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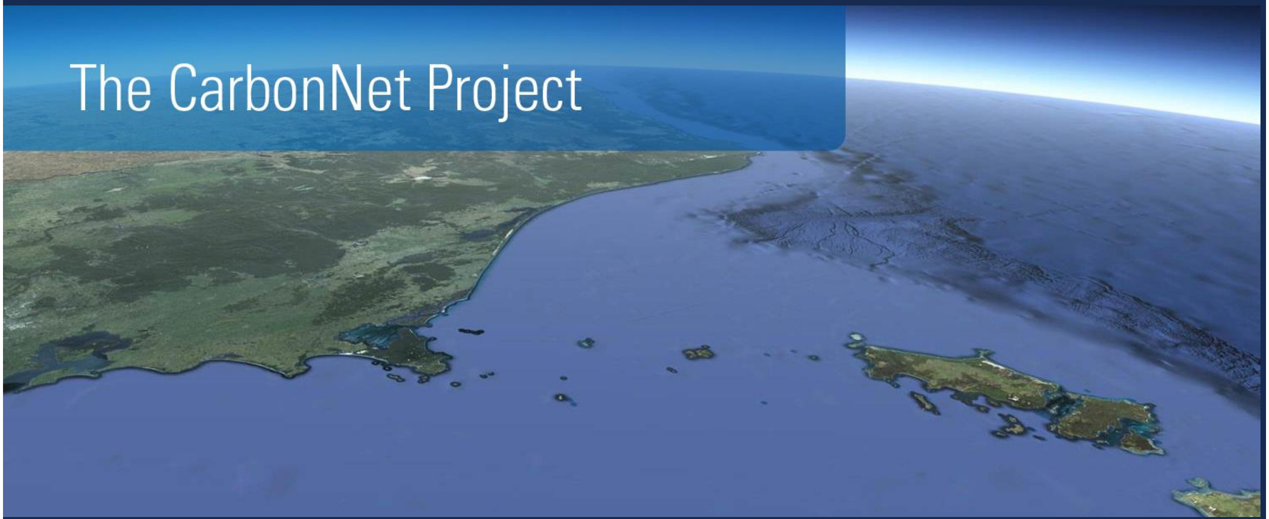

CarbonNet storage site selection & certification: challenges and successes Gippsland Basin

State Government Victoria

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CarbonNet storage site selection and certification: challenges and successes

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www.energyandresources.vic.gov.au/carbonnet

Abstract

The CarbonNet Project is seeking CO_2 storage sites in the nearshore area of the Gippsland Basin that provide permanent and safe storage for 25 to 125 Mt of CO_2.

The process used by CarbonNet for site selection follows international best practice, aligned to DNV GL Recommended Practice (DNV-RP-J203) (DNV, 2012) to provide decision makers and stakeholders with independent expert assurance of environmentally safe, long-term geological storage.

The DNV-RP-J203 requires a systematic approach, based on understanding and minimising storage risks and analysis of diverse geoscience and environmental factors. The main areas of investigation include:

- selection and qualification of storage sites.
- documentation of site characterisation and site development plans.
- risk management throughout the life cycle of CO_2 geological storage projects.
- monitoring and storage performance verification.
- well assessment and management planning.
- planning for site closure and subsequent stewardship.

The CarbonNet Project reviewed more than twenty five storage concepts at fourteen locations, within 25km of the coastline. These were quantified for prospective storage volume and risk for capacity, containment, and injectivity. A portfolio of three sites was shortlisted. CarbonNet has had its storage site selection process endorsed by an Independent Scientific Peer Review and the site selection process was assessed by DNV GL and a Statement of Feasibility issued for the portfolio in January 2013. Detailed site-specific risk analyses and data gap analyses of key elements were prepared for each site. As a result, a prioritised site was selected for further analysis and the development of a site appraisal plan.

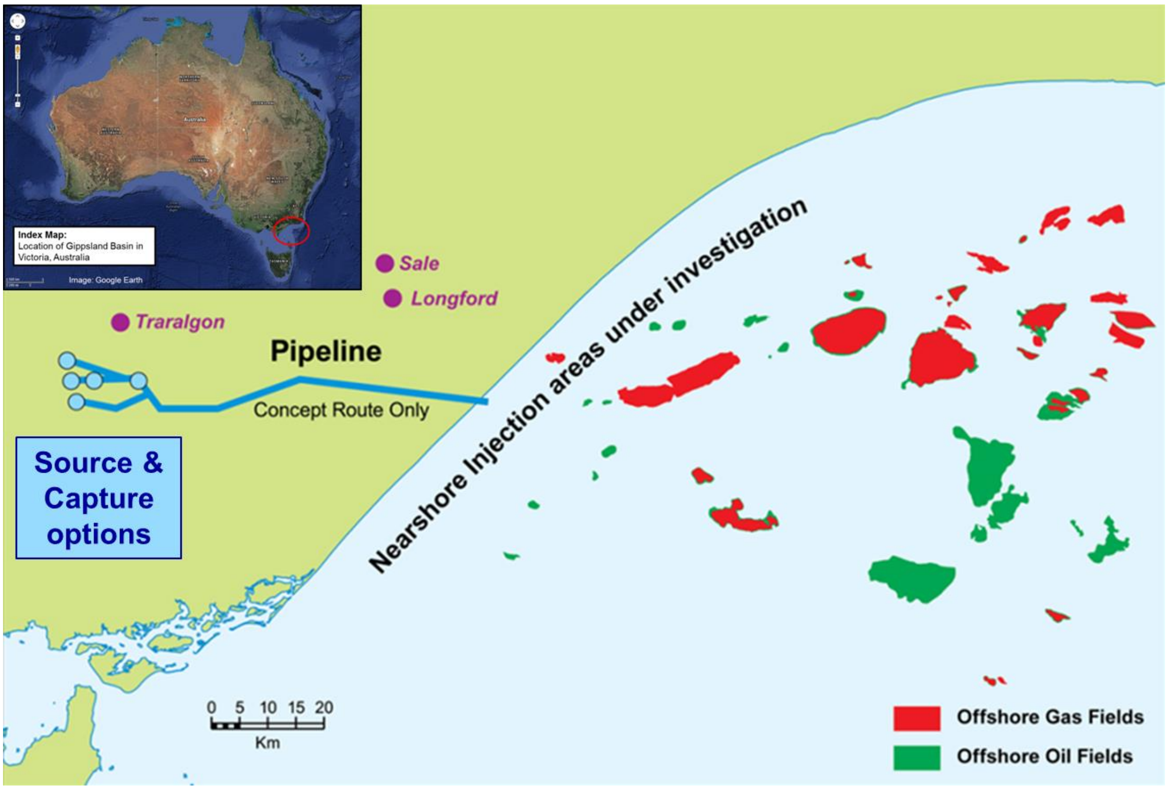
The challenges of completing the work under exacting technical conditions to the satisfaction of a wide range of stakeholders has resulted in an excellent prioritised site. The site selection process represents approximately 20 man-years of geoscience work for an estimated investment of ~ $20 million.

1 Introduction

In this paper, the process and results of geological site selection for the CarbonNet Project are presented and discussed. The site screening process used by CarbonNet follows that laid out in Det Norske Veritas (DNV GL) Recommended Practice DNV-RP-J203 (DNV, 2012) and leads to a portfolio of high-graded sites and one prioritised site for CO_2 storage.

CarbonNet is one of two Australian Government Carbon Capture and Storage Flagship Program projects. The project is currently in feasibility and commercial definition stage, and is investigating the potential for establishing a world class, large scale, multi-user carbon capture and storage (CCS) network in the Gippsland Region of Victoria, Australia (Figure 1). The network will bring together multiple carbon dioxide (CO_2) capture projects in Victoria, transporting CO_2 <100 km via a shared pipeline, and injecting it deep into an underground offshore storage site.

Figure 1: CarbonNet Project Concept



As a first step in establishing commercial storage in this basin, CarbonNet seeks to demonstrate capacity and integrity of CO_2 storage such that the selected site will be suitable for storage of a minimum of 25 million tonnes (Mt) of CO_2 and up to 125 Mt. Anticipated injection rates at the selected site will range from a minimum of one million tonnes per year up to five million tonnes per year, which would occur over a period of at least 25 years. Scalable infrastructure will be designed to underpin long term growth and deployment of a CCS network, at which time additional storage sites may become viable, including depleted oil and gas fields, basin-centre storage, large-scale stratigraphic traps, and some of the targets excluded in the earlier rounds of investigation. Detailed infrastructure design is not part of this paper.

The Gippsland Basin has long been recognised as one of the most promising sedimentary basins in Australia for CO_2 sequestration, due to the combination of a world-class petroleum system with reservoirs, seals, and giant traps, combined with proximity to the Latrobe Valley where 60 Mt of CO_2 is emitted annually by brown-coal power generation and other industrial activity.

A solid legislative base exists for CO_2 storage in Australian waters with a single composite legislative act covering both petroleum and CCS operations, and an open access data regime to encourage new participants to enter the search for safe and secure geological storage sites. In the Gippsland basin, 50 years of oil and gas exploration and production in a world-class petroleum basin have resulted in an extensive well and seismic database which underpins CarbonNet evaluation (see Hoffman et al., 2015a).

The present CarbonNet Portfolio of Storage Sites is the end result of a broad two-stage screening process that reviewed basins across Victoria as potential repositories for Latrobe Valley CO_2, and then progressively focussed on the Gippsland Basin, sub-regions within it, and then compiled an inventory of prospective storage sites and progressively winnowed that inventory to retain only large and secure prospects.

This screening and prioritisation process has taken place in parallel with, and benefitted from the learnings of other Australian projects and reviews such as the CO2CRC Otway Project (Cook, 2014), The Surat Basin project (Farquhar et al., 2013, Hodgkinson and Grigorescu, 2013), the SW Hub Project (Stalker et al., 2013), The northern Perth Basin study (Varma et al., 2013) and the Zerogen Project (Zerogen, 2012). Additional approaches to and methods for site selection and storage validation have also been reviewed and incorporated as appropriate (Kaldi and Gibson Poole, 2008, Gibson-Poole et al., 2009, Oldenberg et al., 2009, TNO 2009, 2011a, b, US DoE 2010, EU 2009, 2011a, b).

Early work identified the nearshore Gippsland Basin as the prime study area for CarbonNet to search for and quantify Prospective Storage Sites for the following reasons:

1. Location should be within known Gippsland Basin reservoirs and under proven topseals.
2. Location should avoid large-value currently producing oil and gas fields in the offshore basin.
3. Location should avoid storage under land areas where access for storage is potentially more difficult and where top Latrobe is generally too shallow for supercritical phase.

This determined the area of study in the nearshore Gippsland Basin, from the shoreline to approx. 25 km offshore, and with southern and northern boundaries defined by major fault systems where the basin stratigraphy thinned significantly (Figure 1).

CarbonNet has, during the past three years, performed numerous technical and non-technical investigations using available data from the three sites and their surrounding area. Results of this work allowed site screening to be completed, resulting in confirmed high-grading of the three potential storage sites from an initial portfolio of 20+ sites distributed across the nearshore Gippsland Basin, within 25 km of the coastline.

CarbonNet has taken a Play Fairway approach to portfolio management in the Gippsland Basin and has worked-up three primary targets (and several secondary ones) with very little more effort than it would have taken to evaluate a single site, and understand its geological context.

CarbonNet has worked to a carefully-designed technical program known as the Geoscience Evaluation Program which was implemented in two phases. Initially, the Accelerated Geoscience Evaluation Program Phase 1 conducted reconnaissance-level screening of the nearshore part of the basin and developed an inventory of 20+ exploration leads and prospective storage sites. The Geoscience Evaluation program Phase 2 (GEP2) then conducted more detailed assessment. Progressive high-grading of the prospective sites, with initial deterministic reviews of capacity and containment, followed by a sophisticated deterministic evaluation, was assisted by the construction of regional and progressively more elaborate local static geologic models in PETREL and dynamic simulations in Eclipse E100 and E300 to study plume movement and multiphase flow.

A substantial input of international and national experts was recruited through direct consultancy, and through the establishment of a series of peer reviews. These peer reviews included risk workshops to understand potential adverse outcomes and to develop mitigation to each of those risks to provide confidence that safe and secure storage for geological time will be assured.

For CarbonNet's site screening process and the future Appraisal Plan for the selected site(s) to meet the highest standards for quality, rigor and international best practice. The CarbonNet team has chosen to follow the recommended practice guidelines established by DNV GL, a worldwide leading organisation in the field of risk management for the safeguarding of life, property, and the environment. This recommended practice involves a multi-step, stage-gated process and is detailed in DNV GL Recommended Practice DNV-RP-J203 (DNV, 2012). The first step in the process is site screening, which CarbonNet successfully completed early in 2013, with the issuance of DNV Statement of Feasibility for the portfolio of three sites.

A prioritised site was then selected on the basis of capacity, storage certainty, and commerciality, with a Conceptual Site Development Plan to demonstrate how the site could be developed with injection wells to achieve up to 125 Mt of secure storage. A comprehensive Appraisal Plan and Preliminary Site Monitoring Plan were then developed in conjunction with Schlumberger Carbon Services to detail how any additional subsurface information would be collected and how the site could be safely monitored for its entire lifetime. This Appraisal Plan was then submitted to DNV GL for verification that it would, if successfully completed, meet the needs of DNV-RP-J203, and also meet Australian legislative requirements for a future injection licence application.

During this multi-year process, the CarbonNet project has evolved substantially and significant learnings have been made. These are summarised for the benefit of other project proponents worldwide.

2 Project Background

The genesis of the CarbonNet Project lies with the *Australian Government's Clean Energy Initiative announced in the 2009-10 Budget.* This included the *CCS Flagships* Program to fund a series of commercial-scale demonstration projects to be proposed by the Australian States as joint Federal-State endeavours.

The CarbonNet Project formally commenced in early 2011 as a joint initiative of Victorian State and Australian Federal government. The project is hosted and managed by the State, through the Department of Economic Development, Jobs, Transport and Resources (DEDJTR)[1]. By mid-2011, the nucleus of a cross-disciplinary technical team was in place, with advisors and core staff specialising in capture, transport, environment and regulatory, communications, and storage, as well as a robust management structure and reporting process to Federal and State funders.

The project reviewed previous studies and scoped out the initial project objectives to provide scalable infrastructure to underpin growth and development of a commercial scale CCS network.

