Review of geological storage opportunities for carbon capture and storage (CCS) in Victoria

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Abstract

The Victorian State Government is committed to developing the Latrobe Valley brown coal resources in an environmentally responsible manner. One possible technology for low emission industries is carbon capture and storage (CCS), in particular geological storage of CO_2. This study has reviewed the Late Palaeozoic to Cenozoic sedimentary basins of Victoria as to their overall suitability for CO_2 geological storage, based on geological, geographical and industrial characteristics. These include factors such as tectonic stability, basin size and depth, reservoir or coal quality, intensity of faulting, existing resources and industry maturity.

A qualitative comparison between the various basins indicates that the offshore Gippsland Basin has the best overall potential for CO_2 geological storage. This basin has an extensive sedimentary fill with numerous reservoir and seal horizons, with mature hydrocarbon fields and an established infrastructure framework. The offshore Gippsland Basin was closely followed in the rankings by the onshore Otway Basin, the offshore Otway Basin and the onshore Gippsland Basin. The other Cenozoic and Late Palaeozoic basins show little potential for CO_2 storage opportunities because they are either too small, too shallow or without suitable geological horizons. If an onshore site is required then the onshore Otway Basin provides the best potential for CO_2 storage, whilst if storage in coal is required (in association with enhanced coal seam methane) then the onshore Gippsland Basin has the most favourable characteristics.

Overall, the geological settings of the State of Victoria and its adjacent waters show considerable potential for CCS opportunities. The adoption of CCS technologies can be an important part of the solution to the problem of reducing large volumes of greenhouse gas emissions into the atmosphere.

Keywords: carbon dioxide, CO_2, carbon capture and storage (CCS), geosequestration, Victoria, Late Palaeozoic infrabasins, Otway Basin, Gippsland Basin, Murray Basin, CO2CRC.

Introduction

At present, 85% of the electricity in the state of Victoria, southeast Australia, is generated from power stations fuelled by the extensive brown coal resources of the Latrobe Valley (DPI 2008). These resources are crucially important to the future economic development of Victoria and the Victorian Government is committed to developing these resources in an environmentally responsible manner. One possible method for reducing large volumes of carbon dioxide (CO_2) greenhouse gas emissions (that result from the combustion of brown coal) is through carbon capture and storage (CCS).

As a result, the Victorian Department of Primary Industries commissioned the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) to undertake a review to determine the potential for geological storage opportunities for CCS within Victoria and its adjacent waters (Gibson-Poole et al. 2006). The study assessed the geology of known sedimentary basins in Victoria and reviewed the results against existing criteria for evaluation of CO_2 geological storage potential, using public domain data sources. This paper summarises that work and provides a technical overview that documents the basin-scale suitability of Victoria for CCS, and identifies and prioritises potential Victorian CO_2 geological storage opportunities, in both onshore and offshore geological settings.

Carbon capture and storage (CCS)

Carbon dioxide (CO_2) capture and storage (CCS) involves capturing and separating CO_2 from a stationary source, transporting it to a storage location and storing it in long-term isolation from the atmosphere. Captured CO_2 can be stored in the geological subsurface, in oceans, or be used for mineral carbonation or industrial uses (IPCC 2005). This study looks only at the options for geological storage of CO_2.

Geological storage of carbon dioxide is the process whereby CO_2 is captured and separated from a source (such as a high-CO_2 natural gas field, LNG or mineral processing plant, or coal-fired power station) and is transported and injected into the geological subsurface for long-term storage (Fig. 1) (Cook et al. 2000; IPCC 2005). The main geological constraints for finding the right place to store CO_2 include a porous and permeable reservoir rock (e.g. sandstone) to allow injection and storage of the CO_2, overlain by an impermeable seal rock (e.g. claystone) to retain the injected CO_2 in the geological subsurface (van der Meer 1992; Bachu et al. 1994; Rochelle et al. 1999).

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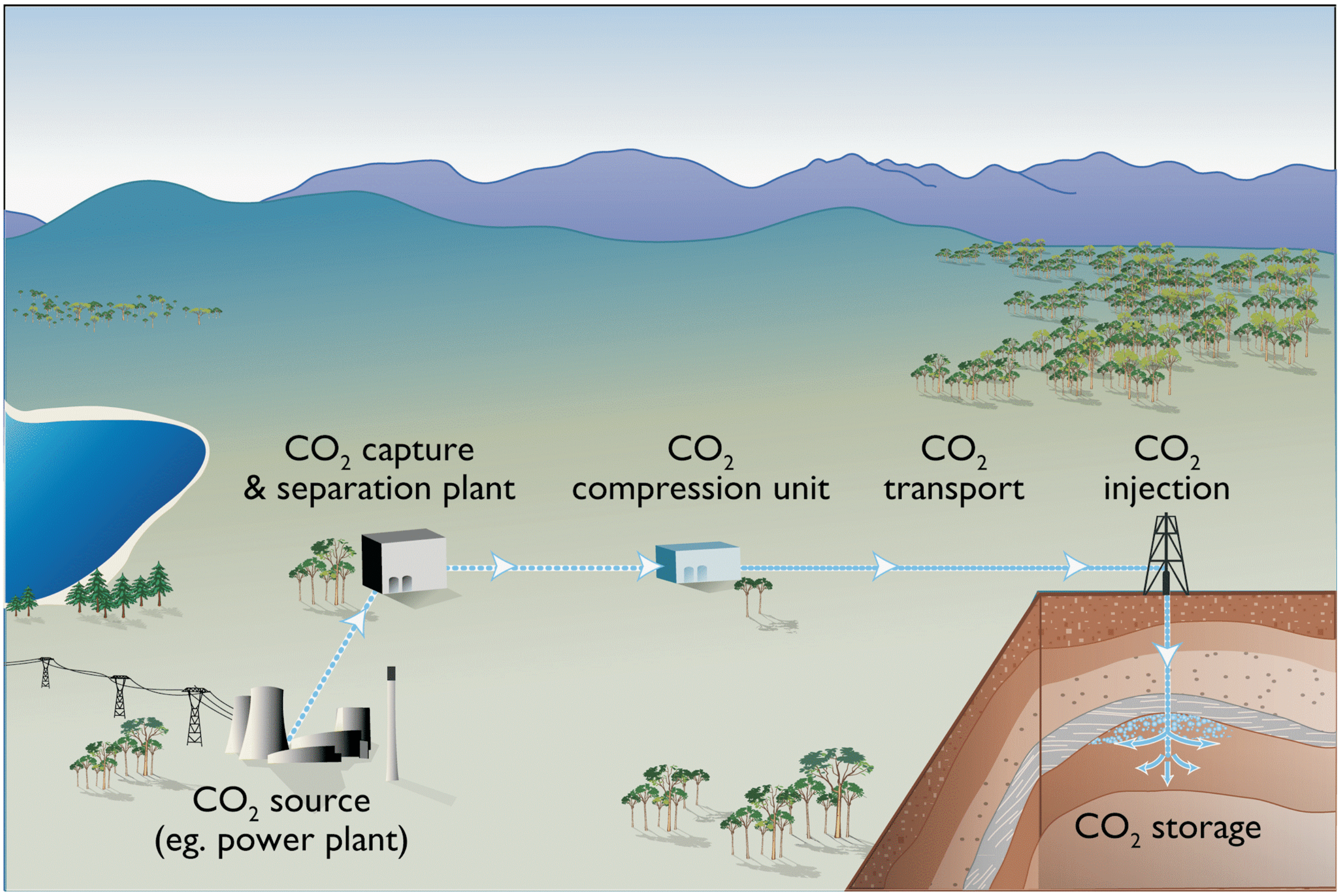

Figure 1. Steps involved in CO_2 capture, transport and geological storage (image courtesy of CO2CRC).

CO_2 properties and subsurface behaviour

For ease of transport and greater storage capacity, CO_2 is best injected as a dense, supercritical fluid. The critical point where CO_2 enters the supercritical phase is defined as 31.1°C and 7.38 MPa (Fig. 2a) (Holloway & Savage 1993; van der Meer 1993; Bachu 2000). Based on worldwide average geothermal and hydrostatic pressure conditions, this equates to an approximate minimum subsurface depth of about 800 m (Fig. 2b) (van der Meer 1992; Holloway & Savage 1993). Below this depth (under normal sedimentary basin conditions) supercritical CO_2 is 30–40% less dense than a typical saline formation water under the same conditions (Ennis-King & Paterson 2001, 2002). This means that the lighter CO_2 will naturally rise upwards by buoyancy through the reservoir rock until trapped by various physical, hydrodynamic or geochemical trapping mechanisms (although in the longer term—hundreds to thousands of years—dissolved CO_2 may sink under the right conditions [Ennis-King & Paterson 2005]).

CO_2 can be stored by a number of different trapping mechanisms, such as;

- Structural or stratigraphic trapping, where the buoyant free-phase CO_2 is physically trapped by the geometric arrangement of reservoir and seal rock units (in a similar manner to hydrocarbon accumulations, e.g. Biddle and Wielchowsky 1994);
- Hydrodynamic trapping, where the dissolved and immiscible CO_2 travels with the formation water for very long residence (migration) times (Bachu et al. 1994);
- Residual trapping, where the CO_2 becomes trapped in the pore spaces by capillary pressure forces (Ennis-King & Paterson 2001; Holtz 2002; Flett et al. 2005);
- Solubility trapping, where the CO_2 dissolves into the formation water (Koide et al. 1992);
- Mineral trapping, where the CO_2 precipitates as new carbonate minerals (Gunter et al. 1993); and
- Adsorption trapping, where the CO_2 adsorbs onto the surface of coal (Gunter et al. 1997).

The exact trapping mechanism will depend on the specific geological conditions and typically involves a combination of the above. The type of trapping that occurs, and when, is dependent on the flow behaviour of the CO_2 and the time-scale involved. With increasing time, the dominant storage mechanism will change and typically the storage security also increases. Figure 3 shows how the initial storage mechanism will be dominantly buoyancy-driven structural and stratigraphic trapping of the immiscible-phase CO_2. With increasing time and migration, more CO_2 is trapped residually in the pore space or is dissolved in the formation water, increasing the storage security. Finally, mineral trapping may occur by precipitation of carbonate minerals after geochemical reaction of the dissolved CO_2 with the host rock mineralogy, permanently trapping the CO_2.

Geological storage options for CO_2

CO_2 can be stored geologically by a variety of different options (Fig. 4). Of these, the three main alternatives are: saline formations; oil and gas fields (once depleted or in conjunction with enhanced oil or gas recovery); and coal seams (deep unmineable or in conjunction with enhanced coal seam methane) (Bachu & Gunter 1999; Cook et al. 2000; IPCC 2005).

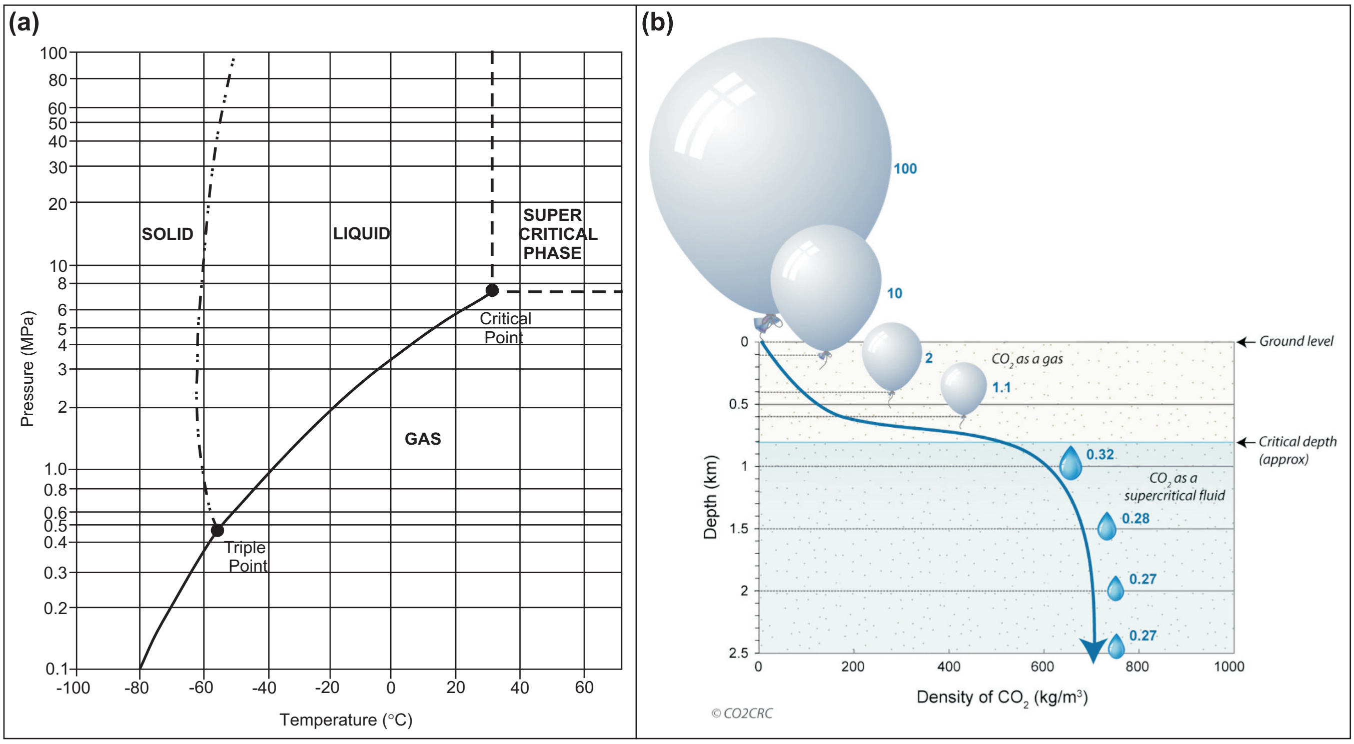

Figure 2. (a) Carbon dioxide phase diagram (after Bachu 2000). (b) Variation of CO_2 density with depth (assuming hydrostatic pressure, geothermal gradient of 25°C/km and surface temperature of 15°C). The size of the balloons/drops represent the relative volume occupied by the CO_2 (image courtesy of CO2CRC).

