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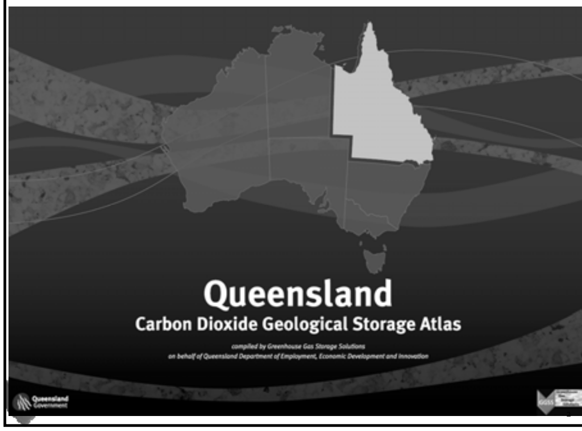
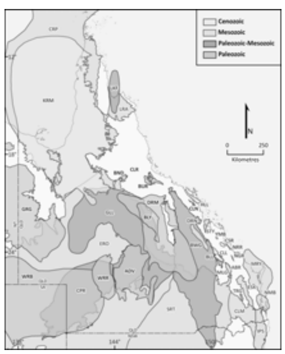
REGIONAL SCALE ASSESSMENT – METHODOLOGY DEVELOPED FOR THE QUEENSLAND ATLAS



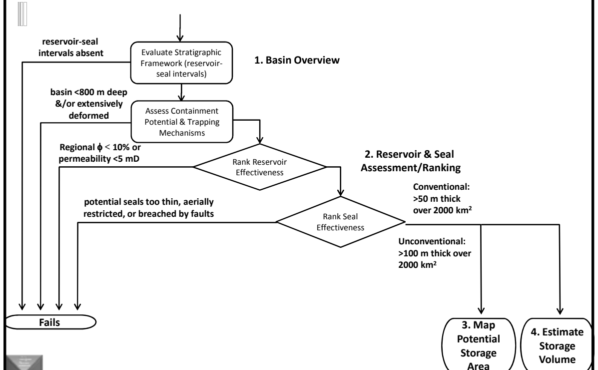
Queensland CO_2 Storage Atlas

- Stage 1 of QDME Carbon Geostorage Initiative: **768 – 1,296** Mt storage capacity required for major emission nodes
- 36 Queensland basins assessed for geological storage prospectivity
- High-grade basins for more detailed studies & data acquisition to identify storage sites
- Geological assessment – excludes existing resources
- Product includes A3 hardcopy atlas and GIS (ArcGIS and MapInfo formats)



Assessed sedimentary basins classified by age

CGSS Assessment Process



Aim of CGSS Regional Methodology

- Repeatable
- Rely on “prospectivity” assessment to drive capacity estimate (map “fairways”)
  - not algorithms in a spreadsheet (divorced from rocks)
- Based on actual rock characteristics and distributions
  - Not supplanted from elsewhere
  - Avoid wherever possible generic or non site specific probabilistic distribution assumptions
    - e.g. CO_2 density, net/gross, SE
- Produce reliable conservative values
  - That policy groups can plan on with certainty
    - e.g. not enormous academic / theoretical numbers – but real / sensible numbers based on “invaded area”

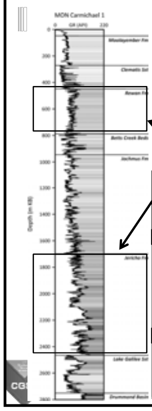
Ranking Methodology

- Reservoir assessed solely for potential to have a reliably sealed effective storage area with good injectivity
- Each reservoir ranked for its seal effectiveness & reservoir effectiveness
- Does not dismiss a reservoir due to lack of data – allows for uncertainty due to lack of data

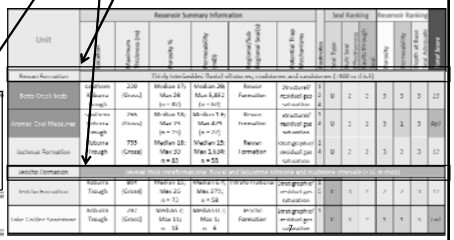
	Ranking Criteria	*Ranking Criteria Selection Options*
Seal Effectiveness	Conventional Seal	Adequate regional conventional seal likely.
		Plausible that significant regional/subregional seals present.
		No significant seal.
	Unconventional Seal	Adequate regional unconventional seal likely.
		Plausible that unconventional seal is extensive.
		No significant unconventional seal present.
	Faults through Seal	No faults mappable or not pervasive.
		Plausible that no significant faults present.
		Multiple faults and/or displacement ≥ seal thickness.
Reservoir Effectiveness	Porosity	Regionally well defined with ≥10 % porosity.
		Plausible that effective storage pore space present.
		Reservoir facies ineffective <10 % porosity.
	Permeability	Permeability known to be good to adequate.
		Plausible that permeability or injectivity adequate.
		Permeability known to be poor or absent.
	Depth at Base of Seal Adequate	~800 m below hydrostatic head.
		~650-800 m below hydrostatic head.
		~650 m below hydrostatic head.

