Government of **Western Australia**
Department of **Mines and Petroleum**

Harvey 1 Stratigraphic Well
Early Drilling Outcomes

South West CO_2 Geosequestration Hub – December 2012

Harvey Shire Councillors visiting the Harvey 1 well drilling site.

www.dmp.wa.gov.au/ccs

Contents

Harvey 1 Well Graphic Summary

The Harvey 1 well was drilled in order to gather underground geological data.

Figure 1 is a diagramitic summary of the position, depth and subsurface geological formations encountered by the well.

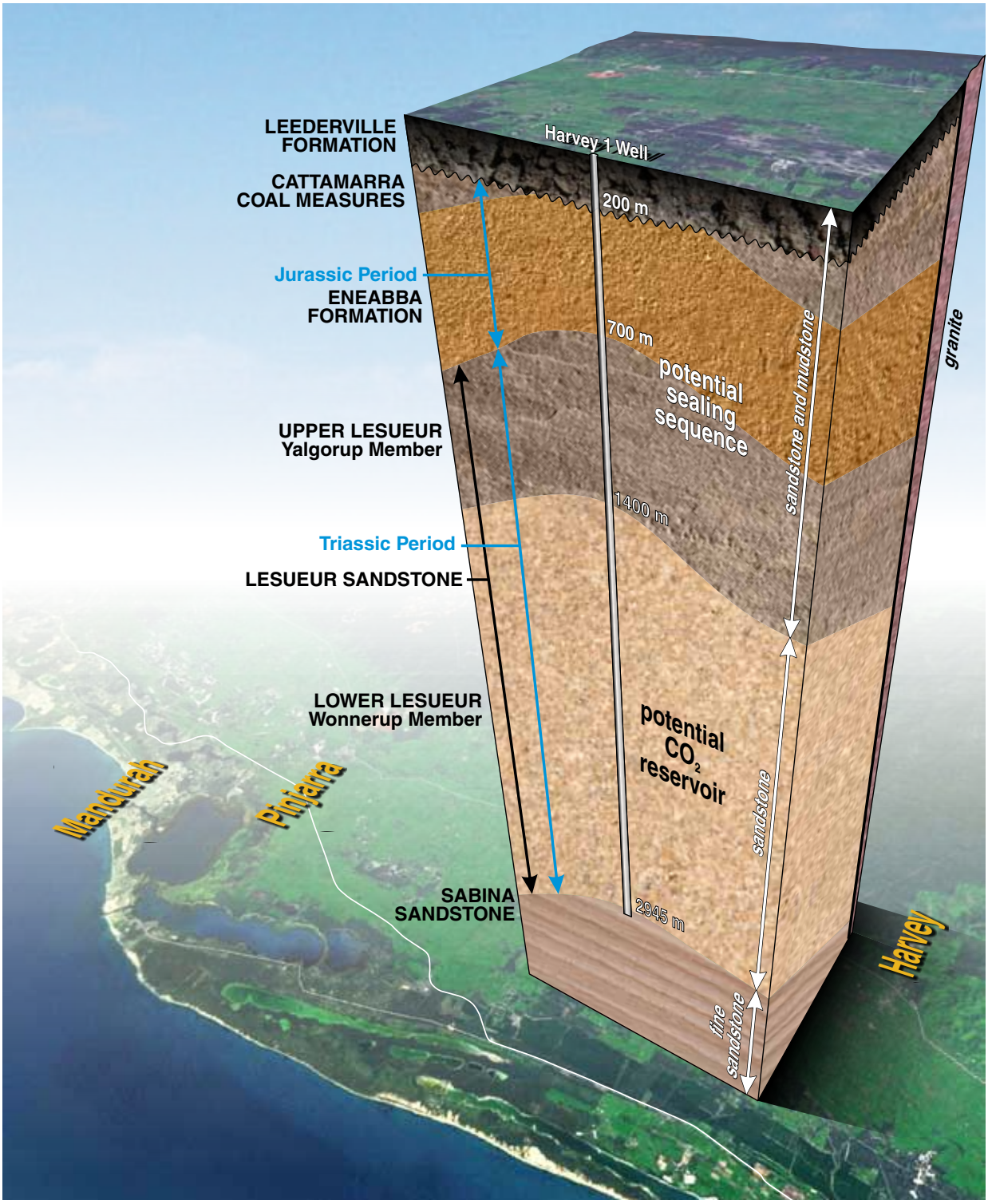

Figure 1. Onshore southern Perth Basin stratigraphy: Harvey 1 well.