Saline formations

Saline formations are deep sedimentary rocks saturated with formation waters that are unsuitable for human consumption or agricultural use. They have been identified by many studies as one of the best potential options for large volume geological storage of CO_2 (e.g. Bachu, 2000; Bradshaw et al., 2002). Storage mechanisms include structural/stratigraphic, hydrodynamic, residual, solubility and mineral trapping. Possible drawbacks are that the containment potential of the seal rock is usually untested and there are often limited amounts of data available for site characterisation. However, their main advantages are that they are distributed widely over the world and their potential storage capacity is large (Koide et al. 1992; Hendriks & Blok 1993; Rigg et al. 2001; IPCC 2005).

Oil and gas fields: depleted or enhanced recovery

CO_2 can be geologically stored in oil and gas fields once they have been depleted and are no longer producing, or can be used to enhance oil or gas recovery (EOR/EGR) in fields that are still producing. The main advantages of storage in depleted oil and gas fields over saline formations is that the containment potential of the site has been proven by the retention of hydrocarbons for millions of years, and there are typically large amounts of geological and engineering data available for detailed site characterisation (Holloway & Savage 1993; IPCC 2005). Possible drawbacks, however, may be the physical size of the structural/stratigraphic trap (i.e. potential storage capacity may be limited), the possibility that pore pressure depletion has led to porosity reduction (which will reduce the potential storage capacity), the presence of existing old wells which may provide potential leak points, and the timing of availability of depleted fields with respect to the source of CO_2 (Bradshaw & Rigg 2001; Bradshaw et al. 2002; Celia & Bachu 2003; Streit & Siggins 2005).

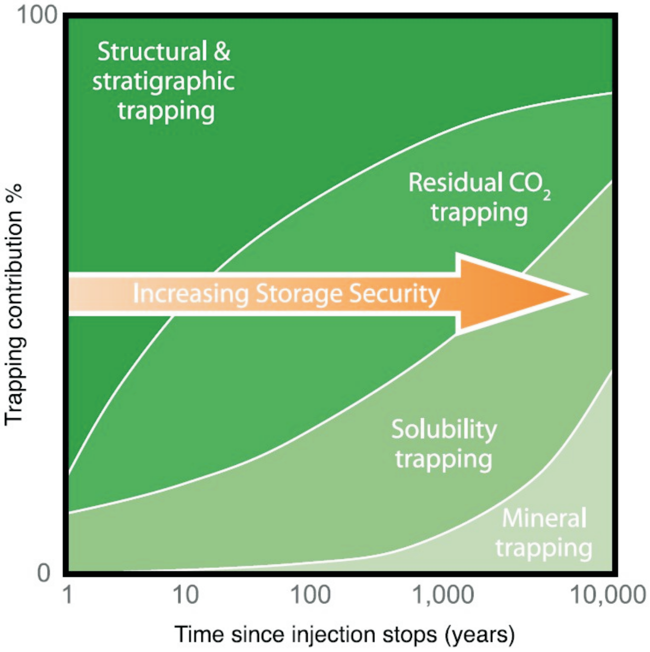

Figure 3. Schematic representation of the change of dominant trapping mechanisms and increasing CO_2 storage security with time (after IPCC 2005).

In EOR or EGR, the CO_2 is used to incrementally increase the amount of hydrocarbons extracted by either immiscible (not mixed) or miscible (mixed together) flooding, thus providing an economic benefit whilst additionally storing CO_2. As with depleted oil and gas fields, the potential storage capacity may be limited

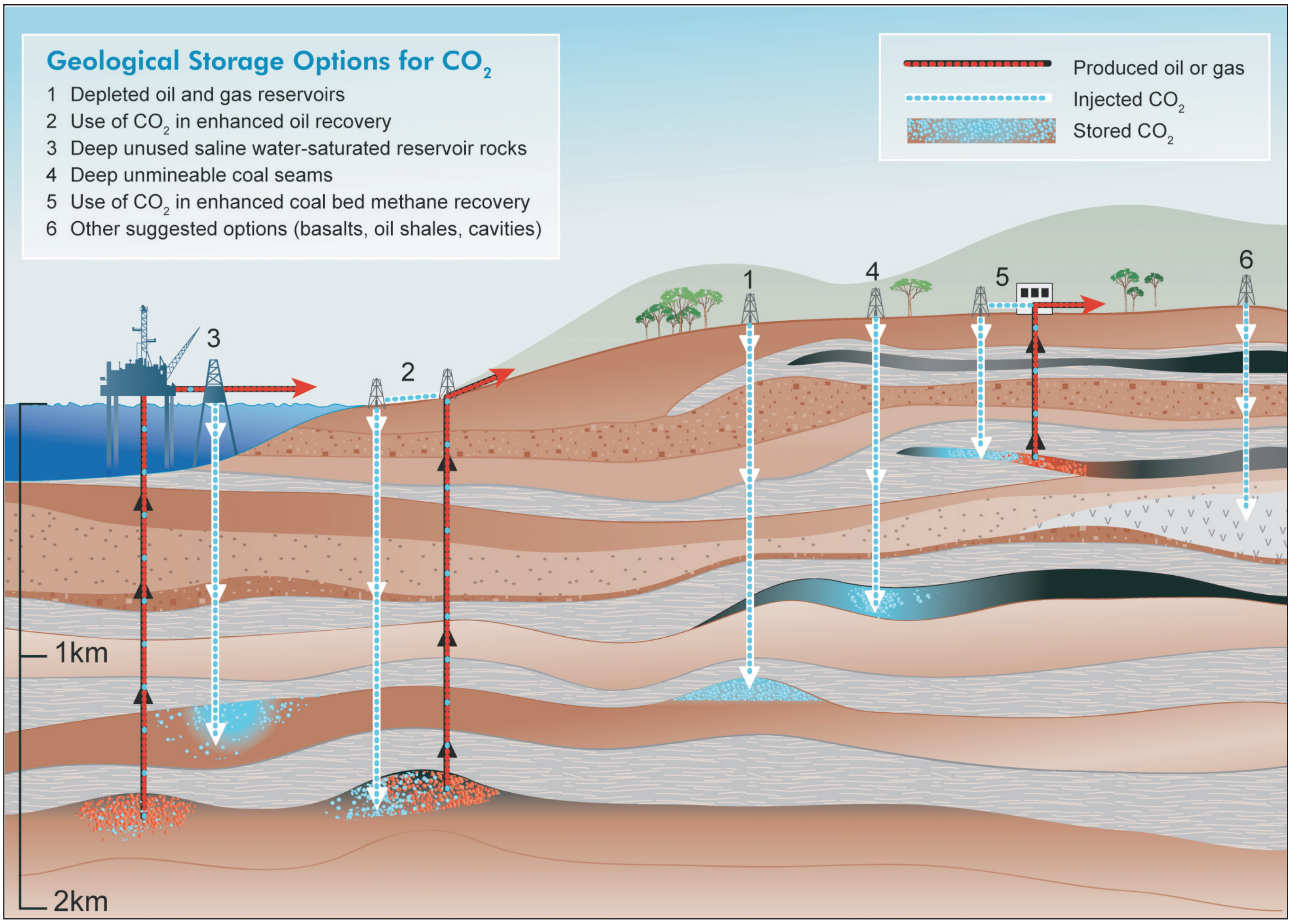

Figure 4. Options for the geological storage of CO_2 (image courtesy of CO2CRC).

due to the size of the field and also due to EOR operational issues such as the rate at which the CO_2 is recycled (Islam & Chakma 1993; Cook et al. 2000; IPCC 2005).

Coal seams: Deep unmineable or enhanced recovery

CO_2 storage in coal seams is very different to storage in saline formations or oil and gas fields, as the trapping mechanism is by adsorption as opposed to conventional storage in rock pore space. CO_2 is preferentially adsorbed onto the coal micropore surfaces, displacing the existing methane (CH_4) if present (Gunter et al. 1997; Bradshaw & Rigg 2001; IPCC 2005). In contrast to saline/hydrocarbon formations, storage density (i.e. storage capacity) is greatest in coals at depths less than 600 m, when CO_2 is in the gaseous phase, not supercritical (Fig. 5) (Ennis-King & Paterson 2001).

CO_2 can be geologically stored in coal beds that are considered economically unmineable, or can be used to enhance coal seam methane recovery (ECSM). Since coals have a higher adsorption affinity for CO_2 than for CH_4 (Killingley 1990), CO_2 injection in coal, coupled with CSM production, is an attractive option for CO_2 storage. In reality, all CO_2 coal storage projects are likely to be in conjunction with an ECSM recovery program, as if CH_4 is present, CO_2 adsorption will release CH_4 from the coal matrix, which has a higher greenhouse radiative effect (21 times stronger by weight) than CO_2. The CH_4 therefore needs to be captured to ensure a net greenhouse emission mitigation outcome (Bachu et al. 2007). Technical challenges for CO_2 storage in coal seams include

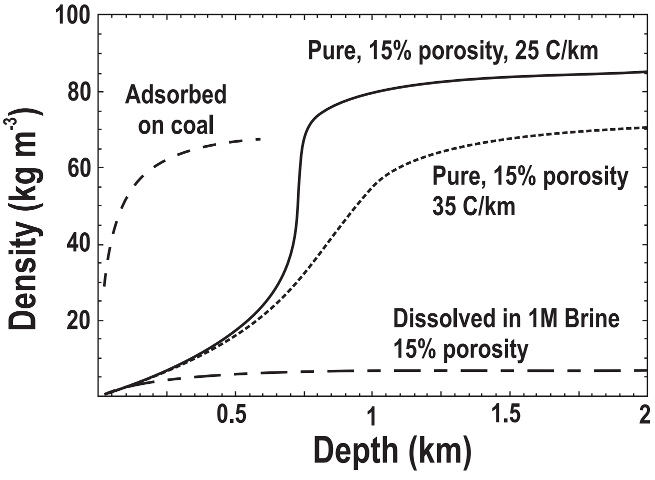

Figure 5. Total storage density as a function of depth, highlighting how the storage density of CO_2 adsorbed on coal at subcritical depths is comparable to the storage density of CO_2 captured in pore space at supercritical depths (hydrostatic pressure gradient is 10.5 MPa, mean surface temperature is 15°C and geothermal gradient is 25°C/km unless noted) (after Ennis-King & Paterson 2001).

the ability to inject the CO_2 due to the typically low permeability characteristics of the coal cleat system (especially with increasing depth and coal maturity), and the economic viability due to the large number of wells that may need to be drilled to overcome injectivity issues relating to low permeabilities (Gunter et al. 1997; Bradshaw & Rigg 2001; IPCC 2005). Research into CO_2 storage in coal is still at quite an early stage, and further work needs to be conducted to fully understand the processes involved and the most suitable coal characteristics for CO_2 storage (IPCC 2005).

Sedimentary basins of Victoria: location and geological setting

Victoria contains a number of sedimentary basins that were included for this study (Fig. 6). The oldest basins are the Wentworth Trough, Netherby Trough, Numurkah Trough and Ovens Graben. These are small northeast and northwest-trending Late Palaeozoic basins, located in the north and northwest of the state, underlying the more extensive and younger Murray Basin. The Otway Basin (including the Torquay Sub-basin) and the Gippsland Basin are large basins that are located in the south and offshore of Victoria. They formed during Mesozoic to Cenozoic times as a result of the separation of Antarctica from Australia. The Murray Basin is a large, shallow intracratonic basin located in the northwest and north part of the state, which developed during the Cenozoic. The Port Phillip and Westernport basins are small, shallow Cenozoic basins that underlie the present-day Port Phillip and Westernport bays in the south of the state (Fig. 6).

