CCS Workshop – Ensuring safety toward public acceptance

18th January 2012

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GEOLOGICAL STORAGE OF CO_2: "PRACTICALITIES" - ISSUES, RISKS AND UNCERTAINTIES ASSOCIATED WITH SITE SELECTION

OUTLINE

- Storage
  - capacity
  - CO_2 density
  - rock volume (pore vs invaded)
  - efficiency
- Storage Ready
- Depositional environments
  - Injectivity
  - Reservoir & Seal prediction
- ? Pressure build up ?

STORAGE CAPACITY? - BASICS

Volumetric (Capacity) Equation

The basic equation for volumetric estimation is:

$$MCO_2 = RV * Ø * \delta_{(CO2)}$$

- 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)*
- $\delta_{(CO2)}$ = *the density of* CO_2 *at the given reservoir depth (pressure and temperature) in kg/*m^3.

Whilst capacity (volume) is important, injectivity (rate) is far more critical for site selection

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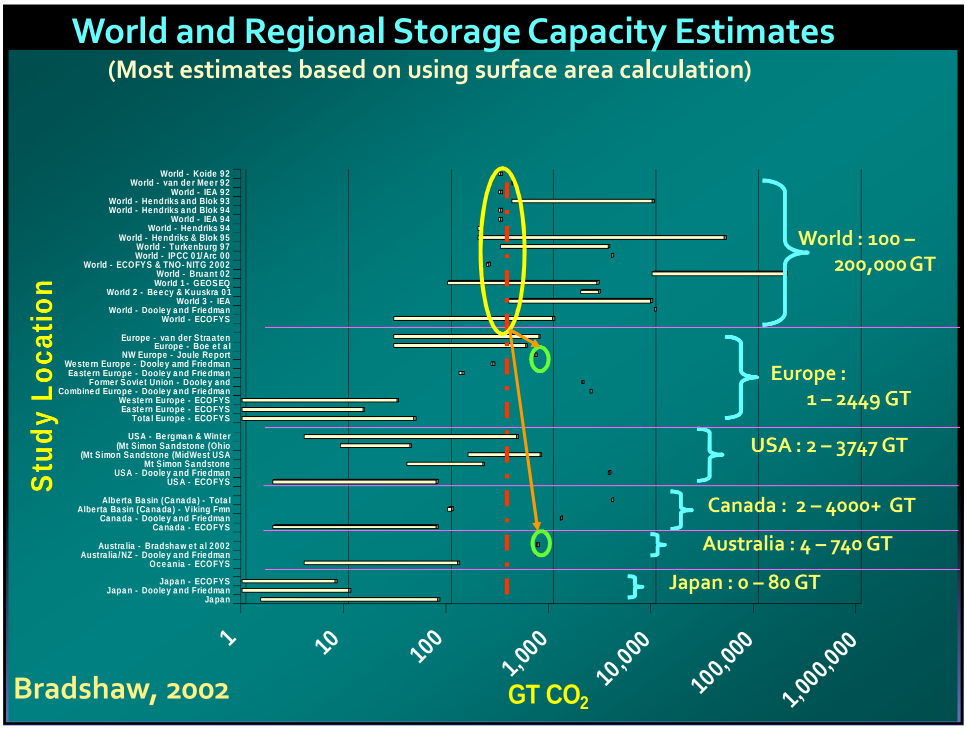


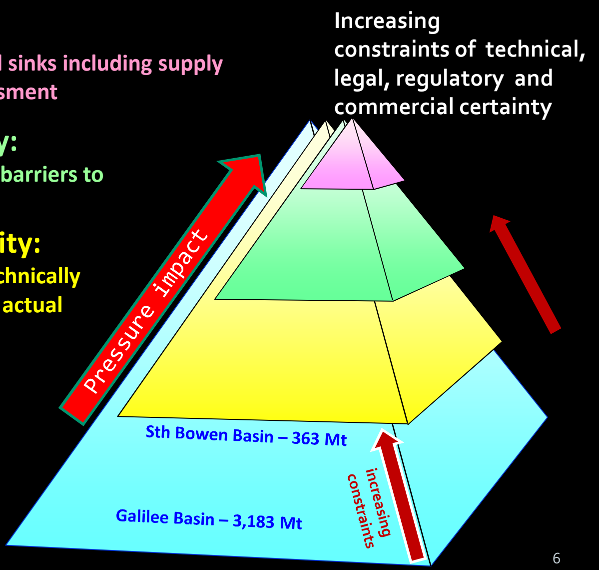
Storage Capacity estimates

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

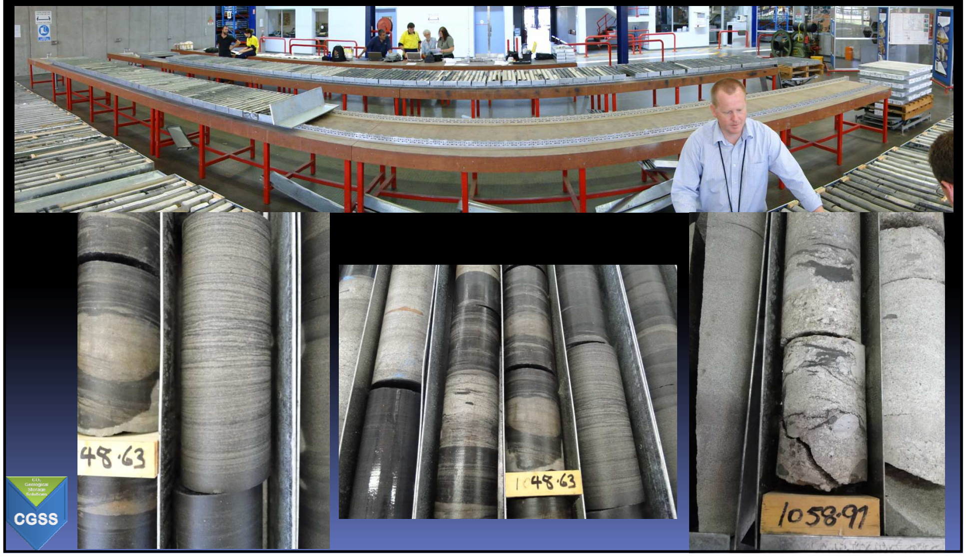
Practical (Viable) capacity:
Applies economic and regulatory barriers to realistic capacity,

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



"ROCK IS KING"



Volumetric (Capacity) Equation

The basic equation for volumetric estimation is:

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

- MCO_2 = mass of CO_2 stored in kilograms
- RV = total reservoir rock volume in m^3 (within fairway – not whole basin)
- Ø = total effective pore space (as a fraction)
- $\delta_{(CO2)}$ = the actual density of CO_2 at the given reservoir depth (pressure and temperature) in kg/m^3.

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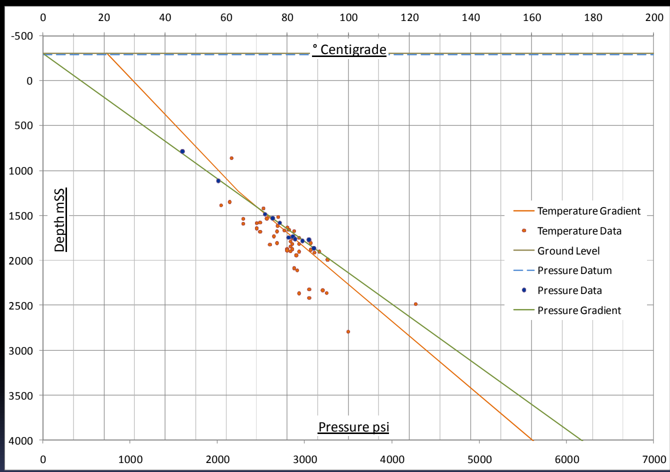
Temperature & Pressure