Ranking	Score
Acceptable	3
Uncertain	2
Below Minimum	1

Conventional vs Unconventional seals

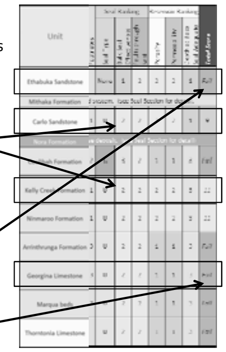


- 'Conventional' seals act as a physical barrier (trap) to the migration of fluids (e.g. Jericho Formation).
- Unconventional seals potentially include greensands, siltstones and very fine-grained sandstones. The main feature is very low but effective bulk rock permeability. To be considered as an unconventional seal the formation has be > 100 m thick over an area of ~2000 km² (e.g. Rewan Formation – Galilee Basin)



Ranking Methodology

- A reservoir that does not have a 'conventional' seal immediately overlying it is set to 'unconventional' and ranked as a 2 (e.g. Kelly Creek Fm).
- The Depth at Base of Seal Adequate is not set as an automatic fail (e.g. Carlo Sandstone)
- Failure occurs if:
  - there is neither 'conventional' nor 'unconventional' seal above the reservoir (e.g. Ethabuka Sandstone);
  - if either the porosity or the permeability of the reservoir is below its respective minimum cut-off (e.g. Georgina Limestone)



Georgiga Basin Ranking Chart

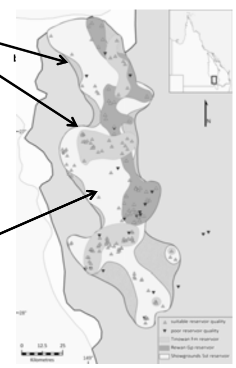
Potential Storage Area Mapping

- Maps generated for the maximum known extent of reservoir-seals intervals within a basin that are evaluated as having potential for geological storage of CO_2
- The maximum potential storage area incorporates
  - A regional seal >800 m deep at its base
  - A seal of suitable thickness to contain CO_2 (>50 m for conventional seal; >100 m for unconventional seal),
  - A suitable quality reservoir for CO_2 (porosity ≥ 10 %; permeability ≥ 5 mD).
    - Note: permeability should probably be much higher; depends on clients requirements
- However, the level of detail in mapping maximum potential storage area varies from basin to basin depending on the data availability and geological complexity.

Storage Area "Fairway"

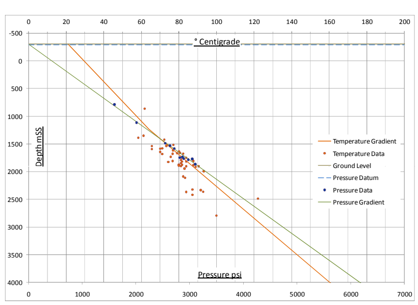
1. Define storage area ("Fairway")

- Extent of regional seal (Snake Creek Mudstone/Moolayember Fm) and reservoir fairways used to define probable storage area in Southern Bowen Basin over the Roma Shelf/Wunger Ridge.
- Fairways difficult to map in detail due to association with thin and narrow fluvial channel sandstones, lack of 3-D seismic data, and limited palaeo-geographic maps
- Showgrounds Sandstone most widespread reservoir – contains good quality sandstones to depths of 2,300 m in high energy fluvial channels
- Reservoir quality generally deteriorates towards eastern flank, but difficult to map where reservoirs end in Taroom Trough



Sth Bowen Basin fairway map

Temperature & Pressure

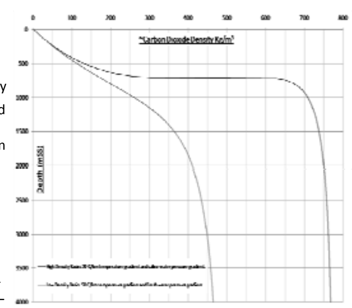


2. Calculate temperature and pressure gradients from WCR's

- Temperature gradient ~35°C through southern Bowen Basin
- Pressure gradient ~1.4374 psi/m

