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Basin Resource Management for Carbon Storage

A Literature Review

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EXECUTIVE SUMMARY

The Collie Hub in the Southern Perth Basin in Western Australia, CarbonNet in the Gippsland Basin in Victoria, and Wandoan in the Surat Basin in Queensland are being investigated as potential sites for CO₂ storage under an Australian Government flagship program. Each of the three Carbon Capture and Storage (CCS) projects are located in resource-rich sedimentary basins, which contain high quality groundwater, oil and gas, unconventional gas, coal and geothermal resources. The Collie Hub CCS site is situated in the Southern Perth Basin in the south west of Western Australia. It is planned to eventually inject up to 10 Mt/yr of CO₂ into the lower Lesueur Sandstone from CO₂ sources in Collie and Kwinana. The CarbonNet CCS site is located in the nearshore and offshore areas of the Gippsland Basin in southeastern Victoria. Initial CO₂ storage of about 1-5 Mt/yr is planned in the Gippsland Basin, with a potential of scaling up to 20 Mt/yr. The Surat Basin in Queensland has been identified for geological storage of carbon dioxide for the Wandoan CCS Project which plans to eventually capture and store up to 2.5 Mt/yr of CO₂. The location of injection wells is yet to be selected at these sites.

CSIRO and its WA:ERA research partner, Curtin University, are jointly conducting an assessment of the site specific resources that are geographically co-located with proposed carbon storage. The project also aims to understand the structural, stratigraphic and geomechanical aspects at these sites to assess the potential impacts of CO₂ injection on adjacent resources. This literature review and data gap analysis forms a first step of the study to understanding the present level of knowledge for conducting such an assessment. Funding for this research has been provided by ANLEC R&D, WA Department of Mines and Petroleum, CSIRO and Curtin University.

The literature reviewed relates both to any direct assessment of potential impacts of CO₂ on other natural resources, as well as those that contain valuable information that would be used for making such an assessment. These include reports on hydrogeology and groundwater prospectivity, hydrocarbon and coal occurrence, geomechanical and structural assessment, and other relevant site specific studies on carbon dioxide storage. To date, only minimal studies assessing the impacts of carbon dioxide storage on the resources have been carried out at each of the three CCS sites included in this review.

Data availability and the knowledge of the subsurface in each basin depend largely on the type and maturity of resource developments (groundwater, coal, coal seam gas, petroleum, geothermal). In all three basins, groundwater is produced for drinking water and/or agricultural purposes; hence there is abundant data available from shallow wells and the hydrogeology of the shallow subsurface is generally well understood. With respect to deeper formations, that would also present injection targets for CO₂ storage, the best data coverage exists for the Gippsland Basin because of its history of petroleum exploration and production. The Surat Basin has some information from petroleum exploration, whereas data from deep wells in the Southern Perth Basin are very limited.

Groundwater

Several studies of the hydrogeology and groundwater resources of the three basins have been carried out by the relevant state Geological Surveys, CSIRO, water supply utilities and private consultants. These studies have defined the extent of the aquifers and the aquitards, and the quality and quantity of groundwater in the regions. The availability of numerical models varies widely for the three basins. For none of the basins does a model exist that simulates the cumulative impacts of CO₂ storage, petroleum production and groundwater extraction. Ideally, multiphase models would be required for simulating injection of CO₂ and migration of the plume and making an accurate quantitative assessment of the consequent effects on the groundwater levels and chemistry. Existing groundwater models for the Gippsland Basin and the Peel Harvey Region of the Southern Perth Basin developed by CSIRO would require some additional enhancement and integration of the more recent geological information, e.g. the 2D seismic and the planned data well in Southern Perth Basin, to enable a quantitative assessment of CO₂ storage related impacts. For the Surat Basin existing groundwater models developed for QGC and APLNG may not become publicly available.

Coal and CSG

In the Surat Basin there is a good spread of data regarding coal occurrence and coal seam gas presence in some places, possibly because of the existence of high quality, extractable coal and gas across the region that is of economic value. Its extent is well known and modeling has been performed widely. Conversely, due to there being far less easily accessible coal or CSG in the Gippsland Basin and the Southern Perth Basin, there is a relative paucity of data, and assessment of potential impacts of CO₂ injection at these sites may include more uncertainty. Nevertheless some data is available that may be extrapolated to ascertain the potential of coal, and identify future data collection requirements and modeling of the coal in these areas that would be necessary to both explore the possible resource conflicts with coal and CSG, and to more clearly identify where future data collection would be required.

Hydrocarbon resources

Among the three sites reviewed, the Southern Perth Basin has the least potential for hydrocarbons although this assessment is based on sparse data coverage. Conceptual exploration models and play concepts are prone to change with addition of new data that may alter the “resource potential” status of any basin. The Whicher Range tight gas is at some distance south of the Collie Hub site and is unlikely to be affected by carbon storage. However, the tight gas potential at the Harvey Ridge would need to be explored. Hydrocarbon – CO₂ resource management issues are more critical for the Surat and Gippsland basins which have proven petroleum systems with conventional oil and gas production. The assessment is particularly important for the Gippsland Basin which is one of the leading hydrocarbon producing basins of Australia despite the current decline in production.

Geothermal

The last decade has seen considerable interest and investment in geothermal research by the state governments of Australia. The Western Australia and Victoria governments have funded the development of geothermal databases and the Queensland government has entered into a similar process. This review identifies the major geothermal reports and databases. It has been found that existing geothermal databases do provide reasonable source information of thermal properties. However, information specific to the proposed Collie Hub, CarbonNet and Wandoan CCS sites is sparse or non-existent.

In the next stages of the project, the resources management issues with respect to CO₂ storage at the three CCS sites in Australia will be evaluated sequentially with the full suite of available data, starting with Collie Hub in the Southern Perth Basin. This will coincide well with the additional data collection program for Collie. This will be followed by a similar assessment at Wandoan (Surat Basin) and CarbonNet (Gippsland Basin) sites. The advanced site-specific understanding of potential for competing subsurface basin resources at the three CCS sites will inform baseline data collection strategy and monitoring and verification (M&V) system design, carbon storage project risks, and provide industry and government with data and analysis to underpin an informed public engagement on carbon dioxide storage.

1. INTRODUCTION

In August 2009, the Australian Government announced a competitive process for obtaining flagship funding towards commercial-scale carbon capture and storage (CCS) demonstration projects. Of the initial 4 projects, the Collie Hub in the Southern Perth Basin in Western Australia, CarbonNet in the Gippsland Basin in Victoria, and Wandoan Power in the Surat Basin in Queensland were later shortlisted as potential flagship CCS projects. All are currently conducting early stage site assessments for potential carbon storage capacity and containment security. Of these, the Collie Hub project is the first to obtain “Flagship Status”. The ZeroGen CCS site was withdrawn from the flagship bid by the proponents for a variety of reasons including a lack of suitable reservoir permeabilities in the initially targeted storage region. Thus ZeroGen is not covered in this report. Each of the three CCS projects are located in resource-rich sedimentary basins, which contain various quantities of high quality groundwater, oil and gas, unconventional gas, coal and geothermal resources.

CSIRO, together with the Curtin University under a WA:ERA (West Australia Energy Resources Alliance) research partnership arrangement, is conducting an assessment of the proposed CCS flagship sites at sub-basin-scale to identify the various resource management issues that may arise with commercial-scale geological storage of carbon dioxide. This project, being carried out under joint funding from ANLEC R&D, WA Department of Mines and Petroleum, Curtin University and CSIRO, will contribute to reducing the risks associated with deployment of CCS in Australia. The project will develop an understanding of the resource potential that may be affected by carbon dioxide storage at the proposed CCS flagship sites. The results of this work will include recommendations for appropriate containment risk analysis and future monitoring strategies designed around recognised resource assets.

Resources such as coal, oil and gas are depleting globally. Undeveloped resources that may not have been of economic value in the past, could become economically viable in the future depending on commodity prices and advances in extraction technology. Similarly, water resources are also depleting in many areas due to climate change and abstraction for drinking water and agricultural or industrial use. There is no doubt that geological storage of CO₂ will add another dimension to the multi-purpose use of subsurface pore space. A basin-scale resource management system is required to ensure that these multi-uses of the pore space can sustainably co-exist.

Additionally, it is important to understand the geomechanics and structural integrity of the geological framework of interest for carbon storage. Geological and structural assessment of the subsurface will identify the degree of containment security a selected storage site may have, given the proposed rate and volume of CO₂ injection.

As public concerns can delay the commencement of the CCS technology deployment, it is important that this advanced site-specific understanding of resource management at the proposed carbon storage sites is available to inform government, industry and the public. The study will demonstrate an understanding of the risks and suggest appropriate monitoring strategies tailored to the distribution and character of other basin resources in the vicinity of proposed carbon storage sites. A comprehensive

resource assessment in the region of proposed carbon storage can assist in the following ways:

- influence the storage site selection;
- help reduce uncertainty in the dynamic storage capacity of a site;
- guide containment security analysis; and,
- influence the monitoring and verification design.

The project workflow is provided below, and will be conducted sequentially for each site commencing with the Collie Hub (Southern Perth Basin, WA), followed by the Wandoan CCS Project (Surat Basin, QLD) and CarbonNet (Gippsland Basin, VIC).

1. Identification and mapping of known and potential resources
 - a. Groundwater
 - b. Conventional hydrocarbons
 - c. Coal and unconventional hydrocarbons
 - d. Geothermal
2. Structural, stratigraphic and geomechanical evaluation for assessment of containment security of stored CO₂
 - a. Stress regime and natural seismicity
 - b. Fault mapping and reactivation risk
 - c. Top seal thickness and hydraulic characteristics
 - d. Leakage from wells and bores
3. Review of injection options for minimising risk
4. Development of monitoring and mitigation strategies
5. Interim reports on assessments at each CCS site
6. Final report

According to the project timelines agreed with ANLEC R&D and WA DMP, the Collie Hub resource management assessment with respect to CO₂ storage will be completed in October 2011, followed by Wandoan in June 2012 and CarbonNet by November 2012. A final report detailing the results of each of the sites will be completed at the end of the project.

The final outcomes of the project will include:

- A proposed national approach to the technical assessment for resource management of carbon storage, water, conventional and unconventional hydrocarbons, coal, geothermal and other mineral resources, and
- Development of guidelines for adoption of monitoring, verification, and mitigation options for carbon storage sites.

As a first step of the project, the relevant Australian and international literature in the public domain was reviewed to understand the present level of knowledge of resource management issues related to carbon dioxide storage and other existing basin resources. The literature search was accompanied with a resource management data gap analysis for each of the three proposed Australian CCS flagship sites. This involved direct contacts with key personnel from the CCS flagship proponents regarding data and reports held with various agencies. Flagship proponents also provided a review and feedback on this report. In addition, a technical peer review of this report was carried out by Geoscience Australia, the Global Carbon Capture and Storage Institute and the Queensland Department of Employment, Economic Development and Innovation (DEEDI). This report provides the outcomes of the literature review and data gap analysis.

2. LEGISLATIVE FRAMEWORK FOR CO₂ STORAGE

The legal and regulatory review of CCS by the International Energy Agency (IEA, 2010) provides an overview of the regulatory developments made by various governments of different countries. In April 2011, the Australian Federal Government's Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulation 2011 came into effect which deals with the injection and geological storage of CO₂ in the offshore Commonwealth waters (> 3 nautical miles). The States have jurisdictions over the onshore and nearshore areas. Legislations dealing with CCS are in place in the States of Victoria, Queensland and South Australia, and are in preparation in Western Australia and New South Wales. In Western Australia it is proposed that greenhouse gas amendments will be incorporated into the Petroleum and Geothermal Energy Resources Act 1967. The long-term liability for storage sites can be transferred to the government under the Australian Commonwealth legislation, while operators retain long-term responsibility under some state legislation (Global CCS Institute, 2011).

Internationally, the European Union regulates CCS through EU Directives e.g. the 2009/31/EC Directive deals with the geological storage of CO₂ which establishes a comprehensive legal framework for management of risk associated with CCS as well as post-closure obligations (IEA, 2010). The EU Directive sets criteria for site selection and requires a finding of 'no significant risk' before a project is allowed (Court, 2011).

In the US, the EPA regulates the injection of fluid underground through the Federal Requirements Under the Underground Injection Control Program which includes CO₂ injection (IEA, 2010; Court, 2011). There is a strong requirement that such activity does not affect the Underground Source of Drinking Water (USDW). The US DOE does not have a regulatory authority relating to CCS but provides the technical information for assessing CO₂ storage prospects through publication of best practice manuals (IEA, 2010).

In Canada, the CCS related matters are covered in the jurisdictions of both the federal and the provincial governments. The federal government is able to regulate greenhouse gas emissions under the Canadian Environmental Protection Act, 1999. The province of Alberta in Canada has legislation in place that clarifies pore space ownership and addresses long-term liability, while in Saskatchewan regulatory framework relating to CO₂ injection exists. British Columbia is in the process of developing such regulations (IEA, 2010).

Pore space ownership rules are different in different countries. Permits to use the pore space issued by the government for hydrocarbon production, or other uses, could result in future competition with CO₂ sequestration. In Australia there is an impact test to assess (and protect) the potential influence on existing hydrocarbon permit holders by greenhouse gas title holders (Court, 2011). According to the International Energy Agency (IEA, 2007), a balance should be struck to protect users of the pore space e.g. hydrocarbon and CO₂ storage from adverse interference from other operators (Court, 2011).

3. SITE DESCRIPTIONS

3.1 Southern Perth Basin – Collie Hub

The study area is located in the south central part of the Perth Basin, which contains about 8000 m of Phanerozoic sediments (Playford et al., 1976). The Perth Basin is bounded to the east by the Darling Fault, where it abuts against the Archaean and Proterozoic rocks of the Yilgarn Craton.

The Collie Hub CCS site lies near the Harvey Ridge, which is a northwest-southeast trending structural high that is present north of Bunbury (Figure 1). If the site proves acceptable, it is planned to inject up to 10 Mt of CO₂ per annum into the lower Lesueur Sandstone from CO₂ sources in Collie and Kwinana regions. The actual injection sites are yet to be selected and evaluated.

A study by the CO₂CRC (Varma et al., 2007) identified that the Harvey Ridge basement structure has the highest potential for storing large volumes of CO₂ in the Lesueur Sandstone at about 3 km depth within 100 km of the major sources of greenhouse gas emissions sources in Collie and Kwinana region (Figure 2). The proposed CCS site has been named as the 'Collie Hub'. The absence of the Yarragadee aquifer, a major public water supply source in the South West of Western Australia, in this area makes this site particularly attractive. The proposed storage site will mainly rely on unconventional trapping mechanisms for CO₂ storage (residual trapping, solution of CO₂ in formation water). The Eneabba Formation (earlier considered a member of the Cockleshell Gully Formation together with the Cattamarra Coal Measures) and the upper part of the Lesueur Sandstone provide a combination of poor quality sealing strata and poor quality reservoir >2 km thick, whilst there are indications that the underlying lower part of the Lesueur Sandstone with its potentially higher transmissivity may provide suitable reservoir conditions for carbon dioxide storage. Water quality is poor in the overlying Eneabba Formation at Lake Preston-1, with high salinities of up to 43 000 ppm which may suggest that there are barriers to flow or recharge thus implying low permeabilities (Varma et al., 2009) in the Eneabba Formation.

Other related studies are reported in Bradshaw et al. (2000), Ennis-King and Wu (2005) and Causebrook et al. (2006). Causebrook et al. (2006) covered the carbon dioxide storage prospects in both the onshore and the offshore parts of the basin. However, the Causebrook study focused more on the offshore potential rather than the onshore, primarily due to the close proximity to the freshwater aquifers such as the Yarragadee Formation. The report by Causebrook et al. (2006) also provides the results of several related studies in its appendix, such as geological modeling, hydrodynamic characterisation, petrological characterisation, geomechanics, numerical simulations and petrophysics.

In June, 2011, the Federal Government announced that the Collie Hub would be awarded a Flagship status and was given \$52M funding to aid activities towards the design of an enabling case for the site. About 100 km of 2D seismic has been acquired by WA DMP in the region to the west of the town of Harvey to aid in the

identification of a suitable site for the data well. Plans for a data well are being finalised, using this acquired 2D seismic data to place the well. The objective of the data well will be to obtain relevant core and well logging data to improve models and reduce geological uncertainty.

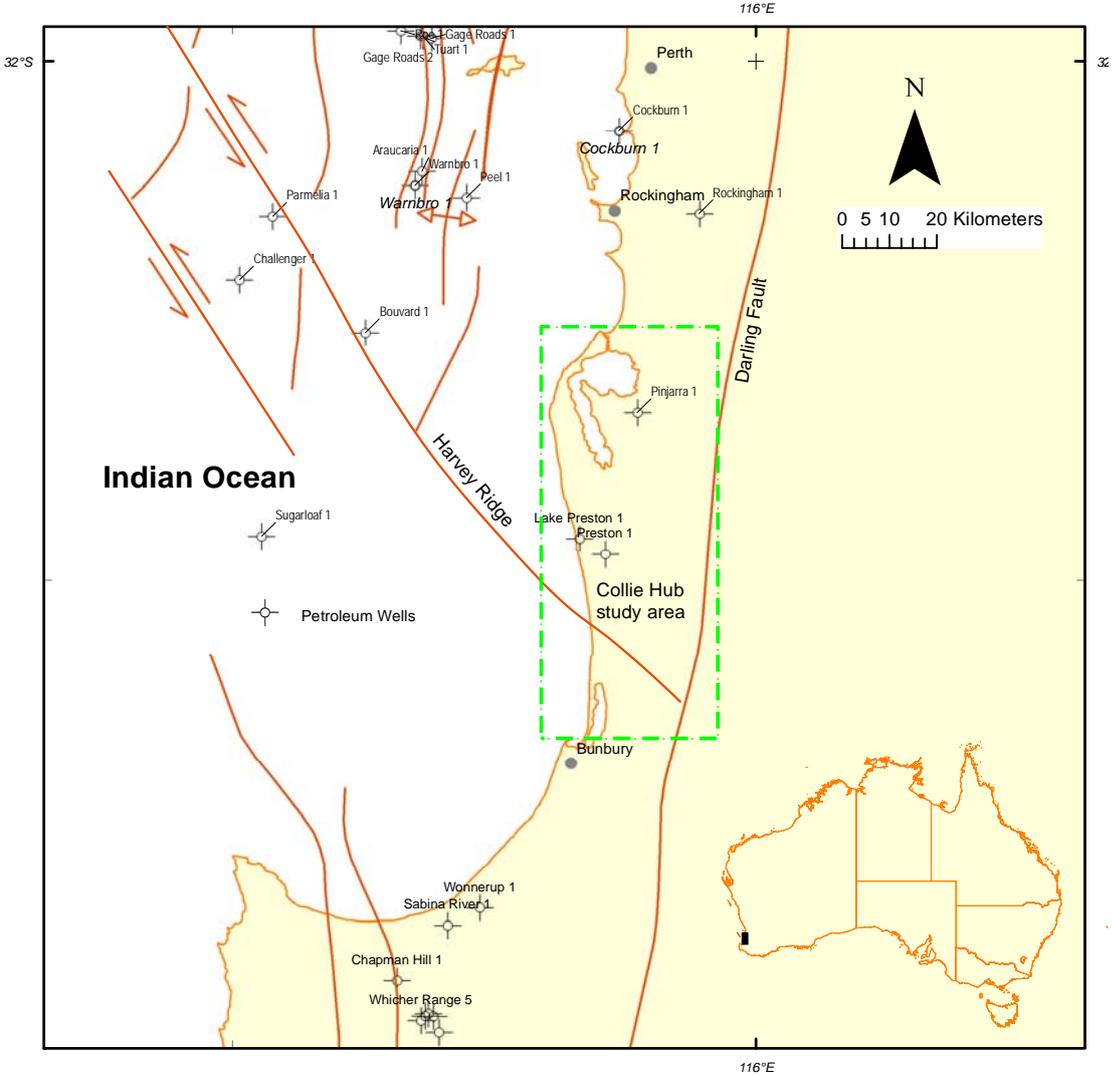


Figure 1: Location of the Collie Hub CCS site in Southern Perth Basin (basemap after Iasky and Lockwood, 2004)

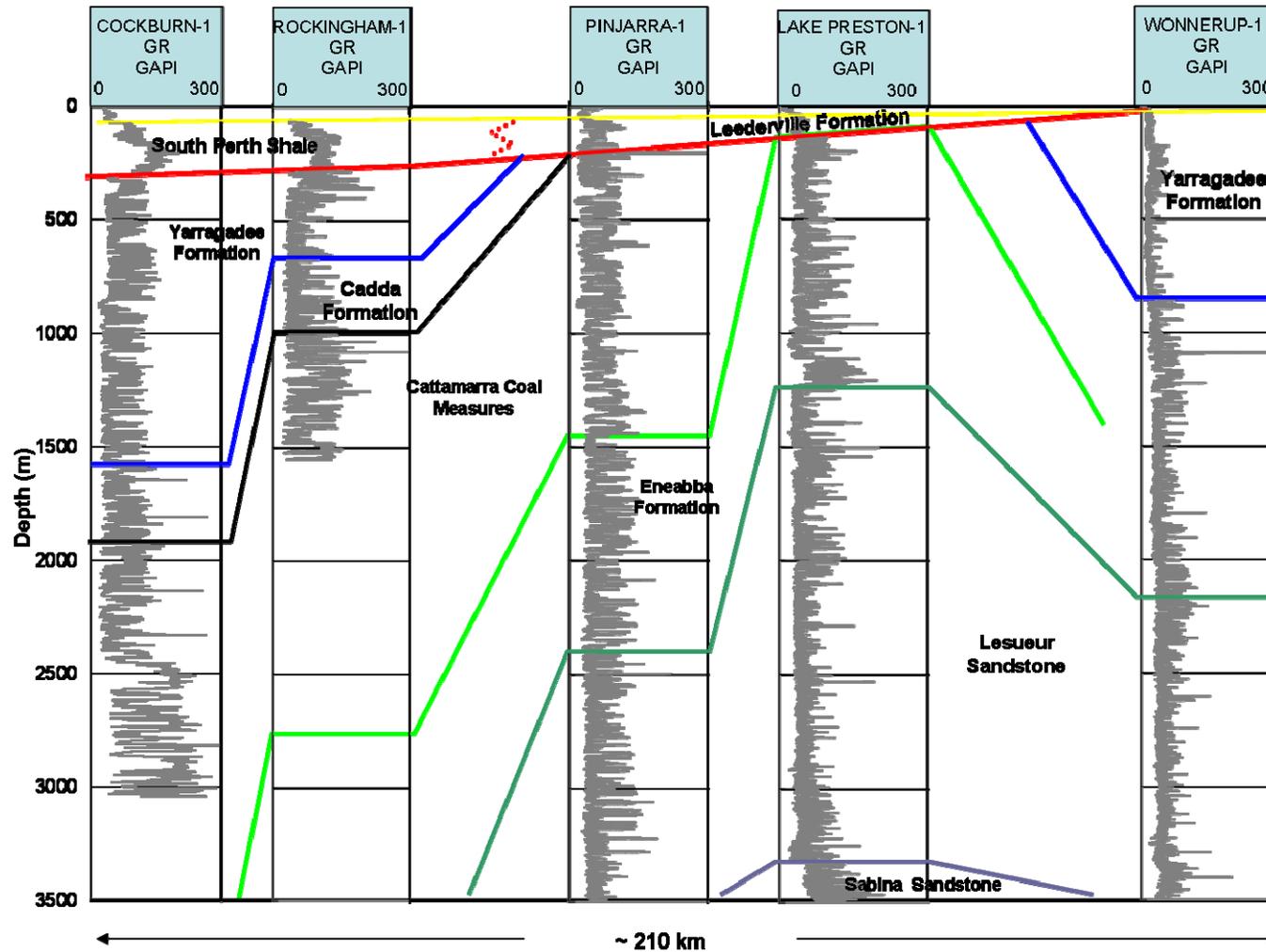


Figure 2: North-south geological section of the Collie Hub study area (Varma et al., 2009). Well locations are shown in Figure 1.