The Late Palaeozoic infrabasins (Wentworth Trough, Netherby Trough, Numurkah Trough and Ovens Graben) were initiated in basement depressions during the Late Silurian or Early Devonian (Knight et al. 1995; Driscoll 2006). Shallow marine to turbiditic sequences were deposited until the Middle Devonian Tabberabberan Orogeny, and in the Late Carboniferous to Early Permian, glacial conditions ensued and a sequence of marine and fluvio-glacial sediments were deposited within the infrabasins (Knight et al. 1995; Driscoll 2006). It is possible that much of Victoria was covered by glacial deposits at this time, which have since been mostly eroded away except for those areas where they were preserved by down-faulting, in bedrock depressions or covered by younger sediments (O'Brien et al. 2003). The Late Palaeozoic infrabasins are genetically unrelated to the other Mesozoic and Cenozoic sedimentary basins in Victoria (Birch 2003).

The large sedimentary basins in Victoria (Otway, Gippsland, Bass and Murray) are related to, or formed after, a major extensional episode during the Jurassic and Cretaceous associated with the breakup of Gondwana (Duddy 2003). This extensional episode ultimately resulted in the separation of Australia from Antarctica and the subsequent formation of the Southern Ocean and the Tasman Sea. Prior to the mid-Cretaceous, extension occurred along a major east–west trending rift system that followed the axis of the Otway, Bass, and Gippsland basins. This resulted in broad similarities of sediment fill between the three basins for the

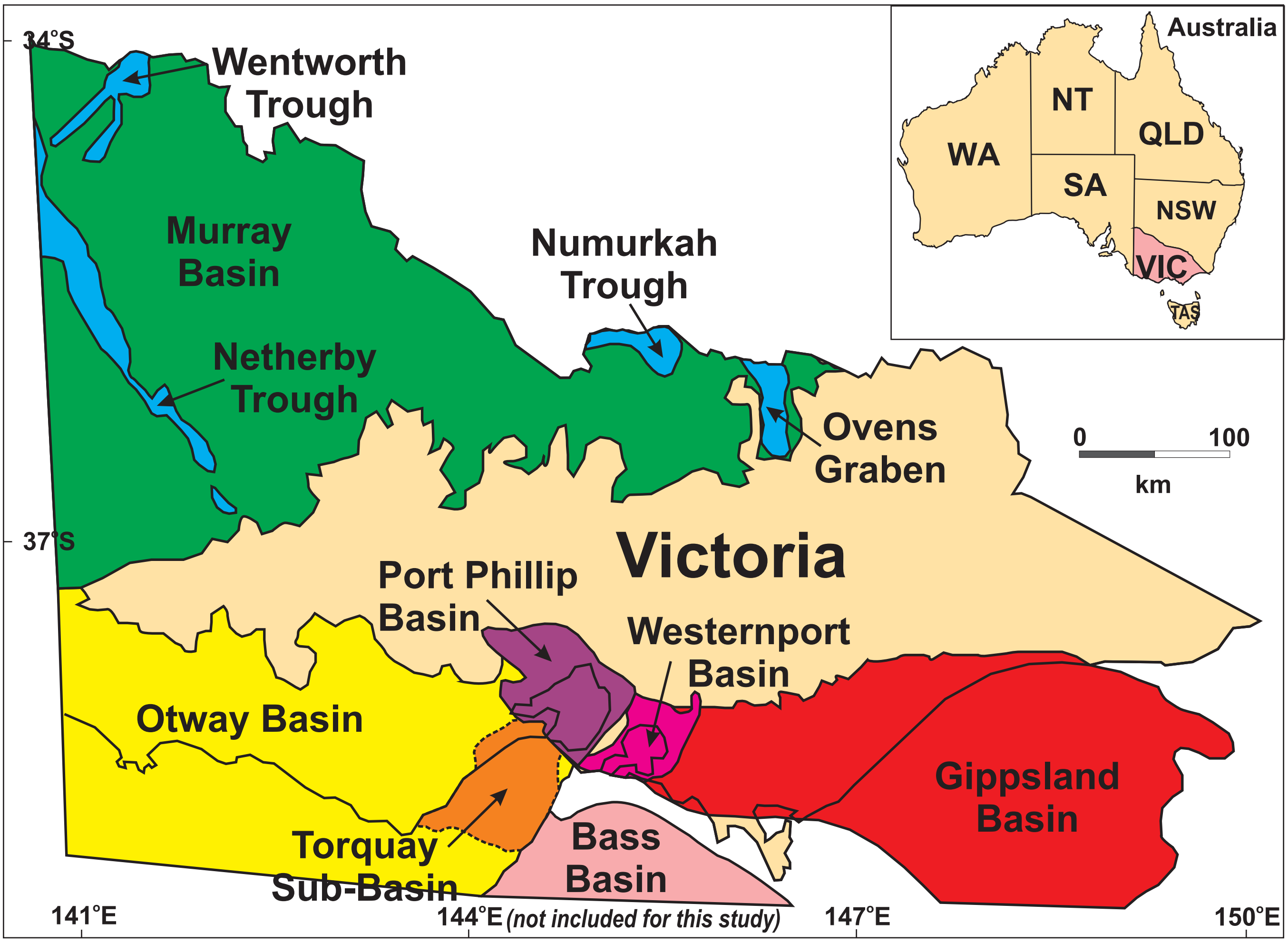

Figure 6. Map of Victoria, southeast Australia, showing the location of the sedimentary basins assessed for this study.

Jurassic and Early Cretaceous strata (Woollands & Wong 2001). Subsidence at the time was primarily associated with normal fault movement and the formation of a complex network of half-grabens, which accumulated thick, non-marine, synrift sediment successions (Woollands & Wong 2001).

The similarity in tectonic history between the basins ended in the mid-Cretaceous, when active rifting in the Otway Basin gave way to oceanic crust formation and a thermally-subsiding passive margin. This change in tectonic regime resulted in local uplift between the area of the present day Otway and Gippsland basins, and interrupted sediment exchange between the two basins (Duddy 2003). While for most of the Late Cretaceous, the Otway Basin was dominated by marine sedimentation, the Gippsland Basin remained a rift basin and accumulated thick non-marine lacustrine and alluvial deposits. Marine deposition in the Gippsland Basin did not occur until the Upper Campanian, when thermal subsidence and opening of the Tasman Sea resulted in a marine incursion (Woollands & Wong 2001; Duddy 2003).

Thermal subsidence and sag basin deposition in the Otway and Gippsland basins during the Tertiary resulted in the establishment of marine sedimentation. The Tertiary was also the time of significant sediment accumulation in the intracratonic Murray Basin—the largest basin in Victoria—when up to 600 m of terrestrial and marine sediment accumulated (Woollands & Wong 2001). The sea retreated from the Murray Basin at the end of the Pliocene due to the Kosciusko Uplift and fluvio-lacustrine sedimentation continued into the Quaternary (Cupper et al. 2003; Driscoll 2006).

Methodology for basin-scale screening and ranking of CO_2 geological storage potential

A regional characterisation process is used to establish the potential of an area for CO_2 geological storage before an actual site location can be selected. Sedimentary basins can be screened and ranked as to their overall suitability for CO_2 storage, based on geological, geographical and industrial characteristics. This study has adapted screening and ranking criteria developed by Bachu (2003), which includes factors such as tectonic setting, basin size and depth, intensity of faulting, hydrodynamic and geothermal regimes, existing resources and industry maturity. Table 1 documents the criteria that were used to assess the basin-scale suitability of each of the Victorian basins studied for geological storage of CO_2. For each criterion, the classes are arranged from least favourable (red) to most favourable (green) left-to-right across the table. The criteria relate to either the containment security, the volume of storage capacity achievable, or consider the economic or technological feasibility.

The present-day tectonic setting of a basin gives an indication as to the likely tectonic stability of the region, which is an important consideration for containment risk (i.e. tectonically-active areas, such as subduction zones, are the least favourable due to their increased susceptibility to natural earthquake risk and attendant fault seal failure). The basin size and depth reflects the possible storage capacity achievable, as the larger and deeper the basin is, the greater the likelihood of having laterally extensive reservoir and seal pairings, possibly in more than one stratigraphic interval. The depth of the sedimentary fill of the basin is also relevant to the phase state of the CO_2 (i.e. depths greater than ~800 m result in dense supercritical CO_2 and hence significantly increased storage capacity) and also impacts on the likely economic feasibility, as the greater the depth to the injection target the larger the associated costs of drilling. The stratigraphy of each area is reviewed to identify possible rock combinations that may provide reservoir and seal pairs. The reservoir-seal pairs criteria is a qualitative assumption about the likely abundance, lateral extent, thickness and depth of possible reservoir-seal horizons. Faulting intensity is both a containment and a capacity issue. The more extensively fractured that an area is, the greater the risk for containment breaches, and the lower the likely storage volume achievable due to the need to inject within individual fault blocks. The geothermal conditions of the basin impact the storage capacity, as within colder basins, more CO_2 can be contained within the same unit volume of rock due to the increased density of the CO_2.

The hydrocarbon potential of a region gives an indication of the suitability of the area for CO_2 storage, on the assumption that if the rocks are suitable for containing and storing oil and gas, then it is likely that they are also suitable for storing CO_2. Maturity of the extractive industries in the region reflects the likely database available, that is the more developed an area is the greater amounts of data available for CO_2 storage assessment. Coals are potential reservoirs and so their presence in sedimentary basins provides another possibility for CO_2 storage. Shallower coals are likely to have better permeability characteristics (and hence easier injection and less cost) than deeper coals, as well as increased storage efficiency at depths of 300–600 m (in comparison to saline formations/hydrocarbon reservoirs at the same depths). With respect to coal rank, bituminous coals are considered to be the best targets for CO_2 storage; although lignites have a better adsorption capacity, their higher moisture content means that the CO_2 is likely to dissolve into the water rather than adsorb onto the coal's surface. Evaporites or salt generally provide the best caprock seals, and hence the presence of salt, particularly in beds, is likely to be beneficial for CO_2 containment. Whether a basin is onshore or offshore provides an important economic consideration, as it is likely to be cheaper and easier to implement a CO_2 injection site onshore rather than offshore. The climate of the region affects the likely surface temperatures (and hence the geothermal conditions) and also the ease of development. Likewise, accessibility and infrastructure have an impact on the ease of future development.

Results of basin-scale screening

The sedimentary basins of Victoria were evaluated against the basin-scale suitability criteria adapted from Bachu (2003). Table 2 summarises the results of the screening criteria for each of the basins studied. A brief discussion of some of the key features of each basin is presented below.

Wentworth Trough

The Wentworth Trough extends from New South Wales into Victoria and only about one third of the basin is within Victoria. The Victorian portion of the basin is small in size, approximately 1,500 km^2. Gravity modelling suggests that the depth to the base of the trough varies from 1,640–2,330 m (Knight et al. 1995). A map of Victoria's earthquake occurrence and magnitude suggests that the area is mostly tectonically stable, as there is a lack of past epicentres over the Wentworth Trough area (Fig. 7). Possible reservoir horizons include fluvio-glacial to lacustrine and marine sandstone and conglomerate facies within the Late Carboniferous to Early Permian Urana Formation, intraformationally sealed by tillite (diamictite) and mudstone facies (Knight et al. 1995). However, these potential reservoir sediments are likely to be strongly cemented and so injectivity could be an issue (Bernecker 2004).

Criterion		Classes				
		1	2	3	4	5
1	**Tectonic stability**	Very unstable (e.g. subduction)	Unstable (e.g. syn-rift, intermontane, strike-slip)	Intermediate (e.g. foreland)	Mostly stable (e.g. passive margin)	Stable (e.g. cratonic)
2	**Size**	Very small (<1000 km^2)	Small (1000–5000 km^2)	Medium (5000-25000 km^2)	Large (25000–50000 km^2)	Very large (>50000 km^2)
3	**Depth**	Very shallow (<300 m)	Shallow (300–800 m)		Deep (>3500 m)	Intermediate (800–3500 m)
4	**Reservoir-Seal Pairs**	Poor		Intermediate		Excellent
5	**Faulting intensity**	Extensive		Moderate		Limited
6	**Geothermal**	Warm basin (>40°C/km)		Moderate (30–40°C/km)		Cold basin (<30°C/km)
7	**Hydrocarbon potential**	None	Small	Medium	Large	Giant
8	**Maturity**	Unexplored	Exploration	Developing	Mature	Over mature
9	**Coal**	None	Very shallow (<300 m)		Deep (>800 m)	Shallow (300–800 m)
10	**Coal rank**	Anthracite	Lignite		Sub-bituminous	Bituminous
11	**Salt**	None		Domes		Beds
12	**Onshore/ Offshore**	Deep offshore		Shallow offshore		Onshore
13	**Climate**	Artic	Sub-artic	Desert	Tropical	Temperate
14	**Accessibility**	Inaccessible	Difficult		Acceptable	Easy
15	**Infrastructure**	None	Minor		Moderate	Extensive

Table 1. Criteria for assessing sedimentary basins for CO_2 geological storage (modified after Bachu 2003).