- Foundation project: 1 to 5 Mt of CO_2 per year (Mtpa) for 25 years.
- Expansion phase: up to 20 Mtpa of CO_2 (2030 and beyond).
- Common user transportation (pipeline) and storage infrastructure.
- Hub-based concept.
- Minimise conflicts with petroleum activities and other resources.
- Foundation storage sites focused on the near shore zone.
- Longer term strategy to use the reservoir volume of depleted oil and gas fields as production ceases (or possible future EOR[2]).

Storage objectives were initially defined as:

- Confirm the presence of sites with 25-125 Mt of accessible CO_2 storage within the Latrobe Group in the near shore Gippsland Basin.
- Demonstrate that the injectivity properties of the Latrobe Group at the short-listed injection sites are adequate.
- Establish that the injection of 1 to 5 Mtpa of CO_2 can be undertaken in a sustainable and secure manner.
- Determine that injected CO_2 will have a minimal and acceptable impact on other users and resources within the basin.
- Commence monitoring programs to establish baseline database(s) for future developments and to provide surveillance procedures to demonstrate that the CO_2 is behaving as modeled and will be constrained over anthropogenic and geological timeframes.

As the project matured, additional constraints were developed and recorded in a formal Decision Register as a "Basis of Design'. This included for example a protocol that CO_2 would not be stored under onshore lands.

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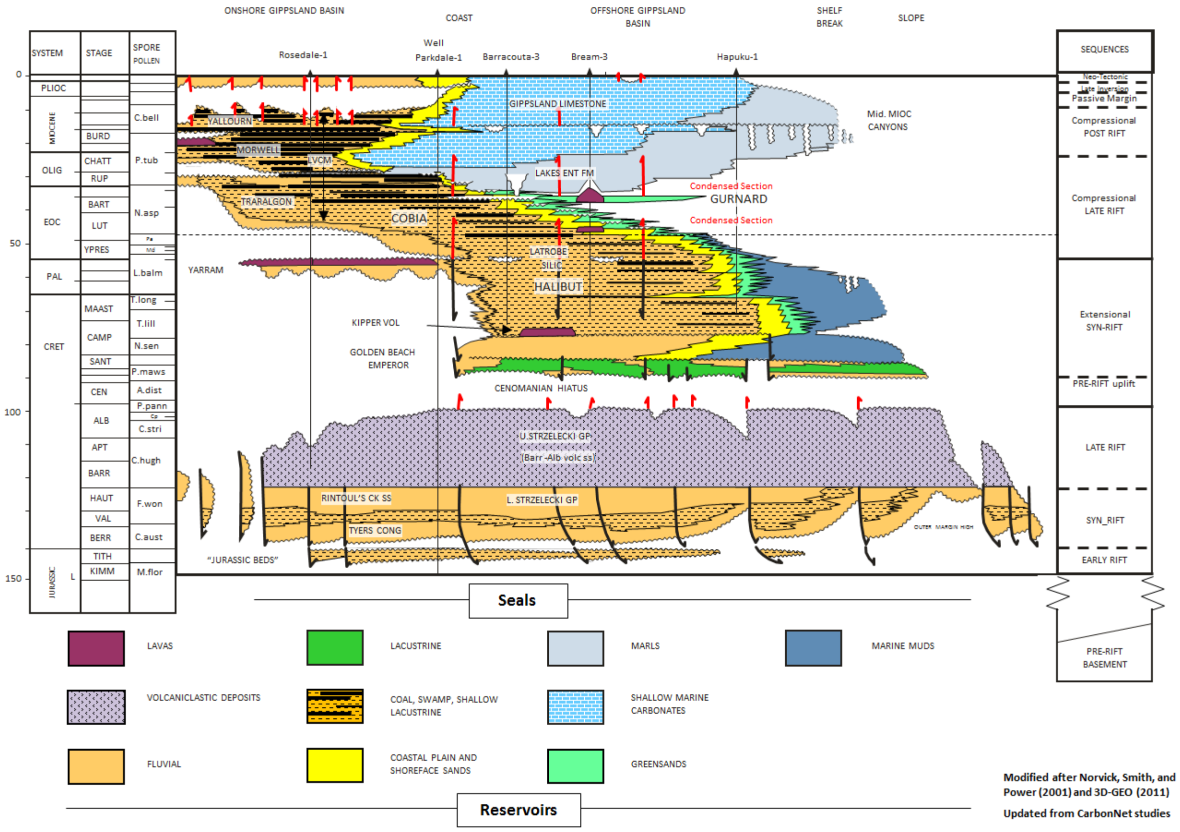
[1] The Project was initiated by the Department of Primary Industries (DPI) and moved to the Department of State Development, Business and Innovation (DSDBI) in 2014 as part of Machinery of Government (MoG) changes. In 2015, a further MoG amalgamation saw the project incorporated in the new Department of Economic Development, Jobs, Transport and Resources (DEDJTR).

[2] The Latrobe Group reservoirs of the Gippsland Basin are less suited to EOR than most since they have very high primary recovery (>85% for oil), driven by an excellent aquifer and very low residual oil saturation (<15%). Nonetheless, for giant fields of 1-1.5 billion barrels recoverable, there is a significant residual oil volume that could potentially be partially recovered by a whole-field miscible flood.

CarbonNet therefore searched for prospective storage sites with capacities ranging from 25-125 million tonne CO_2, with a sound sealing mechanism to provide permanent storage and to have no Significant Risk Of a Significant Adverse Impact (as defined in Australian legislation, abbreviated as SROSAI) on other resources and environmental values.

The project focused on the nearshore/offshore portion of the Gippsland Basin strategically located between the offshore producing oil and gas fields and the onshore brown coal resource, utilised by power stations, and other CO_2 emitting plant. Here, excellent reservoir qualities exist in the petrologically mature Halibut and Cobia Subgroups (of the Latrobe Group) clastics which were deposited in lagoonal, shoreline, beach and barrier bar settings (Hoffman et al., 2015a, b)

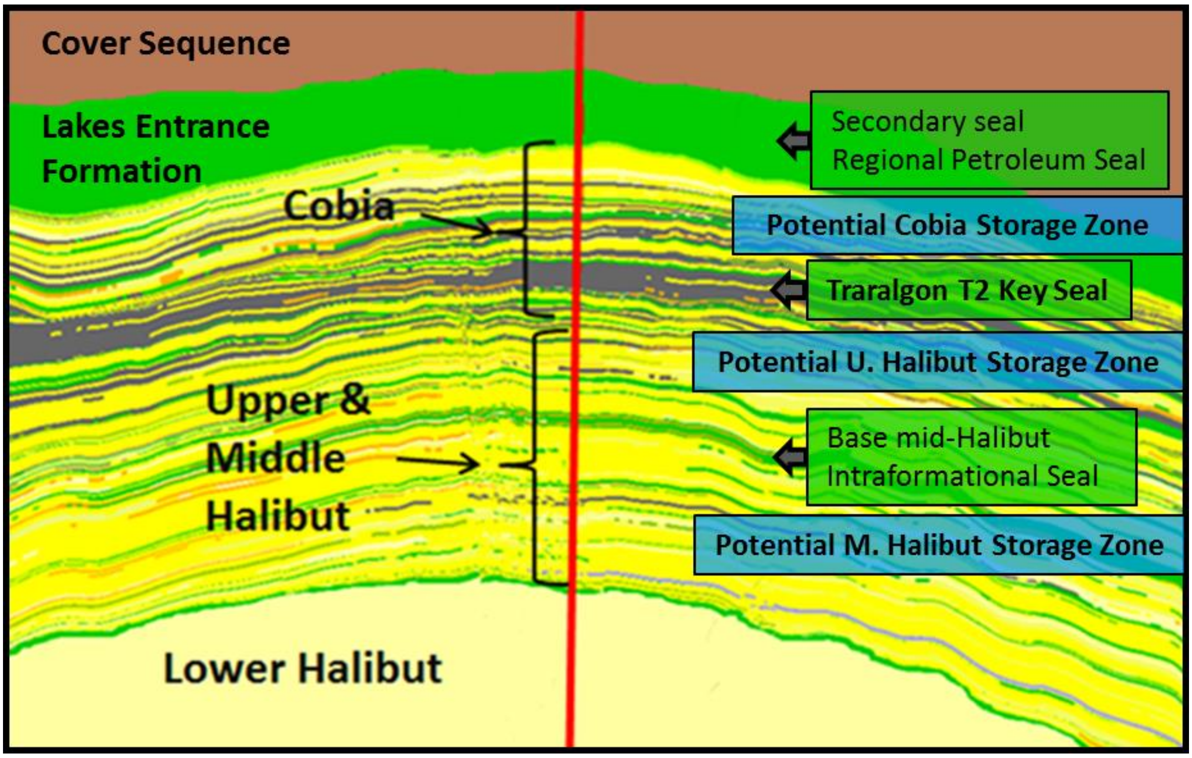
Figure 2 shows the chronostratigraphy of the Gippsland Basin with seals and reservoirs.



Gippsland Basin chronostratigraphy is well-known after 1500+ exploration and development wells and "wall-to-wall" 3D in the offshore core basin area. A clastic-rich retrogradational sequence of terrestrial upper and lower coastal plain sediments is bounded by a backstepping series of paralic barrier bar sands of exceptional (multi-darcy) quality. The entire package is up to 3 km thick with high net:gross (65-75%) and represents an excellent opportunity for multi-storey CO_2 storage, using intraformational seals proven from oil and gas traps.

Intraformational shale and coaly sequences (50-100 metres thick) provide the primary seal to Halibut storage (Figure 3, Hoffman et al., 2015b). The regional caprock to petroleum (the Lakes Entrance Formation) provides insurance as a secondary seal.

Figure 3: Typical CarbonNet vertical stacking of reservoirs and seals in the nearshore. Total reservoir thickness 500m-1,500m



The CarbonNet team reviewed a portfolio of storage concepts ranging from simple and mildly faulted four-way dip closures (structural traps) and discrete stratigraphic reservoir bodies (e.g. linear shoreface sands) on low angle monoclines presenting saline aquifer storage opportunities.

Seal adequacy is demonstrated by Mercury-Injection Capillary-Pressure (MICP) data, Formation Integrity/Leak-Off Tests and in some instances the presence of hydrocarbons (variously biodegraded, water flushed, undeveloped and partially produced). An initial inventory of >25 storage concepts at 14 locations were identified within 20 km of the coastline. These were quantified for prospective storage resources and a probabilistic risk assessment was developed. Geomechanical stability is demonstrated in the context of the basin regional stress state (van Ruth et al., 2006), and the prevailing strong aquifer support and excellent pressure buffering capacity (Varma and Michael, 2012).

This paper discusses the processes whereby the initial inventory was checked for quality and consistency, and then progressively winnowed-down to a high-graded portfolio of three low-risk high-volume sites, and a final Prioritised Site selected for future appraisal operations, while retaining independent contingent storages options at the other two sites.

2.1 Legislative foundation

Australia benefits from comprehensive legislation that prescribes the operations of petroleum explorers, CCS proponents, and other resource users. In particular, applications to drill a well must demonstrate acceptable construction and completion practices including protection of aquifers and potential hydrocarbon and other resource zones. All data acquired under petroleum and other prospecting licences must ultimately be placed in the public domain, after a confidentiality period, for the benefit of third parties. This open-access data regime is instrumental in encouraging new parties to enter the field of resource exploitation, including CCS. International jurisdictions that lack this open access requirement inhibit new participants and limit CCS to existing data holders – largely the petroleum companies, and state geological surveys.

Petroleum exploration had a slow start in Australia with a few well bores after the First World War when resource independence first came to general attention. At this time, the Lakes Entrance oil field was discovered onshore in Gippsland, Victoria with the Lake Bunga borehole in 1924, and represents the first quasi-commercial oil production in Australia. Productivity was very poor with heavy biodegraded oil seeping slowly from low-permeability reservoirs. Hand-dug shafts with excavated side galleries represented the initial production method and recovered 8000 bbl oil in total. Later, more-conventionally drilled wells also had limited productivity.

Exploration in other onshore basins continued on a state-by-state basis, with small finds at Rough Range in Western Australia and a number of interesting oil shows in the 1950's as oil industry technology was imported from overseas, but with little commercial return. Exploration turned to the offshore in the 1960's and very rapidly led to the discovery of a world-class petroleum province in the area of the offshore Gippsland Basin, known as Bass Strait (Balfour, 1968).

The early wells were drilled under State regulatory oversight, but with Federal support through the Petroleum Search Subsidy Act 1957. With significant discoveries and production, the need soon became apparent for more extensive offshore petroleum legislation with allowance for taxation, and tax offsets for approved operations. This legislation culminated in the Petroleum (Submerged) Lands Act 1982 (PSLA) and, later, the Offshore Petroleum Act 2006, and State-by-State equivalents.

The relative lack of an onshore wildcat prospecting industry and the firm regulation of the post-1960's industry onshore and offshore has led to a good state of certainty as to the number, location, and condition of petroleum wells across Australia. Water boreholes have been less regulated and more prolific and in the onshore there is a specific need to check for water boreholes and their condition before planning CO_2 storage operations.

Carbon storage legislation was brought into force in Commonwealth waters (beyond the three nautical mile limit of state jurisdiction) in November 2008 with the Offshore Petroleum and Greenhouse Gas Storage Act 2006, which incorporated and superseded the Offshore Petroleum Act 2006. In the State of Victoria, the Greenhouse Gas Geological Sequestration Act 2008 (Vic) applies onshore and the Offshore Petroleum and Greenhouse Gas Storage Act 2010 (Vic) applies in State waters. There are close similarities between the three sets of legislation with a few differences largely due to historical precedents to liability in the different jurisdictions.

2.2 Evolution of the CarbonNet Project

Against this background, the Australian Petroleum Cooperative Research Centre for Geological Disposal of Carbon Dioxide (GEODISC) Project conducted an Australian-wide assessment to identify Environmentally Sustainable Sites for CO_2 Injection (ESCCI) (Cook et al., 2000; Bradshaw et al.,2000, Bradshaw and Rigg, 2001; Rigg et al., 2001). This four-year study (1999-2003) firstly identified the CO_2 storage potential of suitable basins nation-wide by identifying storage sites and corresponding emission nodes. The basins/sub-basins were ranked on a national scale identifying potential ESSCIs with optimal geology and considered the existence of available infrastructure and proximity to major emission sources.

