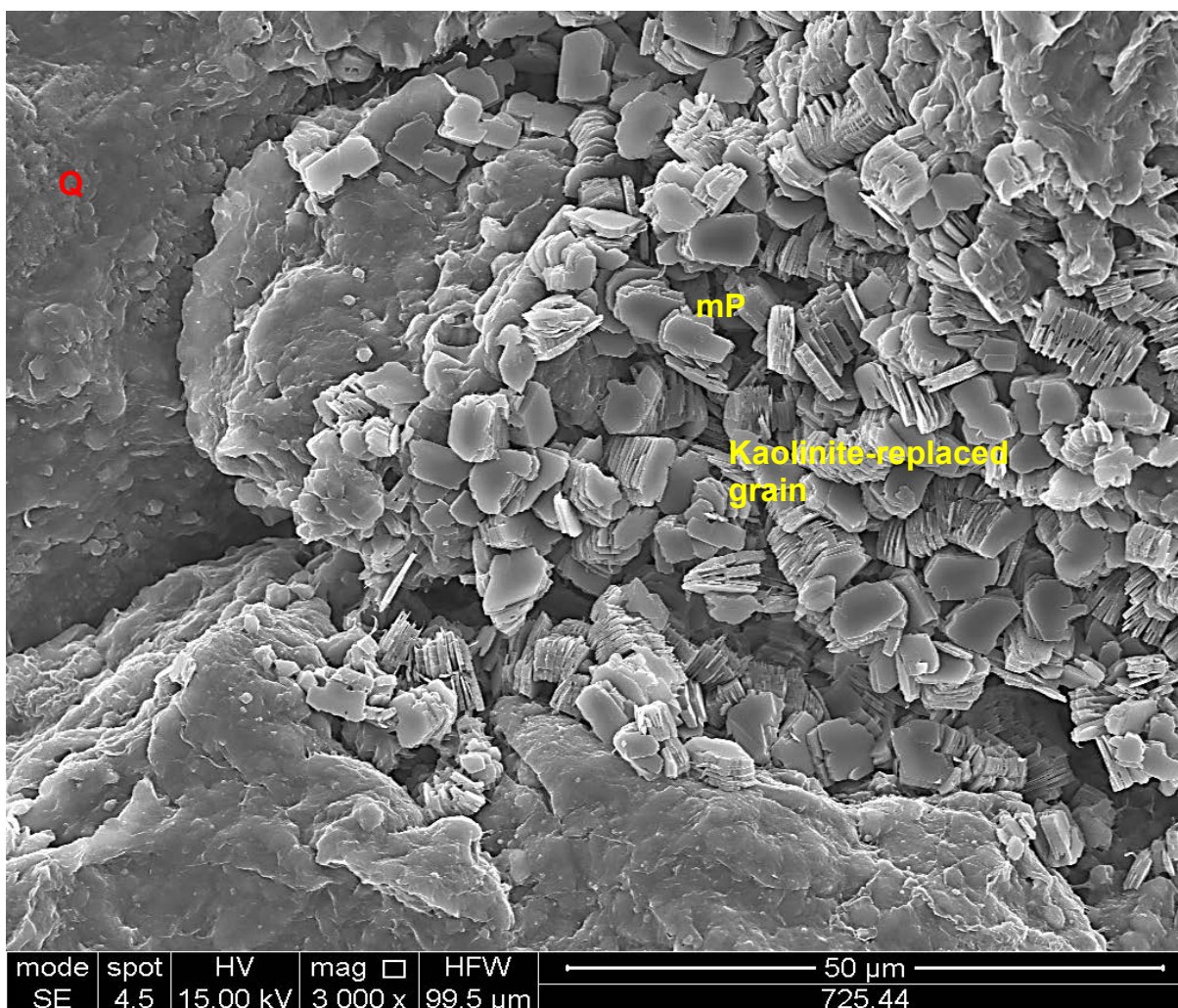
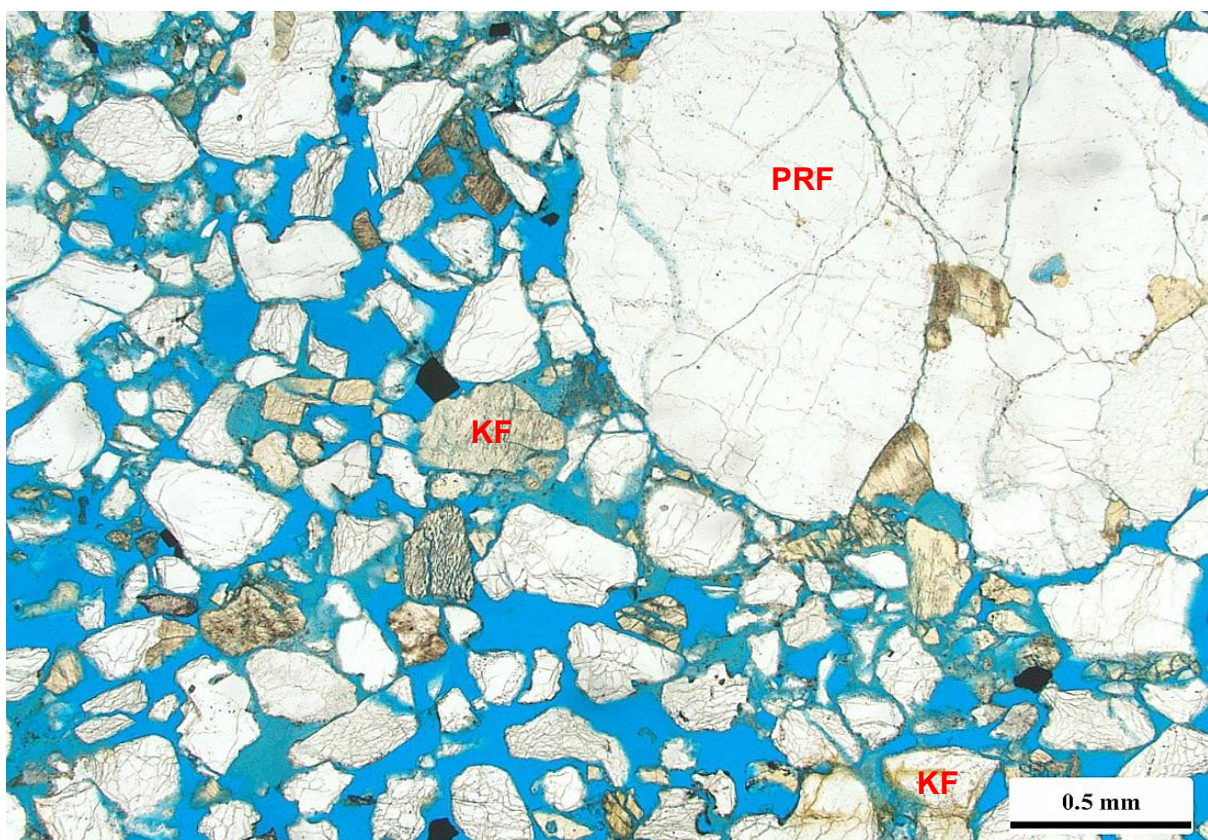


Figure 67: Scanning electron microscope micrograph for a sandy hematitic mudstone sample of the basal Eneabba unit from 725.44m depth in DMP Harvey 3, showing a patch of kaolinite platelets (small crystals) that have replaced a feldspar grain (Nelis, 2015), Quartz grain (Q) and intercrystal micropores associated with patches of kaolinite (mP) are also visible.

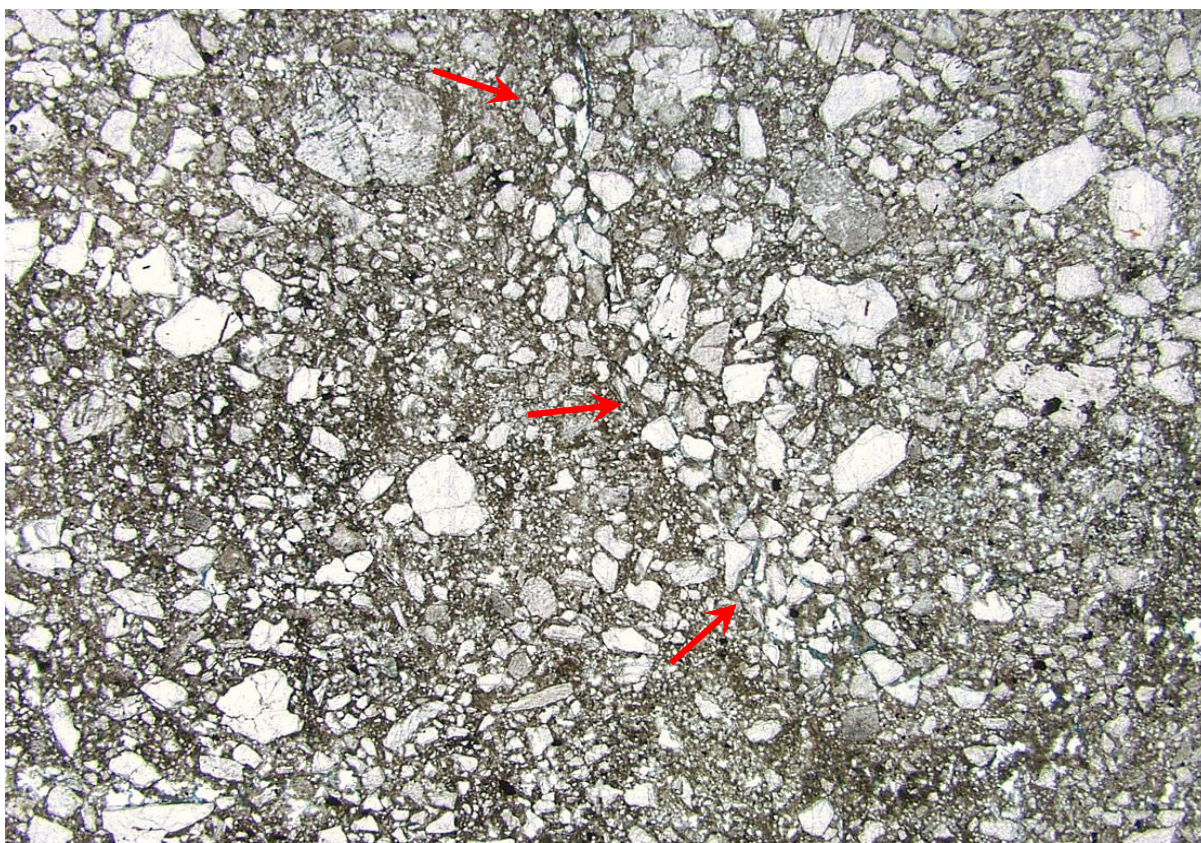
### Yalgorup Member

The Yalgorup Member includes quartz sandstone, argillaceous sandstone, kaolin-rich sandstone, calcite-cemented sandstone and sandy claystone. The sandstones are medium to coarse grained, and comprise quartz, feldspars and plutonic lithic grains. A coarse-grained plutonic lithic fragment is shown in the top right of Figure 68, with smaller quartz grains in white and K-feldspar grains stained yellow. Authigenic minerals include quartz overgrowths and intragranular kaolinite (Nelis, 2015). Heavy trace minerals, such as garnet, appear black and pore spaces appear blue in the photomicrograph (Figure 68).



*Figure 68: Thin section photomicrograph of a quartz arenite sandstone sample from the Yalgorup Member from 760.15m depth in DMP Harvey 3 (Nelis, 2015). Potassium feldspar (KF, stained yellow) is present as grains and within plutonic lithic fragments (PRF).*

An argillaceous sandstone sample from 1079.85m depth has a brecciated fabric of quartz and plagioclase grains with a matrix of illite–smectite. A possible microfault zone is seen cross-cutting the field of view in Figure 69, from the top left to bottom right (Nelis, 2015).



*Figure 69: Thin section photomicrograph of an argillaceous sandstone from the Yalgorup Member at 1079.85m depth in DMP Harvey 3, showing a massive fabric with a possible microfault structure that cross-cuts the sample (red arrows). The slight variation in the color of the matrix reflects irregular hematite staining (Nelis, 2015).*

The Yalgorup Member sample at 1258.05m depth is a massive sandstone comprising quartz, K-feldspar, plutonic lithic fragments, plagioclase and black grains that are dominantly opaque minerals altered to hematite and limonite (Figure 70). Intergranular areas are filled by calcite cement, shown in pink in Figure 70.

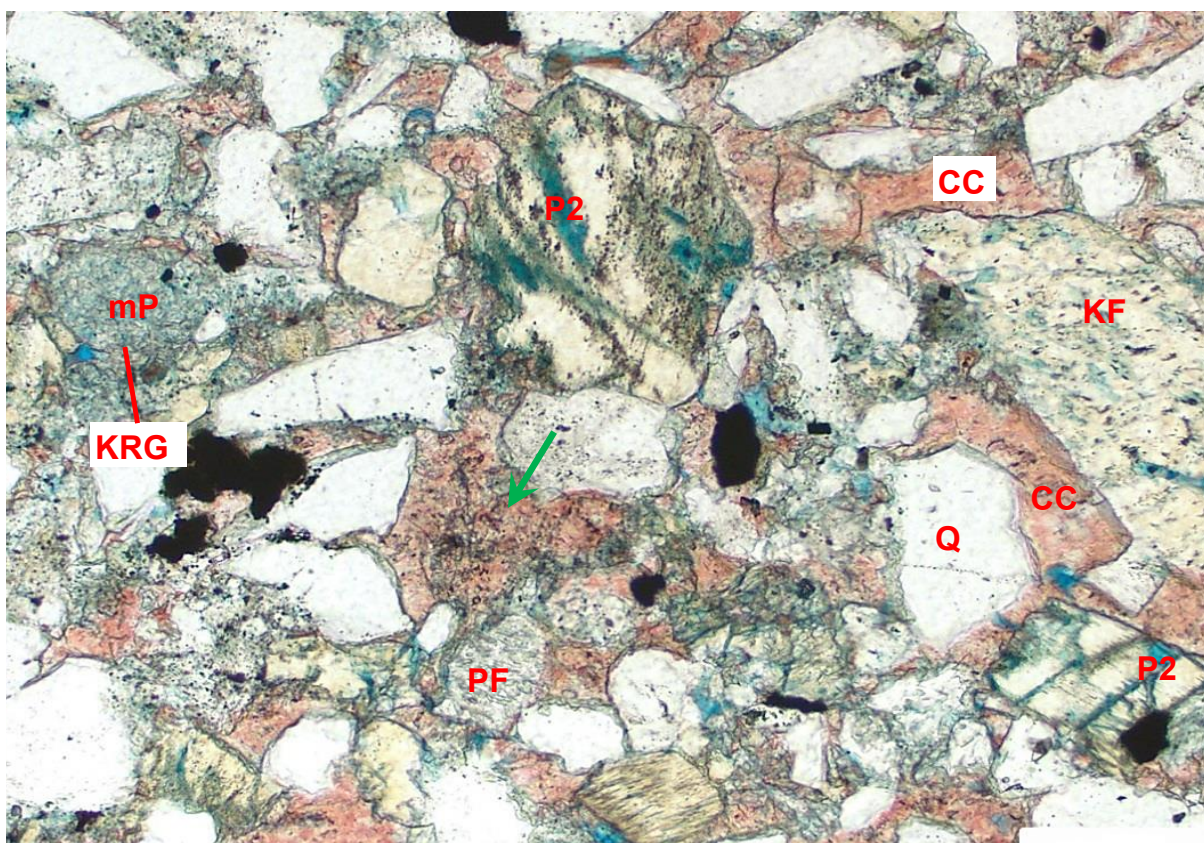


Figure 70: Thin section photomicrograph of a calcite-cemented sandstone within the Yalgorup Member at 1258.05m depth in DMP Harvey 3 (Nelis, 2015). The calcite cement (CC) is stained pink. The green arrows indicate calcite-replaced grains. Framework grains identified include quartz (Q), K-feldspar (KF) and plagioclase (PF). Most of the black grains are opaque minerals, many of which are altered to hematite or limonite. Intragranular pores (P2) are present within K-feldspar grains. Intercrystal micropores (mP) are associated with kaolinite-replaced grains (KRG).

In the Yalgorup Member samples, authigenic minerals include quartz overgrowths (Figure 71) and K-feldspar overgrowths. Scanning electron microscopy show intergranular pores occluded by quartz overgrowths or kaolinite (Figure 71). The large smooth-faced grains to the left are quartz grains with quartz overgrowths. The small kaolinite grains are seen in the centre and right of the image. An intergranular pore (darker coloration) is seen in the upper left.

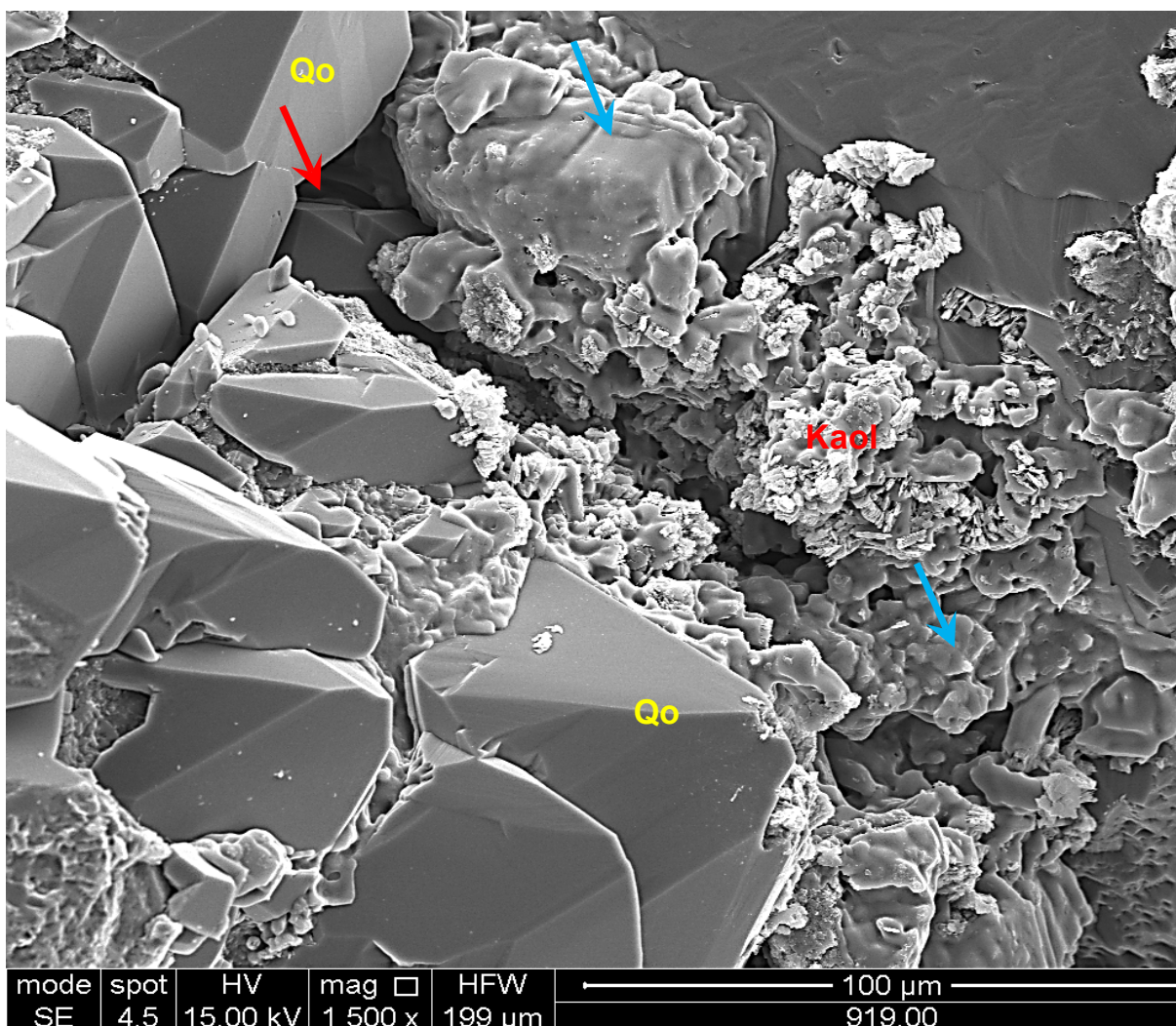


Figure 71: Scanning electron microscope micrograph of a Yalgorup Member sandstone at 919.00m depth in DMP Harvey 3 (Nelis, 2015). Intergranular pores (red arrows) are partly to completely occluded by quartz overgrowths (Qo or kaolinite (Kaol)). Some salt (blue arrows) encases the kaolinite, but is only a contaminant.

Measured porosity for Yalgorup Member sandstones ranges from 5.8 to 29.7 per cent. The lowest measured porosity corresponds to the calcite-cemented sandstone (Figure 70), and the highest porosity corresponds to the coarse quartz arenite sandstone sample at 760.15m depth (Figure 68) having the highest measured permeability.

The six claystone samples in the Yalgorup Member in DMP Harvey 3 have a variety of clay compositions. Total clay content in the claystone ranges from 59.5 to 73.3 per cent (Nelis, 2015).

Figure 72 shows a sandy claystone with a mottled, iron-stained fabric and fine- to medium-sized sand grains. The iron (hematite) staining may be due to infiltration of the sediment (Nelis, 2015).

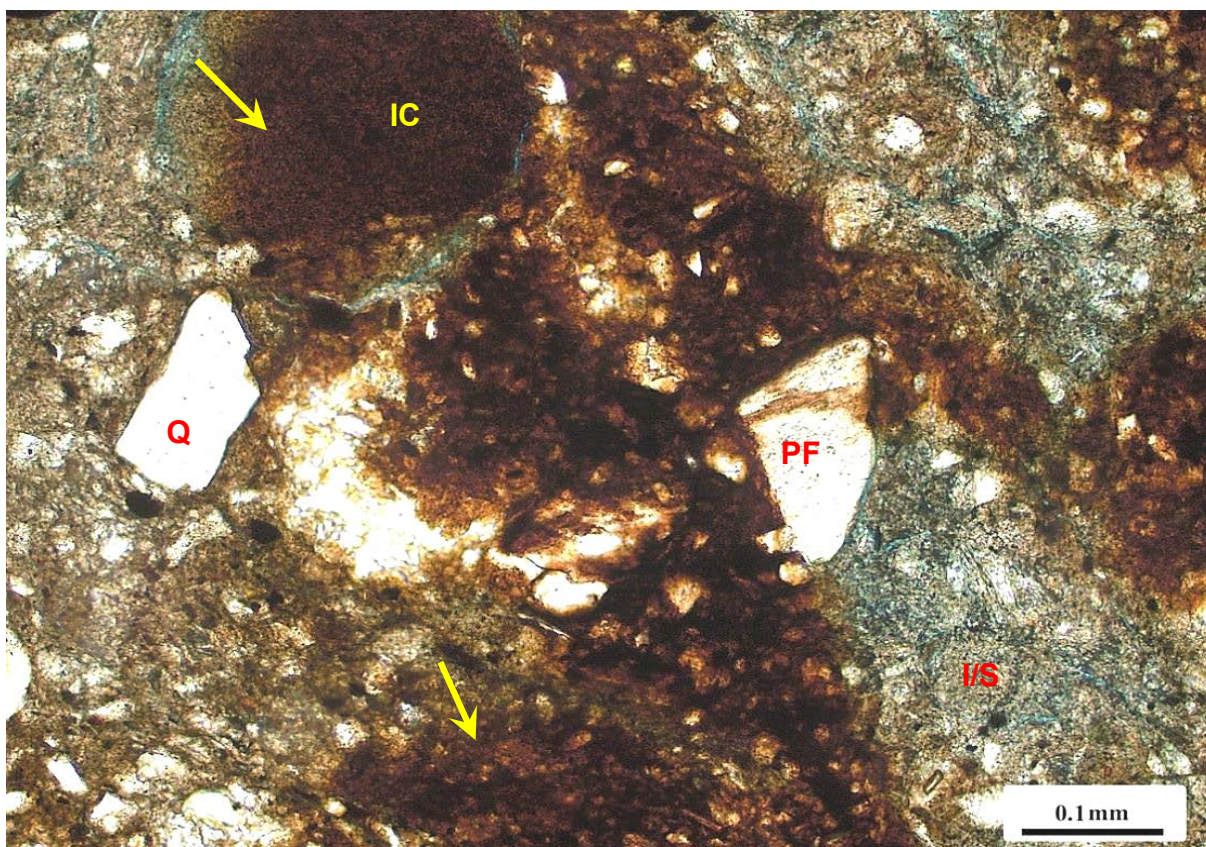
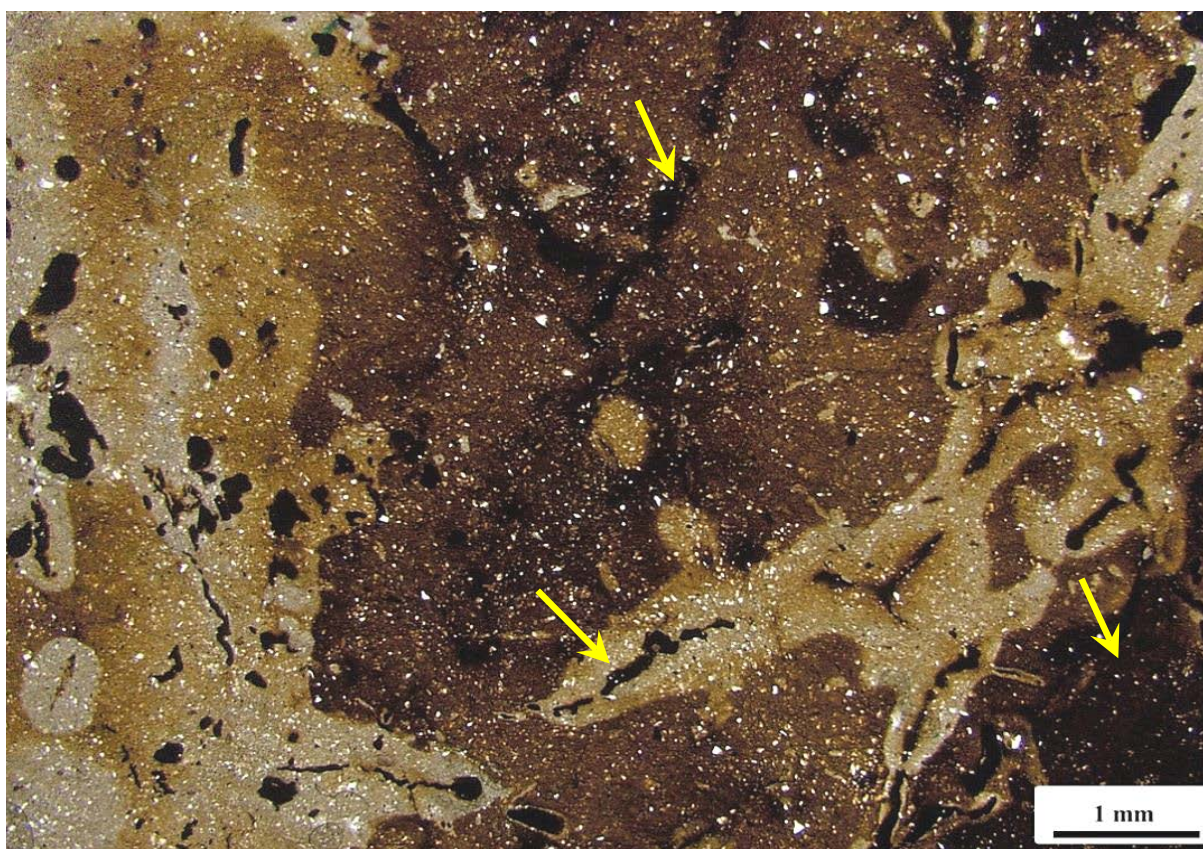


Figure 72: Thin section photomicrograph of a calcite-cemented sandy claystone from the Yalgorup Member at 1291.61m depth in DMP Harvey 3 (Nelis, 2015). Sample displays a mottled fabric due to minor hematite staining (yellow arrows) and areas containing scattered, fine and medium sand grains. The larger grains include quartz (Q) and plagioclase (PF). Argillaceous intraclasts (IC) are noted.