Criterion	Went-worth Trough	Neth-erby Trough	Num-urkah Trough	Ovens Graben	Onshore Otway	Offshore Otway	Torquay Sub-basin	Onshore Gipps-land	Offshore Gipps-land	Murray Basin	Port Phillip Basin	Western-port Basin
Tectonic stability	Mostly stable	Mostly stable	Mostly stable	Mostly stable	Mostly stable	Mostly stable	Inter-mediate	Inter-mediate	Mostly stable	Stable	Mostly stable	Mostly stable
Basin Size	Small (1500 km^2)	Small (4000 km^2)	Small (3600 km^2)	Very small (760 km^2)	Medium (15500 km^2)	Very Large (62000 km^2)	Small (4480 km^2)	Medium (16000 km^2)	Large (40000 km^2)	Very large (80000 km^2)	Small (4500 km^2)	Very small (900 km^2)
Depth	Int. (2330 m)	Int. (2080 m)	Int. (1100 m)	Very shal. (<300 m)	Int. (<3500 m)	Deep (12000 m)	Deep (>6000 m)	Int. (<3500 m)	Deep (14000 m)	Shallow (<650 m)	Shallow (800 m)	Shallow (400 m)
Reservoir-Seal Pairs	Poor	Poor	Poor	Poor	Excellent	Excellent	Inter-mediate	Inter-mediate	Excellent	Poor	Poor	Poor
Faulting intensity	Moderate	Moderate	Mod. to limited	Assumed mod. to limited	Extensive to moderate	Extensive to moderate	Moderate to limited	Moderate to limited	Moderate to limited	Limited	Assumed mod. to limited	Assumed mod. to limited
Geothermal regime	Warm (42°C/km)	Warm (42°C/km)	Assumed Warm	Assumed Warm	Moderate (36°C/km)	Assumed Moderate	Assumed Moderate	Warm (45°C/km)	Assumed Moderate	Warm (42°C/km)	Assumed Moderate	Assumed Moderate
Hydrocarbon potential	None to small	None to small	None to small	None to small	Medium	Medium	Small	Small	Large	None	None	None
Maturity	Expl.	Expl.	Expl.	Exploration	Developing	Developing	Exploration	Exploration	Mature	Exploration	Exploration	Exploration
Coal	None	None	V. shal. to shal. ?	None	V. shallow to deep	Deep	V. shallow to deep	V. shallow to shallow	Deep	Very shallow	Very shallow	Very shallow
Coal rank	N/a	N/a	Assumed sub-bit.	N/a	Sub-bit. to lignite	Sub-bituminous	Assumed sub-bit.	Bituminous to lignite	Assumed bituminous to sub-bit.	Lignite	Lignite	Lignite
Salt	None	None	None	None	None	None	None	None	None	None	None	None
Onshore/ offshore	Onshore	Onshore	Onshore	Onshore	Onshore	Shallow to deep offshore	Onshore to shallow offshore	Onshore	Shallow to deep offshore	Onshore	Onshore to shallow offshore	Onshore to shallow offshore
Climate	Temp.	Temp.	Temp.	Temperate	Temperate	Temperate	Temperate	Temperate	Temperate	Temperate	Temperate	Temperate
Accessibility	Accept. to easy	Accept. to easy	Accept. to easy	Accept. to easy	Easy	Difficult to easy	Acceptable to easy	Easy	Difficult to easy	Acceptable to easy	Acceptable to easy	Acceptable to easy
Infrastructure	None to minor	None to minor	None to minor	None to minor	Moderate	Minor to moderate	None	Moderate	Extensive	None to minor	None to minor	None to minor

Table 2. Results of basin-scale screening criteria for each basin assessed in Victoria.

Netherby Trough

The Netherby Trough extends from South Australia into Victoria. The Victorian section is a small basin, approximately 4,000 km² in size. Gravity modelling by Knight et al. (1995) indicates that the depth to the base of the trough is approximately 2,000 m. As with the Wentworth Trough, the area appears to be fairly tectonically stable, with little past earthquake activity in the area (Fig. 7). Two potential reservoir horizons have been identified within the Netherby Trough: the Late Silurian–Early

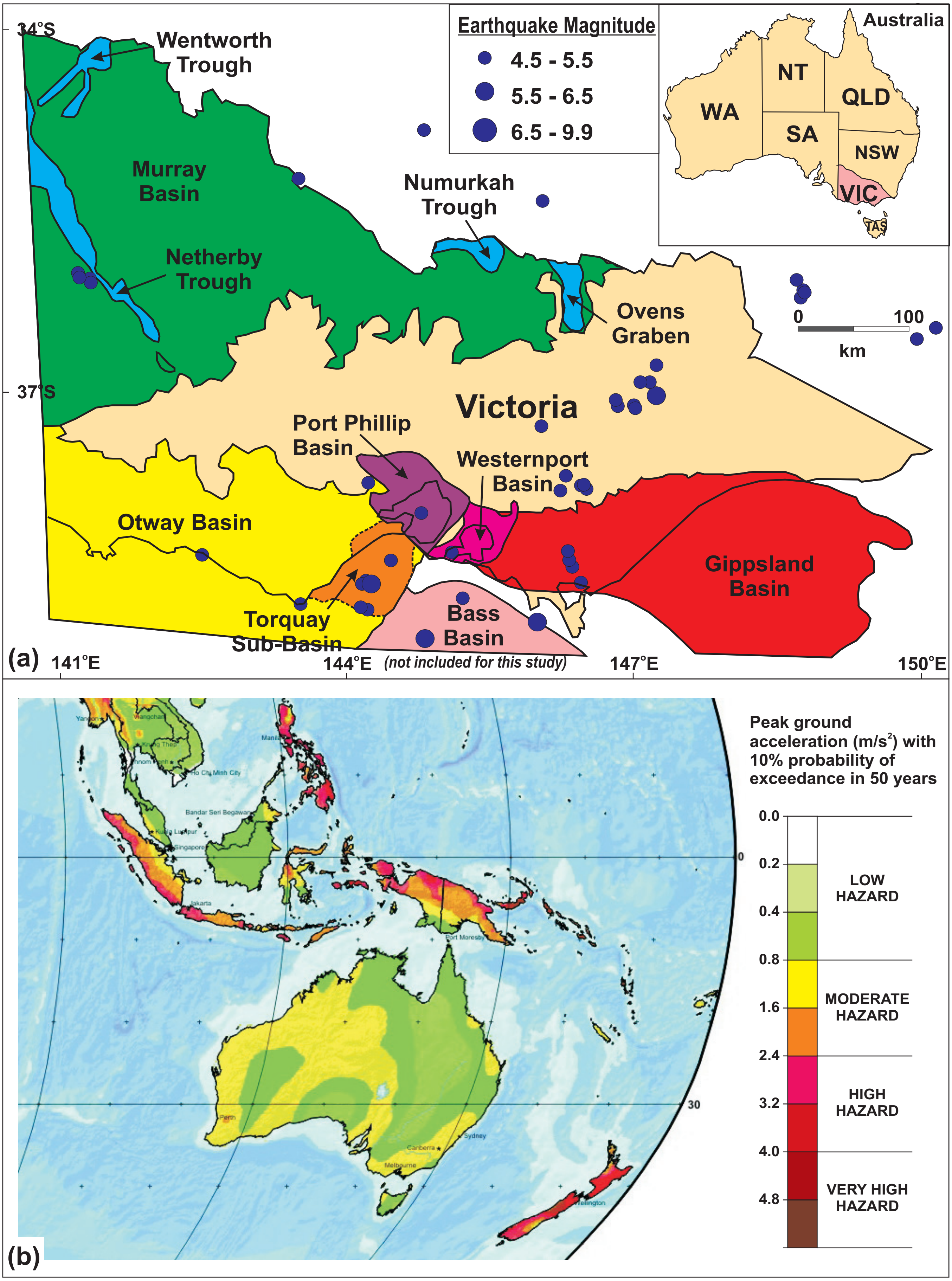

Figure 7. (a) Past earthquake occurrence (1840–2007) with magnitude 4.5 or greater for Victoria (modified after Geoscience Australia 2008). (b) Seismic hazard map for the southwest Pacific region of the Global Seismic Hazard Assessment Program (GSHAP) (modified after Giardini et al. 1999).

Devonian Grampians Group and the Late Carboniferous–Early Permian Urana Formation (Knight et al. 1995). The prospective seal horizons would be intraformational for both these reservoir intervals. However, the Upper Carboniferous–Lower Permian sediments may not occur at sufficient depths for supercritical CO_2, as the deepest intersected sediments were at a depth of only 466 m below ground level (Knight et al. 1995).

Numurkah Trough

The Numurkah Trough extends from New South Wales into Victoria, with about half located in Victoria, covering an area of approximately 3,600 km^2. The maximum depth of the sedimentary fill is about 1,100 m, and consists of fluvial-glacial sediments of the Permian Urana Formation (Holdgate 1995). The area is likely to be mostly tectonically stable, based on its past earthquake occurrence and present-day tectonic setting (Fig. 7). Very little is known about the Permian sediments and it is possible that reservoir quality may be inadequate despite the presence of adequate seal facies (Holdgate 1995). In contrast to the Netherby and Wentworth troughs, boreholes in the Numurkah Trough have intersected coal-rich sediments that are probably equivalent to the Late Permian Coorabin Coal Measures (Brown & Stephenson 1991).

Ovens Graben

The Ovens Graben extends from New South Wales into Victoria, with about one fifth of the graben area within Victoria, covering an area of only 760 km^2. The tectonic stability of the area is probably mostly stable, based on its present-day tectonic setting and past earthquake occurrence (Fig. 7). The basin fill consists of glacio-marine sediments of the Early Permian Urana Formation, unconformably overlain by Late Permian Coorabin Coal Measures, which are in turn unconformably overlain by Triassic clastics of the Jerilderie Formation (Yoo 1995). The Jerilderie-1 well in New South Wales intersected Permian sediments down to a depth of 1,328 m. However, the graben shallows significantly into Victoria and the Permian sediments in Victoria are less than 300 m deep (Holdgate 1995). In addition, the Coorabin Coal Measures do not appear to extend into the Victorian part of the graben (Holdgate 1995). Therefore, the potential for CO_2 storage in either saline formations or coal seams is extremely limited.

Otway Basin

The Otway Basin is a large basin extending from Cape Jaffa in South Australia to the northwestern coast of Tasmania (O'Brien et al. 2006). Approximately 50% of the basin is located within Victoria, covering an area of 77,500 km^2 (Woollands & Wong 2001). The sedimentary fill ranges in age from Late Jurassic to Recent, with up 12 km of sediments deposited in the deeper parts of the basin. The sedimentary fill consists of at least 6 km of Early Cretaceous rocks, 4 km of Late Cretaceous rocks and up to 2 km of Tertiary sediments (Duddy 2003). Faulting is most extensive in the lower synrift portion of the basin fill (Jurassic-Early Cretaceous), where a large number of half-grabens developed. Faulting intensity decreases into the Late Cretaceous section, with most deformation centred around a single offshore structural low, the Voluta Trough, which is surrounded by topographically high platforms (Woollands & Wong 2001). Faulting is least intensive in the overlying Tertiary passive margin sequence. Both the onshore and offshore Otway Basin areas are assessed as being relatively tectonically stable at present, as there is limited past earthquake activity (Fig. 7).

The Otway Basin has a long history of hydrocarbon exploration. Over 200 wells have been drilled with mixed success (Woollands & Wong 2001). The gas fields discovered in Victoria are reservoired within the Late Cretaceous Waarre Formation and occur onshore in the Port Campbell Embayment and offshore in the Shipwreck Trough. A total of 19 small gas fields have been discovered in the Port Campbell area and are at various stages of development (some are yet to be produced whilst others are nearing depletion) (Mehin & Kamel 2002; O'Brien et al. 2006). The depleted gas fields are potential sites for natural gas storage, and the Iona gas field has been used for this purpose since December 2000 (Mehin & Kamel 2002). CO_2 storage is another potential use for these depleted gas fields, and one of these depleted gas fields, Naylor, is currently being used to evaluate CO_2 storage as of April 2008 (CO2CRC 2008 a, b, c). Appendix 1 provides an estimate of the potential CO_2 storage capacity that may be available within the existing hydrocarbon fields once depleted.

Reservoir-seal pairs that may be suitable for CO_2 storage are abundant within the Cretaceous to Tertiary sequences of the Otway Basin, and potential CO_2 storage opportunities may exist in both deep saline formations and depleted hydrocarbon fields. Reservoir-seal pairs with CO_2 storage potential include:

- Pretty Hill Formation–Eumeralla Formation (Early Cretaceous): onshore area
- Intra-Eumeralla Formation (Early Cretaceous)
- Waarre Formation–Flaxman Formation/Belfast Mudstone (Late Cretaceous)
- Paaratte Formation–intra-Paaratte Formation/Massacre Shale (Late Cretaceous–Early Paleocene)
- Pebble Point Formation–Pember Mudstone (Early Paleocene –Early Eocene)
- Dilwyn Formation/Mepunga Formation–Narrawaturk Marl (Early–Late Eocene)

Table 3 details the key characteristics of each of these reservoir-seal pairs and Figure 8 maps their extents.