The second phase of the GEODISC Project further assessed the four most highly-ranked ESCCI sites, which included the Gippsland Basin (Gibson-Poole et al., 2006). This report reviewed all available Victorian basins against objective ranking criteria (Bachu 2000, 2003). According to the report, the offshore Gippsland Basin has the best overall potential for CO_2 storage because it has:

- deep sedimentary fill with numerous reservoir and seal horizons (including what appears to be a proven regional seal),
- moderate to limited faulting (generally confined to the deeper stratigraphic intervals)
- a relatively tectonically stable setting,
- mature hydrocarbon fields (many of which are reaching depletion)
- well-established infrastructure framework.

Overall, the basin ranked as “excellent” for CO_2 storage.

A key assessment of the State’s CO_2 storage potential was made by the Carbon Storage Taskforce (CSTF), which was established by the Australian Government under the National Low Emissions Coal Initiative in October 2008 to develop the National Carbon Mapping and Infrastructure Plan (Carbon Storage Taskforce, 2009). The Taskforce identified, graded and ranked potential integrated CCS projects across Australia and found that the Gippsland Basin has prospective storage resources of at least 31 GT. Clearly, the basin has the potential to store hundreds of years of captured CO_2, with a “potential CO_2 injection capacity of 50 Mtpa for 25 years”. The CSTF project demonstrated that the Gippsland Basin offered the largest potential in Australia for an integrated CCS project in terms of the existence of large stationary emission stations in close proximity to viable storage sites. Based on this encouraging assessment, a number of groups set out to explore storage options in the Gippsland Basin.

Onshore Victoria initiatives included an invitation in 2009 for industry to apply for Victorian State government Energy Technology Innovation Scheme (ETIS) funding for a CCS Storage demonstration. Industry groups developed firm work program proposals including the LASSIE concept and onshore GHG blocks were defined and gazetted. However no funding was awarded and no blocks awarded. Many of the intended plume paths were best developed by commencing offshore, with only the “head” of the plume reaching under the land.

The Victorian Government Geological Survey(GSV) developed CCS program initiatives to provide public knowledge foundations on Geological Carbon Storage generally in the Gippsland Basin resulting in a series of VICGCS (Goldie-Divko et al., 2009a; 2009b; 2010a; 2010b;VicGCS, 2010a; 2010b).

Collaborations with researchers from the CO2CRC and CSIRO led to a number of published and in-house studies (Root et al., 2004; Root, 2005; Bunch, et al., 2009a; 2009b; 2010; Bunch, 2013; Menacherry, et al., 2010; Bu Ali, et al., 2011).

These studies identified potential storage concepts and quantified the storage potential for a number of offshore sites - some still described as Environmentally Sustainable Sites for CO_2

Injection (ESCCI). These efforts were supported in part by dynamic modelling performed by CSIRO which provided some tangible conclusions for storage capacity but in general most proposals relied on wide ranging assumptions for “storage efficiency” (Van der Meer, 1995; Bachu and Adams, 2003; USDOE, 2007, 2010).).

CarbonNet work has progressed beyond generic storage efficiency estimates and calculated actual dynamic storage capacity for specific sites, however we recognise that in the absence of detailed site-specific information, a generic efficiency factor has value in the earliest stages of basin screening and preliminary storage quantification.

After the initial onshore GHG acreage offering, attention turned mostly to the offshore, where fewer potential issues were anticipated. As a joint exercise between Victorian State and Federal governments and their geoscience organisations (GSV and Geoscience Australia (GA), respectively), a plan was developed to examine storage potential on the southern flank of the Gippsland Basin, away from existing oil and gas assets. Three areas were delimited for Federal release and a new 2D seismic survey grid of 8,000+ line km laid out over this area to form a uniform and consistent dataset for interpretation of storage potential in this area. The 2D seismic survey was managed by GSV and acquired successfully in 2010.

2.3 Accelerated Geoscience Evaluation Program (AGEP-1)

The CarbonNet Project was initiated and staffed with a dedicated team with administrative and project management experience, and the assistance of advisors and consultants in key technical areas. Initial technical support was also provided by the Geological Survey of Victoria (GSV) and a joint program of activities was designed to provide background data and interpretations in the nearshore area, under the AGEP-1:

- Detailed mapping of a 15 Nautical Mile (~30 km) Coastal Strip Zone offshore.
- Chimney cube neural network study to look for any through-seal leakage.
- Fluid Inclusion Stratigraphy (FIS) study of 10 key wells to study fluid migration history.
- Aquifer modelling to quantify the adjacent onshore freshwater resource.
- Soil Gas Program to look for evidence of any petroleum seeps.
- SedSim - Fast Track depositional model to build a forward model of depositional facies.
- Remote Sensing Radiometrics Study to look for additional signs of surface seeps.
- Semi Regional Stress Study for Evaluation of Potential Loss of Containment.
- Airborne Gravity/Gradiometry Survey to provide structural detail in the nearshore Transition Zone (TZ) where seismic is ineffective/expensive.
- Fast Track Permedia modelling for plume studies of selected potential sites.

These studies are variously reported in Blevin et al., (2013); GSV (2010); Goldie-Divko et al., (2009a); (2009b); (2010a); (2010b); Gonsalves (2013); Green and Paterson (2012); McLean and Blackburn (2013); Michael and Paterson (2012); Miranda et al., (2012); (2013); VicGCS, (2010a); (2010b); O’Brien et al.,(2008); (2011a); (2011b); (2013).

2.4 Geoscience Evaluation Program Phase 2

By 2011, the CarbonNet Project had gathered sufficient regional data through the AGEP1 modules to permit the drafting of a detailed Site Selection and Appraisal Program documented as “Implementation Plan for Geoscience Evaluation Program Phase 2 (GEP2) in the nearshore Gippsland Basin”. In July 2011, a dedicated team of specialists was assembled to undertake the Work Program. The GEP2 Implementation Plan was comprised of 19 modules (described in more detail in the following section) and invoked periodic Peer Reviews.

In September 2011, the Victorian government formally applied for, and was awarded Flagship funding and set-up the CarbonNet Project, independent of the previous GSV framework. Soon after commencement, The State of Victoria applied for, and was awarded (in January 2012) the first offshore GHG Assessment permit in Australia – VIC-GIP-001. This permit was the closest inshore of the three 2010 offered areas and was taken up because it overlapped with the nearshore area of interest to CarbonNet.

3 CarbonNet Site Selection Process/Work Flow

The GEP2 Implementation Plan was designed and documented to take the project forward through Site Selection and Appraisal and included an indicative 5 year rolling Work Plan and Budget. It was intended that the Work Plan and Budget be reviewed and re-assessed annually to ensure adequate cash-flows.

In practice, a more general funding agreement and budgetary basis would have been more appropriate, with approved new specific activities placed in appropriate general expenditure categories such as "subsurface reservoir investigations", etc.

Table1: GEP2 Implementation Plan Modules

Module	Notes
Module 2.1: Prospect Inventory	Build and evaluate an inventory and progress the identified leads to Prospective Storage Resources through the identification and quantification of Qualified Sites.
Module 2.2: Structural/Stratigraphic Review over high-graded Leads	Review and reinterpret the nominal top six Prospective Storage Sites within the nearshore zone (up to 25 km offshore).
Module 2.3: Stratigraphic Petrophysical Characterisation	A comprehensive suite of petrophysical analyses for the interval Top Latrobe to total depth for all wells in the area of interest for the six selected sites.
Module 2.4: Reservoir Engineering Rock and Fluid Data	Available rock and fluid data from wells in the area of interest collated and screened to provide the reservoir properties that are necessary for injection simulation modelling.
Module 2.5: Seal Capacity Laboratory Data	Update the VICGCS Containment studies (including seal capacity calculations from Mercury Injection/Capillary Pressure Studies, Cap Rock Isopach data and Quantitative Mineralogical Analysis) for the Lakes Entrance Formation in the nearshore area and investigate intraformational seals.
Module 2.6: Geocellular Static Model	The high-graded leads are to be characterised by a fully characterised geocellular static model to petroleum industry standards.
Module 2.7: Dynamic Model and Injection Plume Volume Simulation	Dynamic flow simulation to study injection rates, CO_2 flow behaviour, migration and plume development.
Module 2.8: Work-shopped Final Leads Inventory (Risked and	The Final Leads Inventory will be Risked and Ranked with Peer review input.

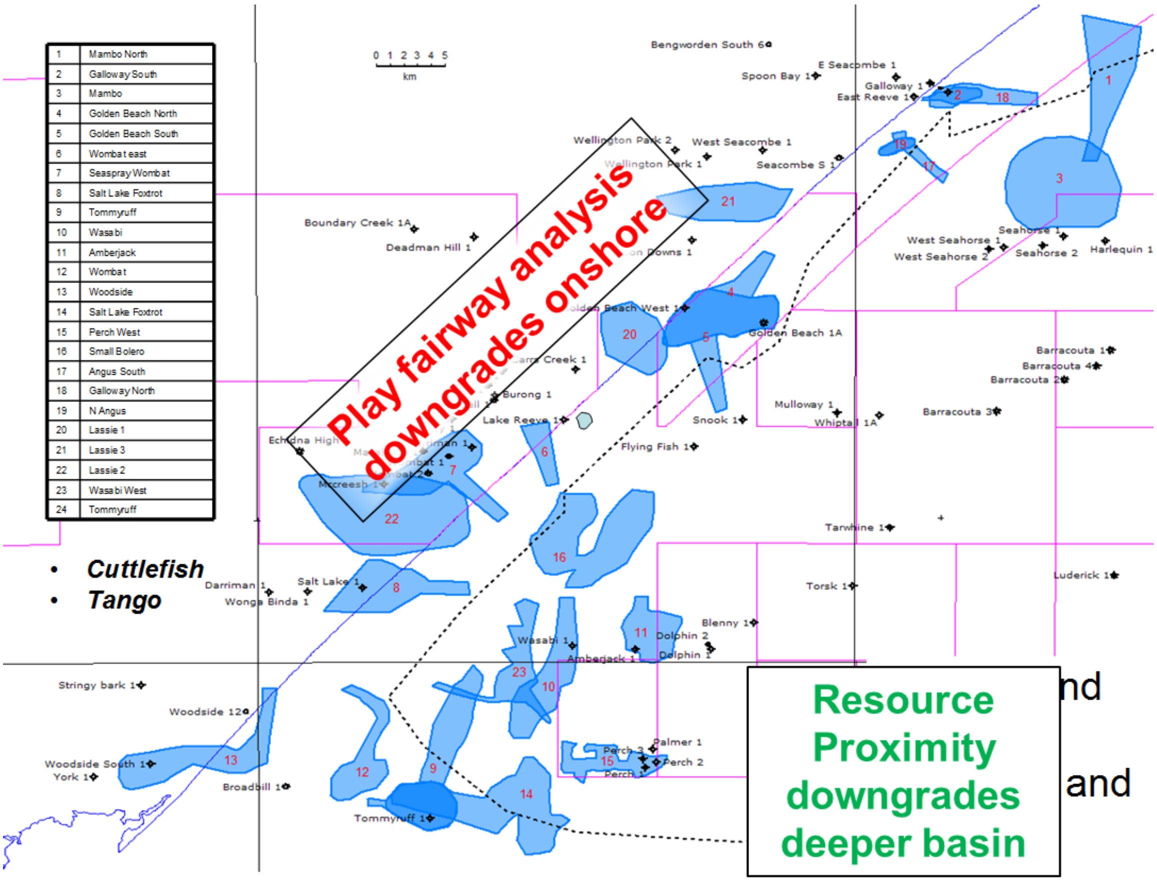
Ranked)	
Module 2.9: Seismic reprocessing	The seismic coverage of the high-graded leads will be considered for reprocessing.
Module 2.10: Regulatory Administration and Baseline Reservoir Studies	Water, soil, air and habitat monitoring compliance with State and Federal Regulations. Review methodology and technology for baseline and ongoing reservoir monitoring studies.
Module 2.11: Seismic Operations	New seismic data may include small local surveys over a nearshore injection site of dense 2D or 3D data.
Module 2.12: Nearshore and Offshore Drilling Feasibility and Planning	Consider the relative suitability of using horizontal as opposed to vertical injection wells (from a drilling engineering standpoint) and develop well designs and material selection, formation evaluation and well injectivity testing. This module will also prepare fully documented Well Drilling Proposals for optional Nearshore Research Appraisal wells.
Module 2.13: Pipeline Feasibility	Commence feasibility studies of transport options to deliver CO_2 to the sites.
Module 2.14: MMV Planning	It is proposed to utilise the measurement, monitoring and verification (MMV) experience of other storage operations worldwide to develop an MMV Program for CarbonNet’s activities.
Module 2.15: Optional Nearshore Appraisal wells	Drill, and acquire formation evaluation data for reservoir and seal characterisation including extensive coring for SCAL and PVT analysis and conduct fluid injectivity tests in close proximity to Nearshore sites.
Module 2.16: Optional Nearshore Injection Well	Drill and acquire formation evaluation data for reservoir and seal characterisation, including extensive coring for SCAL and PVT analysis and complete the well as a CO_2 Injector for a minimum injection rate of 1 Mtpa (2-4 Mtpa if possible).
Module 2.17: Optional Offshore Appraisal Wells	As for GEP 2.15, in close proximity to Offshore sites.
Module 2.18: Southern Flanks Seismic Interpretation	Receive 8,000 line km 2D GDPI10 seismic data processed during 2011 and make a full structural and sequence stratigraphic interpretation to build the Leads Inventory for potential storage sites on the Southern Flanks of the Gippsland Basin.

The GEP2 evaluation program was not originally designed to fulfil the requirements of DNV-RP-J203, and the recommended practice had not been published at that time. However, a number of QC and Peer Review steps were envisaged and the DNV Recommended Practice was later added to this list.

GEP2 envisaged a very large amount of activity in a short timeframe and in hindsight it is clear that GEP2 contained tight timeframes that proved unrealistic in practice. The details of the CarbonNet process, and the evolution through GEP2 to the present day are detailed in subsequent sections of this paper.

Nonetheless, GEP2 set out a methodical approach to evaluating the portfolio of storage options and a transparent process and reporting arrangements to non-technical management and sponsors of the Project.