Calculate temperature and pressure gradients from WCR's

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

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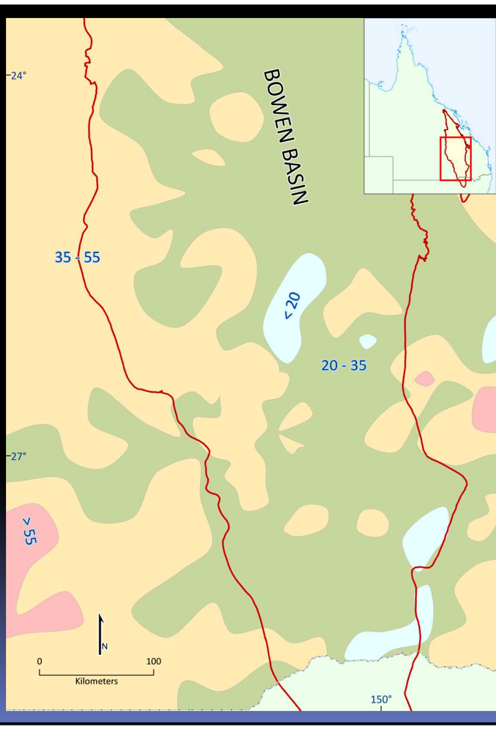
Geothermal Gradient Variation



Detailed temperature gradient map (° C / km) over southern and western Bowen Basin - basin outline in red.

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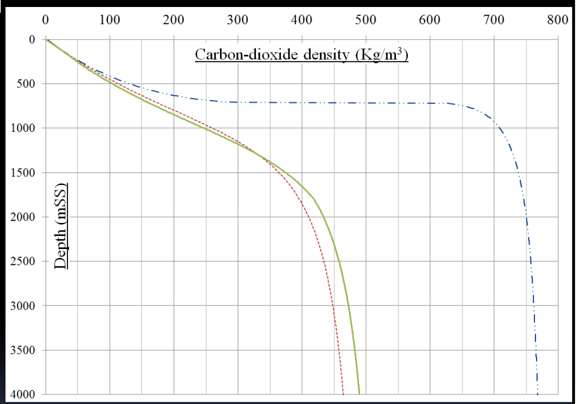
CO_2 Density

- Under the normal range of pressure/ temperature conditions found in sedimentary basins, the density of CO_2 can vary significantly
- The precision of the CO_2 density estimate depends on the accuracy of pressure and temperature estimates.



CO_2 density given two end-member basin conditions: a hot fresh-water (red curve) a cold saline-water basin (blue curve); Eromanga Basin in (green curve)

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So what is occurring with CO_2 Density

- Repeatedly authors are using default values
  - E.g. 600 to 700 kg/m^3
- Some, whilst also quoting geothermal gradients

- So let's look at some real data & identify the issue

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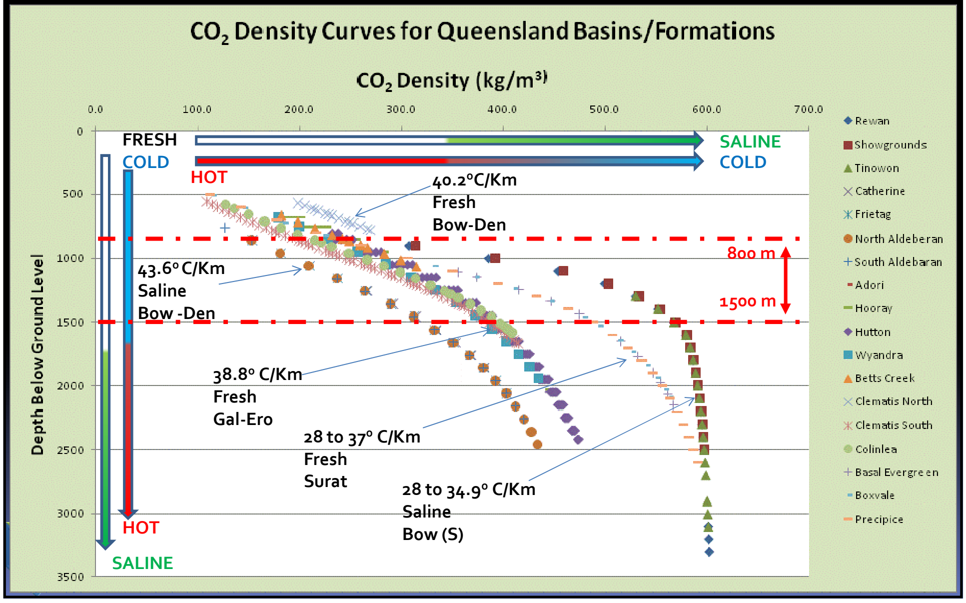
Density of CO2 & Factors that control Storage Capacity



Australian Government : National Carbon Mapping & Infrastructure Plan
Monte Carlo Probabilistic Approach – Australian Basins

STORAGE CAPACITY ESTIMATE

Parameter	Unit	Score (P90)	Score (P50)	Score (P10)	Distribution
Area of storage region	km²	20000	40000	120000	Triangular
Gross thickness of saline formation	m	15	100	250	Triangular
Average porosity of saline formation over thickness interval	%	14	17	20	Triangular
Density of CO_2 at average reservoir conditions	tonne/m³	0.5	0.6	0.7	Triangular
E-storage efficiency factor (% of total pore volume)	%	4	4	4	
Calculated storage potential	gigatonnes	11.6	26.8	52.5	

CO_2 density given two end-member basin conditions: a hot fresh-water (red curve);
cold saline-water basin (blue curve);
Eromanga Basin in (green curve)

http://www.ret.gov... n.pdf

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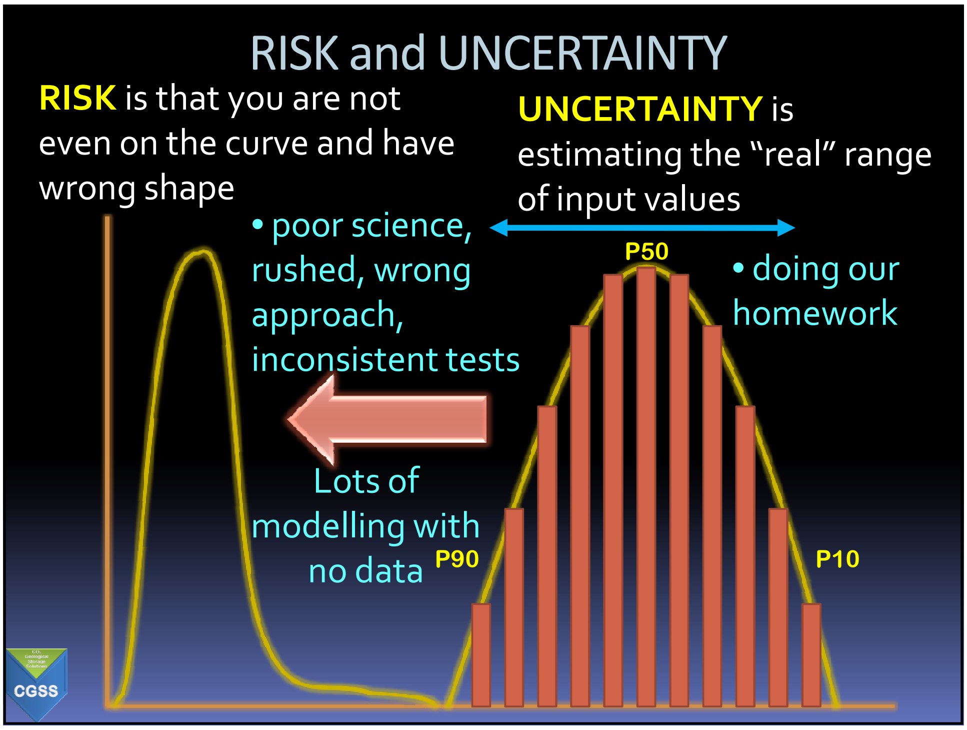
So, these valu... urve of reality



Message 1

Do your homework on CO_2 density for your site,

and,

avoid generic approaches

and, above all else;

look at your rocks and your data

("get your hands dirty")

WHAT ABOUT ESTIMATING THE INVADED ROCK VOLUME?