The Otway Basin also contains Cretaceous- and Tertiary-aged coals, although it is comparatively coal-poor in relation to the other Victorian sedimentary basins (Holdgate 2003). Early Cretaceous coals of the Otway Group are mainly sub-bituminous rank and occur at depths of zero to 2000 m (Ward 1995). Recent coal bed methane exploration by Purus Energy Ltd in the Aptian-Albian Eumerella Formation (Otway Group) has revealed very low permeability seams (< 1 mD) at depths of between 600–950 m. The seams had a lower than expected methane gas content and also a high nitrogen content, suggesting that the areas tested are not economic for coal seam gas (Purus Energy 2006). Whether other areas within the Early Cretaceous coal-bearing sequences have coal seam methane potential is presently unknown. Tertiary brown coal deposits are very limited within the Otway Basin, and only three small coal deposits within the upper part of the Dilwyn Formation have been mined at the northeastern end of the Port Campbell Embayment (Holdgate 2003; Holdgate & Gallagher 2003).

Torquay Sub-basin

The Torquay Sub-basin occupies an area of about 4,480 km^2, of which 90% is offshore. The sedimentary fill consists of 6–7 km of deposited sediments (Driscoll & Thomas 2004). The Early Cretaceous succession mirrors that of the Otway Basin, but the Late Cretaceous to Tertiary stratigraphy shares more similarities with the Bass Basin. The Torquay Sub-basin has a higher

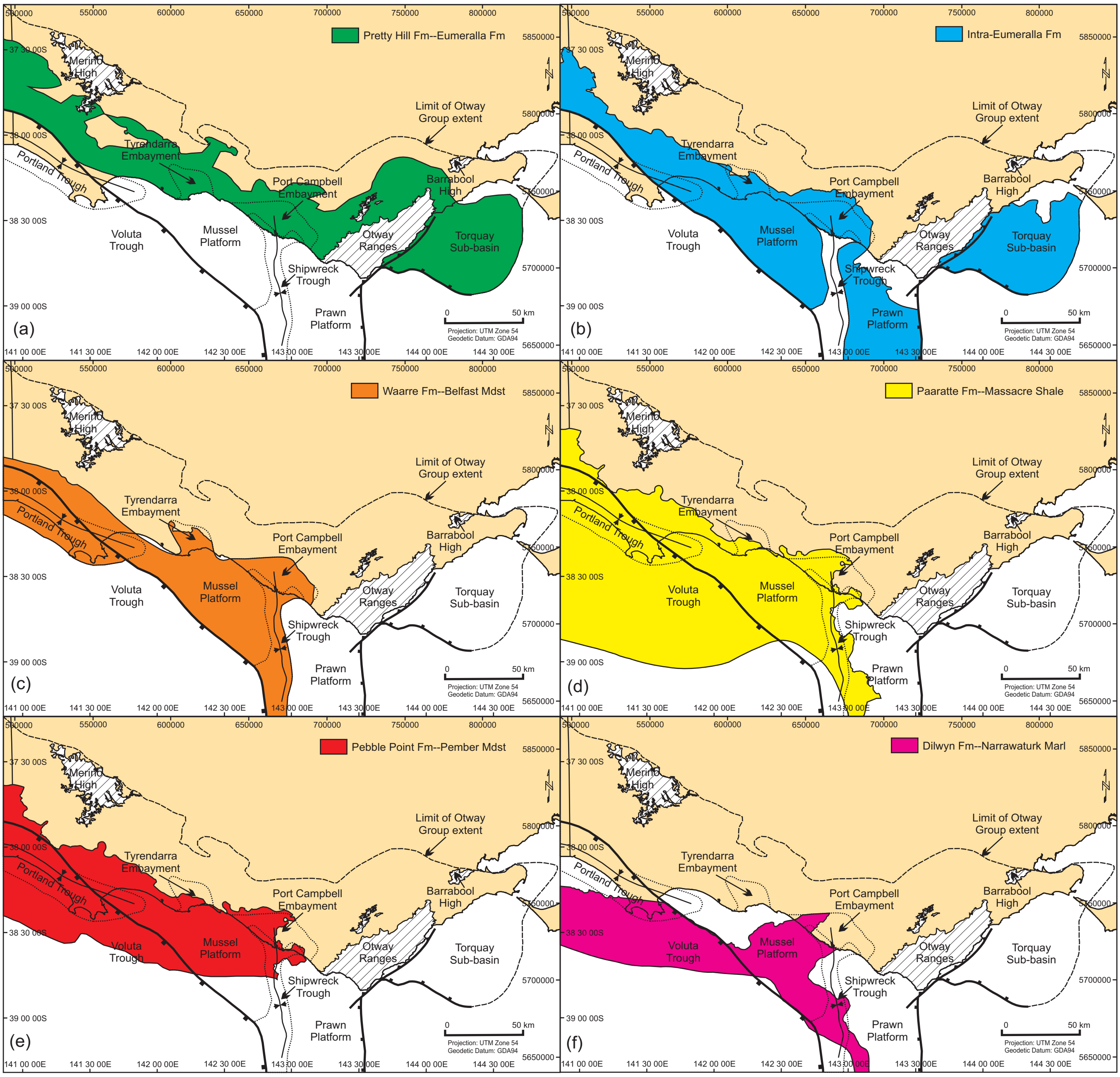

Figure 8. Extent of reservoir-seal pairs where they may be suitable for CO_2 storage in the Otway Basin, for: (a) Pretty Hill Formation-Eumeralla Formation; (b) intra-Eumeralla Formation; (c) Waarre Formation-Flaxman Formation/Belfast Mudstone; (d) Paaratte Formation-intra-Paaratte Formation/Massacre Shale; (e) Pebble Point Formation-Pember Mudstone; and (f) Dilwyn Formation/Mepunga Formation-Narrawaturk Marl.

number of reported earthquakes (Fig. 7a) and hence may not be as tectonically stable as the rest of the Otway Basin. However, this is just relative to the other Victorian basins, as Victoria (and Australia) on a global scale is classed as having a low to moderate earthquake hazard risk (especially in comparison to parts of Malaysia, Indonesia, Papua New Guinea and New Zealand) (Fig. 7b). Some hydrocarbon exploration has taken place within the Torquay Sub-basin, although there have been no discoveries to date from four wells.

Reservoir-seal pairs that may be suitable for CO_2 storage are present within the Cretaceous to Tertiary sequences of the Torquay Sub-basin, and potential CO_2 storage opportunities may exist in both the onshore and offshore deep saline formations. Reservoir-seal pairs with CO_2 storage potential include:

- Pretty Hill Formation–Eumeralla Formation (Early Cretaceous)
- Eastern View Group (Late Cretaceous to Mid Eocene)
- Boonah Formation–Anglesea Siltstone (Mid–Late Eocene)

Table 4 details the key characteristics of each of these reservoir-seal pairs and Figures 8 and 9 map their extents.

The Torquay Sub-basin also contains extensive brown coal deposits within the upper part of the Late Cretaceous to Eocene Eastern View Group. These coals are low rank lignites and occur at depths of 0–600 m (Barton 1995). The uppermost and thickest coal seam (the A Seam) is mined at Anglesea. The A Seam has a relatively high sulphur content of 3.8%, but has the lowest moisture content (44–48%) of any economic brown coal in Victoria (Holdgate 2003).

Reservoir-Seal Pair	Location	Onshore/ Offshore	Water Depth (m)	Depth Top Reservoir (m)	Permea-bility (mD)	Porosity (%)	Reservoir Thickness (m)	Seal Type	Seal Thickness (m)	Existing Resources
Pretty Hill Fm –Eumeralla	Northern Otway	Onshore	–	865–2950	0.01–5093 (avg. 704)	13–32 (avg. 21)	25–650	Regional (untested)	670–>2400	None
Intra-Eumeralla Fm	Western Otway	Onshore	–	0–3300	0.004–4.3	3–24 (avg. 19)	65–135	Local (untested)	n/a	None
Waarre Fm–Belfast Mudst	Western Otway	Onshore	–	625–2920	0.01–9000 (C unit)	1–29 (avg. 17)	5–290 (C_b = 6–60)	Regional (proven)	5–570 (Flx = 5–245)	19 known gas fields
Intra-Paaratte Fm	Western Otway	Onshore	–	245–1760	n/a	25–30	25–960	Local (untested)	10–30	None
Pebble Point–Pember Mdst	Western Otway	Onshore	–	210–1650	0.02–1135 (avg. 45.3)	5.5–31 (avg. 23)	10–145	Regional (untested)	15–490	Water?
Dilwyn Fm–Narrawaturk	Portland Trough & Port Campbell	Onshore	–	130–1055 (M = 90–640)	n/a	25–33	25–1020 (M = 10–220)	Regional (untested)	15–85	Main water aquifer
Intra-Eumeralla Fm	Prawn Platform	Offshore	40–80	0–2400	n/a	n/a	n/a	Local (untested)	n/a	None
Waarre Fm–Belfast Mudst	Portland, Mussel & Shipwreck	Offshore	< 100	1600–2500	30–20000	11–27	180–570	Regional (proven)	60–350 (Fl = 18–170)	6 known gas fields
Intra-Paaratte	Portland, Mussel Shipwrk & Voluta	Offshore	< 100–3000	840–1740	0.1–10000	12–38	105–1130	Local (untested)	5–25	None
Pebble Point–Pember Mdst	Portland, Mussel Shipwrk & Voluta	Offshore	< 100–1000	630–1300	low	26–44	35–130	Regional (untested)	35–1000	None
Dilwyn Fm–Narrawaturk	Voluta, Mussel & Shipwreck	Offshore	< 100–1000	715–900 (M=655–1195)	high	20–40	255–1000 (M=145–365)	Regional (untested)	90–565	None

Table 3. Summary of key characteristics of reservoir-seal pairs for CO_2 storage in the Otway Basin.

Reservoir-Seal Pair	Location	Onshore/ Offshore	Water Depth (m)	Depth Top Reservoir (m)	Permea-bility (mD)	Porosity (%)	Reservoir Thickness (m)	Seal Type	Seal Thickness (m)	Existing Resources
Pretty Hill Fm –Eumeralla	Torquay Sub-basin	Onshore & offshore	50–90	> 2500 offshore?	9.5–94.5	12.5–15.5	n/a	Regional (untested)	n/a	None
Intra-Eastern View Group	Torquay Sub-basin	Offshore	50–90	760–1000	Up to 1 D?	30	5–50	Local (untested)	10–60	None
Boonah Fm–Anglesea Slst	Torquay Sub-basin	Offshore	50–90	360–1380	1–2 D?	30–33	65–120	Regional (untested)	120–300	None

Table 4. Summary of key characteristics of reservoir-seal pairs for CO_2 storage in the Torquay Sub-basin.

Gippsland Basin

The Gippsland Basin covers an approximate total area of 56,000 km^2, of which one third is onshore and two thirds offshore (Driscoll 2006). The sedimentary fill ranges in age from the Early Cretaceous to Recent, with up to 14 km of sediments deposited in the main depocentres (Duddy 2003). The sediments of the Early–Late Cretaceous synrift succession are moderately faulted, but those in the overlying Maastrichtian–Eocene sag succession show only limited faulting. Past seismic activity is higher onshore than offshore, but is limited mainly to where the Strzelecki Group outcrops (Balook Block), suggesting that the basin is relatively stable tectonically (Fig. 7).

The Gippsland Basin is a mature hydrocarbon basin and one of Australia's most prolific oil and gas provinces. The majority of the oil and gas fields (~90 %) are trapped in structural closures formed in the coarse clastics at the top of the Latrobe Group, beneath the Lakes Entrance Formation regional seal. Most of the remaining significant reserves are trapped in intraformational or stratigraphic traps within the intra-Latrobe Group (Rahmanian et al. 1990). Some of the earliest oil fields to be developed are now reaching depletion and may be available for CO_2 storage within the next decade or so. Enhanced oil recovery using CO_2 was not being considered by the operators for the oil fields recently, since primary recoveries are already very high (Adem Djakic pers. comm. Esso Australia 2005). Appendix 1 provides an estimate of the potential CO_2 storage capacity that may be available within the existing hydrocarbon fields once depleted.