3.2 Gippsland Basin – CarbonNet

The area considered for CO₂ storage in the CarbonNet project is part of the Gippsland Basin in southeastern Victoria. About 60 Mt/yr of carbon dioxide are emitted from the Gippsland Basin's Latrobe Valley coal fired power stations. The VicGCS, a Victorian state government initiative, has been investigating the geological carbon storage potential of the Gippsland Basin (Goldie-Divko et al., 2009b). A pilot storage project is under planning that will initially capture and store 1.2 million tonnes of carbon dioxide emissions per annum before 2020, and thereafter the network will have the potential to rapidly scale up to support over 20 million tonnes per annum (Source: [Global CCS Institute](#)).

The Gippsland Basin is a post-orogenic, continental margin basin that lies near the junction of complex rift systems between the Australian plate, Antarctic plate and Lord Howe Rise (Figure 3a). Its evolution relates to the break-up of the Gondwanan supercontinent, which involved rifting between the Australian and Antarctic plates as well as opening of the Tasman Sea (Griffiths, 1971; Hocking, 1972).

The basin is an approximately E–W-trending depocentre with major fault systems and is bounded by exposed Palaeozoic rocks of the Lachlan Fold Belt to the north, northwest and south, and by Late Cretaceous oceanic crust of the Tasman Sea to the east (Foster and Gray, 2000) (Figure 3b). It extends both onshore and offshore and hosts depositional sequences ranging in age from Early Cretaceous to Holocene. Approximately two thirds of the basin is located offshore, mainly in shallow water with depths less than 200 m. At the eastern margin of the basin, water depth increases rapidly and exceeds 3000 m in the Bass Canyon. Five main fault-bounded structures are defined across the basin: (i) Northern Platform; (ii) Northern Terrace; (iii) Central Deep; (iv) Southern Terrace; and (v) Southern Platform.

The basin is one of the most prolific producing oil basins in Australia and also has substantial brown coal resources. Coal mining in the Latrobe Valley provides fuel for electricity generation for the state of Victoria, which is a key input to the state's manufacturing and industrial base. Continued utilisation of these coal resources raises concern over the release of greenhouse gases from fossil fuel combustion. Geological carbon storage is a key mitigation strategy that is being considered to minimise the release of CO₂ into the atmosphere. Accordingly, the Victorian Department of Primary Industries is carrying out detailed geological assessments to evaluate the Gippsland Basin's suitability for geological carbon storage.

Containment of CO₂ in the Gippsland Basin is contingent upon the regional top seal, the Lakes Entrance Formation, providing an effective seal. The majority of commercial hydrocarbon accumulations in the basin are sealed by the Lakes Entrance Formation which is composed of clay-rich, calcareous mudstones, grading into hemipelagic, fossiliferous mudstones (Swordfish Formation) towards the deeper basin. In general, effective top seals are demonstrably present at the onshore / nearshore oil and gas fields at Wombat, Golden Beach, Lakes Entrance and Woodside and offshore at over 30 fields. However, various hydrocarbon leakage and seepage indicators have been

reported (Goldie Divko et al., 2010) suggesting that the Lakes Entrance Formation may not be an effective top seal across the entire basin.

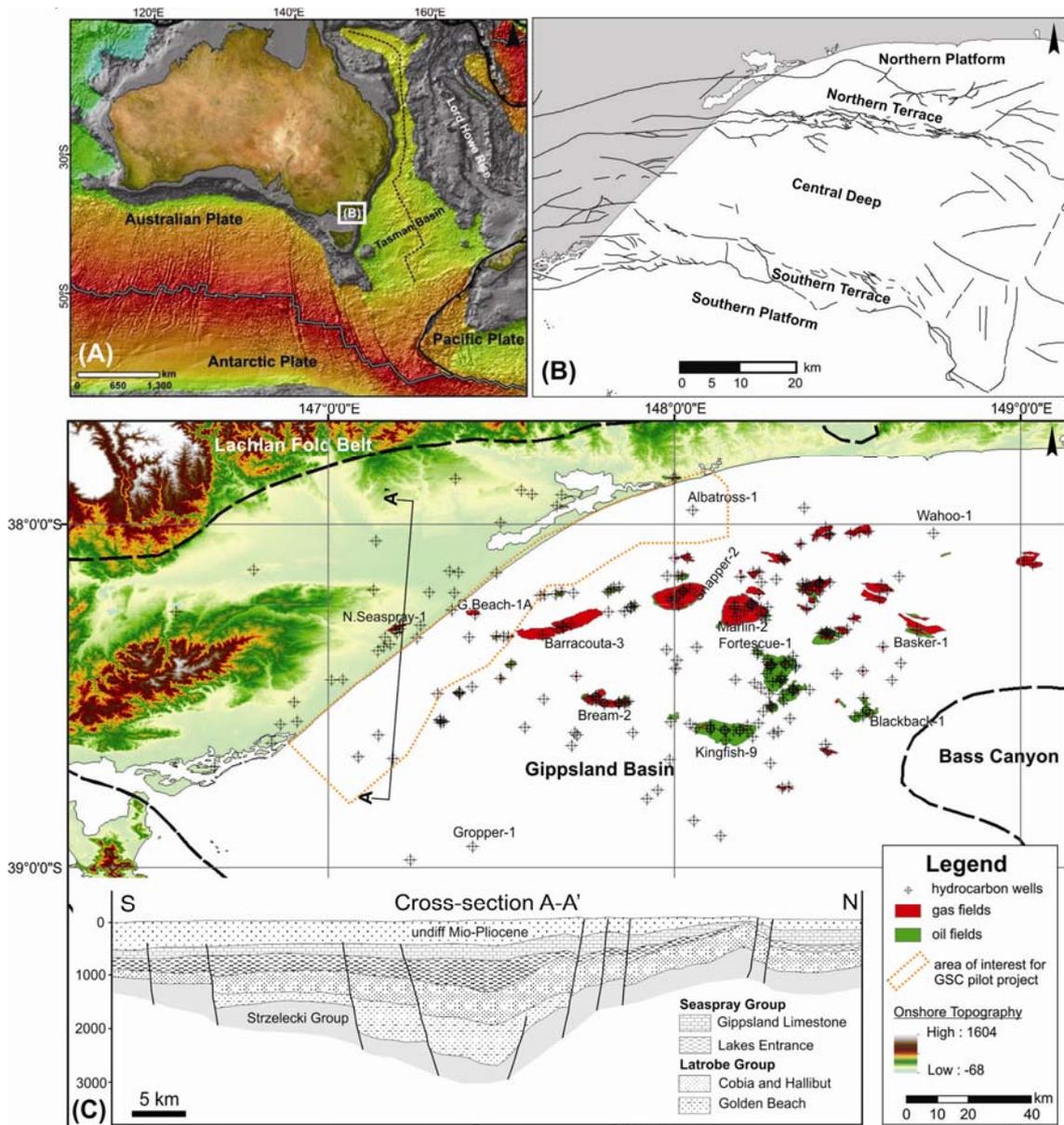


Figure 3: (A) Tectonic setting of the Gippsland Basin. The white rectangle shows the location of the Basin (after Mueller et al., 1996), (B) Main structural elements of the basin. (C) An approximate location of CarbonNet CCS site is shown by the orange polygon, and a cross-section depicting the basic geological framework (inset).

The Latrobe Group underlies the Lakes Entrance Formation and includes multiple reservoir levels as the leading candidate reservoir for the storage of CO₂. Petrophysical data from the hydrocarbon fields shows that the reservoir intervals have suitable porosity (15% - 30%) and permeability (10 mD - >10000 mD) (Malek and Mehin, 1998). Although there is limited information regarding the reservoir potential, the Strzelecki Group may also provide some storage capacity in the basin (Goldie Divko et al., 2009b). However, the available data generally indicates low porosity (<20%) and

permeability (<10 mD) for the group suggesting that low CO₂ injectivity in the Strzelecki may be an issue.

Previous work in relation to the feasibility of carbon dioxide storage in the Gippsland Basin was reported by Bradshaw and Rigg (2001), Rigg et al. (2001), and Bradshaw et al. (2002) as part of the GEODISC program. Even though the GEODISC reports are not publicly available, the references that are cited here, providing the results from the GEODISC study, were published in journals. More detailed investigations for site selection for carbon dioxide storage were carried out by the CO2CRC and reported in Hooper et al. (2005), Gibson-Poole et al. (2006), and more recently by Bunch et al. (2009), which identified three onshore sites with potential for storage of carbon dioxide: Tyers River Subgroup, Golden Beach Subgroup, and Intraformational Latrobe Subgroup.

On a regional scale, O'Brien et al. (2008) and Goldie-Divko et al. (2009a) have looked at fluid migration within the basin and the top seal quality as part of the VicGCS program. Goldie-Divko et al. (2009a) expanded the list of carbon dioxide storage plays to six and discussed technical uncertainties for each. A general discussion of potential impacts on other resources such as coal, hydrocarbon, geothermal and groundwater resources were also made based upon the buoyancy migration pathways, seal geometry and proximity of the sites to these resources. The study concluded that there could be significant impacts of carbon dioxide storage on freshwater resources in the top Latrobe and intraformational Latrobe Group aquifer system in the onshore Gippsland Basin depending on the volumes to be stored. However, a thorough assessment of the impact of carbon dioxide storage on geothermal, petroleum, water and coal resources has not been carried out to date.

3.3 Surat Basin - Wandoan CCS Project

The Surat Basin in Queensland (Figure 4) was selected for geological storage of carbon dioxide for the Wandoan Power IGCC Project which plans to generate 341 MW of electricity and capture 90% of the CO₂ emissions estimated as 75 Mt over 30 years with commercial operation starting in 2017/18 (Wandoan Power, 2011). The carbon transport and storage facilities for Wandoan CCS will be managed by CTSCo, a subsidiary of Xstrata Coal. The exact location of the injection site is unknown at this stage. The principal targets for carbon dioxide injection are the Precipice Sandstone in the Surat Basin with the Evergreen Formation as the regional seal (Figure 5). There is the suggestion that the Triassic Showgrounds Sandstone equivalent will also be considered (Jonathan Hodgkinson, pers. comm., 2011). These units were also identified in a previous Queensland Carbon Geostorage Initiative (QCGI) study (QCGI, 2010).

Bradshaw et al. (2009) reported on potential reservoir quality and seals in the Surat Basin (Figure 5). They stated that the Precipice Sandstone is a laterally extensive reservoir, thick with good porosity (maximum 37%, median 17%) and permeability (maximum 7908 mD, median 6.4 mD).

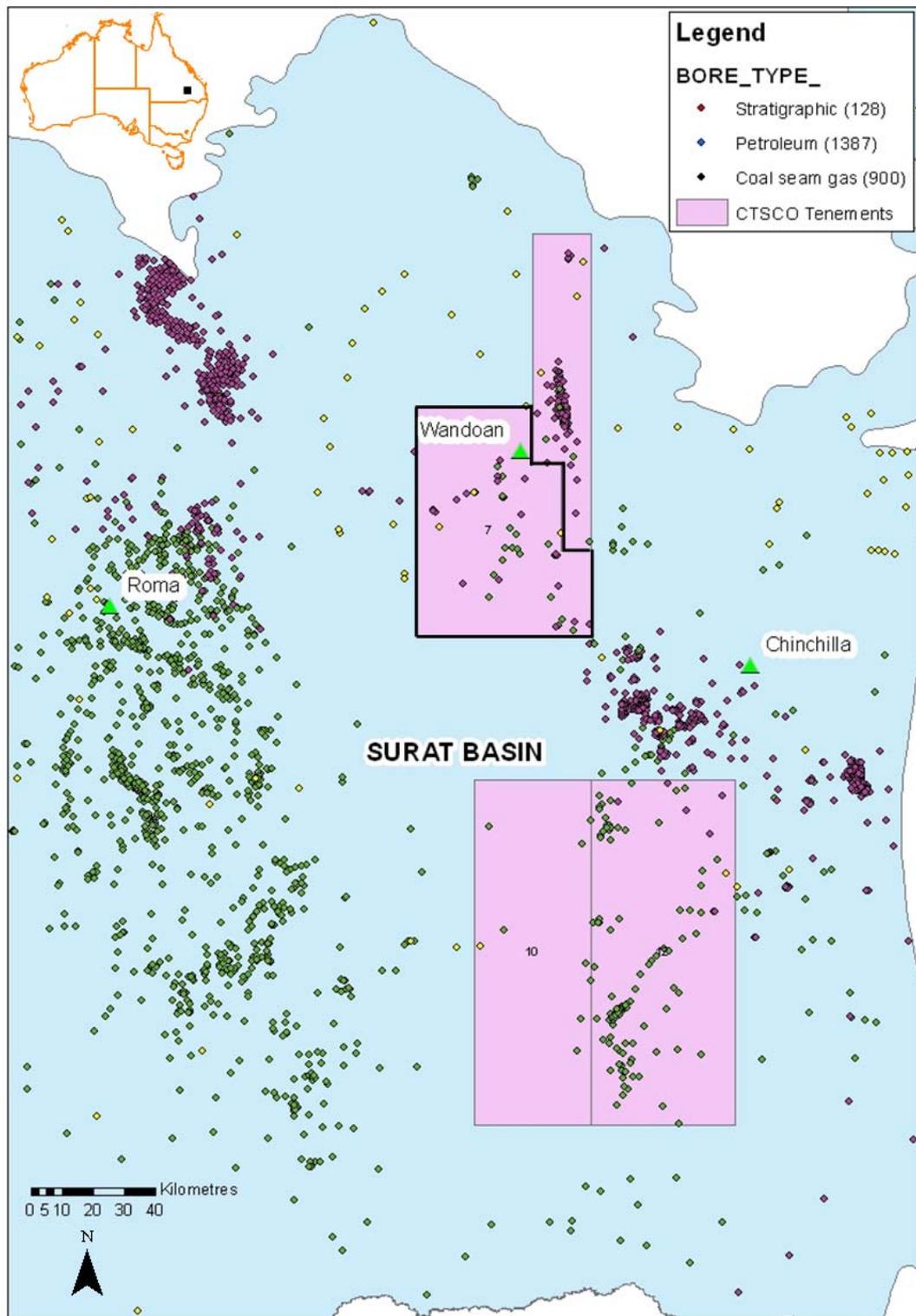


Figure 4: Location of the Wandoan CCS site in Surat Basin. The tenements are yet to be awarded to CTSCo. The primary focus for CO₂ storage by CTSCo is the EPQ7 tenement (highlighted).

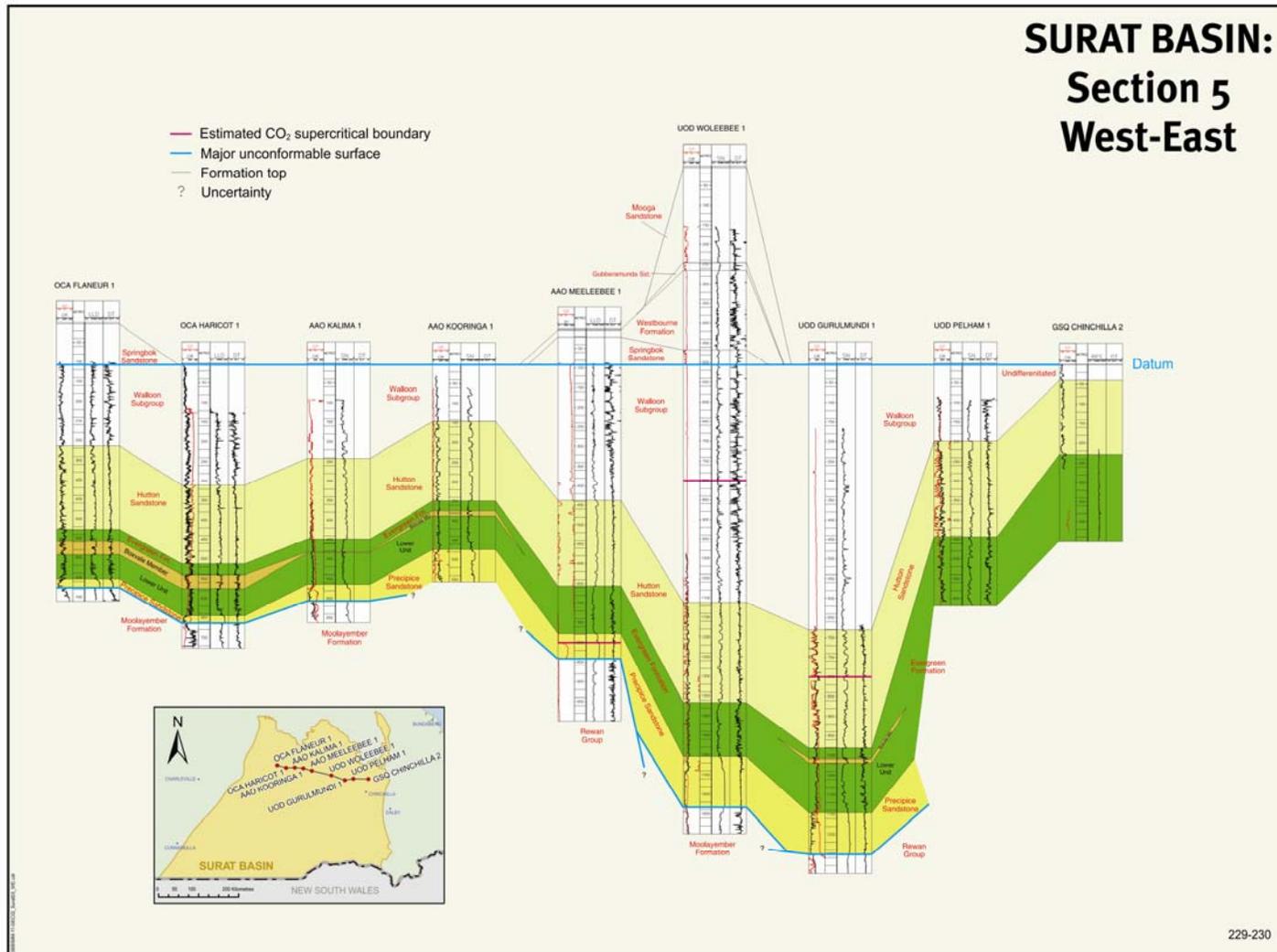


Figure 5: Geological section of the Surat Basin showing the Precipice Sandstone reservoir and the Evergreen Formation seal (QCGL, 2010).

The stratigraphy of the Surat Basin has been well described in Green et al. (1997) and Hoffmann et al. (2009). The Precipice Sandstone is a sequence of extensive fluvial braid plain sediments deposited in a low accommodation setting. The reservoir sandstones of this formation are sealed in some areas by a discontinuous shale horizon at the top of the unit and in others by the overlying Evergreen Formation. Hydrocarbon accumulations are present in both the Precipice Sandstone and the Evergreen Formation and the latter contains the Boxvale Sandstone Member. This discontinuous member divides the Evergreen Formation into upper and lower shale and fine-grained sediment dominated sub-units. Reservoir properties are variable with porosities of approximately 15% and permeability ranges from 6 to 475 mD. The Evergreen Formation is considered to form a regional seal above the Precipice Sandstone and although dominated by fine grained lithologies, exhibits extensive heterogeneity.