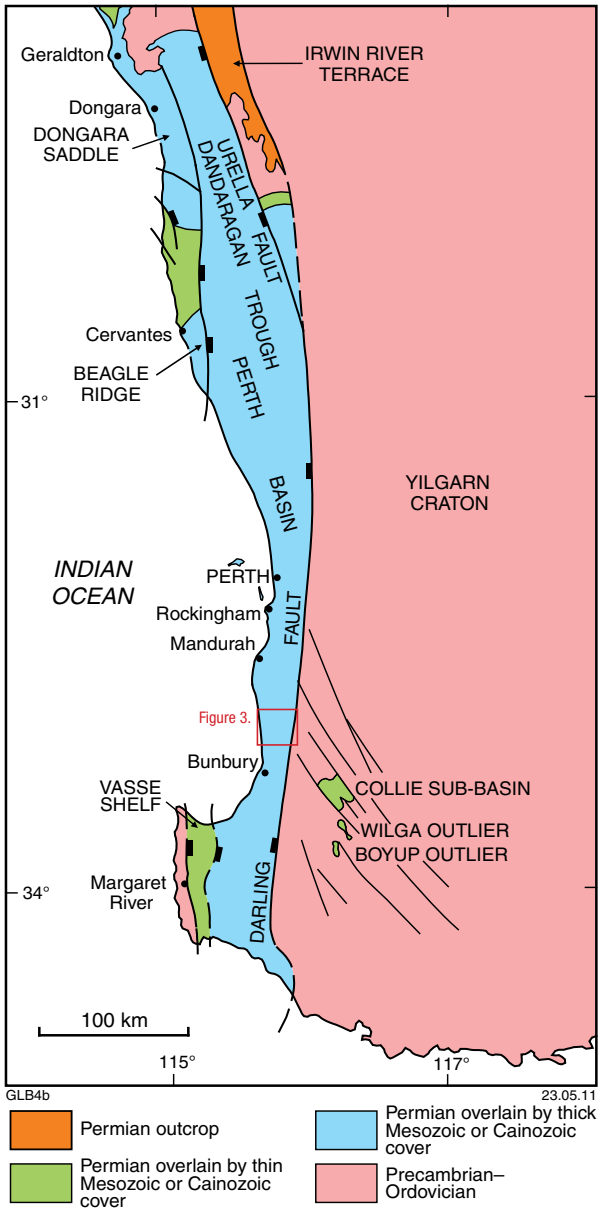

Figure 2. Map of the Perth Basin.

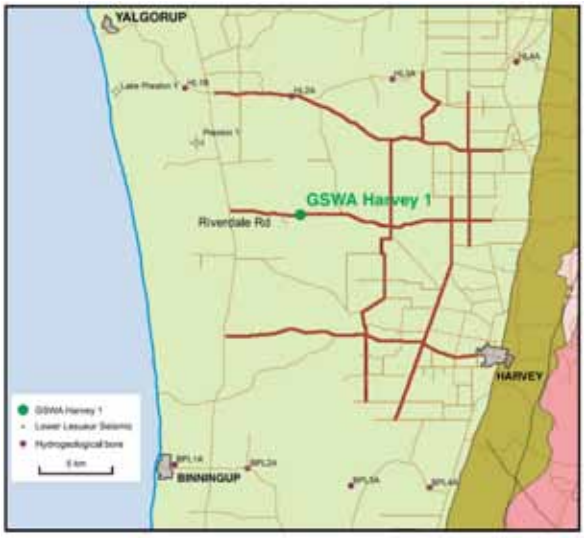

Figure 3. Site map showing the Lower Lesueur 2D Seismic Survey lines, the Harvey 1 well location and water bores along the Harvey and Binningup lines.