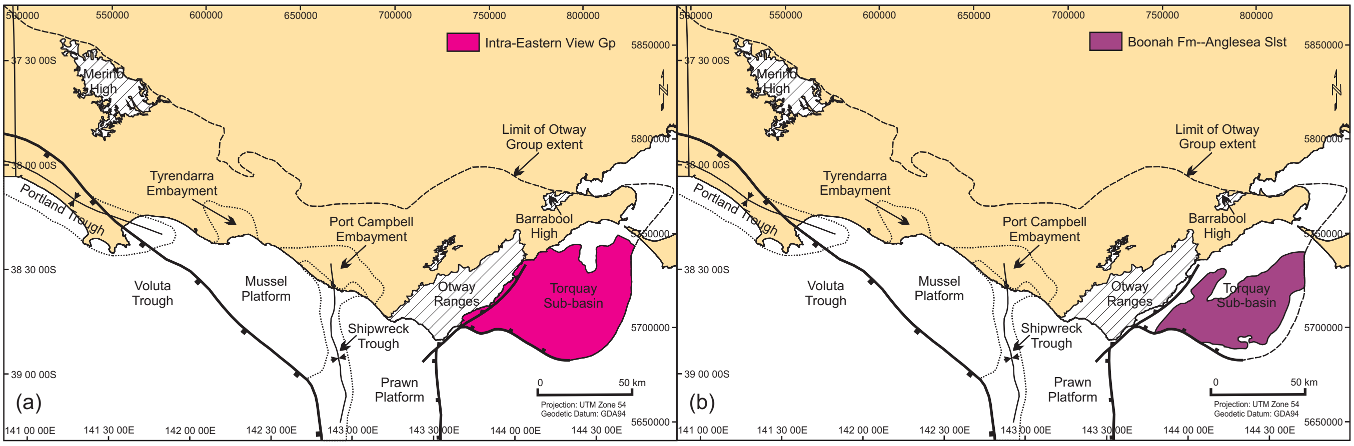

Figure 9. Extent of reservoir-seal pairs where they may be suitable for CO_2 storage in the Torquay Sub-basin, for: (a) intra-Eastern View Group; and (b) Boonah Formation-Anglesea Siltstone.

Reservoir-Seal Pair	Location	Onshore/ Offshore	Water Depth (m)	Depth Top Reservoir (m)	Permea-bility (mD)	Porosity (%)	Reservoir Thickness (m)	Seal Type	Seal Thickness (m)	Existing Resources
Intra-Strzelecki Gp	Seaspray Depression	Onshore	–	1250–1350	n/a	10–14	60–240	Regional (untested)	30	None
Intra-Golden Beach Subgp	Seaspray Depression	Onshore	–	1530	n/a	14	120	Local (untested)	n/a	(Golden Bch gas field)
Intra-Latrobe Group	Seaspray Depression	Onshore	–	900–1400	n/a	n/a	n/a	Local (untested)	25–200	Water?
Admiral Fm–Kipper Shale	Northern Terrace	Offshore	< 75	1785	n/a	7–11	125	Local (untested)	Up to 250	(Longtom gas field)
Curlip Fm–Kipper Shale	Southern Terrace	Offshore	~ 50	~ 1300	n/a	15–20	n/a	Local (untested)	n/a	None
Intra-Golden Beach Subgp	NE Central Deep	Offshore	100	1470–1950	400 +	18	100	Local (proven)	30–100	Kipper gas field
Intra-Golden Beach Subgp	SE Southern Terrace	Offshore	85	3600	n/a	15–20	n/a	Local (untested)	n/a	(Archer & Anemone)
Intra-Golden Beach Subgp	SE Central Deep	Offshore	165–275	3350–4150	n/a	13	30–230	Local (proven)	40	Archer & Angler
Intra-Golden Beach Subgp	Bass Canyon	Offshore	200–2000	> 4000	n/a	8–18	~ 500	Local (untested)	n/a	None
Intra-Latrobe Group	Central Deep & Northern Terrace	Offshore	50–100	1450–3370	1–3000	12–25	2–120	Local (proven)	n/a	10 known oil/gas fields
Base Eocene Channels	Central Deep	Offshore	~ 700	> 3000	n/a	n/a	n/a	Local (untested)	n/a	None ?
Top Latrobe Gp–LE Fm	Central Deep	Offshore	40–85	1090–2400	100–40000	19–27	12–225	Regional (proven)	150–700	17 known oil/gas fields
Top Latrobe Gp– LE Fm	Bass Canyon	Offshore	400	2810	10–5000	19	24	Regional (proven)	~ 300	Blackback oil field
Top Latrobe Gp– LE Fm	Southern Tce & Southern Platform	Offshore	15–800	860–1815	n/a	17–22	120–190	Regional (proven)	50–300	None
Intra-Seaspray Gp	Central Deep	Offshore	~ 60	1100–1300	n/a	10?	n/a	Regional (untested)	n/a	None

Table 5. Summary of key characteristics of reservoir-seal pairs for CO_2 storage in the Gippsland Basin.

Reservoir-seal pairs that may be suitable for CO_2 storage are plentiful within the Cretaceous to Tertiary stratigraphy of the Gippsland Basin, and potential CO_2 storage opportunities may exist in both deep saline formations and depleted hydrocarbon fields. Reservoir-seal pairs with CO_2 storage potential include:

- Tyers Conglomerate/Rintouls Creek Sandstone–intra-Strzelecki Group (Early Cretaceous): onshore area;
- Admiral Formation–Kipper Shale (Turonian): offshore area;
- Curlip Formation–Kipper Shale (Turonian): offshore area;
- Golden Beach Subgroup–intra-Golden Beach Group/basal Halibut Group (Late Cretaceous): onshore area;
- Intra-Golden Beach Subgroup (Santonian–Campanian): northeastern Central Deep area;
- Intra-Golden Beach Subgroup (Santonian–Campanian): southeastern offshore area;
- Intra-Golden Beach Subgroup (Santonian–Campanian): Bass Canyon area;
- Intra-Latrobe Group (Maastrichtian–Eocene);
- Base Eocene Channels–Flounder Formation/Lakes Entrance Formation (Eocene–Oligocene): offshore area;
- Top Latrobe Group–Lakes Entrance Formation (Eocene–Oligocene): Central Deep area;
- Top Latrobe Group–Lakes Entrance Formation (Eocene–Oligocene): Bass Canyon area;
- Top Latrobe Group–Lakes Entrance Formation (Eocene–Oligocene): Southern Terrace and Platform area; and
- Intra-Seaspray Group (Oligocene–Miocene): offshore area.

Table 5 details the key characteristics of each of these reservoir-seal pairs and Figure 10 maps their extents.

The Gippsland Basin also contains Cretaceous- and Tertiary-aged coals. Early Cretaceous coals of the upper Strzelecki Group are predominantly black coals of a high volatile bituminous rank. They usually occur at depths exceeding 300 m (Ward 1995). However, recent coal seam methane exploration in the western part of the Gippsland Basin discovered that individual seams are typically thin (<1 m thick) and had low gas contents (Karoon Gas Australia 2006), suggesting that neither CSM or ECSM with associated CO_2 storage may be viable options. The Tertiary coals are Australia's most extensive brown coal deposits and occur within the Traralgon, Morwell and Yallourn formations (Fig. 11). In onshore regions, these are very low rank lignites. The Morwell and Yallourn formations are mined extensively in open cut operations at Hazelwood, Loy Yang and Morwell. From a CO_2 storage perspective, the Traralgon Formation has the greatest potential, particularly in the eastern onshore Gippsland Basin. Here the Traralgon seams occur at depths of 300–700 m, and seam thicknesses aggregate up to 150 m thick (Barton et al. 1995; Holdgate et al. 2000; Birch 2003).

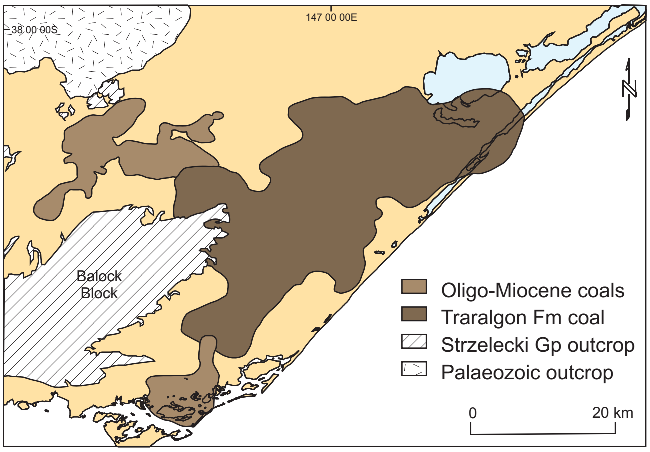

Figure 11. Distribution of Tertiary brown coals in the onshore Gippsland basin (modified after Holdgate et al. 2000).

Murray Basin

The Murray Basin is Victoria's largest sedimentary basin, covering an area of 80,000 km^2 in Victoria (300,000 km^2 in total across the three states) (Bernecker 2004). It is a shallow basin with relatively flat-lying Tertiary and Quaternary deposits. The sediments dip very gently and thicken towards the northwest

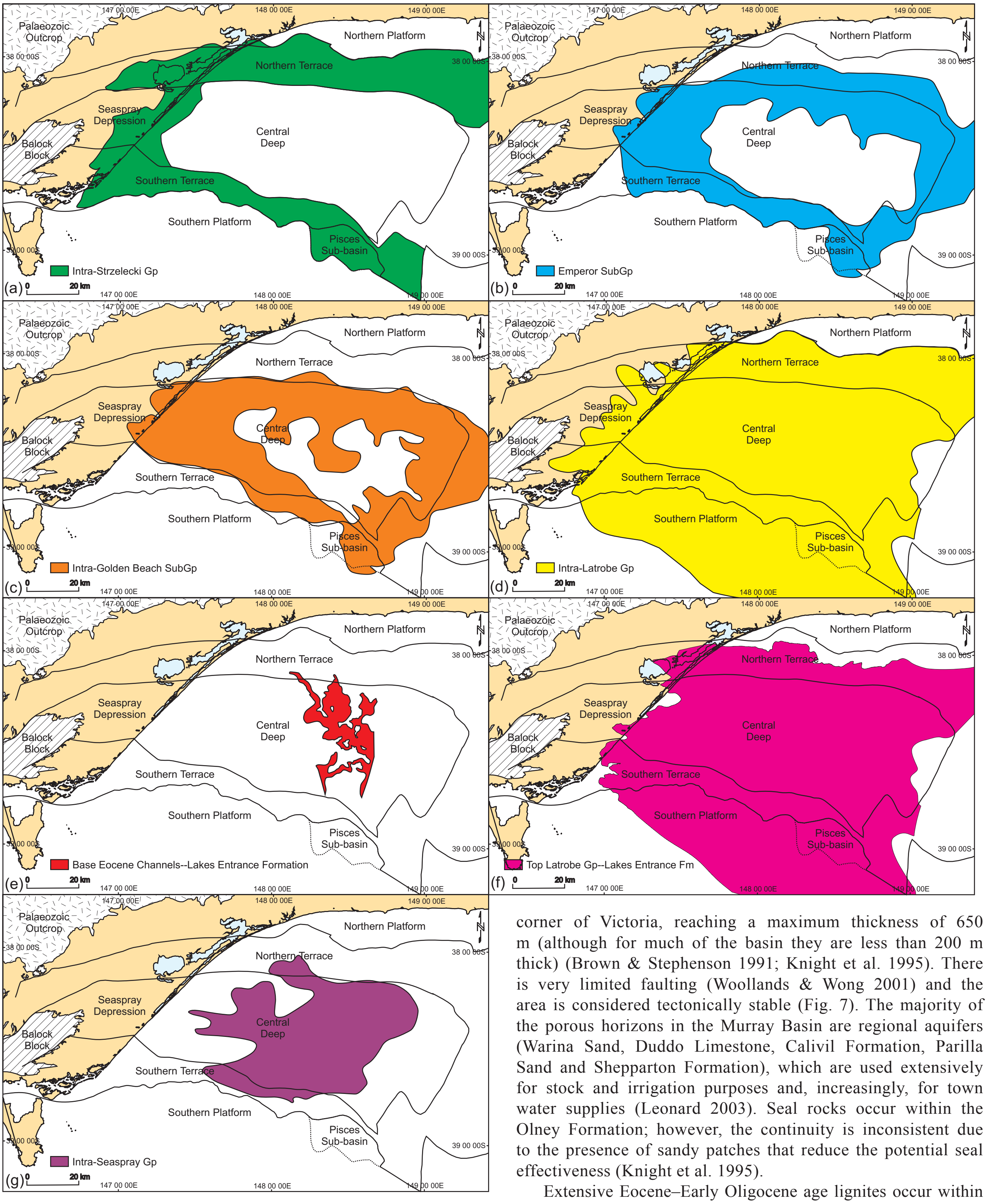

Figure 10. Extent of reservoir-seal pairs where they may be suitable for CO_2 storage in the Gippsland Basin, for: (a) intra-Strzelecki Group; (b) Emperor Subgroup (Admiral Formation–Kipper Shale and Curlip Formation–Kipper Shale); (c) intra-Golden Beach Subgroup; (d) intra-Latrobe Group; (e) Base Eocene channels–Lakes Entrance Formation; (f) top Latrobe Group–Lakes Entrance Formation; and (g) intra-Seaspray Group.

corner of Victoria, reaching a maximum thickness of 650 m (although for much of the basin they are less than 200 m thick) (Brown & Stephenson 1991; Knight et al. 1995). There is very limited faulting (Woollands & Wong 2001) and the area is considered tectonically stable (Fig. 7). The majority of the porous horizons in the Murray Basin are regional aquifers (Warina Sand, Duddo Limestone, Calivil Formation, Parilla Sand and Shepparton Formation), which are used extensively for stock and irrigation purposes and, increasingly, for town water supplies (Leonard 2003). Seal rocks occur within the Olney Formation; however, the continuity is inconsistent due to the presence of sandy patches that reduce the potential seal effectiveness (Knight et al. 1995).