The Hutton Sandstone overlying the Evergreen Formation is a thick reservoir bearing unit with good porosity (average 17.8%) and permeability (441.8 mD). The Walloon Subgroup is a heterogeneous unit composed of fluvial-lacustrine deposits and although exhibiting some seal characteristics, can only be considered an 'unconventional seal' for the Hutton Sandstone. The unit hosts significant thermal coal resources with high ash contents. The Walloon Subgroup coals are also exploited for their coal seam gas endowment. A third reservoir seal pair overlies the Walloon Subgroup, which consists of the Springbok Sandstone and the Westbourne Formation. The latter unit is up to 153 m thick and exhibits similar properties to the Walloon Subgroup, but with less abundant coal seams. It may provide some sealing potential for the underlying Springbok Sandstone reservoir (Bradshaw et al., 2009). These units are, however, too shallow to be considered for the storage of carbon dioxide in the supercritical state in many areas of the Surat Basin.

4. LITERATURE REVIEW

4.1 Groundwater Resources

4.1.1 Introduction

Several studies have been published, comprising analytical and numerical techniques for evaluating the region of influence both during and after injection of CO₂ and evaluating implications for shallow groundwater resources (e.g. Nicot, 2008; Chabora and Benson, 2009; Birkholzer et al., 2009; and Birkholzer et al., 2011). Studies carried out show that the pressure induced by CO₂ injection may impact a volume of the basin significantly larger than the CO₂ plume itself. In addition, studies by Bachu et al. (1994), Nordbotten et al. (2005a), Bachu and Bennion (2008), Doughty (2008), Doughty et al. (2008), Michael et al. (2008) and Qi et al. (2009) have improved the understanding of injection of CO₂ into saline aquifers.

The MODFLOW-2005 groundwater modeling code (Harbaugh, 2005) and the TOUGH2/ECO2N multiphase simulator (Pruess et al., 1999; Pruess, 2005) have been used to model the behaviour of the injected CO₂ and the associated induced pressure regime, and its impact on shallow groundwater systems. Several other reservoir engineering codes such as Schlumberger's ECLIPSE, Roxar's TEMPEST and CMG can be used in place of TOUGH2. Geochemical alterations with respect to CO₂ storage were studied by Gunter et al. (1993), Gunter et al. (1997), Gunter et al. (2000), Gaus et al. (2005a & b), IPCC (2005) and Tsang et al. (2007). Nordbotten et al. (2005b) and Celia et al. (2010) studied the leakage risks posed by existing and abandoned oil and gas wells and provided semi-analytical means of quantifying such leakage. A recent PhD thesis (Court, 2011) from Princeton University looked at ways of better quantification of CO₂ and brine leakage, and integrating water management across all CCS operations.

Increases in dissolved CO₂ concentration that could occur as CO₂ migrates from a storage reservoir to the surface in the absence of an effective seal or if the plume took an unpredicted pathway, may alter groundwater chemistry, potentially affecting shallow groundwater used for potable water and industrial and agricultural needs. Dissolved CO₂ forms carbonic acid, altering the pH of the solution and potentially causing indirect effects. For this reason, it is important to assure isolation of injected CO₂ from any groundwater that may be used for human purposes.

In order to assess the effectiveness of geological storage of CO₂, it is important to have the ability to detect and quantify potential CO₂ leakage in the near-surface environment. Chabora and Benson (2009) studied the potential impacts of pressure build up due to CO₂ storage and impacts on shallow aquifer pressures across the caprock and found that most of the pressure signals will be marginally detectable. Limited studies have been carried out to quantify potential CO₂ leakage in the near surface environment from CO₂ storage sites through a controlled release of CO₂ at the ZERT facility in Montana, USA (Spangler et al., 2009; Strazisar et al., 2009; Oldenburg et al., 2010; Lewicki et al., 2010). Leuning et al. (2008) studied the methods of

distinguishing the leakage from CO₂ storage and natural fluctuations in CO₂ concentrations due to biogenic sources.

Several reports were reviewed in order to ascertain the present level of understanding of potential impacts of carbon dioxide storage in the Southern Perth, Surat and Gippsland basins on the available groundwater resources in these basins. The literature reviewed relate both to any direct assessment of potential impacts as well as those that contain valuable information that would be used for making such an assessment. These include reports on hydrogeology and groundwater prospectivity, geomechanical and structural assessment, and relevant site specific studies on carbon dioxide storage. To date, only minimal studies assessing the impacts of carbon dioxide storage on the groundwater resources have been carried out at each of the three CCS sites included in this review.

4.1.2 Southern Perth Basin

To date, the most comprehensive study for carbon dioxide storage feasibility in the Southern Perth Basin was carried out by Schlumberger Carbon Services (Unpublished Schlumberger report of June 2010). The studies by Schlumberger were a follow up of an initial feasibility study conducted by CO₂CRC (Varma et al., 2007). The assessment of carbon dioxide containment risk was carried out by Schlumberger (Unpublished Schlumberger report of June 2010) utilising the RISQUE methodology (Bowden and Rigg, 2004). The study did a qualitative assessment of the potential leakage risks including faults, seismicity and wells. However no quantitative assessment of the leakage and its consequent impacts on the groundwater resources was done. There has been no direct assessment of the potential effects of carbon dioxide storage in the onshore Southern Perth Basin on the groundwater resources in the region. Hence, a review of the key literature that would allow such an assessment to be carried out was conducted. This was done to determine whether ready information regarding the geology, hydrogeology and groundwater resources, and the knowledge of carbon dioxide behaviour in the subsurface exists to enable an assessment of the resource conflict issues.

Several studies of the hydrogeology and groundwater resources of the Southern Perth Basin have been carried out by the Geological Survey of Western Australia (GSWA), Water Corporation, WA Department of Water and CSIRO. These studies have defined the extent of the aquifers and the aquitards, and the quality and quantity of groundwater in the region. However, these studies has focused on aquifers that contain fresh groundwater.

The hydrogeology of the superficial and Leederville formations that occur at the site was described by Commander (1988), Deeney (1989a, b & c) and Passmore (1967, 1970). The South Perth Shale underlies the Leederville Formation (Commander, 1974 and Davidson, 1995) but its occurrence is not well defined in the southern part of the study area where it is not separated from the Leederville Formation (Baddock, 2005). The hydrogeology of the Yarragadee Formation was studied by Wharton (1980) and Commander (1984). The Cockleshell Gully Formation consists of the Cattamarra Coal Measures and the Eneabba Member. However, each of these were assigned recently

an independent formation status (Crostella and Backhouse, 2000). There is very little information on the hydrogeology of Cockleshell Gully Formation in the study area with only Deeney (1989a and b) looking at the upper 600 m of the formation as part of the Harvey and Binningup lines drilling investigation. Similarly, no hydrogeological study has been carried out for the underlying Lesueur Sandstone in the study area. The Lesueur Sandstone occurs at shallow depths in the southern margin of the Perth Basin where it contains fresh groundwater and is considered part of the Yarragadee aquifer (Baddock, 2005) and is used for Augusta town water supply. A numerical groundwater flow model of the study area was developed by CSIRO as part of the South-West Sustainable Yields study (CSIRO, 2009; URS, 2009a & b). However, the model does not include the strata beneath the Leederville Formation, which is a major limitation for its use in the carbon dioxide-groundwater resource conflict assessment. Hydrogeology of the central part of the Perth Basin is described in detail in Davidson (1995) and Davidson and Yu (2008); however, information on the hydrogeology of the deeper parts of the basin in this area is limited. The groundwater use and the water resource management issues are covered in the various water resource management reports by the Department of Water (2007a & b, 2008), and in the water resource protection report for the Preston Beach Water Supply (Department of Water, 2006).

While there is good knowledge of the groundwater resource occurrence in the shallow part of the study area, the hydrogeology of the deeper parts of the basin is not well known. Recent work by WA DMP including the interpretation of the new seismic data, and the planned data well at the Harvey Ridge will improve the understanding of the hydrodynamics of the area.

4.1.3 Gippsland Basin

The onshore Gippsland Basin contains substantial resources of groundwater within a complex set of both unconfined and confined aquifers. The groundwater in the basin has been abstracted for town water supply schemes, domestic and horticultural use, facilitation of coal mining and power generation, and oil and gas production. Groundwater also provides baseflow to rivers and creeks that flow into the Gippsland Lakes system. Several studies in the past involving drilling, testing and monitoring, carried out by the Victorian Government, along with coal mining, power generation and petroleum exploration companies have helped unravel the hydrogeology of the basin. Key studies describing the hydrogeology and groundwater resources of the basin were carried out by Walker and Mollica (1990), Nahm (2002), Schaeffer (2004), Schaeffer (2008), and more recently by Varma et al. (2010) and Varma et al. (2011).

Previous work on the falling water levels in the Latrobe Group aquifer system of the Gippsland Basin was conducted by CSIRO in 2004 (Hatton et al., 2004). It concluded that significant withdrawal of fluid from the Gippsland Basin had resulted in a complex pattern of pressure decline in the aquifer, potentially associated with coal mining, irrigation and offshore oil and gas production. Further investigations by CSIRO (Underschultz et al., 2006) and more recently by Varma et al. (2010) enabled an improved understanding of the controls on falling water levels through a detailed pressure decline study of the Gippsland Basin using selected onshore and offshore wells, available historical production and pressure data, and a review of the basin's

structural and lithological complexity. The work conducted thus far on the Gippsland Basin hydrodynamics suggests that the virgin state of the formation water flow system has been significantly altered by human activity through resource development (coal, oil, gas, and water).

A 2D GMS/MODFLOW based model of the Latrobe Aquifer has been developed and used to estimate the impact of a potential reduction in recharge due to a decline in rainfall over the past 30 years (Varma et al., 2010). The model was also used to simulate water level drawdowns in the Latrobe Aquifer as a result of groundwater and other fluid extractions. A more detailed 10 layer regional model of the Gippsland Basin has very recently been calibrated under steady state through joint research with VicDPI. This model needs to be further calibrated under transient state to enable its use for prediction of impacts of carbon dioxide injection on the groundwater resources (Varma et al., 2011). A large amount of data exists on the hydrogeology and groundwater resources of the Gippsland Basin. In addition, the modeling work being carried out under a joint CSIRO and VicGSV program will greatly assist in an assessment of the potential impacts of CO₂ storage on these resources.

4.1.4 Surat Basin

The most up-to-date compilation of the potential impacts of carbon dioxide storage in the Surat Basin on the groundwater aquifers is presented in Hodgkinson et al. (2009). The study looked at the potential changes in groundwater chemistry in response to injection of carbon dioxide and potential of vertical hydraulic connection between the aquifers. One of the key outcomes of this study was the review of all potential issues related to the effect of carbon dioxide injection on the freshwater aquifers in general through an extensive literature review, as well as those specific to the Great Artesian Basin (GAB). The study reports that the lack of information available for deep aquifers was a major shortcoming in many GAB modeling studies. Hitchon and Hays (1971) in Hodgkinson et al. (2009) used petroleum well data to construct a 2D flow model for the Surat Basin, which provided information on the pre-stress flow regime prevalent in the deeper, unexploited regions of the aquifer systems in the Surat Basin. Subsequent studies on the groundwater flow systems in the region were carried out by Habermehl (1980) and Radke et al. (2000) and then by the CO₂CRC (Hennig, 2005; Sayers et al., 2005; Daniel, 2006; Kalinowski, 2006; Patchett, 2006; Hennig et al., 2006).

The study by Hodgkinson et al. (2009) indicated that the acid buffering capacity of the groundwater is large and in line with the high pH and alkalinity measurements across the GAB. Preliminary modeling carried out as part of this study indicated that the groundwater systems have a natural capacity to remediate the induced low pH due to carbon dioxide injection. A hydrodynamic assessment of the aquifers indicated that the flow system in the Precipice Sandstone aquifer was different to that in the underlying and overlying aquifers. This identified a lack of hydraulic communication providing evidence that a regional seal exists above the Precipice Sandstone. However, other data suggests that this regional seal pinches out to the north. Interpreted flow patterns in the Precipice Sandstone show that hydrodynamic forcing may not be of great enough magnitude to contain a large carbon dioxide plume migrating north under buoyancy forces and as a result contaminating the shallower aquifers. Monitoring and

mitigation of impacts on the loss of containment of carbon dioxide has been discussed generally in Hodgkinson et al. (2009) as part of economic implications and no study area specific recommendations were made.

Hodgkinson et al. (2009) recognised that the resolution of published regional flow models for the GAB (Habermehl, 1980; Radke et al., 2000) is too coarse for carbon geostorage assessment and that better constrained interpretations were required for an improved understanding of the aquifer interconnections and the behaviour of aquitards. The study made note of a future work plan including collection of new data through a deep well drilling program together with nested piezometers and resampling of existing groundwater bores, and analysis of cores for porosity and permeability. The locations of future carbon storage injection sites are yet to be defined. The location of these sites relative to other basin resources and areas of environmental sensitivity is important for characterising resource interactions and developing a basin management plan. The long-term effects of injection-induced pressure build up and consequent effects on carbon dioxide plume migration and changes in the hydrodynamic regime need to be better modeled (Hodgkinson et al., 2009).

More recently, Australia Pacific LNG (APLNG, 2010a) and QGC (Golder Associates, 2009) have conducted detailed groundwater assessments including numerical modeling for the eastern Surat Basin to assess the impact of CSG development. While the reports are in public domain, the actual models may not be publicly available. At the time of writing this report Coal Seam Gas (CSG) planning and development is occurring at a rapid pace. There are current plans for the CSG industry to design its own monitoring and verification systems in the Great Artesian Basin tailored to characterising interactions between CSG development and groundwater resources. Ideally, these plans for M&V systems in CSG will also be useful input for carbon storage opportunities and can ultimately be incorporated in overall basin management plans.

4.2 Hydrocarbon Resources

Hydrocarbon basins with proven petroleum systems tend to also possess suitable reservoir/seal sequences for the storage of CO₂. This brings along potential competition for the pore space and a need for the assessment of how the storage will affect both the producing fields and potential future discoveries in the basin. This assessment will require clear understanding of the petroleum systems and plays in the basin as well as subsurface behaviour and movement of the CO₂ plume and associated pressure field. The following information is critical in this assessment:

- Location of the hydrocarbon pools not yet drained and estimated time to depletion;
- Reservoir architecture, reservoir/pore pressures, hydrocarbon water contacts and drive mechanism;
- Location of the wellbores;
- Location of the tested dry traps and untested potential traps;
- Data gaps and how these gaps may impact future exploration opportunities;

- Location of prospective CO₂ injection sites and long-term plume behaviour;
- Location of fracture or high permeability zones that can act as fluid conduits.

Among the three sites reviewed, the Southern Perth Basin has the least potential for commercially viable hydrocarbon accumulations based on the currently sparse data coverage in the vicinity of proposed carbon storage. However, conceptual exploration models and play concepts are prone to change with addition of new data that may alter the status of any basins resource potential. Hydrocarbon and CO₂ resource conflict assessments are more critical for the Surat and Gippsland basins which have proven petroleum systems with conventional oil and gas production in the vicinity of proposed carbon storage. The assessment is particularly important for the Gippsland Basin as one of the leading hydrocarbon producing basins of Australia.

4.2.1 Southern Perth Basin

Hydrocarbon systems of the Southern Perth Basin are defined by Crostella and Backhouse (2000) with some uncertainties due to limited availability of data and lack of commercial hydrocarbon fields. The Northern Perth Basin could provide further insight into the hydrocarbon potential of the region with several commercial fields identified in the region (e.g. Mory and Iasky, 1996). However, many hydrocarbon shows and significant, currently non-commercial gas reserves were reported from the Southern Perth Basin based on more than 10 hydrocarbon exploration wells (Crostella and Backhouse, 2000). Although gas accumulations are mostly in the Late Permian reservoirs with future tight-gas development potential, hydrocarbon shows extend up to the early Cretaceous section. Structural and stratigraphic traps associated with the Neocomian break-up unconformity are primary conventional exploration targets with potential for Gage Sandstone reservoirs.

The Triassic Lesueur Sandstone and Gage Sandstone below the South Perth Shale are identified as the most suitable reservoirs for storage of carbon dioxide. However, these reservoirs partly overlap or remain in close stratigraphic proximity to main targets of hydrocarbon exploration and possible future tight-gas development efforts. There is a potential impact of carbon dioxide sequestration on hydrocarbon resources and future exploration efforts. This impact was briefly noted by Causebrook et al. (2006) for the Gage Sandstone. However, this needs more detailed assessment, especially in extending to the potential for tight-gas developments, which already offers a significant untapped gas potential in the basin (Campbell, 2009).

The Harvey Ridge structure is identified as the most suitable geological feature for the underground storage of CO₂ for the Collie Hub, the primary injection target being the Lesueur Sandstone (Varma et al., 2007). There is no study available that properly assesses the impact of carbon dioxide storage on the potential conventional and unconventional hydrocarbon resources at the Collie Hub site. This assessment is particularly critical for unconventional gas as the Lesueur Sandstone immediately overlies the Permian section with proven tight gas potential. The Whicher Range, a tight sand gas field, is located approximately 100 km SW of Collie with an estimated gas volume of between 1 and 4 trillion cubic feet (Crostella and Backhouse, 2000). Gas in this field accumulated in the sandstone intervals of the Sue Group and is trapped by

a rollover anticline on the hangingwall of a normal fault. Porosity and permeability are generally poor across the reservoir intervals with formation damage due to clay content further deteriorating the reservoir potential.

A quantitative evaluation of the impacts of CO₂ storage requires better subsurface characterisation by integrating the site-specific borehole and seismic data to capture facies architecture and deformation patterns of the target interval and the overlying and underlying sections. This will help to better constrain pore-scale properties and subsurface behaviour of the injected carbon dioxide and its interaction with the Permian section. Proper geological characterisation will be impaired for the Harvey Ridge due to the scarcity of the data. Acquisition of additional data (borehole and seismic) is critical for a more confident characterisation of the subsurface.

4.2.2 Gippsland Basin

Ongoing hydrocarbon production (Malek and Mehin, 1998), relatively recent exploration (conventional) efforts (e.g. Chiupka, 1996; Bernecker et al., 2002) and growing interest in unconventional hydrocarbon resources (Campbell, 2009) are likely to preserve the position of the Gippsland Basin into the future as a significant hydrocarbon producing basin from the Latrobe and possibly Strzelecki reservoirs. Preliminary studies confirm the basin's potential for storage of carbon dioxide contained under the regional Lakes Entrance Formation top seal or under the tight upper Strzelecki Group formations (Gibson-Poole et al., 2006; Gibson-Poole et al., 2008; Goldie-Divko et al., 2009a & b). However, hydrocarbon production/exploration efforts and carbon dioxide storage plans have a common stratigraphic interval of interest focusing on the Latrobe and Strzelecki groups. This could raise some issues between these two users of the basin's pore space. The impact of carbon dioxide storage on undiscovered hydrocarbon resources is briefly noted by Goldie-Divko et al. (2009b) for the onshore part of the basin. However, more detailed assessments are required to clearly understand and evaluate the nature and extent of competition for the pore space from these uses.

A portfolio of prospective storage sites is under evaluation in the Gippsland Basin with the near shore / offshore areas being closely examined on account of the lower cost of development compared with sites further offshore. Basin scale assessments are currently available for carbon dioxide containment potential, and CarbonNet is currently preparing static and dynamic models to mature 4 to 6 sites to potentially contingent resources storage sites. Although Goldie-Divko et al. (2009b) have provided some conceptual discussions on the potential resource impacts, data density is reasonable in the Gippsland Basin and should be utilised for quantitative assessments. Extensive coverage of 2D and 3D seismic data are available and the Victorian DPI has recently commissioned merge of over 30 3D seismic surveys and 100 2D surveys integrated with over 500 wells with quality downhole data. The data coverage will improve further with detailed analysis of a recently acquired 2D seismic survey along the southern margin.

4.2.3 Surat Basin

A general framework of the hydrocarbon habitat in the Bowen/Surat superimposed basin system is defined by Elliott (1989), Green et al. (1997) and Korsch et al. (1998). These papers identify the main hydrocarbon production and exploration targets as the Jurassic Precipice and Triassic Showgrounds sandstones sealed by the Evergreen and Moolayember formations respectively. Although exploration activities targeting conventional hydrocarbons have decreased in recent years, these activities are sensitive to oil prices and a renewal of interest that may bring along new discoveries is always a possibility, particularly at the current range of oil prices.

Suitability of the Surat Basin for geological storage of carbon dioxide was suggested by numerous studies (Greenhouse Gas Storage Solutions, 2009; Queensland Carbon Geostorage Initiative, 2009; Patchett, 2006). These studies commonly refer to the Precipice-Evergreen, Boxvale-Evergreen and Hutton-Walloon in the Surat Basin and the Showgrounds-Moolayember in the underlying Bowen Basin as forming potentially suitable reservoir/seal pairs for carbon dioxide storage. Accordingly, some stratigraphic overlaps become apparent between the exploration and exploitation of conventional/unconventional hydrocarbon resources and likely injection targets of carbon dioxide developments in the Surat Basin. There is a potential need for integrated basin management of the pore space.

Some previously selected CO₂ storage sites in the Dennison Trough of the Bowen Basin (ZeroGen) were discarded due to poor injectivity and high cost of development, although the subsurface conditions would not have hindered the development of a pilot scale demonstration project at these sites (Jonathan Hodgkinson, pers. comm., 2011). On the other hand, the approximate locations of potential storage sites in the Surat Basin are still undecided. For this reason, a scenario based approach can be used by experimenting with multiple injection sites/targets that can potentially interact with conventional hydrocarbon fields. This requires data integration, detailed subsurface characterisation and building reservoir models for the different sites/scenarios on which the assessments can be carried out. In this way, an outline can be drawn for potential resource management issues which have not been assessed so far for the Surat Basin.

4.3 Coal and Coal Seam Gas Resources

For the purposes of assessing impacts of CO₂ storage on coal and unconventional gas in each area, the following information would be required:

- Location and full extent of coal seams
- Quality of coal in each seam
- Existence of coal seam gas
- Current extraction rate of coal and coal seam gas
- Future intention to extract coal or coal seam gas

At present, Australian coal is typically mined at shallow levels and although not all activity is open-cut mining, most deep coal is not currently economically viable to extract. However, deeper coal and those that host coal seam gas (CSG) may be of economic interest for future energy production. Such resources could have its value diminished if carbon dioxide is stored in or close to coal bearing rocks, and therefore, deeper, currently unexploited coal seams are considered in this report as valid for resource management consideration.

