Australian Government

Geoscience Australia

Storage of CO_2 in Saline Aquifers

Overview of Mechanisms and Theory and the Current Storage Capacity Evaluation Methods

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cags China Australia Geological Storage of CO_2

中澳二氧化碳地质封存

Review of Basic Concepts

Sedimentary basins and geological storage

- Saline aquifers suitable for storage occur almost exclusively in sedimentary basins
- These are depressions in the crust in which sediments have accumulated over millions of years and which have not experienced significant uplift and folding
- They may be tens of kilometres thick and occur both on the continents and under ‘shallow seas’
- All oil and gas accumulations occur in sedimentary basins

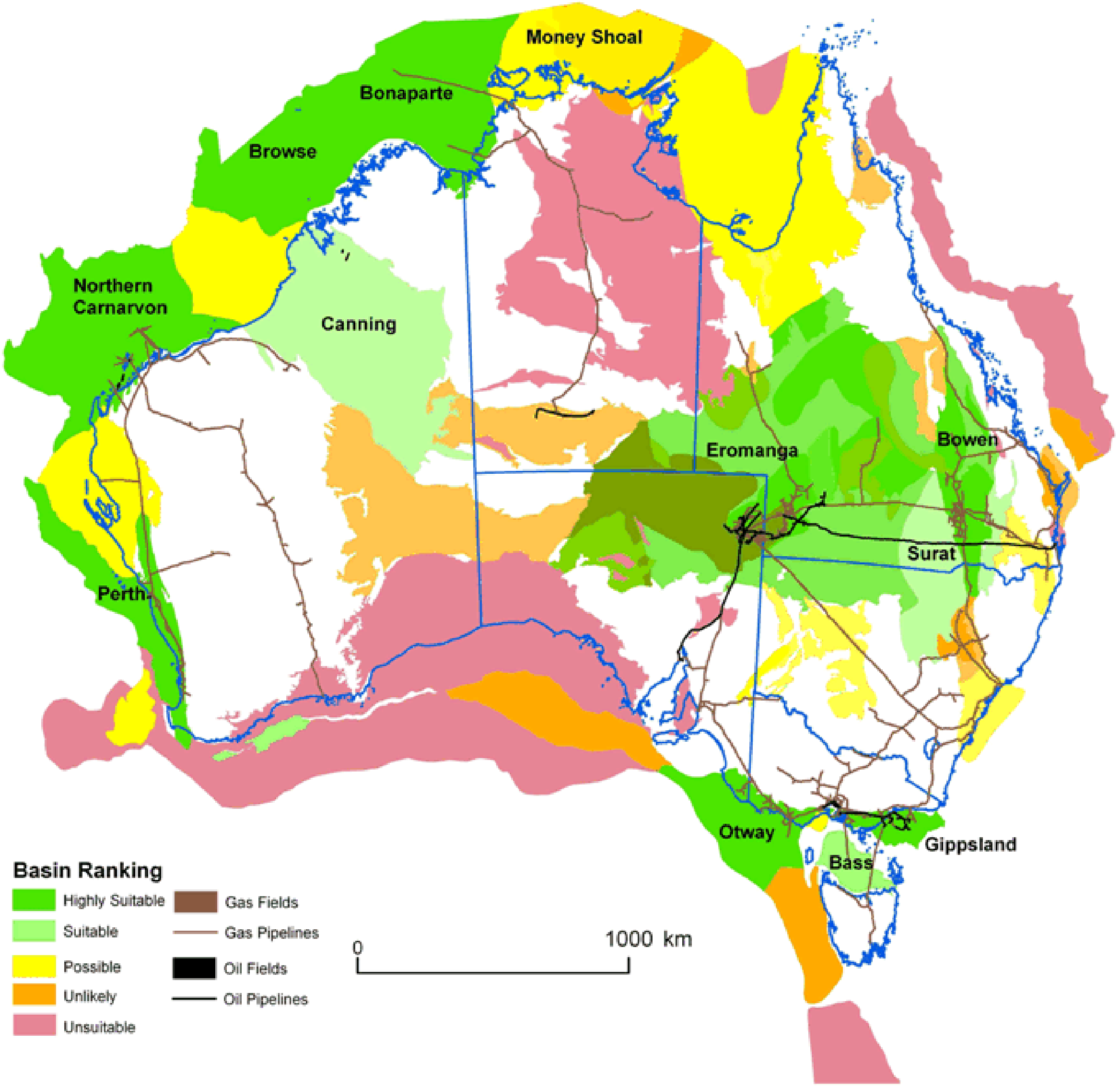
Basins are not equal

- Sedimentary basins are the regions that offer the opportunity for geological storage of $CO_{2.}$