Harvey 1 Well Overview:
Mapping The Underground (Stratigraphy)

The Harvey 1 well was drilled between February 7 and March 23 in 2012 on farmland at Lot 1326 Riverdale Road in Harvey.

The site is part of Western Australia's (WA) Swan Coastal Plain which lies to the west of the Darling Ranges, and the well was sunk into the southern part of the Perth Basin.

Beneath the Swan Coastal Plain is the Perth Basin running south to north-northwest, onshore and offshore along the WA coast, extending for about 1300km along the south western margin of the Australian continent.

The Perth Basin covers 172,300km^2 and is structurally complex, formed during the separation of Australia and Greater India in the Permian to Early Cretaceous periods (300 to 140 million years ago).

The Perth Basin (see Fig. 2) includes a significant onshore component and extends offshore to the edge of the western continental crust, where water depths are up to 4500m.

Following a review of the subsurface geology of the onshore Perth Basin, the general location for the project was selected in the shires of Harvey and Waroona and a two-dimensional (2D) Seismic Survey along 106km of shire roads was conducted there in March 2011 (Fig. 3).

The location for Harvey 1 was chosen based on data from the 2D Seismic Survey and other pre-existing data, and where the most information could be gained on understanding the potential of the geological formations to become a storage reservoir for carbon dioxide (CO_2).

Harvey 1 was a stratigraphic well designed to provide data and core samples from the underlying rock strata. When combined with information from subsequent research projects, this data will be used to build a model of the subsurface formations and to simulate CO_2 injection scenarios.

Of particular interest was the rock formation known as Lesueur Sandstone which potentially has the properties desirable for a CO_2 storage reservoir. At this stage of the research and modelling, the Lesueur Sandstone is showing good potential as a reservoir.

Following the completion of the data acquisition program from Harvey 1, the well has been plugged at several levels with cement, capped at the surface and the drill site is being remediated to its previous condition.

Further Information

In addition to this 'Early Drilling Outcomes' report, an 'End of Well' report summarising the drilling operation has been prepared and a final 'Well Completion' report is due to be issued in early 2013.

Technical information is available on the WA Department of Mines and Petroleum website online system within the Petroleum and Geothermal Information Management System (WAPIMS) located at www.dmp.wa.gov.au/wapims. It should be noted that a certain level of technical knowledge is required to interpret this data in a meaningful way.

Geosequestration and the South West Hub

Around the world, scientists have identified Carbon Capture and Storage (CCS) as one of the tools to reduce the amount of greenhouse gas being emitted into the atmosphere.

Geosequestration is a form of Carbon Capture and Storage (CCS) which captures CO_2 from industrial emissions and injects it into deep underground reservoirs for permanent storage.

The preferred geology for such reservoirs is well documented by scientists and Harvey 1 was designed to allow for the measurement of these properties, in addition to providing samples of the various subsurface rock strata.

The South West Hub is a partnership between the State Government's Department of Mines and Petroleum (DMP) and industries operating in the South West region.

The South West Hub was the first CCS project identified and funded under the Australian Government's Carbon Capture and Storage Flagships Program, receiving $52 million in 2011.

Drilling Outcomes

Harvey 1 Well Objectives

DMP's Geological Survey WA (GSWA), which has been gathering and publishing information on the geology of Western Australia since the 1880s, undertook the management of the drilling of the Harvey 1 well. The well was designed to reduce the geological data gaps in an area north west of Harvey town site.

The drilling was part of the preparation phase for the South West Hub, which is undertaking a four-year research program to determine whether the Lesueur Sandstone could become a permanent storage reservoir for industrially generated CO_2.