Volumetric (Capacity) Equation

The equation for volumetric estimation is:

$$MCO_2 = RV * Ø * δ_{(CO2)}$$

- *MCO_2 = mass of CO_2 stored in kilograms*
- *RV = total reservoir rock volume in m^3 (within fairway – not whole basin)*
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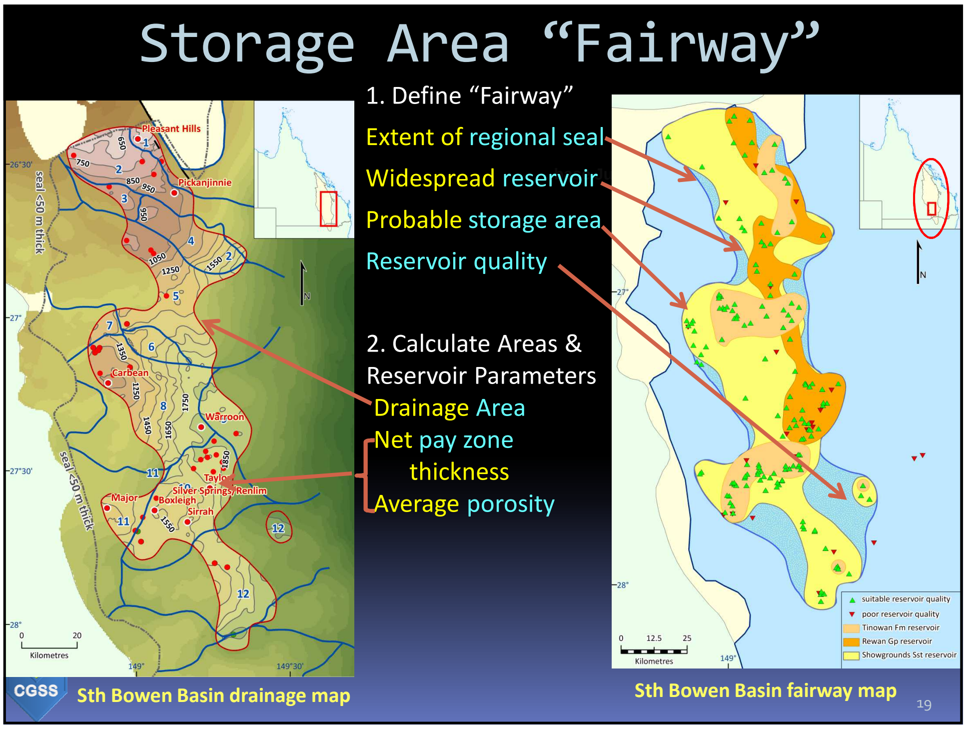
Storage Area "Fairway"
1. Define "Fairway"
Extent of regional seal
Widespread reservoir
Probable storage area
Reservoir quality
2. Calculate Areas & Reservoir Parameters
Drainage Area
Net pay zone thickness
Average porosity
Pleasant Hills
Pickanjinnie
Carbean
Warroon
Silver Springs/Renlim
Major
Boxleigh
Sirrah
seal <50 m thick
Kilometres
suitable reservoir quality
poor reservoir quality
Tinowan Fm reservoir
Rewan Gp reservoir
Showgrounds Sst reservoir
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Sth Bowen Basin drainage map
Sth Bowen Basin fairway map
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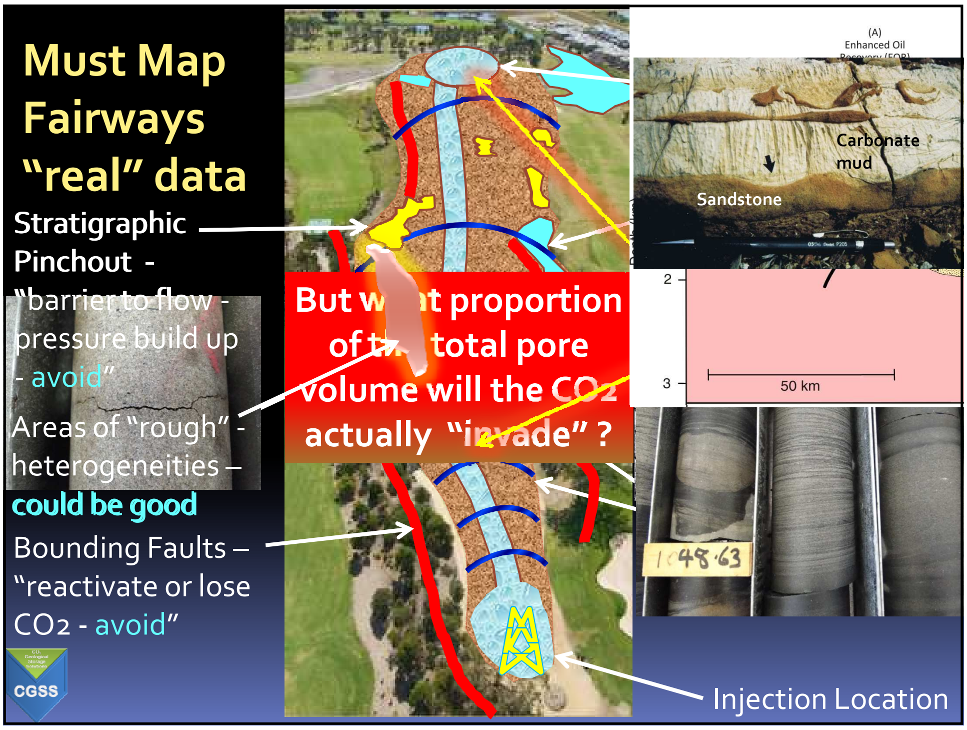
Must Map Fairways "real" data
Stratigraphic Pinchout -
"barrier to flow - pressure build up - avoid"
Areas of "rough" - heterogeneities – could be good
Bounding Faults – "reactivate or lose CO2 - avoid"
But what proportion of the total pore volume will the CO2 actually "invade" ?
Carbonate mud
Sandstone
50 km
Injection Location
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Volumetric (Capacity) Equation

- *So what does RV =*

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

1. *Entire golf course ?*
   - *From car park to course to golf club (19th hole)*
2. *Full extent of the fairway ?*
   - *Including out of bounds?*
3. *Or just the areas and points the golf balls travels along and lands in? – i.e. CO_2 migration pathway*

And let's not forget what happens with the 3rd dimension - thickness (depth)

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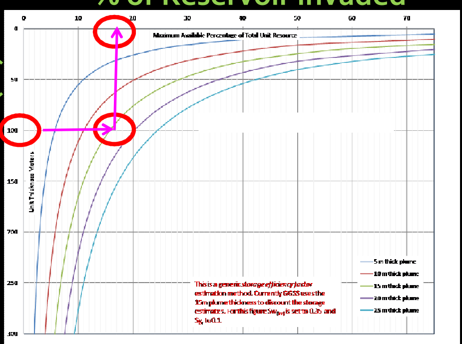
MAS efficiency factor

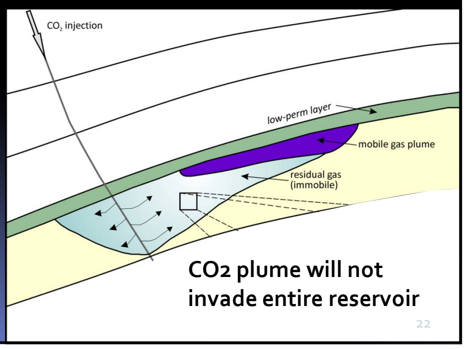
% of Reservoir invaded

Unit Thickness (m)



- Must make allowance for the % of reservoir actually invaded by the migrating CO_2 plume

- 100m thick reservoir
- 15m thick plume
- = 16% of reservoir actually accessible