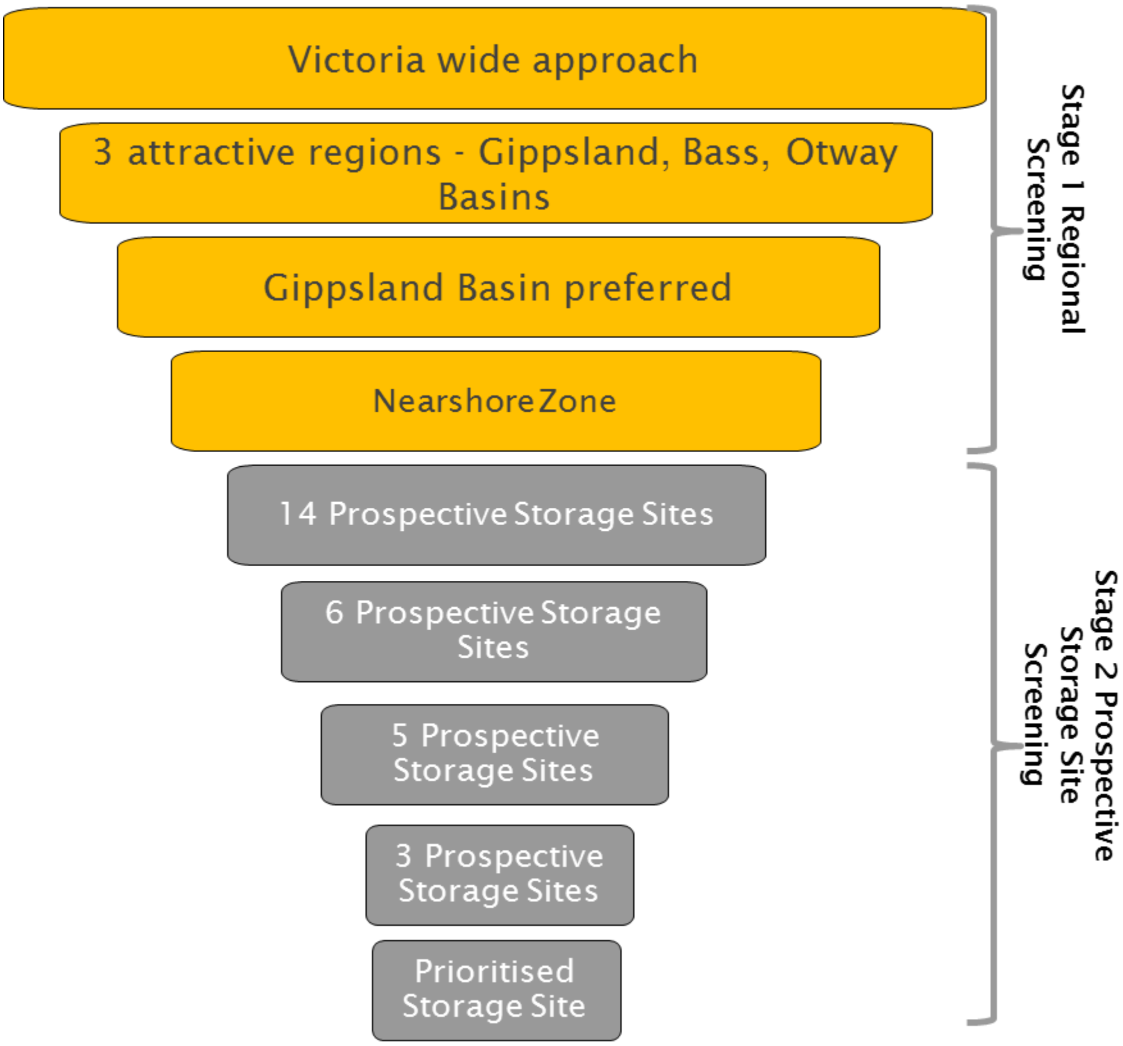
Figure 4: The initial CarbonNet portfolio of 14 geographic areas. Note: sites Cuttlefish and Tango are additional sites, not represented by shapes on this map



During the first 2 years of the GEP2 program, the prospect inventory of potential sites was risked and ranked. A steady progression of high-grading and winnowing reduced the shortlist from 14 locations (Figure 4), mostly with two stratigraphic targets (a total of 24 3D storage volumes) to 6 viable sites by the first Peer Review. Many sites have overlapping injection options with different degrees of updip migration or different vectors of approach to a structural culmination. Some sites were envisaged onshore in early stages of the project, but play fairway analysis downgraded these sites. A wide variety of trap types were deliberately collected in the portfolio, including Structural traps (fault and anticline), Aquifer traps, Stratigraphic traps, and small depleting oil and gas fields. No sites were included in the deeper basin due to proximity to producing petroleum resources. Future sites may be viable in the deeper basin when petroleum fields are depleted.

This was further reduced to a shortlist of three sites, each with a secure minimum capacity of 25 Mt at the second Peer Review meeting (ISPR) and ultimately the Prioritised Site (with a capacity now demonstrated to be 125 Mt) was selected after a series of in-house and facilitated workshops on potential commerciality and non-geoscience aspects of the sites (Figure 5).

Figure 5: Site Selection process for CarbonNet



The screening process took place in two stages. In Stage 1, regional screening identified the nearshore Gippsland Basin as the best area to search for near-term commercial storage sites. In Stage 2, CarbonNet was set-up and conducted a portfolio-based search, ultimately focussing on a single prioritised site.

Not all of the low-graded sites were discarded. Some have value as add-on sites in the future, or represent alternative sites with similar characteristics to others retained in the shortlist. An important requirement of a viable portfolio is to have independent risk elements for the sites, so that if two sites are too similar in concept and geological characteristics, they are likely to succeed or fail together. To maintain a healthy and diverse portfolio, one must deliberately choose to downgrade some sites that essentially duplicate the ones that are retained – but in the future if a retained site is proven for storage, the duplicates can be revived as highly viable additional sites.

Despite the selection of a single prioritised site, the CarbonNet Project has made applications for three new GHG Assessment permits, covering each of the top three sites, in order to preserve the optionality and portfolio breadth required for a robust commercial project. Should the understanding of key storage risks change in the light of new data from exploration wells or seismic data, the project need not wait for another multi-year regulatory/licencing cycle to obtain a second exploration site.

3.1 Static and Dynamic Modelling

The CarbonNet Project has built three full generations of Static Models. In the first generation, a large-scale coarse model of the entire nearshore was constructed to provide a context for the multiple local fine-scale models required – one for each site, or cluster of sites. At all subsequent stages, only fine-scale models were constructed.

At each stage, models were designed to be fit-for-purpose and were generated using horizon and fault frameworks in depth, isopachs of key reservoir facies, and geostatistical parameters derived from well petrophysics and 3D seismic analysis of geobody extents, aspect ratios, and orientations for both reservoirs and seals (Golab et al., 2013). The models evolved in complexity over time, but were designed not to be excessively complex. As an example, faults were generally verticalised in the models, rather than explicitly mapped as dipping surfaces.

However, as discussed by Gibson Poole et al.,2009, the requirements for dynamic modelling of CO_2 injection include the consideration of long-distance migration and significant vertical penetration of the stratigraphy by the CO_2 plume. Therefore these models are more complex and extensive than an equivalent oilfield model would be. The presence of extensive coals also required a consideration whether they would contribute to or detract from conventional reservoir storage of CO_2 (e.g. Golding et al., 2013, Pinetown 2013).

3.1.1 First Generation

Static modelling of six prospective sites commenced after the preliminary Prospect Inventory Ranking peer review workshop held in October 2011. The CarbonNet team developed in-house high-resolution PETREL™ static models to honour 50 offset wells and 2D and 3D seismic facies analysis. These models were used to evaluate possible available pore space for static capacity assessment and for dynamic simulation to estimate dynamic structural storage capacity of individual sites. Sediments of the Cobia Subgroup and upper sections of the Halibut Subgroup were modelled. However, the structure at top Cobia under the regional seal was the main assessment object during that stage and therefore only sediments of the Cobia Subgroup were finely layered and modelled in any detail. As an example, for one site, the model covers 608 km^2 and is comprised of 28 million cells and 59 layers. This model was used for the first dynamic modelling (GEP2.2 to GEP2.8) for the high-graded sites and was presented to the second peer review panel (May 2012).

3.1.2 Second Generation

This model was constructed after the selection of three high-graded sites at the Independent Scientific Peer Review (ISPR) workshop 16-17 May 2012 (further details presented below). This builds on the first generation model, and incorporates recommendations of the ISPR panel workshop and focuses on deeper reservoirs that can be more efficiently used for CO_2 injection/storage. Accordingly, the second generation PETREL™ model was designed to evaluate reservoir sands situated in the Upper Halibut Subgroup and overlain by shale and coal sequences of the Traralgon Formation (Hoffman 2015b) and to assess Middle and Lower Halibut reservoirs for CO_2 injection.

The second generation model included:

- more-sophisticated analysis of seismic and well facies and petrophysical parameters.
- better analogues for reservoir and seal facies.
- improved depth surfaces and faults.
- model deepened to base Halibut Subgroup.
- correlation of units across a varying distance-scale.
- seismic sequence stratigraphy study.
- regional seal analysis study.
- review of coal geology of onshore Latrobe Group.

The modelling area covered an area of 926 square kilometres and the 50x50 metres grid totalled over 55 million grid cells. Second generation dynamic models were run using this second generation of the static models (October 2012).

A sub-generation model (2.2) was also generated for CSIRO regional aquifer modelling (Ricard et al., 2015). The model needed to cover both onshore and offshore regions to delineate the meteoric water wedge adequately. CSIRO used TOUGH2 software for dynamic aquifer modelling, which has a limit on model complexity, therefore a coarser model was generated with only 33 layers, and upscaled to a 100x100 metres grid, reducing the total number of grid cells to 3.8 million.

3.1.3 Third Generation

The main phase of modelling has involved the third generation of models over the prioritised site. New models have been constructed to better characterise the site and to incorporate newly interpreted data. The initial 3.1 generation model was evolved to versions 3.2 and 3.3 as more detailed seismic interpretations were developed or to meet specific needs, such as more sophisticated aquifer modelling.

Second generation models highlighted that Lower Halibut sands (below the “KT” shale) have their permeability reduced due to cementation (mainly dolomitic cement) and are not suitable for injection. Therefore, model 3.1 focused on the Middle Halibut where good permeability (injectivity) was suggested by the previous model. New seismic interpretation allowed more detailed modelling of the T2 key seal. Seismic reinterpretation also identified a new coal layer within the offshore area that downlaps onto top Halibut, resulting in an improved well-to-well correlation and additional intra-Halibut control surfaces.

Additional core analysis from wells within and around the modelling area were reviewed to better represent permeabilities of the principal sand facies and/or sand intervals. As a result, a more detailed porosity-permeability relationship was recognised.

The model approximately covered an area of 900 square kilometres and gridded to and average cell size of 50x50m. A total of 222 layers were generated based on the variation in lithological facies, which range from a few centimetres to ~10 metres. Total model size was 82 million cells. This model was used for CarbonNet’s latest dynamic modelling (February 2014 onward).

Model 3.2 updated the depth conversion and well ties, and improved the vertical resolution for zones where Injection, migration, accumulation and storage of the buoyant CO2 are expected to take place. A better representation of the internal structure of the Key Traralgon T2 seal was correlated with onshore Traralgon coals after Holdgate (2012). A 50x50m cell size grid with a total of 59 zones and 266 layers was created, and totalled over 98 million grid cells. An expanded area model 3.3 with 161 million cells was also generated for an updated aquifer modelling study, but supplied in a downscaled version

3.1.4 E100 Dynamic Modelling

The 1st Generation Static models for 6 sites were upscaled to 2-4 million cellular ECLIPSE100™ models for CO_2 injection and capacity simulations over 250-1000 year time periods. Benchmarking was provided by independent modelling by CSIRO (using TOUGH2™) and The Netherlands Organisation for Applied Scientific Research (TNO)(also using PETREL-ECLIPSE™). The three sets of modelling were reviewed on 16th and 17th May 2012 at an Independent Storage Peer Review (ISPR) – see below, under "Peer Reviews" for details.

The principal aim of this phase of modelling was to demonstrate an assurance of capacity at a minimum of 25 Mt per site. There was no requirement to optimise injection schemes or maximise storage volumes, but in the course of the modelling it became clear that for some sites the maximum capacity was likely to be significantly larger than 25 Mt. Other sites failed to achieve 25 Mt by a large margin and it became clear that a more simple volume-scoping exercise could have eliminated several possibilities, without dynamic modelling.

For the CarbonNet area of interest, a simple rule of thumb was ultimately developed that for the thick reservoirs of the Latrobe Group, with nett:gross of 60%+ and average porosity of 20-27%, a minimum of 1/3 of a cubic km of gross rock volume was required in a structural closure to store 25 Mt of CO_2. For stratigraphic or aquifer traps, a larger volume would be required, depending on storage efficiency, initially assessed to be nominally 4% - later tested by detailed dynamic modelling which derived actual storage capacity for highgraded sites. Applying this deterministic volume requirement proved to be a decisive measure of commercial potential for a storage structure. Many of the previous portfolio candidates proved to be an order of magnitude too small for commercial storage, although they may have been suitable for a pilot or technology demonstration project. Of the original portfolio of fourteen sites, only five structural sites and one aquifer site passed this volume threshold, although a number of additional aquifer sites were newly identified that had not previously been mapped.

Model boundary conditions were set for the regional context – an almost infinite aquifer at the boundaries of the model, or a constant pressure boundary, depending on the software and modeller.

At this stage of modelling, parameter sensitivity was not addressed. Geologic static models were built and checked against well and seismic data, but only a single realisation of each model was populated, and bulk petrophysical properties were not varied as sensitivities. However, with two or three independent models for each site, built at different cell sizes, with different assumptions, and different software, a first view was obtained of how plume behaviour might vary in different circumstances.

Typically, an injection site was defined crestally in a structural site, with the aim of symmetric fill of the storage volume, and for aquifer traps a relative downdip location was selected for injection. In some cases, the injection point was adjusted up- or down dip if the site did not appear to be well-utilised (the plume either escaping laterally at the downdip end, or not enough of the dip slope being used). For some obviously small structural sites, an attempt was made to combine aquifer and structural storage by injecting downdip, but the outcome was generally unfavourable with the small structural traps (1-5 Mt capacity) being overwhelmed by the 25 Mt plume, even if large amounts of plume were retained downdip by dissolution or residual saturation.

3.1.5 E300 Dynamic Modelling

During 2013, multi-scenario E300 compositional dynamic modelling was run over an upscaled 3.9 million cell model (at the prioritised site) derived from static model generation 3.1. Injection scales of 25, 80 and 125 Mt were modelled to assess CO_2, pressure, and pH plume development and stabilisation, over time periods up to 1000 years post-injection. An upscaled version of an areally expanded static model version 3.3 was integrated into a semi-regional hydrogeological model developed under contract by CSIRO using TOUGH2 to assess regional aquifer pressures and salinities. This model extended approximately 25km both shoreward and offshore and demonstrated no significant adverse impact on aquifer pressure, pH and salinity in the regions of onshore water utilisation and offshore petroleum operations.