Goethite, an iron hydroxide mineral that may be present in soil, was identified in the claystone sample from 1416.65m depth (Figure 73). This sample contains possible root traces and a siltstone-filled vertisol (shrinking and swelling clay soil) fracture, indicating that the claystones and mudstones underwent weathering and soil development.



*Figure 73: Thin section photomicrograph of a slightly silty claystone from the Yalgorup Member at 1416.65m depth in DMP Harvey 3 (Nelis, 2015). The abundant clay matrix of kaolin and lesser mixed-layer illite–smectite contains sparse flecks of quartz and minor feldspar. Anastomosing, branching to blob-shaped goethite staining (yellow arrows) resembles possible root traces.*

### **Wonnerup Member**

Eight Wonnerup Member samples from well DMP Harvey 3 were submitted for inorganic petrographic analysis. These were mostly massive, coarse-grained sandstones with grains of quartz and K-feldspar and plutonic lithic fragments (Figure 74). Oversized and grain-sized patches of kaolinite (seen as speckled blue in Figure 74) indicate extensive replacement of micas. The kaolinite cement is microporous (Nelis, 2015).

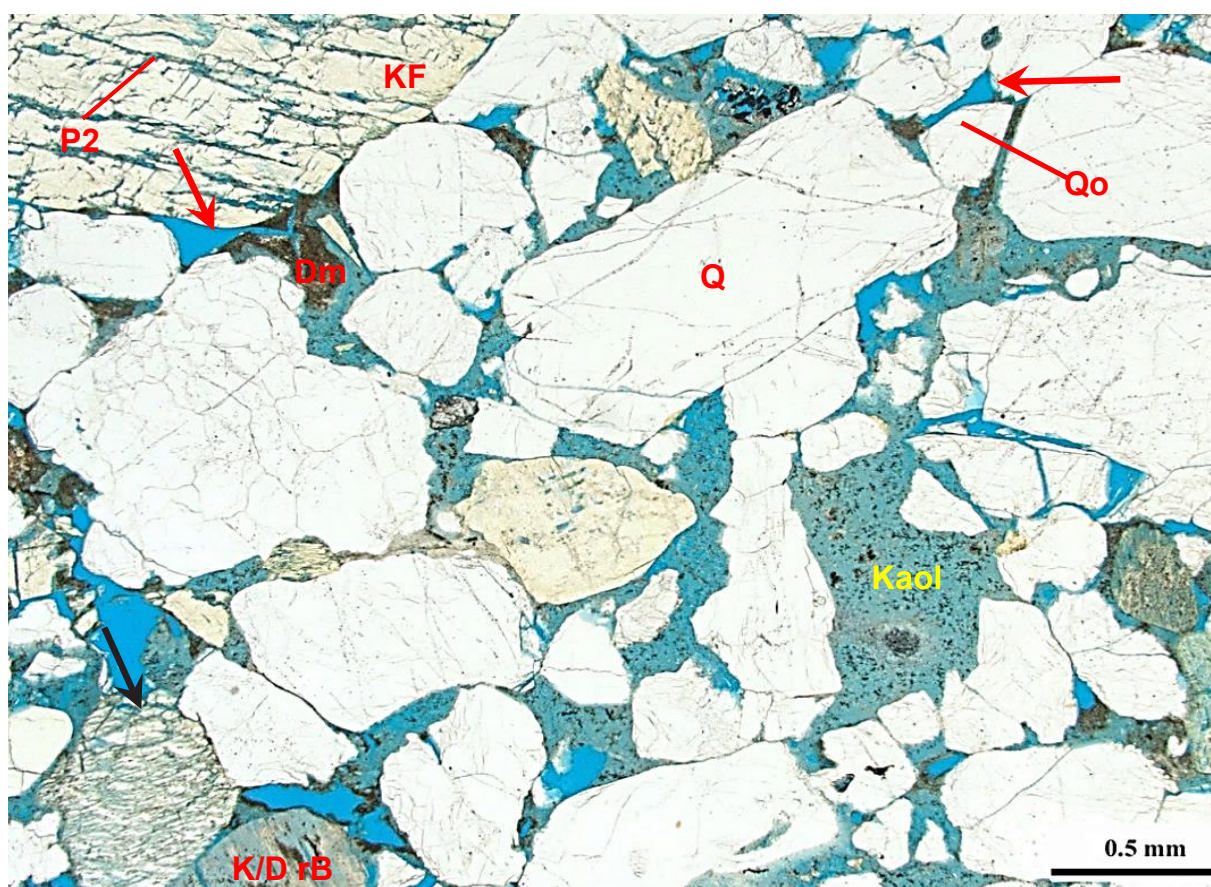


Figure 74: Thin section photomicrograph of a Wonnerup Member sandstone from 1544.00m depth in DMP Harvey 3 (Nelis, 2015). This sample is a coarse-grained sandstone with a massive fabric. Identified framework grains include quartz (Q) and K-feldspar (KF). One biotite flake altered to kaolinite– dickite is present (K/DrB). Intergranular kaolinite (Kaol) cement is identified. Note that some areas of kaolinite are oversized. The red arrows indicate intergranular pores reduced in size by the presence of quartz overgrowths (Qo). Some of the feldspar grains exhibit intragranular dissolution pores (P2) or intragranular fractures (black arrow). Feldspar dissolution and fractures follow cleavages. The speckled blue coloration of the kaolinite cement indicates that it is microporous. The dark material is drilling mud contamination (Dm).

Quartz overgrowths help to bind the Wonnerup Member sandstones and result in reduced pore size (Nelis, 2015). Pore types in the Wonnerup Member are intergranular pores, intragranular fractures in K-feldspar grains and micropores in finely crystalline kaolinite (Figure 75).

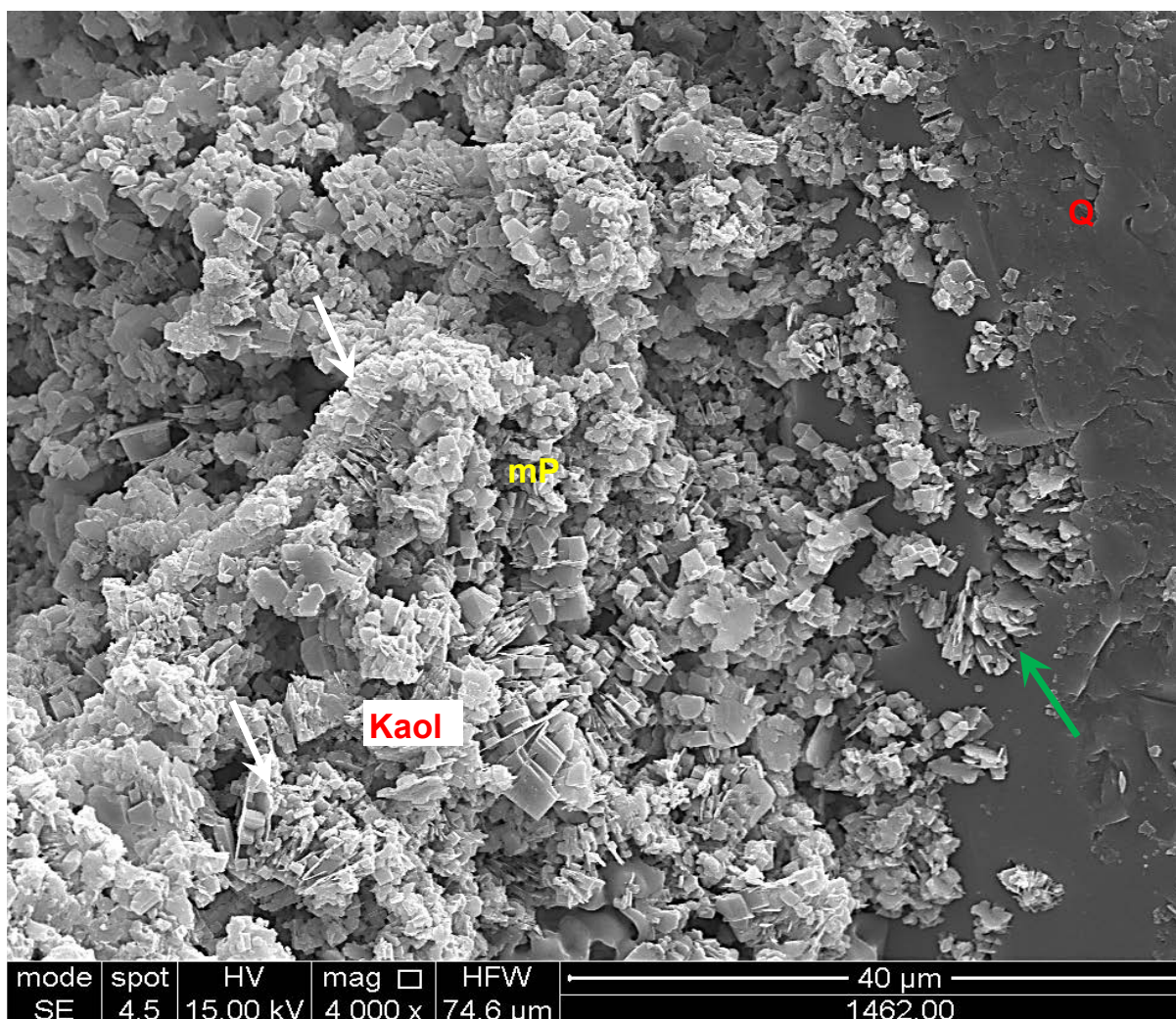


Figure 75: Scanning electron microscope photomicrograph showing kaolinite cement and abundant intercrystalline micropores in a Wonnerup Member sandstone sample from 1462.00m depth in DMP Harvey 3 (Nelis, 2015). Kaolinite cement (Kaol) features abundant intercrystal micropores (mP). Quartz grains are present (Q). Kaolinite engulfed by quartz overgrowths (green arrow) indicates the cements grew concurrently.

The Wonnerup Member sandstone from 1793.00m from DMP Harvey 4 contains more kaolin clay than the samples from the Yalgorup Member and basal Eneabba unit (Figure 76), which is highly microporous. It is suggested that the high permeability of the Wonnerup Member sample from 1793.00m depth (2230md) is attributed to the abundance of microporous intergranular kaolin (Nelis, 2015).

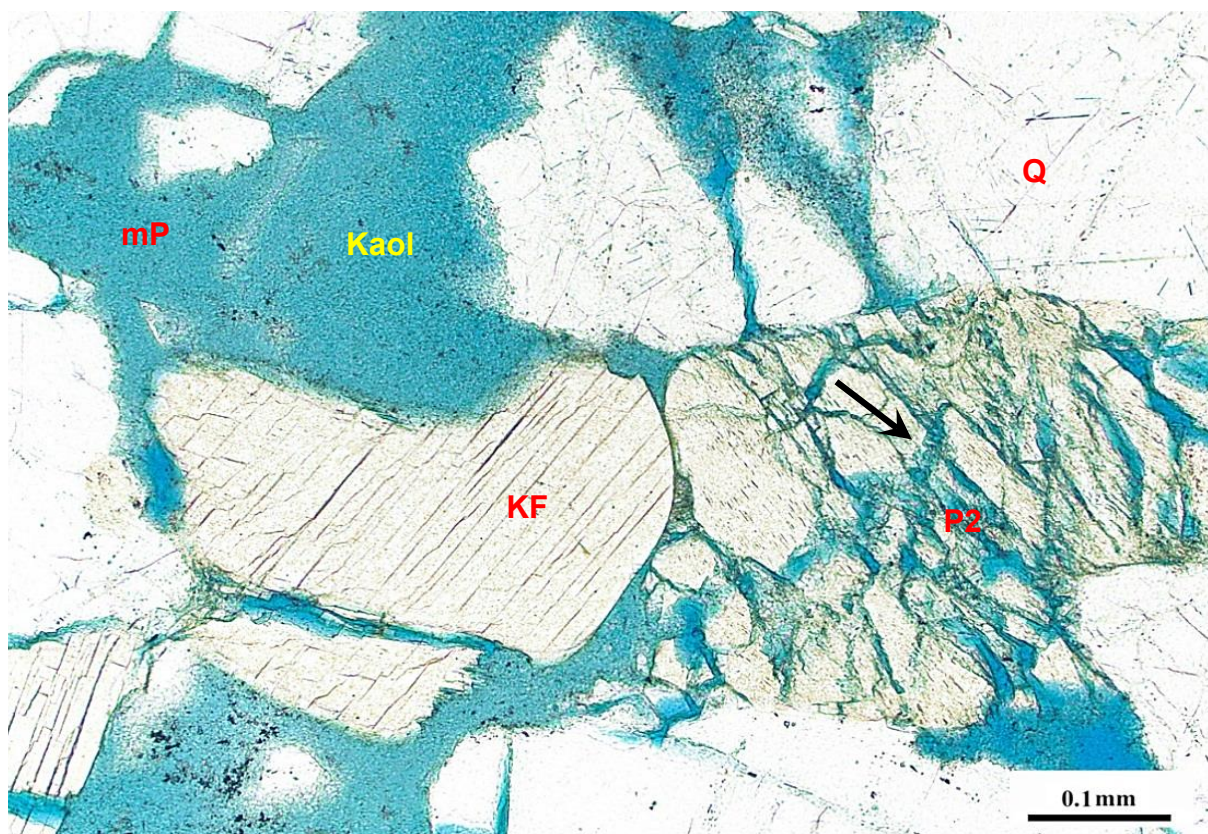


Figure 76: Photomicrograph of coarse quartz-arenite Wonnerup Member sandstone sample from 1793.00m depth in DMP Harvey 4. The blue areas are dominated by kaolinite (Nelis, 2015). This coarse-grained sandstone is composed of abundant quartz (Q) and lesser K-feldspar (KF; stained yellow) and plutonic lithic fragments. Moderate compaction is indicated by fractured K-feldspar grains (black arrows). Authigenic minerals include quartz overgrowths and kaolinite (Kaol). Pore types include intergranular pores, intragranular dissolution pores in K-feldspar (P2) and intercrystal micropores (mP) associated with authigenic kaolinite (blue haze is due to epoxy).

## DMP Harvey 4

### Eneabba Formation

The four samples analysed from the basal Eneabba unit comprised one sandy mudstone and three claystones. Of the three claystones, clay content ranges from 49.6 to 73.9 per cent with smectite-rich mixed-layer illite–smectite predominant. Circular clay structures (Figure 77) in the claystones suggest root zones within a vertisol (Nelis, 2015).

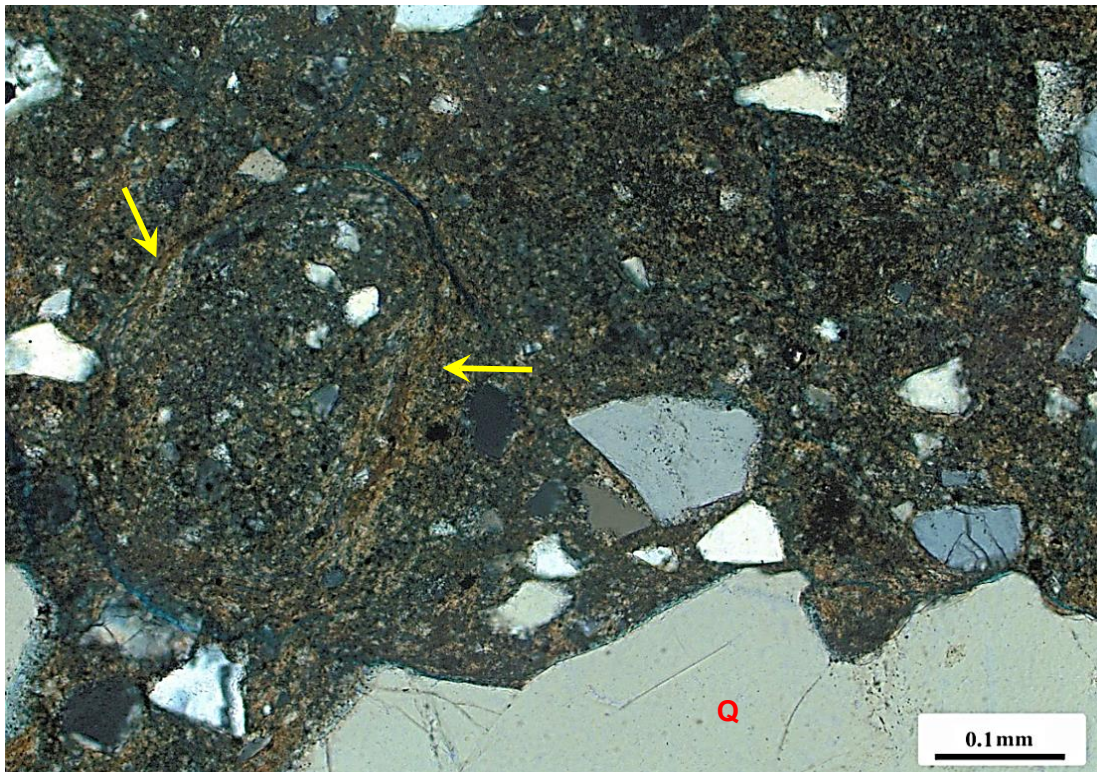


Figure 77: Photomicrograph of a sandy claystone from the basal Eneabba unit at 902.78m depth in DMP Harvey 4 (Nelis, 2015). Lithic fragments can be seen in a smectite–illite clay matrix. Quartz is the most common grain type (Q). The clay matrix exhibits circular domains of aligned clay (yellow arrows) that are interpreted to reflect a root zone.

### Yalgorup Member

The sandstones of the Yalgorup and Wonnerup Members are similar in texture and framework composition, but have different clay and pore types. The Yalgorup Member sandstone sample from 1326.25m has an illite–smectite matrix and minor intergranular pores.

### Summary

The inorganic petrography work has identified low-energy depositional sediments, dominated by mudstone-rich units with interbedded sandstones. The mudstones are poorly sorted, strongly weathered and exhibit paleosols. The clays in the paleosol units are illite–smectite dominant.

The sandstones are quartz dominant, but also contain common feldspar and lithic fragments and minor mica-group minerals. Alteration of feldspars (and lithic fragments) to kaolinite is also evident. During sample preparation, fractures formed in clay-rich samples. It is considered that the fractures in the swelling clays of the stratigraphy are sealed in brine-saturated strata in situ.

The sandstones of the Yalgorup and Wonnerup Members are similar in texture and framework composition and the differing clay compositions reflect different depositional environments. The clays within the Wonnerup Member are dominated by kaolinite.

The inorganic petrography analyses of the Wonnerup and Yalgorup Members of the Lesueur Sandstone and the Eneabba Formation has identified both allogenic and authigenic minerals, the latter of which are evidence of diagenesis. The quartz overgrowths and kaolinite clay limit the porosity of the samples analysed.

## Preliminary interpretation

The basal Eneabba unit comprises interbedded sandy mudstones and claystones, with the predominant clay types being smectite–illite (Figures 66 and 67). The Yalgorup Member has a higher sandstone content (Figure 71), with interbedded mudstones and claystones (Figure 73). This unit contains clay minerals of the kaolin group (kaolinite and dickite) and smectite group (smectite–illite). The smectite–illite abundance by weight is greater than that of kaolin in the upper sections of this unit, switching to kaolin being the dominant clay group in the lower sections of the Yalgorup Member.

The Wonnerup Member dominantly comprises quartz arenite with a clay content in the range of 7 to 27 per cent. The dominant clay type (by weight) in this unit is kaolin (Figures 65 and 74).

Nelis (2015) advises that the minerals plagioclase and pyroxene have the potential to react with CO<sub>2</sub> and brine (Olierook et al., 2014). Plagioclase is present in low percentages in some of the samples tested by CoreLab, most notably within the Yalgorup Member.

### 5.4.3.3 Special core analysis (SCAL)

All SCAL tests, with the exception of mercury injection analysis (MICP), were conducted at CoreLab's Advanced Technology Centre in Houston, USA. The SCAL sample schedule, laboratory procedures, analyses and plots for the flow studies; mercury injection analysis and geomechanical analysis are in Appendix D and are summarised below.

## Flow studies

The following SCAL flow studies were carried out:

- Steady-state, supercritical CO<sub>2</sub> – water relative permeability.
- Unsteady-state, supercritical CO<sub>2</sub> – water relative-permeability endpoints.
- Permeability to brine and threshold pressure to supercritical CO<sub>2</sub> at NOBP.

Each of these flow studies is discussed below.

### Steady-state supercritical CO<sub>2</sub> - water relative permeability

Residual CO<sub>2</sub> saturation is an important parameter used in dynamic modelling to simulate how any injected CO<sub>2</sub> will migrate through the reservoir. Samples from the Wonnerup Member, #20 (1429.00m) from DMP Harvey 3 and #7 (1797.00m) from DMP Harvey 4, were selected for 'steady-state, supercritical CO<sub>2</sub> – water relative-permeability' (K<sub>rel</sub>) tests. During the course of testing, sample #7 from DMP Harvey 4 failed due to fracturing. This sample was replaced with sample #10 from DMP Harvey 4. Unfortunately, steady-state could not be achieved in sample #10, attributed to the migration of fines between flow cycles. As such, steady-state supercritical CO<sub>2</sub> – water relative-permeability data are available for only one sample, sample #20 from DMP Harvey 3. Refer to Appendix D for CoreLab's laboratory procedures.

The steady-state supercritical CO<sub>2</sub> – water relative-permeability test was performed at 47.8°C temperature and at 1700psi net confining stress, while maintaining the supercritical point for CO<sub>2</sub> throughout testing. The sample was saturated with tagged simulated formation brine and specific permeability to brine was determined. Following that, CO<sub>2</sub> and brine were injected at several ratios, to increase the CO<sub>2</sub> saturation. Finally, CO<sub>2</sub> only was injected.

At initial conditions, the Wonnerup Member sample #20 from 1429.00m in DMP Harvey 3 gave a specific permeability to brine of 4.24md. The effective permeability to CO<sub>2</sub> at terminal conditions was 0.792md and the relative permeability to CO<sub>2</sub> was 18.7 per cent (relative to the specific permeability to brine). Brine recovery was 50.8 per cent of the brine in place.

The sample was then tested for water-displacing CO<sub>2</sub>. The effective permeability to CO<sub>2</sub> at the beginning of this test was 0.792md. The effective permeability to brine was 0.467md and the relative permeability to brine was 11.0 per cent (relative to the specific permeability to brine). The final CO<sub>2</sub> recovery was 47.9 per cent of the gas in place and the residual CO<sub>2</sub> saturation was 26.5 per cent of pore space.

### Unsteady-state supercritical CO<sub>2</sub> — water relative-permeability endpoints

Four samples were submitted for the gas–water and water–gas displacements as shown in Table 40. These samples had previously undergone RCA analysis.

Table 40: DMP Harvey 3 and 4: Wonnerup Member samples scheduled for unsteady-state supercritical CO<sub>2</sub> – water relative-permeability analysis (Singh, 2016)

Well	Sample number	Plug type	Depth (m)
DMP Harvey 3	11	Horizontal	1420.00
	135	Horizontal	1544.00
DMP Harvey 4	4	Horizontal	1793.00
	8	Horizontal	1799.00

The samples were tested for unsteady-state supercritical CO<sub>2</sub>-displacing-water relative permeability determinations (endpoints) at 1700psi net confining stress. Test temperatures of 48–56°C were selected to maintain the supercritical point for CO<sub>2</sub> and were estimated from the temperature versus depth plot for the four SW Hub wells (Figure 31). CoreLab's laboratory procedures are reported in Appendix D.

Synthetic formation brine was injected through brine-saturated Wonnerup Member samples and specific permeability to brine was measured at two injection rates. The CO<sub>2</sub> was then injected at a constant pressure, and effective permeability to gas was determined.

Following the gas injection, the water saturations ranged from 41.9 to 64.8 per cent of the pore space. The relative permeability to CO<sub>2</sub> ranged from 10.9 to 23.4 per cent (relative to the specific permeability to water). Water recoveries ranged from 35.2 to 58.1 per cent of the water in place.

At the conclusion of the CO<sub>2</sub> gas-displacing-water tests, unsteady-state water–gas relative permeability endpoint tests were performed on the same four samples. Brine was injected into the core sample, again at a net confining stress of 1700psi, and at the varied temperatures. The CO<sub>2</sub>-gas recoveries ranged from 13.8 to 69.0 per cent of the gas in place. The residual CO<sub>2</sub>-gas saturations ranged from 18.0 to 37.4 per cent of the gas in place (Appendix D).

### *Effective permeability to brine and supercritical CO<sub>2</sub> threshold capillary pressure*

Twelve preserved samples were selected for effective permeability to brine and threshold entry pressure to supercritical CO<sub>2</sub> as shown in Table 41.

Table 41: Preserved samples scheduled for effective permeability to brine and threshold capillary pressure analysis (Singh, 2016)

Well	Stratigraphic unit	Sample number	Plug type	Depth (m)
DMP Harvey 2	Yalgorup Member	PSSH-1	Horizontal	776.00
	Yalgorup Member	PSSH-2	Horizontal	1132.10
	Yalgorup Member	PSSV-1	Vertical	1132.20
DMP Harvey 3	Yalgorup Member	PSSH-8	Horizontal	743.88
	Yalgorup Member	PSSH-9	Horizontal	778.40
	Yalgorup Member	PSSH-3	Horizontal	1171.75
	Yalgorup Member	PSSH-4	Horizontal	1333.10
	Yalgorup Member	PSSV-2	Vertical	1377.80
	Yalgorup Member	PSSH-5	Horizontal	1378.00
	Yalgorup Member	PSSV-3	Vertical	1393.43
	Yalgorup Member	PSSH-6	Horizontal	1416.70
DMP Harvey 4	Basal Eneabba unit	PSSH-7	Horizontal	907.92

Horizontally and vertically cut core samples were selected to determine whether the orientation of the core impacts on the measurements. The vertically cut samples are assumed to have bedding planes perpendicular to the core's orientation.

Each sample was saturated with brine of 50,000mg/L. At ambient temperature and pressure the effective permeabilities to brine ranged from  $2.7 \times 10^{-6}$  to  $2.37 \times 10^{-5}$ md.

Confining pressure was elevated to 1250psi and temperature was elevated to 38°C (100°F). Carbon dioxide gas was then injected at one end of the cylindrical core sample, and the downstream end was monitored for effluent flow. Threshold entry pressure breakthrough of supercritical CO<sub>2</sub> for all of the twelve preserved samples was less than 1100psi. The threshold pressure testing was used to determine the injection pressure at which CO<sub>2</sub> started to form continuous flow channels through the pore system.

### **Mercury injection analysis**

Mercury injection capillary pressure (MICP) analysis can facilitate an understanding of the ability of low-permeability strata (termed 'baffles' in this study) to impede the through-flow of CO<sub>2</sub>. Determination of pore-throat sizes and their distribution, and measured injection entry pressures, can be used to determine an equivalent column height of CO<sub>2</sub> that the formation represented by a low permeability sample could withstand. Full details of the analytical procedures and the MICP testing results are in CoreLab's SCAL report in Appendix D.

### *Samples tested*

The depths of samples scheduled for testing were selected following a review of the wireline logging data in conjunction with the lithological logs for the three wells. Eighteen samples were prepared from plug off-cuts from low permeability lithologies from the Yalgorup Member and the basal Eneabba unit. The majority of the samples selected were mudstone rich and horizontally orientated (Table 42: Samples tested for mercury injection analysis and results (Singh, 2016)). Plugs labelled with prefix PSSH and PSSV are fresh-state samples drilled from preserved core. The remainder are samples from the Wonnerup Member.

To determine the impact of bedding plane orientation on the formations' abilities to withstand, or impede, the through-flow of CO<sub>2</sub>, horizontally and vertically cut core samples from similar depths within the Yalgorup Member were scheduled for MICP analysis (Table 42). These samples were in wells DMP Harvey 2 (PSSH 2 and PSSV1) and DMP Harvey 3 (PSSV2 and PSSH5).