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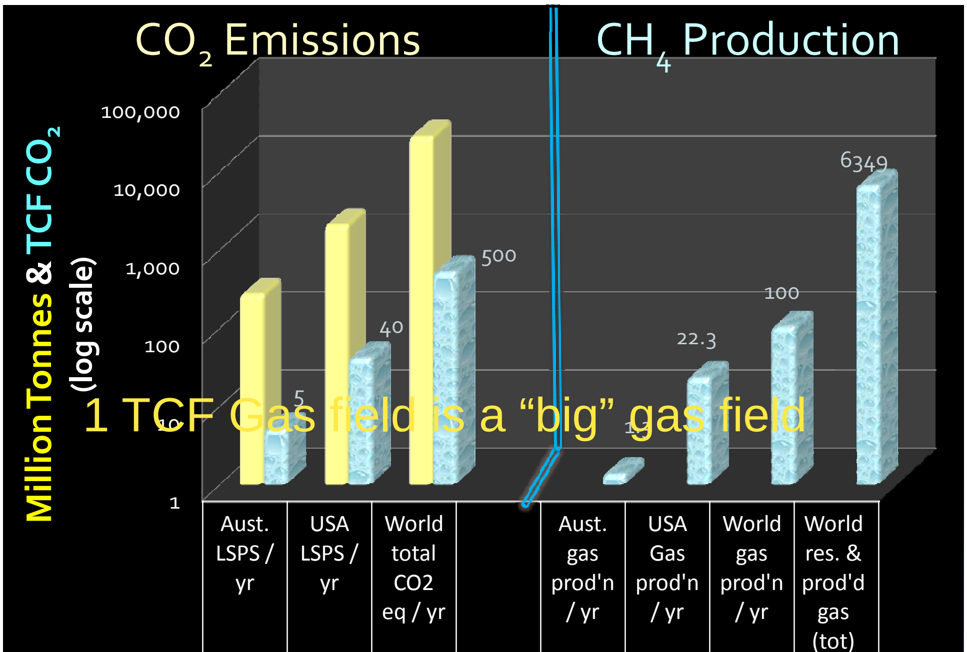
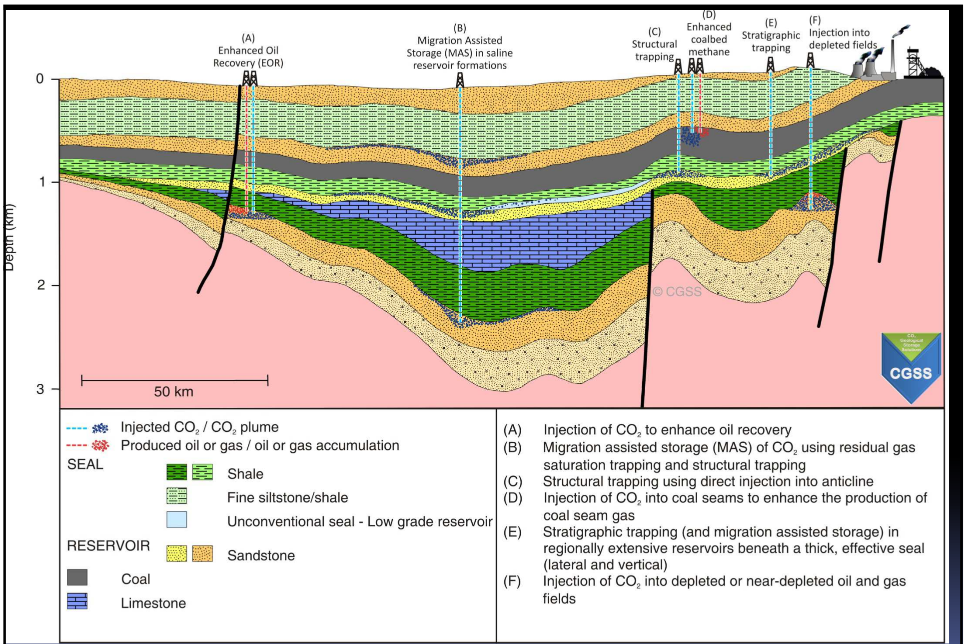


	Aust. LSPS / yr	USA LSPS / yr	World total CO2 eq / yr		Aust. gas prod'n / yr	USA Gas prod'n / yr	World gas prod'n / yr	World res. & prod'd gas (tot)
Mt CO2	260	2000	27000					
TCF CO2/CH4	5	40	500		1.3	22.3	100	6349



Importance of Saline Reservoirs

Message 2

Think about the actual rock volume and the rocks that CO_2 will invade,

and,

the importance of MAS to trap large volumes of CO_2

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STORAGE EFFICIENCY (SE) PITFALLS?

Volumetric (Capacity) Equation

- *So what about **S**torage **E**fficiency factors*

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

- Many authors now use SE to allow for a range of geological considerations – not examined at scale
- Often use between 1% and 6% to get quick regional estimates

CGSS does not use them – why?

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CGSS method vs Storage Efficiency

BASIN	Area of Basin Km^2	CGSS Capacity (Mt CO_2)	SE Capacity Approach (4% of pore volume) (Mt CO_2)	CGSS capacity as % of pore volume
Galilee	147,000	3,430	122,245	
Bowen	180,000	339	13,104	
Surat	327,000	2,300	61,803	

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

Note: The thicker the reservoir, the larger the discrepancy

…. and then there are the pressure impacts

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Message 3

Estimate the real capacity by mapping the migration pathway (fairways),
and,
don't rely on efficiency factors

(Usually done in detail with reservoir modelling once a specific site is chosen)

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Wrong Question:
Better to ask about cost …

& if Car park, Basin, Country or the World?

1. What is the price on CO_2 ?

2. How far are you prepared to transport it?

3. How many wells do I need / afford

SO JOHN, ……..

WHAT IS "THE BEST" CAPACITY ESTIMATE ?

…… to reliably estimate the cost we need to understand the potential storage site

(“Storage Ready”)

SO TO GET TO CAPACITY WE NEED TO UNDERSTAND THE COST

What is Storage Ready? (CGSS definition)

The processes and outcomes from identifying, proving and securing a geological storage site that is capable of having industrial quantities of CO_2 injected and stored in the deep subsurface on a sustainable basis, whilst maintaining high geological integrity in the geological structures and formations both during and after the injection and storage period.

… ideally a risk assessment should establish benchmarks like these to measure against …

BU

-
- does not elaborate on levels of proof and certainty that may be required,
- does not express the conceptual nature of the understanding of the geological attributes of the deep subsurface, and
- does not document the actual impacts that the geological characteristics of the deep subsurface may have on a site being proven to be storage ready.

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Zerogen objectives for Risk and Uncertainty

- Test 1. *Containment & Capacity*
  - *a P50 level of confidence in secure containment of 60 Mt.*
- Test 2. *Capacity & Injectivity*
  - *a P50 level of confidence in injection of 2 Mt pa sustained over 30 years.*
- Test 3. *Injectivity (esp. well count)*
  - *a P50 level of confidence in life-cycle CTS unit costs of less than* A$50/t for carbon transported and stored.