The pressure boundary conditions of the aquifer were analysed in more detail. Rather than a nominally infinite aquifer, evaluation of published data on the giant gas fields Marlin and Barracouta (Hart et al., 2006) allowed a determination that the minimum aquifer volume sensed by each field was $0.6*10^{15}$ litres. This was a minimum assessment because two relatively adjacent fields supplied the pressure and production data and they were both assumed to be independent, but mapping of the gross aquifer volume indicated a probable overlap of these aquifer volumes, and hence a probable pressure interaction over the production timescale.

A range of injection locations, rates, durations, and total volumes was trialled to optimise storage for each site, and to match with the evolving Project scenarios for pipeline transport from potential upstream sources over the 25-30 year life of each storage site. These trial scenarios were developed into one or two key injection scenarios for each site to use as the Basis of Design and for subsequent development of an Appraisal Plan.

Initial sensitivities of key seal and reservoir parameters were tested to confirm long term containment over 1000 years of modelling and a scope of future dynamic sensitivity modelling was defined to enable exploration of the range of potential plume paths as required by Australian legislation for a “Declaration of Identified Storage Formation” (See Hoffman 2015a for more details).

4 Risk Analysis

Addressing and reducing risk is a key aspect of the DNV-RP-J203. The Project has taken a broad, project-wide approach to risk and has developed a series of whole-of-project risk registers. Within this context, specific subsets of risk have been developed for specific activities or subsets of the project. Examples of these include operational risk assessments for mobilising and operating drill rigs and seismic vessels, pipeline construction and operating risks, etc. in order to address the entire storage risk. Risk assessment has been updated to follow the methodology of Bourne et al., 2014, and be fully consistent with DNV-RP-J203.

For the CarbonNet Project, storage is defined to begin at the wellhead and to cover all operations and situations that relate to the well and the subsurface. This includes the field operations of the appraisal program, the future development phase, and ultimate transition from post-injection to secure abandonment and handover to the government.

The CarbonNet Risk Management Plan provides a whole-of-project context for risk thresholds and definitions on likelihood and consequences. These whole-of-project scale risks include the key Geoscience and site-specific risks identified by detailed site studies. There is a particular emphasis placed on making risk evaluation consistent across the project to ensure that risk elements are neither omitted nor duplicated, and that risk treatment is consistent in different project areas.

Early CarbonNet site-specific risk analysis incorporated CarbonNet whole-of-project risk registers comprising:

- a preliminary Risk Register in June 2011, which was included in the GEP-2 Implementation Plan.
- generic Storage Site Selection risks (not site specific), workshopped in-house in meetings facilitated by NCD Risk Management Consultancy on 8/2/12 and 10/4/12.
- CarbonNet Risk Management Plan and register.

The project has conducted four major Storage risk reviews for the prioritised site; these were the FEPs version1 Risk Review of 2012 (Quintessa, 2012), the Senergy-facilitated Preliminary Risk Review of May 2013 and the Updated Risk Assessments of April 2014, facilitated by Lighthouse Pty Ltd.

In September 2014, the April 2014 risk report for the prioritised Storage Site was updated in-house to be more fully conformable with the expectations of Recommended Practice DNV-RP-J203 by application of the Bowtie method of risking (Bourne et al.,2014).

CarbonNet Project Storage risk can be described in four key classes:

1. Intrinsic Subsurface Risk driven by uncertainty about exact subsurface conditions:
    a. Nearshore approach of the injected CO_2 plume and its potential affects.
    b. General subsurface uncertainty - characterisation of which would allow better prediction of item (a).
    c. Seal integrity, especially in crestal areas where the highest buoyancy pressures will occur.
    d. Integrity of the existing wells on the structure.
2. Operational risk associated with field appraisal activities to reduce subsurface uncertainty.
3. Risk of obtaining approval/support from communities, stakeholders, and regulators.
4. Risk of future facilities design and operation – in particular when future wells are drilled on the structure, there will be design and operational risks associated with them that must also be addressed.

The site characterisation plan was defined to focus on items 1 (a to d), item 2, and item 4 as it relates to new wells which are all specific risks of containment. By addressing these risks, it is anticipated that there will be an associated reduction in the risk of not receiving acceptance (item 3).

In most cases these subsurface risks are driven by subsurface uncertainty and have been identified as data gaps in the appraisal plan and will be addressed by further data acquisition from seismic and/or drilling, including the acquisition of physical rock and fluid samples, and petrophysical logs.

5 Peer Reviews

Peer review of the geoscience and reservoir engineering work of the GEP2 Work Program was planned as an important element of quality control and an opportunity for external experts and informed observers to offer technical feedback. Peer review took place at various levels:

5.1 Internal reviews

Internal project peer review took place in two distinct ways:

1. Between the Storage Director and Storage Team professionals. These discussions were generally robust and conducted at a deep level of geoscience understanding between well-informed experts. The advantage is a good analysis of geoscience issues, but a weakness is an inability to see outside the geoscience “frame” and a possibility that important external considerations are not adequately considered.
2. Between Storage Team and the wider project and its management. This included technical presentations and discussions of work assumptions and outputs and included in-house and externally facilitated risk workshops which identified data gaps /risks and served to modulate the storage work flow objectives. The advantage of these interactions is the ability to include a wider range of world views and understanding of wider non-technical issues. The corresponding downside is a possibility that non-technical factors have undue influence on technical decisions. However, in any project such different viewpoints exist and must be reconciled appropriately.

5.2 External reviews

The CarbonNet Project identified a range of Australian and International experts (with review experience on CCS projects in North America, Europe and Australia) to include on external peer review panels. They were invited to support significant workflow milestones.

5.2.1 First Peer Review panel

The first peer review panel met on 21st October 2011 and was comprised of 12 CO_2 storage experts (predominantly Australian) from research institutions, government advisors, industry and independent consultants. This workshop endorsed selection of six prospective sites from an overall inventory of 24 storage concepts for ongoing consideration.

The Peer Panel endorsed CarbonNet’s methodology and the experts conducted an independent ranking exercise. The workshop assessed the sites purely from a geoscientific standpoint. In general the workshop concluded that offshore sites being 10-20 km from the shoreline offered larger, lower risk and more pragmatic solutions (in terms of long term geoscientific monitoring) than the coastal sites.

Workshop feedback highlighted several points:

1) The Panel endorsed the probabilistic methodology presented by CarbonNet preferring it to a more basic deterministic assessment, also offered.
2) It may be premature to exclude sites from consideration on a geoscience assessment only, before an extra layer of legislative and technical “do-ability” was added.

3) The concept of a “site” or “prospect” should be extended to consider those features that are coupled into a hydrodynamic system with spill from one structure moving to another structure in the chain.
4) Not enough consideration had been given to non-structural or saline aquifer traps where an extended CO_2 plume would develop, streaked across a large volume of reservoir, leading to ultimate sequestration by residual trapping or dissolution.
5) CarbonNet assumptions and methodologies (both deterministic and probabilistic) are probably highly conservative and therefore significantly larger volumes/masses of CO_2 may be expected to be stored.
6) A factor of greatest uncertainty at this stage is the (aquifer) displacement efficiency that will be achieved.
7) There is some uncertainty of the extent of the wedge of low-salinity meteoric water aquifer extending into the Latrobe Group sediments of the Gippsland Basin.
8) MICP data suggests limited seal capacity may exist on the southern margin of the basin.
9) The Gippsland Basin has a history of depth conversion issues related to Miocene channels. These must be explicitly mapped and caution applied to small depth closures inferred from seismic time mapping.
10) Nearshore (coastal) sites generally carry higher risk due to small sizes and poor definition of structural closure.

The six sites were carried through a series of static and dynamic modelling exercises in-house to demonstrate storage capacity and plume behaviour. Independent plume models were also commissioned from TNO and CSIRO (see above) to offer an objective view of plume evolution.

5.2.2 Second Workshop

After a batch of technical work to address the feedback from the first Peer Review, and to incorporate detailed CarbonNet dynamic modelling (as discussed above), a second Independent Storage Peer Review (ISPR) Workshop was hosted by the CarbonNet project on 16-17 May 2012. A panel of 10 experts was assembled in order to conduct the peer review. The review was facilitated by a petroleum expert with an industrial track record of facilitating risk and prospect review meetings. It was conducted under the Terms of Reference for an ISPR panel recommended by the Global CCS Institute in 2011.

The ISPR reviewed the integrity of site characterisation and modelling assumptions and outcomes and developed a ranking of the six high-graded sites identifying the top three sites for certification as Contingent Storage Sites. The workshop also developed a list of recommendations requiring additional technical work which was carried out to the satisfaction of the ISPR over the ensuing six months.

A key objective of the workshop was to review proposed new work modules, including sub-regional geoscience evaluation work, and the results of site-specific static and dynamic modelling. Feedback was therefore collected from the panel on the adequacy of the datasets, the methodologies used, and the interpretations made during the subsurface evaluation to date.

A second key objective of the workshop was therefore to provide an external expert perspective as to whether a site was adequately a) “technically mature”, and b) “material” in terms of the CarbonNet project selection criteria (storage capacity of 25-125Mt and injection rates of 1-5Mtpa), and therefore a genuine candidate for appraisal.

Looking forward from the ISPR workshop, the CarbonNet team focussed further evaluation work on those three sites that were justified in progressing to the DNV-RP-J203 M2 milestone, at which point a prioritised storage site (or sites) was to be selected for appraisal, subject to environmental and economic screening.

Accordingly, independent specialists were contracted (for seismic sequence stratigraphy, seals, coal stratigraphy, sedimentology) and additional studies made on new bathymetry data (LiDAR) for seafloor anomalies and seismic velocity analysis. E300 compositional modelling was also commenced. The work was finalised to the satisfaction of the ISPR in February 2013.

5.2.3 Project reviews by third party experts and consultants

Project reviews by third party experts and consultants also formed an important peer review of and technical input to the storage work stream activities at various stages over the period 2011-2014. At this early stage of deployment of CCS technology worldwide, the relevant expert knowledge resides with a diverse set of institutions and individuals, and it is important for a new project to access and integrate the existing knowledge base, rather than trying to innovate independently. These interactions included discussions and service contracts with staff and experts of various Australian and international organisations:

- the Geological Survey of Victoria and Geoscience Australia working on VICGCS and national CCS Projects.
- CSIRO and TNO during the screening stage discussion and modelling.
- CO2CRC experts during CRC Research Symposia, various Victorian State CO_2 storage initiatives including the development of the CRC Application for EIF funding during 2013.
- Flagship and peer-projects in Australia known as the SW Hub, ZeroGen, Wandoan, Darling Basin and Otway Projects.
- international peer/CCS consultants, administrators, researchers and operational geoscientists and engineers (including but not limited to British Geological Survey, UK Crown Estate, Universities of Nottingham and Edinburgh, British Petroleum, Statoil, Shell International and Chevron) risk workshop discussions facilitated by CCS experts from Senergy International.
- Parsons Brinckerhoff (PB), and PB Energy Storage Services (PBESS) during analysis of the interface of geological storage/ reservoir engineering Basis of Design with whole-of-project Basis of Design particularly at the transition from transport pipeline to storage wellhead and well design.
- Schlumberger Carbon Solutions during the Appraisal planning stage.

External Project reviews were also conducted as part of the DNV certification process (see later sections for full details). This included not only specialists working within DNV but also third party sub-contractors with specialist skills in MMV, geochemistry and geomechanics.

6 International Best Practices and Certification

As an addition to the peer review contained within the original GEP2 Implementation Plan, the CarbonNet Management Team made a project-level decision to commit to an external Certification Service to provide an independent and informed technical audit and to provide further stakeholder assurance. A review of Best Practices available internationally concluded that comprehensive guidelines exist in North America such as:

- US DOE IEAGHG Methodology for Development of Carbon Sequestration Capacity Estimates Appendix A.
- NETL Best Practices for Site Screening Site Selection and Initial Characterisation for Storage of CO_2 in Deep Geological Formations (DOE/NETL. (2012)).
- Carbon Sequestration Leadership Forum (CSLF) Comparison between Methodologies Recommended for Estimation of VCO_2 Storage Capacity in Geological Media (CSLF, 2008).
- CSLF Phase II Final Report from the Risk Assessment Task Force identified key areas for attention to provide performance indicators (Mckee 2012).
- A Technical Committee on Geological Storage of carbon dioxide, which is a joint Canada-USA Technical Committee, with support from IPAC-CO2 Research Inc, commenced joint development of a best practice standards for CCS to be submitted to the Canadian Government. The first edition of a report CSA Z741-Geological storage of carbon dioxide, was developed over the time frame 2010-2012.

The main issue is that North American Recommended Practices are designed for situations not prevalent in Australia. For example, the number of wells drilled in State of Texas pre-1930 (before effective legislation) number in the 100,000's whilst the total of all wells drilled in Australia under a Petroleum Act (post 1950's) is only a few thousand, and documentation and completion practices are generally to a high standard. North American ground water legislation is also very different from that in Australia.

Comprehensive guidelines also exist in Europe such as Chadwick et al., 2008. The European Union commissioned DNV to facilitate a Joint Industry Project between member countries and industry to produce guidelines for geological storage of CO_2 in the form of the CO2QUALSTORE and CO2WELLS documents produced in 2010 and 2011 respectively. This led to the development of the formal "European Commission Guidance Documents 1, 2, 3 and 4 Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide" (EU. 2009, 2011a, 2011b) – about the same time that CarbonNet was writing the GEP2 Implementation Plan. The UK developed its own guidelines over a similar timeframe e.g. Senior (2010).

In contrast to North America and Europe, comprehensive guidelines do not yet exist in Australia at a national or state level. In 2011 the CO2CRC conducted a review of existing international best practice manuals for CO_2 storage and regulation as a first step towards developing an Australian-specific recommended practice. The review highlighted the DNV documents (CO2QUALSTORE and CO2WELLS) as being the more detailed with comprehensive discussion and generally generic.

In April 2012, DNV produced a new Recommended Practice (RP) of geological storage of CO_2 in the form of the DNV-RP-J203 which was built by merging (and enhancing) the CVO2QUALSTORE and CO2WELLS documents with another DNV product (CO2RISKS).