Table 42: Samples tested for mercury injection analysis and results (Singh, 2016)

Well	Stratigraphic unit	Sample number	Sample orientation	Depth (m)	Porosity (%)	Injection entry pressure (psia)	Mean hydraulic radius (µm)
DMP Harvey 2	Yalgorup Member	PSSH1	Horizontal	776.00	0.154	249.8	0.087
	Yalgorup Member	PSSH2	Horizontal	1132.10	0.130	28.2	0.412
	Yalgorup Member	PSSV1	Vertical	1132.20	0.127	52.9	0.360
DMP Harvey 3	Yalgorup Member	PSSH8	Horizontal	743.88	0.146	539.5	0.030
	Yalgorup Member	PSSH9	Horizontal	778.40	0.154	3259.5	0.006
	Yalgorup Member	PSSH3	Horizontal	1171.75	0.106	1026.4	0.020
	Yalgorup Member	PSSH4	Horizontal	1333.10	0.109	35.1	0.425
	Yalgorup Member	PSSV2	Vertical	1377.80	0.106	52.8	0.280
	Yalgorup Member	PSSH5	Horizontal	1378.00	0.106	218.7	0.141
	Yalgorup Member	PSSV3	Vertical	1393.42	0.108	793.2	0.018
	Yalgorup Member	PSSH6	Horizontal	1416.70	0.070	248.6	0.057
	Wonnerup Member	11	Horizontal	1420.00	0.211	14.8	1.754
	Wonnerup Member	20	Horizontal	1429.00	0.224	5.3	4.488
DMP Harvey 4	Basal Eneabba unit	PSSH7	Horizontal	907.92	0.151	8.9	2.534
	Wonnerup Member	4	Horizontal	1793.00	0.196	1.5	16.315
	Wonnerup Member	7	Horizontal	1797.00	0.187	1.5	16.728
	Wonnerup Member	8	Horizontal	1799.00	0.149	13.0	1.415

### *Mercury injection entry pressure*

Mercury injection entry pressure is when mercury injection first occurs (it is not threshold capillary pressure). Mercury injection entry pressure measurements were determined as shown in Table 42, recorded as pounds per square inch, absolute, (psia). The mean pore throat radius was recorded in microns (µm).

The data in Table 42 show that the mercury injection entry pressures ranged from 8.9 to 3259.5psia for the preserved samples taken from the Yalgorup Member and basal Eneabba unit. The six samples selected from the Wonnerup Member gave lower entry pressures, ranging from 1.51 to 14.8psia.

### Pore-throat distribution

In reporting the pore-throat distribution for each sample, CoreLab used the pore radii classification shown in Table 43 and the pore-throat radii semi-log<sub>10</sub> plots (Figures 78 to 80).

Table 43: Pore-radii classification table used by CoreLab

Classification number	Pore-radius classification	Pore radius (μm)	
		Minimum	Maximum
1	Micro	<0.50	0.50
2	Micro	0.50	2.5
3	Micro	2.5	>10

Figures 78 to 79 show the pore-throat radii distributions for the two samples cut from a similar depth from GSWA Harvey 2 within the Yalgorup Member – one horizontal (Figure 78) and the other vertical (Figure 79). The majority of pore throats are in the micropore radii range (0.001 to 0.5μm). However, the vertically cut sample has an accentuated bimodal pore-throat radii in the mesopore range (0.1 to 1.0μm) than that exhibited by the horizontally cut sample (Figure 78). This suggests that the horizontally cut sample would have a greater impedance to CO<sub>2</sub> through-flow than the vertically cut sample. This argument is supported in the calculated equivalent columns of supercritical CO<sub>2</sub> data (Table 44), where the horizontal sample has been computed to retain a larger supercritical CO<sub>2</sub> column length (17.5m) than for the vertical sample (15.4m).

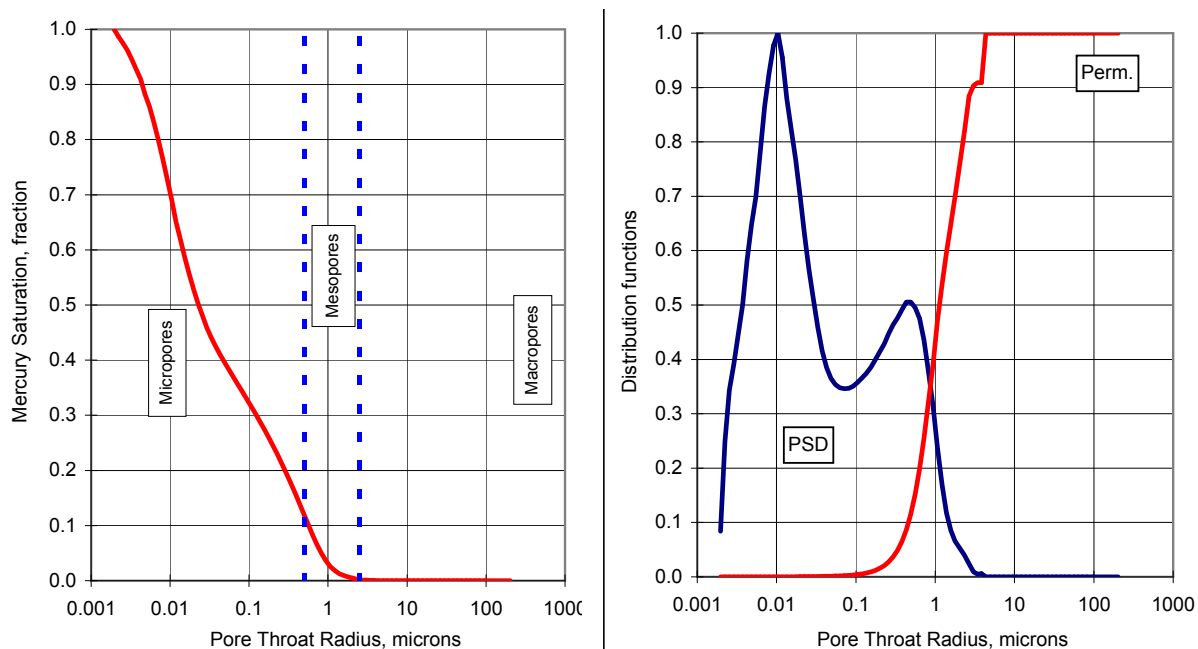


Figure 78: DMP Harvey 2: pore-throat radii distribution figures for preserved, horizontally cut Yalgorup Member sample PSSH2, from 1132.10m depth. Injection sample porosity was 13.0 per cent (Singh, 2016).

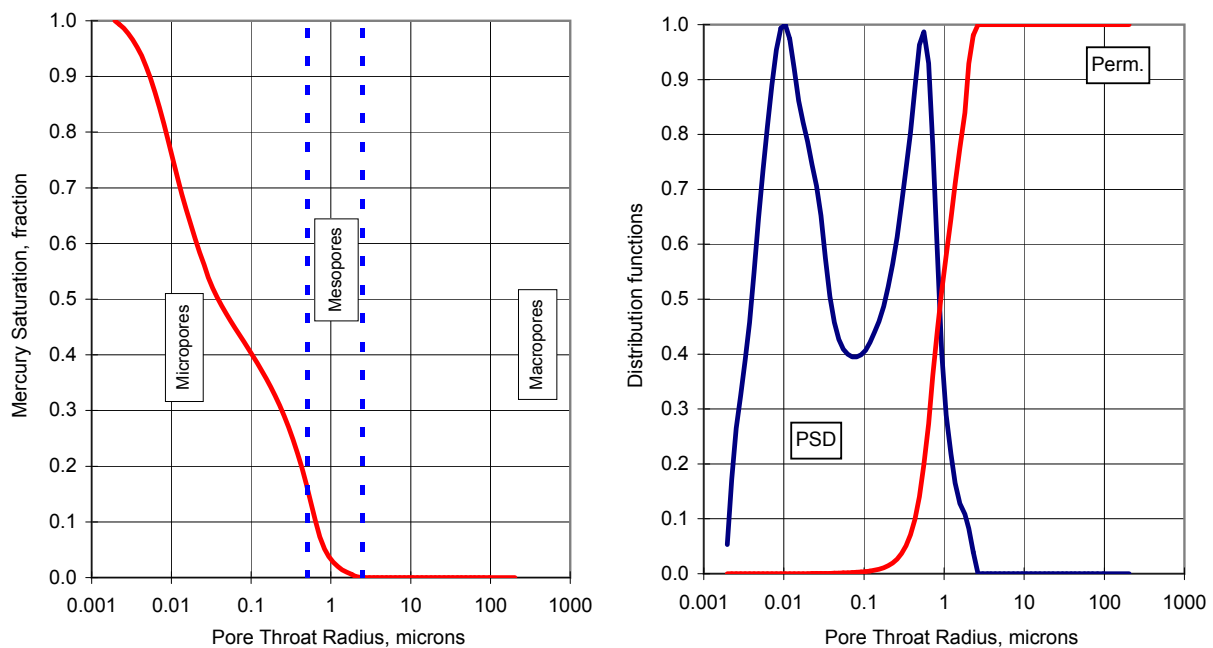


Figure 79: DMP Harvey 2: pore-throat radii distribution figures for preserved, vertically cut Yalgorup sample PSSV1 from 1132.20m depth. Injection sample porosity was 12.7 per cent (Singh, 2016).

Figure 80 shows the pore-throat radii plots for a Wonnerup Member sample (#135) from 1544m depth in the DMP Harvey 3 well, and that micropores, mesopores and macropores are present (image on the left). The pore-size distribution plot (image on the right) shows that the Wonnerup Member sample from DMP Harvey 3 has a high distribution of pore throat radii in the 10 to 100 $\mu$ m range. The pore-throat size and distribution for the Wonnerup sample differs significantly from the pore-throat size and distribution for the Yalgorup samples PSSH2 and PSSV1 in Figures 78 and 79. Increased pore-throat size and distribution are likely to result in increased permeability. This theory is supported by the mercury injection entry pressure analyses data given in Table 42, where the mercury injection entry pressures are lower for the Wonnerup Member samples than for the paleosol samples from the Yalgorup Member.

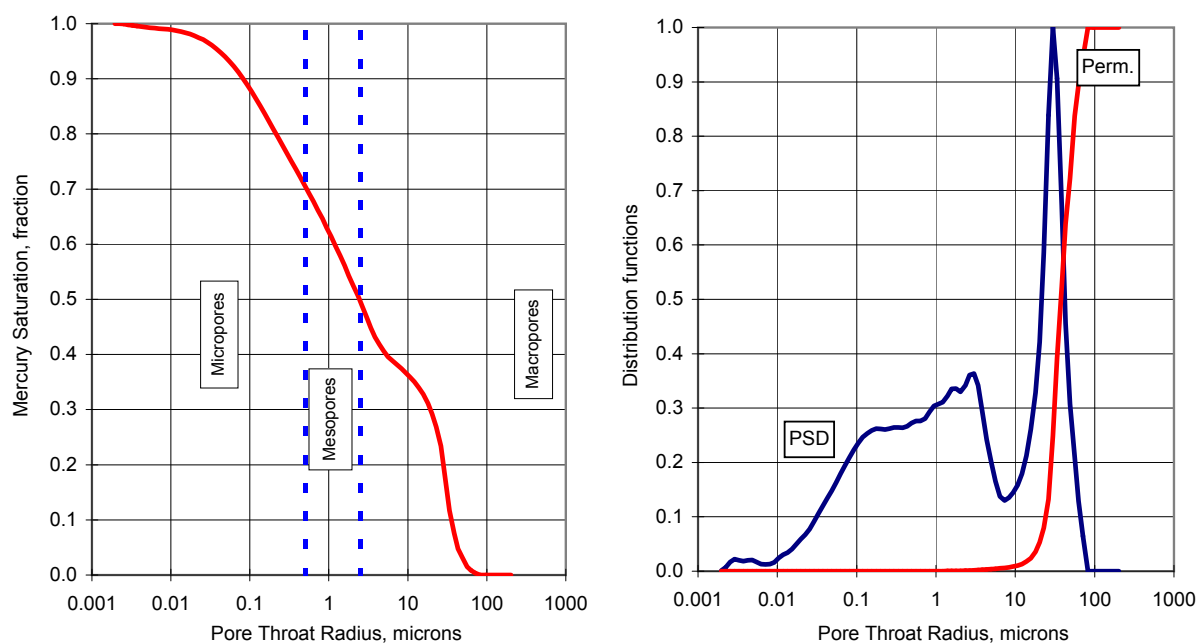


Figure 80: DMP Harvey 3: pore-throat radii distribution figures for Wonnerup Member sample #135, from 1544.00m depth. Injection sample porosity was 16.8 per cent (Singh, 2016).

### Mean hydraulic radius

The measured mean hydraulic radii for the 18 samples tested from wells DMP Harvey 2, 3 and 4 are shown in Table 42. Figure 81 shows an inverse linear relationship between the  $\log_{10}$  of mercury injection entry pressure and  $\log_{10}$  mean hydraulic radius for the samples tested.

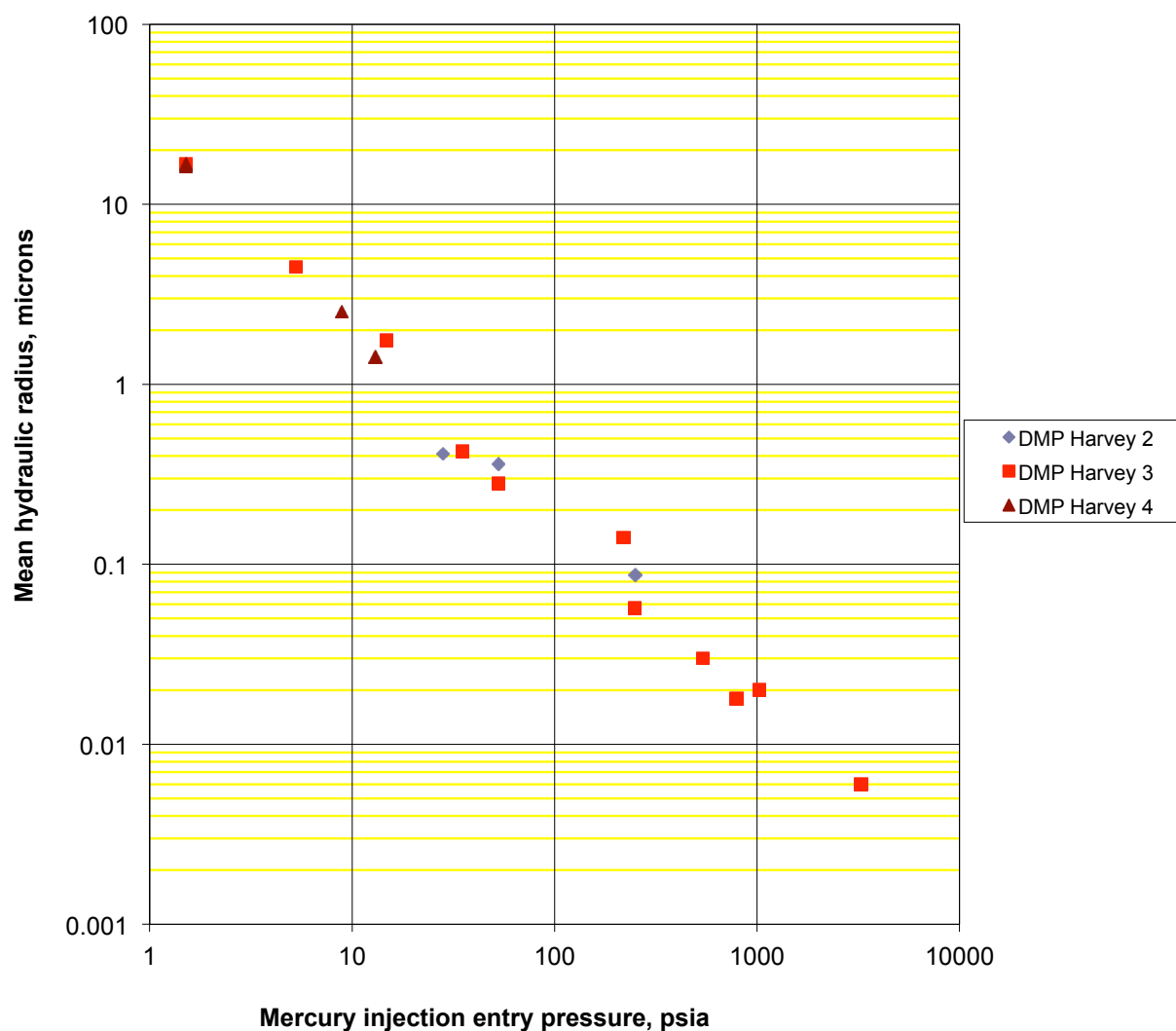


Figure 81: Mercury injection entry pressure plotted against mean hydraulic radius.

### Mercury threshold (breakthrough) pressure

Laboratory-measured mercury threshold (breakthrough) pressures are shown in Table 44.

### Equivalent column height of CO<sub>2</sub>

Equivalent column height of CO<sub>2</sub> data (Table 44) were calculated using the parameters advised by DMIRS, shown in Table 45.

Table 44:Mercury injection capillary pressure test results: entry pressure and threshold or breakthrough pressure, with equivalent column heights of CO<sub>2</sub> (Singh, 2016)

Well	Stratigraphic unit	Sample number	Depth (m)	Mercury injection capillary pressure			Column height of supercritical CO <sub>2</sub> (m)	
				Entry Pressure (psia)	Threshold or breakthrough pressure		7.5% PV Hg	10% PV Hg
					7.5% PV Hg (psia)	10% PV Hg (psia)		
DMP Harvey 2	Yalgorup Member	PSSH-1	776.00	249.8	613	773	56.4	71.1
	Yalgorup Member	PSSH-2	1132.10	28.0	160	190	14.7	17.5
	Yalgorup Member	PSSV-1	1132.20	53.0	150	167	13.8	15.4
DMP Harvey 3	Yalgorup Member	PSSH-8	743.88	540.0	1932	2407	177.8	221.5
	Yalgorup Member	PSSH-9	778.40	3259.5	6220	6883	572.4	633.4
	Yalgorup Member	PSSH-3	1171.75	1026.4	2149	2445	197.8	225.0
	Yalgorup Member	PSSH-4	1333.10	35.1	437	539	40.2	49.6
	Yalgorup Member	PSSV-2	1377.80	52.8	292	347	26.9	31.9
	Yalgorup Member	PSSH-5	1378.00	218.7	307	354	28.3	32.6
	Yalgorup Member	PSSV-3	1393.42	793.2	3452	4311	317.7	396.7
	Yalgorup Member	PSSH-6	1416.70	249.0	4575	6255	421.0	575.6
DMP Harvey 4	Basal Eneabba unit	PSSH-7	907.92	8.9	30	39	2.8	3.6

Table 45: Assumptions and equations used to calculate equivalent height of CO<sub>2</sub> columns impeded by strata tested for mercury injection capillary pressure (MICP) analysis (Singh, 2016)

Assumptions for column height calculations		
IFT CO <sub>2</sub> /water, dynes/cm	25	Based on Shojai Kaveh et al. (2013)
Contact angle CO <sub>2</sub> /water, degrees	40	Based on Shojai Kaveh et al. (2013)
Cosine contact angle, CO <sub>2</sub> /water	0.766	Need cosine of angle for height calculations
IFT Air/Hg, dynes/cm	480	
Contact angle Air/Hg, degrees	40	140 degrees through Hg: 180–140 through ‘wetting phase’
Cosine contact angle, Air/Hg	0.766	
Supercritical CO <sub>2</sub> gradient, psi/m	0.895	Based on density 0.6293g/cm <sup>3</sup>
Brine gradient, psi/m	1.461	Based on 50,000ppm formation brine, density 1.029g/cm <sup>3</sup>
Equations to calculate column height		
Pth CO <sub>2</sub> /water =	Pth Air/ Hg*	IFT*Cos CA CO <sub>2</sub> /Water
		IFT*Cos CA Air/Hg
Column Height, m =	Threshold Pressure, CO <sub>2</sub> /water	
	Brine gradient, psi/m -	CO <sub>2</sub> gradient, #psi/m

The data show that, for the samples tested, the entry pressures vary from 9 to 3260psia and the threshold or breakthrough pressures range from 30 to 6220psia, for 7.5 per cent PV Hg and 39 to 6883psia for 10 per cent PV Hg. The equivalent column heights for supercritical CO<sub>2</sub> range from 3.6 to 633.4m.

The differences between horizontally and vertical samples cut at similar depths (ie. PSSH-2 and PSSV-1, and PSSV-2 and PSSH-5) are minimal. For those samples tested (Table 42), the orientation of the core with respect to bedding plane, which is assumed to be perpendicular to the core orientation, does not appear to have influenced the entry pressure, threshold (breakthrough) pressure, or the equivalent column height of supercritical CO<sub>2</sub>.

### ***MICP analysis: data limitations***

The limitations to MICP analysis are recognised when the analytical data are used in the simulation of reservoir conditions. There are several drawbacks of the MICP technique:

- The small sample size may not properly represent a more heterogeneous baffle.
- The mercury injection entry pressure is not the same as the mercury injection threshold pressure. Critical saturation has to be assumed or deduced before the associated mercury injection threshold pressure can be derived.
- The samples tested are dry. Lack of clay-bound water can influence the data.
- Tests are not run at net overburden pressure (NOBP).

For the above reasons the computed CO<sub>2</sub> column heights are considered to be pessimistic values. If the samples were saturated with brine and the clays were allowed to swell, it is considered that the equivalent CO<sub>2</sub> column heights would have been greater than those reported in Table 44 (Singh, 2016).

### *Preliminary interpretation*

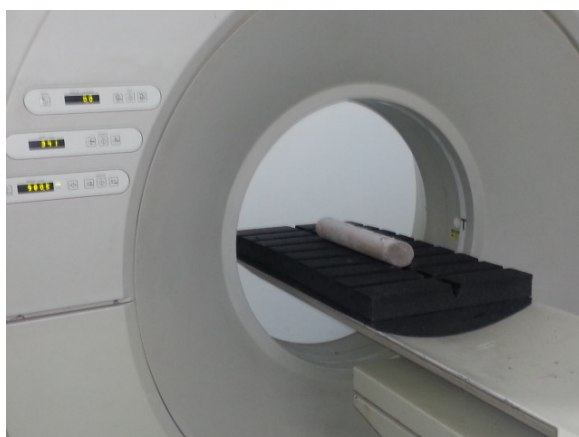
The measurements of pore-throat size and distribution have an impact on the ability of a low-permeability facies (baffles) to withstand or impede the through-flow of CO<sub>2</sub>. The computed CO<sub>2</sub> column heights for shale-rich samples from the Yalgorup Member and basal Eneabba unit indicate that these units can withstand the flow of CO<sub>2</sub> if they are contiguous.

### **Geomechanical analysis**

Data from geomechanical analysis have been used in conceptual rock mechanics models to predict how the strata at depth may respond to changes in stresses within the reservoir. Wonnerup Member samples from well DMP Harvey 3 have undergone triaxial and acoustic velocity testing, and Mohr-Coulomb failure analysis, as discussed below. Full details of the analytical procedures and the geomechanical test results are in CoreLab's SCAL report in Appendix D.

### *Samples tested*

Nine selected core lengths were scanned using computed tomography (CT) in CoreLab's laboratories (Figure 82) in Kewdale, WA, in order to check for microfractures before being packaged and sent to CoreLab's Houston geomechanics testing facility. The samples are described in Table 46.



*Figure 82: Computed tomography (CT) scanning of core from the Wonnerup Member in DMP Harvey 3 at CoreLab's Kewdale premises, to check for microfractures prior to transport to the Houston laboratory for geomechanical testing.*

Table 46: DMP Harvey 3: Wonnerup Member samples submitted for geomechanical analysis

Sample number	Depth (m)
1VA	1420.65
1VB	1420.65
1VC	1420.65
2VA	1471.45
2VB	1471.63
2VC	1471.73
3VA	1511.71
3VB	1511.79
3VC	1511.86

*NOTE: All samples are vertical plugs.*

### ***Triaxial testing***

In the triaxial test, the samples' circumference and length were measured as a function of applied stress. The triaxial compressive strength tests are used to simulate in situ reservoir stress conditions and provide compressive strength and static values of elastic constants, these being Young's modulus and Poisson's ratio. Young's modulus is the slope of a line when axial stress is plotted against axial strain. Poisson's ratio is defined by the ratio of lateral expansion to vertical contraction. Poisson's ratio is a critical parameter in determining formation stress and influences fracture height and width. Triaxial testing on samples from the Wonnerup Member in DMP Harvey 3 resulted in the Young's modulus and Poisson's ratios shown in Table 47. The core plugs given in Table 47 were photographed before and after testing. The photographs are in CoreLab's SCAL report in Appendix D.

Table 47: DMP Harvey 3: Young's modulus and Poisson's ratio data for Wonnerup Member samples

Sample number	Depth (m)	Confining pressure(psi)	Compressive strength (psi)	Young's modulus (x10 <sup>6</sup> psi)	Poisson's ratio
1VA	1420.65	435	4224	1.915	0.264
1VB	1420.65	725	5176	2.574	0.257
1VC	1420.65	1160	7717	2.814	0.242
2VA	1471.45	435	4058	2.633	0.190
2VB	1471.63	725	5210	2.841	0.187
2VC	1471.73	1160	6976	3.035	0.095
3VA	1511.71	435	4623	1.934	0.179
3VB	1511.79	725	5525	1.975	0.183
3VC	1511.86	1160	8222	2.870	0.175

### ***Acoustic velocity***

Acoustic velocity measurements were performed on samples (1VA, 2VA and 3VA) at the same confining stresses as listed in Table 47, and at varied axial pressures. The acoustic velocities ranged from 10,303 to 11,813ft/sec for the compressional waves and from 5810 to 7268ft/sec for the shear waves. The corresponding dynamic Young's modulus ranged from 2.40 x 10<sup>6</sup>psi to 3.54 x 10<sup>6</sup>psi and the Poisson's ratio ranged from 0.18 to 0.31.

### ***Mohr-Coulomb failure analysis***

Using the results of the triaxial compressive tests, the compressive strengths ( $\sigma_1$ ) were plotted against confining pressure, Mohr semicircles were constructed, and a Mohr-Coulomb failure envelope was fit to the Mohr semicircles. The unconfined compressive strength, angle of internal friction, coefficient of internal friction and formation cohesion strength (inherent shear strength) were determined. The results of the Mohr-Coulomb analysis are summarized in Table 48.

Table 48: DMP Harvey 3: Mohr-Coulomb analysis for Wonnerup Member samples

Depth (m)	Unconfined compressive strength (psi)	Cohesion (psi)	Angle of internal friction (°)	Coefficient of internal friction
1420.65	1917	433	41.37	0.88
1471.45–1471.63	2300	573	37.03	0.75
1511.71–1511.86	2209	491	42.07	0.90

### *Preliminary interpretation*

The geomechanical or rock strength analysis indicates that the Wonnerup Member is very competent at reservoir conditions, depth and pressure, and that any CO<sub>2</sub> injection is unlikely to damage or fracture the formation.

## **5.4.4 Analysis to determine age and stratigraphic sequencing**

Cores from wells DMP Harvey 2, 3 and 4 were sampled by GSWA staff for palynology, and organic petrography studies in order to understand the age and stratigraphic sequencing of the geological units. Samples were selected for analysis using the on-site geologists' detailed lithological logs (Appendix C) and visual inspection of the core at the Perth Core Library.

### **5.4.4.1 Palynology**

Palynological studies were attempted on all three Harvey wells as an aid to formation picking and stratigraphic interpretation, with specific attention paid to the stratigraphic succession<sup>14</sup>. Twenty-two samples from DMP Harvey 2 and 14 samples from DMP Harvey 3 were submitted for palynological analysis. The full report is in Appendix N.

### **DMP Harvey 2**

The palynological analysis was carried out by Backhouse Biostrat Pty Ltd. The results of the palynological analysis are summarised in Table 49.

<sup>14</sup> The stratigraphy of the southern Perth Basin, including the usage of nomenclature originally defined in the northern Perth Basin, is currently under review by GSWA. The formation names used in the SW Hub studies are those in current use and the formation tops are as interpreted by Byrne (2016), with these subject to change following the GSWA review.