Well objectives are outlined below:

- To confirm the predicted stratigraphy.
- To evaluate the sealing capacity of the lower Eneabba Formation and confirm the presence of a lower shale unit.
- To collect core samples of the Eneabba Formation to test its seal capacity and Lesueur Sandstone to test the potential CO_2 reservoir characteristics.
- To obtain seismic data that allows for better comparisons between the rock properties and what happens when surface seismic measurements are taken (i.e. a better time-depth relationship).
- To update the current three-dimensional (3D) geological model showing the various subsurface strata, based on site specific information.
- To assist in the planning and development of future stratigraphic wells and seismic programs for evaluating the CO_2 storage potential of the area.
- To run evaluation logs, take core samples and obtain clean formation water samples from a range of depths. To develop a good understanding of the reservoir properties, the formation waters in these rocks and the potential sealing unit in the vicinity of the well.
- To assess the hydraulic relationships (water flow rates, pressures and directions) above and below the heterogeneous Eneabba Formation to find out if this 'unconventional' seal has the capacity to contain CO_2.
- To assess the geothermal and hydrocarbon potential.

Outcome 1: What geologists expected to, and did, find was that the Lesueur Sandstone consisted of porous sandstone in a saline (salty) aquifer. It has overlying strata of denser mudstone (a mix of silt and clay) and shale (mudstone that is laminated or fissile) which would act as a sealing mechanism, retarding the upward migration of CO_2 towards the surface.

All of the objectives have been achieved, with the exception of the evaluation of the sealing capacity of the Eneabba Formation which is on-going.

The Harvey 1 well contributes significantly to the initial modelling exercise of the subsurface geology in the South West Hub area, replacing estimated parameters taken from older wells in the area with actual measured data.

This subsurface modelling of the Lesueur Sandstone will continue to evolve with the acquisition of more data from a planned 3D Seismic Survey, drilling additional wells, laboratory testing of core samples and other analyses and data sources.

Stratigraphic Well Data Collection

Stratigraphy is the study of rock strata, their extent, when and how they were laid down and the age of sedimentary rocks. The Harvey 1 well is deemed a 'stratigraphic well' since its main purpose was to investigate the nature of the subsurface strata in the area for data that would contribute towards a better understanding of the regional geology.

The role of this well included the provision of core samples, rock samples or fine cuttings and very comprehensive sets of measurements of the subsurface strata. Specifically, the drilling intersected the Lesueur Sandstone and confirmed expectations that it consists of sandstone laid down in the Triassic Period (200 to 250 million years ago) forming a saline aquifer with overlying 'tight' rocks called shales which are a mixture of mudstone and claystone.

The drilling operation was a complex project requiring detailed planning and supervision to optimise the value of the data acquisition program. The result was a total length of 217m of core samples, 102 millimetres (4") in diameter, taken at various depths. These samples are being used to assist in evaluating critical injection and storage performance targets that would be applied to any future geosequestration project.

Harvey in the Triassic? This may be how the area looked when the Lesueur was being formed 200 to 250 million years ago.

In addition to the core samples, rock samples and broken materials brought up in the drilling muds were collected every 15 metres down the hole. A series of measurements were taken by lowering specialised probes and sensors into the well to measure rock properties such as density, natural radiation, water salinity and porosity and permeability.

Determining Subsurface Strata Properties

Core samples from Harvey 1 provide the opportunity to study the properties of both the potential reservoir and the sealing mechanism or caprock intersected by the well.

The presence of a seal, extending over the area, is an important requirement for the storage system, since this will form the uppermost and ultimate barrier to any vertical migration of stored CO_2.

The CO_2 is injected into the lower depths of the saline aquifer and it then commences to migrate upwards and outwards under the effects of buoyancy – resulting from the different densities of the water and CO_2.

During this process the majority of gas is trapped within the sandstone pores, some is dissolved in the saline aquifer and some will remain mobile and find a torturous path to the base of the overlying shale which is a potential sealing layer.

Before the gas can move to the upper reaches of the storage structure, numerous, but less extensive lenses of shale create a system of 'baffles' that retards the movement of the gas and causes it to spread horizontally. This more effectively disperses the gas to occupy the porous reservoir rocks that lie beneath the top seal.

Outcome 2: The Harvey 1 well was successful, achieving 95% of the data acquisition objectives set for the drilling project.

Initial results confirm expectations that the Lower Lesueur Sandstone or Wonnerup Member is a potential CO_2 storage reservoir.