The CarbonNet Project issued an RFT for Certification services in 2012. Eleven proposals were considered from a wide range of international service companies, geological survey and scientific organisations, and risk specialists. DNV-RP-J203 was selected on the basis that it:

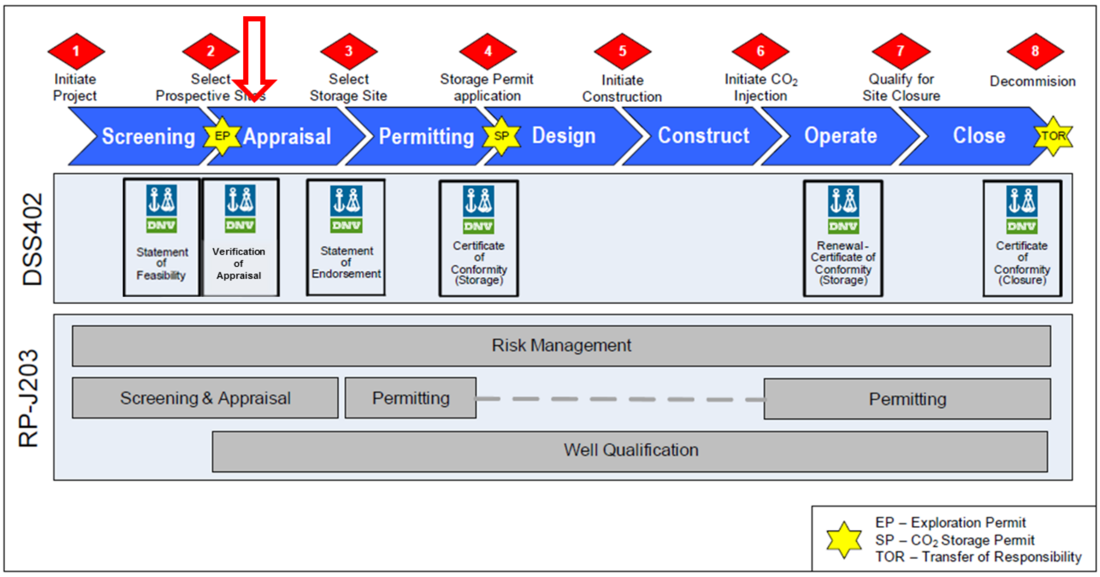
- Is commercially available and published.
- Has been peer reviewed by industry and government including Australian Federal Government.
- Is applicable to both onshore and offshore environments.
- Is risk based.
- Is not overly prescriptive.
- Is transparent and includes International Peer Reviews.
- Is administered by industry-experienced and professional geoscientists and engineers.
- Has received partial bench testing during the Shell Quest Project.
- Was considered to offer Value for Money, in a government procurement context.

It must be noted, however, that the CarbonNet Project represents the first occasion when the full RP has been field-tested and that some issues might be identified during the application of the RP to a near-shore scenario that was not specifically envisaged in the drafting of the RP.

7 DNV stages of certification

The certification process laid out in DNV-RP-J203 (DNV, 2012) / DNV-DSS-402 (DNV, 2013) (Figure 6) envisages a series of steps or stages at which project reviews would take place, and the process and results to date be checked against DNV-RP-J203 and certified, if deemed acceptable.

Figure 6: DNV-RP-J203 Certification process for CarbonNet



The standard DNV service delivery (DSS402) has been modified by the addition of a pre-Appraisal Verification step to confirm that the Appraisal plan meets all Legislative, Project and Certification requirements. The CarbonNet Project is currently at the position of the red arrow, having verified the Appraisal Plan for the prioritised storage site.

The four key steps are defined in sections C200 to C500 of DNV-DSS-402:

C200 Statement of Feasibility (Milestone M2)

> ***"DNV may issue a Statement of Feasibility for a storage site or portfolio of storage sites after verifying that such storage sites have been evaluated by an operator in accordance with DNV RP-J203, Section 4.2, "Screening", and fulfils the requirements given in the Screening Basis.***
>
> ***By issuing a Statement of Feasibility DNV considers the storage site(s) conceptually feasible and thereby suited for further development and qualification according to DNV RP-J203."***

C300 Statement of Endorsement (Milestone M3)

> "***DNV may issue a Statement of Endorsement for a storage site after verifying that the Appraisal work has been conducted in accordance with DNV RP-J203, Section 4.3, "Appraisal", and fulfils the requirements given in the Appraisal Basis.***
>
> ***By issuing a Statement of Endorsement DNV considers that the storage site and Well Engineering Concept have the required characteristics for injecting the specified mass of CO_2 (tonnes) over the specified duration of the project (years) and storing it on a long-term basis. The mass of CO_2 and duration of injection shall be specified in the Appraisal Basis."***

C400 Certificate of Fitness for Storage (Milestone M4, renewable at M6 and M7)

> ***"DNV may issue a Certificate of Fitness for Storage in order to confirm that the Storage Development Plan for a specified storage site is in accordance with DNV RP-J203 and that DNV considers the storage site as fit for service subject to the constraints of the Plan."***

C500 Certificate of Fitness for Closure (Milestone M7)

> ***"DNV may issue a Certificate of Fitness for Closure in order to confirm that the Closure Qualification Statement for a specified storage site is in accordance with DNV RP-J203 and that DNV considers the storage site as fit for closure subject to the constraints of the Statement."***

In addition, an optional extra service is Verification. This is defined (D100):

> ***"The verification service differs from the certification service in terms of the scope of verification. Whereas the certification service includes certification against a scope dictated by the document DNV RPJ203, the verification service allows for verification against a scope determined by the client.***
>
> ***The scope of the verification could be parts of DNV RP-J203, other standards or internal procedures provided by the client."***

7.1 Stage 1: Statement of Feasibility.

As described above, DNV Milestone M2 requires analysis of a portfolio of storage sites and their evaluation through a screening process. The requirement is that a screening basis document is produced which sets out the requisite conditions for each site in the portfolio and that they are then screened against those conditions and the resulting high-graded sites are presented as the outcome. It is anticipated that all sites which pass screening are conceptually feasible for development and suited for further investigation.

CarbonNet presented a screened portfolio of 3 sites for consideration as Contingent Storage Sites. CarbonNet had already built static models for each of these and had run dynamic models and consequently the three sites were more than adequately characterised for this stage. After review against DNV-RP-J203 requirements (see below), DNV provided a Statement of Feasibility in January 2013 for the portfolio of three sites as the first stage of the DNV-RP-J203 / DNV-DSS-402 certification process.

A key step in the DNV GL Recommended Practice is to define the Screening Basis – the conditions required for adequate, safe, long-term storage of CO_2 to be viable, and the first step in site characterisation. Once the basis is defined, then it is straightforward to check potential sites against the quantitative and qualitative requirements in the screening basis. Sites which fail to meet the requirements can be rejected. Sites which do meet the requirements can be ranked in a prospect seriatim according to how well they satisfy the quantitative requirements.

7.1.1 Screening Basis Document (DNV J203)

The Screening Basis Document "defines the requirements to be fulfilled during the project Screening Stage in order to be able to regard a storage site as prospective and thereby qualified for appraisal."- DNV-RP-J203 4.2.2.

This document defines a series of criteria/thresholds that can be used to screen possible storage sites and allowed CarbonNet to define which ones are prospective.

For the CarbonNet Project the following screening criteria were applied:

Minimum Capacity

The minimum project requirement of total capacity is 25 MT storage, and capacity up to a total of 125 Mt is desirable.

Each of the identified three prospective sites met this requirement.

Minimum Injectivity

The minimum project requirement of annual injectivity is 1 Mtpa, and injectivity of up to 5 Mtpa for each site is desirable.

Capacity and Injectivity requirements are already defined in the CarbonNet storage implementation plan. These may be viewed as "commercial" thresholds below which a prospect is "non-commercial". Each of the identified three prospective sites met this requirement.

Injection Depth

Injection depths for all targets are to be deep enough for the CO_2 to be supercritical in-reservoir.

Under Gippsland Basin temperature and pressure conditions, CO_2will be supercritical in-reservoir at densities between 300-500 kg/m3 at the prospective injection points and a minimum injection/storage depth of 800-850m. Each of the identified three prospective sites met this requirement.

Primary Seal

At least one significant seal unit is to be identified in a nearby offset well.

- "Significant" is defined here as a minimum of 20m thick – which is a typical measure of seismic resolution. Seals thinner than this can easily be offset by faults and small channels that are too small to image. The seal should certainly be thicker than the throw (offset) of any mapped faults that encounter the seal unit. Seal capacity should be supported by measurements such as Mercury Injection Capillary Pressure (MICP), well Leak Off Tests (LOT), or observed fluid pressure difference above and below the seal that demonstrate the support of a pressure equivalent to a CO_2 column of at least 50m height (i.e. at least 35 to 50 psi, depending on the calculated CO_2 density for that storage location).
- "Nearby" is defined here to be within 10 km of the prospective storage site and correlated to it by good quality 2D seismic data, or within 20 km and correlated by good quality 3D seismic data. The prospective target should be covered by a close 2D grid with better than 3 km line spacing, or a 3D grid, to allow seal continuity to be mapped across the whole storage area.

Significant intraformational and regional seals have been identified in nearby offset wells for all three prospective sites (Hoffman et al., 2015b).

Well records

Detailed records of the completion status and tests conducted on all wells within the plume path/storage area should be filed with regulatory authorities and should pass integrity checks.

Under the Australian regulatory regimes for petroleum, mineral, drinking water, and other activities a good record-keeping scheme is enforced and high standards of completion are the norm (Goebel et al., 2015)

Earthquakes

The project area should have a demonstrable history of tectonic stability. For example, a typical threshold might be that no seismic events greater than magnitude 6 have occurred over the past 100 years.

If an earthquake greater than the proposed limit were to occur, then a detailed seismic impact study would be recommended to demonstrate that facilities design and geological storage were adequate for the scale of ground movement now expected.

A demonstration of long-term geologic trapping of natural fluids in the prospective structure or nearby analogues would be an advantage.

Records show no earthquake greater than magnitude 6 has occurred over the past 100 years and the major accumulations of oil and gas trapped in the Gippsland Basin provide evidence of long-term trapping.

Faults and flow-paths

There should be no evidence that faults breach the identified seal, and no credible evidence of any other flow paths or fluid escape indicators indicating present-day or geologically recent escape.

This requirement can be subdivided as follows:

- Faults identified in wells and on seismic nearby to the site should have less throw than the identified seal thickness.
- There should be no evidence of fluid escape structures on seismic lines across the entire storage area.
- There should also be no associated surface manifestations of fluid escape structures such as mud volcanoes, gas vents, gas chimneys, HRDZ, etc. on the land surface or seafloor, or on shallow seismic data either above or close to the Prospective Storage Site.

There is no evidence of leakage at CarbonNet sites but further detailed work will be undertaken on a preferred site, particularly on identification of faults near to the site.

Access

The prospective sites should be located in one or more jurisdictional regimes that permit the evaluation, appraisal, injection, and storage of CO_2 at both research and commercial scales.

Ideally, an assessment permit should be available over the prospective storage location, or reasonable grounds should exist to believe that a permit can be successfully applied for under established legislation.

The prospective sites should have a demonstrable physical accessibility to the land or ocean surface overlying and surrounding the storage area, and the subsurface volume containing the Storage Formation, over the anticipated storage lifetime (25 years injection plus the post-closure monitoring phase).

Proximity to CO_2 sources

The prospective site should be located within a reasonable transport distance of existing or potential future CO_2 sources in the Latrobe Valley and elsewhere in Gippsland.

Studies and reviews indicate the nearshore Gippsland Basin is preferred for storage. Transport Studies will advise on appropriate transport methods, distances, and costs.

CO_2 composition

The provisional composition of the CO_2 supply should be within the nominal project CO_2 specification which is used to design transport, compression, and storage.

There is a complex cost trade-off between capture, transport, and storage costs. This is a whole-of-project calculation and an optimum solution may not be ideal for storage. Hence, as wide as possible a range of compositions should be allowed at the screening stage.

Natural Environment

The environmental context of the proposed storage site should be understood at a preliminary level, and be amenable to future detailed studies to characterise conditions over and around the repository and allow risk-based assessment of the proposal to proceed with storage at any specific location.

Work done for petroleum exploration and development in the Gippsland Basin provides a base of knowledge on which to assess the general location but site specific work will be required prior to seeking operational approvals.

Other uses of the Subsurface

The Prospective Storage site should be located in an area where clear policies, regulations, and legislation describe the context of the following activities:

- groundwater extraction.
- oil or gas production.
- geothermal energy extraction.
- acid gas disposal.
- natural gas storage.
- waste disposal.

Ideally, access should be available to databases which record all subsurface activity in the above categories and allow characterisation and monitoring of extractive and injection activities and the composition and distribution of subsurface fluids and subsurface pressures in all zones adjacent to or connected with the proposed Storage Formation.

The mutual impact of planned CO_2 storage with current levels of activity in the above areas, and likely forecasts of future possible changes in activity should be considered. Australian legislation provides for the co-existence of rights.

Protected and Sensitive Areas

Use and monitoring of the proposed storage site should have no significant adverse impact on sensitive areas such as nature reserves, indigenous reserves, and military reserves.

The siting of storage infrastructure will be undertaken with consideration of protected and sensitive areas.

Water Sources

Use of the proposed storage site will have no detrimental impact on the beneficial use of active and potential sources of groundwater or surface water for human or animal consumption, nor for agricultural purposes.

Work by Ricard et al., (2015) indicates that injection of CO_2 will not detrimentally impact water resources.

Social and Cultural Context

There should be a clear community engagement and communication strategy outlining public perceptions and potential concerns, supported by an implementation plan including a range of communication channels with the target communities and identified key stakeholders.

Legal and Regulatory Environment

The prospective sites should be located in one or more jurisdictional regimes that permit the evaluation, appraisal, injection, and storage of CO_2 at both research and commercial scales.

Australia (and Victoria) have a single composite legislative act covering both petroleum and CCS operations, and an open access data regime to encourage new participants to enter the search for safe and secure geological storage sites.

Expectations of Operator, Regulators, and Stakeholders

The screening process should be transparent, open, and clearly documented.

Stakeholders should be confident that an impartial and open screening process has occurred which includes all satisfactory candidates, excludes unsatisfactory ones, and documents the reasons for inclusion and exclusion. The process should be adequately documented so that new future candidate storage sites can be reviewed in an equivalent way and added to or rejected from the list of acceptable candidates, whenever they may be identified.