Table 49: DMP Harvey 2: summary of palynology results

Period	Interpreted stratigraphy (Byrne, 2016)	Depth	Sample type	Yield	Preservation	Spore-pollen zone	Environment	Thermal- alteration index	Age	Comments
Jurassic	Eneabba Formation	213.90	Core	Moderate	Good	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
		219.30	Core	High	Good	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
		248.95	Core	Low	Good	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
		283.10	Core	Extremely low	Good	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
		344.75	Core	Barren	–	<i>Indeterminate</i>	–	–	–	–
		377.00	Core	High	Good	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
	Basal Eneabba unit	450.90	Core	Extremely low	Fair	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
	Yalgorup Member	552.20	Core	High	Fair	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	–
		610.95	Core	Low	Fair	<i>Corollina torosa</i>	Non-marine	2	Hettangian – early Toarcian	<i>First-appearance datum abundant Corollina</i>
		644.9	Core	Barren	–	<i>Indeterminate</i>	–	–	–	–
Triassic – Jurassic		686.9	Core	Barren	–	<i>Indeterminate</i>	–	–	–	–
Triassic	Yalgorup Member	732.50	Core	Low	Good	<i>?Ashmoripollis reducta</i>	Non-marine	2 to 2+	?Rhaetian	Last-appearance datum abundant <i>F. australis</i> type pollen
		793.10	Core	Moderate	Good	<i>?Ashmoripollis reducta</i>	Non-marine	2 to 2+	?Rhaetian	<i>Several A. reducta</i>
		821.20	Core	–	–	Sample contaminated	–	2 to 2+	–	Resampled at 821.25m due to contamination
		821.25	Core	Extremely low	Fair	?Late Triassic indeterminate	Non-marine	2 to 2+	?Triassic	Abnormal assemblage
		908.25	Core	–	–	Sample contaminated	–	2 to 2+	–	Resampled at 908.26m due to contamination
		908.26	Core	Low	Fair	?Late Triassic indeterminate	Non-marine	2 to 2+	?Triassic	Abnormal assemblage
		1006.95	Core	Barren	–	<i>Indeterminate</i>	–	–	–	–
		1111.90	Core	Moderate	Fair	<i>?lower Samarapollenites speciosus – Staurosaccites quadrifidus</i>	Non-marine	2 to 2+	Ladinian– Carnian	<i>S. quadrifidus present</i>
	Wonnerup Member	1242.50	Core	Low	Fair	<i>?lower Samarapollenites speciosus – Staurosaccites quadrifidus</i>	Non-marine	2 to 2+	Ladinian– Carnian	–
		1315.70	Core	Extremely low	Fair	<i>?lower Samarapollenites speciosus – Staurosaccites quadrifidus</i>	Non-marine	2 to 2+	Ladinian– Carnian	Minor contamination
		1348.25	Core	Low	Fair	<i>?lower Samarapollenites speciosus – Staurosaccites quadrifidus</i>	Non-marine	2 to 2+	Ladinian– Carnian	–

As shown in Table 49, 20 samples from DMP Harvey 2 were initially sent for palynological processing and analysis, of which four were barren of palynomorphs. Two of the samples (at 821.20 and 908.25m) were found to be contaminated by drilling mud, and were subsequently resampled, with the new samples analysed by the same processes.

The results indicate that the palynological assemblages in DMP Harvey 2 can be divided into four main groups: *Corollina torosa* Zone (Hettangian to early Toarcian) assemblages from 213.90 to 610.95m, possible *Ashmoripollis reducta* (Rhaetian) Zone assemblages from 732.50 to 793.1m, indeterminate Triassic assemblages from 821.25 to 908.26m, and assemblages assignable to either lower *Samaropollenites speciosus* or *Staurosaccites quadrifidus* zones (Ladinian–Carnian) in the interval 111.90 – 1348.25m. All of these assemblages are non-marine.

Using the formation tops interpreted for this well (Byrne, 2016) the Eneabba Formation contains assemblages of the *C. torosa* Zone and is Early Jurassic in age, whereas the interval defined as the Yalgorup Member appears to be to Middle Triassic to Early Jurassic in age, as it contains assemblages of the *C. torosa* and likely *A. reducta*, and lower *S. speciosus* or *S. quadrifidus* Zones. The Wonnerup Member section seen in this well only contains assemblages of either the lower *S. speciosus* or *S. quadrifidus* Zones, and is Middle to Late Triassic in age (Table 49 and Figure 83).

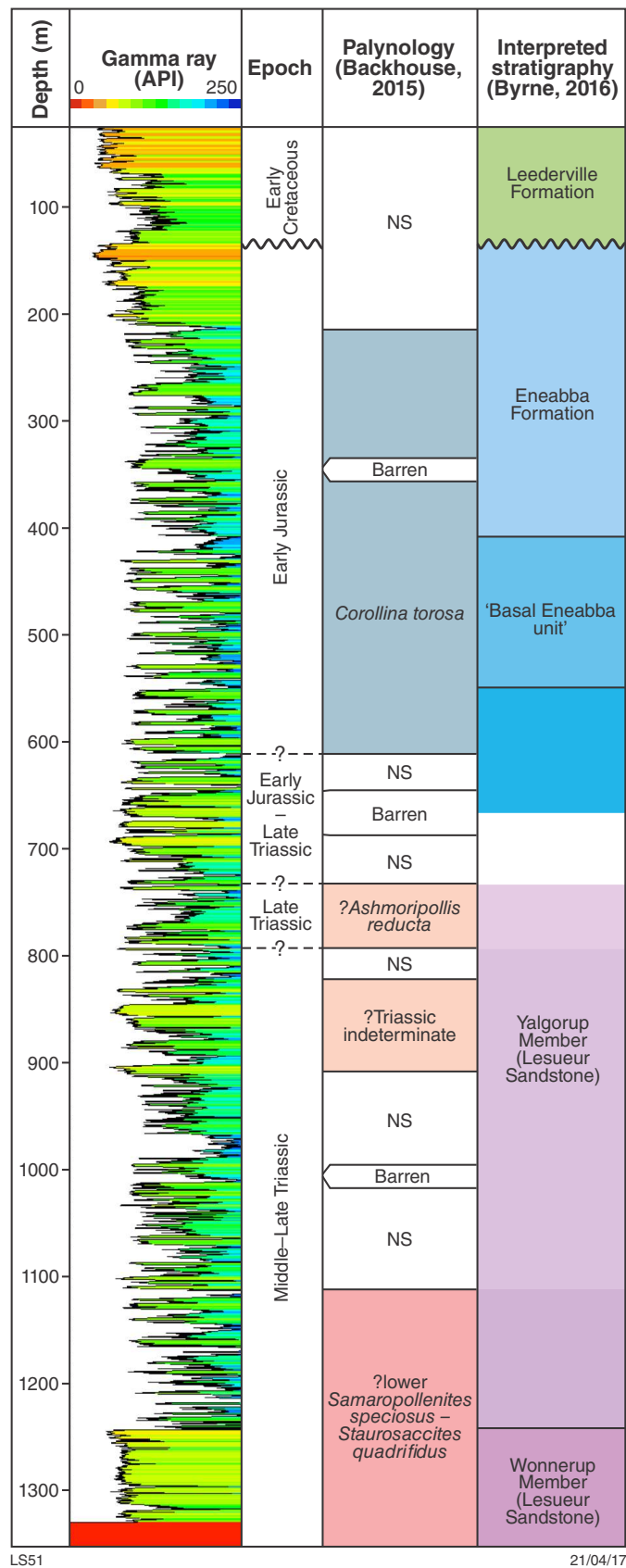


Figure 83: DMP Harvey 2: palynological results (Backhouse, 2015; Appendix N) and interpreted formation tops and marker horizons. Horizons not sampled are labelled (NS).

### DMP Harvey 3

Although some of the 14 samples preserved rare palynomorphs, they were considered to be laboratory contaminants, and all samples proved to be barren of in situ palynomorphs. In order to confirm that this absence was not a result of processing issues, two of the samples were reprocessed by a different laboratory, with both samples again proving barren of palynomorphs.

### DMP Harvey 4

The core from DMP Harvey 4 is dominantly sand-rich facies containing fine-grained sand, with strong red, purple and mottled colouring indicative of oxidised sediments. Due to the oxidation of these sediments, this core is considered to contain no lithologies suitable for palynological analysis.

#### 5.4.4.2 Organic petrography

Energy Resources Consulting (ERC) Pty Ltd was contracted by GSWA to conduct organic petrography analysis to provide thermal maturity data for samples from wells DMP Harvey 2 and 3. The detailed reports are in Appendix O.

### Sample selection and analysis

Source-rock organic matter reflectance and typing analysis were conducted on six core samples from DMP Harvey 2 and on six core samples from DMP Harvey 3. Suitable organic material was not observed in the limited core available from DMP Harvey 4, as the sand-dominant units had little or no organic matter and any fine-grained units were oxidised. Therefore, no samples from DMP Harvey 4 were scheduled for organic petrography.

Sample preparation is detailed in ERC's two reports (Appendix O). Reflectance was determined for a  $2\mu\text{m}^2$  area of mounted and polished sample, at 546nm, using a magnification of 500x. The samples were examined in reflected white light and blue-light fluorescence using a royal-blue light-emitting diode (LED) as the excitation source.

### Results and discussion

The vitrinite reflectance data and images are available in Appendix O. The vitrinite reflectance data are summarised in Table 50. Figure 84 shows the mean reflectance ( $R_v\text{max}$ ) data for the samples from DMP Harvey 2 and 3 plotted against depth. These results are discussed below.

Table 50: DMP Harvey 2 and 3: mean-reflectance analyses for discrete-depth samples

Well	Depth (m)	Mean reflectance ( $R_v\text{max}$ )
DMP Harvey 2	322.10	0.28
	793.10	0.46
	1260.60	0.34
	1262.05	0.34
	1312.20	0.35
	1337.10	0.34
DMP Harvey 3	789.60	0.29
	841.10	0.21
	967.90	0.34
	1193.10	0.36
	1434.10	0.34
	1540.15	0.49

NOTE: Data from ER Consulting Pty Ltd.

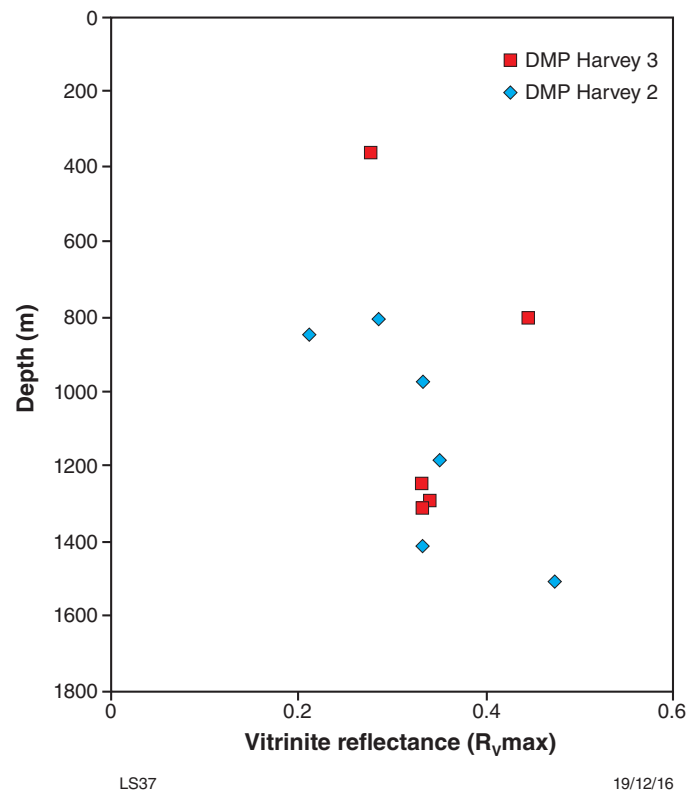


Figure 84: DMP Harvey 2 and 3: mean vitrinite reflectance ( $R_{vmax}$ ) data plotted against depth.

### DMP Harvey 2

Coal fragments, commonly weathered or altered, were reported in all samples analysed from DMP Harvey 2. In the core sample from 1337.1m depth, some coal grains were oxidised and organic matter in the coal had been replaced by pyrite, as shown in Figure 85.

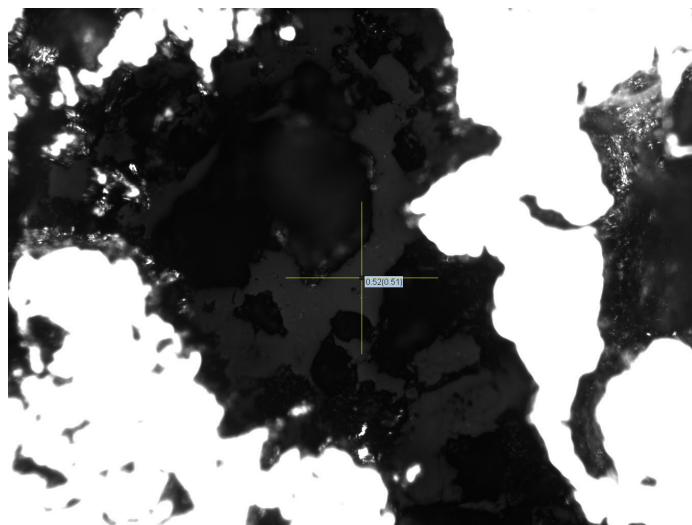


Figure 85: Image of core sample from 1337.1m depth from DMP Harvey 2. Coal comprises about 80 per cent of the sample and consists exclusively of vitrinite. Pyrite has replaced organic matter in coal, presenting as reflected white light (magnification 50x).

### **DMP Harvey 3**

All samples selected for analysis contained coal, which were at different stages of weathering. Unaltered cellulose was detected in a coal sample from 841.66m depth (Figure 86).



Figure 86: Mounted sample from 841.66m depth in DMP Harvey 3 in reflected white light (magnification 50x), showing telinite with unaltered cellulose.

### **Summary**

Each of the 12 samples analysed contained coal fragments at differing stages of weathering and alteration, as evident by one or more features such as desiccation cracks, fracturing, oxidation or pyrite replacement of coal grains. The mean reflectance data (mean  $R_v$  max) for the processed samples, which were from the Yalgorup and Wonnerup Members in wells DMP Harvey 2 and 3, indicate that the samples are thermally immature (0.21–0.49 per cent).

#### **5.4.4.3 Total organic carbon**

Geologists from GSWA selected suitable samples from DMP Harvey 2 for total organic carbon (TOC) analysis, including several containing coal fragments. Wells DMP Harvey 3 and 4 were not sampled for TOC evaluation. Intertek-Geotech Services Pty Ltd was contracted to carry out this work. The full report is in Appendix O.

### **Sample selection**

Fifty-four core samples were selected from DMP Harvey 2 for TOC analysis, with these being from the Eneabba Formation and Yalgorup Member. Figure 87 shows the TOC values with sample depth.

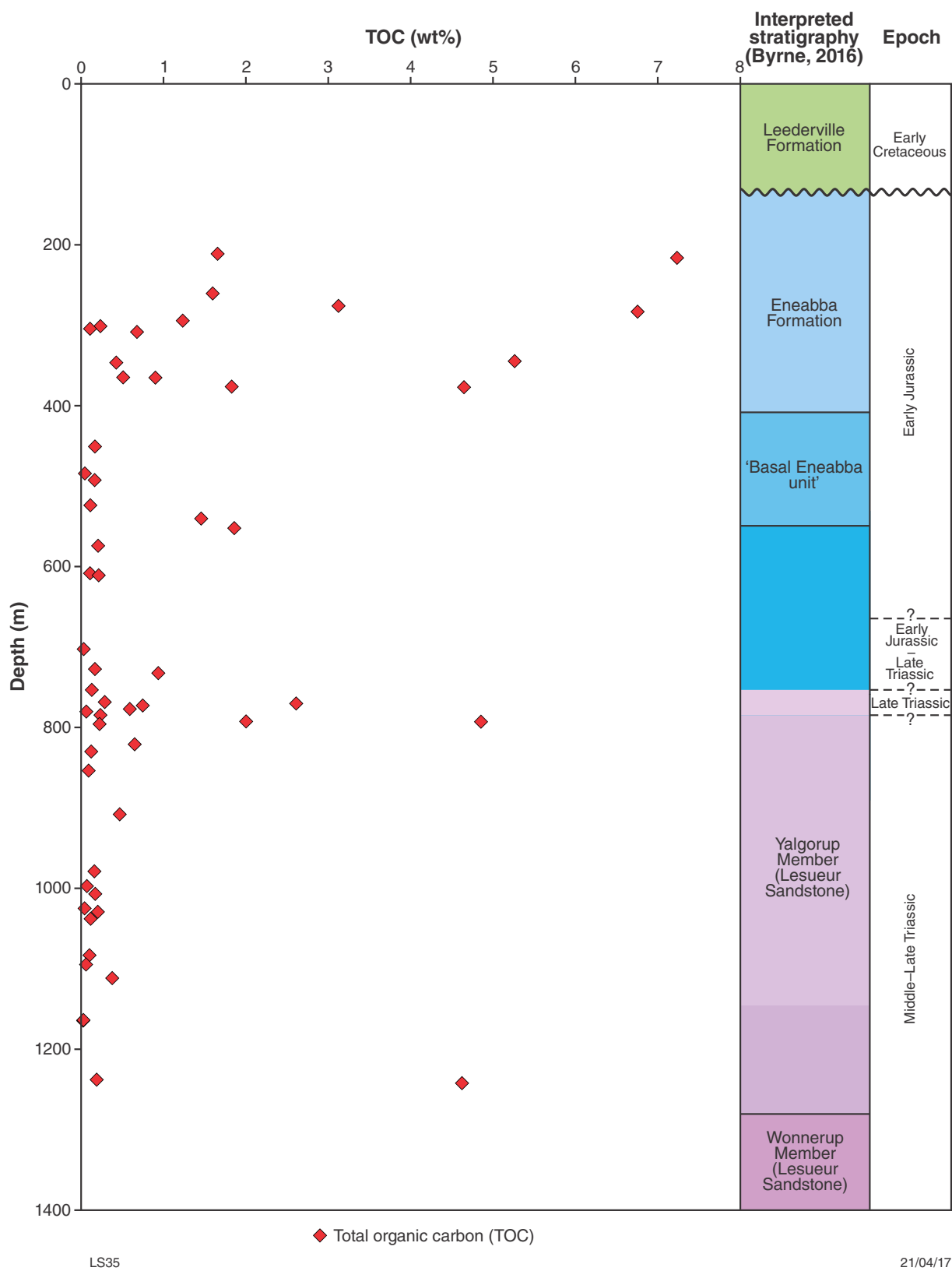


Figure 87: Total organic carbon analysis for samples from the DMP Harvey 2 well, shown with ODIN's (Byrne, 2016) interpreted stratigraphy.

## Results and discussion

Analysis of core samples from the Eneabba Formation and Yalgorup Member resulted in reported TOC values ranging from 0.03 to 7.23 per cent (Figure 87). The two highest results were for samples from the Eneabba Formation.

### Preliminary interpretation

The organic petrology analysis for select samples from DMP Harvey 2 and 3, along with the TOC, inorganic petrography and the palynology results, indicates fluvial sedimentary deposition for the Yalgorup and Wonnerup Members. Thermal immaturity of the samples indicates that the Lesueur Sandstone was not buried at significant depth, and suggests that either the Yarragadee Formation was not present or that the erosion of the Yarragadee Formation may not have been as significant on the Harvey Ridge as previously interpreted by GSWA.

## 6.0 Wireline formation analysis and processing results

The logs run in wells DMP Harvey 2, 3 and 4 by Halliburton are listed in Table 22 (section 4.2). The digital raw wireline logging data for wells DMP Harvey 2, 3 and 4 are appended to this report (Appendix G). The processed logs with the names of the processors are documented in section 4.1. The digital processed log data and ODIN's interpretation reports are in Appendix P. Interpretations of the processed wireline data are summarised below.

### 6.1 Petrophysical analysis

The petrophysical analysis was carried out by Kennedy (2015) on behalf of ODIN. Kennedy interpreted the petrophysical logs run in DMP Harvey 2, 3 and 4 with the logs run in GSWA Harvey 1 by Baker Hughes. The logs were merged, analysed and interpreted using industry standard techniques.

#### 6.1.1 Caliper logs

The caliper logs show washouts in front of the mudstones within the wells. In DMP Harvey 4, the caliper log shows that the hole can be up to five centimetres greater than the bit diameter and that the hole conditions were generally good in front of the sandstones. Inspection of the processed image log in GSWA Harvey 1 suggests that the roughness of the well's walls is caused by breakout in a north–south direction, as well as general caving and enlargement (Kennedy, 2015).

#### 6.1.2 Gamma, resistivity, dipole sonic and neutron–density and nuclear magnetic resonance logs

Kennedy (2015) reports that the log responses are consistent with a clastic-dominated system comprising sandstones and mudstones. The log responses are typical of water-bearing lithologies. The nature of the sandstones, quality of the logs and the availability of core and nuclear magnetic resonance (NMR) data were used to provide estimates of porosity, grain density, rock mineralogy, shale content and geomechanical parameters. In general, the calculated porosities agree with those reported in the core analyses data (section 5.4, above). Log analyses of the Wonnerup Member sandstones in DMP Harvey 3 slightly underestimate core porosity (Kennedy, 2015).

The porosity data for core samples from the Yalgorup and Wonnerup Members of wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4 are shown in Figures 88 and 89. At any given depth in the Yalgorup Member, the measured porosities vary by 15–20 per unit (pu, Figure 88), whereas, for samples from the Wonnerup Member, the measured porosities vary by 10pu (Figure 89). The wider range of porosities measured in samples from the Yalgorup Member is considered to reflect the broader spectrum of facies present. The wider range in facies has an associated wider range in pore-throat sizes and, subsequently, porosities.

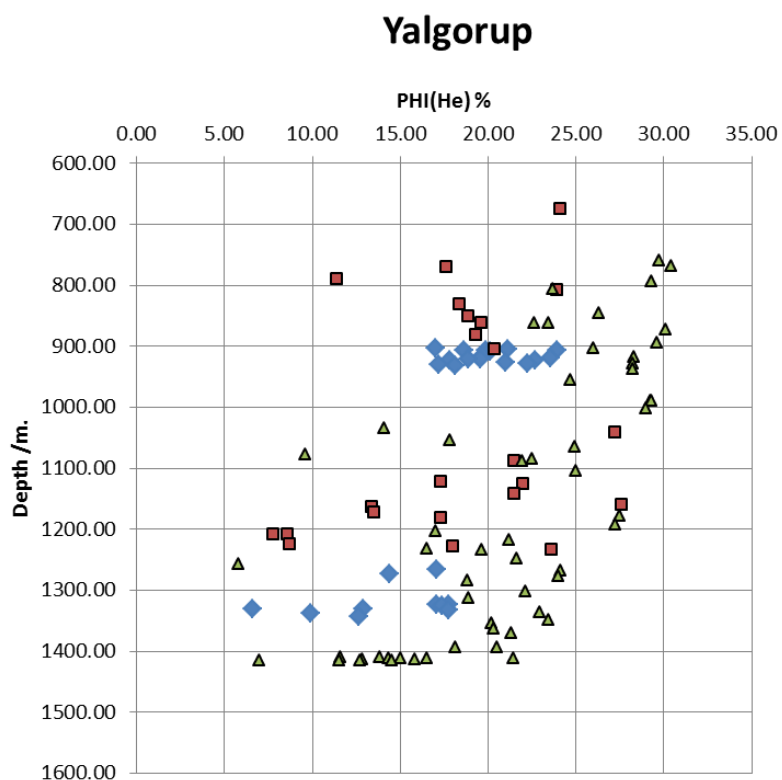


Figure 88: Measured core porosities plotted against sample depth for the Yalgorup Member (Kennedy, 2015).

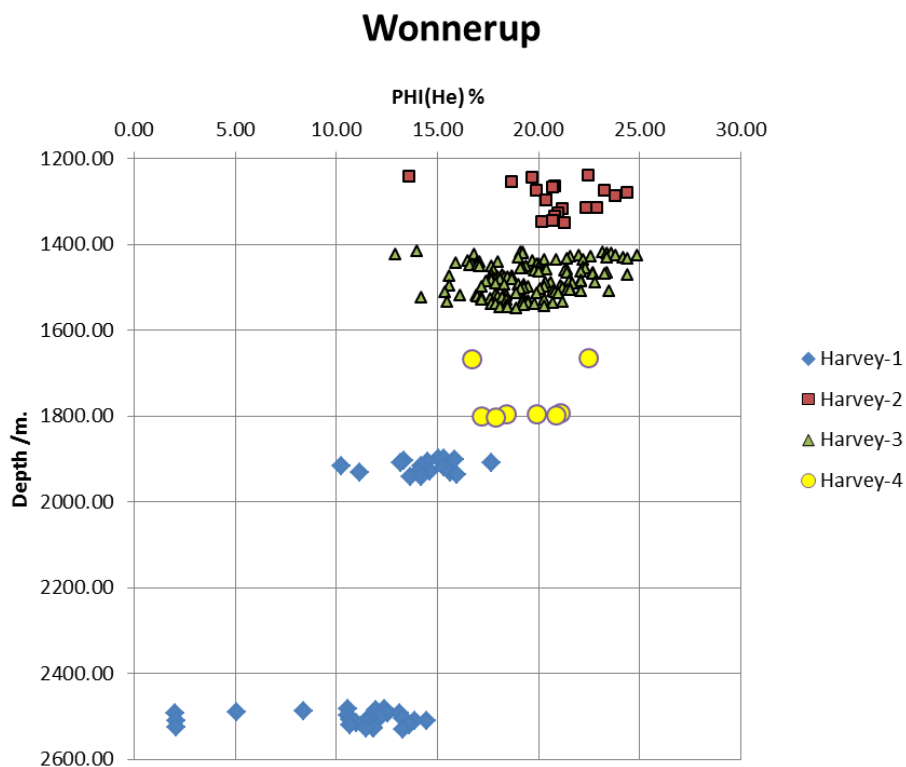


Figure 89: Measured core porosities against sample depth for the Wonnerup Member (Kennedy, 2015).

The porosity and permeability data from core samples from the Yalgorup and Wonnerup Members of wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4 are shown in Figures 90 and 91, respectively. In the Yalgorup Member, the separation of the mudstone-rich lithologies generally results in a large increase in neutron porosity, with the density varying little between sandstones and mudstones. For the Wonnerup Member, log-calculated density is generally higher in the mudstones than in the sandstones, although the mudstones are often too thin to be properly resolved by conventional logs (Kennedy, 2015).

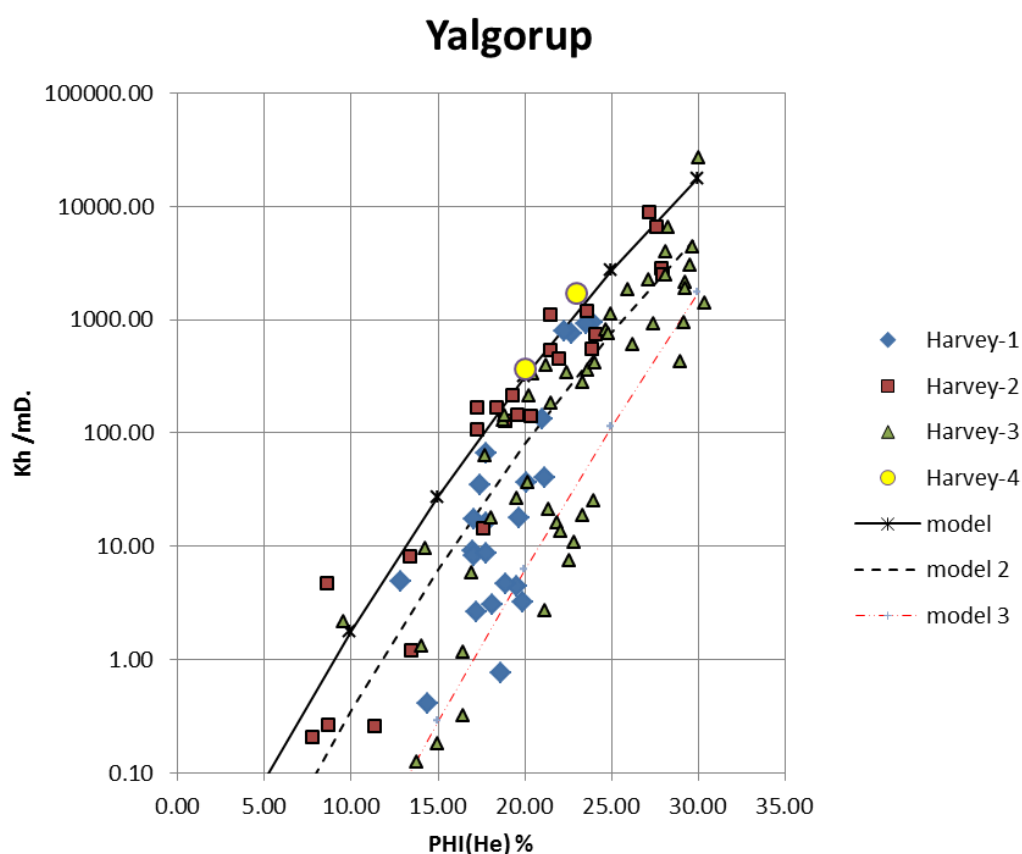


Figure 90: Porosity–permeability data for the Yalgorup Member (Kennedy, 2015).