It may also be possible for CO₂ injection and coal seam gas extraction to co-exist. In coal beds, CO₂ is preferentially adsorbed onto the coal micropore surfaces, displacing the existing methane (CH₄) (Gunter et al., 1997; Bradshaw & Rigg, 2001; IPCC, 2005, Pan and Connell, 2007). CO₂ can be geologically stored in coal beds that are considered economically unmineable, or can be used to enhance coal bed methane recovery (ECBMR). Technical challenges for CO₂ storage in coal seams include the ability to inject the CO₂ due to the typically low permeability characteristics of the coal cleat system (especially with increasing depth and coal maturity), swelling of the coal and the economic viability due to the large number of wells that may need to be drilled (Gunter et al., 1997; Bradshaw & Rigg, 2001; IPCC, 2005). Research into CO₂ storage in coal is still at quite an early stage and further work needs to be conducted to fully understand the processes involved and the most suitable coal characteristics for CO₂ storage (IPCC, 2005).

4.3.1 Southern Perth Basin

Coal is mined at the surface in the Collie Coal Basin about 50 km south east from the Collie Hub CCS site. This is an isolated basin on the Yilgarn Craton separated from the Southern Perth Basin and is considered unsuitable for carbon storage (Varma et al., 2007). However, in the Southern Perth Basin, coal or coal seam gas is not a resource exploited in this area at present. Carbon dioxide storage is planned to be in the Lesueur Sandstone, but geological characterisation of the underlying rocks does not appear to have been considered and must be assessed with respect to coal occurrences as future resource potential that will otherwise be 'locked out' below a carbon dioxide plume as extraction from below the CO₂ plume may require drilling through the CO₂ reservoir formation.

Millar (2011) wrote a short article for the Royalties for Regions group at the 'Promoting Prospectivity of Western Australia' meeting, outlining the potential projects for underground coal gasification, use of sub-bituminous coal, coal-to-liquids and new coal mining projects and their importance for Western Australia. Although coal is mined in the Collie Basin (different to the Southern Perth Basin), the industry is presently not well developed in WA. If this situation is going to change due to future resource and energy needs, the coal mining and coal seam gas industrial potential may need to be assessed to identify whether coal seams present but largely under-explored are not prematurely discounted by carbon dioxide injection near their locations. Of particular note, the Lake Preston-1 well completion report (Young and Johanson, 1973) identifies that although '...no significant shows were recorded during drilling', there was coal seam gas in the Sue Coal Measures, confined to the coal beds themselves '...which were up to 3 m thick'. More detail of what units lie below the storage site may be useful

(including below the lower Lesueur Sandstone onshore), although a future economic interest in potential CSG is unlikely due to the large depths.

Schlumberger's unpublished report of June 2010 shows good detail of what is available from the wells (petroleum and hydrological) in the area. Stratigraphy from Geoscience Australia (McPherson and Jones, 2005: [GA6548](#)) shows that the Sue Group largely sits under the Lesueur Sandstone and hosts coal measures.

The Lake Preston-1 well completion report (Young and Johanson, 1973) provides a good geological description of the area along with some detail of other wells in the area. The Lake Preston-1 and Wonnerup-1 wells (Figure 1) penetrated the Sue Coal Measures so stratigraphy at that depth may be available from logs of those wells. Coal and gas were reported at these sites and depth. At Lake Preston 1, close to the Harvey Ridge, where the depth of occurrence of the Sue Coal Measures is expected to be the shallowest in the region, it is still about 4000 m and therefore deemed unmineable. ECBM production may be of interest in the future and CO₂ storage close to this site may not prevent or disrupt such activity. Other wells in the area did not penetrate deeper than the Lesueur or Eneabba units (Figure 6). Backhouse (1991) provides a good background and some detailed lithology of the region.

Baddock (2005) summarises some of the work performed to the south of the Collie Hub area and describes the Sue Coal Measures occurring at varying depths across the region. Baddock (2005) also describes the depth of occurrences of the Sabina Formation, the Lesueur Sandstone and the Cockleshell Gully (Eneabba) Formation in different wells that intersect these units. Coal is reported to be occurring in most of these units.

4.3.2 Gippsland Basin

Coal is cited by various authors as being present at varying depths in the Gippsland Basin and may have potential as a future economic asset even at depth. A report by VicGCS that reviews the storage potential of the onshore Gippsland Basin (Goldie Divko et al., 2009a) states that all carbon storage plays discussed in the report have 'some potential impact with undiscovered petroleum resources' in relation to the Strzelecki Group for both petroleum and coal interests, and a low impact potential on petroleum in the Latrobe Group. A subsequent report by Goldie Divko et al. (2009b) reviews the area's geology and identifies a number of coal deposits. For example in the Strzelecki Group, several coal-rich horizons exist; in the Latrobe Group, Curlip Formation, minor coal is present; the Golden Beach Subgroup contains some coals and in the Halibut Subgroup Kingfish Formation, coal rich sediments are reported. In the nearshore environment, the Golden Beach, Halibut and Cobia subgroups located in the Latrobe Group in the on/nearshore Seaspray Depression all host coal (Goldie Divko et al 2009b). There are extensive coal horizons seen in offshore wells with individual coals up to about 20 metres in Tommyruff-1. They are eminently mappable using amplitude extraction methods. Hatton et al. (2004) state that the 100-300 m thick sediments of the onshore basin are host to 'great amounts of coal, oil, gas and groundwater' suggesting there may be resources throughout the basin of future economic interest.

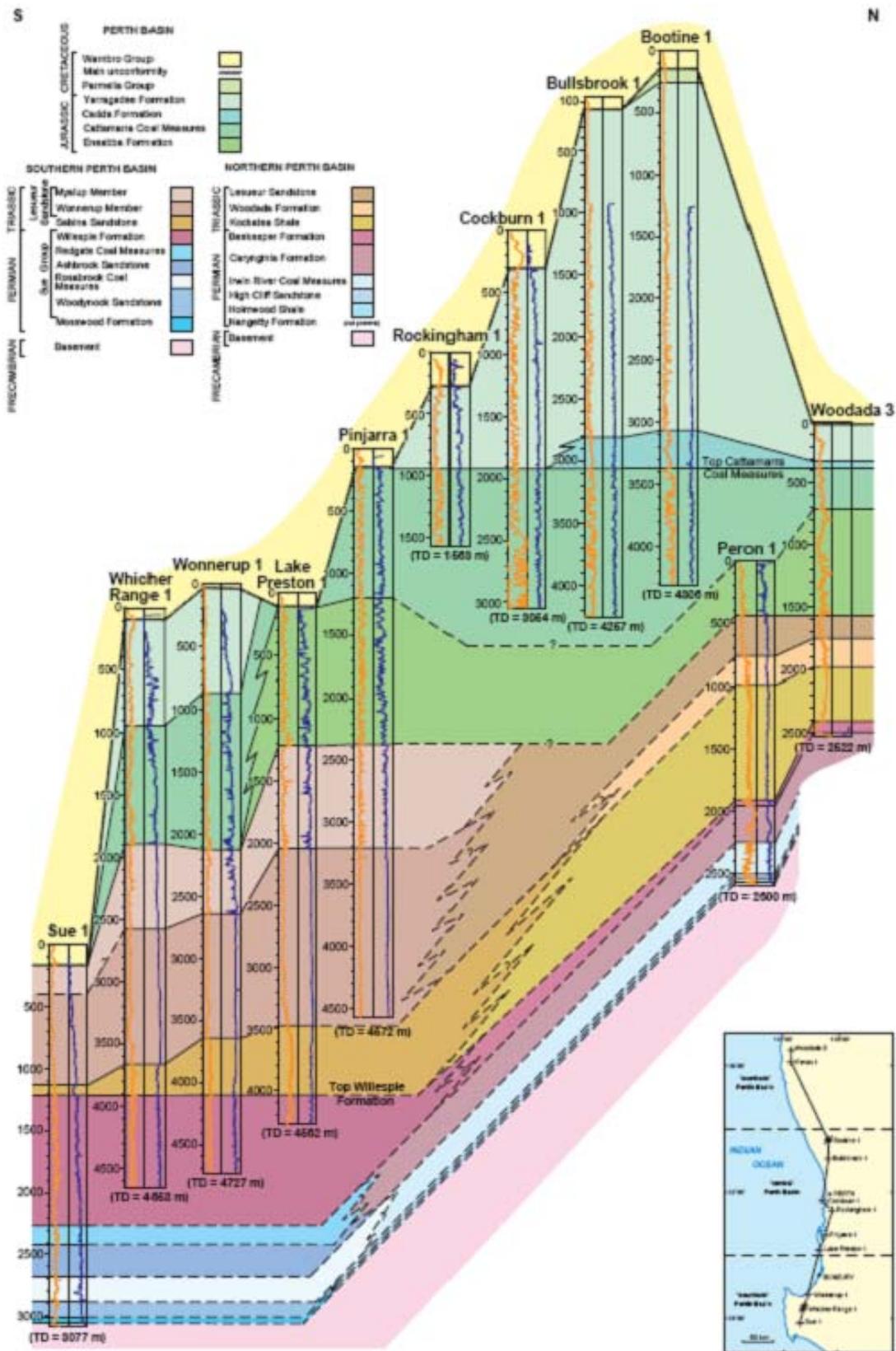


Figure 6: North – south well correlation (Crostella and Backhouse, 2000)

In a report on potential opportunities for CCS in Victoria, Gibson-Poole et al. (2006) assessed potential storage in Early Cretaceous, black coals. Some of the seams were mined up to the 1960s but whether they will be of economic interest in the future was not stated. The coal was of high rank and moderate ash content. Its future mineability should be assessed if the coal lies within close proximity to a potential storage site. Additionally, some CSG was identified in the area but the report suggests the volume may not be of interest either for coal seam gas production or coal bed methane with a CO₂ storage option. Although storage in this coal was discounted, storage near this area or where this coal may be in a migration pathway and may reduce the value of any potential future for this coal or coal seam gas as a future resource. Viability of coal seam gas extraction as a future resource, should future economics allow, may be worth exploring.

Similarly, storage in the Eocene Traralgon Formation was assessed and identified as a possible site (Figure 7) due to the quality and extent of the coal (Gibson-Poole et al., 2006). The deeper coal of the Traralgon Formation was reported as having a particularly high sulphur content suggesting it may not be of mineable interest. The economics of mining such a coal in the future or with additional processing was not reported on and should be assessed further.

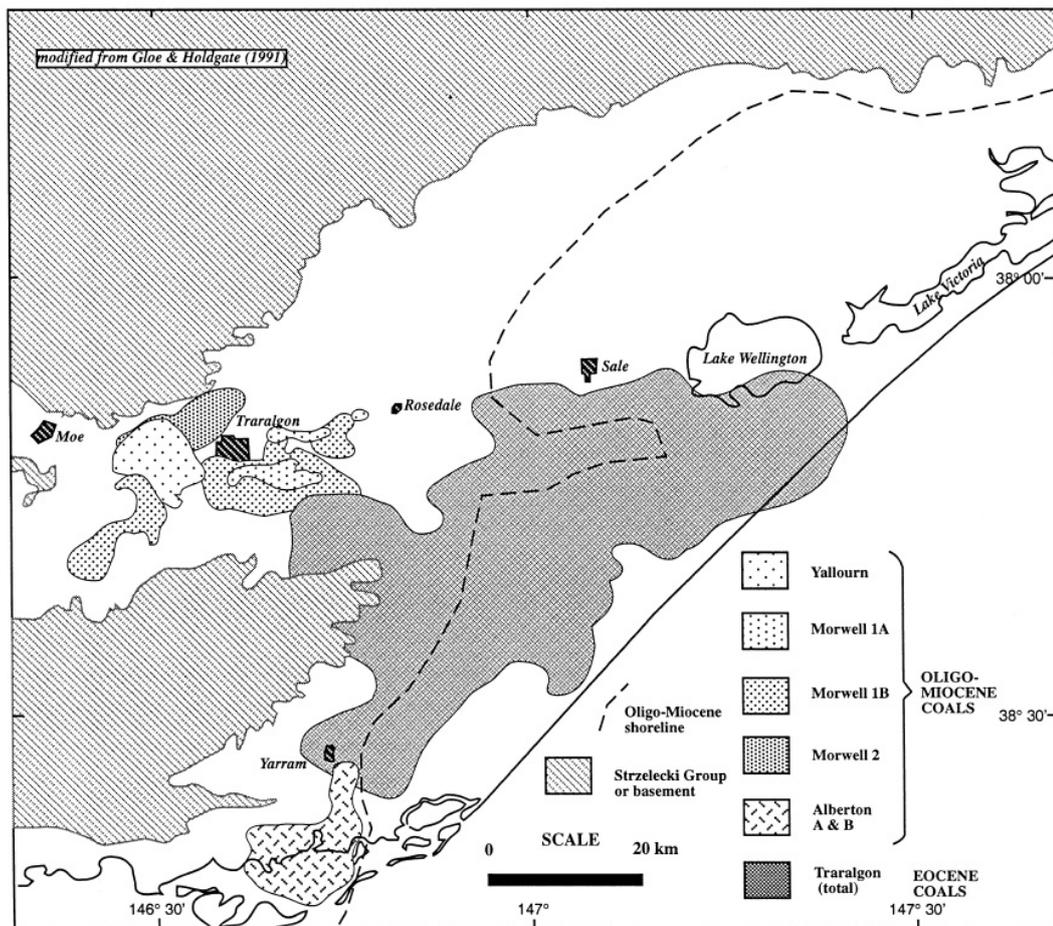


Figure 7: After Holdgate et al. (2000), map showing location of coals in Gippsland area particularly the Traralgon Coals (Cited in Gibson-Poole et al 2006).

Sulphur liberation techniques are of great interest to the coal market and if an economic method of reducing organic sulphur content becomes available, this coal may be of mineable interest. Also, low quality coal is frequently blended with higher quality coal to become a viable resource. Gibson-Poole et al., (2006) additionally identified that carbon dioxide may be used for enhancing CSG production and marine shales will provide good containment, but the report concludes that the main risks of storage in this area include potential impacts on coal resources.

Gibson-Poole et al. (2006) stated that the Kingfish Field is most likely the first site for CO₂ storage. It is due to be depleted between 2015 and 2025 and will provide a prospective storage site in coals. This site was also assessed by Hooper et al. (2005), Gibson-Poole et al. (2008) and Bernecker and Partridge (2001). However, the site is currently not a focus for CO₂ storage. Although submarine coal mining does take place in some places such as Canada, Japan and Chile, it is typically relatively close to shore. This site is located approximately 70 km offshore and in deep water and potential as a future resource either as coal or for ECBM production is improbable. According to the Australian Mines Atlas, there does not appear to be any impact on other mineral resources in the potential storage areas, although the atlas may not show all or future undiscovered potential. Neal et al. (2006) performed an economic evaluation of offshore storage in the Gippsland Basin. The impact on sterilising a future resource (i.e. lost revenue) was not assessed.

O'Brien et al. (2008) identified a relationship between the coal measures and the existence of oil and gas in the Gippsland Basin (demonstrating that oils were generated from coal-rich facies), suggesting the existence of significant coal measures off-structure the hydrocarbon fields throughout the area. This implies that if there is sufficient coal in the region, there could be an option of enhanced coal seam gas production in the future.

Well logs and seismic data need to be reviewed to better describe the extent and quality of deep coal, whether there is remaining gas present, and to assess the potential of this as a future resource, including whether injecting carbon dioxide could enhance CSG production. Confirmation of future energy plans and of the geology below the storage site(s) should also be sought. The future prospects for mineability of Early Cretaceous Black Coals identified by Gibson-Poole et al. (2006) should be explored in addition to the potential future economic interest of gas found in coals of the Strzelecki Group. Better knowledge of the coal resources in the Gippsland Basin would assist in understanding the future possible extent of coal mining and coal seam gas extraction.

Holdgate and Gallagher (2003) provide a good review of the geology of the area including some cross sections. O'Brien et al. (2008) also provide a good assessment of stratigraphy including petroleum system elements in the basin and occurrences of coal. Malek and Mehin (1998, Oil and Gas Resources of Victoria) provide a very good geological and hydrocarbon resource review, including cross sections and data availability for the region. The latest Victorian coal inventory (VicDPI, 2007) describes coal in the Gippsland basin and provides a GIS data package for mapped coal including coal quality and occurrences. The report identifies 4 coalfields in the

Seaspray Depression each hosting brown coal of significant thickness in places. Further assessment and extrapolation of the data could be performed to identify potential for CO₂ injection conflicts or ECBMR opportunities. There is a general lack of information on the economic assessment of currently known deep coals and perhaps modeling of coals across the area is warranted to assess the potential for these as a resource in the future. Detailed information about the coal at depth appears to be lacking as does general coal rank, quality and extent. ECBMR may be considered a viable option for the deep, unmineable coals in the Gippsland area and CO₂ injection close to such seams may not be an issue.

4.3.3 Surat Basin

As previously mentioned, Wandoan is situated in the centre of the Surat Basin and the project does not yet have a clearly defined storage site, although it is expected to be in the eastern Surat Basin. The project is designed to supply storage for carbon dioxide from thermal coal, which is a major resource mined in the area that will continue to be of economic interest for some time. Coal mining here is presently a surface mining activity. Additionally, gas from the coal seams (CSG) has been confirmed as being an economically viable resource and hydrological studies have also been carried out in this area to assess the impacts of CSG extraction on groundwater (Golder Associates, 2009). CSG exploration and production will likely be active for a long time in the basin as evidenced by 2P (proven plus probable) CSG reserves of 27 992 PJ (Geological Survey of Queensland, 2011) and once LNG infrastructure is financially committed to.

The Queensland Carbon Dioxide Geological Storage Atlas (Bradshaw et al. 2009) provides an assessment of the Surat Basin for storage suitability using all available data, and states that storage suitability is highly variable but concentrated mainly in the west and along the eastern part of the basin. The atlas states that coal and coal seam gas, oil and natural gas in addition to groundwater are all valuable resources presently exploited in this basin. Many of the resources are not close to exhaustion and continued mining would be expected. Most mining is not directly in the potential lease area of the project, but until a more precise location is announced, all local resources should be considered. In a more recent Queensland Government review "Potential for carbon geostorage in the Taroom Trough, Roma Shelf and the Surat, Eromanga and Galilee basins" (2009), data availability for the Surat was assessed further. Knowledge of basic geology is available due to over 2400 wells, some of which are deep petroleum and gas exploration wells and completion reports (of mixed quality) are available.

CO2CRC report RPT06-0037 App 10.3 (Patchett, 2006) states that the coal in the Walloon Subgroup, although not currently in production, may be used in the future, but, because of good seals, injection into the nearby Precipice Sandstone would not compromise the coal in that area. The [Australian Mines Atlas](#) shows the location of known mineral occurrences and commodities in the region, confirming the presence of coal, oil and gas. Northeast of Taroom, gold and limestone are also mined or mapped.

Exploration for coal seam gas resources continues and is currently taking place in the Wandoan region for supplying liquid natural gas (LNG) facilities at Gladstone for

export. Hodgkinson (2008) reported in the Queensland Coal Inventory (Geological Survey of Queensland) a potential resource of 4,782 Mt of coal (measured, indicated and inferred), some of which will be extracted from underground mines. Additionally, although most coal mining in the area is open cut, Scott et al. (2007) confirmed that coals in the Walloon Subgroup (which exists in the Wandoan area) ‘...contain sufficient quantities of gas to be commercially viable as a coal seam gas source’. Gas was found throughout their testing range from less than 100m depth to >900m depth. Although CSG in the Walloon Subgroup should be considered, it may be possible for it to coexist with CO₂ storage in the deeper Precipice Sandstone. However, modelling work must be conducted to confirm this.

A study by Australia Pacific LNG (APLNG, 2010b) who have tenements overlying the Surat Basin (in the Wandoan region), reports on hydraulic fracturing to enhance coal seam gas production due to the variable permeability of the ‘tight’ coal seams in the Walloon Subgroup. A groundwater study was performed by Golder Associates (2009) specifically to assess impacts associated with coal seam gas (CSG) extraction in the eastern Surat, part of the study area overlapping with the potential Wandoan injection site. Additionally a government report “Coal Seam Gas Water Management Study’ by Queensland DNRME (2004) assessed the Surat Basin for groundwater impacts in relation to CSG, in which a good geological and hydrogeological setting is provided. It is therefore apparent from the latter reports that coal seam gas extraction is a potentially significant developing industry in this area, whether or not it is to be enhanced by fracturing.

An old report produced by Mack and Roy (1962) describes the geology and resource potential of Prospect 57P, which covers the Wandoan area and may be approximately the location of a prospective storage site. No recent report for this area has been found. The report specifically mentioned the Wandoan-1, Cabawin-1 and Moonie-1 wells, and identified gas in the deep Cabawin Formation overlain by impermeable sediments, in addition to methane gas in coal seams in the shallower Kianga Formation.

Detailed cross sections, logs, coal and gas content of deep units at the defined target site, as well as knowledge of plans for future energy and resource extraction will be required for a basin-scale resource management study. The cross-sections and some logs are available, as is some mapping of coal and gas at depth (for example QCGI, 2010). A book is also available that shows data and results of Wandoan no. 1, and U.K.A. Burunga No. 1 may be of use if the target area covers this borehole (Bureau of Mineral Resources, 1964). Other well completion reports may be available depending on the selected site. GIS data of current leases can be obtained from the Queensland Government. An up-to-date dataset can be requested once a more specific location is defined.

More detailed geological information depending on the site selected for the project may need to be sought depending on the area selected. Additionally for this area, more detail would be required of ongoing or planned exploration and projects regarding CSG and underground mining.