Feasibility Certification

Commencing December 2012, the CarbonNet site selection process was audited by a panel of experts from DNV against its Recommended Practices DNV-RP-J203 and the three sites were certified under DNV's DSS-402 services schedule - the Statement of Feasibility, to provide independent expert assurance to decision makers and stakeholders.

7.2 Stage 2: Statement of Verification of Appraisal Plan

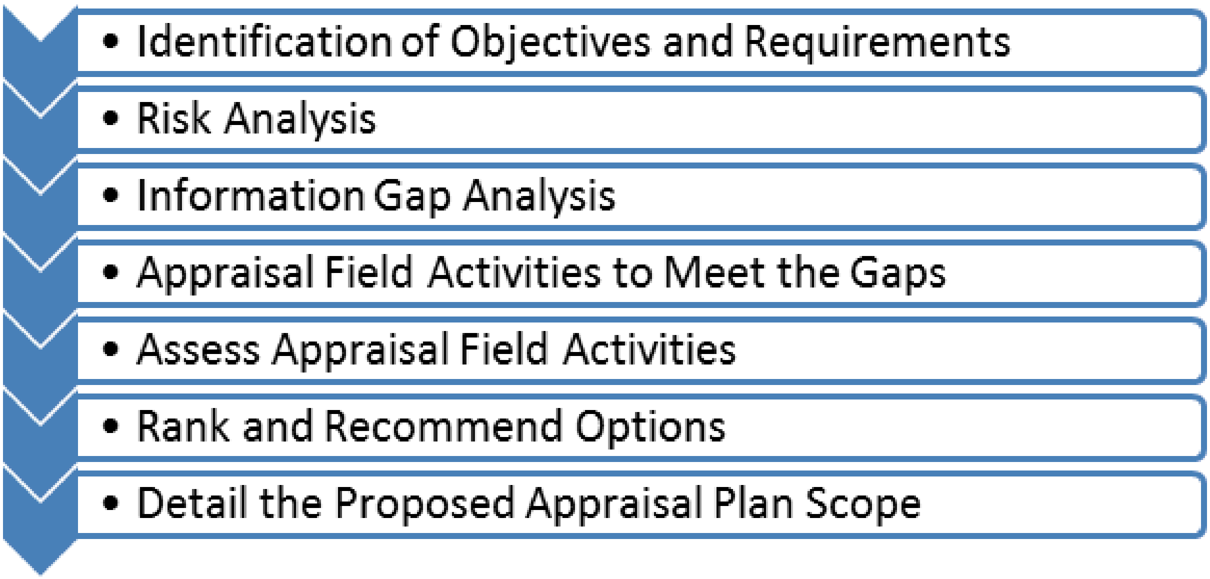
In December 2013, CarbonNet began to develop an initial plan for Appraisal activities and associated studies of a single prioritised site, in conjunction with Schlumberger Carbon Services. The Appraisal Plan was designed to meet all objectives laid out in a detailed Appraisal Basis document as prescribed in DNV-RP-J203 Section 4.3.2. The Appraisal Basis for the CarbonNet Project included the requirement that the Appraisal Plan would provide all foreseeable future data needs for regulatory, environmental and project best practice needs through to the 'Application for an Injection Licence' whilst demonstrating Value for Money.

The standard certification process laid out in DNV-RP-J203 / DNV-DSS-402 does not envisage an intermediate certification step between the Statement of Feasibility (pre-appraisal) and the Statement of Endorsement (post-Appraisal). However, in order to supply confidence to the State and Federal funders of the project, CarbonNet requested that DNV supply an additional Verification of the Appraisal Plan against both DNV-RP-J203 and Australian legislation to demonstrate that the Appraisal Plan contained all the necessary activities to demonstrate safe storage and enable Stage 3 verification and an application for an Australian Injection Licence – subject to the successful technical outcome of the Appraisal activities.

8 Development of Appraisal Plan

In March 2013, the CarbonNet project adopted a Prioritised Storage Site for the Foundation Project based on various technical and non-technical factors, including environmental, social, commercial and financial. The development of the Appraisal Plan followed a structured process (Figure 7) to identify what the risks of CO_2 storage were, based on current available geoscience information, and how to reduce those risks by collecting additional data, in a cost-effective manner, and with a view to integrating key elements into the future monitoring plan for the site.

Figure 7: Appraisal Plan structure and methodology



The Appraisal Plan was developed in a systematic manner to identify what the risks of CO_2 storage were, based on current available geoscience information, and how to reduce those risks by collecting additional data, in a cost-effective manner, and with a view to integrating key elements into the future monitoring plan for the site.

The Objectives of the Appraisal Plan were outlined in a series of in-house scoping workshops that inevitably required one document to perform many different tasks. The Plan needed to address all DNV-RP-J203 sections, to address Australian Legislative requirements under the GHG Acts, and a cluster of other environmental, heritage, and other legislation. The Plan needed to meet all the defined project requirement of the CarbonNet project as recorded in the Decision Register and adhere to the Basis of Design for site development. Not surprisingly, this list of requirements made the Plan rather cumbersome and unwieldy.

Workshops involving expertise from Senergy International (March 2013) and Schlumberger Carbon Services (December 2013) compiled the perceived knowledge and information gaps at the Prioritised Site to complete (i) site characterisation for long term monitoring, (ii) a Declaration of Storage Formation, and (iii) Application for Injection Licence (as required by the relevant regulatory jurisdictions) whilst complying also with DNV-RP-J203. Multi-scenario field operations (involving options of 2D and 3D seismic and wells both shore-based and offshore and desktop studies) were analysed from a value-for-money standpoint to develop a comprehensive Appraisal Plan completed in 2014.

This was a long and complex process requiring substantial iteration and interaction between CarbonNet and Schlumberger to ensure that the many and sometimes conflicting requirements could be combined with high-cost and potentially risky field operations (well drilling and seismic acquisition) with the return of adequate data to de-risk the storage concept, all within approved budget.

One particular requirement was the concept of value for money. To demonstrate this, a number of alternative options for de-risking the site through drilling and data acquisition were scoped out and costed. Also the relative benefits in reducing subsurface uncertainty and associated risk were assessed to identify which activities would ***not*** provide sufficient data, and therefore should be excluded. Then to compare alternatives which would provide sufficient data, but might provide this to a greater or lesser degree, at an individual cost.

In this whole process, the role of imponderables or the “unknown-unknowns” was crucial. Reasonable geoscience and engineering assumptions had to be tabulated for a range of potential outcomes for each option. This rapidly became a complex multi-dimensional task and required significant analysis before a meaningful comparison could be achieved. As a sense check, the outcomes of the analysis – the recommended options and sequence of operations – were checked for completeness against the list of data gaps and risks, and confirmed that they represented a realistic choice.

The outcomes are strongly dependent on development scenario and, with two alternative options, there could easily have led to two completely distinct Appraisal Plans. These were instead merged into a single Plan, with the understanding that as the likelihood of one or other development option evolved, so might the emphasis between or sequence of different elements of the Appraisal program.

8.1 Appraisal Verification

The Appraisal Plan was initially presented to DNV for verification in mid-2014. An expert panel was led by two DNV certification experts with experience in petroleum and CO_2 projects, and the support of three external experts in fields of geochemistry, geomechanics, and MMV. The review process was highly informative. An open discussion of the merits and challenges of the prioritised site, and the CarbonNet process of evaluation was held and many assumptions were tested.

The outcome of the first verification review was that the Appraisal Plan was seen as cumbersome and unwieldy and that, in a relatively few areas, the document fell short of the requirements of DNV-RP-J203. The Site itself was judged to be of a high standard – in fact of world class in many respects - but the documentation was insufficient or the approach inappropriate in some areas such as risk management, monitoring plan, geochemistry and geomechanics.

A second pass of development of the Appraisal Plan ensued. In this round, the document was restructured to primarily follow DNV-RP-J203, with other Project and government requirements moved to appendices. Additional external modules were commissioned in the key expert areas of monitoring, geochemistry, and geomechanics, and a full in-house review of risk treatment was conducted to conform with DNV-RP-J203 and Bourne et al., (2014).

The second version of the Appraisal Plan was developed and completed in late 2014 and submitted to DNV for a second review.

The Appraisal Plan (which includes 3D seismic acquisition and drilling of well(s) to complement the existing rich data set of 2D/3D seismic, three wells and preliminary geochemical and geomechanical models that currently characterise the site) has now been verified by DNV as Stage-2 of the DSS-402/DNV-RP-J203 service.

9 Lessons Learned

A large number of learnings have been accumulated in a range of areas. Many of these are not unique to the CarbonNet Project, and all should be reviewed by other CCS projects aiming to screen large numbers of prospects into a high-graded portfolio of injection sites. Other learnings are more relevant to government-led projects, where government process and experience may not be fully familiar with petroleum industry scale and scope of operations. For any Project, a holistic approach to risk management and project cost management is required to conduct an operation at the required scale, speed, and efficiency needed for large scale integrated CCS projects.

At this early stage of world-wide implementation of CCS, and in the absence of an agreed international financial accounting system for carbon emissions and storage, it is inevitable that government-led and -supported projects will feature heavily in the list of ongoing projects. It is important that these governments consider how to set-up an effective and flexible organisation to deliver the required result.

9.1 Work Program and Budget

The GEP2 work program was originally designed without reference to DNV-RP-J203 which had not been published at that time. With the later Project decision to adopt a Certification service and the selection of J203, it became clear that some additional elements needed to be added to the originally envisaged geoscience and engineering plan.

The well planned, holistic and structured work program (and budget) was found be very important whilst working in a government environment since it provided stakeholder confidence in a methodical and structured work flow. The GEP2 work plan was also found to largely fit the requirements of the RP-J203.

In CarbonNet, the GEP2 Implementation Plan provided an appropriate work flow framework but omitted to incorporate adequate budget for certification processes, and did not contain enough flexibility for technical variation – since it was originally envisaged as an "evergreen" plan that could be adjusted as required with changing circumstances. It is therefore recommended that future projects allow more flexibility and contingency in their initial planning and budget.

The GEP2 Implementation process took substantially longer than planned (4 years vs 2 for the geoscience elements) due the changes and additions to the original plan. Regulatory approval processes have also taken longer than expected. These factors had whole of project implications and should be anticipated in any future project in a new organisation not familiar with CO_2 storage.

The forecast cost of major field activities such as wells and seismic acquisition was found to be underestimated, when the full details of data requirements for CO_2 storage were worked-up, and practical well designs established.

Many of the significant cost elements relate to the requirement to "prove" the capacity a topseal, in the absence of an existing hydrocarbon pool. If a hydrocarbon pool does exist, however, that zone cannot be used for storage until petroleum recovery operations are completed – which may still be a matter of one or more decades.

The “proof” of topseal could be done by new well pressure tests across the seal interval, with above-zone pressure gauges to detect any pressure leakage, but the cost of a new well can be quite high. CarbonNet has focused on using existing offset well data to demonstrate intraformational seal effectiveness on a regional basis (Hoffman et al.,2015).

The GEP2 Implementation Plan contained insufficient detail to account for the requirements for geochemical and geomechanical data gathering, laboratory studies and modelling as required by Sections 4.3.5.4 and 4.3.5.5 of DNV-RP-J203. Fortunately there were sufficient available funds within the program to adsorb these additions.

9.2 Development of a portfolio of prospective stores

Following the common petroleum exploration technique, a portfolio approach to identifying and selecting prospective stores was adopted by CarbonNet. An initial portfolio of 24 prospective stores comprised of one or more stratigraphic targets at 13 geographic locations was compiled for future screening. This method of site screening and selection proved to be advantageous as it ensured that in the event of one site being rejected there remained a suite of alternative ‘successors’. It also services DNV-RP-J203 requirements.

Section 4.2 of the DNV-RP-J203 assumes that a number (unspecified) of potential storage sites will be screened. Projects that have only one prospect will be challenged to meet the certification requirements but DNV have demonstrated some flexibility during the early developments of the RP in that the Shell Alberta Quest Project has received DNV certification for a single site.

Section 4.3 of the RP is written as though more than one site will be Appraised before final site selection is made. Clearly, this would require a major financial commitment. In the case of CarbonNet , following the Statement of Feasibility for three prospective sites the Project was able to mature a single site to Prioritised Status for Appraisal on the basis that an adequate database already existed on all three sites.

9.3 Play Fairway Mapping and Portfolio Management

To date, the majority of CO_2 storage projects have been one-off exercises to find a storage site for a particular source of CO_2. The source is generally stationary, or relatively immobile – a new build coal power plant must be close to the mines, or a transportation route, and other types of industrial sources are similarly constrained by their process material and historical location. There has therefore been little incentive to consider economies in finding multiple alternatives when assessing potential storage sites. All that has been required is a single site within a reasonable transport distance of the source.

The result of this style of single-minded search is that in some cases a suitable low-risk storage site cannot be located, and the CCS project fails. In other cases, a site is located, but the cost of the search is generally significant. CarbonNet investment is of the order of $20 million during the site selection phase (March 2011 - December 2014) and this appears to be typical of other projects worldwide which have deployed large geoscience teams and worked for 5-15 years to prove a single storage site. In the CarbonNet case, however, a portfolio of three prime or high-graded sites has been worked-up, and backup candidates are available beyond the shortlist, if required. This is a more efficient use of exploration effort.

There are many learnings to be taken from the petroleum industry. Oil companies do not, in general, seek a single isolated oilfield. They seek a cluster of fields which can be explored for and developed with economy of number by shared technical analysis and shared infrastructure. This type of approach develops a Portfolio of sites which are selected so as to share some geological characteristics, and be independent in others. This type of approach is generally described as a play fairway, where a suite of prospective targets is evaluated within a single geological system.

The reason for this approach is exploration risk management. If one of these sites is drilled and some major defect is discovered with the trap concept (such as lack of reservoir, or seal), then all sites that share that attribute are similarly affected. A single well could thus rule-out a whole family of prospective targets. However, a successful well would improve the ranking of that whole family. It is therefore prudent to have several families of prospective targets available within a close enough area that information from one exploration well can inform independently (be it favourably or unfavourably) on the different families.

Thus, one would ideally find a set of families which shared a reservoir, but had different seals, or shared a seal but had different reservoirs. The important aspect of this approach is that one exploration program can de-risk multiple traps – perhaps a few or as many as five or ten at once, reducing the unit cost of exploration by a similar factor.