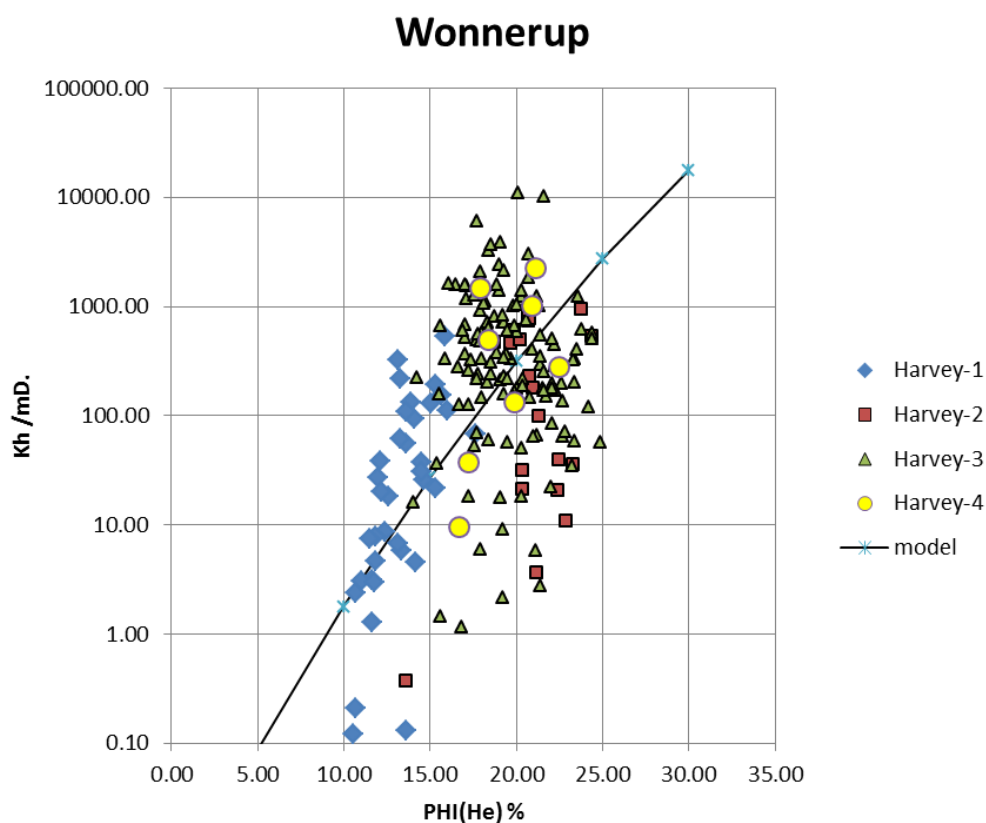


Figure 91: Porosity–permeability data for the Wonnerup Member (Kennedy, 2015).

The sandstones are characterised by low gamma activity and ‘classic’ negative separation between the density and neutron curves. Resistivity values for the sandstones vary from 1ohm-m in the shallower more porous sandstones, to 5ohm-m in the tighter sandstones near the base of the Wonnerup Member in GSWA Harvey 1. These resistivity values are low for sandstones, and could reflect saline formation fluid or mudstones interbedded within the sandstones, or both. The mudstones have higher resistivity values, of the order of 10ohm-m (Kennedy, 2015).

The shale volume (Vsh) was computed from the wireline logging and core data, using the gamma-ray and neutron–density cross-plot methods. Total shale thickness for the Yalgorup Member is about 145m based on a shale cut-off value of 50 per cent. This thickness of shale is about 21 per cent 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, or less than two per cent of the total thickness of this member (Strachan, 2016).

The sandstones identified by conventional log responses provide little information on permeability, as these standard logs are unable to distinguish between connected and non-connected pores. The routine core analysis data (in section 5.4.3.2, above) show that permeability can vary considerably for a particular porosity value. The nuclear magnetic resonance (NMR) logs acquired in GSWA Harvey 1 and DMP Harvey 4 explain why this is the case.

Figure 92 shows downhole logs for a 75m section of the Yalgorup Member in DMP Harvey 4, including gamma, nuclear, porosity, resistivity, NMR, computer processed interpretation (CPI) and permeability logs. For the same logging interval, the permeability log (far right) varies more than the porosity log (third from the left). The black porosity 'bins' in the NMR log show how the bound water<sup>15</sup> in the strata varies with depth. Despite the total porosity being fairly consistent, the bound water fluctuates with depth. This observation is considered to reflect a large range of grain sizes and silt content within the strata (Kennedy, 2015). The mudstones are indicated by the elevated gamma readings (left-hand log) and dark green in the CPI log and coincide with those depth sections containing silt and, subsequently, bound water. Low-permeability strata are considered to result from lithologies having high clay and silt contents.

<sup>15</sup> Bound water is the water in the formation which is not free to move. Due to very small pore-throat sizes in the strata, the water is 'tied' or held within the pore spaces.

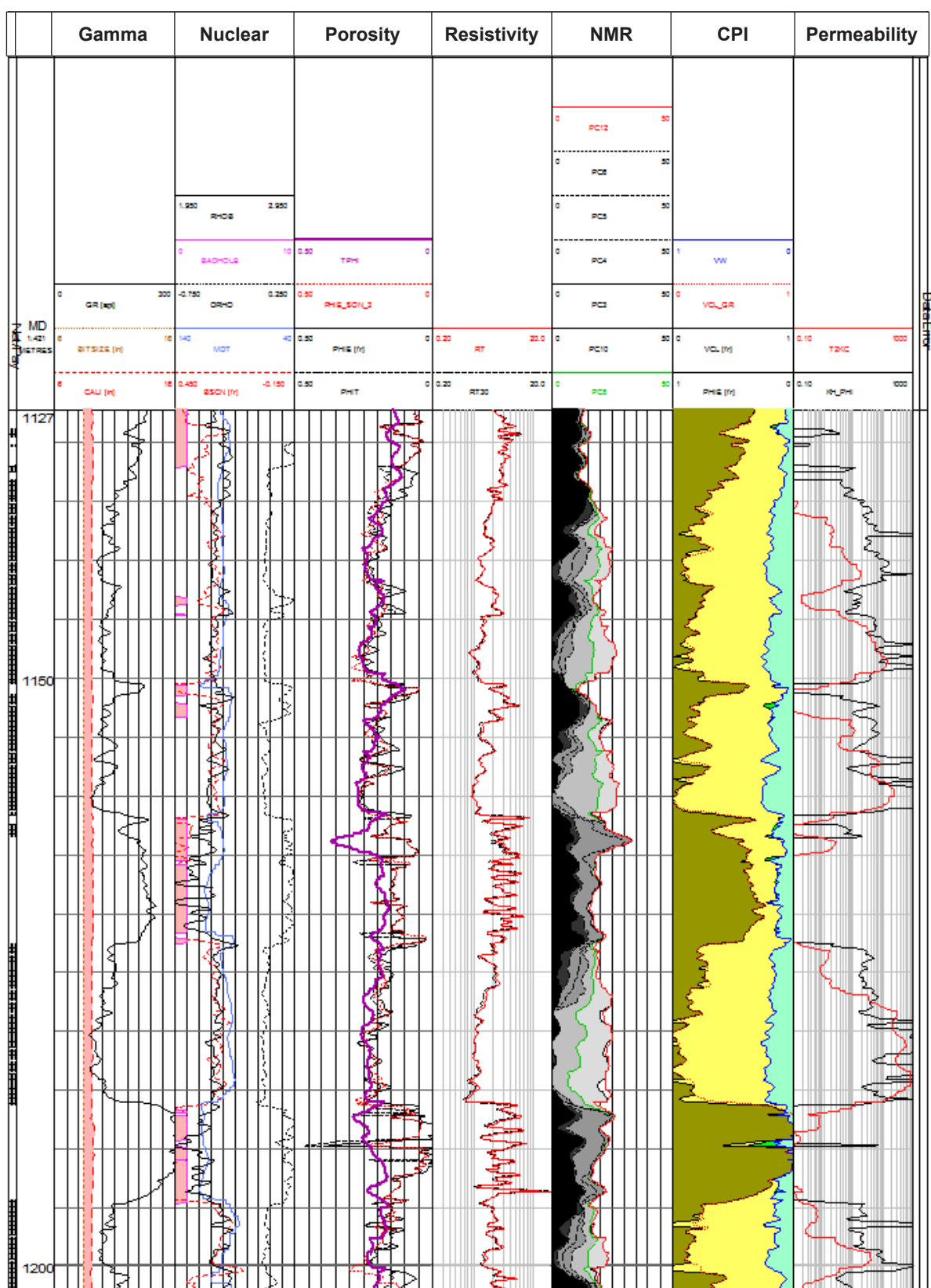


Figure 92: Raw and interpreted curves for an interval of sandstones and mudstones in the Yalgorup Member of DMP Harvey 4, from 1127 to 1200m depth. The NMR log shows porosity 'bins' shaded so that bound water is black and water in the largest pores is white (Kennedy, 2015).

The porosities in the Yalgorup Member are in the order of 25–30 per cent, and in the Wonnerup Member they fall from 25 per cent near the top of the member to 20 per cent at TD in DMP Harvey 4 (1740m). In GSWA Harvey 1, porosities fall to as low as 10 per cent at the base of the Wonnerup Member (2840m). Core data for the Yalgorup Member show three or four roughly parallel porosity–permeability trends (Figure 90). The large distribution of grain size in the Yalgorup Member is considered to have caused the large range in porosity.

The resistivity of the formation fluid was calculated using both the resistivity logging data for DMP Harvey 4 and the calculated resistivities for various petrophysical zones plotted against porosity (Pickett plots), which were used by Kennedy (2015) to indicate that the sandstones are saturated with water with a salinity of approximately 30,000ppm (NaCl, w/w). As this value is subject to a number of assumptions on formation parameters the salinity of the formation fluids needs to be confirmed through the collection of reservoir fluid samples (Kennedy, 2015).

### **6.1.3 Vertical seismic profile data**

The vertical seismic profile (VSP) surveys for DMP Harvey 2, 3 and 4 were carried out by Halliburton, using their downhole array tool, with a mini-vibe as a source at each well. The VSP surveys were processed by Halliburton to provide time–depth curves and tables showing the first breaks. The VSP field reports for DMP Harvey 2, 3 and 4 catalogue the details of the work done and are available in Appendix S of this report or DMIRS' WAPIMS database.

The VSP raw data were processed by geophysicists at Curtin University, to provide the interval velocities. These have been used to improve the velocity model for the static model and the processed up-going waves can be compared with the processed 3D seismic survey data to provide better time to depth correlations for the wells. Work by ODIN included aligning the processed VSP data with the surface 3D seismic survey data to validate the formation tops used in the 3D static geological model.

### **6.1.4 Sonic data**

The sonic data were acquired by Halliburton in conjunction with other logs (Table 22). The data are used for porosity determination (one of the many logs used for this purpose), geomechanics and synthetic seismograms. The delta time ( $\Delta t$ ) compressional and shear data are also used to determine formation anisotropy. In sections where the well had to be cased before openhole logs were acquired, Halliburton processed the waveforms in the sonic data to obtain the delta times; however, the resulting data are quite sparse. The processed data are available for download from DMIRS' WAPIMS database.

### **6.1.5 Image data**

The image-log datasets from wells GSWA Harvey 1 and DMP Harvey 4 (Table 22) cover nearly three kilometres of vertical section of stratigraphy. Two raw data files were reprocessed and processed by ODIN, respectively:

- GSWA Harvey 1: Harvey-1\_STAR\_RAW\_1285-2723m.
- DMP Harvey-4: Harvey 4\_S2R2\_XRMI\_Main\_250-1784.0m.

The processed image logs were used to determine the depositional facies units and their orientation with depth in the image-logged sections of GSWA Harvey 1 and DMP Harvey 4, specifically within the Wonnerup Member. The main sedimentary features seen on the image logs were:

- thalweg-orientated planar cross-bedding in the point bars between paleosols of the Yalgorup Member
- planar-parallel and tangential cross-bedding in definitive cross-bed strata and cosets separated by truncation surfaces and paleosol horizons in the Wonnerup Member.

For both the Yalgorup and Wonnerup Members, the dominant orientation of the bedding planes is east to northeasterly trending azimuthal dips (Roostenburg, 2016). The bedding planes also contain northeasterly to northerly trending azimuthal dips.

Non-planar features shown on the image logs in both wells are attributed to the destruction of primary sedimentary structures by post-depositional diagenetic processes. Non-planar siderite nodules and cross-cutting 'boudins' in siderite layers were identified by Roostenburg (2016).

The interpreted data advised the depositional model and the construction of the static geological model for the SW Hub study area. Full details of the processing and interpretation of the image log data are in the ODIN report in Appendix P (Roostenburg, 2016). The processed image log data for GSWA Harvey 1 (reprocessed by ODIN) and DMP Harvey 4 are available for download from DMIR WAPIMS database.

### **6.1.6 Preliminary interpretation**

The logged sections within the Yalgorup and Wonnerup Members are of fluviially deposited interbedded sandstones and mudstones, sourced from detrital clastic material. The dominant depositional direction of the bedding planes is determined as easterly to northeasterly with a minor depositional direction component to the northeast to north (Roostenburg, 2016). The azimuthal dip of the bedding planes indicates a sedimentary provenance of the strata from the west to southwest, with a minor component from the southwest to south.

The porosities in the Yalgorup Member are approximately 25–30 per cent. The porosities of the Wonnerup Member fall from 25 per cent near the top of the unit to 10 per cent at the base of the unit (at 2840m depth in well GSWA Harvey 1). The large range in porosity in the Yalgorup Member is attributed to a wide distribution of grain sizes. Within the Yalgorup Member, silt within the mudstones results in bound water (Kennedy, 2015). These silt-rich mudstones exhibited low permeabilities during routine core analysis.

On behalf of ODIN, Strachan (2016) used Kennedy's (2015) and Roostenburg's (2016) log interpretation with Halliburton's processed sonic log data, Curtin University's processed VSP log data and CoreLab's core-analysis data to construct 3D geological stochastic models of the SW Hub study area, as discussed in section 7.0, below.

## **7.0 Geological interpretation**

Department of Mines, Industry Regulation and Safety contracted ODIN to provide geological and geophysical interpretation and modelling services. A description of the project deliverables and summary of the results are provided below.

### **7.1 Project deliverables**

#### **7.1.1 Scope of works**

The services provided by ODIN included a number of deliverables:

- interpretation of the 3D seismic survey
- geological advice and depth prognoses for the siting locations of wells DMP Harvey 2, 3 and 4
- petrophysical analysis of the data from the three wells and creation of correlation panels
- report on the geological environment and a suitable analogue for the depositional environment for use in a static model

- review of image log data to determine the bedding plane orientation in wells GSWA Harvey 1 and DMP Harvey 4
- a preliminary geomechanical study
- static geological models to adequately describe the reservoir sequences in the area of interest
- dynamic models representing multiple scenarios to simulate the injection, containment and migration of CO<sub>2</sub> injected into the lower Wonnerup Member reservoir.

### 7.1.2 Technical review

Technical assurance was maintained through a peer assist and review system. Support for the reviews was provided by Chevron Australia Pty Ltd, INPEX Operations Australia Pty Ltd, Shell Australia Pty Ltd, CSIRO and Department of Industry, Innovation and Science (DolIS), the latter being overseen by GeoGem Consultants Pty Ltd and University of Queensland.

### 7.1.3 Acceptance criteria

The results and recommendations were tested against the following acceptance criteria:

- Deliver >P50 confidence to inject 800,000tpa of CO<sub>2</sub> across 30 years, with a total injection of 24Mt of CO<sub>2</sub>.
- Deliver a >P50 level of confidence that injectivity of more than 100,000tpa per well could be feasible, so that no more than 10 wells in total would be required.
- Deliver >P50 confidence that ‘the plume’ remains below the basal Eneabba unit, or below 800m, and within the storage complex for 1000 years.

The results of ODIN’s integration of the 3D seismic survey data, core analysis data, petrophysical analysis and geomechanical analysis, and the creation of the geological model, is summarised in the section below. The full report from ODIN is in Appendix Q.

## 7.2 Interpretation results

### 7.2.1 Structural geology

The 3D seismic survey focused on acquiring high-fold data over the Wonnerup Member, which has resulted in good structural mapping and fault definition in the Wonnerup Member, with less certainty of structure and faults in the Eneabba Formation and the Yalgorup Member. The structural and faulting controls in the Eneabba Formation and the Yalgorup Member, as a consequence of the 3D seismic interpretation, have improved since the interpretation of the 2D seismic survey (Zhan, 2014).

Processed 3D seismic data were interpreted by ODIN to assist in advising the depths to the formation and bench-marker surfaces and the location and throw of the faults. These were inputs to the 3D geological model of the SW Hub study area (Figure 93). The model used ODIN’s interpretation of the depths to formation and bench marker surfaces, the dips of strata (particularly structural dip and sedimentological dip) and the location and orientation of faults (Byrne, 2016). Before the drilling of DMP Harvey 2, 3 and 4, ODIN’s 3D geological model was only tied to GSWA Harvey 1, the only stratigraphic well to have been drilled to the Sabina Sandstone in the study area.

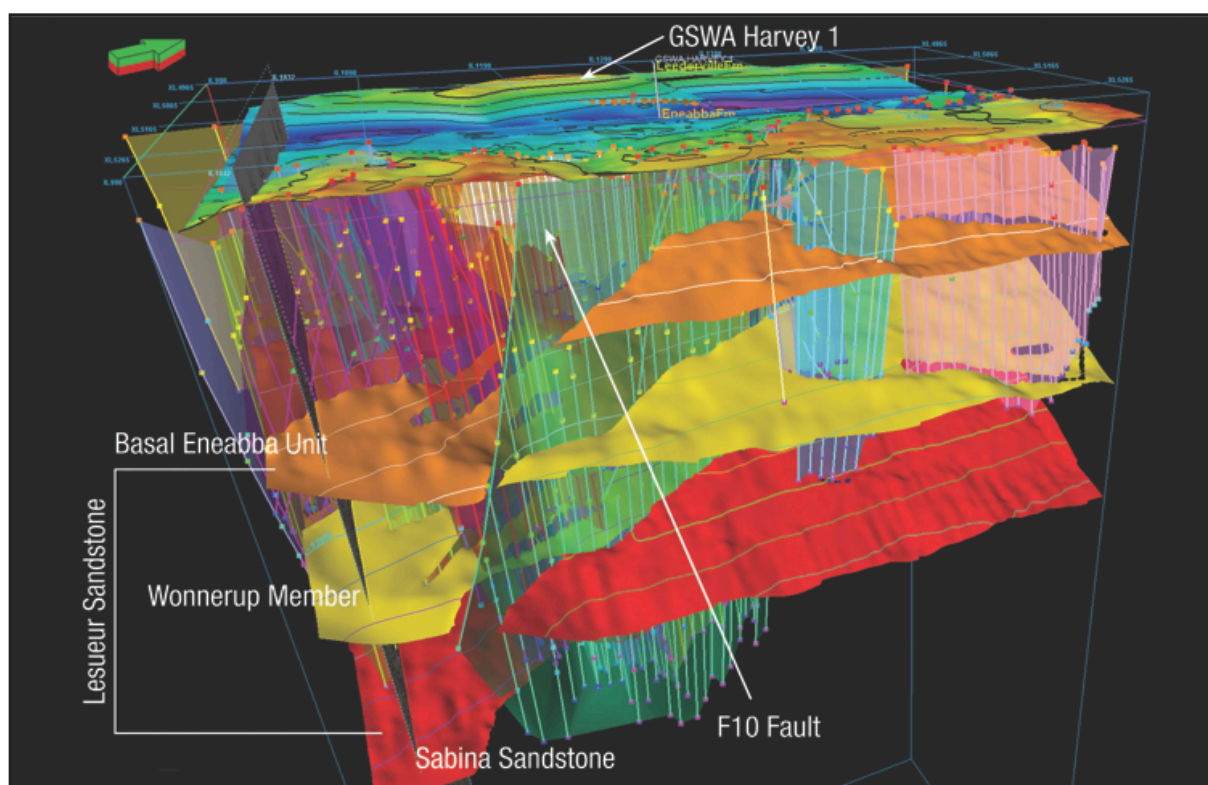


Figure 93: Pre-drilling 3D geological model tied to GSWA Harvey 1 for the SW Hub study area, as viewed from the southeast (ODIN presentation to DMIRS, 2015). Tops of formations shown are the basal Eneabba unit (orange), Wonnerup Member (yellow) and Sabina Sandstone (red). Major faults include the F10 Fault (blue-green) and F7 Fault (brown).

The surfaces of the basal Eneabba unit, the Wonnerup Member and the Sabina Sandstone dip to the east, as shown in Figure 93. The F10 Fault generally runs north-northwesterly (Figure 93). The F7 Fault is mostly to the south of the area shown in Figure 93.

Along the F10 Fault, the hangingwall is to the west, and the footwall is to the east. Prior to the drilling of DMP Harvey 2, 3 and 4, the depths of the strata were constrained at the location of well GSWA Harvey 1 (shown in the west, on the upper surface of the model).

Following the drilling of the wells DMP Harvey 2, 3 and 4 ODIN updated its interpretation of the 3D seismic data (Byrne, 2016) and revised the 3D geological model for the SW Hub study area (Figure 94; Strachan, 2016). The updated model used Velseis' processed and Curtin University's reprocessed 3D seismic data. These data were tied to wells using the VSP data as a guide and quality-control mechanism.

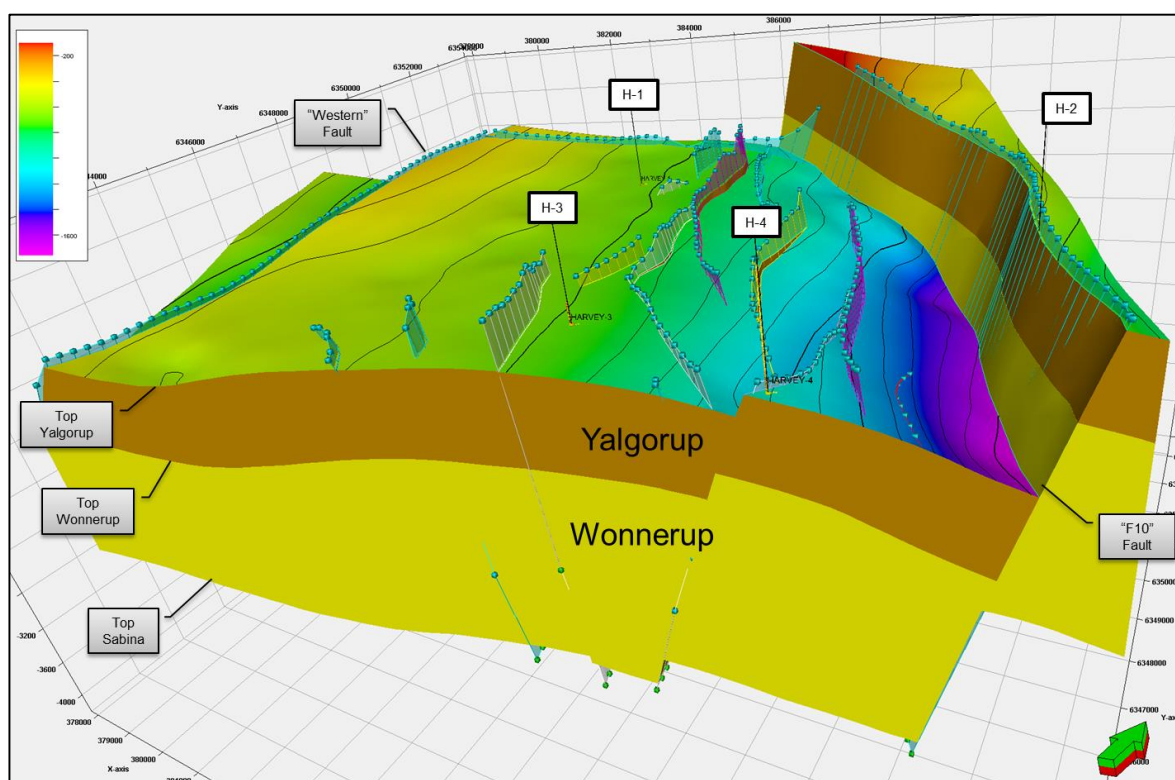


Figure 94: Post-drilling 3D geological model for the SW Hub study area with fault sticks showing fault planes, as viewed from the south-southeast (Strachan, 2016).

The stratigraphy and well correlation in the Triassic–Jurassic zone was problematic. The non-marine, fluvial depositional environment, with a paucity of paleontological control and homogeneous stratigraphy, meant well to well correlation was subjective, particularly in the separation of the Eneabba Formation from the underlying Yalgorup Member (Byrne, 2016; Strachan, 2016).

Figure 94 shows the surfaces of the Yalgorup and Wonnerup Members. The 3D seismic interpretation confirms that the Lesueur Sandstone broadly dips to the southeast with the propensity for faulting increasing in proximity to the F10 Fault. In ODIN'S updated geological model (Figure 94), the 'sticks' represent seismic picks along interpreted fault planes. The main faults are the westerly dipping, north-northwesterly striking F10 Fault, the westerly dipping F7 Fault in the south of the study area, the major northerly striking Western Fault, and the F15 Fault that links the Western Fault with the F10 Fault north of well GSWA Harvey 1.

The throws of faults visible within the seismic resolution are interpreted by Byrne (2016) to be in the vicinity of 15m. These are all extension faults with no inversion or reverse faults observed. The fault with the greatest throw in the SW Hub study area is the F10 Fault. This fault is interpreted by ODIN as the amalgamation of two faults (Byrne, 2016). The strike along the F10 Fault changes direction from northwesterly in the southeast of the 3D seismic survey area to northerly as it exits the northwest of the study area. There are two main jogs along the fault, suggesting that the F10 Fault consists of multiple linking faults (Byrne, 2016). The vertical throws along the F10 Fault vary from approximately 400 to 1000m. The DMP Harvey 2 well is in the footwall of the F10 Fault where displacements are considered to be approximately 700m on the Wonnerup Member depth surface (Figure 94).

Four faults are interpreted to penetrate the Cretaceous Leederville Formation, including the F10, F7, F15 and F16 Faults. The F15 Fault is the only fault to strike easterly and this fault dips to the north (Byrne, 2016).

Using Curtin University's processing of the 3D seismic survey data and subsequent new well ties, ODIN verified that well DMP Harvey 2 had intercepted the F10 Fault, as advised by Byrne's (2016) interpreted depth surfaces of the basal Eneabba unit and Yalgorup Member. It was also interpreted that DMP Harvey 4 was likely to have intercepted the F7 Fault in the well's lower section (Figure 95). These faults were interpreted within the resolution of the processed seismic data (Figure 95). Throughout the paleosol horizons a number of slickensides are evident in the various cores indicating possible post-depositional movements due to geostatic load adjustment (Jon Roestenburg 2015, [ODIN Reservoir Consultants Pty Ltd], pers. comm., February 2016).

The daily drilling records (Appendix A), final well reports (Appendix A) and lithological logs (Appendix C) contain records of potential shear and fault zones encountered during the drilling of DMP Harvey 2, which are listed in Table 51. The drillers' and on-site geologists' reports do not document any faults or shear zones being encountered in wells DMP Harvey 3 and 4.

Table 51: DMP Harvey 2: possible faults or shear zones reported from drilling

Depth (m)	Description	Stratigraphic unit	Lithological description	Source
507.7	Small fault	Yalgorup Member	Sandstone	Lithological log
615.1	Pressurised shear zone	Yalgorup Member	Sandstone	Final well report
674.5	Possible fault	Yalgorup Member	Sandstone	Lithological log
772.95–773.70	Complex fault zone	Yalgorup Member	Conglomerate	Lithological log
808.80–811.35	Possible fault or shear zone	Yalgorup Member	Mudstone	Lithological log
877.6	Fault	Yalgorup Member	Silty sandstone	Lithological log
1333.75	Small faults	Wonnerup Member	Sandstone	Lithological log

The fault or shear zones identified in DMP Harvey 2 were within a 370m interval within the Yalgorup Member, with the exception of small faults located in the Wonnerup Member at a depth of 1333.75m (Table 51). HyLogger data have been interpreted to suggest that the F10 Fault zone in DMP Harvey 2 could be within a depth range of 347 to 870m (refer to section 5.4.1).