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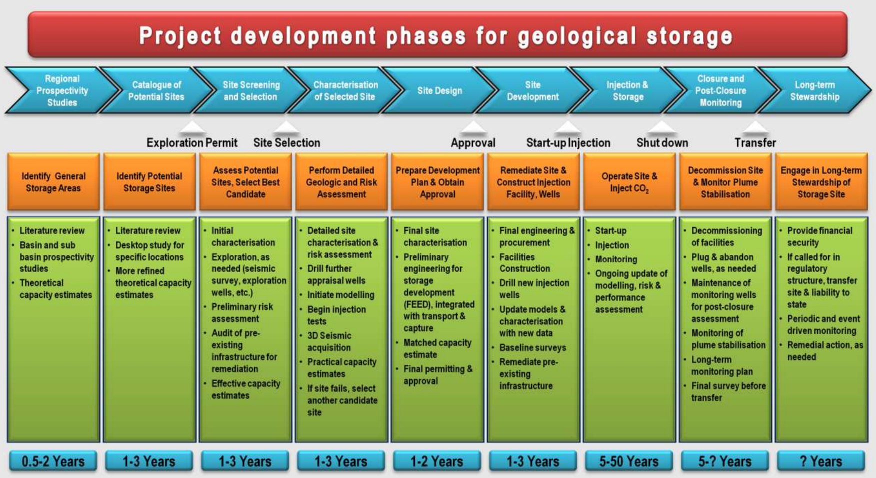
Zerogen GHGT10 - 2010

"Storage Ready" could take 5 - 10 years



Note: Orange boxes refer to "Project Developer Goals"; Green boxes refer to "Developer Activities"
Source: Senior CCS Solutions and Bradshaw Geoscience Consultants ©

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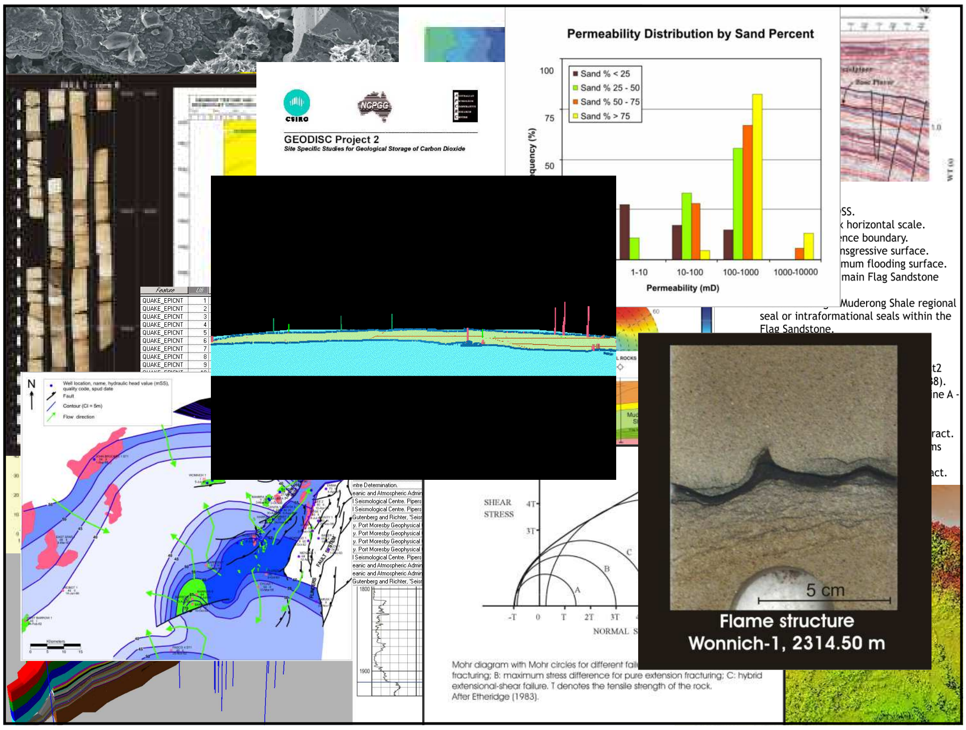


Site Characterisation & Selection Work Flow

Data Acquisition & Analysis

- Field Studies
- Petrophysical Analysis
- Analogue Studies
- Rock Typing
- Core Analysis & Sampling
- Well Log Interpretation & Correlation
- Seismic Interpretation
- Time-Depth Analysis
- DST, RFT & BHT Analysis
- Hydrogeological Study

Modelling

- Geomechanical Model
- Seal Potential Model
- Petrophysical Model
- Facies & Seqence Stratigraphic Maps & Models
- Depth-Structure Maps & Models
- P/T Gradients
- Groundwater, Salinity

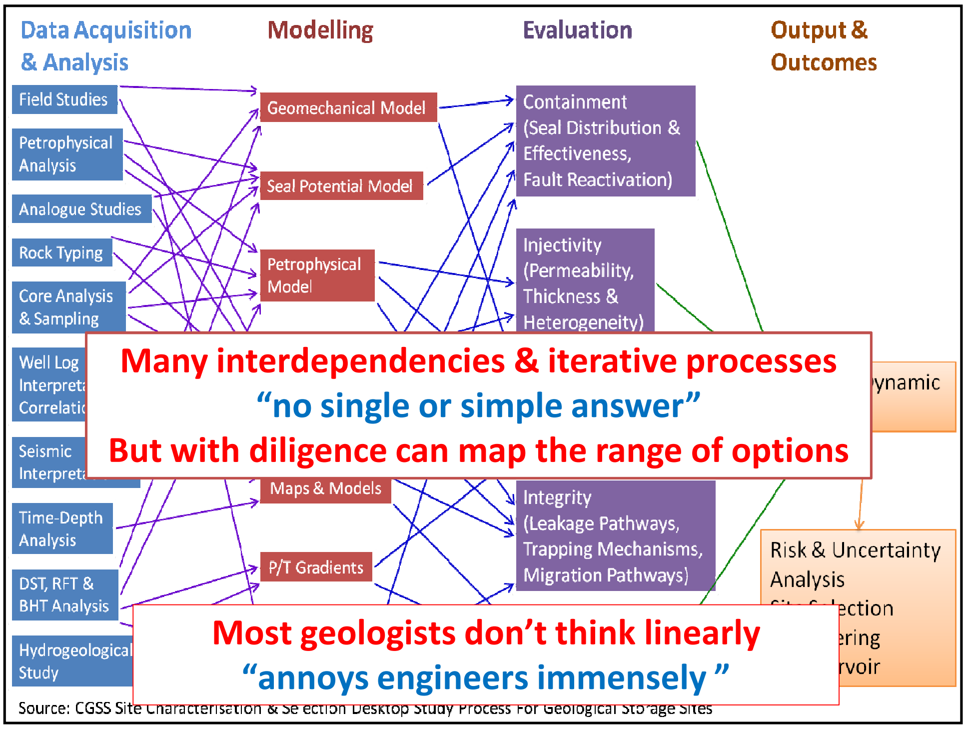
Evaluation

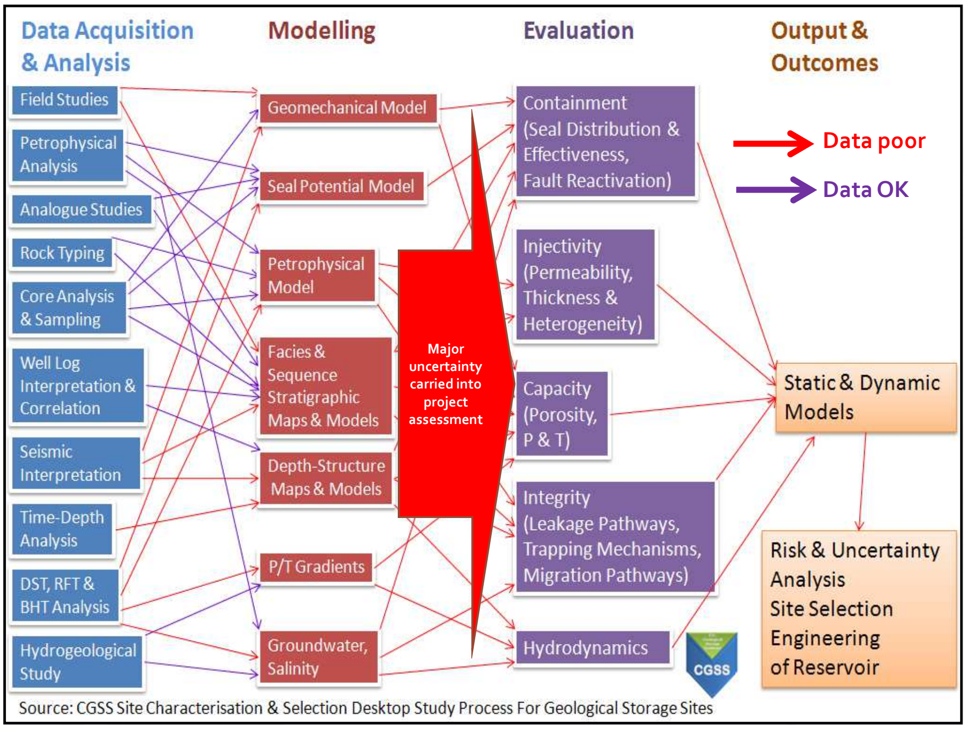
- Containment (Seal Distribution & Effectiveness, Fault Reactivation)
- Injectivity (Permeability, Thickness & Heterogeneity)
- Capacity (Porosity, P & T)
- Integrity (Leakage Pathways, Trapping Mechanisms, Migration Pathways)
- Hydrodynamics