This is a common petroleum technique but does not form a compulsory part of the DNV-RP-J203 site screening process. CarbonNet has taken this approach to portfolio management in the Gippsland Basin and has worked-up three primary targets (and several secondary ones) with very little more effort than it would have taken to evaluate a single site, and understand its geological context. Thus, the geoscience and reservoir engineering cost of site selection can be divided by at least 3. This is still a significant cost, but CarbonNet has the opportunity to make further cost reductions in the future by using an Appraisal well on one site to test trap concepts applicable to other sites. As an example, a well drilled on a structural site will provide fresh rock core for analysis. A value of residual saturation (Sgr) from this structural site can be applied to the modelling and site design for a nearby open aquifer site.

CarbonNet adopted the petroleum industry standard of Common Risk Segment mapping to evaluate seal and reservoir potential in the nearshore Gippsland Basin and to define the most attractive play fairways for CO_2 storage. The petroleum topseal (Lakes Entrance Formation) was mapped for quality (Hoffman et al., 2012), following earlier work by GeoScience Victoria (Goldie-Divko et al., 2009a, b, 2010). Top Latrobe sand fairways have been mapped within the CarbonNet Project (Hoffman et al., 2012, 2015b), following earlier work by 3D-GEO (2011), and intraformational seal fairways and intra-Latrobe Group reservoir fairways have been mapped over a wide area (Hoffman 2015b).

9.4 Planned Peer Reviews

Peer reviews must be carefully managed, or they will become exercises in self-congratulation at one extreme, or open conflict at the other, and even without this, they may waste everyone's time with little concrete result. Good professional facilitation is a must-have. The expectations and desired outcomes of the review must be agreed with the facilitator and communicated in advance to the panel. All briefing material must be supplied on time, and be commensurate in volume and complexity with the task in hand, and the panel members must allow sufficient time to prepare for the workshop by reading and actively questioning the provided material.

The GEP2.1 and GEP2.8 peer review workshops provided a sound basis for maintaining Project funder confidence whilst advancing the project to DNV-RP-J203 certification. DNV-RP-J203 requires a certain detailed knowledge of specialised geosciences and engineering and accordingly DNV sub-contracts specialists to participate in the certification review process. It is important that neither the project proponent, DNV nor the subcontracted specialists exercise over-zealous ambitions in reviewing model assumptions until the appraisal program has delivered the prerequisite data.

Risk Management. The DNV RP places high importance on the documentation and management of risks and their utilisation to formulate and guide Appraisal Planning. The CarbonNet Appraisal Plan for the Prioritised Site is accordingly driven by a need to reduce risk, specifically through clarifying subsurface uncertainty.

There were a number of logistic outcomes that would benefit future planning of similar reviews:

- Convening a panel of 10-12 is always difficult—finding a date to suit everyone. It is necessary to have some flexibility in membership and alternate representatives for key review disciplines.
- It is important that funds are budgeted for accommodation and travel, and flexible access to these is available to cover a range of participant circumstances.
- There is potentially an issue of remuneration for non-sponsored participants, and the perception of equality and fairness for all. A nominal per-diem allowance to all participants may go some way to levelling the playing field, but key external experts are necessary and must be sponsored if their institution will not cover their time.
- Timeframes are tight. Even in a whole-day workshop there is little time for participants to become comfortable with the overall objective of a screened suite of sites. This can be alleviated by sending out a data pack in advance, but some of the participants don't do their "homework", and the data pack delivery date becomes a delivery millstone for the project.

9.5 Feedback from Peer Reviews

Whilst scientifically sound, in many cases the detailed feedback covered details that were not relevant to the stage of assessment. Each technical expert suggested additional work in their own area of specialisation, as might be expected, but finding an appropriate balance of the level of technical work, compared to the stage of site characterisation requires a careful analysis of the value of information versus the cost of delay, and an understanding of what is fit for purpose at any stage.

In some cases, the feedback considered data gaps that would be impossible to answer without commencing appraisal drilling or 3D seismic acquisition, and those appraisal activities could not be conducted until a portfolio progresses past the screening phase.

It is important to lay out the ground rules for a peer review workshop and to ask for advice, and not instruction. It is important to reveal the weaknesses of any site, but excessive academic detail is not useful when a large portfolio is being screened. In short, the workshop needs to be scoped to the stage of prospect screening, and all participants need to be clear how high the hurdles should be set at each particular screening stage. Ultimately, a relative ranking is sought, and only if there are obvious problems with all the proposed sites should the review panel issue red flags.

9.6 Independent External Modelling

The outcome of the independent modelling was instructive. Different modelling houses made quite similar assumptions about the framework geology, but different assumptions about the effectiveness of particular units within it. For instance, some modellers felt that seal was unproven in some areas and were reluctant to run a model that tested this “unproven” seal, even as a concept to be risked. Other modellers were ready to run extreme models and then apply risk after the event, essentially using the modelling as a scenario screening tool.

Overall, the results by different modellers for a single site generally agreed in storage volume, and the relative volume ranging of sites was agreed by all three modelling streams. Sites where modelling outcomes were more different were analysed and the assumptions that led to the differences were catalogued and set as areas for additional geoscience evaluation in subsequent work phases.

9.7 Information sharing

In any novel plan to undertake new activities that are unfamiliar to the local community and other stakeholders, public perception is critical to acceptance of both the overall goals of the Project, and the actual implementation plan. It is important to demonstrate understanding of actual local issues and interests, and to maintain close liaison with local government, authorities, and community groups.

Methods to achieve these include briefings to and discussions with community and industry groups and the provision of easy access to information in the form of fact sheets, website and e-newsletter/blogs and presentations on a range of Project themes.

Periodically, CarbonNet has made public progress reports (Carman, 2011, 2013, Hoffman 2014) and scientific and engineering findings (Bagheri and Nicholson, 2012, Hoffman, Arian and Carman, 2012, Hoffman and Preston, 2014).

It was found that the CarbonNet peer review panellists and DNV reviewers relied heavily on published data and interpretations. Unfortunately, from an early stage the CarbonNet Project exercised a cautious approach to knowledge sharing which was detrimental to the review process. With hindsight, it would have been advantageous for the GEP2 Implementation Plan to have included a scheduled release of information. A Storage Workstream Publications Policy was eventually developed and approved during the Appraisal Planning stage and this is now being activated (this paper, Hoffman et al., 2015 a; 2015b; Goebel et al., 2015).

Uninformed stakeholders were considered to be some of the toughest judges of the project. Much of this difficulty could, as noted, have been addressed with more information. There are still issues in merging technical and non-technical viewpoints, but this is a necessary process in any Project, and the final project scope and design must address non-technical stakeholders including the general public who are the ultimate beneficiaries of emissions reduction and must be confident that the proposed solutions are safe and effective.

9.8 Data and Risk are coupled

Working in a mature petroleum basin provides a wealth of historical data and the opportunity to prove many concepts with respect to seal integrity, storage capacity, and injectivity (permeability) using data already collected an paid for by previous explorers. This significantly reduces the up-front cost of basin evaluation for CCS. The required data for carbon storage may not always be collected, since the intervals of interest for storage may differ from those for petroleum exploration but much serendipitous data is available which, when carefully mined and sifted, will reveal useful nuggets of information.

In this context, an open data access regime is vital, since otherwise only the petroleum exploration companies will have access to the necessary detailed data, and CCS may not be an active part of their agenda.

In the case of the CarbonNet portfolio of Prospective Storage Sites, the majority were defined by fair to good 2D (and often 3D) seismic data with one or two plugged and abandoned wells on structure, and some 50 offset petroleum wells (some producers) in the storage play fairway. The availability of this database allowed a detailed evaluation of each site during the site selection phase and provided confidence to interpreters, reviewers and stakeholders alike.

There is an additional perceived risk for “empty” structures in a proven petroleum fairway. CCS proponents would naturally seek a similar structure to those hosting oil and gas, but empty. It is important to ask the question “why is it empty”? If it can be reasonably demonstrated that the structure is not linked to a hydrocarbon producing source rock and/or is outside the timing of hydrocarbon migration, then the site may well be viable for storage. If the site should have a petroleum accumulation, but is empty, then careful checks of its structural history and seal integrity must be made to demonstrate that it did not leak in the past and will not leak at the present day.

The existence of on-site historical wells introduces some uncertainty with respect to well integrity (e.g. Matteo et al., 2011). This has proven to be a major issue in North America where many thousands of wells were drilled before any regulations were in place. In Australia, the completion of petroleum exploration and production wells has been stringently regulated since the 1960’s, prior to the wells being drilled. Whilst this does not guarantee well integrity, the resulting mandated completion records do provide a firm basis for evaluation of historical well integrity (Goebel et al., 2015).

In any mature basin, potential resource conflict exists. This may be for any or all of petroleum, geothermal, water, CSG, coal, minerals, etc. Integrated environmental and whole-of-basin resource management is necessary, and there may be constraints placed on various parties as to how they operate, how basin-wide pressure is managed (Varma and Michael, 2012, Kuttan et al., 1986), where they explore, and how they complete and abandon their boreholes so as not to adversely affect other potential future users (Loizzo et al., 2013, Goebel et al., 2015) .

It is important to document these potential conflicts early-on and address them as potential “show stoppers” or project-level risks. It may be possible to develop some of them into synergistic benefits of co-development, rather than negative interactions and hence remove the conflict, or the conflict may be managed and minimised to an acceptable level.

In mature petroleum basins and storage projects close to shore, there will always be concerns over resource management. The CarbonNet project has worked to assess and understand these, and develop risk management practices to specifically address the potential conflicts. This is particularly important in the area of CCS-Petroleum interaction where the Offshore Petroleum and Greenhouse Gas Storage Act 2006 defines a requirement to avoid a Significant Risk Of A Significant Adverse Interaction (SROASAI) – a legislative requirement, plus actual and perceived stakeholder reactions (Petroleum Holder and Community).

9.9 Seal Evaluation

The fundamental requirement for any CO_2 sequestration is that the CO_2 is retained underground. This requires the existence of an identified seal interval with proven capacity to retain the full volume of injected CO_2. A geological seal interval forms a vertical trap in the first instance. Second-order trapping must offer side seal, either by the seal unit being formed into a structure, or by the presence of lateral barriers to fluid migration such as faults, stratigraphic pinch-outs, or very long distance run-out in an open saline aquifer. Without a seal, there can be no effective storage.

The CarbonNet Project is no exception and our feedback from peer review meetings, stakeholder concerns, and risk registers all point to the importance of containment. This topic is addressed in more detail in the accompanying paper on T2 seal integrity (Hoffman et al., 2015b). CarbonNet has identified an important family of intraformational seals in the nearshore Gippsland Basin and intends to use these seals to configure multi-level storage at moderate depths (1-2 km) for efficient volumetric usage of the available storage sites.

Identifying multiple seals is a two-edged sword. It demonstrates that backup seals exist, in the unlikely event of failure or bypass of the main seal. Many projects such as Gorgon adopt such an approach to storage seal. However, to the layman, the "need" for a second seal can cast doubt on the efficacy of the first seal, and, by extension, with the whole scientific analysis of storage. This is not an easy issue and requires careful and extensive argument about risk, seal capacity and sufficiency, and storage lifetimes.

Surprisingly, geological seal containment and integrity has a relatively low profile in RPJ203 (in Table 4-2 – only points 9 and 10 pertain to the 'confining zones') – perhaps because it is a "given" that a competent seal must exist for any site to even be considered for storage. In DNV-RP-J203 there is significantly more detail concerning legacy well containment and integrity (the entirety of Table 4-3.5).

Note that seal cannot actually be "proven" until a full-scale test is done on the seal capacity. This test may take the form of a geological storage for an analogue fluid, in the case of a depleted petroleum field, but the "proof" is only over the area of the original fluid pool, and up to the pressure of the original buoyant column, and does not "prove" seal capacity against CO_2 – that must be separately measured or calculated from fluid/seal interface properties (MICP, interfacial tension, contact angle, mineral stability etc.). For unfilled structures, and beyond the limits of the original petroleum pool, seal can never be definitively "proved" until the full volume has been injected, and has stabilised within the structure and developed the full buoyancy pressure over the trapping geometry.

9.10 Other Issues

Carbon Storage and climate science are potentially contentious and a wide range of public opinions exist. Any project operating in this sphere needs to understand and address realistic concerns of the public and other stakeholders, but also to address non-technical objections.

As a government-led project, CarbonNet has inevitably experienced political change and varying support in the wider context of climate change mitigation. Nonetheless, there has been a sustained financial support of the project, recognising its value as an insurance policy against the requirement to implement active carbon management.

The Latrobe aquifer onshore is an important agricultural water source. Pressure depletion of this aquifer has been noted over five decades of petroleum production. Any new changes due to CO_2 injection need to be carefully assessed and demonstrated to be beneficial, or at worst, not further detrimental. (Hortle et al., 2010; Jenkins et al., 2012; Ricard et al., 2015.)

There are many challenges that relate to the scientific community. Each expert or group has their own special interest and would like to see detailed studies conducted in their field, or into intriguing side aspects of the storage system, rather than the fundamental aspects. The result may be an unnecessary and academic program of research, rather than a rational commercial assessment of storage suitability.

There is also a danger in the competitive field of publications and media publicity that an article, scientific paper or news release may be inappropriately or emotively titled with a view to attracting attention to the researcher, with adverse consequences for the project, or the whole concept of CCS. Debates have taken place around the area of induced seismicity in the US (e.g. Zoback and Gorelick, 2012, and the responses thereto). The Gippsland Basin has experienced a local version of this (Ciftci et al., 2012; 2011). Coupled with the issues of public perception, fear of public perception, and potential misquoting by interested parties, the science of CCS represents a delicate path to tread.

10 Conclusions

CarbonNet has completed a robust and comprehensive review of Carbon storage potential in the data-rich nearshore area of the Gippsland Basin, using (petroleum) industry standard play fairway analysis to define a portfolio of high-graded storage sites. Three of these have been short-listed and one is the Prioritised Site for future appraisal operations to prove storage of up to 125 Mt of CO_2.

The storage site selection process has been guided by external peer reviews and by the DNV GL Recommended Practice DNV-RP-J203.

The challenges of completing the work under exceptionally exacting technical conditions to the satisfaction of a wide range of stakeholders and under uncertain and sometimes wavering political support has resulted in the identification of an excellent prioritised site. The whole site selection process represents some 20 man-years of geoscience work for an estimated investment of ~$20million.

Significant learnings, detailed above, have been acquired in the areas of cost-efficient site search, using a play fairway approach to characterise multiple potential sites in one pass.

Positive and negative learnings have also been acquired and documented in areas of government process and budget management, information-sharing, risk analysis, and the value of external reviews and procedures to guide the search process.

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