In ODIN's 3D geological model the F10 Fault is intercepted by DMP Harvey 2 at 531m. The position of DMP Harvey 2 and ODIN's interpretation of the F10 Fault are shown in Figure 95.

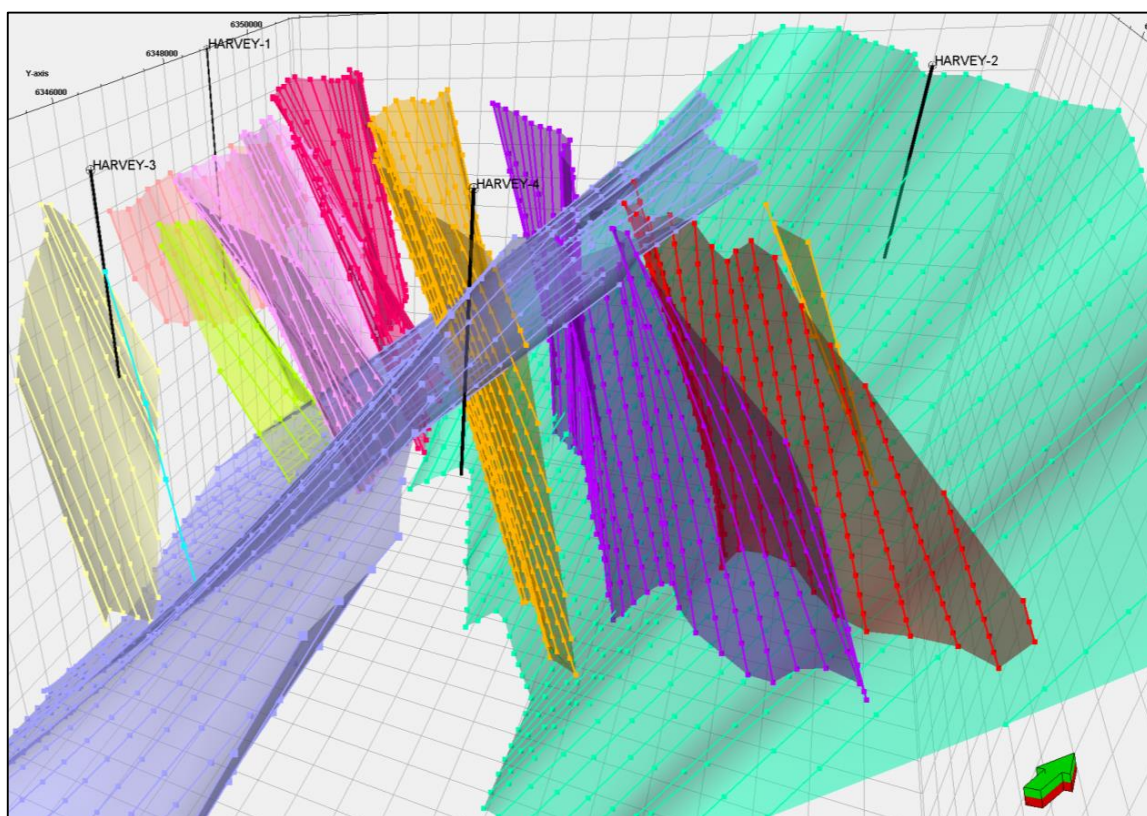


Figure 95: Fault sticks representing fault planes in ODIN's structural model (Strachan, 2016), highlighting the relative dips of the faults, viewed from the south-southeast. The F10 Fault is depicted in green. Well DMP Harvey 4 is considered to have intercepted the F7 Fault (violet colour) in the well's lower section. The distance between wells GSWA Harvey 1 and DMP Harvey 2 is approximately seven kilometres.

### 7.2.2 Geomechanical analysis

Using the data acquired during the drilling of GSWA Harvey 1 and DMP Harvey 2, 3 and 4, ODIN carried out a preliminary geomechanical analysis of the SW Hub study area. The objective of the geomechanical study was to estimate the critical injection-induced pressures that could induce shear failure along faults, and to scope the requirements for geomechanical measurements in any future deep well (notionally 'DMP Harvey 5').

Analysis of the caliper logs in GSWA Harvey 1 and DMP Harvey 4 indicate annular enlargement in the mudstone horizons in the middle to lower depths of the Yalgorup Member. Data from Baker Hughes' circumferential borehole imaging log (CBIL™) for GSWA Harvey 1 was interpreted by (Castillo 2015) to characterise the style of drilling-induced well failure, which indicated that well breakouts were pervasive in the Yalgorup Member and present to a lesser extent in the Wonnerup Member. The majority of the breakouts were in a north-northeast to south-southwest direction, giving a direction of maximum horizontal stress between 90°N and 105°N (Castillo, 2015). The annular well enlargements and rotation breakouts are considered to be in the direction of minimum horizontal stress (270°N and 285°N; Castillo, 2015).

From the interpreted 3D seismic data the generalised orientation of faults indicates that fault dips are from 40 to 75°. Fault-dip azimuths are considered to be clustered from approximately N45°E to N100°E and approximately N165°E to N280°E (Castillo, 2015). The maximum horizontal stress, which is the orientation, or strike, of stressed faults, is determined to be in a west-northwest–east-southeast direction (Castillo, 2015). The full geomechanical assessment report is appended (Appendix D).

The geomechanical analysis focused on estimating the critical injection pressures that could induce shear failure along faults or fractures. Due to remaining uncertainties, especially the minimum horizontal stress ( $Sh_{min}$ ), three geomechanical models were constructed to estimate the injection-induced pressures that could reactivate ODIN's interpreted faults. Castillo 2015 recommends further data acquisition concepts during any future drilling campaign in the SW Hub study area, to reduce the number of stress models required.

### 7.2.3 Lithostratigraphy

The stratigraphy in wells DMP Harvey 2, 3 and 4 is broadly consistent with the current understanding of the stratigraphy of the southern Perth Basin (Millar and Reeve, 2014), as shown in Figure 96.

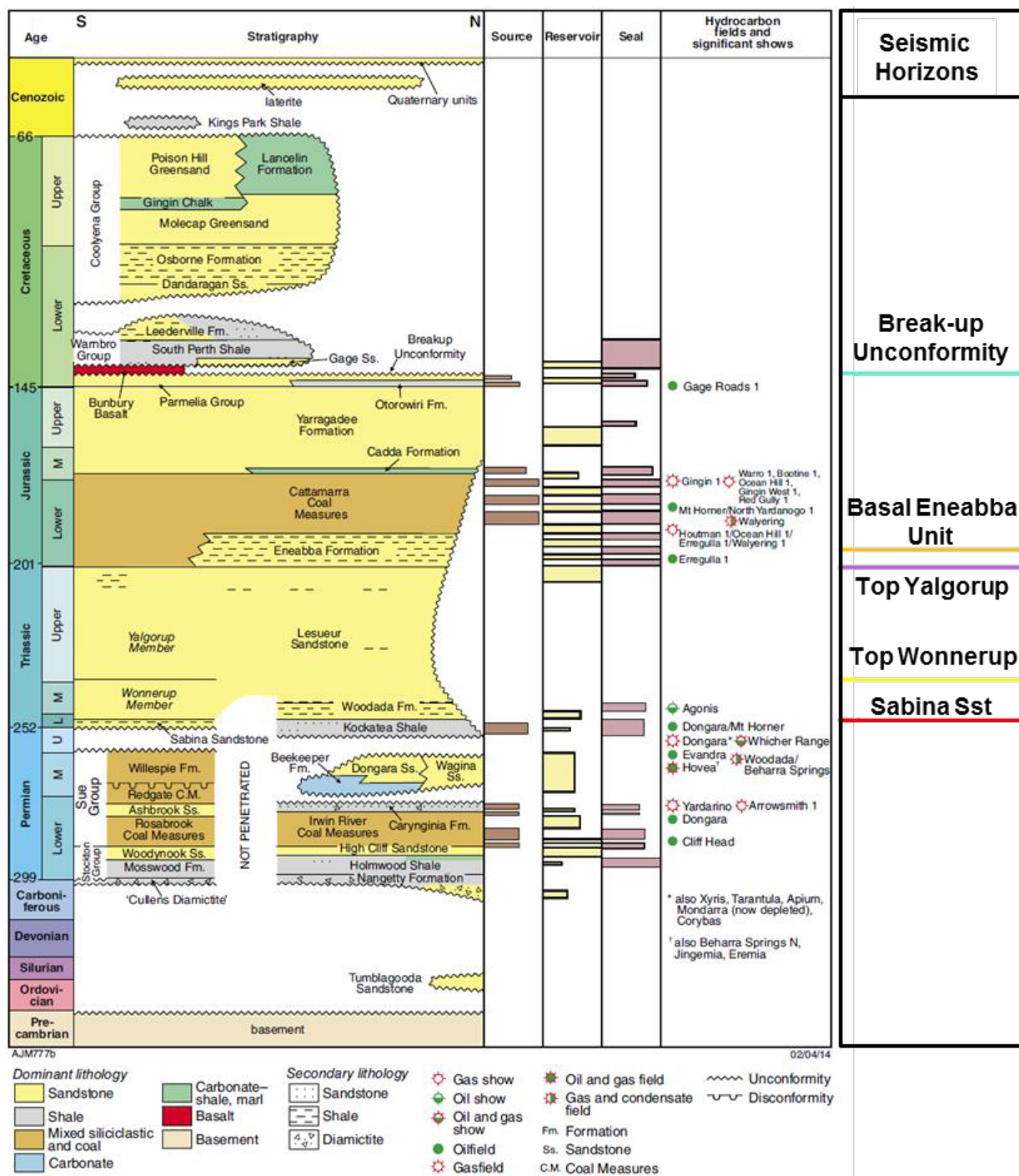


Figure 96: Perth Basin stratigraphy with seismic horizons, as reported by ODIN (Byrne, 2016; adapted from Zhan, 2014).

Rockwater's on-site geologists and CoreLab's core analysis studies describe a number of lithofacies in rock chips retrieved during rotary drilling and from core obtained during diamond core drilling. The lithofacies range from coarse, high-energy sands to finely laminated mudstones.

Rockwater's composite logs, which include geological formations or units, caliper and gamma logs, well-construction detail, lithology log and lithological description (mud) logs, are in Appendix C of this report. For each well, the mud logs show the percentages of silt, clay, mud and sand facies throughout the drilled stratigraphy.

In the composite logs, the stratigraphy above the Cretaceous unconformity is shown in green (Appendix C). In the SW Hub study area the Cretaceous Leederville Formation comprises silt-rich and sand-rich facies with minor claystone. The Eneabba Formation (shown as blue in the composite logs) is predominantly sand rich, with thickly multi-coloured interbedded siltstones, claystones and mudstones. In comparison with the other units described here, the Yalgorup Member (shown in mauve in the composite logs) has proportionately more mud - rich facies, with sandstones and minor claystones and siltstones that reflect the thick sequences of paleosols in the unit. The Wonnerup Member (shown in purple) is predominantly sand rich (93 to 96 per cent), with minor mud-rich, clay-rich and silt-rich facies.

The provenance of nine facies types identified from data for the GSWA Harvey 1 well have been interpreted by CSIRO (Delle Piane et al., 2013). Facies types interpreted by CSIRO have been simplified into three broad facies groups by ODIN:

- high-energy fluvial
- low-energy fluvial
- paleosols, with some overbank facies in the Yalgorup Member.

The interpretation of the well-to-well correlation using the petrophysical logging data and the above facies groupings is in Figure 97, where it is shown that the Harvey core is dominated by fluvial facies; classified into braided fluvial, point bars, paleosols and overbank claystones. These were divided into high-energy and low-energy units on the image logs (Roostenburg, 2016).

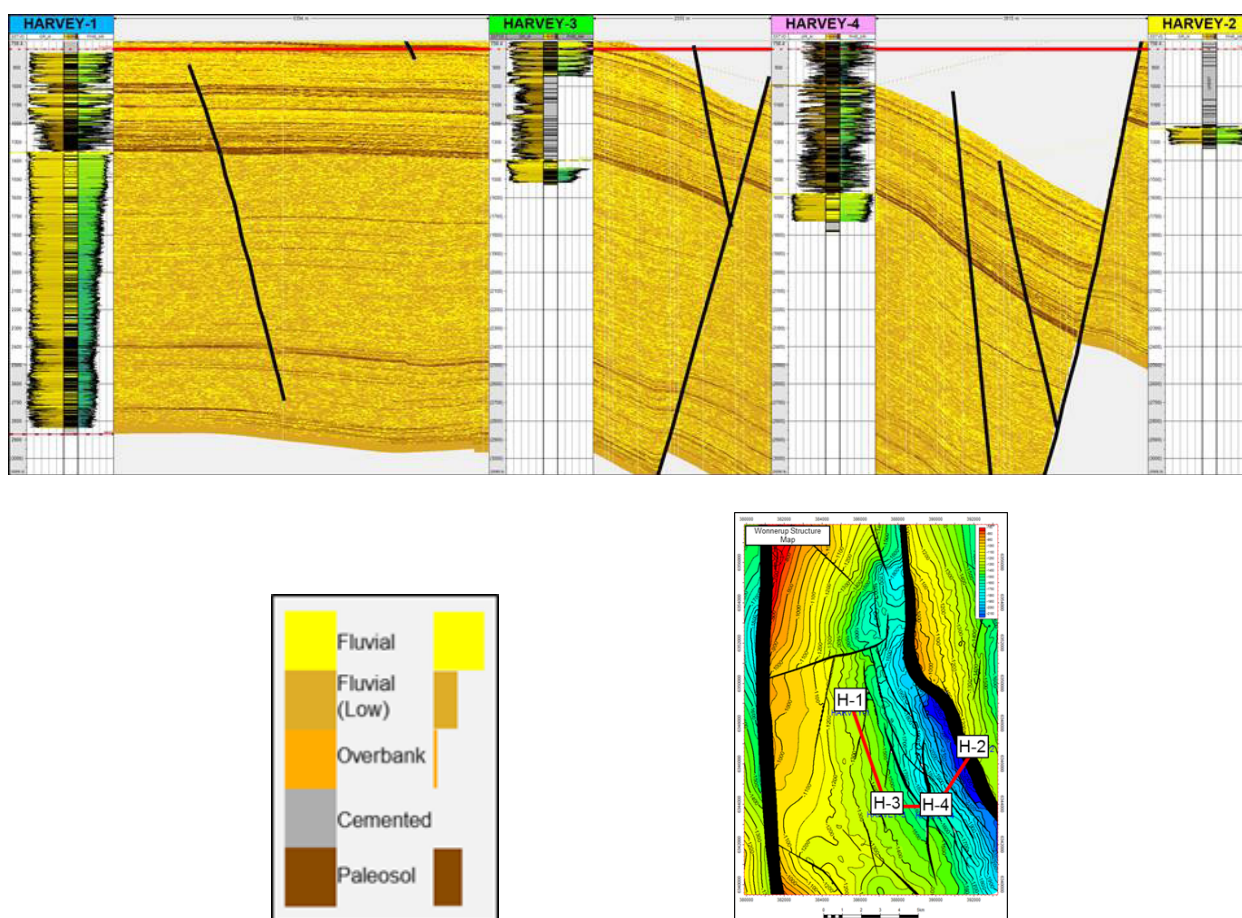


Figure 97: Fence diagram for the four Harvey wells using petrophysical logging data and ODIN's facies groupings (modified after Strachan, 2016).

The vertical proportions of the three facies groups in the Wonnep and Yalgorup Members were modelled by ODIN, as shown in Figure 98 (Strachan, 2016). The volume of mudstone (reported as 'shale' in the ODIN reports) in the Wonnep Member is modelled as approximately three per cent, whereas, in the paleosol sequences in the Yalgorup Member, the volume of mudstone has been modelled as approximately 31 per cent.

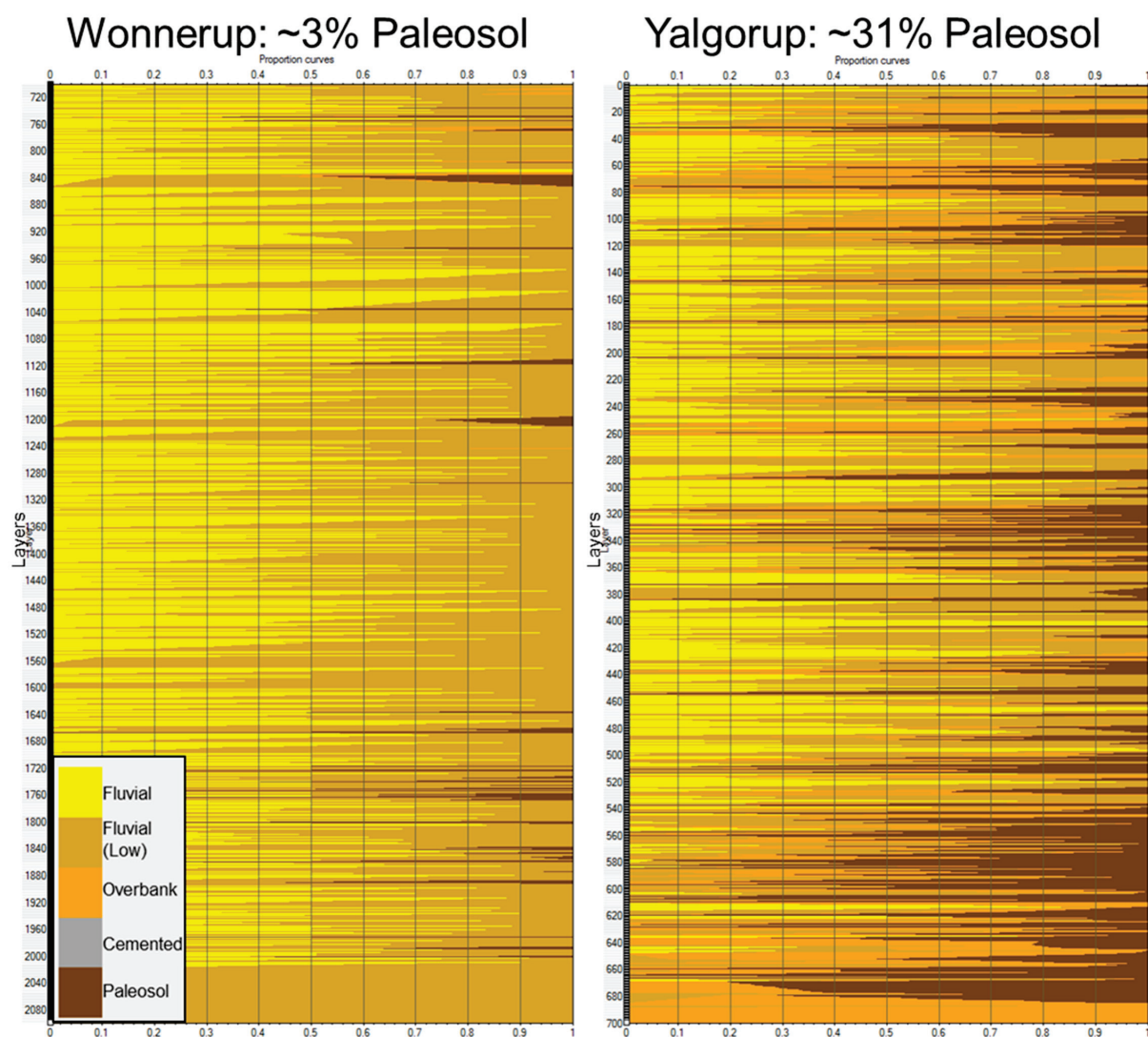


Figure 98: Vertical proportions of facies in the Wonnerup and Yalgorup Members as modelled by ODIN (Strachan, 2016).

## 7.2.4 Formation properties and quality

This section reports on the porosity and permeability of the confining strata (Eneabba Formation and Yalgorup Member) and of the target CO<sub>2</sub> reservoir (Wonnerup Member).

### 7.2.4.1 Eneabba Formation

The porosities of preserved mudstone-rich samples from the Eneabba Formation are in the order of 0.15 per cent, with permeabilities to brine ranging from no recorded flow and <0.00001 to 0.101md (at NOBP of 800psi).

#### 7.2.4.2 Lesueur Sandstone

The core samples and the wireline logging data confirm that the Lesueur Sandstone comprises interbedded sandstones and mudstones (paleosols). The porosities of the sandstones in the Yalgorup Member are of the order of 25 to 30 per cent and in the Wonnerup Member they fall from 26 per cent near the top of the member to 20 per cent at TD in DMP Harvey 4 (1802m). In GSWA Harvey 1 porosities fall to 10 per cent towards the base of the Wonnerup Member, at approximately 2840m (Strachan, 2016).

The permeabilities of the sandstones in the Yalgorup Member range from approximately 4md to more than 10,000md. For the Wonnerup Member permeabilities reduce from less than 10md to more than 4000md. As expected, there is a trend in porosity and permeability reduction with depth (Strachan, 2016).

In summary, good reservoir properties are recorded in the Wonnerup Member. In contrast, the overlying Yalgorup Member is far more heterogeneous with excellent reservoir properties noted in the sandstone intervals. Both members of the Lesueur Sandstone have a porosity and permeability depth trend where porosity and permeability decrease with depth.

### 7.3 Depositional environment

#### 7.3.1 Depositional facies

Three depositional facies groups for the Eneabba Formation and the two units of the Lesueur Sandstone have been defined for the SW Hub area by ODIN. Deposited in an active braided fluvial environment, the three facies groups are:

- high-energy channel-fill sands
- low-energy channels to swampy overbank deposits
- paleosols or floodplain sediments (Strachan, 2016).

The Wonnerup and Yalgorup Members represent depositional differences. The Wonnerup Member was formed by a braided fluvial system that was hundreds of kilometres wide and dominated by linguoid bars, where episodic flow events resulted in sandstones interbedded with minor mudstones (paleosols<sup>16</sup>). The Yalgorup Member was formed by a meandering fluvial system dominated by point bars and paleosols (Roostenburg, 2016).

The paleosols (mudstones) have been modelled as one-metre thick and up to 40 metres wide, with cross-cutting sandstones. The direction of flow and deposition of these sediments was interpreted from processed image log data from wells GSWA Harvey 1 and DMP Harvey 4 (see section 6.1.5 above). The depositional direction of sedimentation was to the east-northeast, with a less-persistent component to the north-northeast (Roostenburg, 2016).

#### 7.3.2 Depositional analogues

An analogue for the Middle to Upper Triassic Wonnerup Member is suggested by Dr Alan Millar (GSWA, 2015, pers. comm.) to be braided middle reaches of the Indus or Brahmaputra Rivers as shown in Figure 99. The Brahmaputra River rises in Tibet and flows through the Assam Valley in eastern India as an extensive braided channel, before flowing south through Bangladesh to exit at the Ganges–Brahmaputra Delta into the Bay of Bengal (Figure 100). There is constant shifting of the river channels and sandy shoals in the braided channel environment (Figure 99).

<sup>16</sup> The paleosols were long-standing alluvial plains with a mix of sand and mud parent material on which soils developed to differing degrees (Alan Millar [GSWA] 2016, pers. comm.).



Figure 99: The Brahmaputra River, a possible contemporary depositional analogue for the Lesueur Sandstone, principally the Wonnerup Member and portions of the Yalgorup Member, which are interpreted to have been deposited in a point bar environment (© Hbh I Dreamstime.com ID 11503176).



Figure 100: Location of the Brahmaputra River in Tibet, eastern India and Bangladesh.

<sup>16</sup> The paleosols were long-standing alluvial plains with a mix of sand and mud parent material on which soils developed to differing degrees (Alan Millar [GSWA] 2016, pers. comm.).

In addition to the lower energy, meandering channel of the Brahmaputra River, the lower Murray River in South Australia was proposed by ODIN as a suitable analogue for the Yalgorup Member (Jon Roostenburg [ODIN Reservoir Consultants Pty Ltd] 2016, pers. comm., 10 August). Both environments are arid regions, with significant drainage catchments and broad alluvial plains, point bar systems and high instances of water pulses in a highly sinuous, meandering system. Such an environment would have resulted in the development of significant thicknesses of paleosols, as observed in the Harvey cores. During quiet periods, the soils would have been subject to drying and cracking, which is considered to have led to the formation of the ‘sand dykes’ seen in the paleosols in the Harvey cores.

Roostenburg 2016 used the Middle Triassic Hawkesbury Sandstone in New South Wales as a point of reference for the Triassic Wonnerup Member to establish the orientation, supply of sediments, cyclicity and depositional energy in the Harvey cores. The source of cyclically deposited erosional components is reported as being from the west and southwest, with the dominant flow direction being to the west and northeast direction (Roostenburg, 2016).

Modelling the dimensions, including the lateral extent, of the paleosols was reportedly challenging (Strachan, 2016). To the southeast of the SW Hub study area the seismic response changes, with more seismic character in the Wonnerup Member. This change was interpreted by ODIN to represent of an area of increased paleosol development, so a trend map was produced to populate the facies model with a higher percentage of paleosol objects (Strachan, 2016). A photograph of a Hawkesbury Sandstone outcrop (Figure 101), used as a depositional analogue, was used as a guide for interpreting the potential breadth and thickness of the paleosol horizons within the dominant sandstones in the Wonnerup Member. The interpreted dimensions of these paleosol horizons were used in ODIN’s 3D geological models.



*Figure 101: Section of the Hawkesbury Sandstone showing paleosols in lighter coloured sandstone (ODIN presentation to DMIRS, 2015).*

## 7.4 Modelling

The ODIN static and dynamic modelling reports are available in Appendices Q and R of this report. The modelling data can be downloaded from DMIRS' WAPIMS database or, in the case of large datasets, requested from DMIRS by email to [pet@dmirs.wa.gov.au](mailto:pet@dmirs.wa.gov.au). The modelling work is summarised below.

### 7.4.1 Static geological model

A number of 3D static geological stochastic models for the Lesueur Sandstone extending outside the SW Hub study area were constructed by ODIN. These were created to assess the impact of geological uncertainties on the CO<sub>2</sub> storage process, to subsequently establish the suitability of the study area to act as a CO<sub>2</sub> storage area. Static modelling work included building various 3D grids, facies modelling, property distributions and fault-seal analysis.

#### 7.4.1.1 Modelled areas

Figure 102 shows ODIN's modelled areas, which include the 'seismic interpretation area with faults', 'Greater Area', 'GeoGrid' area and the 'Sector Model' area (Figure 102). The 'seismic interpretation area with faults' captures the major Western Fault and F10 Fault and ODIN's interpreted minor faults within, and extending outside of, the 3D seismic study area. The Greater Area is 117km<sup>2</sup> and is bounded by the Western and F10 Faults (Figure 102). The GeoGrid area is 54km<sup>2</sup> and contains the F10 Fault and minor faults. The Sector Model area (0.25km<sup>2</sup>) was selected between wells GSWA Harvey 1 and DMP Harvey 4, where there is good geological control on the full section of the Lesueur Sandstone. The Sector Model was used for single-well injectivity modelling and sensitivity analysis.