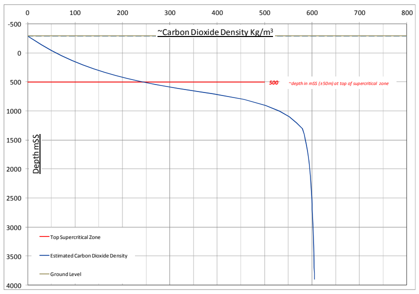
CO_2 Density

- Under the normal range of pressure/ temperature conditions found in sedimentary basins, the density of CO_2 can vary significantly
- Uses the industry standard method of calculating CO_2 density using pressure & temperature data (Span and Wagner 1996).
- The precision of the CO_2 density estimate depends on the accuracy of pressure and temperature estimates.
- Data obtained from CSIRO Pressureplot database, then cross-checked with well data (ideally 10–20 data points).



CO_2 density given two end-member basin conditions: a hot fresh-water (red curve) and a cold saline-water basin (blue curve).

CO_2 Density



3. Calculate CO_2 density gradient

- Supercritical below 500 m SS (800 mGL)
- Little increase in density below 1,300 mSS (1,600 mGL)

Volumetric Equation

The equation for volumetric estimation is:

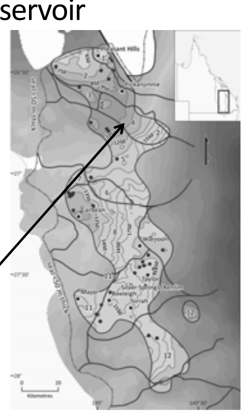
$$MCO_2 = RV * Ø * Sg * \delta_{(CO2)}$$

- *MCO_2 = mass of CO_2 stored in kilograms*
- *RV = total reservoir rock volume in m^3*
- *Ø = total effective pore space (as a fraction)*
- *Sg = the gas saturation within the above pore space as a fraction of the total pore space (10 %)*
- *$\delta_{(CO2)}$ = the density of CO_2 at the given reservoir depth (pressure and temperature) in kg/m^3.*

Area & Reservoir

4. Calculate Areas & Reservoir Parameters:

- Area calculated for each depth range over mapped storage area
- Average net pay zone thickness obtained from gas fields over reservoir area
- Average porosity obtained from QPED database
- Drainage cells defined but not used in calculations (beyond regional scope of Atlas)
- Alternatively, can use isopach maps and regional porosity trends if known (e.g. Eromanga Basin)



Storage Capacity estimates

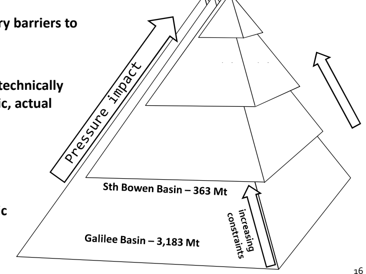
Matched capacity:
Detailed matching of sources and sinks including supply and reservoir performance assessment

Practical (Viable) capacity:
Applies economic and regulatory barriers to realistic capacity,

Effective (Realistic) capacity:
Applies technical cut off limits, technically viable estimate, more pragmatic, actual site / basin data

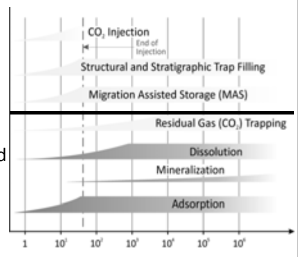
Theoretical capacity:
includes large volumes of "uneconomic" opportunities. Approaches physical limit of pore rock volume ; unrealistic and impractical estimate

Increasing constraints of technical, legal, regulatory and commercial certainty



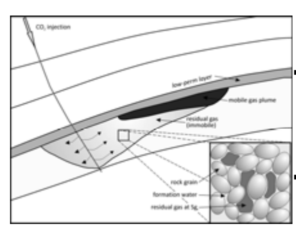
Trapping Mechanisms

- There are different mechanisms which immobilise (trap) CO_2 in the subsurface, and the timescales over which they operate (Bachu et al. 2007).
- The lower three mechanisms (dissolution, mineralisation and adsorption) are, mostly, very long-term and are not considered here further.
- The volumetric estimations calculated in this atlas are based around free-phase trapping



Time dependency of processes involved in CO2 geological storage (modified after Bachu et al. 2007). Top four green processes are relevant to the atlas.