Output & Outcomes

- Static & Dynamic Models
- Risk & Uncertainty Analysis
  Site Selection
  Engineering of Reservoir

Source: © CGSS Site Characterisation & Selection Desktop Study Process For Geological Storage Sites


Data Acquisition & Analysis
Modelling
Evaluation
Output & Outcomes
Field Studies
Petrophysical Analysis
Analogue Studies
Rock Typing
Core Analysis & Sampling
Time-Depth Analysis
DST, RFT & BHT Analysis
Geomechanical Model
Seal Potential Model
Petrophysical Model
Maps & Models
P/T Gradients
Containment (Seal Distribution & Effectiveness, Fault Reactivation)
Injectivity (Permeability, Thickness & Heterogeneity)
Integrity (Leakage Pathways, Trapping Mechanisms, Migration Pathways)
Risk & Uncertainty Analysis
Many interdependencies & iterative processes
“no single or simple answer”
But with diligence can map the range of options
Most geologists don’t think linearly
“annoys engineers immensely ”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DST, RFT & BHT Analysis
Hydrogeological Study
Geomechanical Model
Seal Potential Model
Petrophysical Model
Facies & Sequence Stratigraphic Maps & Models
Depth-Structure Maps & Models
P/T Gradients
Groundwater, Salinity
Major uncertainty carried into project assessment
Containment (Seal Distribution & Effectiveness, Fault Reactivation)
Injectivity (Permeability, Thickness & Heterogeneity)
Capacity (Porosity, P & T)
Integrity (Leakage Pathways, Trapping Mechanisms, Migration Pathways)
Hydrodynamics
Data poor
Data OK
Static & Dynamic Models
Risk & Uncertainty Analysis
Site Selection
Engineering of Reservoir
Source: CGSS Site Characterisation & Selection Desktop Study Process For Geological Storage Sites

Poor project definition will lead to loss of value

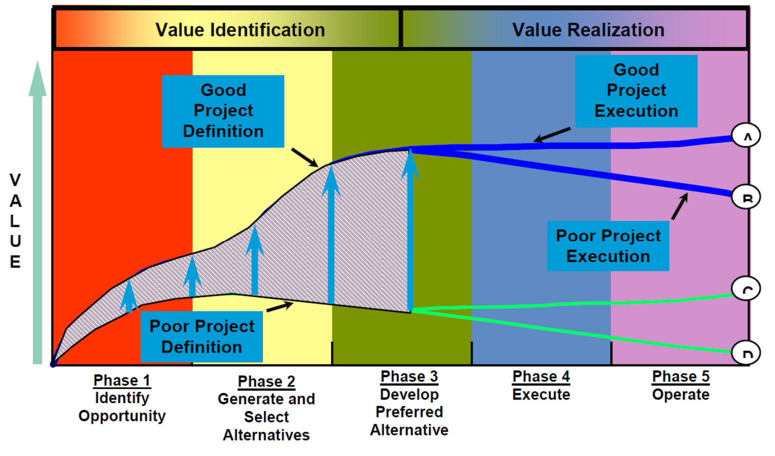

Figure 1: CPDEP Impact on Asset/Project Value, PM100SP Chevron Project Development & Execution Process (CPDEP)

i.e. Changing criteria mid-project – bad practice

Understand technical reality & impact of what is required

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Depositional environments and models

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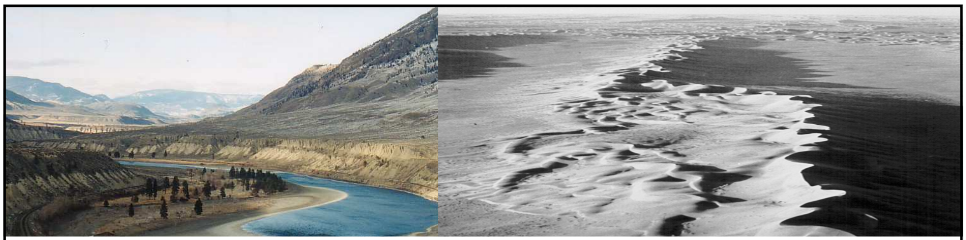
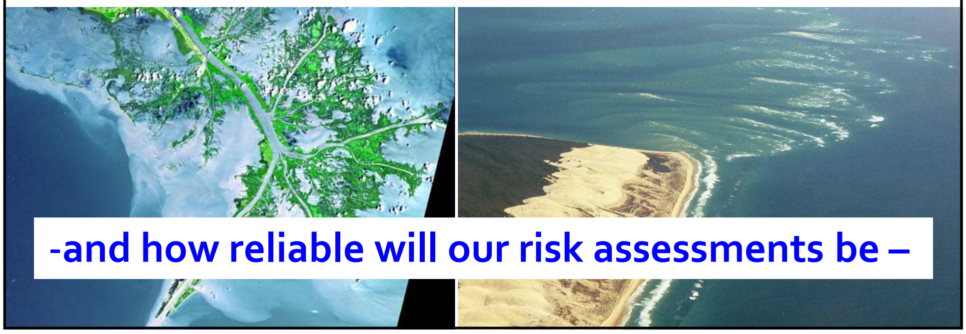
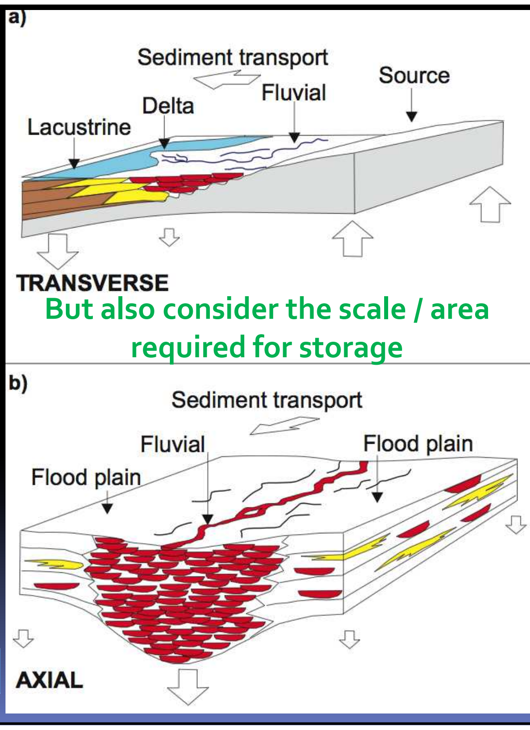


Are some geological solutions / sites going to be a lot better, more manageable & predictable, than others



-and how reliable will our risk assessments be –



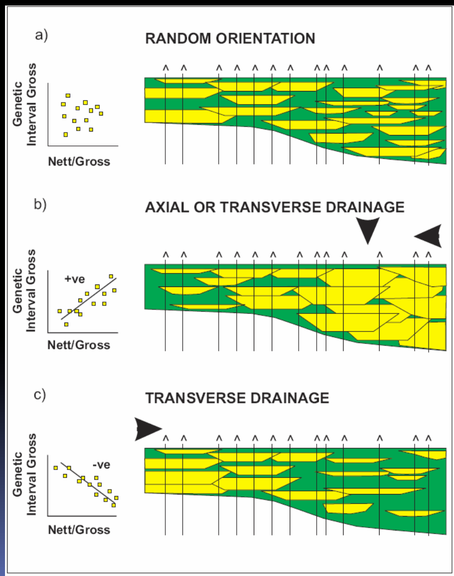
DEPOSITIONAL MODELS will greatly influence the predicted reservoir and seal distribution:

… and thus the effectiveness of connectivity and containment …

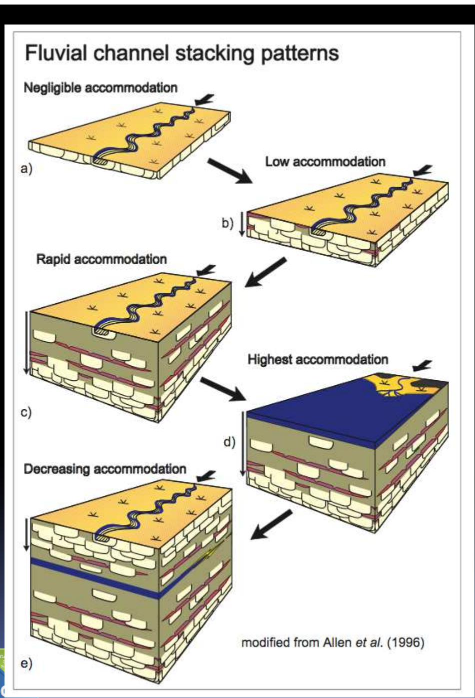
and the amount of data and proof required

Stacking patterns

- Critical issues in exploration strategy and pressure management will include;
  - Sediment supply
  - Provenance
  - Sediment type



From Lang et al 2001, and Musakti 1997.



"Accommodation" is the relative amount of subsidence/uplift and sea level change in a sedimentary basin that results in the infilling of it by sediments or erosion by downcutting.

The interplay of sediment source (sand/mud), sea level change (up/down), subsidence rate (high/low), will all influence the thickness, distribution and type of sediment in a basin.

Cyclical deposition are commonly observed in geology

How interconnected and variable are reservoirs ?

Do they change laterally ?

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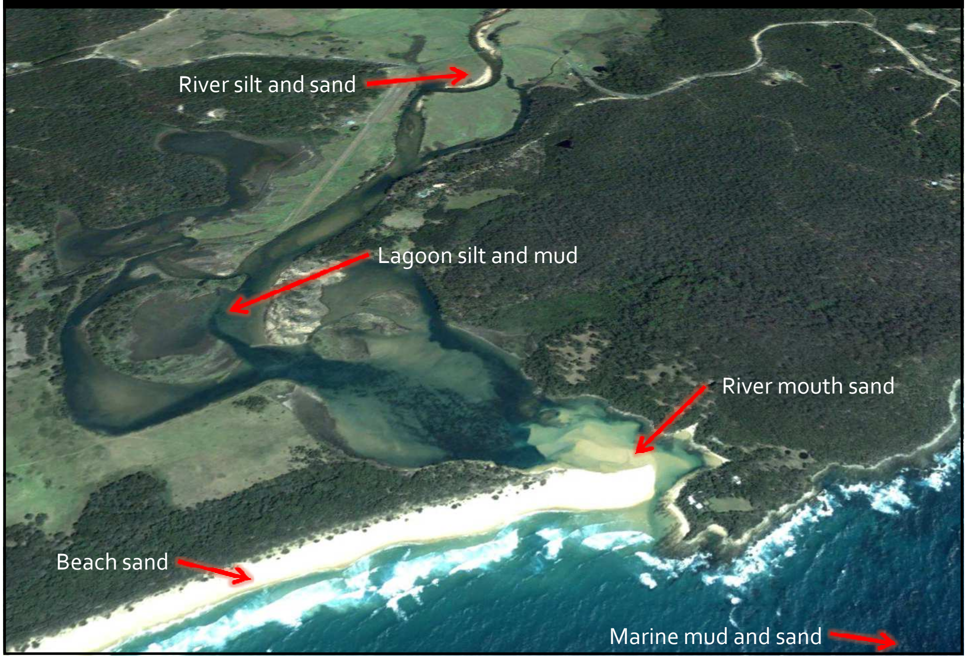
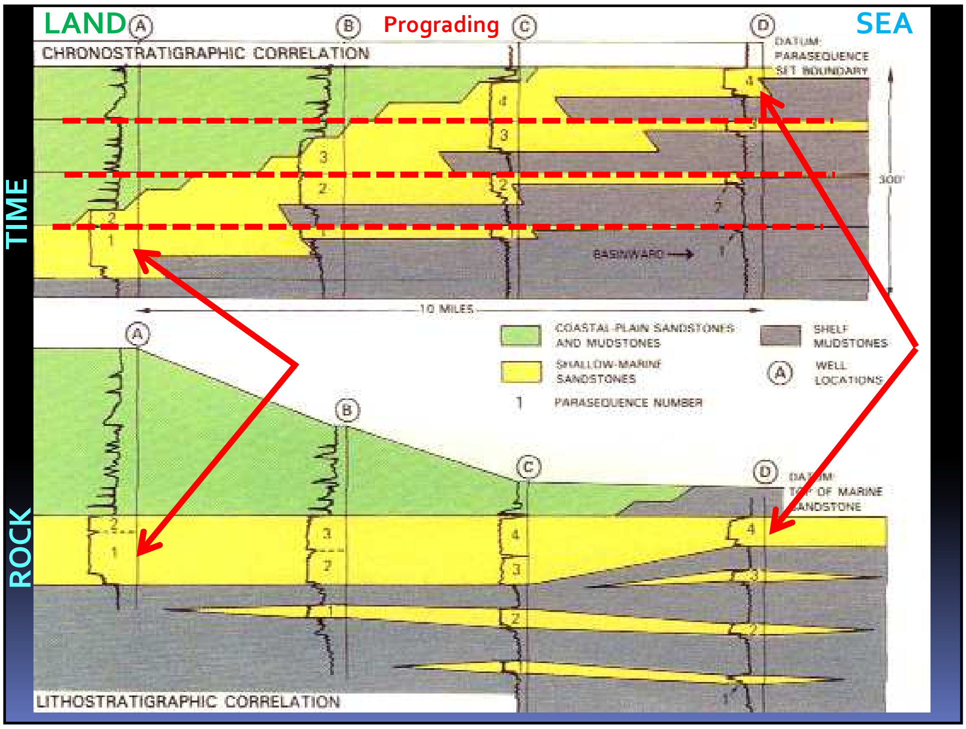
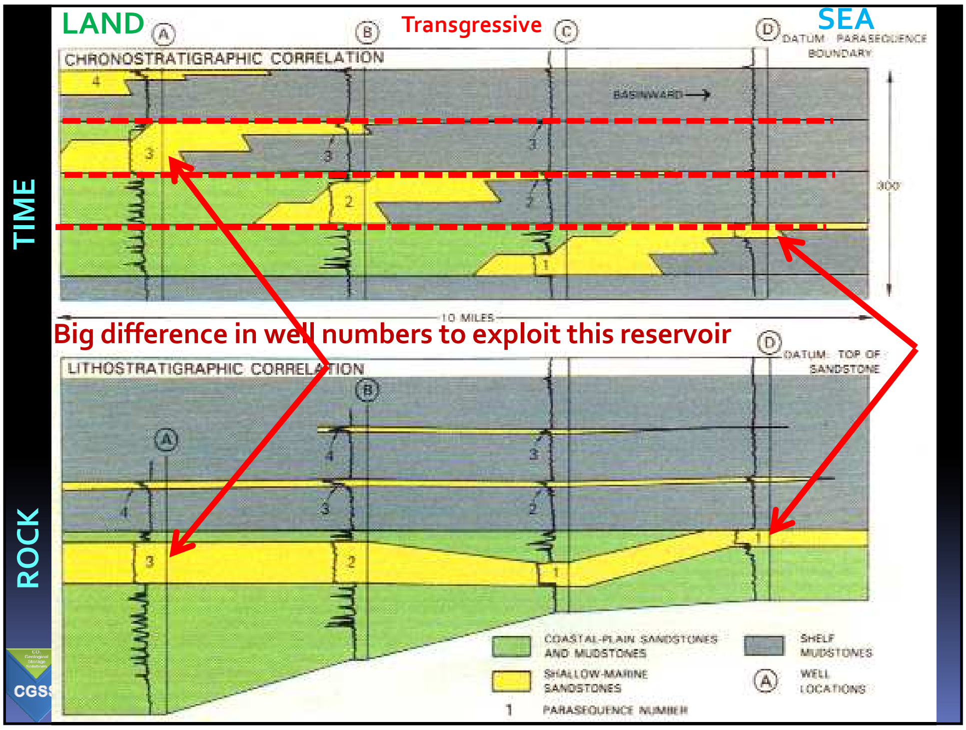
Lateral variation in rock types (lithologies)