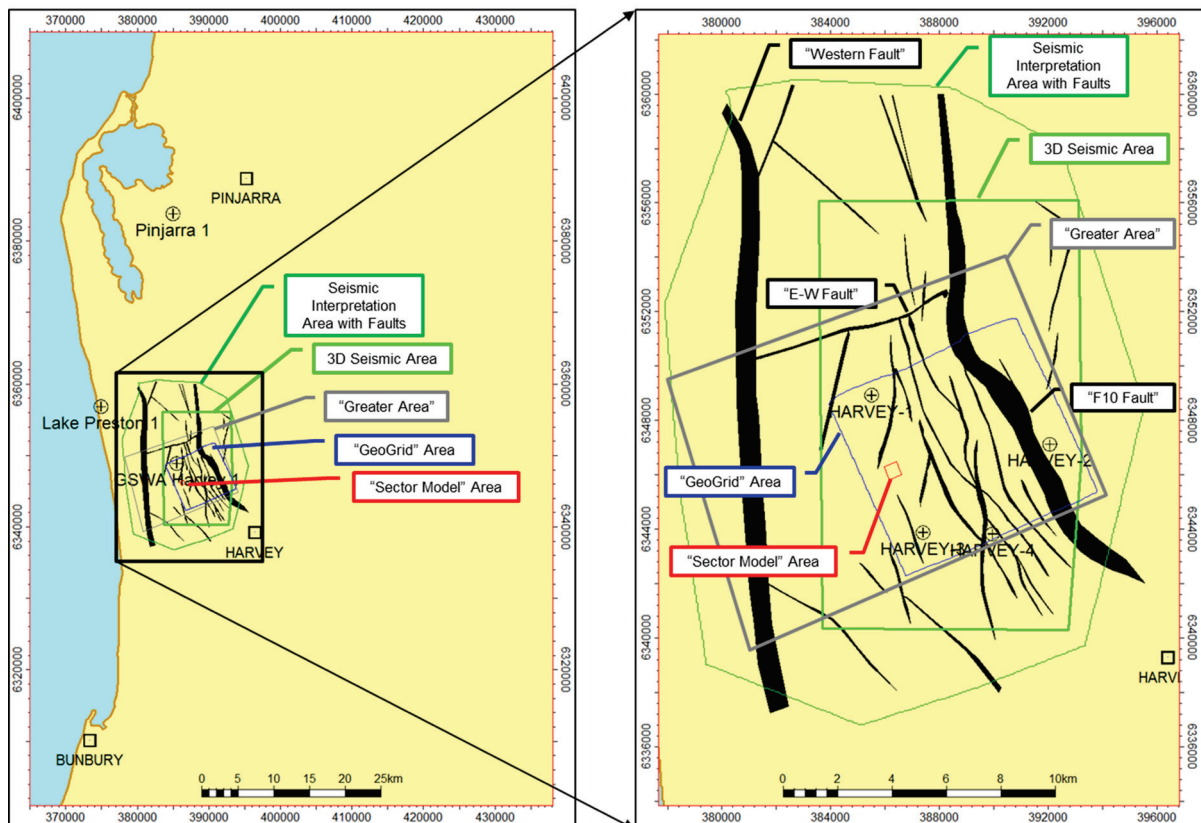


Figure 102: Modelling areas defined and used by ODIN for the static and dynamic models (Strachan, 2016; Lim, 2016).

The modelled cells were sized 25m by 25m. Upscaling trials resulted in ODIN modelling the Wonnerup Member as a four-metre thick layer and the Yalgorup Member as a one-metre thick layer. The modelled grids contained up to 214 million cells (in the 'Greater Area'; Strachan, 2016). Following upscaling in the Greater Area, the simulation grid was reduced to 1049m layers, with 1.1 million cells.

#### 7.4.1.2 Facies models

Inputs and assumptions for the various facies models comprised depositional analogues, image log interpretation and core descriptions. The models were populated with petrophysical properties, including porosity and permeability transforms and porosity–depth trends.

The lateral change in lithology in ODIN's depositional model was determined as increasingly mudstone-rich to the north and east, and is captured as lower energy and lower permeability units increasing in prevalence to the north and east of the study area. Figure 103 shows a facies model for the Lesueur Sandstone within the GeoGrid area (Figure 102), as viewed to the north-northeast. The F10 Fault is on the right of the figure.

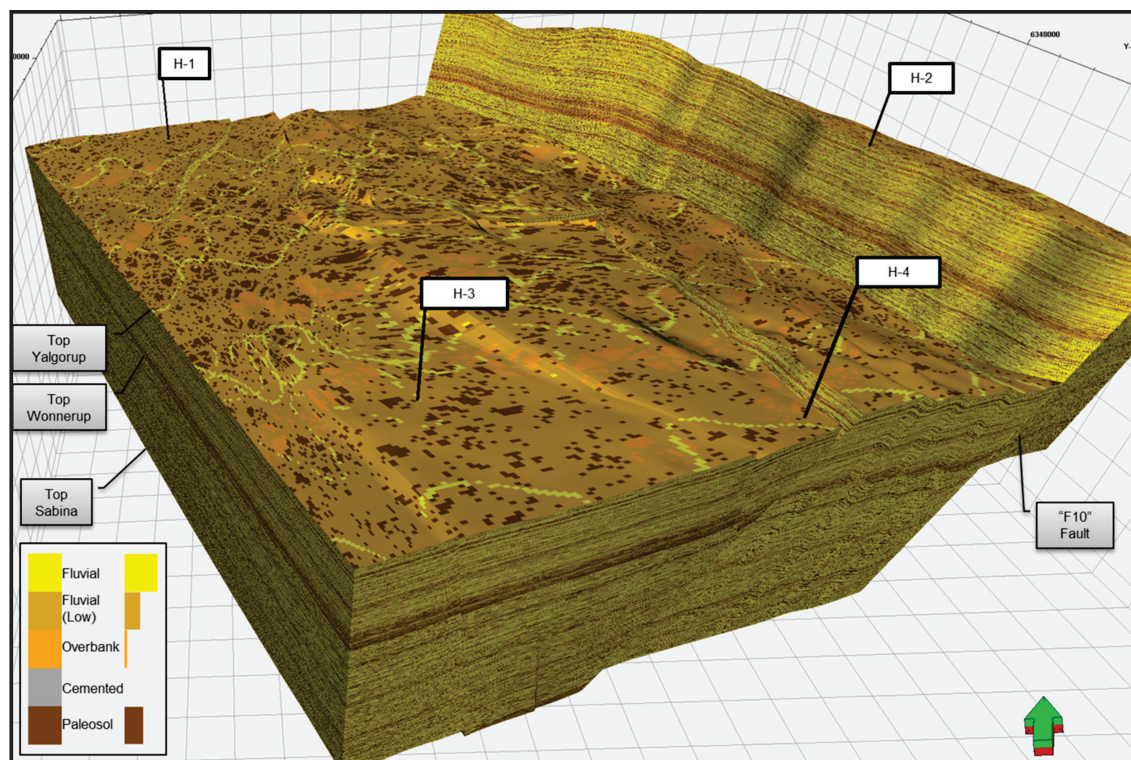


Figure 103: Facies model for the Lesueur Sandstone (Strachan, 2016). The green arrow in the bottom right corner points north.

Eight static models were constructed stochastically to investigate the impact of geological uncertainties on the effectiveness of the strata to contain injected CO<sub>2</sub>. These included a deterministic case using the seismic response to populate the paleosols in those areas outside well control (Strachan, 2016).

### 7.4.1.3 Fault-seal analysis

A fault-seal analysis was undertaken to assess the potential seal of the major faults in the SW Hub area (Strachan, 2015). The ‘major’ northerly striking faults were interpreted to have a throw of 300m or more (ie. the Western Fault and the F10 Fault). The ‘minor’ faults with throws in the order of 50–100m were considered unlikely to result in compartmentalisation to CO<sub>2</sub> in the sand-rich Wonnerup Member where sand would be juxtaposed against sand. Byrne (2016) states that there is only one interpreted easterly striking fault, the F15 Fault. The F15 Fault is a minor fault.

### 7.4.1.4 Uncertainties

Key uncertainties identified by the static modelling include: the reservoir quality – such as the percentage of sand, permeability, degree of heterogeneity and reservoir connectivity – paleosol dimensions and continuity, and the sealing capability of the faults.

## 7.4.2 Dynamic model (CO<sub>2</sub> injection simulation)

There is no proven thick, regional shale layer to act as a conventional seal in the SW Hub study area. However, large packages of clay-rich paleosol lenses are evident. The SW Hub study investigations were designed to investigate containment through dissolution and residual trapping mechanisms within the Lesueur Sandstone, a deep, saline aquifer. Secondary containment would be provided by the overlying formations. The Lesueur Sandstone storage complex consists of the lower Lesueur Sandstone (Wonnerup Member) as the injection reservoir, the upper Lesueur Sandstone (Yalgorup Member) as a lower confining layer and the Eneabba Formation, including the ‘basal Eneabba unit’ (sequence of thick paleosols), as the upper confining layer.

Two phases of dynamic modelling were carried out:

- a single-well model in a representative area for injectivity modelling
- an up-scaled model over the ‘Greater Area’ (Figure 102), which is bounded by the easterly striking F15 Fault to the north for full simulation, including plume-profile modelling and pressure developments.

The two phases of dynamic modelling are summarised below.

### 7.4.2.1 Injectivity modelling

Injectivity studies were performed for the Wonnerup Member to create a cumulative probability distribution function to test whether it is possible to inject at least 24Mt of CO<sub>2</sub> in a well over 30 years, as per the acceptance criteria (section 7.1.3).

### Reference case

The reference case is for one well and is defined as follows:

- a bottom-hole pressure (BHP) constraint of 360 bars at 2948m as determined from the geomechanical model, with pressure derived from the calculation [pore pressure + 0.9 x 69bar]
- average  $k_v/k_h$  of 0.75, as derived from the Petrel model
- no formation damage, so a skin factor of zero
- well completion is 250m from the base of the Wonnerup Member for horizontal permeability ( $k_h$ ) of 20,330mD-m
- arbitrary start date of 1 January 2020.

The results of the reference case model are shown in Figure 104. The results suggest that a maximum injection rate of approximately 390,000m<sup>3</sup> per day (700 tonnes of supercritical CO<sub>2</sub> per day) could be achieved with a single well, with injectivity declining as a function of time as the reservoir pressure increases due to the injection of gas. The model indicates that 6.9Mt of supercritical CO<sub>2</sub> could be injected over 30 years (Lim, 2016).

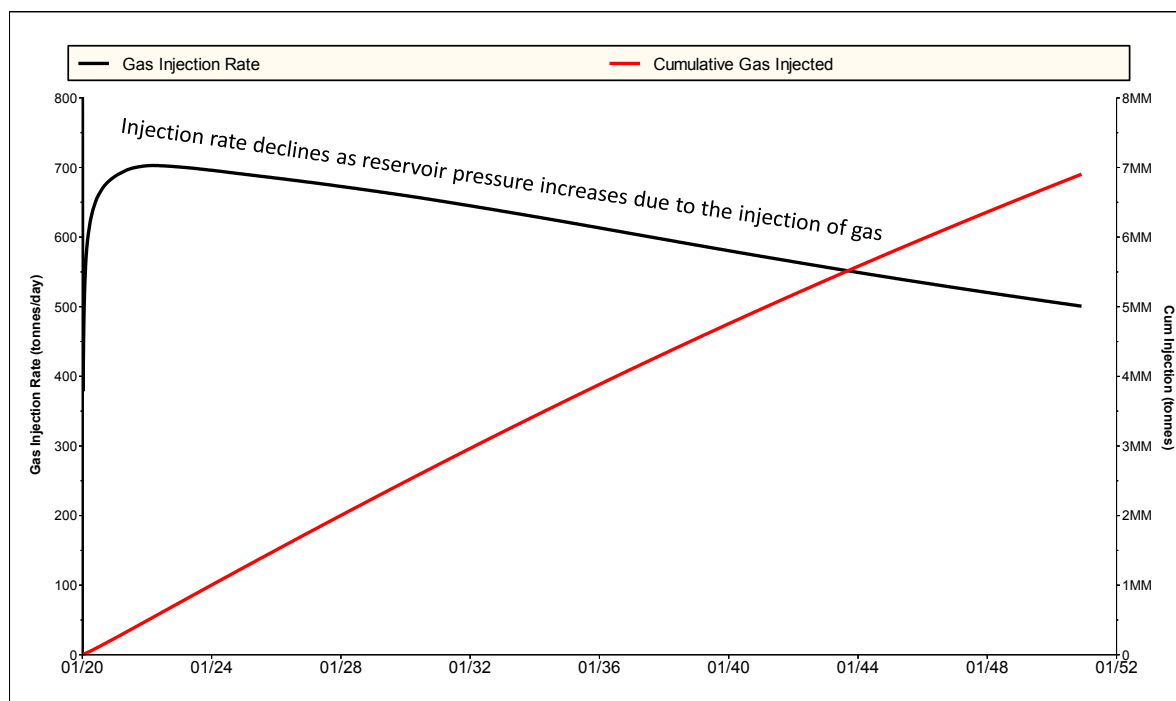


Figure 104: A reference case for probabilistic estimates of volumes of supercritical CO<sub>2</sub> that could be injected into the Wonnerup Member using a single-well model (Lim, 2016).

### Sensitivity analysis

A range of sensitivity studies was conducted in which the impact of the variance of parameters was assessed on the potential total injectivity of supercritical CO<sub>2</sub> within 30 years. Table 52 lists the parameters tested with the corresponding number of million tonnes of supercritical CO<sub>2</sub> injected (Lim, 2016).

Table 52: Modelling parameters for CO<sub>2</sub> injectivity sensitivity studies (Lim, 2016)

Scenario	Million tonnes of CO <sub>2</sub> injected over 30 years
Low relative permeability to CO <sub>2</sub> gas	3.1
Small compartment	3.6
Low bottomhole pressure constraint	4.3
Low relative permeability to water	4.6
Low permeability	5.1
Low vertical permeability	6.6
Reference case	6.9
Large compartment	7.4
High relative permeability to water	7.8
High permeability	9.0
High bottomhole pressure constraint	9.3
High relative permeability to CO <sub>2</sub> gas	9.8

Combinations of the above parameters were used to create a probability density function for volumes injected via a single well. Probabilistic estimates are shown in Figure 105.

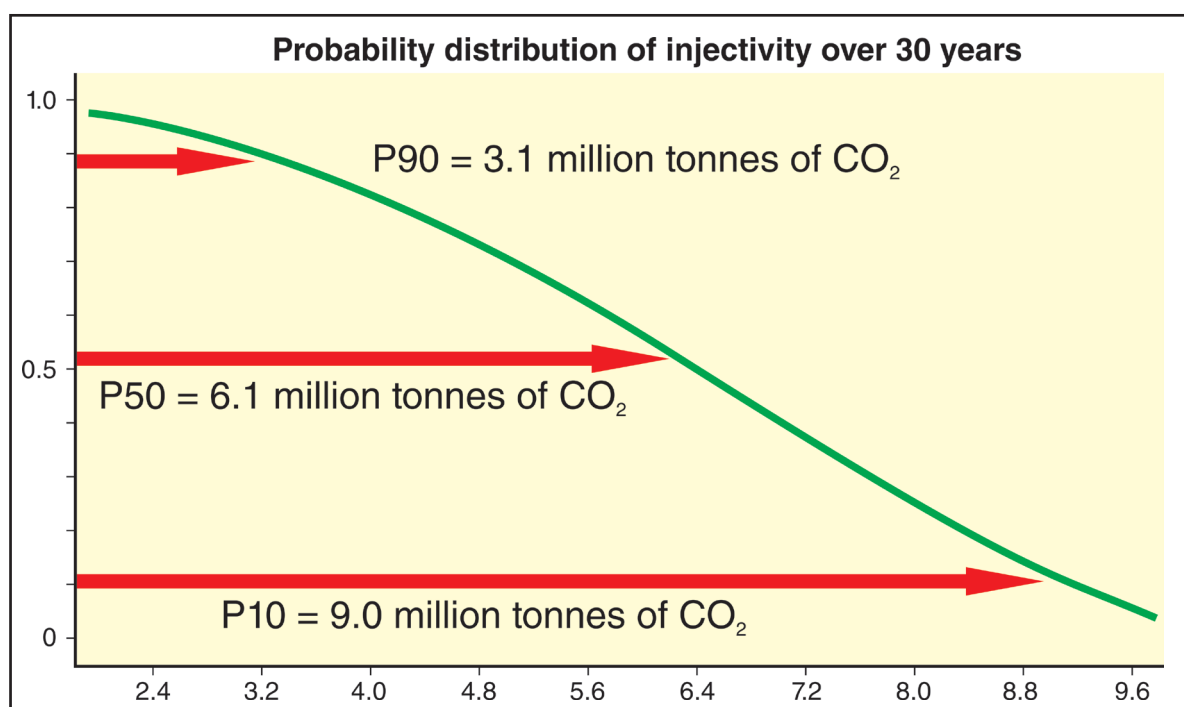


Figure 105: Probabilistic estimates of volumes of CO<sub>2</sub> injected through a single well (Lim, 2016).

Modelling indicates that, under the current set of assumptions and sensitivity ranges tested, there is confidence that the acceptance criteria for injectivity can be met by the Wonnepur Member.

### 7.4.2.2 Full-field simulation

The full-field model was built to integrate all of the available subsurface information into a dynamic reservoir model to represent and describe fluid-flow processes in the reservoir. The model was up-scaled from the 'Greater Area' model based on the grid sensitivity studies. To further reduce the number of cells, all cells with a depth shallower than 800m were made void, as migration of CO<sub>2</sub> to depths shallower than 800m would be considered a breach of the containment criteria (section 7.1).

Full field simulations were performed to model the movement of the CO<sub>2</sub> plume after 30 years of injection at 800,000tpa and 1000 years of shut-in. The simulation model assumed nine CO<sub>2</sub> injectors in a staggered line configuration, all completed in the bottom 250m of the Wonnerup Member.

The reference case assumed that the interpreted and measured parameters for reservoir fluid salinity, trapped gas saturation, bottom-hole pressure (BHP) constraints from the geomechanical assessment study and relative permeability from SCAL data were fair and reasonable. All faults in the Wonnerup Member were assumed to be non-sealing, as they result in sandstone juxtaposed with sandstone.

Full-field simulation modelling using the reference case assumptions shows that the plume has a limited spread of 7km by 7km and remains within the Wonnerup Member (Figure 106).

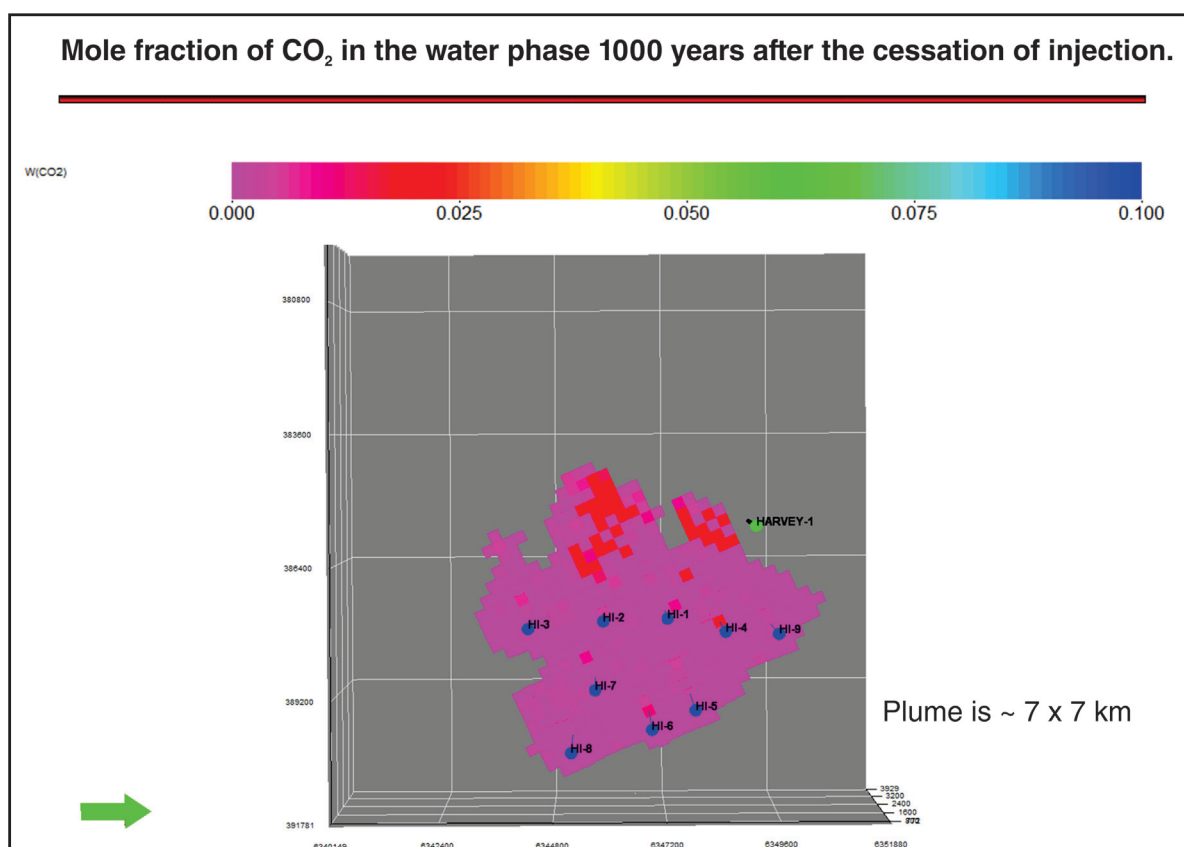


Figure 106: Dynamic-model reference case: a plan view of CO<sub>2</sub> distribution as a mole fraction in the formation brine, for 1000 years after the cessation of injection of CO<sub>2</sub>.

Eight scenarios were considered in addition to the reference case to test against the decision criteria. Two additional 'stress' scenarios were tested to examine the impact of 'extreme' assumptions on plume migration.

These were:

- low trapped gas saturation and low solubility to force more CO<sub>2</sub> upwards
- a significantly higher rate of injection, this being three million tpa.

The motivation for testing the larger volumes is that it equates to the emissions of a 500MW thermal power station.

The results of all the modelled scenarios are consistent with the injection of 800,000tpa of CO<sub>2</sub> across 30 years in the Wonnerup Member using nine wells. The injected CO<sub>2</sub> remains within the Wonnerup Member even after 1000 years. Notwithstanding, uncertainties remain, and these will be documented in an updated uncertainty-management plan, as discussed below.

### 7.4.3 Uncertainty-management plan

An uncertainty-management plan is being developed by DMIRS to address the key technical uncertainties. Principal among these are:

- vertical flow uncertainty within the Wonnerup Member
- properties in the deeper sections of the Wonnerup Member, as only one data point currently exists, this being well GSWA Harvey 1
- compartmentalisation effects of faults interpreted within and outside the resolution of the seismic data
- short-range horizontal and vertical heterogeneities in the formations
- paleosol dimensions and baffling effects in the Yalgorup Member
- reservoir fluid geochemistry.

When the range of each of the uncertainties is narrowed, it is proposed that the static and dynamic models be updated.

## 7.5 Carbon-storage potential

The current modelling results indicate that it could be feasible to inject 800,000tpa of CO<sub>2</sub> across 30 years in the Yalgorup and Wonnerup Members in the SW Hub study area. The modelling supports an average injectivity of 100–300 thousand tonnes per annum per well using three to nine injection wells.

Modelling studies to date indicate that all of the injected CO<sub>2</sub> would remain in the Wonnerup Member and that the main factors controlling CO<sub>2</sub> plume migration are trapped gas saturation and the solubility of CO<sub>2</sub> in brine.

## 8.0 Contributions to geological knowledge

The significant volume of data resulting from the drilling and subsequent investigation of the shallow Harvey wells, DMP Harvey 2, 3 and 4, has clarified and added to the geological understanding of the southern Perth Basin. Insights are summarised below.

## 8.1 Faulting

Faults in the 3D seismic study area are well defined in the deeper Wonnerup Member, where the capture of high-fold seismic data was achieved. The faults are less well defined in the shallower Eneabba Formation and Yalgorup Member, but the major faults penetrating these can be identified. The major faults are the F10 Fault to the east of the SW Hub study area with a throw of 400 to 1000m and the Western Fault to the west of the SW Hub study area (outside the 3D seismic study area; Figure 102). The majority of the faults strike north-northwesterly and are normal faults with dips to the northeast or southwest. The F10 Fault has penetrated the break-up unconformity surface, which indicates that the F10 Fault was active in the Cretaceous Period.

The DMP Harvey 2 well was drilled through the F10 Fault. However, the fault zone is not easily discernible in the core, possibly due to the uncompacted nature of the sediments. The drillers and on-site geologists reported potential faults between 508 and 878m depth (Table 51). The HyLogger spectral data indicate elevated sylvite, water 'locked' in the core and amorphous silica, all of which may suggest that the F10 Fault is between 347 and 870m in the DMP Harvey 2 core (refer to section 5.4.1 for details). Using Byrne's, (2016) interpretation of the 3D seismic data, Strachan, (2016) positioned the F10 Fault intersect in well DMP Harvey 2 at 531m.

The slickensides visible in the paleosol sections of the cores are considered to be pedogenic and unrelated to tectonic faulting.

## 8.2 Lithostratigraphy

The wells DMP Harvey 2, 3 and 4, in addition to GSWA Harvey 1, were integrated into ODIN's pre-drilling 3D seismic survey interpretation and provided depth surfaces of the 'break-up unconformity' (base of the Leederville Formation), the top of the 'basal Eneabba unit', and the top of the Yalgorup Member and top of the Wonnerup Member of the Lesueur Sandstone. These surfaces, with Byrne's, (2016) interpreted faults, were used in the construction of a revised 3D structural model (Strachan, 2016). The interpretation of the 3D seismic data indicates that the Yalgorup Member and Wonnerup Member are continuous across the SW Hub study area.

The three-well drilling program has shown that the paleosol packages identified in the Eneabba Formation and Yalgorup Member in well GSWA Harvey 1 in 2012 extend across the SW Hub study area. The integration of observations from the Harvey core; along with interpretations from the 3D seismic data, core analysis data and image log data; indicates that the paleosols become more pervasive with stratigraphic depth to the north and east of the 3D seismic study area.

The three wells DMP Harvey 2, 3 and 4 have added to existing knowledge about the lithologies across the SW Hub study area. The Leederville Formation comprises silt-rich and sand-rich facies, with minor claystone. The Eneabba Formation is predominantly sand rich, with paleosol packages of thickly interbedded siltstones, claystones and mudstones. In comparison with the other units, the Yalgorup Member has more mud-rich facies; with sandstone and minor siltstone and minor claystone facies reflecting the thick sequences of paleosols in the unit. The Eneabba Formation and Yalgorup Member are similar lithologically and it is difficult to differentiate between the two without palynological data. The Wonnerup Member is predominantly sand rich (93–96 per cent), with minor mud-rich, clay-rich and silt-rich facies.

The Lesueur Sandstone is approximately 2200m thick with the Yalgorup Member typically 500–700m thick at the Harvey well locations. The Wonnerup Member is at least 1500m thick in GSWA Harvey 1 and, although the full section was not drilled in wells DMP Harvey 2, 3 and 4, it is considered to be of similar thickness based on the seismic survey data.

The seismic signature of the stratigraphy differs on either side of the F10 Fault. The processed seismic data indicates that there is an increase in the number of reflective horizons in the Wonnerup Member to the east of the F10 Fault. This could indicate an increased propensity for paleosol packages with stratigraphic depth to the east of the F10 Fault. Further deep drilling would be required to clarify the stratigraphy and depositional environment to the east of the F10 Fault.

The facies types in the Lesueur Sandstone as defined by Delle Piane et al., (2013) have been simplified by ODIN into three broad facies groups: high-energy fluvial, low-energy fluvial and paleosols. In the Yalgorup Member, low-energy fluvial deposits include overbank facies.

## 8.3 Petrography

### 8.3.1 Inorganic petrography

Inorganic petrography supported the geological description from lithological logging and wireline logging. This, in combination with other data, has assisted with the interpretation for the depositional environments. Mudstone-rich units with interbedded sandstones were identified as low-energy depositional sediments. The mudstones are poorly sorted, strongly weathered and exhibit soil development (paleosols). The clays in the paleosol units are illite–smectite dominant.

The sandstones are quartz dominant and contain common feldspar and lithic fragments, and biotite and muscovite. The biotite is altering to kaolin-group clays (Nelis, 2015, Appendix M). Fractures within the clay-rich fabric opened during sample preparation. It is considered that the fractures within the swelling clays of the stratigraphy are sealed when brine-saturated and subject to confining pressure in situ.

The inorganic petrography analysis has identified allogenic and authigenic minerals. The presence of authigenic minerals indicates depositional diagenesis (chemical altering) in the Wonnerup and Yalgorup Members of the Lesueur Sandstone, and in the Eneabba Formation. The quartz and K-feldspar overgrowths and kaolin clay observed have the potential to reduce the permeability of the reservoir. Further work is required to understand the diagenetic processes and the impact these may have on the injection, storage and migration of supercritical CO<sub>2</sub> in the Wonnerup Member reservoir. This may assist in the planning and management of any future injection program.