The Upper Lesueur Sandstone, or Yalgorup Member, and the Eneabba Formation lying above it would potentially form a seal over such a reservoir to trap the injected CO_2 permanently.

Subsurface Geology

Prior to drilling Harvey 1 the hydrology of the area was relatively well known to depths of approximately 800m. This knowledge came from Department of Water and local experience with water bores, particularly the Harvey line of wells to the north and the Binningup line of wells to the south of Harvey 1 (locations marked on Fig. 3). A bore supplying water for the Harvey 1 well confirmed the presence of shallow freshwater to about 50m. The ground water becomes saltier with depth and below 200m the Eneabba Formation and Lesueur Sandstone are hypersaline at up to 60,000ppm (seawater is approx. 35,000ppm).

A clear understanding of water use and salinity in the area aids in the identification of appropriate CO_2 storage sites. Aspects of the hydrology such as flow direction are important in understanding where stored CO_2 might migrate to over the long term, which in turn assists in the design of appropriate CO_2 monitoring and verification programs.

GSWA's 2011 Lower Lesueur 2D Seismic Survey broadened knowledge about the local subsurface rock stratigraphy (seismic survey lines are marked on Fig. 3). However, detailed information concerning the Lesueur Sandstone's capacity for the injection and containment of CO_2 could only be assessed through drilling a deep well into this formation.

Information was also needed to define the properties of the overlying strata that could potentially provide a sealing mechanism to securely trap injected CO_2.

Early in 2012, the Harvey 1 well was drilled into the Lesueur Sandstone to a depth of 2945 metres. The well penetrated the Leederville Formation to 200m, the Eneabba Formation to 700m and the Lesueur Sandstone to approximately 3000m where it touched the top of the Sabina Sandstone (see Fig.1.)

The Lesueur Sandstone consists of the Upper Lesueur Sandstone or Yalgorup Member (approx. 700m to 1400m) and the Lower Lesueur Sandstone or Wonnerup Member (approx. 1400m to 3000m).

Outcome 3: The Harvey 1 well led to the recovery of 217m of core samples collected from the Lesueur Sandstone.

Testing of the core samples will provide critical input into building a 3D model of the area's subsurface rock strata and determining the potential for the Lesueur Sandstone to become a CO_2 storage reservoir.

CO_2 Storage in a Saline Aquifer

Of all the possible CO_2 storage options, geosequestration in saline aquifers is generally regarded as having the greatest CO_2 storage potential, and by a significant margin, relative to storing in depleted oil and gas fields. In choosing a potential reservoir site for the South West Hub, the focus was directed at finding porous strata filled with saline water - such strata are referred to as saline aquifers.

The Lesueur Sandstone, which is a saline aquifer, is estimated to have a storage capacity sufficient to accommodate the expected volume of CO_2 captured from industrial emissions by the South West Hub partners. Such storage projections are currently based on relatively sparse control data and, consequently, the drilling of a number of wells is critical to further the evaluation process and provide certainty.

Key control data gave no indications to expect the presence of hydrocarbons within the general vicinity of the South West Hub area and none were observed in the Harvey 1 well.

Outcome 4: Harvey 1 confirmed that the Lesueur Sandstone contains water with relatively high salinity, thus the injection of CO_2 does not present a risk of contamination of waters as saline water is not suitable for community use.

The water pressure in the formation is 'normal hydrostatic', which means it is at the pressure expected for the depth that the water samples were taken based on gravity, and the area is not hydrocarbon bearing.

Harvey 1 Core Samples

The protocol for the core sample handling set by GSWA allowed for a range of testing on site, at commercial laboratories and by the South West Hub research partners.

Core samples of varying lengths were extracted in 9 m sections, then cut into 3m lengths and prepared for transport within the aluminium tubes used to extract them from the well (examples are shown in Fig. 4). As each section was unearthed it was measured for natural radioactivity which will assist with describing various aspects of the rocks in the future.

Figure 4. Harvey 1 core samples from the Lesueur Sandstone; from top, Yalgorup Member at 1335m, at 1336m, at 1337m and Wonnerup Member at 2491m.