4.4 Geothermal Resources

Long et al. (2010) reported that in January 2010 there were a total of 54 companies holding 409 geothermal exploration licences and license applications covering 432 000 km² in Australia. Several reports and papers presented the potential for geothermal resources across Australia (i.e. Bestow 1982, Chopra 2005, Chopra and Holgate, 2005, Cull 1997, Chopra and Holgate 2007, Cull and Denham 1978).

A considerable and more recent general review is provided in Chapter 7 of the [Australian energy resource assessment](#). Also CSIRO is in the process of completing an "[Australian Geothermal Energy R&D Capability Audit](#)" that forms part of the Australian governments "[Geothermal Industry Development Framework Initiative](#)". Clearly there is the intent in Australia to harvest geothermal energy from a range of settings. The three study areas addressed in this report for carbon storage potential are within the Southern Perth Basin, Gippsland Basin and Surat Basin. For these sites the geothermal resource would fit within category "Hot Sedimentary Aquifers (HSA)".

Put very simplistically, desirable characteristics for a Hot Sedimentary Aquifer are high temperatures and high hydraulic conductivity. Reviews of how to evaluate Hot Sedimentary Aquifers can be found in Cooper and Beardsmore (2008), Driscoll (2010) and as a power point presentation at the company [Hot Dry Rocks web site](#) (Mortimer et al., 2010). For power generation, temperatures from 160 to 250 degrees centigrade would be targeted. For low grade heat exchange systems like those used for heating swimming pools or driving geothermal powered air-conditioning systems lower temperatures could be acceptable. The risks associated with geothermal developments are analysed by Cooper and Beardsmore (2008), while Lawless et al. (2010), have considered the Australian code for geothermal reserves and resources reporting.

There is some research that suggests that CO₂ storage and geothermal energy can co-exist. Carbon dioxide may be used as a working fluid to help recover geothermal heat from the underground (Randolph and Saar, 2011).

A key point when considering resource management issues involving geothermal energy is the intended application. If geothermal energy is intended for power supply (i.e. from a Hot Sedimentary Aquifer) then target depths greater than approximately 3500 m might be expected. If low grade heat is targeted (e.g. heating and air-conditioning) then water at shallower depths (e.g. near surface to thousands of meters) may be used provided sufficient permeability and appropriate thermal properties exist.

4.4.1 Southern Perth Basin

As of 2011 the major application for geothermal energy within the Perth Basin is the heating of swimming pools. However two large scale projects are in the planning stage.

These are the:

1. The Pawsey Geothermal Supercomputer Cooling Project, and
2. The UWA geothermal powered air conditioning and refrigeration project.

The Pawsey Centre project is well documented on the [CSIRO web site](#). The UWA geothermal powered air conditioning and refrigeration project is described by [Greenrock Energy](#) on their web site. Greenrock Energy is one of many private companies championing the concept of commercial geothermal heating and air-conditioning in the Perth Basin. The [Western Australian Geothermal Centre of Excellence](#) is a key player in both the Pawsey Centre and the UWA geothermal powered air-conditioning projects. The most current activity for Geothermal in the Perth Basin is focused on technologies that use low grade heat in an urban setting (e.g. Perth City). A comprehensive review of the geothermal potential for the Perth Basin was provided by the [Department of Industries and Resources in 2008](#). The report was written by Hot Dry Rocks Pty Ltd and provides details of temperature measurements and thermal properties estimates at a large number of wells. The report also contains thermal conductivities for 36 core samples. Thermal conductivity is identified as a major source of uncertainty in temperature projections.

For the Collie Hub site south of Perth the major formation targeted for investigation of CO₂ injection is the lower Lesueur Sandstone. In the depth range of the lower Lesueur, it is unlikely that temperatures would be sufficient for geothermal power generation. However, there are only two deep wells and information concerning the key drivers for development of a geothermal resource is not sufficient. For the Collie Hub a more reasonable proposition is that a geothermal energy or heat exchange system may in some way be linked in or combined with the CO₂ injection. While there is no literature or evidence to support this, it could be investigated.

4.4.2 Gippsland Basin

Like the Perth Basin, the Gippsland Basin is being explored for its geothermal potential. Of note is the suggestion made by the [company Petratherm](#) with respect to its East Gippsland geothermal exploration permit. "Preliminary economic analysis indicates that the project is capable of producing commercially viable, large-scale base load, power generation."

The state of Victoria encourages exploration and development of geothermal power as it is one method of reaching its [green energy targets](#). According to the [Victorian Department of Primary Industries](#) there are several data sets in the temperature database derived from 353 wells and boreholes. The [Victorian Department of Primary Industries](#) also included highly simplified notes on possible risks associated with geothermal projects.

In about 2005, GeoScience Victoria attempted to consolidate all open file geothermal data collected in Victoria. A summary of the process with references can be found in Driscoll (2006).

The potential for CO₂ injection into onshore formations in the Gippsland Basin are reviewed in [Gibson-Poole et. al. \(2006\)](#). Several formations are identified and typical depths are less than 2000m. Estimated temperature gradients are of the order of 45°C/km for the onshore Gippsland Basin (Driscoll, 2006). While the temperature gradients are higher than average the limited depths of permeable sediments identified

by Gibson-Poole et. al. (2006) may be an impediment to development of geothermal energy for power generation in the onshore Gippsland basin. Considerably more work (e.g. deep drill holes) would be required before any definitive statement could be made on the geothermal potential of the onshore Gippsland basin. GeoScience Victoria's 'Rediscover Victoria in 3D' initiative will go some way to determining both onshore and offshore Gippsland basin structure and geothermal potential.

4.4.3 Surat Basin

The [Queensland Government](#) is focusing geothermal research and exploration on coastal areas. Aside from thermal and hydraulic properties, a major criterion for geothermal development for power is proximity to existing transmission lines. The Surat Basin Wandoan CCS study area falls within the area covered by the [Queensland Government's Coastal Geothermal Energy Initiative](#). The objective of this Queensland government funded initiative appears to be similar to those completed by the Victorian government in 2005 (Driscoll, 2006) and the [Western Australia government in 2008](#). That is, their intent is to assemble all geothermal data and encourage geothermal development in the state. Queensland based research programs and links to major companies engaged in geothermal activity can be located on the [University of Queensland Geothermal Centre of Excellence](#) web site.

The suitability of the Surat Basin for development of geothermal resources has not been tested and there also remains uncertainty concerning the viability of the Surat Basin for any major geothermal development. There appears to be less readily available information concerning geothermal data or modeling in the Surat Basin compared to the Perth and the Gippsland basins.

5. STRUCTURAL, STRATIGRAPHIC AND GEOMECHANICAL ASSESSMENT

Assessment of potential impacts of geological storage of carbon dioxide on other existing natural resources requires a thorough understanding of the structural geology and stratigraphy. Assessment of top seal and fault seal integrity with respect to pressure build up due to carbon dioxide injection and knowledge of migration pathways is critical in understanding the potential impact of carbon dioxide on other resources.

The required data for such an assessment would include:

- Seismic data, well data and well picks, velocity models, stratigraphic and structural interpretation used to build up coherent static models integrating the local structural and stratigraphic elements; additional geophysical data (e.g. gravity, magnetics) could be used as regional interpretation guide;
- Net to gross data (Vshale log or inversion), fault throw models (3D), stress data (orientation and gradient), pore pressure data and fault mechanical properties (coefficient of friction and cohesive strength) for the geomechanical prediction of fault seal (i.e. slip tendency/stability, dilation tendency and fracture stability), reservoir juxtaposition assessment and intra-reservoir or intra top seal fracture prediction;
- Additional petrophysical parameters and elastic properties for the stratigraphic units (Young's Modulus, Poisson's Ratio, cohesive strength, tensile strength, permeability, porosity, friction angle, dilation angle) and deformation rate for coupled geomechanical deformation-fluid flow modeling.

The following sections discuss the data availability and related literature for the individual sites.

5.1 Southern Perth Basin

Information regarding the seismic surveys for the Perth Basin is provided in the online Western Australian Petroleum and Geothermal Information Management System ([WAPIMS](#)). Open file SEG Y data (field seismic, processed, reprocessed) are available through [Geoscience Australia](#). The density and seismic quality ranges from poor in the older surveys to average-good in more recent data (Figure 8). Causebrook et al. (2006) detail the acquisition history from the 1960s. Onshore data (paper or SEG Y) from the 1950s to early 1980s over the Mandurah Terrace and the Bunbury Trough are sparsely distributed with a general E-W and N-S orientation (i.e. Median 1982 S.S., Cookernup 1982 S.S., Ambergate 1981 S.S., Happy Valley 1981 S.S. and Rockingham 1975 S.S.). The onshore 2D seismic data are located in the vicinity of Lake Preston-1 and Preston-1 wells near Lake Preston (line spacing c. 1-5 km), in the vicinity of Pinjarra-1 well (line spacing c. 2-3 km) and in the vicinity of Rockingham-1 well (line spacing c. 2-3 km). It is unlikely that the seismic coverage would be sufficient to define an accurate geomodel for the onshore Mandurah Terrace and Bunbury Trough. A 2D survey has recently been carried out by the WA DMP and processed for the Harvey Ridge

(Dominique van Gent, pers. comm., 2011) and is being interpreted at the time of writing this report. No 3D survey is available for the onshore and offshore Mandurah Terrace and Bunbury Trough and the southern Vlaming Sub-basin.

The 2D offshore seismic coverage is usually much better with line spacing between 300 m and 3 km. The line orientation is usually WSW-ENE and NNW-SSE. The seismic quality is usually much better for the offshore lines than the onshore lines with interpretable lines down to 5-6 sec TWT. The seismic coverage could be sufficient to define an accurate geomodel for the offshore Mandurah Terrace and Vlaming Sub-basin, however line density decreases in the offshore Bunbury Trough (c. 2-6 km).

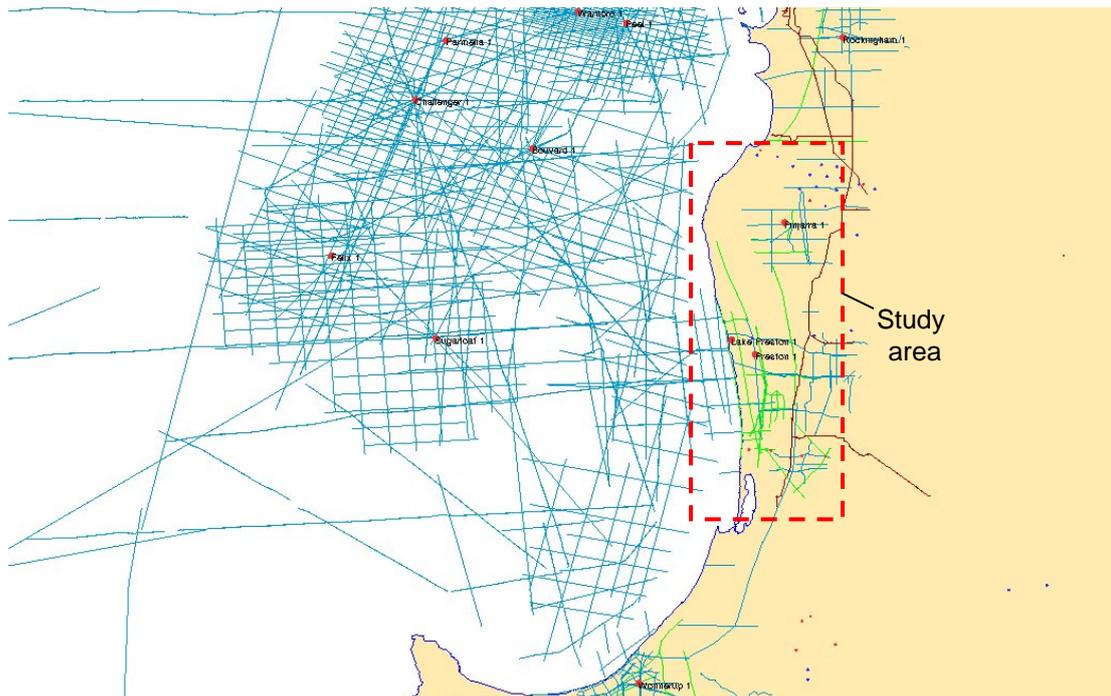


Figure 8: Distribution of seismic data (green lines are available online from [WAPIMS](#)) and petroleum wells (red) for the southern Perth Basin from Rockingham-1 to Wonnerup-1. Small red and blue dots are for drillholes with and without core with GSWA respectively.

Information regarding petroleum wells present in the Southern Perth Basin (Figure 8) is available in the online Western Australian Petroleum and Geothermal Information Management System ([WAPIMS](#)) data base. Well completion reports and wireline logs can be downloaded from the WAPIMS database. Well picks are available from well completion reports and in the [National Petroleum Well Database](#). [CSIRO's PressurePlot](#) database also has well picks sourced from the well completion reports. In the study area for Collie Hub, six onshore petroleum wells have been drilled in the Mandurah Terrace and Bunbury Trough - Rockingham-1, Pinjarra-1, Lake Preston-1, Preston-1, Wonnerup-1 and Sabina River-1, and five offshore wells are present in the southern Vlaming Sub-basin, Mandurah Terrace and Bunbury Trough - Parmelia-1, Challenger-1, Bouvard-1, Felix-1 and Sugarloaf-1.

There is no pore pressure data available for the study area specifically. However, a stratigraphic data well is planned for drilling in the first quarter of 2012 by the WA DMP

near the Harvey Ridge site and will acquire a suite of wireline data including pore pressure. O'Sullivan (2004) presents permeability, porosity and net to gross values for Warnbro-1, Charlotte-1, Gage Roads-1 and Mullaloo-1 in the Vlaming Sub-basin. Cores are available at the [GSWA Core Library](#). Core derived permeability and porosity values are available for Pinjarra-1 (Jones and Nicholls, 1966), Sue-1 and Whicher Range-1 in the WAPIMS data base.

Gravity data and magnetic data are available from the [Geophysical Archive Data Delivery System](#). Crostella and Backhouse (2000), Iasky and Lockwood (2004) and Causebrook et al. (2006) published an interpretation of the gravity and magnetic data available for the southern Perth Basin (Figure 9).

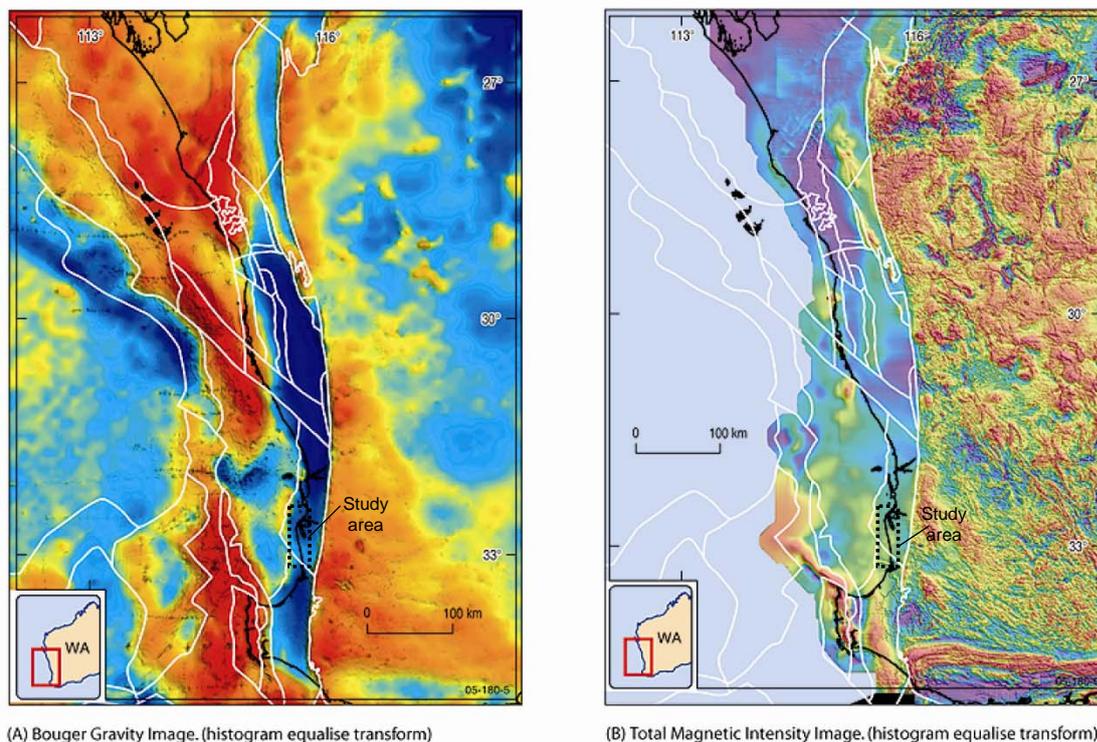


Figure 9: Examples of the Gravity and Magnetic National Grids of Australia depicting the boundary between the Yilgarn Craton to the east and the Perth Basin to the west (Perth sub-basin outlines in white) (from Causebrook et al., 2006).

A static geological model is important for conducting geomechanical assessment of an area. Crostella and Backhouse (2000) detailed the stratigraphy and structures of the southern Perth Basin. Causebrook et al. (2006) created a regional 3D model of the Vlaming Sub-basin. Additionally, they show time and depth structure maps and depositional model. Schlumberger Carbon Storage Solutions Pty Ltd built a static geological model to integrate current knowledge and understanding of the Preston area (Lower Lesueur Sandstone). However, due to sparse data coverage, stratigraphic and structural accuracy is ambiguous (Unpublished Schlumberger Report of June 2010). This model is not publicly available. Schlumberger Carbon Storage Solutions Pty Ltd also assessed the stability of the main faults interpreted in the Preston area using a sparse 2D seismic coverage. Schlumberger assessed the stability of the main faults

interpreted in the Preston area using a sparse 2D seismic coverage. Their assessment relies on the computation of a triangle diagram (Lake Preston-1) used to evaluate fault juxtaposition without the need for 3D mapping of fault plane and stratigraphic horizons. They also initially assessed the displacement on faults, the Shale Gouge Ratio (SGR) and define fault transmissibility multipliers. However, the entire Schlumberger work is not in public domain. No geomechanical modeling assessing the integrity of the top seal(s) has been carried out for the Collie Hub site. Van Ruth (2006), and Reynolds and Hillis (2000) estimated the direction of the maximum horizontal stress from WNW to WSW.

5.2 Gippsland Basin

For the Gippsland Basin, information about the 2D seismic surveys are provided by the VicDPI Earth Resources [web mapping application](#) (Figure 10). Seismic line images from seipia are available through [VicDPI Petroleum Client Services Officer](#). SEGY data (field seismic, processed, reprocessed) are available through the [VicDPI Petroleum Client Services Officer](#) or [Geoscience Australia](#).

Offshore blocks GIPP-01, GIPP-02, GIPP-03 are well covered with line spacing ranging from 10's of meters to 3 km. The line orientation is variable with mostly NE-SW and SE-NW line in blocks GIPP-01, GIPP-02, GIPP-03. The depth is usually around 5-6 second TWT and is sufficient to capture main geologic elements and formations. The data quality is average to high. It is likely that the current 2D data set is sufficient to build up robust geological models and perform fault seal analysis, at least at the basin and block scale.

3D seismic survey locations are displayed on the VicDPI Earth Resources web mapping application ([GeoVic](#)). Seismic line images from seipia are available through [VicDPI Petroleum Client Services Officer](#). SEGY data (field seismic, processed, reprocessed) are available through [VicDPI Petroleum Client Services Officer](#) or [Geoscience Australia](#). Such data would be required to build up accurate geological models and assess thoroughly top seal and fault seal. Seismic resolution for onshore survey might represent a technical issue.

The 3D survey GBA02B-3D partially covers blocks GIPP-01 and 02. Archer 3D is located in the northern part of block GIPP-02. Tuskfish 3D and Angler 3D covers blocks GIPP-02 and 03. VicDPI commissioned a merged mega 3D survey covering the offshore Northern Terrace and the Central Deep.

Petroleum wells present in blocks GIPP-01, GIPP-02, GIPP-03 are displayed on the VicDPI earth resources web mapping application ([GeoVic](#)) (Figure 11). Well completion reports are available from [VicDPI](#), and the [National Petroleum Well Database](#). Well picks are available from well completion reports, while [CSIRO's PressurePlot](#) database also contains some well picks. Bernecker et al. (2002) describe the stratigraphic succession in the main wells for the offshore Gippsland. Wireline logs are available from [Spectrum Data](#) and Geoscience Australia, older digitised wireline logs are available from [Occam Technology](#).