MAS – Migration Assisted Storage

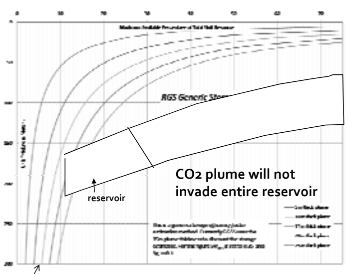


Schematic of trail of residual CO_2 that is left behind because of snap-off as the plume migrates upwards during post-injection period (modified from Juanes et al. 2006)

- The migration assisted storage (MAS) process is the main process that can theoretically store enormous quantities of CO_2 in the absence of any subsurface closure.
- The dominant primary trapping mechanism in MAS is discontinuous free-phase trapping as *residual gas saturation (RGS)* in the trail of a migration plume.
- Using the porosity cut-offs a residual gas saturation (Sgr) of 0.2-0.6 is likely but this is difficult to calculate without core. Therefore a likely conservative value of Sgr = 0.1 has been used for all volumetric calculations.
- Ultimately the CO_2 trapped by these mechanisms is dissolved into the surrounding formation water

Invaded Volume efficiency factor

- Simple volumetric estimation calculations overestimates capacity: calculating the volume of CO_2 that could be stored over the *entire* reservoir unit.
- As the migrating plume will not access a large proportion of the reservoir this value is unrealistic (assuming homogenous reservoir, injection over entire interval, & entire formation water displaced uniformly)
- Therefore to limit extreme values developed a very basic Invaded Volume efficiency factor - 15m plume estimate used



As the reservoir thickness increases, a smaller proportion of the total reservoir volume can be theoretically considered as potentially available for storage.

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19

Showgrounds Sandstone example

Basin:	Southern Bowen	Ranked Reservoir Unit:	Showgrounds Sandstone	Storage Mechanism:	Residual Gas Saturation

Estimated theoretical carbon dioxide storage resource of the Southern Bowen Basin - Showgrounds Sandstone reservoir is 191 Megatonnes

Regional Storage Volume Estimation - Data Quality		Comment
Structural Surface Constraints:	Good	Regional GA/GSQ interpretation - considered likely to be accurate ± 100 m.
Reservoir Thickness Constraints:	Fair	Braided fluvial channels - generally trending east west - intersected randomly by wells.
Reservoir Porosity Constraints:	Good	Measured porosities from QPED database.
Reservoir Sg. Constraints:	Fair	Average value of 10% of total pore volume used across entire porosity range.

Regional Carbon Dioxide Density Estimation - Data Quality		Comment
Temperature Profile Constraints:	Probable Temperature Profile	Data from CSIRO - selectively edited and final regional temperature profile estimated by GGSS.
Pressure Profile Constraints:	Probable Pressure Regime	Data from CSIRO - selectively edited and final regional pressure profile estimated by GGSS.

Theoretical Storage Resource		Comment
Storage Volume Estimation Method:	Statistical	Net pay zone thicknesses from limited field log analysis. Storage efficiency factor is 1.
Subjective Estimate Accuracy:	Average	

Estimated Potential Storage:	191	Megatonnes (theoretical storage resource)	NB: Residual Gas Saturation storage has been approximated using unit specific storage cut-offs (See Volumetric Methodology Section for discussion).

Statistical Summary Data	Nett Thickness (m)	Porosity %
Data Point Count	21	1634
Average	5.12	12.40
Median	4.60	12.90
Standard Deviation	3.01	4.90
Kurtosis	0.44	0.20
Skewness	0.81	-0.20

5. Calculate Theoretical CO_2 Storage Capacity

- Sum of storage volume in each depth range (accounts for changes in CO_2 density with depth)
- Residual Gas saturation= 10%
- RGS efficiency factor determined based on reservoir thickness (high for thin reservoirs, low for thick reservoirs)
- Residual gas saturation storage mechanism volume calculated as 1% of total calculated storage volume; Note: 5m thick (100%) and less if used total area
- 191 Mt of theoretical capacity in Showgrounds Sandstone storage area (additional 172 Mt in Tinown and Rewan)

20

CGSS method vs Storage Efficiency

BASIN	Km^2	CGSS Capacity (Mt CO_2)	SE Capacity Approach (<u>4% of pore volume</u>) (Mt CO_2)	CGSS capacity as <u>% of pore volume</u>
Galilee	147,000	3,430		
Bowen	180,000	339		
Surat	327,000	2,300		

Note: The thicker the reservoir, the larger the discrepancy

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Conclusions

- Queensland CO_2 Geological Storage Atlas assessed 36 basins at regional level
  - High graded basins
- Used the prospectivity in determining capacity
  - Seal and reservoir distribution, heterogeneity and quality
  - Trapping options and viability
  - CO_2 density at each location – not generic value
  - Estimated "Invaded volume of reservoir" for RGS
- Did not use SE methodology ("couldn't ?")
  - Relied on practical geological knowledge (looked at rocks - prospectivity) & conservative / sensible estimates
    - **<u>Must map "fairways" for sensible capacity estimates</u>**

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Must Map Fairways