Any gaps in the sandstone samples were injected with foam space filler to give them stability during transportation and samples containing shale were covered with mineral oil to stop them drying out and affecting data acquisition.

The tubes were sealed and sent to a commercial laboratory where they were exposed, inspected and prepared for both further testing and permanent preservation.

The careful handling, recording and preservation of the precious core samples is important for the South West Hub project as well as for future reference, with sections or 'fillets' of each sample retained in the GSWA Core Library. Various studies are in progress to further investigate the chemistry of the water and the rock from Harvey 1.

This information will be used in the construction of a model to characterise the storage capabilities of the Lesueur Sandstone saline aquifer. However, further seismic surveys and additional drilling in the area will be necessary in order to establish the extent of the aquifer.

Core Samples Recovered from Harvey 1

Core #	Start Depth (m)	End Depth (m)	Recovered metres	% Recovery	Formation	Lithology
Core 1	895	931	36.62	101.72%	Yalgorup Member, Lesueur Sandstone	Sandstone, minor Claystone
Core 2	1266	1320	53.16	98.44%	Yalgorup Member, Lesueur Sandstone	Interbedded Claystone, Sandstone, Siltstone
Core 3	1320	1336	15.22	95.13%	Yalgorup Member, Lesueur Sandstone	Interbedded Claystone and Sandstone
Core 4	1336	1345	7.76	86.22%	Yalgorup Member, Lesueur Sandstone	Claystone with Sandstone at base
Core 5	1896	1950	51.64	95.63%	Wonnerup Member, Lesueur Sandstone	Sandstone
Core 6	2480	2534	52.59	97.39%	Wonnerup Member, Lesueur Sandstone	3 metres Claystone at top, remainder Sandstone

Outcome 5: Six cores, 102mm (4") in diameter and totalling 217m in length, were successfully recovered from Harvey 1. The cores were mostly recovered from sandstones and some from shale formations.

The process of opening the cores and making preliminary descriptions took six weeks. The core plug sampling, core slabbing and the first sets of physical and chemical analysis were completed within six months. The core samples have been assigned to different formations based on the core observations and the well logging data from the down hole probes.

The core samples are currently undergoing extensive testing programs. Preliminary findings are that cores from the Lesueur Sandstone have physical characteristics which can be considered as positive indicators for successful CO_2 injection potential.

Testing core samples at the CSIRO laboratory in Bentley. Photo courtesy CSIRO

Core Sample Testing

The initial chemical and mechanical studies on the core samples, including porosity and permeability measurements, were completed at a commercial laboratory.

The original cores are stored in the GSWA Core Library and samples have been sent out for specific measurements at various research institutions.

Some samples have been prepared for CO_2 injection tests under simulated reservoir conditions and five ongoing research projects, summarised overleaf, are being undertaken by CSIRO, University of Western Australia and Curtin University.

Research Projects

1) STRATIGRAPHIC FORWARD MODELLING FOR THE LESUEUR SANDSTONE

This demonstration will assess storage reservoir characteristics and produce a static model of the predicted grain size distribution in subsurface strata.

2) FACIES-BASED ROCK PROPERTIES DISTRIBUTION ALONG THE HARVEY 1 STRATIGRAPHIC WELL

This research project is designed to provide high-end analysis of core samples to support stage gate decisions on (1) the South West Hub 3D Seismic data acquisition and processing workflow, and (2) site selection for a pilot CO_2 injection.

3) GEOCHEMICAL CHARACTERISATION OF GASES, FLUIDS AND ROCKS IN THE HARVEY 1 DATA WELL

This project will obtain geochemical data from the Harvey 1 well which is required as input for improving the understanding of the geology in the target region for the South West Hub.

4) INTEGRATION OF DATA FROM HARVEY 1 WELL TO SUPPORT DECISIONS – FAULT SEAL

This project will evaluate the hydraulic behaviour of faults within the Lesueur Sandstone and Eneabba formations. A secondary objective is to investigate the distribution of sub-seismic fractures and their impact on the trap integrity and reservoir compartmentalisation.