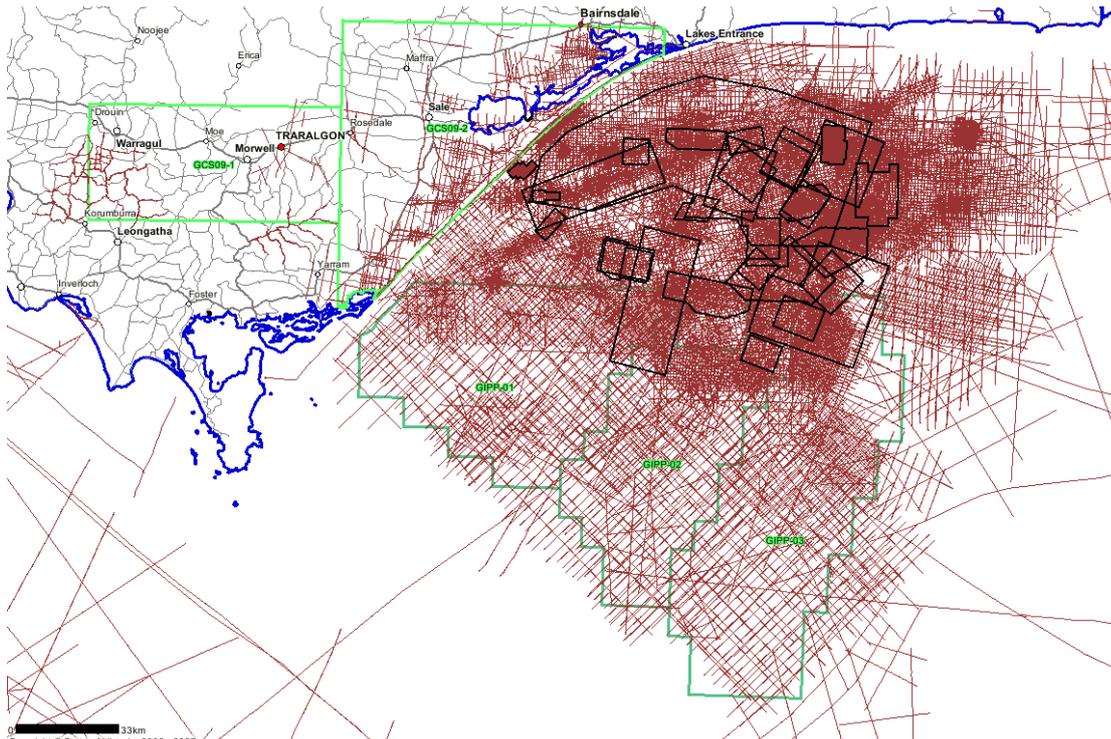


Figure 10: Seismic coverage in the Gippsland Basin. CCS tenements are shown in green. Note the onshore blocks GCS09-1 and GCS09-2 no longer exist.

Several density logs are available from CSIRO's HydroGroup database. Selected (selected depth and selected wells) Vshale data are available from CSIRO's previous work in Gippsland Basin (Varma et al., 2011). Gippsland Basin biostratigraphic data is available from [VicDPI](#). Pore pressure data is available from [CSIRO's PressurePlot](#) database.

Regional data regarding petrophysical properties of rocks are published in Hooper et al. (2005) and contains information on porosity, permeability, cohesive strength, friction coefficient). Gibson-Poole et al. (2006) and Van Ruth et al. (2006) also present (regional) data for cohesive strength and friction coefficient used for fault reactivation modeling. Although the petrophysical parameters required for top seal and fault seal modeling can be inverted from wireline logs, calibration from rock sample is recommended. Cores are available for examination only at the [VicDPI Earth Resource Core Library](#).

Stress data required for top seal and fault seal modeling is available in Gibson-Poole et al. (2008) for the Kingfish Field area; in Nelson and Hillis (2005) and Nelson et al. (2006) for the Tuna Field area; in Van Ruth et al. (2006) for the Central Deep. Regional stress data are available in Nelson et al. (2006).

Gravity data and magnetic data (line spacing 200m) are available from the [Geophysical Archive Data Delivery System](#). 3D geological and gravity inversion models of intrusive bodies in Western Victoria are available from [VicDPI](#).

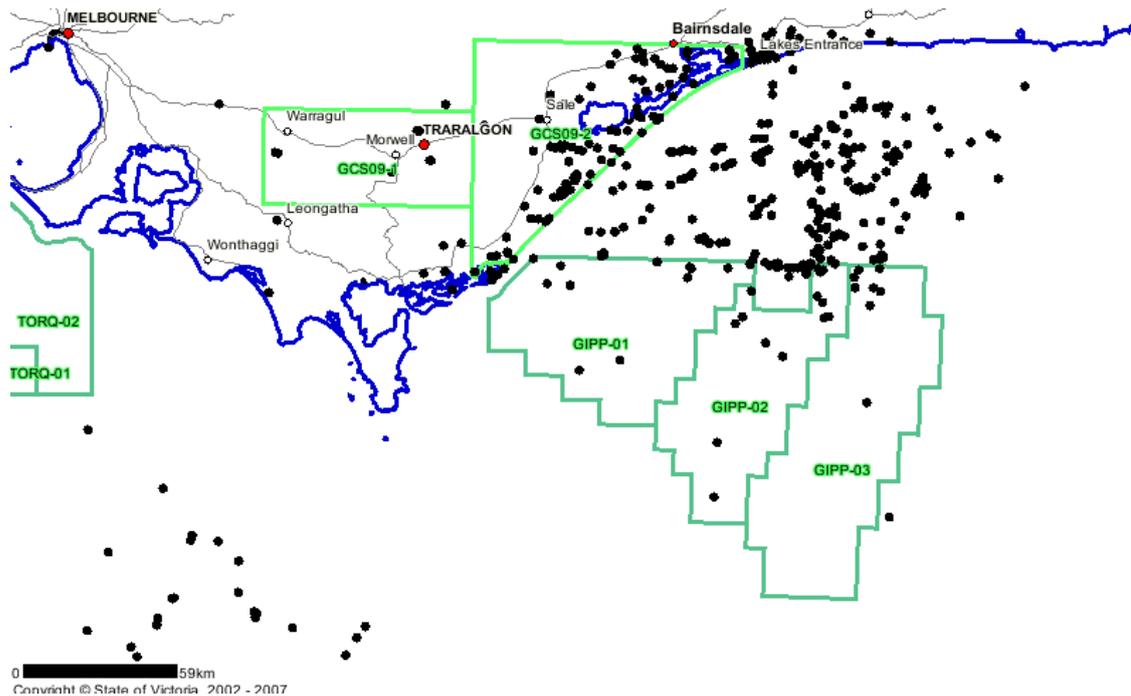


Figure 11: Distribution of petroleum wells for the Gippsland Basin. CCS tenements are shown in green (VicDPI earth resource web mapping application). Note the onshore blocks GCS09-1 and GCS09-2 no longer exist.

Mudge and Thompson (1990) and Gibson-Poole et al. (2008) published a stratigraphic and depositional model of the Kingfish Field. Malek and Mehin (1998) present various structure maps and cross-section of the main hydrocarbon reservoir in the offshore Gippsland. Basin scale interpretation of the main seismically resolvable faults and seismically mappable horizons are available from VicDPI. Gibson-Poole et al. (2008) assessed the likelihood of fault reactivation and reactivation of migration pathways for the Kingfish Field area; Hooper et al. (2005) published results for similar models for the overall Gippsland Basin while Van Ruth et al. (2006) focused on the Central Deep.

5.3 Surat Basin

Several reports from the Geological Survey of Queensland were available for this review. However, there may be some unpublished reports that might potentially include data or information on data required to assess impacts of CO₂ storage on other resources and evaluate risk of fault reactivation and reservoir leakage. The sources of information for the structural and geomechanical evaluation of the Surat Basin are provided below:

- The [Carbon Geostorage Initiative](#) that assesses sites for the safe long term geological storage of carbon dioxide in Queensland.
- The Queensland Geological Record 2011/05 “Jurassic groundwater hydrochemical types, Surat Basin, Queensland - a carbon geostorage perspective”
- The Queensland Geological Record 2011/02 “Mineralogy of the south-eastern Bowen Basin and north-eastern Surat Basin, Queensland”

- Queensland Geological Record 2010/03 “A new subsurface map of the solid geology of the Bowen Basin underlying the Surat Basin”
- Queensland Petroleum Exploration Data ([QPED](#)) contains general well history, company and GSQ stratigraphic picks, drill stem tests, hydrocarbon indications, references, wireline log types, downhole temperatures, analytical results (e.g. oil, gas, pyrolysis, petrophysics, thermal maturity), and location information for over 7000 petroleum, coal seam gas, and stratigraphic wells.
- Queensland Minerals and Energy Review Series “The potential impact of carbon dioxide injection on freshwater aquifers: the Surat and Eromanga Basins in Queensland” (Hodgkinson et al., 2009) and “Potential for carbon geostorage in the Taroom Trough, Roma Shelf, and the Surat, Eromanga and Galilee Basins - Preliminary Report” by QCGI (2010).
- The Bowen and Surat Basins Regional Structural Framework Study developed by SRK Consultants presents regional structural framework and basin model study for the Bowen and Surat basins.

The 2D seismic survey locations are displayed on the [interactive resource and tenure maps of the Geological Survey of Queensland](#). Open file SEG Y data (field seismic, processed, reprocessed) are available through [Geoscience Australia](#). Line density varies throughout the Surat Basin. To the SW the coverage is good and the line spacing varies between 10s of meters and 2-3 km. To the SE the density decreases. To the north of the basin seismic data becomes increasingly sparse. The close vicinity of the town of Wandoan (within 100 km radius) presents sparse seismic coverage with line spacing between 2 and 10 km. The general line orientation is N-S and E-W. Seven 3D surveys shot between 1983 and 2004 are available for the Surat Basin. The seismic coverage of the Surat Basin is shown in Figure 12.

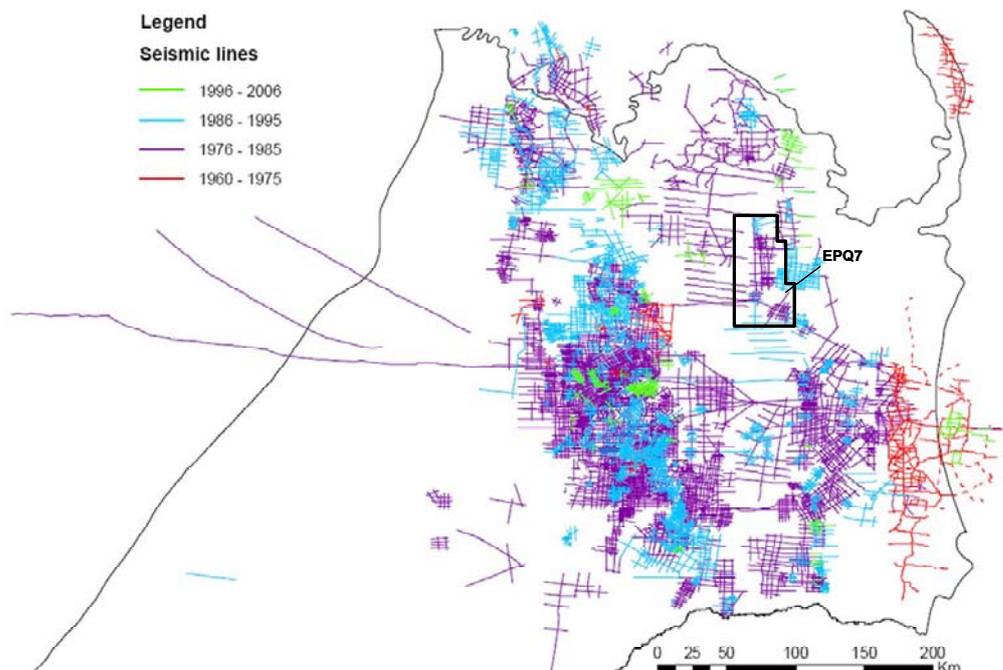


Figure 12: Seismic coverage in the Surat Basin (QCGI, 2010).

Petroleum and coal seam gas wells present in the Surat Basin (Figure 13 and Figure 14) are displayed on the [interactive resource and tenure maps of the Geological Survey of Queensland](#). Well density varies throughout the Surat Basin and follows the distribution trend of the seismic data. Well completion reports and wireline logs are available from the Queensland Digital Exploration Reports ([QDEX](#)). Well picks are available from well completion reports and in the [National Petroleum Well Database](#). [CSIRO's PressurePlot](#) database contains some well picks. Queensland Petroleum Exploration Data ([QPED](#)) contains stratigraphic picks for over 7000 petroleum, coal seam gas, and stratigraphic wells. At the present stage of the review no Vshale data are available. Pore pressure data are available from [CSIRO's PressurePlot](#) database. Daniel (2006) presents MICP of Mercury Injection Capillary Pressure (MICP) analyses of samples of the Snake Creek Mudstone (Wunger Ridge, Bowen Basin) from Harbour-1 and Hollow Tree-1. The Snake Creek Mudstone is the sealing formation above the Showgrounds Sandstone reservoir, which is being investigated as a potential carbon dioxide storage play.

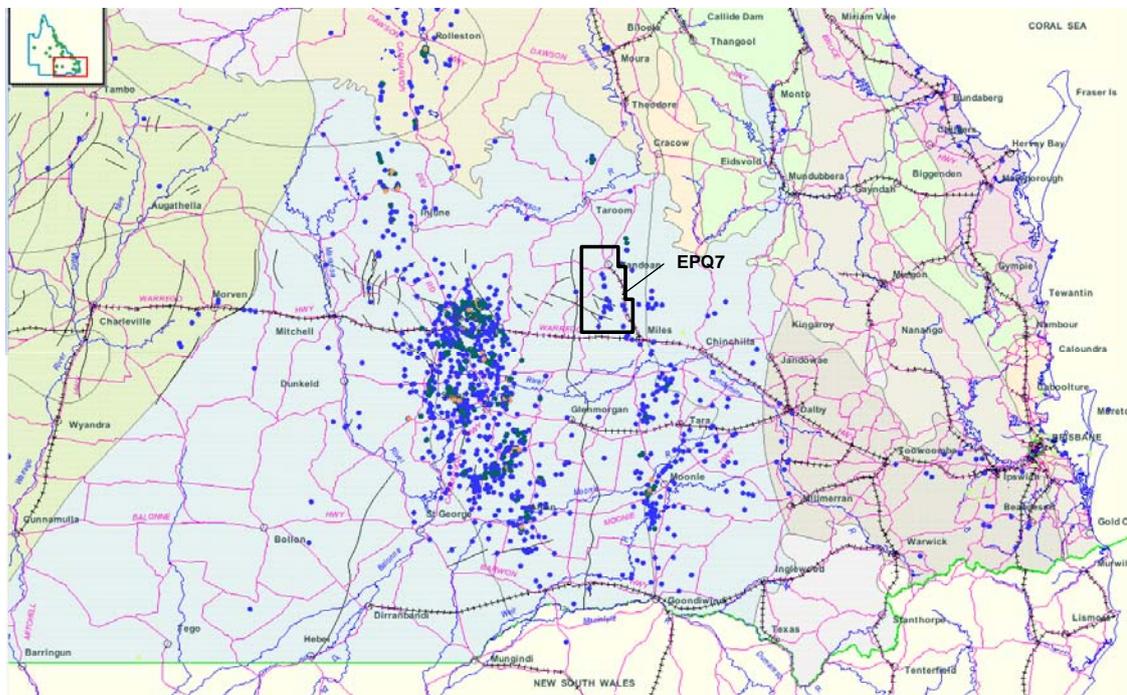


Figure 13: Distribution of petroleum wells for the Surat and Bowen Basins. The Surat Basin is in blue. Exploration wells in dark blue, development wells in orange and appraisal well in green.

The Queensland Petroleum Exploration Data ([QPED](#)) contains information for over 7000 petroleum, coal seam gas, and stratigraphic wells with some petrophysical data. Bashari (2000) assessed the petrography of the sandstones of the Early Triassic non-marine Rewan Group in the southern Bowen Basin and its impact on petrophysical properties of the reservoir.

At this stage of the data and literature review no petrophysical and geomechanical data usable for fault reactivation and top seal deformation modeling have been assessed. Such information or part of it is likely to exist in the Queensland Petroleum Exploration Data ([QPED](#)) but are not directly accessible. Few fully cored wells are available (such

as Chinchilla-15) for this area but more would be required for a full geological assessment of the area.

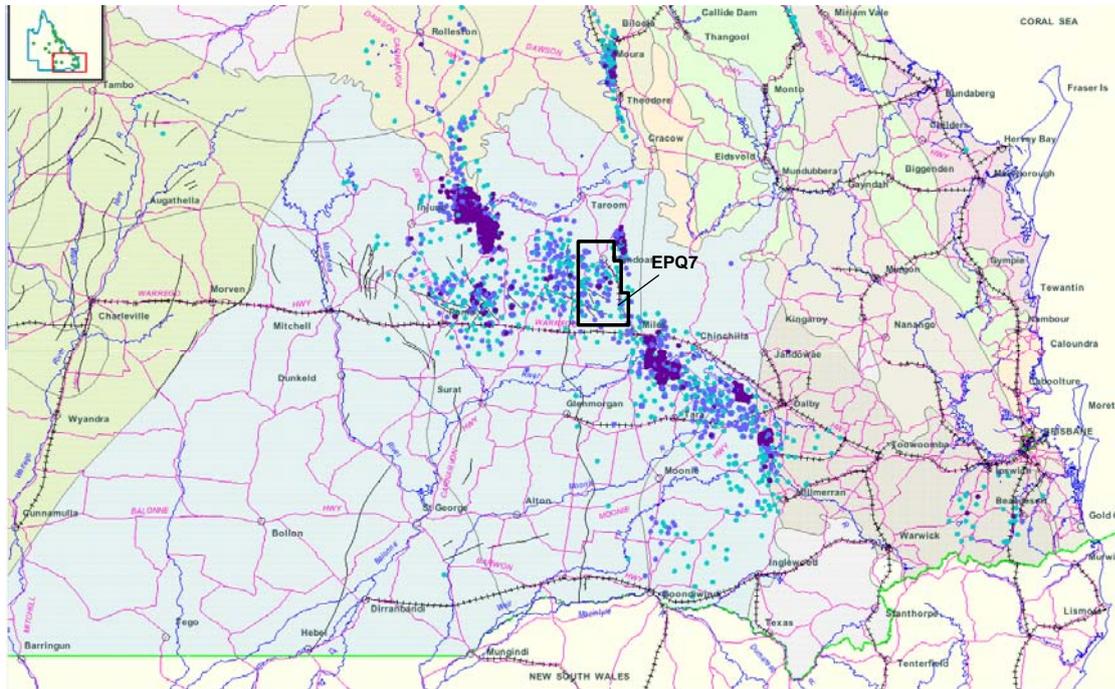


Figure 14: Distribution of coal seam gas wells for the Surat and Bowen Basins. The Surat Basin is in blue. Exploration wells in light blue, development wells in purple and appraisal well in dark blue.

Hillis et al. (1998; 1999), and Hillis and Reynolds (2003) present some horizontal stress data for the Bowen and Surat Basins. Additional (general) data are shown on the [Australian Stress Map webpage](#). Reynolds et al. (2004, 2005 and 2006) present stress data from the neighbouring Cooper-Eromanga Basins.

Geophysical surveys are displayed on the [interactive resource and tenure maps of the Geological Survey of Queensland](#) (Figure 15). A gravity survey covering 114,000 square kilometres of the western part of the Surat Basin overlying the Bowen Basin, was collected on a 4x4 km grid. Daishsat Ltd completed the survey in 2006 and results are available for download from the [National Gravity database](#) at the Geoscience Australia website or from the [Department of Employment, Economic Development and Innovation](#).

Airborne magnetic and radiometric data covering the Bowen and Surat Basins are available for download from the [National Gravity database](#) at the Geoscience Australia website or from the [Department of Employment, Economic Development and Innovation](#). Geoscience Australia produced a structural and sequence stratigraphic map of a regional grid of seismic reflection data in the Bowen and Surat Basins. These results were also compiled into a series of structure contour and isopach maps, which have been used to build a 3D geological model.

The Geological Survey of Queensland produced a record (2011/01) providing a regional interpretation of the three dimensional geometry of the fault systems on the

eastern flanks of the southern Bowen Basin and the Surat Basin. No geomechanical modeling assessing the integrity of the top seal(s) has been identified. No fault reactivation modeling has been identified. No fault seal modeling has been identified.

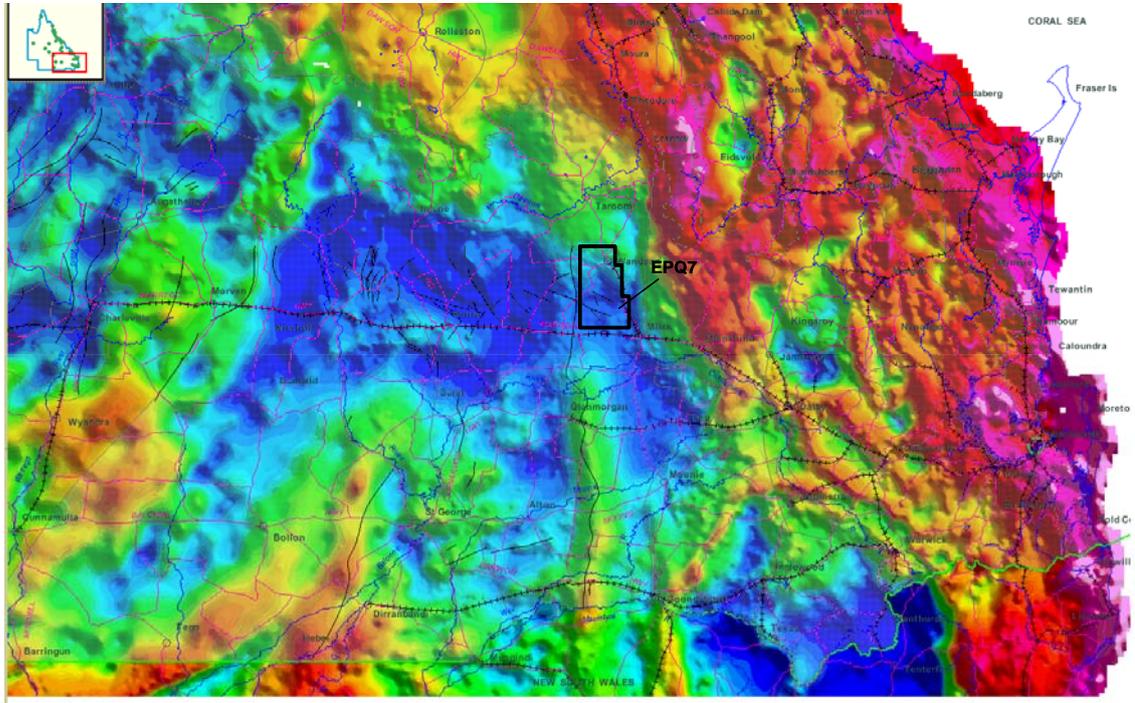


Figure 15: Example of gravity image over the Surat Basin.