Extensive Eocene–Early Oligocene age lignites occur within the Olney Formation (the upper part of the Renmark Group). There are only a few recognised coal seams, which range in thickness from 6–40 m and occur at depths of 0–300 m (Brown & Stephenson 1991; Holdgate 2003). Both the saline formations and the coal seams within the Murray Basin are likely to be unsuitable for CO_2 storage due to the shallow depths.

Basin	Containment	Capacity	Feasibility	Overall Suitability		Rank
Offshore Gippsland Basin	0.78	0.84	0.79	0.80	Very good	1
Onshore Otway Basin	0.67	0.68	0.82	0.72	Good	2
Offshore Otway Basin	0.72	0.77	0.64	0.71	Good	3
Onshore Gippsland Basin	0.61	0.68	0.82	0.70	Good	4
Torquay Sub-basin	0.67	0.65	0.64	0.65	Intermed.	5
Murray Basin	0.67	0.55	0.71	0.64	Intermed.	6
Numurkah Trough	0.61	0.52	0.75	0.63	Intermed.	7
Wentworth Trough	0.61	0.35	0.75	0.57	Poor	= 8
Netherby Trough	0.61	0.35	0.75	0.57	Poor	= 8
Port Phillip Basin	0.56	0.45	0.64	0.55	Poor	10
Westernport Basin	0.56	0.42	0.64	0.54	Poor	11
Ovens Graben	0.50	0.26	0.64	0.47	Very Poor	12

Table 6. Comparative ranking of each basin for containment, capacity, feasibility and overall suitability for CO_2 storage (sorted by rank from best to worst).

Port Phillip Basin

The Port Phillip Basin is a small basin, covering an estimated area of 4,500 km^2. The infill of Cenozoic sediments and volcanic rocks extend to depths of about 800 m in the central bay area. Onshore, the thickness is generally less than 250 m (Leonard 2003). The basin-bounding Rowsley and Selwyn faults have been intermittently active during the Quaternary (Cupper et al. 2003); however, the past earthquake occurrence and magnitude suggest that the area is mostly tectonically stable (Fig. 7). As with the Murray Basin, the majority of the porous rocks are aquifers (such as the sandstones, gravels and limestones of the Werribee, Fyansford and Bridgewater formations and the Brighton Group, plus basalts of the Older and Newer Volcanics), many of which are hydraulically interconnected (Leonard 2003). Brown coal seams are also present within the Paleocene–Eocene Yaloak Formation and the Oligocene–Early Miocene Werribee Formation (Holdgate 2003). However, this basin is generally unlikely to be suitable for CO_2 storage, as it is too shallow for both coal seam storage and saline formation storage.

Westernport Basin

The Westernport Basin is a very small basin, covering an area of only 900 km^2 (Leonard 2003). The Tertiary stratigraphy consists of Eocene Older Volcanics overlain by fluvial/paralic to marine sediments of the Baxter Formation and Sherwood Marl, and reaches a maximum thickness of 400 m (Holdgate & Gallagher 2003). The majority of the porous rocks are aquifers (such as the Childers Formation, Older Volcanics, Yallock and Baxter formations), from which the groundwater resources have been extensively exploited, principally for irrigation, stock and domestic uses. The basin was declared a Groundwater Conservation Area in 1971 to enable resource development to be controlled for the benefit of all users (Leonard 2003). The shallow depths of the rocks, plus the groundwater conservation status, mean that this basin is not likely to be suitable for CO_2 storage.

Qualitative ranking of potential CO_2 geological storage opportunities

The sedimentary basins of Victoria were evaluated against basin-scale suitability criteria adapted from Bachu (2003). Table 2 summarised the results of the screening criteria for each of the basins studied. Each of the criteria relate to either the containment security (e.g. tectonic stability), the volume of storage capacity achievable (e.g. basin size) or consider the economic or technological feasibility (e.g. onshore versus offshore). Some criteria can apply to more than one factor (e.g. depth can be a containment, capacity and feasibility issue). The basins were allocated simple scores for each criterion relevant to containment, capacity and feasibility, to provide a simple qualitative ranking to allow comparison between the characteristics of each basin. The results of this simple qualitative ranking are detailed in Appendix 2 and summarised in Table 6 and Figure 12.

The basin-scale suitability analysis established that the offshore Gippsland Basin has the best overall potential for CO_2 storage. The offshore Gippsland Basin has excellent potential because it has a deep sedimentary fill with numerous reservoir and seal horizons (including what appears to be a proven regional seal), has moderate to limited faulting (generally confined to the deeper stratigraphic intervals) and is relatively tectonically stable. It has mature hydrocarbon fields (many of which are reaching depletion) and has a well-established infrastructure framework. The onshore Otway Basin provides the best suitability for CO_2 storage in an onshore setting (within the state-owned areas). In comparison to the offshore Gippsland Basin, the onshore Otway Basin is more faulted, but its depth range is optimal for CO_2 storage capacity and drilling costs, and its onshore location means that the technological and economic feasibility is perhaps greater. The offshore Otway Basin and onshore Gippsland Basin are closely ranked behind the onshore Otway Basin, with similarly good characteristics for CO_2 storage. In terms of CO_2 storage in coals, the onshore Gippsland Basin has the best potential, as it has coals up to bituminous in rank located in the optimum depth range of 300–800 m.

The Torquay Sub-basin is fifth in the rankings. Its potential is slightly reduced due to its small size, its more limited number of reservoir-seal opportunities and its higher possibility of tectonic activity (comparatively). The Murray Basin ranks closely behind the Torquay Sub-basin, purely because of its large size, tectonic stability, limited faulting and its onshore location. However, the shallow depth for both the coal systems and the saline formations severely downgrade the suitability of this basin as a potential CO_2 storage opportunity. The remaining Cenozoic and Late Palaeozoic basins show little potential for CO_2 storage opportunities (with the Ovens Graben showing the least potential of all the areas assessed) because they are all too small, mostly too shallow and do not have suitable reservoir-seal pairs or coal systems.

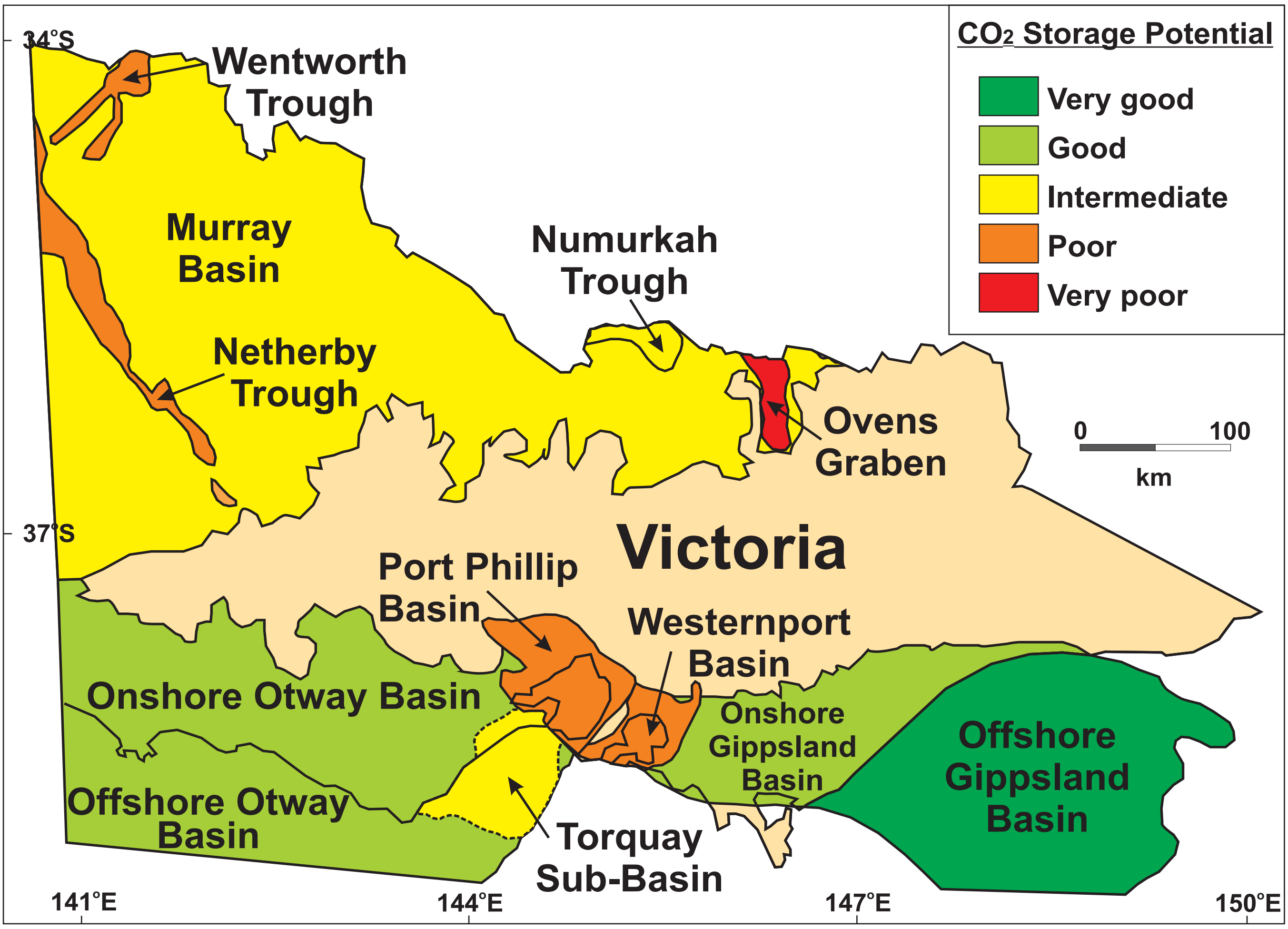

Figure 12. CO_2 storage potential of the sedimentary basins of Victoria.

Conclusions

The geology of the sedimentary basins of Victoria have been reviewed to assess the potential for carbon capture and storage (CCS) opportunities within Victoria and its adjacent waters. Utilising screening and ranking criteria modified from Bachu (2003), Late Palaeozoic, Mesozoic and Cenozoic basins were assessed on a number of geological, geographical and industrial characteristics. CO_2 geological storage options included deep saline formations, depleted oil and gas fields, and coal seams. A qualitative comparison between the various basins was undertaken. Based on currently available information, the main outcomes are as follows:

- The offshore Gippsland Basin has the most favourable characteristics for CO_2 geological storage, followed by the onshore Otway Basin, offshore Otway Basin and the onshore Gippsland Basin;
- The Ovens Graben has the least favourable characteristics for CO_2 geological storage;
- The storage prospectivity of the Cenozoic basins (Murray, Port Phillip and Westernport basins) and other Late Palaeozoic basins (Netherby, Wentworth and Numurkah troughs) is low because of being either too shallow, too small or without suitable geological horizons;
- The onshore Otway Basin provides the best potential for CO_2 storage within an onshore setting; and
- The onshore Gippsland Basin has the best potential for opportunities to store CO_2 within coal beds.

The basin-scale suitability assessments (including the identification of possible reservoir-seal pairs and coal systems) and the comparative rankings are all based on publicly available reports and data that were available at the time of this study (late 2006). The study is intended to provide a broad overview of the possible geological storage opportunities for CCS that may exist within Victoria, but is not an exhaustive study. As new data and information are obtained on the basins from continued exploration or subsequent release from confidential sources, the storage prospectivity of these basins will change and new opportunities may arise.

Overall, the geological settings of Victoria and its adjacent waters present considerable potential for CCS opportunities. The implementation of CCS technologies in Victoria may provide an important component of the overall strategy for reducing large volumes of greenhouse gas emissions to the atmosphere.