### 8.3.2 Organic petrography

The thermal immaturity of the Lesueur Sandstone as indicated by vitrinite reflectance data suggests that it was not buried at significant depth, and suggests that either the Yarragadee Formation was not present, or that the erosion of the Yarragadee Formation may not have been as significant as previously considered on the Harvey Ridge.

## 8.4 Palynology

Palynological analysis identified an *Ashmoripollis reducta* – *Samaropollenites speciosus* zone at 732.50m in DMP Harvey 2. This is the first time that this pollen species has been captured in the southern Perth Basin and indicates that the Yalgorup Member strata in DMP Harvey 2 as defined by Byrne, (2016) ranges from Early to Middle Triassic to Early Jurassic in age. There is the potential for palynological analysis and research to assist the determination of the stratigraphic succession and terminology of the southern Perth Basin.

## 8.5 Wireline Logging

The log interpretation confirms that the Lesueur Sandstone consists of interbedded sandstones and paleosols. Kennedy's, (2016) interpretation of the gamma-ray and density–neutron logs resulted in Strachan, (2016) constructing the static model with the Yalgorup Member comprising approximately 31 per cent paleosols and the Wonnerup Member being approximately 3 per cent paleosols (Figure 66).

Good reservoir properties are recorded in the homogeneous, sandstone-rich Wonnerup Member. These fall from 25 per cent near the top of the unit to 20 per cent at the final well DMP Harvey 4 (1740m), and to 10 per cent in GSWA Harvey 1 at the base of the Wonnerup Member (2840m). In contrast, the overlying Yalgorup Member is far more heterogeneous with porosities of the order of 25–30 per cent in the sandstone intervals.

The Yalgorup Member has a broader range of porosities than the Wonnerup Member, associated with a wider range in facies, and a correspondingly wide range in permeabilities. There is a clear trend in permeability reduction with depth. Permeability reduces from more than 4000md to less than 10md for the Wonnerup Member. For the Yalgorup Member, the permeability of sandstone intervals ranges from 4md to more than 10,000md. There is a good correlation between the measured and calculated permeabilities.

As observed in the lithological logs and interpreted wireline logs from the wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4, the lithologies within the SW Hub study area are increasingly mudstone rich to the north and east. The direction of deposition has been interpreted as from the southwest to the northeast.

Interpretation of the caliper logs indicates that well break-out and general caving and enlargement were in a north–south direction. The maximum compressive stress at the reservoir level is interpreted to be orientated east–west.

## 8.6 Depositional analogues

The Lesueur Sandstone as defined by Byrne, (2016) was deposited during the Triassic and Jurassic Periods in a braided fluvial environment within the southern Perth Basin. The suggested analogues for the depositional environment of the Wonnerup Member are the braided fluvial systems in the Hawkesbury Sandstone in New South Wales and the middle reaches of the Brahmaputra River or the Indus River, with a meandering fluvial system suggested for the overlying Yalgorup Member.

# 9.0 Observations and lessons learned from drilling

Observations and the lessons learned during the drilling campaign have been documented by DMIRS. These are summarised below.

## 9.1 Land access

The development of relationships and consultation with the LCCC and land owners assisted in gaining access to land and in minimising inconvenience to the local community during the drilling program. Minimisation of vehicular movement, noise, rig lighting, visual impact and access to a reliable and adequate water supply were considerations addressed in dialogues with Department of Main Roads, the Harvey and Waroona Shires and land owners.

## 9.2 Drilling operations

The lessons learned during the operational drilling of wells DMP Harvey 2, 3 and 4 are summarised below.

### 9.2.1 Drilling specifics

#### 9.2.1.1 Optimal drill bits

Generally ground conditions were harder and more abrasive than anticipated. Frequent bit changes were also required in those sections of the Eneabba Formation and Yalgorup Member where the lithology varied rapidly, resulting in slower drilling rates. The lithologies encountered to the east of the F10 Fault, in DMP Harvey 2, differed from those encountered to the west of the F10 Fault. The lithologies to the east of the F10 Fault were richer in mud facies than those to the west of the fault.

Many drilling bits were trialled, but the optimal bit for drilling the variably interbedded mudstones and sandstones within paleosols was a surface-set internal discharge step bit with large protruding diamonds, as used in DMP Harvey 2. The optimal drill bit for drilling the sandstones of the Wonnerup Member in DMP Harvey 4 was a four-blade, hard-formation, PCD or compact bit.

#### 9.2.1.2 Management of a pressurised formation

Formation swelling, down-hole backfill and deteriorating hole conditions resulted in drilling difficulties in the three wells, particularly in the Eneabba Formation and Yalgorup Member. These were managed by increased reaming runs to condition the holes. Washed-out sections were observed using the multi-arm caliper during wireline logging runs of wells DMP Harvey 3 and 4. Drilling through the pressurised formation in DMP Harvey 4 was managed by the addition of barite to the drilling fluid as a weighting agent.

Any further drilling in the SW Hub area will need to consider management of the formations while drilling, the impact of the changing formations on the estimated time to drill, and dispersive and pressurised formations in the planning of an optimal drilling fluid.

#### 9.2.1.3 Leak-off tests

Leak-off tests were attempted, but only limited data could be obtained, as summarised in section 4.3.1. In order to obtain more data to constrain the minimum horizontal stress, the following are recommended during any future drilling campaign:

- selection of pump capacity following review of leak-off test data from wells drilled in the same region
- recording the pumping rate
- longer duration tests or extended leak-off tests
- formation stress tests using a wireline tool. This was planned for DMP Harvey 4, but was not performed due to poor hole conditions.

#### 9.2.1.4 Fluid losses and fluid gains

Following the drilling of DMP Harvey 2, 3 and 4, it is recommended that any scope of works requires qualitative and quantitative descriptions, and reporting and monitoring of fluid losses and fluid gains. These should be documented in detail in the daily drilling reports. The resulting information will assist in better drilling-fluid management and well conditions.

The presence of an on-site mud engineer is recommended during any future drilling, in order to provide timely advice and dynamically manage the mud chemistry, weight and rheology to optimise drilling time and costs. An on-site mud engineer's records should be captured in the daily drilling reports.

### 9.2.2 Drilling fluids

The experiences gained with the use of drilling fluids used in the three wells resulted in the following observations and recommendations:

- The information available in well completion reports for wells drilled in the same region, specifically the final well reports and daily drilling records, should be read during the planning stage of any drilling project to advise on the drilling-fluid requirements. The type of rig used to drill a well can affect the choice of drilling fluid. For example, during the drilling of GSWA Harvey 1, which employed an oil-industry and gas-industry rotary rig, the focus was on the pressure-based system with inadequate appreciation of the dispersive formations. Conversely in the planning phase of wells DMP Harvey 2, 3 and 4, which used mineral-well and water-well rigs, the initial focus was on a dispersive system, using an inhibitor and an encapsulator. The focus changed as drilling progressed in well DMP Harvey 2, to incorporate the pressurised formations.
- Any further drilling in the SW Hub area will need to consider dispersive and pressurised formations, and the prognosed time to complete the well in the planning of an optimal drilling fluid.
- Barite was required in DMP Harvey 4 and not in DMP Harvey 2 or DMP Harvey 3 due to the latter holes being slim holes. A KCl polymer (KCl/PAC-R) fluid was successfully used, allowing drilling-fluid density to be controlled without the addition of contained solids.
- High mud weights, typically greater than 10ppg, were required to maintain hole stability in GSWA Harvey 1 and DMP Harvey 2, 3 and 4. Australian Mud Company advises that the use of sodium chloride as a weighting agent could be considered to reduce drilling fluid costs in any future drilling in the SW Hub study area (Nims and Pollock, 2015).
- Any further drilling in the CCS study area should consider using higher concentrations of KCl and barite and increased use of LCM (Russell and Iley, 2015) in zones of fluid loss.
- Running the intermediate casing to a 500–700m depth is recommended to counteract formation squeezing, such as in paleosol units in the Eneabba Formation and Yalgorup Member.
- Seepage losses should be monitored and correlated to changes in mud weight.
- The continuous on-site presence of an oilfield mud engineer is recommended.

### 9.3 Site supervision

DMIRS 'bundled' the drilling service contracts such that all services were managed by the drilling company, DDH1 Drilling. The bundled contracts included the site works and on-site geologists. The provision of the geologists was subcontracted by DDH1 Drilling to Rockwater.

Following DMIRS experiences, it is recommended that the on-site geologists are contracted separately from the drilling rig provider for future drilling programs utilising a petroleum rig. The optimal scenario is for an experienced representative from DMIRS to be on-site to make the necessary decisions and to document issues as they arise and the action taken.

## **9.4 Contract management**

Department of Mines, Industry Regulation and Safety's contract with the drilling company was written such that DMIRS paid a meterage rate, rather than a time rate. This was an advantage to DMIRS budget. However, the absence of an on-site supervisor acting on behalf of DMIRS, and the absence of an on-site mud engineer, resulted in prolonged drilling time, particularly with respect to DMP Harvey 3 and 4. This resulted in delays in the analysis and modelling stages that followed the drilling program. The contracted cost arrangement meant that the costs associated with any drilling delays were borne by the drilling contractor unless specific delays were justified by the driller and negotiated with DMIRS.

## **9.5 Benefits of using the HyLogger spectral scanner**

During the shallow drilling program, DMIRS' HyLogger spectral scanner was recognised as an important value-adding instrument that can efficiently and effectively provide core-tray imagery and qualitative data. In any future drilling program it is recommended that prior arrangements are made with Perth Core Library's mineralogical investigation staff to have the core processed by the HyLogger spectral scanner as soon as the core arrives at the Perth Core Library. Such action will ensure that the core does not undergo any physical or chemical changes, such as desiccation and cracking, reaction with the air and evaporation of drilling salts from the core's surface. All of these processes diminish the HyLogger's ability to report the mineralogical composition of the core, hindering effective core sampling.

The HyLogger imagery and data assisted in the determination of core selection depths. The uncertainty of the depth offset in the wireline logs, which was caused by different logging datums or stretching of the cable during electrical logging of the wells, was reduced through a correlation between the HyLogger data and the lithological logs.

## **9.6 Risk management**

Risk was identified and managed by DMIRS in the planning, operational and data analysis stages of the drilling program. Risk matrices were developed and used to create 'what-if' scenarios to streamline the decision making on-site and identify potential problem areas. The process was accepted by DMIRS contractors, but reporting was limited and the escalation matrix did not always work as intended. This could be avoided in the future by having a DMIRS on-site supervisor.

It is recommended that, at the end of any drilling program, a close-out meeting is held where all aspects of the drilling activities are reviewed by all parties involved, with the lessons learned being captured and reported.

## **9.7 Project evaluation**

Department of Mines, Industry Regulation and Safety successfully managed the drilling of three wells to ascertain the character and lateral extent of the containing strata in the SW Hub study area. The lessons learned and documented in this report and in the final well report for the GSWA Harvey 1 well can be used in any future drilling campaign.

## 10.0 Conclusions and recommendations

The SW Hub storage concept postulates that injection at the bottom end of the thick Lesueur Sandstone reservoir sequence, at a depth of about 3000m, will promote dissolution and residual trapping by providing a convoluted percolation path for CO<sub>2</sub> induced by buoyancy. This would result in safe containment of the CO<sub>2</sub>, even in the absence of a conventional structural sealing layer. The absence of the Yarragadee Formation aquifer and lack of conflict with other resources provide additional support to examining the potential of the Lesueur Sandstone for CO<sub>2</sub> storage in the SW Hub study area.

In order to provide the additional data for analysis of the concept, DMIRS has conducted 2D and 3D seismic data acquisition programs and drilled a total of four wells to date. Through the 2014–15 drilling program, DMP has successfully drilled three wells to ascertain the character and lateral extent of the strata in the SW Hub target area. As a result of this shallow-well drilling program, over 2100m of core and significant wireline logging data have been obtained. This provides a wealth of geological information and potential research material.

The resulting data, when added to that obtained from the GSWA Harvey 1 well (2012) and the 2D (2011) and 3D (2014) seismic data, have been interpreted to create 3D structural geological models for the lower Eneabba Formation and Yalgorup and Wonnerup Members of the Lesueur Sandstone. These models were then used for the creation of dynamic models, which indicate, within model assumptions, that supercritical CO<sub>2</sub> injected into the target reservoir at a rate of 800,000tpa for 30 years at a depth of 3000m can be contained within the Wonnerup Member.

In order to further prove up the injection potential and storage capacity of the Wonnerup Member (the target reservoir), it is considered that well tests will be required in order to capture dynamic reservoir data. The drilling reports for wells GSWA Harvey 1 and DMP Harvey 2, 3 and 4 should be used in any further well drilling and investigation to ensure the lessons learned during the Harvey drilling campaigns, and the recommendations made, are incorporated into any future drilling in the SW Hub study area.

All reports and data captured and associated with DMP Harvey 2, 3 and 4 have been stored by DMIRS in [WAPIMS](#) and can be accessed free of charge. Some very large datasets have not been uploaded to the WAPIMS database, but can be requested from DMIRS via email request ([petdata@dmirs.wa.gov.au](mailto:petdata@dmirs.wa.gov.au)).

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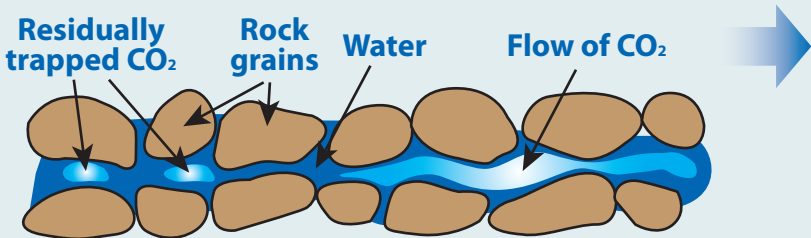
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## Glossary of terms

Allogenic	Minerals that are formed elsewhere and transported into the area of deposition to form sediments
Anisotropy	In reservoir rocks, variation in seismic velocity measured parallel or perpendicular to bedding surfaces. Common in shales, where it is typically caused by platy minerals, such as micas and clays, aligning parallel to depositional bedding as sediments are compacted
Annulus	The gap between the formation and the casing in a well or borehole
Aquifer	Rock or a stratum that can store and transmit water. In the oil industry an 'aquifer' is referred to as a 'reservoir' (for petroleum product)
Aquiferous	Water bearing
Authigenic	Chemical sedimentary minerals formed by precipitation or recrystallisation at the site of deposition, instead of being transported from elsewhere (allogenic) by water or wind
Baffle	A stratum with very low permeability and the potential to impede the migration of carbon dioxide. In the South West study area the baffles are typically paleosols (ancient former soils) and comprise siltstones, claystones, mudstones and minor sandstones
Barite	Naturally occurring, barium-based mineral with the chemical formula $\text{BaSO}_4$ . It has a high specific gravity of $4.50\text{g/cm}^3$ , which makes it a useful and relatively inexpensive weighting material in the formulation of drilling mud. Barite increases the hydrostatic pressure of the drilling mud, allowing it to compensate for any high-pressure zones experienced during drilling. The softness of barite prevents it from damaging drilling tools and enables it to act as a lubricant during drilling operations. The American Petroleum Institute (API) has established specifications for barite in drilling mud
Biostratigraphy	The branch of stratigraphy concerned with fossils and their use in dating rocks
Blowout preventer (BOP)	A specialised valve used to seal, control and monitor oil and gas wells to prevent the uncontrolled release of well fluids or gas (eg. brine, crude oil or natural gas)
Buoyancy	An upward force exerted by a fluid that opposes the weight of an immersed object. In a column of fluid, pressure increases with depth as a result of the weight of the overlying fluid
Chromium steel	Carbon steel with added chromium creating a corrosion-resistant alloy material
Completion	With respect to wells, this is the final state of the well following the installation of casing, tubing and any monitoring equipment
Contamination	Effect on reservoir fluid properties as a result of mixing with drilling fluids that filter through the wall of the well
Core analysis	Laboratory study of a sample of a geologic formation, usually reservoir rock, taken during or after drilling a well and used for understanding key properties of reservoir rock, such as porosity, permeability and wettability
Core barrel	Drilling equipment that retains rock core samples from well coring operations. Typical lengths vary from 0.5 to 3m
Core plug	A plug, or sample, taken from a conventional core for analysis. Core plugs are typically 1–1½ inches (2.5–3.8cm) in diameter and 1–2 inches (2.5–5cm) long
Craton	Ancient, stable geological province at the core of a continent

Detrital	Referring to particles transported through sedimentary processes into depositional systems such as riverbeds, lakes or the ocean, forming sedimentary successions
Diagenesis	Diagenesis is the process by which sediments are lithified into sedimentary rocks and represents the sum of physical and chemical changes that take place during burial
Diverter	A valve that is used to divert the flow of well fluids or gases (crude oil, gas or water) away from the well
Electrical conductivity (EC)	Measurements characterising the ability of a reservoir rock and its in situ fluids to conduct electricity. In sedimentary rocks this is affected by the composition of the reservoir fluids, rock porosity and pore geometry
Facies	Sedimentary facies are bodies of sediment that are recognizably distinct from adjacent sediments that resulted from different depositional environments
Fault	A planar fracture or discontinuity in a volume of rock, across which there has been displacement as a result of rock mass movement
Fault block	The block of rock positioned adjacent to a geological fault
Ferruginisation	The process of introducing iron into a rock
Footwall	The block of rock positioned under a geological fault
Geosequestration	Physical storage of an entity within geological strata
Groundwater	Water stored within a geological formation, below the water table
Hangingwall	A block of rock positioned above a geological fault
Homogeneous	In geology, strata having consistent properties, commonly the spatial attributes of 'homogeneity' are described, eg. laterally homogeneous
Heterogeneous	This term is used to describe geological strata having inconsistent properties, eg. laterally or vertically heterogeneous
Intergranular	The spaces between the grains in a sediment or rock
Interval coring	Coring activity during drilling where rotary drilling is switched to drilling with a core barrel to obtain core. Rotary drilling results in rock chips being brought to the surface of the well by the returning drilling fluids and muds
Intraclast	An irregularly shaped grain, formed by the redeposition of eroded material from an original deposit
Intragranular	In inorganic petrography analysis, the spaces within the grains
Jurassic	Period covering the time span of 203–145Ma
Klinkenberg permeability	The equivalent permeability of a non-reactive fluid in the formation
Linguoid	Asymmetrical ripples, formed in a flood-prone or tidal fluvial system with low flows
Lithofacies	See Facies, above
Lithology	The description of the physical characteristics of a rock visible at outcrop, in hand or core samples or with low magnification microscopy, such as colour, texture, grain size or composition
Liquefied	The process of compressing a gas to form a liquid; in this case, carbon dioxide (CO <sub>2</sub> ) gas
Microseismic	Microseismic monitoring is the passive observation of very small scale, natural earth tremors or those resulting from fluid injection

Mineral rig	Equipment used to drill and core wells in the mining industry. Such rigs typically can core the formation continuously
Net overburden pressure	The pressure a rock sample would experience at a specified depth, caused by the weight of the interstitial pore water and rocks above the formation
Organic petrography	The study of organic matter in rocks, including its origin and thermal maturity due to burial within the earth's crust
Packer	A device with expandable elastomers that can be used to isolate different parts of a well or well completion from each other
Paleosol	An old soil that has since been compressed to form mudstone, siltstones or claystone. The rock formed is dependent upon the predominant particle size within the original soil horizon
Palynology	The study of spores and pollens, the identification of which can inform the age of the rocks in which these are identified
Pedogenic	Relates to processes taking place in soil, or that lead to the formation of soil
Permeability	A measure of the ability of a porous material to transmit fluid. In petroleum studies, the unit of permeability is a Darcy (d). In core analysis the unit used for permeability is the millidarcy (md), which is one thousandth of a Darcy
Petrography	The study of the description and classification of rocks, as advised by examination of thin sections
Petrology	The study of the origin, composition, structure and properties of rocks
Phanerozoic	The name for the geological Eon covering the time span between 540Ma and the present
Plume fairway	The direction a modelled volume of supercritical CO <sub>2</sub> will take once injected into a stratum. As in golf, the 'fairway' is the course, and direction, of a migrating plume of injected CO <sub>2</sub>
Porosity	A measure of the pore volume as a fraction of the bulk volume of a material
Pre-competitive data	Data and analyses resulting from activities conducted by a government regulatory body to suitably inform industry about a CO <sub>2</sub> storage opportunity. In this specific case, it would include the research being conducted jointly with participating research organisations, for the purpose of better delineating the reservoir or potentially developing new commercially applicable technologies, or both
Pyrolysis	Thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible. The word is coined from the Greek-derived elements pyro 'fire' and lysis 'separating'
Ram	A single blowout preventer that uses a pair of opposing steel plungers (rams) to restrict or permit flow
Reservoir	Porous and permeable rock that yields oil, gas or water

Residual trapping	<p>This term describes the process for primary containment of CO<sub>2</sub> within the rock matrix. Here CO<sub>2</sub> is retained in a non-continuous state (ie. isolated bubbles) in the pores within the rock matrix as shown in the figure below.</p> 
Rotary rig	Equipment used to drill wells in the oil and gas industry. Such rigs can typically drill larger hole sizes and to greater depths than mineral rigs
Run (wireline logging)	Refers to a number of tools being lowered (or raised) in a well to obtain a continuous record of a formation's rock properties
Seismic survey	Acquisition of seismic data to map the earth's subsurface
Secondary	In geological terms 'secondary' refers to a geological process that followed the primary process, such as secondary silicification, where the mineral silica has been introduced into the rock after deposition of the sediments that formed the rock
Scanning electron microscope (SEM)	A type of electron microscope used to scan a thin section of rock with a focused beam of electrons. The electrons interact with atoms in the sample, producing signals that contain information about the sample's surface topography and composition.
Sheared pipe	The pipe that is cut off by shear rams to seal the well
Spectral analysis	Analysis done by a spectrometer
Spectrometer	An apparatus that measures one or more spectra (intensity as a function of wavelength, frequency, energy, momentum or mass)
Spud	The process of starting to drill a well, typically an oil or gas well. A large drill bit is used to drill a wide-diameter surface hole, which is lined with casing and cement to protect groundwater.
Stochastic	With respect to statistical computer modelling this term means that the model was populated using an unpredictable or random sequencing process, representing the evolution of a system
Strata	Plural of stratum
Stratigraphy	The study of strata
Stratum	A layer of sedimentary rock or soil with internally consistent characteristics that distinguish it from adjacent layers. The stratum is the fundamental unit in a stratigraphic column and forms the basis of the study of stratigraphy.
Suite	In wireline logging, a number of wireline logging runs, usually carried out simultaneously.
Total organic carbon (TOC)	The amount of organic carbon in a geological formation, particularly the source rock for a petroleum play (a group of oil prospects in the same region)
Triassic	The name for the geological Epoch where the rocks are between approximately 200 and 250Ma in age
Triple stack	An assembly of three blowout preventers

Two-way travel time (TWT)	The time taken for a seismic wave to travel from the shot down to a reflector or refractor and back to a geophone at the surface, measured in milliseconds (ms)
Vitrinite reflectance (VR)	A key method for identifying the maximum temperature history of sediments in sedimentary basins. It was used by coal explorers to diagnose thermal maturity of coal beds. With suitable calibration, vitrinite reflectance can also be used as an indicator of maturity in hydrocarbon source rocks. Vitrinite reflectance data is presented in units of %Ro, the measured percentage of reflected light from a sample immersed in oil
Vug	A small cavity in a rock, commonly lined with crystals of a different mineral composition from the surrounding rock
X-ray diffraction (XRD)	A non-destructive analytical technique that reveals information about the crystal structure, chemical composition and physical properties of materials
Wireline core drilling	Method of drilling whereby the core barrel is positioned within the drill rod, allowing rapid placement and withdrawal of the core
Wireline logging	Acquisition and analysis of geophysical, reservoir and well data obtained as a function of wellbore depth. The oil and gas industry uses wireline logging to obtain a continuous record of a formation's rock properties

### Abbreviations, acronyms and initialisations

2D	Two dimensional
3D	Three dimensional
ANLEC R&D	Australian National Low Emissions Coal Research and Development
AMC	Australian Mud Company Pty Ltd
API	American Petroleum Institute
BOP	Blowout preventer
c.	circa or approximately. Circa is commonly used in reference to geological age of rocks or strata.
CCS	Carbon capture and storage
CO <sub>2</sub>	Carbon dioxide
CPI	Computer processed interpretation, associated with wireline logging
CSNG™	Halliburton Pty Ltd's Compensated Spectral Natural Gamma Ray logging tool
DMIRS	State of Western Australia's Department of Mines, Industry Regulation and Safety
EC	Electrical conductivity
GSWA	Geological Survey of Western Australia, a division of the Department of Mines, Industry Regulation and Safety
HQ	A minerals drilling-industry reference standard size for the diamond coring drill bit, drilling rods, hole and casing

HSFT™	Halliburton Pty Ltd's Hostile Sequential Formation Tester tool. This tester is designed to acquire formation pressure data and fluid samples under high temperature and pressure conditions in narrow wells
$K_h$	Permeability of core, in a horizontal direction, perpendicular to orientation of core
$k_{if}$	Klinkenberg permeability, which is the equivalent permeability of a non-reactive fluid in the formation
$k_v$	Permeability measured in a vertical direction
LCM	Lost circulation materials
LOT	Leak-off test
m AHD	Metres relative to Australian Height Datum (sea level)
MDRT	Measured depth below the rotary (drilling) table
MICP	Mercury injection capillary pressure
MPa	Megapascals are units used to define pressure or stress, as experienced by the formation. One pascal (Pa) is equivalent to one newton (1N) of force applied over an area of one metre squared (1m <sup>2</sup> ). One MPa is equivalent to 145.038 pound-force per square inch (psi).
MRI <sup>LR</sup>	Halliburton Pty Ltd's Magnetic Resonance Imaging Logging tool
NMR	Nuclear magnetic resonance, associated with wireline logging
NM	Nano Meters
NOBP	Net overburden pressure
PAC-R™	A trademarked polymer used in drilling fluids
PCD	Polycrystalline diamond composite, in reference to drill bits
PGERA	Petroleum and Geothermal Energy Resources Act
PQ	A minerals drilling-industry reference standard size for the diamond coring drill bit, drilling rods, hole and casing
ppg	Pounds per gallon, an imperial measure of density, commonly used in the petroleum drilling industry
psia	Pressure per square inch, absolute. One psi is equivalent to 0.007 MPa.
pXRD	Portable X-ray diffraction, a mobile machine used to qualitatively determine the mineralogical composition of spot-sampled core
RCA	Routine core analysis, referring to measurements carried out on core plugs in the laboratory; for example, the porosity and permeability of a core plug
RCI™	Baker Hughes Pty Ltd's Reservoir Characterisation Instrument, which is a fluid characterisation and testing tool

RDT™	Halliburton Pty Ltd's Reservoir Description Tool
ROP	Rate of penetration, which is a term use by a driller to specify drilling rate, typically quoted as metres drilled per day
SCAL	Special core analysis is the laboratory procedure for conducting flow experiments on core plugs taken from rock brought to the surface by drilling
SEM	Scanning electron microscope
SQ	A minerals drilling-industry reference standard size for the diamond coring drill bit, drilling rods, hole and casing
TD	Total depth, which refers to the depth drilled, as reported by the driller.
TDS	Total dissolved solids, measured in units of mg/L or ppm (parts per million), is a chemical parameter used to define the salinity of a liquid sample, being a measure of the combined content of all inorganic and organic substances contained in a liquid in suspended form
TOC	Total organic carbon
tpa	Tonnes per annum. In this report this refers to the potential injection of tonnes of supercritical CO <sub>2</sub>
TSG™	The Spectral Geologist, software used in the processing and analysis of data from the HyLogger
TVD	True vertical depth, which is the depth of the well measured vertically from the spudded drill point. If the drilled path of the well deviates from the vertical, then the true vertical depth will be less than the total depth of the well.
TWT	Two-way travel time as measured during a seismic reflection survey
VSP	Vertical seismic profile
Vsh	The volume of shale in a given interval of strata, calculated from spectral gamma-ray data collected during wireline logging
WAPIMS	Western Australian Petroleum and Geothermal Information Management System database managed by DMIRS
XRD	X-ray diffraction
XRMI™	Halliburton Pty Ltd's X-tended Range Micro Imager tool

## Appendices

In digital format on USB

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