LAND
Prograding
SEA
CHRONOSTRATIGRAPHIC CORRELATION
DATUM: PARASEQUENCE SET BOUNDARY
TIME
ROCK
BASINWARD
10 MILES
COASTAL-PLAIN SANDSTONES AND MUDSTONES
SHELF MUDSTONES
SHALLOW-MARINE SANDSTONES
WELL LOCATIONS
PARASEQUENCE NUMBER
DATUM: TOP OF MARINE SANDSTONE
LITHOSTRATIGRAPHIC CORRELATION


LAND
Transgressive
SEA
DATUM: PARASEQUENCE BOUNDARY
CHRONOSTRATIGRAPHIC CORRELATION
TIME
ROCK
BASINWARD
10 MILES
Big difference in well numbers to exploit this reservoir
DATUM: TOP OF SANDSTONE
LITHOSTRATIGRAPHIC CORRELATION
COASTAL-PLAIN SANDSTONES AND MUDSTONES
SHELF MUDSTONES
SHALLOW-MARINE SANDSTONES
WELL LOCATIONS
PARASEQUENCE NUMBER

Injectivity ?

Core versus formation permeabilities

- Corrected core permeabilities (air vs brine etc) often do not match formation permeabilities
  - Due to heterogeneity and barriers and overburden pressures
- Zerogen core corrected permeabilities Kh ~100mDm – Catherine Sandstone
- Zerogen formation permeabilities (on well test) $1/10^{th}$ of corrected core permeabilities (Kh)
- Exacerbated by low permeabilities and rock type

Message 4

Understand your depositional environment systems very well,
(get your feet wet and sandy looking at modern systems)

and,

think about the area/volume required and what that means for facies (lithology) heterogeneity,
and,

get “formation” (not just core) injectivity data to help predict your well numbers

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Depositional Environments

- Understanding reservoir and seal heterogeneity will influence numerous outcomes
  - Technical
  - Commercial
- ...... this is just doing our homework properly – normal business practices
- **– or is it**
  - The scale/volume of CO_2 injection dwarfs oil and gas production operations

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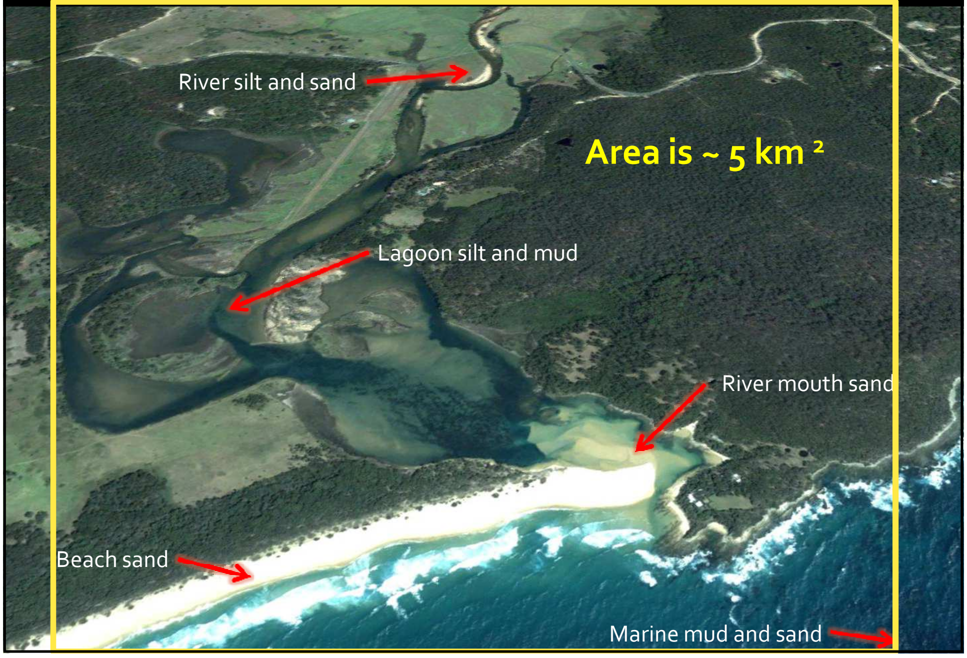
HOW BIG A FOOTPRINT IS REALLY REQUIRED FOR LARGE STORAGE VOLUMES ?

Lateral variation in rock types (lithologies)



"Pilot Scale" ?

- 100,000 t/yr
- Compared to 5 to 10 Mt CO_2 /year (power station) is small ...... but
- 100,000 t CO_2/yr
  - = 5.2 mmscf/d (6.49mmscf/d @ 80% online)
- This rate equivalent to
  - EOR "field" injection rates in Texas
    - i.e. multiple injection wells
  - Water injection floods
  - It is industrial injection rates for oil and gas operations
    - (Thus need to apply those standards for safe and secure storage)

SACROC EOR/CO_2 Field

CO2 injection rate

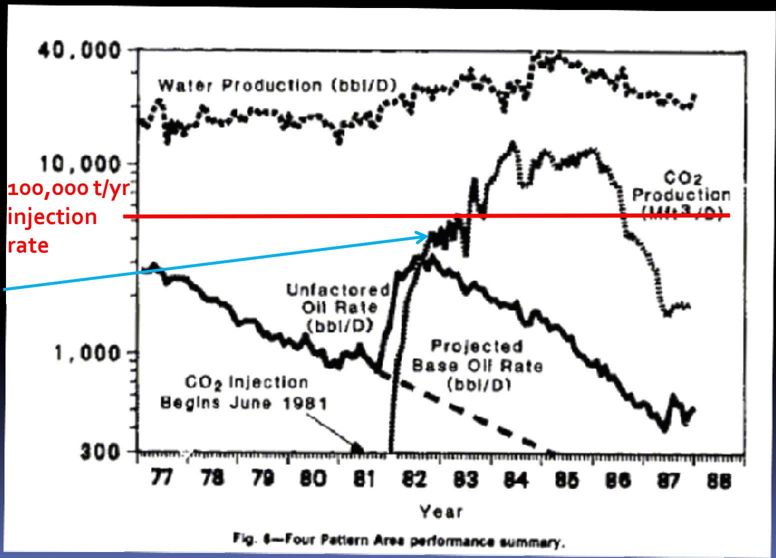


Fig. 6—Four Pattern Area performance summary.

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Message 6

- Most geological storage sites will be faced with injection challenges (including pressure management);
  - whether at pilot or industrial scales (for emissions)
- Detailed sequence stratigraphy will be required

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Conclusions : Storage Ready in Japan

- What does Japan think Storage Ready means for current projects?
- Is Japan there now?
- What does Japan need to do to get there?
- By when does it need to be in place?
- What threatens or is holding Japan back?

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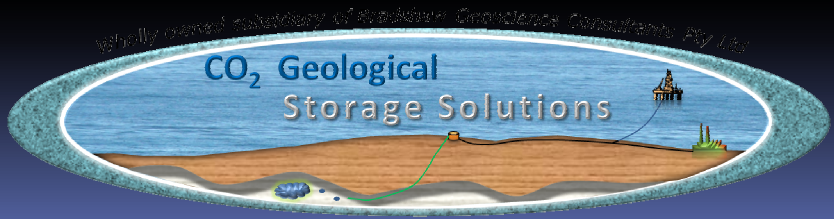

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