5) ADVANCED GEOPHYSICAL DATA ANALYSIS FOR THE SOUTH WEST HUB HARVEY 1 WELL SITE

The outcomes of the geophysical data analysis will be used to assist further development of the South West Hub project, including designing the 3D seismic acquisition and processing program, updating the storage site 3D geological model and targeting positions for the next set of wells.

Geophysical data analysis will assist with assessment of the storage site key parameters: reservoir storage capacity, injectivity, sealing potential and long term site stability (stress, seismicity, and seal).

Core Testing Program

Porosity/Permeability (Reservoir):
90 plugs taken; 21 vertical plugs and 69 horizontal plugs.

Hylogger:
Completed on all six full cores (photography and multi spectral analysis).

XRD Mineralogy:
28 samples processed.

Thin Sections:
62 thin sections for petrography.

Palynology:
To be selected.

Organic Geochemistry:
To be selected.

Geochronology: (U/Pb dating of zircons)
17 samples analysed.

Shale plugs:
MICP and seal capacity testing at CSIRO.

Trapping Mechanisms

Reservoirs are complex storage ‘tanks’ that have multiple trapping mechanisms, and confining structures or geometries that can be mapped using data collected via geological surveys and stratigraphic wells.

Natural oil and gas deposits (hydrocarbons) are ‘trapped’ in subsurface, porous sedimentary rock formations, referred to as reservoirs, for millions of years. A successful CO_2 storage reservoir will require many of the properties that characterise a conventional hydrocarbon reservoir.

The CO_2 trapping mechanism within a reservoir involves physical, chemical and mechanical reactions which are being assessed through the testing of data and core samples taken from the Harvey 1 well.

The subsurface strata is being tested for a range of properties including the salinity of the aquifer, the porosity and permeability of sandstone in the potential reservoir and shales in the sealing strata, natural radioactivity, temperature, the age of rocks and palynology which studies the tiny pollen, spores and algae fossils in the rocks.

Outcome 6: An important outcome from the Harvey 1 well was that aquifer thickness expectations were met and the initial inspection of the core and well measurements have provided a positive indication that the sediments are likely to meet key performance criteria set for a potential CO_2 storage reservoir and top sealing cap rock.