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Appendix 1: CO_2 storage capacity of existing hydrocarbon fields

An assessment of the available pore volume in the existing hydrocarbon fields of the Otway and Gippsland basins was undertaken to determine their possible CO_2 storage capacity once the fields are depleted. The main sources of information for the properties for each of the fields was Malek and Mehin (1998) and Mehin and Kamel (2002), with additional data supplemented from well completion reports where necessary. The reservoir volumes currently occupied by hydrocarbons were computed and converted to equivalent CO_2 volumes, using the equation:

Field	Pressure (psia)	Temp (degF)	Area (km^2)	Thick-ness (m)	Trap Geom. Corr. Factor	Net/Gross (%)	Porosity (%)	S_w (%)	RS_h (%)	Z Factor	B_g (ft^3/ft^3)	Capacity (Bcf)	Capacity (MMt)
Boggy Creek	2455	160	1.400	83.5	0.88	0.37	24.0	25.0	0.40	0.4543525	0.0032421	75.06	3.98
Dunbar	2117	145	1.119	8.5	0.81	0.88	21.0	48.0	0.40	0.4105999	0.0033151	7.88	0.42
Fenton Creek	2517	140	0.368	39.2	0.45	0.88	19.0	23.6	0.33	0.4094529	0.0027578	10.57	0.56
Grumby	2291	155	0.324	25.3	0.78	0.74	22.0	35.0	0.38	0.4400566	0.0033377	7.16	0.38
Iona	1739	134	3.000	30.0	0.60	0.80	22.0	21.0	0.31	0.4010447	0.0038705	68.29	3.62
La Bella	3232	201	0.813	83.0	0.87	0.35	17.0	35.0	0.40	0.5673011	0.0032783	24.02	1.27
Minerva	2745	203	4.700	120.0	0.68	0.89	18.0	17.0	0.40	0.5705607	0.0038939	460.64	24.44
Mylor	2301	150	1.133	66.0	0.71	0.40	21.4	45.2	0.33	0.4248125	0.0031820	27.41	1.45
North Paaratte	2020	153	1.474	12.0	0.88	0.79	25.0	34.0	0.40	0.4512863	0.0038695	18.48	0.98
Penryn	2171	153	2.500	81.0	0.52	0.23	19.0	27.0	0.41	0.4371279	0.0034874	33.28	1.77
Skull Creek	1614	132	0.167	18.3	0.71	0.93	27.0	38.0	0.41	0.4287104	0.0044429	2.67	0.14
Wallaby Creek	2163	152	1.407	7.0	0.94	0.94	25.0	30.0	0.40	0.4345401	0.0034739	15.47	0.82
Wild Dog Rd	1815	153	2.500	81.6	0.46	0.56	19.0	33.0	0.25	0.4907480	0.0046831	50.66	2.69
Total												**801.58**	**42.54**

Table 7. CO_2 storage capacity of existing hydrocarbon fields in the Otway Basin.

Field	Pressure (psia)	Temp (degF)	Area (km^2)	Thick-ness (m)	Trap Geom. Corr. Factor	Net/Gross (%)	Porosity (%)	S_w (%)	RS_h (%)	Z Factor	B_g (ft^3/ft^3)	Capacity (Bcf)	Capacity (MMt)
Angelfish	4656	226	6.83	52.0	0.87	59.23	14.0	57.0	0.30	0.6793435	0.0028282	96.34	5.11
Archer	5095	204	0.80	229.5	0.45	67.71	13.0	53.0	0.30	0.6877335	0.0025326	33.51	1.78
Barracouta	1705	170	60.00	133.0	0.85	92.48	25.0	20.0	0.30	0.5919589	0.0061802	5018.25	266.30
Batfish	2373	216	7.00	62.0	0.76	87.10	25.0	23.0	0.30	0.6283134	0.0050575	270.30	14.34
Blackback	4031	194	2.60	24.0	0.69	100.00	19.0	18.0	0.30	0.5983213	0.0027429	60.46	3.21
Bream	2770	194	54.00	78.0	0.74	64.10	22.0	20.0	0.30	0.5463054	0.0036445	2385.18	126.57
Cobia	3430	220	19.25	30.0	0.59	83.33	22.0	16.0	0.30	0.6095468	0.0034146	379.88	20.16
Dolphin	1805	155	3.00	19.5	0.35	56.41	25.0	21.0	0.30	0.5044568	0.0048572	11.61	0.62
Flounder	3689	220	24.00	84.0	0.74	79.76	21.0	23.0	0.30	0.6179318	0.0032185	1477.83	78.42
Fortescue	3433	220	44.00	79.5	0.67	69.18	20.0	22.0	0.30	0.6099045	0.0034136	1831.71	97.20
Grunter	5171	246	4.00	23.3	0.43	18.45	14.5	52.5	0.30	0.7033887	0.0027136	4.64	0.25
Halibut	3430	220	13.00	154.0	0.43	61.36	22.0	16.0	0.30	0.6095468	0.0034146	706.74	37.50
Kingfish	3318	215	77.00	83.0	0.63	74.70	21.0	18.0	0.30	0.5977472	0.0034360	3726.07	197.73
Kipper	3315	226	38.00	109.0	0.81	49.91	17.9	48.7	0.30	0.6196895	0.0036235	1046.03	55.51
Leatherjacket	1102	118	4.20	33.2	0.65	74.70	25.5	45.5	0.30	0.6116901	0.0090647	25.66	1.36
Luderick	2864	197	8.00	2.0	0.93	100.00	24.1	20.0	0.30	0.5519557	0.0035777	19.82	1.05
Mackerel	3430	220	46.00	100.0	0.68	91.10	20.0	22.0	0.30	0.6095468	0.0034146	3214.76	170.59
Marlin	2265	171	110.00	226.0	0.61	53.10	25.0	13.6	0.30	0.4976578	0.0039173	10975.39	582.42
Moonfish	2435	174	28.00	36.0	0.63	80.56	25.0	24.0	0.30	0.4974042	0.0036593	656.60	34.84
Perch	1795	151	3.10	38.0	0.68	44.74	27.0	15.0	0.30	0.4842569	0.0046574	43.65	2.32
Seahorse	2054	151	5.60	27.5	0.81	49.09	23.0	14.0	0.30	0.4376821	0.0036787	81.39	4.32
Snapper	2027	163	82.00	205.0	0.67	58.54	24.0	15.0	0.30	0.4938339	0.0042886	7752.51	411.39
Sunfish	3250	212	12.00	20.0	0.69	50.00	22.0	30.0	0.30	0.5901074	0.0034477	91.43	4.85
Tarwhine	2008	163	5.30	21.0	0.71	66.67	23.0	21.0	0.30	0.5001922	0.0043849	53.97	2.86
Tuna	2905	213	14.30	120.0	0.67	37.50	18.0	37.0	0.30	0.5920769	0.0038758	311.84	16.55
Turrum	3435	220	32.00	17.5	1.00	74.29	12.5	22.5	0.30	0.6099045	0.0034116	292.01	15.50
West Kingfish	3318	215	38.00	32.0	0.68	50.00	19.0	37.0	0.30	0.5977472	0.0034360	356.04	18.89
West Tuna	2006	163	27.00	12.0	0.97	91.67	24.0	35.0	0.30	0.5001922	0.0043892	253.11	13.43
Whiptail	1967	170	2.00	18.0	0.71	75.00	21.5	24.0	0.30	0.5336241	0.0048291	16.03	0.85
Whiting	2106	215	3.40	15.0	0.42	80.00	24.0	17.0	0.30	0.6566523	0.0059470	14.19	0.75
Wirrah	3764	220	5.40	100.0	0.70	26.00	12.0	50.0	0.30	0.6215237	0.0031727	45.94	2.44
Yellowtail	3376	198	18.00	10.5	0.68	100.00	18.8	33.0	0.30	0.5665743	0.0031202	127.91	6.79
Total												**41380.84**	**2195.91**

Table 8. CO_2 storage capacity of existing hydrocarbon fields in the Gippsland Basin.

$$CO_2 \text{ volume} = a * t * c * n/g * Ø * (1\text{-}S_w) * (1\text{-}RS_h) * (1/B_g) \quad [\text{ Eq.1}]$$

where: a is area, t is thickness, c is trap geometry correction factor, n/g is net thickness/gross thickness, Ø is porosity, S_w is water saturation, RS_h is residual hydrocarbon saturation (assumed to be 40% in the Otway Basin and 30% in the Gippsland Basin where not known), and B_g is the CO_2 formation volume factor.

B_g was calculated using the equation:

$$B_g = C\,\frac{zT}{P} \qquad [\text{Eq. 2}]$$

where: C is a constant of 0.02827 for B_g in scf/scf, z is the compressibility factor of CO_2, T is temperature in Rankine, and P is pressure in psia. The compressibility z-factor for each field was calculated using a CO_2 thermophysical properties website calculator created by the Carbon Capture and Sequestration Program at the Massachusetts Institute of Technology (MIT 2008), using site-specific pressure and temperature data.

Conversion factors used were as follows:

- cubic metres (m^3) to cubic feet (ft^3): 35.31467
- trillion cubic feet (Tcf) to million tonnes (MMt): 53.0657705140448 (assumes 14.65 psia and 60°F surface conditions).

The CO_2 storage capacity (available pore volume) for each of the hydrocarbon fields in the Otway Basin is shown in Table 7 and for the Gippsland Basin in Table 8. The Gippsland Basin hydrocarbon fields are considerably larger than those in the Otway Basin and this is reflected in the storage space available for CO_2. The assessment shows that the existing hydrocarbon fields in the Otway Basin have the potential to store ~40 MMt, whilst those in the Gippsland Basin have the potential to store ~2,000 MMt CO_2. It is important to note that this number represents the structural closures only, and does not take into account the potentially significant additional capacity that could be obtained through stratigraphic trapping deeper than the structural closures, dissolution into the formation water and residual gas trapping along the migration pathways.

Appendix 2: Methodology and detailed results of ranking process

The final ranking of the sedimentary basins of Victoria was calculated by allocating simple scores for each criterion relevant to containment, capacity and feasibility. Tables 9, 10 and 11 document the criteria and scores allocated for containment, capacity and feasibility, respectively. The maximum score that could be achieved for any criteria was determined by the number of classes for each criteria (listed in parenthesis underneath each criteria). The normalised totals for containment, capacity and feasibility were summed and divided by three to calculate the mean average to provide the final ranking.

Basin	Tectonic Stability (5)	Depth (4)	Reservoir-Seal Pairs (3)	Faulting Intensity (3)	Salt (3)	Total (18)	Normalised Total
Wentworth Trough	4	3	1	2	1	11	**0.61**
Netherby Trough	4	3	1	2	1	11	**0.61**
Numurkah Trough	4	3	1	2	1	11	**0.61**
Ovens Graben	4	1	1	2	1	9	**0.50**
Onshore Otway Basin	4	3	3	1	1	12	**0.67**
Offshore Otway Basin	4	4	3	1	1	13	**0.72**
Torquay Sub-basin	3	4	2	2	1	12	**0.67**
Onshore Gippsland Basin	3	3	2	2	1	11	**0.61**
Offshore Gippsland Basin	4	4	3	2	1	14	**0.78**
Murray Basin	5	2	1	3	1	12	**0.67**
Port Phillip Basin	4	2	1	2	1	10	**0.56**
Westernport Basin	4	2	1	2	1	10	**0.56**

Table 9. Scores allocated for criteria relating to containment.

Basin	Size (5)	Dpt (4)	Res-Seal Pairs (3)	Fault Inten (3)	Geo-thml Grad (3)	HC Pot (5)	Coal (4)	Coal Rank (4)	Total (31)	Normalised Total
Wentworth Trough	2	3	1	2	1	1	1	0	11	**0.35**
Netherby Trough	2	3	1	2	1	1	1	0	11	**0.35**
Numurkah Trough	2	3	1	2	1	1	3	3	16	**0.52**
Ovens Graben	1	1	1	2	1	1	1	0	8	**0.26**
Onshore Otway Basin	3	3	3	1	2	3	3	3	21	**0.68**
Offshore Otway Basin	5	4	3	1	2	3	3	3	24	**0.77**
Torquay Sub-basin	2	4	2	2	2	2	3	3	20	**0.65**
Onshore Gippsland Bn	3	3	2	2	1	2	4	4	21	**0.68**
Offshore Gippsland Bn	4	4	3	2	2	4	3	4	26	**0.84**
Murray Basin	5	2	1	3	1	1	2	2	17	**0.55**
Port Phillip Basin	2	2	1	2	2	1	2	2	14	**0.45**
Westernport Basin	1	2	1	2	2	1	2	2	13	**0.42**

Table 10. Scores allocated for criteria relating to capacity.

Basin	Dpth (4)	Fault Inten (3)	Mat-urity (5)	On/Offs hore (3)	Clim-ate (5)	Access-ibility (4)	Infra-structure (4)	Total (28)	Normalised Total
Wentworth Trough	4	2	2	3	5	3	2	21	**0.75**
Netherby Trough	4	2	2	3	5	3	2	21	**0.75**
Numurkah Trough	4	2	2	3	5	3	2	21	**0.75**
Ovens Graben	1	2	2	3	5	3	2	18	**0.64**
Onshore Otway Basin	4	1	3	3	5	4	3	23	**0.82**
Offshore Otway Basin	3	1	3	2	5	2	2	18	**0.64**
Torquay Sub-basin	3	2	2	2	5	3	1	18	**0.64**
Onshore Gippsland Bn	4	2	2	3	5	4	3	23	**0.82**
Offshore Gippsland Bn	3	2	4	2	5	2	4	22	**0.79**
Murray Basin	2	3	2	3	5	3	2	20	**0.71**
Port Phillip Basin	2	2	2	2	5	3	2	18	**0.64**
Westernport Basin	2	2	2	2	5	3	2	18	**0.64**

Table 11. Scores allocated for criteria relating to feasibility.