6. SUMMARY OF DATA AVAILABILITY AND KNOWLEDGE GAPS

Based on the literature and data review conducted for the three study areas in the preceding sections, the knowledge gaps identified for each basin are summarised below. The specific data needs and availability are summarised in Table 1.

6.1 Southern Perth Basin

- Currently there is no study that has assessed the potential impacts of carbon dioxide storage on the groundwater, hydrocarbon, coal and geothermal resources, in the southern Perth Basin, and there is no study on the monitoring and mitigation strategies of risks associated with carbon dioxide storage.
- The potential injection sites are yet to be decided for the Collie Hub however the broad area of the Harvey Ridge has been identified for pilot scale CO₂ storage.
- There is a lack of information on the hydrodynamic regime of the deeper strata (Cockleshell Gully Formation and the Lesueur Sandstone in particular) e.g. the pressure and hydraulic head data allowing an understanding of the groundwater flow systems in aquifers and hydraulic connections through aquitards.
- A 2D seismic survey has recently been acquired and processed and is being interpreted. There is a data well planned for the first quarter of 2012. These would help to improve the geological model and better understand the rock properties of the formations.
- Additional geomechanical data would be required in order to calibrate inversion of well logs. This could result either from estimation from regional analogue or from laboratory test on rock samples. A regional static model has been developed by Schlumberger but is not yet in public domain.
- CSIRO PHRAMS groundwater model covering the broad Collie Hub site in the southern Perth Basin is available; however, the model requires addition of deeper strata for use in CO₂ related studies. Integration of geological, geomechanical and hydrogeochemical data in a multiphase hydrodynamic model is required to make a quantitative assessment of the carbon dioxide leakage on the groundwater resources. A dynamic model was developed by Schlumberger for a small part of the study area (not in public domain), and a regional reservoir model is planned.
- Fault reactivation and fault seal models and 3D static and dynamic models are required to accurately assess the risk of lateral and vertical migration and potential leakage of CO₂.
- Coal extent and commercial value for coal or coal seam gas under the target site would need to be explored.

6.2 Gippsland Basin

- A portfolio of prospective storage sites is under evaluation in the Gippsland Basin with the near shore / offshore areas being closely examined.

- There is no study that has assessed the potential impacts of carbon dioxide storage on the fresh groundwater resources, and there is no study on the monitoring and mitigation strategies of risks associated with carbon dioxide storage. However, there are some studies underway e.g. hydrodynamic modeling and fault seals analysis that will aid in assessing potential impacts of CO₂ injection on shallow groundwater. These include the CSIRO 2D Latrobe Group and the regional Gippsland Basin Modflow models. Reservoir models for specific petroleum fields are available with ESSO but they not in public domain. A reservoir model for the CO₂ storage area is being developed by Victoria DPI.
- Basin scale assessments are currently available for CO₂ containment potential. The basin-scale study was based on MICP work that is usually one sample per well and is inadequate for detailed use. DPI is currently submitting additional site specific samples for MICP analysis. Accurate assessment of impacts of carbon dioxide storage requires subsurface characterisation at the reservoir scale (at the storage site) which is currently unavailable. CarbonNet is currently preparing static and dynamic models for 4-6 sites.
- There is a lack of multi-phase regional and local-scale models around proposed injection areas. Reservoir scale characterisation by integrating all the available data in order to better understand the migration of the carbon dioxide plume and assess its potential impact on the nearby hydrocarbon fields, potential unconventional/conventional hydrocarbon discoveries and fresh groundwater resources is also lacking.
- A comprehensive understanding of the location of freshwater-saltwater interface and offshore extent of the fresh groundwater will be required to understand how they will be impacted by CO₂ storage.
- There is lack of information on the economic assessment of currently known deep coals and perhaps modeling of coals across the area to assess potential for these as a resource in the future. Detailed information of the coal at depth appears to be lacking as does general coal rank, quality and extent.
- Geomechanical data has to be estimated either from regional analogue or from laboratory test on rock samples in order to calibrate inversion of well logs.
- Fault reactivation and fault seal models have to be built or constrained and 3D model should be built in order to accurately assess risk of lateral migration/leakage.

6.3 Surat Basin

- The locations of pilot scale CO₂ injection wells are currently unknown. The locations of the injection sites relative to existing resource and environmentally sensitive areas are critical to the understanding of the potential resource management issues.
- Most petroleum and gas exploration in the Surat and Bowen basins took place from the 1960s to early 1990s therefore well completion reports are of mixed quality and

- Static models for the area are unavailable at this stage. 2D/3D seismic might be required to build up an accurate geological model and define throw distribution for fault seal attributes.
- At this stage of the data and literature review no petrophysical and geomechanical data usable for fault reactivation and top seal deformation modeling have been found in the public domain. Geomechanical data either from estimation from regional analogue or from laboratory test on rock samples will be required in order to calibrate inversion of well logs.
- The long-term effects of injection-induced pressure build up and consequent impacts on the hydrodynamic regime need to be modelled. Hydrodynamic models developed by APLNG and Golder Associates (for the QGC) exist for coal seam gas applications but may not be in the public domain.
- Multiphase fluid flow models would be required for simulating injection of CO₂ and migration of the plume and making an accurate quantitative assessment of the consequent effects on the groundwater levels and chemistry.

Table 1: Summary of data availability and gaps

Site	Data required	Current availability	Remarks
Southern Perth Basin	Petroleum wells	Preston 1, Wonnerup 1, Cockburn 1, Rockingham 1, Lake Preston 1, Wonnerup 1 drilled in the area; not all wells extend to the base of the Lesueur Sandstone, and they do not have complete datasets.	A stratigraphic data well is planned for early 2012 near the Harvey Ridge site.
	Groundwater bores and wells	There is sufficient availability of bores in shallow aquifers, but limited availability of deeper bores with only Harvey and Binningup line bores providing information for the Eneabba Formation; there is a good data on volumes and location of existing groundwater extraction in the region. Groundwater salinity and other chemistry data available from shallow bores.	
	Gravity and magnetic	Gravity data and magnetic data available from the Geophysical Archive Data Delivery System. Iasky and Lockwood (2004) detail the results of gravity and magnetic data interpretation for the region.	
	Seismic	Several 2D seismic lines available (density and quality are poor to average);	A 2D seismic survey has recently been acquired and processed and is being interpreted.
	Well picks	Regional picks are available in well completion reports	

Site	Data required	Current availability	Remarks
Southern Perth Basin (contd.)	Geomechanical/petrophysical data	A regional static model has been developed by Schlumberger but is not yet in public domain. Fault throw model is unavailable; stress data available only for the offshore region; specific coefficient of friction and cohesive strength are unavailable. Cores available only for the Pinjarra-1 well.	Liaise with WA DMP regarding model availability. Review existing Schlumberger 3D model and subsurface characterisation; assess their capacity to realistically capture the subsurface geology and reservoir/seal. Assess potential improvements of existing interpretations and models. Identify additional data requirements for more confident subsurface characterisation. Fault reactivation and fault seal models have to be built or constrained and 3D model should be built in order to accurately assess risk of CO ₂ migration/ leakage. Additional petrophysical and pressure data will be available when the planned data well is drilled.
	Pore pressure data	No pore pressure data is available from any wells	Some pore pressure data will be available when the data well is drilled. Look at means for predicting pore pressure based on logs and seismic.
	Groundwater model	CSIRO PHRAMS model is available for the shallow part of the basin.	Extend the PHRAMS model to include the Yarragadee aquifer, Eneabba Formation and the Lesueur Sandstone in the model. Apply the model to simulate pressure build up due to CO ₂ injection and potential impacts on aquifers. Integrate with a multiphase reservoir model for the area.
	Dynamic reservoir model	Developed by Schlumberger for a small part of the study area (not in public domain); a regional reservoir model planned.	Check with WA DMP when models are publicly available.

Site	Data required	Current availability	Remarks
Southern Perth Basin (contd.)	Coal occurrence	Detailed cross sections showing coal is lacking; information CSG is lacking	Characterisation at Harvey Ridge coal resource is difficult due to the scarcity of the data and more holes would be required for more confidence. For the mapping of known coal and CSG, we need to review the existing data from petroleum wells that will better constrain maps or identification of gaps and provide recommendations for further data acquisition.
	Hydrocarbon occurrence	Evaluation of past exploration activity documented in Crostella and Backhouse (2000).	Review petroleum system for potential future discoveries and note data gaps that can impact the exploration strategies.
	Geothermal resource	The principal published resource is the Department of Industry and Resources report on Geothermal resource of WA. Further temperature data exists along the Binningup and Harvey bore hole lines (i.e. Department of Water monitoring bores) and at the deep petroleum wells.	Obtain and review geothermal data from the Harvey and Binningup bore-hole lines along with any end of hole temperatures available from the small number of deep petroleum wells. Consider basin hydrodynamics and how this may impact on distribution of temperature with depth over the Harvey Ridge. Estimate the temperatures at the range of depths that may be expected for CO ₂ injection in the Lesueur Sandstone (i.e. at the Collie Hub site). This may require limited hydrothermal modeling.

Site	Data required	Current availability	Remarks
Gippsland Basin	Petroleum wells	Petroleum wells completion reports and wireline logs are available from Spectrum Data and GA, older digitised wireline logs are available from Occam Technology. Wells in blocks GIPP-01, GIPP-02, GIPP-03.	
	Groundwater bores and wells	Groundwater data available from VicDSE, Southern Rural Water and aquifer review reports from coal mining companies. Groundwater salinity and other chemistry data available from shallow bores.	
	Gravity and magnetic	Gravity data and magnetic data available from the Geophysical Archive Data Delivery System. 3D geological and gravity inversion models of intrusive bodies in Western Victoria available from VicDPI	
	Seismic	2D and 3D seismic surveys are available; Blocks GIPP-01, GIPP-02, GIPP-03 are well covered with 2D seismic. 3D surveys partially cover blocks GIPP-01, 02 and 03.	
	Well picks	Regional picks in well completion reports and from VicDPI and the National Petroleum Well Database. CSIRO Pressure Plot contains the main picks.	

Site	Data required	Current availability	Remarks
Gippsland Basin (contd.)	Static geological model	A merged seismic volume of >30 3D surveys with >60 3D surveys, >1200 wells and stratigraphic picks for >500 wells by 3DGEO which has not yet published by VicDPI. However, the interpretation density and accuracy need to be assessed. 'Biostratigraphic data is available from VicDPI. VicDPI can provide a basin scale interpretation of the main seismically mappable horizons. VicDPI can provide a basin scale interpretation of the main seismically resolvable faults.	
	Geomechanical/petrophysical data	3DGEO produced an initial Vshale model, however the coverage and calibration of the model need to be assessed. Selected Vshale data available from CSIRO's in-house databases. 'No fault throw model publicly available. Stress data available in Gibson-Poole et al. (2008) for the Kingfish Field area; in Nelson and Hillis (2005) and Nelson et al. (2006) for the Tuna Field area; in Van Ruth et al. (2006) for the Central Deep. Regional stress data are available in Nelson et al. (2006). Regional data of porosity, permeability, cohesive strength, friction coefficient are published in Hooper et al. (2005). No elastic properties publicly available to date. 'Cores are available for examination only at the VicDPI Earth Resource Core Library.	Review 3D geological model to ensure it captures subsurface reservoir/seal sequences, rock properties, structures and their relative distribution with respect to injection site. Assessment of the potential impact of the CO ₂ plume and injection induced pressure changes on existing and potential hydrocarbon traps. Assessment of the data gaps and additional data requirements.
	Pore pressure data	Pore pressure data is available from CSIRO's PressurePlot database. Cohesive strength and friction coefficient in Gibson-Poole et al. (2006) and Van Ruth et al. (2006).	

Site	Data required	Current availability	Remarks
Gippsland Basin (contd.)	Groundwater model	Schaeffer (2008) and Nahm (2002) regional model exist but are not publicly available. CSIRO variable density model presently developed as a steady state model and will be calibrated in a transient state in 2011-12 (Varma et al., 2011).	Review and upgrade the CSIRO regional variable density Modflow-Seawat model according to the results of the geomechanical assessment. Apply the model to understand pressure build-up due to CO ₂ injection and resultant impacts on the groundwater resources.
	Dynamic reservoir model	No dynamic reservoir model is currently available for the Gippsland Basin. CarbonNet is currently developing static and dynamic models for 4-6 prospective storage sites.	Check with VicDPI regarding status of the modeling plan.
	Coal occurrence	Well completion reports and analysis reports are available in parts of the Gippsland Basin. Cores and physical data available for some areas across Gippsland Basin.	Assess known data and identify data that can be used to build model and characterise subsurface geology; identify possible location of coal seams and interpolate from local or distal wells across the area the coal and known gas resources. Identify future data acquisition requirements including cores, coal quality and gas testing.
	Petroleum occurrence	Data available from producing hydrocarbon fields – active petroleum system. There is relatively extensive subsurface data coverage including reservoir-seal systems; basin-scale top seal assessment; hydrocarbon charge model; hydrodynamic model; and fault seal assessment in parts of the basin.	Conduct data review, integration of existing model, further interpretations if required. Mapping of hydrocarbon fields and dry or untested structural closures; assessment of stratigraphic trapping potential in the target area.

Site	Data required	Current availability	Remarks
Gippsland Basin (contd.)	Geothermal resource	Principal source of data is the GeoScience Victoria Geothermal Database	Retrieve available geothermal data from the QGS. Use available wire line log data to estimate the temperatures at the range of depths and the formations that may be expected to support CO ₂ sequestration at Wandoan CCS Hub site. Hydrothermal modeling will be completed as required to support the above.
Surat Basin	Petroleum wells	There is extensive well data coverage for the study area. Wireline logs are available from the GGS interactive resource and tenure maps.	
	Groundwater bores and wells	Available from Qld DERM online databases.	
	Gravity and magnetic	Gravity, magnetic and radiometric data are available from the Geoscience Australia National Gravity database or from the Department of Employment, Economic Development and Innovation.	
	Seismic	2D and possibly 3D seismic available for the study area. Line density varies throughout the basin.	
	Well picks	Regional picks in well completion reports and from the Queensland Digital Exploration Reports and the National Petroleum Well Database. Stratigraphic picks from the Queensland Petroleum Exploration Data (QPED).	

Site	Data required	Current availability	Remarks
Surat Basin (contd.)	Structural interpretation and static geological model	Regional 3D interpretation of fault systems available for eastern flanks of the southern Bowen Basin and the Surat Basin. Structural and sequence stratigraphic regional interpretation and 3D model also available from Geoscience Australia and Queensland DEEDI.	
	Geomechanical data	No Vshale data publicly available. No fault throw model publicly available. Horizontal stress data in Hillis et al. (1998), Hillis et al. (1999) and Hillis and Reynolds (2003) and on the Australian Stress Map. Stress data for the Cooper-Eromanga Basins in Reynolds et al. (2004, 2005 and 2006). Well by well interpretation is required to assess the availability of specific cohesive strength and friction coefficient data.	Build 3D geological framework to capture subsurface geology and reservoir/seal characteristics of the target area. Assessment of additional data requirements for more confident subsurface characterisation. Geomechanical data either from estimation from regional analogue or from laboratory test on rock samples will be required in order to calibrate inversion of well logs. Fault reactivation and fault seal models have to be built.
	Pore pressure data	Some pore pressure data is available from CSIRO's PressurePlot database.	
	Petrophysical data	Petrophysical data in Queensland Petroleum Exploration Data (QPED). Well by well interpretation is required to assess the availability of specific elastic and petrophysical properties. No specific deformation rate. Deformation rate can be estimated from regional sections.	

Site	Data required	Current availability	Remarks
Surat Basin (contd.)	Groundwater model	Golder Associates (QGC) and APLNG model exists but may not be publicly available.	Check with Golder Associates, QGC and APLNG regarding model availability. If required, develop a 3D groundwater model of the area.
	Dynamic reservoir model	A dynamic reservoir model is not available.	
	Coal occurrence	Gas and coal known of in area and CSG-LNG also potential. Coal inventory available that identifies extent of known coals resources. Some cross sections and depth to coal available. Basin model available including structural framework (GSQ/CSIRO). Coal isopach maps (Bowen and Surat basin Regional Study Framework). CBM maps available on the online Australian Mines Atlas website	Examination of data available for target area, assessing whether new models are required and whether enough data are available – construction of new models to identify extent of coal and map quality spatially to assess whether it is sufficiently poor to not be mineable, or sufficiently distal from storage site to not be sterilised by CO ₂ plume.
	Hydrocarbon occurrence	Oil and gas in the basin indicating working petroleum system.	Mapping of hydrocarbon fields and dry or untested structural closures, assessment of stratigraphic trapping potential in the target area. Assessment of the potential for hydrocarbon discoveries in the target area(s).
	Geothermal resource	No completed online geothermal database appears to be available at present.	Data may need to be assessed on a well by well basis.

7. CONCLUSIONS

A review of the publicly available literature and data regarding the existing level of knowledge in order to make an assessment of potential impacts of CO₂ storage with other natural resources has been carried out for three potential CCS sites in the Perth, Gippsland and Surat basins. Little work to date has been carried out that specifically looks at resource management requirements for carbon storage either internationally or for the Australian detailed storage areas. However, numerous studies are available that provide the background information to allow such an assessment to be initiated, although there are still some knowledge gaps.

Data availability and the knowledge of hydrogeology in each basin depend largely on the type and maturity of resource developments (groundwater, coal, coal seam gas, petroleum, geothermal). In all three basins, groundwater is produced for drinking water and/or agricultural purposes; hence there is abundant data available from shallow wells and the hydrogeology of the shallow subsurface is generally well understood. With respect to deeper formations, that would also present injection targets for CO₂ storage, the best data coverage exists for the Gippsland Basin because of its history of petroleum exploration and production. The Surat Basin has some information from petroleum exploration, whereas data from deep wells in the Southern Perth Basin is very limited.

The availability of numerical models varies widely for the three basins. For none of the basins does a model exist that simulates the cumulative impacts of CO₂ storage, petroleum production and groundwater extraction. While several single-phase groundwater models exist for these sites, they either require significant enhancement before they can be used (e.g. PHRAMS), or are not publicly available. Ideally, multiphase models would be required for simulating injection of CO₂ and migration of the plume and making an accurate quantitative assessment of the consequent effects on the groundwater and other resources.

Clearly, where the specific storage sites are still uncertain, as in Queensland, a less specific assessment can be achieved than where the site is well constrained. Nevertheless, from the data available, a very useful analysis of future basin management between CO₂ storage and other existing resources in the area can be achieved in each of the sites.

In the next stages of the project, the resources management issues with respect to CO₂ storage at the three CCS sites in Australia will be evaluated sequentially with the full suite of available data, starting with the Collie Hub in the Southern Perth Basin. This will coincide well with the additional data collection program for Collie. This will be followed by a similar assessment at the Wandoan (Surat Basin) and CarbonNet (Gippsland Basin) sites. The workflow to be adopted for each of the sites will include:

- Identification and mapping of known and potential resource e.g. groundwater, conventional hydrocarbons, coal and unconventional hydrocarbons, and geothermal.

- Structural, stratigraphic and geomechanical evaluation for assessment of containment security for CO₂ storage.
- Review of Injection options for minimising risk.
- Development of monitoring and mitigation strategies.

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APPENDIX A

Description of key references

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This report provides brief outline of the Gippsland Basin's petroleum geology that is relevant to offshore part of the basin. It summarises source, reservoir, seal and trap elements of the petroleum system and indicate the Miocene and the Late Palaeocene/Early Eocene as the timing of hydrocarbon generation and expulsion. Although potential for stratigraphic trapping is noted, fault bounded structural traps are presented as the main exploration targets. The report also depicts variation of the reservoir formation across the Latrobe Group in producing fields and emphasises the close association of the basin's hydrocarbon potential to the Latrobe group.

Campbell, I., 2009. An overview of tight gas resources in Australia. PESA News June/July 2009, 95-100.

This brief article emphasises the importance of tight gas as a natural gas reserve and presents cases of tight gas production efforts. It also briefly reviews the tight gas potential of Australia and indicates the potential of onshore Gippsland Basin by referring to the Wombat Field. The Wombat Field has been assessed as having a contingent gas initially in place reserves of 700 Bscf trapped in the Lower Cretaceous Strzelecki Group. Oil was also encountered in the formation (recovered 8 bbl of 39 API°) which believed to originate from a deeper terrestrial source. There is a potential for both unconventional and conventional hydrocarbon resources on the onshore Gippsland Basin.

Chiupka, J. W., 1996. Hydrocarbon play fairways of the onshore Gippsland Basin, Victoria. Victorian Initiative for Minerals and Petroleum Report 30. Department of Natural Resources and Environment.

This report describes three hydrocarbon play fairways across the onshore Gippsland Basin offering a significant untested potential in the region. These plays suggest possible hydrocarbon accumulations reservoired at: (i) Early Neocomian of the Strzelecki group; (ii) Late Cretaceous Golden Beach Formation; and (iii) Intra-Latrobe sands.

Gibson-Poole, C. M., Svendsen, L., Underschultz, J., Watson, M. N., Ennis-King, J., van Ruth, P. J., Nelson, E. J., Daniel, R. F., Cinar, Y., 2008. Site characterisation of a basin-scale CO₂ geological storage system: Gippsland Basin, southeast Australia. Environmental Geology 54, 1583-1606.

This study investigates geological storage of CO₂ in the offshore Gippsland Basin and presents detailed site characterisation of the Kingfish field using a methodology provided by Gibson-Poole et al. (2004). In the detailed characterisation, sequence stratigraphy and depositional model, reservoir geometry and connectivity, reservoir quality, seal distribution and continuity, seal capacity, impact of hydrodynamic system, fault reactivation risks were assessed in the estimation of the storage capacity. Storage capacity of the hydrocarbon fields were estimated in the basin and concluded that Gippsland Basin has a sufficient capacity to store very large volumes of CO₂.