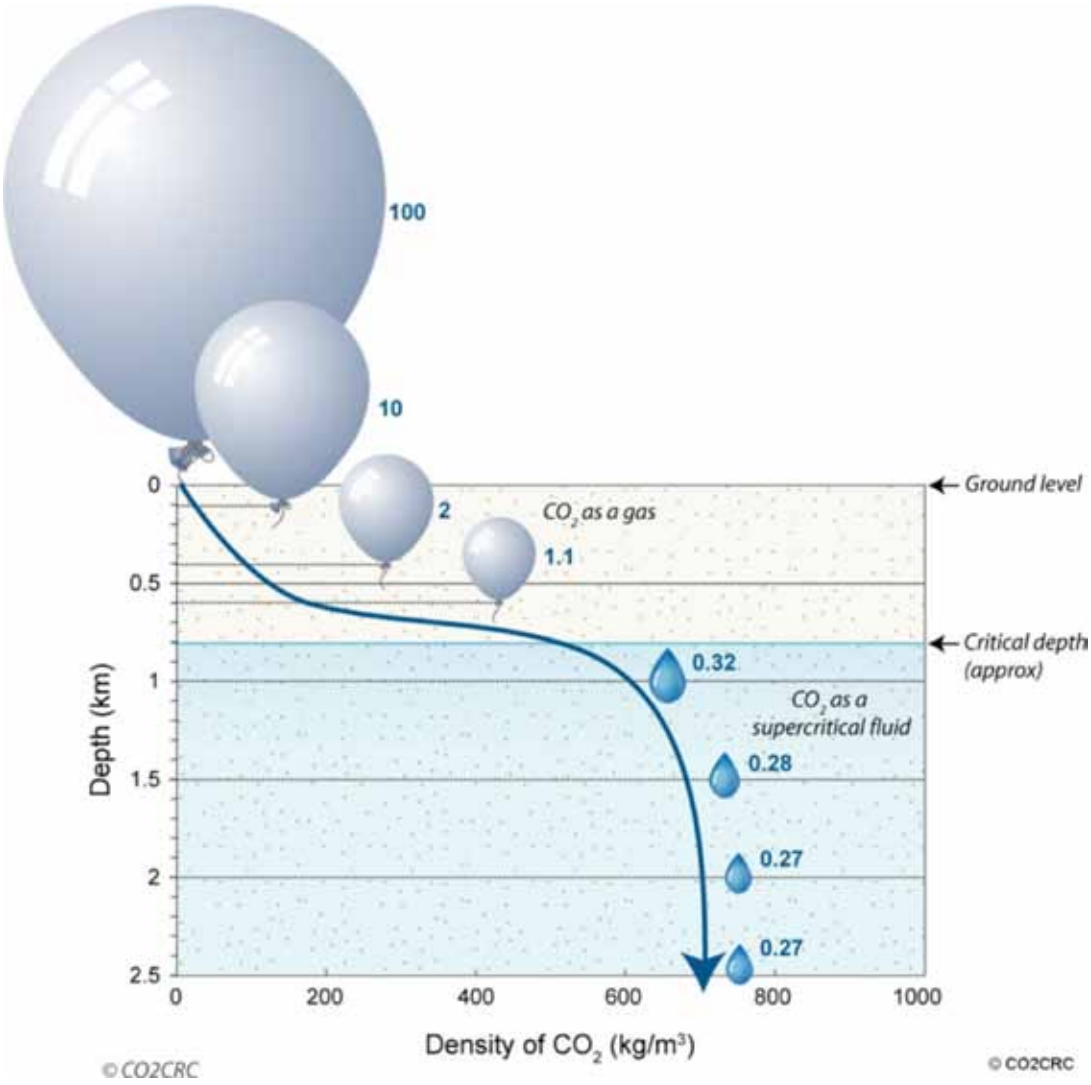

Figure 5. How the CO_2 is changed during injection from the surface. As depth (increased temperature and pressure combined) increases, the CO_2 transitions to supercritical and is at its most dense. This means that less volume in the rocks is required to store the same volume of CO_2.

Supercritical CO_2

CO_2 has some special properties that impact on the evaluation of storage in aquifers. These will be studied in the laboratory through test injections into core sample material taken from the Harvey 1 well.

At some point prior to or during injection, the CO_2 gas is processed to increase temperature and pressure to levels that change it from a gas into a state known as a 'supercritical fluid', in which it exhibits the physical properties of both a liquid and a gas.

To achieve and maintain a supercritical state, heat and pressure need to be applied to the CO_2 to bring it above a temperature of 31 degrees C and a pressure of 73 atmospheres – conditions which occur naturally below 800 metres underground (see Critical depth on Fig. 5).

A primary benefit of injecting CO_2 as a supercritical fluid is that the aquifer volume required to store the CO_2 will be about 200 times less than in a gaseous phase, depending on pressure and temperature conditions in the aquifer.

In practical terms, injection depths of more than 2000m are more commonly considered for the operational planning, of CO_2 geosequestration projects. Harvey 1 well was drilled to almost 3000m.

Outcome 7: Research on the core samples will be specifically directed at the behaviour of CO_2 in a supercritical state, as it comes into contact with the various subsurface strata intersected by the Harvey 1 well.

Conclusions

Information about the properties of the Lesueur Sandstone and the strata above it has been obtained for depths down to nearly 3000m to ensure a deep understanding of the subsurface strata.

Although more data needs to be obtained, no technical showstoppers have been identified.

Several results from this study are favourable to CO_2 injection:

- Good reservoir properties
- High fracture gradient
- Stable faults
- Preliminary area-specific relative permeability curves suggesting higher residual trapping potential than in the previous study

While there are still uncertainties relating to geological structure and trapping potential that need to be addressed before any final investment decision is made, early results from the Harvey 1 well support the continuation of the South West Hub data acquisition and investigation program.

Outcomes

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The 3D Seismic Survey is managed by the WA Department of Mines
and Petroleum and funded by the Australian Government through the CCS Flagships Program.

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