Goldie Divko, L. M., O'Brien, G. W., Tingate, P. R., Harrison, M. L., 2009a. Geological carbon storage in the Gippsland Basin Australia: Containment Potential. Victorian Geological Carbon Storage Initiative (VicGCS) Report 1.

This study evaluates the top seal potential of the Lakes Entrance Formation in the Gippsland Basin as a key element to CO₂ containment potential of the basin. Thickness, spatial extend and facies distribution of the Lakes Entrance Formation are presented and integrated with the results of Mercury Injection Capillary Pressure tests to draw first order conclusions about the seal potential of the formation. According to the results, seal potential of the Lakes Entrance

Formation is: (i) Excellent in the Central Deep, western Northern Terrace and the onshore Lake Wellington Depression with capacity to support hundreds of meters high CO₂ column; (ii) Very good in Southern Terrace and Southern Platform with capacity to support significant CO₂ column; (iii) Good to moderate in Seaspray depression and Northern Terrace with capacity to support relatively short CO₂ column; and (iv) Poor in the offshore Northern Platform and the onshore Lakes Entrance Platform, Baragwanath Anticline and Alberton depression.

Goldie Divko, L. M., Campi, M. J., , Tingate, P. R., O'Brien, G. W., Harrison, M. L., 2009b. Geological carbon storage potential of the onshore Gippsland Basin, Victoria, Australia. Victorian Geological Carbon Storage Initiative (VicGCS) Report 2.

This report assesses the CO₂ storage potential of the onshore Gippsland basin. Six CO₂ storage play concepts were defined by assessing seal and reservoir potential. These plays are: (i) Tyres River Subgroup of the Strzelecki Group; (ii) upper (Albian-Aptian) Strzelecki Group; (iii) Golden Beach Subgroup of the Latrobe Group; (iv) Halibut and Cobia subgroups of the Latrobe Group; (v) top Latrobe sands; and (vi) Latrobe Valley Group. The report briefly emphasises that all the plays with the exception of Latrobe Valley Group have some potential impact on the undiscovered hydrocarbon resources as the Strzelecki group reached maturities to generate hydrocarbons in the area. Despite the shortness of data for a confident calculation, total storage capacity estimates for the onshore basin varies between 65 to 1000 million tonnes of CO₂.

Malek, R., Mehin, K., 1998. Oil and gas resources of Victoria. Department of Natural Resources and Environment.

This report presents an introduction to hydrocarbon prospective basins of Victoria, especially the Gippsland Basin. It explains basic stratigraphic and structural framework of the basin and a brief history of evolution. The report also provides a production overview of the basin with summaries of the individual fields. The field summaries from 32 fields incorporate fundamental data such as structure maps, geological cross sections and production profiles. Production in the developed fields, reserves in the undeveloped fields and the potential for future oil and gas discoveries (conventional) are briefly reviewed to emphasise the remaining hydrocarbon potential of the Gippsland Basin.

Elliott, L., 1989. The Surat and Bowen basins. The APEA Journal, 29(1), 398-416.

This manuscript provides a brief overview of the geology, exploration history and hydrocarbon potential of the Surat and Bowen basins which supply a significant portion of the Queensland's energy requirement. The Bowen and the overlying Surat basins form a superimposed basin configuration comprising Late Carboniferous to Middle Triassic stratigraphic section of the Bowen and Early Jurassic to Early Cretaceous section of the Surat basins. The rock units are almost entirely clastic with minor limestone and volcanics. Hydrocarbon accumulations were discovered at structural closures and predominantly reservoided within Jurassic Precipice and Triassic Showgrounds sandstones occurring in 40 and 30 fields, respectively. Jurassic Boxvale sandstone member, Triassic Moolayember and Rewan formations, Permian Tinowon and Kiangra formations also contribute to the production. Although there is both oil and gas production in the basin, the risk for new discoveries is much higher for oil than gas.

Geological Survey of Queensland, 2011. Queensland's petroleum exploration and development potential. The State of Queensland, Department of Employment, Economic Development and Innovation.

This recent report provides an outlook of the Queensland's petroleum (conventional and unconventional) potential with up to date production/reserve profiles of the state's sedimentary basins including Bowen/Surat basins. It was noted in the report that exploration for conventional hydrocarbons has waned in Bowen/Surat basins in recent years and replaced with increased coal seam gas (CSG) activities particularly focusing on the Permian coal measures of the Bowen Basin and Middle Jurassic Walloon coal measures of the Surat Basin. The change of focus is well reflected in the production and reserves data that CSG production in Bowen/Surat basins increased from 36 to 212 PJ and 2P reserves from 4116 to 27992 PJ during 2005-2010 period. In the year of 2009-10 conventional gas production remained one fourth of CSG

production around 74 PJ with 2P reserves of 539 PJ. In the same year, conventional oil production was reported around 432 ML with 2P remaining reserves of 5322 ML.

Greenhouse Gas Storage Solutions, 2009. Queensland Carbon Dioxide Geological Storage Atlas. State of Queensland, Department of Employment, Economic Development and Innovation.

A major capacity for geological storage of CO₂ is required in Queensland for future development of clean coal technologies which would require capture and storage of hundreds to thousands of megatonnes of CO₂. The potential of the state's sedimentary basins for CO₂ storage was regionally assessed in this report without considering the interferences with other resources.

The key finding of the report is that the largest potential for storage is associated with deep, regional, reservoir-seal intervals requiring structural trapping or residual gas saturation trapping. The Bowen, Cooper, Eromanga, Galilee and Surat basins contain reservoir-seal pairs that are highly prospective for CO₂ storage. Mimosa Syncline in the Surat basin contains the highest ranked reservoirs including Precipice Sandstone, Boxvale Sandstone Member and Hutton Sandstone sealed by shale and mudstone units of Upper Evergreen Formation and Walloon Subgroup. Note that, most of the structures along the northwestern and eastern flanks of the Mimosa syncline contain commercial hydrocarbons. Theoretical storage capacity using residual gas saturation trapping is in the range of 1,289 Mt in the Precipice Sandstone to 475 Mt in the Boxvale Sandstone and 1,198 Mt in the Hutton Sandstone. Storage options to depleted oil fields provide several orders of magnitude less capacity.

Korsch, R. J., Boreham, C. J., Totterdell, J. M., Shaw, R. D., Nicol, M. G., 1998. Development and petroleum resource evaluation of the Bowen, Gunnedah and Surat basins, Eastern Australia. The APEA Journal, 38(1), 199, 236.

This paper reviews the structural evolution, sequence stratigraphic framework and petroleum system of the superimposed Bowen-Surat basins. The basin evolution started with Early Permian rifting and followed by series of contractional events during mid-Permian to Middle Triassic and thermal subsidence during Early Jurassic to Early Cretaceous. Accordingly, source rocks were mostly deposited during Late Permian and reservoir/seal sequences during Late Permian-Early Triassic and Early-Middle Jurassic intervals. Traps have predominantly formed by the Triassic contractional events and the burial during the following phase of thermal subsidence led to peak hydrocarbon generation by Early Cretaceous. Based on the geochemically derived yields, the volumes of generated oil and gas are enormous and far exceed the volume of discovered hydrocarbons in the basin. Although this discrepancy emphasises preservation risks in the basin, it should also stimulate exploration activities especially for the generally overlooked stratigraphic traps.

Patchett, A. M., 2006, CO₂ storage potential of environmentally sustainable sites for CO₂ injection (UEI 37 &39), Eastern Bowen Basin, Queensland. (Appendix 10.3 of report no RPT05-0225). Cooperative Research Centre for Greenhouse Gas Technologies, Canberra. Report Number RPT06-0037.

This report assesses the storage potential of Flat Tap Formation and Showground Sandstone in the Bowen Basin and the Precipice Sandstone in the Surat Basin. It suggests that the Flat Tap formation is highly variable with poor reservoir quality and negligible storage potential. Showground Sandstone also exhibit poor reservoir quality and is hydraulically connected to the overlying units. The best storage potential is associated with the Precipice Sandstone which possesses good porosity and permeability with lateral and vertical continuity and is likely to provide ideal storage site when associated with anticlinal closures. The storage capacity was estimated as 250-1680 Bcf in the northern Burunga anticline and between 0.3-15.9 Bcf in the southern Trelinga. A potential conflict between fresh water resources and CO₂ storage is noted for the Precipice Sandstone.

Queensland Carbon Geostorage Initiative, 2010. Potential for carbon geostorage in the Taroom Trough, Roma Shelf and the Surat, Eromanga and Galilee Basins – Preliminary Report. Geological Survey of Queensland, Department of Mines and Energy.

This report provides a review of some generalised ideas on the potential of CO₂ storage in Surat Basin and the other potential locations in the state of Queensland. The report suggests that any reservoir sandstone above the Walloon Subgroup is generally shallower than the supercritical depth or missing an adequate top seal in the Surat Basin. Precipice Sandstone and Walloon Subgroup are emphasised as the potential reservoir for CO₂ storage 'plays' targeting the deep aquifer storage in the south of the basin. It was also noted that storage capacity cannot be assessed purely on the basis of structural closure, stratigraphic pinch-out and seal capacity because these systems are not hydrostatic and the trap capacity for low density fluids are likely to be effected by groundwater flow dynamics. Two strategies were proposed for CO₂ storage efforts: (i) targeting settings similar to major oil/gas fields in the basin (e.g., Moonie oil field); and (ii) targeting deeper regions along the axis of major synclines (e.g., Mimose Syncline) which requires drilling and testing. Acquisition of good quality formation pressure, formation water and petrophysical data are essential to put reliable constraints to the behaviour of these systems.

Baddock, L., 2005, South West Yarragadee Hydrogeological Investigations and Evaluation - Southern Perth Basin, Report prepared for Infrastructure Planning Branch, Planning and Development Division, Water Corporation.

The study area for this report is the southern Perth Basin in the southwest of Western Australia, extending from Kemerton to the South Coast covering an on-shore area of about 5800 km². The groundwater investigation is one of the largest carried out in Western Australia, involving drilling a total of 15,702 meters at 67 sites upon the Blackwood Plateau, ground and aerial geophysical surveys, water chemistry and carbon-14 isotopic sampling, groundwater recharge studies, stream flow and salinity measurements, groundwater level monitoring, and a pumping test. Drilling investigations were undertaken in two phases. The first phase of investigations during January to October 2003 was to define aquifer and aquitard properties, piezometric heads within the aquifers and groundwater flow directions, and the extent and outcrop areas for the various hydrogeological units, particularly of the Yarragadee Formation. A second drilling phase during May and June 2004 supported studies of groundwater dependent ecosystems in areas potentially sensitive to reduced potentiometric heads within the underlying regional aquifer. Investigations have allowed the distribution of hydrogeological units to be defined in far more detail than previously, and identified several new units important in the understanding of groundwater flow within the southern Perth Basin.

Deeney, A. C., 1989, Hydrogeology of the Binningup borehole line, Perth Basin: Western Australia Geological Survey, Professional Papers, Report 25, p. 7-16.

This report describes the hydrogeology of the Perth Basin near Binningup, about 20 km north of Bunbury. The investigations comprised drilling of six bores at four sites along an east-west section in the southern part of the Harvey Ridge a structural subdivision of the Perth Basin. The bores were drilled to a maximum depth of 800 m. Drillings intersected the Cockleshell Gully Formation, overlain by the Leederville Formation. The drilling intersected a maximum thickness of 700 m of the Cockleshell Gully Formation having salinity of 2510 – 26 100 mg/L. The higher salinities reflect an inactive groundwater flow system resulting from low permeabilities in the Cockleshell Gully Formation.

Deeney, A. C., 1989, Hydrogeology of the Harvey borehole line, Perth Basin: Western Australia Geological Survey, Professional Papers, Report 26, p. 59-68.

This report presents the hydrogeology along the Harvey Line from investigations drilling of eight bores at four sites along an east-west line near Waroona. The bores were drilled to a maximum depth of 810 m in the northern part of the Harvey Ridge of the Perth Basin. Drillings intersected the Cockleshell Gully Formation, the Leederville Formation and the superficial formations of the Perth Basin. The geology and hydrogeology of these formations is well described in the report. The report describes the salinities of the groundwater in each formation - superficial formations (<500 mg/L); Leederville Formation (500 – 1500 mg/L); Cockleshell Gully Formation (2300 –

7000 mg/L in the upper part and 7000 – 32500 mg/L in the remaining lower part). High salinities in the Cockleshell Gully Formation reflect slow movement of groundwater because of low permeabilities.

Young, R. J. B. and Johanson, J. N., 1973, Lake Preston No. 1, Well Completion Report, Perth Basin (E. P.25), West Australian Petroleum Pty Ltd.

The Lake Preston 1 petroleum exploration bore was drilled in 1972 to a depth of 4566 m in the Harvey Ridge subdivision of the Perth Basin. The report describes the drilling and sampling methodology and results from this bore. A description of the generalised geology of the area is presented along with the results of lithological sampling from this bore site. The bore intersected the Sue Coal Measures, Sabina Sandstone, Lesueur Sandstone, Cockleshell Gully Formation, Leederville Formation and superficial formations. A palaeontological report is also included. No significant oil or gas was recorded in the well. The wireline surveys included Induction Electrical Survey (IES), Borehole Compensated Sonic – Gamma Ray with (and without) calliper (BHCGR-C), Formation Density Compensated (FDC), High resolution Dipmeter Tool (HDT) and Velocity Survey. The 'salinity of the fluids' is presented in the report, however, it is unclear whether the salinity values are interpreted from the wireline logs or is that of the borehole fluid.

Crostella, A. and Backhouse, J., 2000, Geology and Petroleum Exploration of the Central and Southern Perth Basin, Western Australia.

The report presents a geological review of the central and southern portion of the Perth Basin based on 'critical examination of unpublished reports on oil exploration wells'. The report provides a comprehensive description of the regional setting, stratigraphy, basin evolution and a 'post-mortem' of each oil exploration well in terms of its structure, stratigraphy, reservoir and seals, and their relation to the hydrocarbon potential at each site.

Commander, D.P., 1974. Hydrogeology of the Mandurah-Pinjarra area. Geological Survey of Western Australia. Annual Report 1973 p20-25

This report is based upon results from 18 government bores drilled in the Mandurah – Pinjarra area between 1962 and 1969, and 23 drilled for industry east of Pinjarra between 1969 and 1972. This information has also been incorporated by Deeney (1989b). The primary focus of this report is upon the deeper aquifers formed in the Mesozoic or older Sedimentary formations. Only limited mention is made about the shallower systems. This early study provides information on local stratigraphical units, water quality and aquifer yield. The study mentions a green clay layer which has a major effect on groundwater quality in the Leederville Aquifer. The study provides hydrogeological interpretations which have been used to guide the regional hydrogeological investigations.

Commander, D.P., 1984. The Bunbury Shallow-Drilling Groundwater Investigation. Geological Survey of Western Australia. Report 12 p32-52 professional.

This report describes the hydrogeology of the Bunbury area based upon information gained from twenty six sites at which a shallow (20 m) and deep bore (100 m) were drilled between 1975 and 1980. The bores associated with this report are not mentioned in Deeney (1989b).

The superficial formations in the Bunbury area cover the coastal plain to a maximum depth of about 20 m, they are relatively clayey and thin. Groundwater dominantly flows in a westerly direction. In the Bunbury area the Superficial Aquifer receives recharge directly from rainfall, but also from upward groundwater flow from the Leederville Formation. Commander notes that "Groundwater tends to be fresh in areas of sand, and brackish to saline in areas of clay". This is a consistent trend throughout each of the papers.

Commander, D. P., 1988. Geology and hydrogeology of the superficial formations and coastal lakes between Harvey and Leschenault Inlets (Lake Clifton Project): Western Australia Geological Survey, Report 23, Professional Papers.

The report provides a comprehensive account of the superficial formation hydrogeology based upon data from 61 bores drilled for the Geological Survey of Western Australia. It should be noted that the information for all of these bores, and the findings of Commanders' report have been synthesised along with more recent information in Deeney (1989b).

The report does, however, vary from Deeney (1989b) in that it provides a much more detailed description of the characteristics of the coastal lakes which occur in Peel – Harvey area (Lake Preston, Lake Clifton and Martins Tank Lake).

The lakes are fed by little to “no runoff, and are maintained by direct rainfall accession and groundwater inflow”. They are groundwater sinks and have no outflow other than evaporation. They are underlain by hypersaline groundwater. Commander studied the salinity at different points across each of the lakes, and with this information he was able to create a summary which shows the salinity range in each of the coastal lakes over a 5 year period.

Bradshaw, J., Bradshaw, B., Spencer, L., Mackie, V., 2000. Geodisc Project 1 – Regional Analysis Stage 2 Basins – Perth Basin, Western Australia. UEI Report 60.

This report investigates suitability of the Perth Basin for geological CO₂ sequestration. Reports conclude that the regional geology of the basin limits the sequestration potential over much of the basin due to: (i) absence of proper top seal in the onshore South Perth Basin; and (ii) complex structural history which will cause seal integrity problem due to intense faulting wherever a proper seal exists. There is a major simplification in the report that the rare occurrence of hydrocarbon accumulations is considered as a general containment problem that would also impact the CO₂ storage potential. Accordingly, depleted hydrocarbon fields are noted as the most suitable storage sites. The report also assesses lower Cretaceous sandstones beneath the South Perth Shale as a conceptual ESSCI (Environmentally Sustainable Sites for Carbon-dioxide Injection) play in the south Perth Basin and concludes that these reservoirs have some potential to sequester large scale CO₂ emissions.

Causebrook, R., Dance, T., Bale, K., 2006. Southern Perth Basin: Site investigation and Geological Model for storage of Carbon Dioxide. CO2CRC Report No: RTP06-0162

The report presents a geological assessment of the southern Perth Basin for CO₂ storage. The report covers both the onshore and the offshore parts of the basin. One of the major outcomes of the project was the compilation of a comprehensive database of geological and geophysical information in an ArcGIS format. The report presents an assessment of containment potential of reservoir and seals in the study area. Impact of any CO₂ storage options on the natural resources such as groundwater supplies etc have been covered in the report. The report also provides the results of several related studies in the appendix such as Geological Modelling, Hydrodynamic Characterisation, Petrological Characterisation, Geomechanics, Numerical Simulations and Petrophysics. This report forms an important basis for more detailed studies in the potentially suitable areas.

The aim of this study is to identify the sites most suitable for CO₂ capture and storage surrounding the emission centres of the Perth region. Onshore basin, offshore reservoirs beneath the Neocomian unconformity and the Gage Sandstone reservoir were assessed based on geology, stratigraphy, reservoir capacity, containment potential and impacts on natural resources. Lack of suitable sealing mechanisms is noted for the onshore basin as the most critical risk to storage efforts. For the onshore basins, Gage Sandstone was recognised as the most suitable reservoir top-sealed by the South Perth Shale. The reservoir is extensive and thought to possess good properties based on limited well data. However, a containment risk was noticed due to lateral variation of the South Perth Shale to more sandy facies to the south of the basin. Furthermore, hydrocarbon leakage related diagenetic zones were also mapped.

CO₂ storage in the Gage Sandstone was also assessed in terms of its impact on potential hydrocarbon resources of the offshore basin. Although non existence of hydrocarbon fields and low probability of a significant discovery in the offshore basin were emphasised by the study, Gage sandstone was still acknowledged as the most likely reservoir for any future discoveries of hydrocarbons.

Crostella, A., and Backhouse, J., 2000. Geology and Petroleum Exploration of the central and southern Perth Basin, Western Australia. Geological Survey of Western Australia, Report No. 57.

The report covers a general overview of the hydrocarbon potential of the central and southern Perth Basin. It provides critical background to stratigraphy, main structural features, basin

evolution and compartmentalisation in the area and assesses hydrocarbon potential within this regional framework. The report defines elements of the hydrocarbon system and provides post-mortem evaluation of the exploration wells drilled in the region. Hydrocarbon occurrences or shows are reported from numerous wells in early Cretaceous, Jurassic and Permian reservoirs. Permian is particularly interesting where the estimated hydrocarbon reserves are high but the reservoir quality is poor and therefore might be interesting for tight gas development. Preliminary petrophysical, geochemical, engineering and seismic data are included in the report

Mory, A. J., Iasky, R. P., 1996, Stratigraphy and structure of the onshore northern Perth Basin, Western Australia. Geological Survey of Western Australia, Report No: 46.

Data from numerous wells, outcrops and geophysical surveys were assessed to establish the main stratigraphic framework and tectonic history of the northern Perth Basin. The petroleum potential of the basin was evaluated in the light of 6 commercial hydrocarbon fields in the basin and the basics of the petroleum system were described. Spatial variation of source rock maturity for Permian and Triassic units was discussed based on the geohistory modeling of wells. It was noted that rapid subsidence due to break-up in Early Cretaceous brought the source rock into the oil window and led to peak period of hydrocarbon expulsion. Accordingly, Early Neocomian anticlines forming synchronously to peak expulsion host all the known fields and smaller hydrocarbon accumulations in the basin.

Varma, S., Dance, T., Underschultz, J., Langford, R. P., Dodds, K., 2007. Regional study on Potential CO₂ geosequestration in the Collie Basin and the Perth Basin of Western Australia. CO₂CRC Report No: RPT07-0529.

This report assesses the Collie and Southern Perth basins for potential geological storage of CO₂ within a 50 km radius of town of Collie. The stratigraphy of the basins was reviewed to identify potential reservoir/seal sequences that can be suitable for CO₂ injection and containment. The evaluation showed that the potential is low for large scale storage within the sediments of the Collie basin. However, the Southern Perth Basin, particularly the Harvey Ridge, was identified as an area with the highest potential for storage of significant volumes of CO₂. The study proposes injection of CO₂ at 3000 m depth into the lower part of the Triassic Lesueur Sandstone at the Harvey Ridge.



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