- But all sedimentary basins do not have the same potential for storage

- We need to consider the tectonic settings and reservoir characteristics of each basin

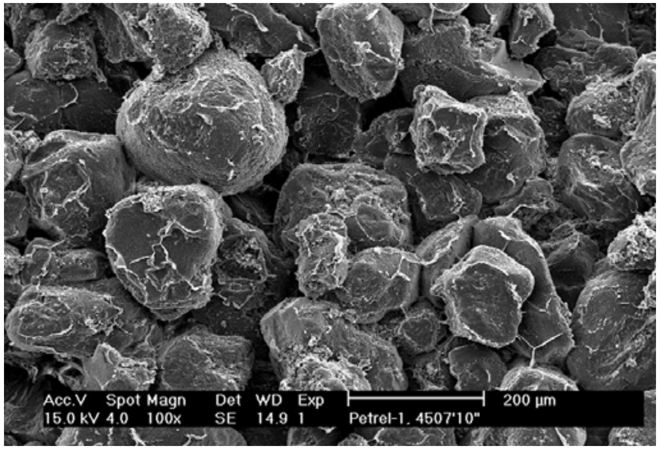
An example of the ranking of basins for carbon dioxide storage from a recent Australian Government Study conducted by Geoscience Australia

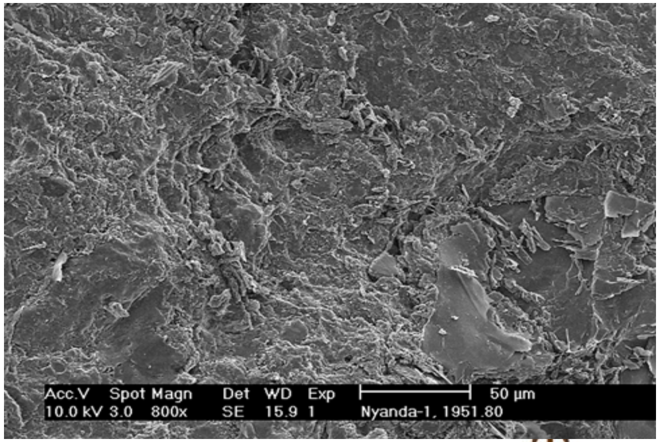


Reservoirs and Seals

- **Reservoir rocks** are medium to coarse grained and hold fluids in pores between the grains of the rock.
- Interconnection between the pores allows the fluids to flow through them (permeability).
- E.g. Sandstones and limestones

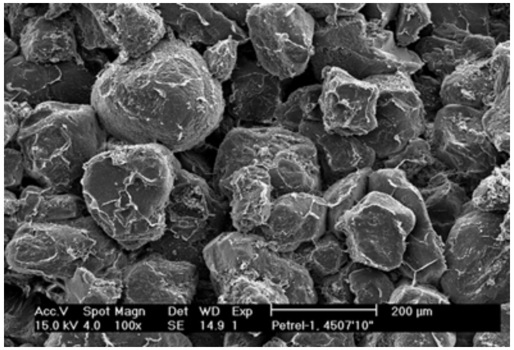
- **Sealing rocks** are very fine grained with no practical permeability.
- E.g. Mudstones or shales.

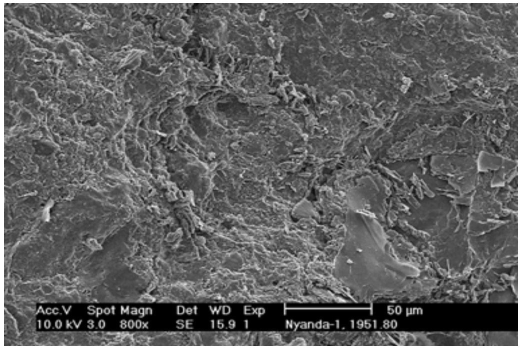




Reservoirs and Seals

- Where a sealing rock overlies a porous reservoir rock the seal is able to prevent buoyant fluids such as oil, gas or carbon dioxide from rising out of the reservoir.





The geological characteristics of the subsurface can be seen exposed in coastal outcrops

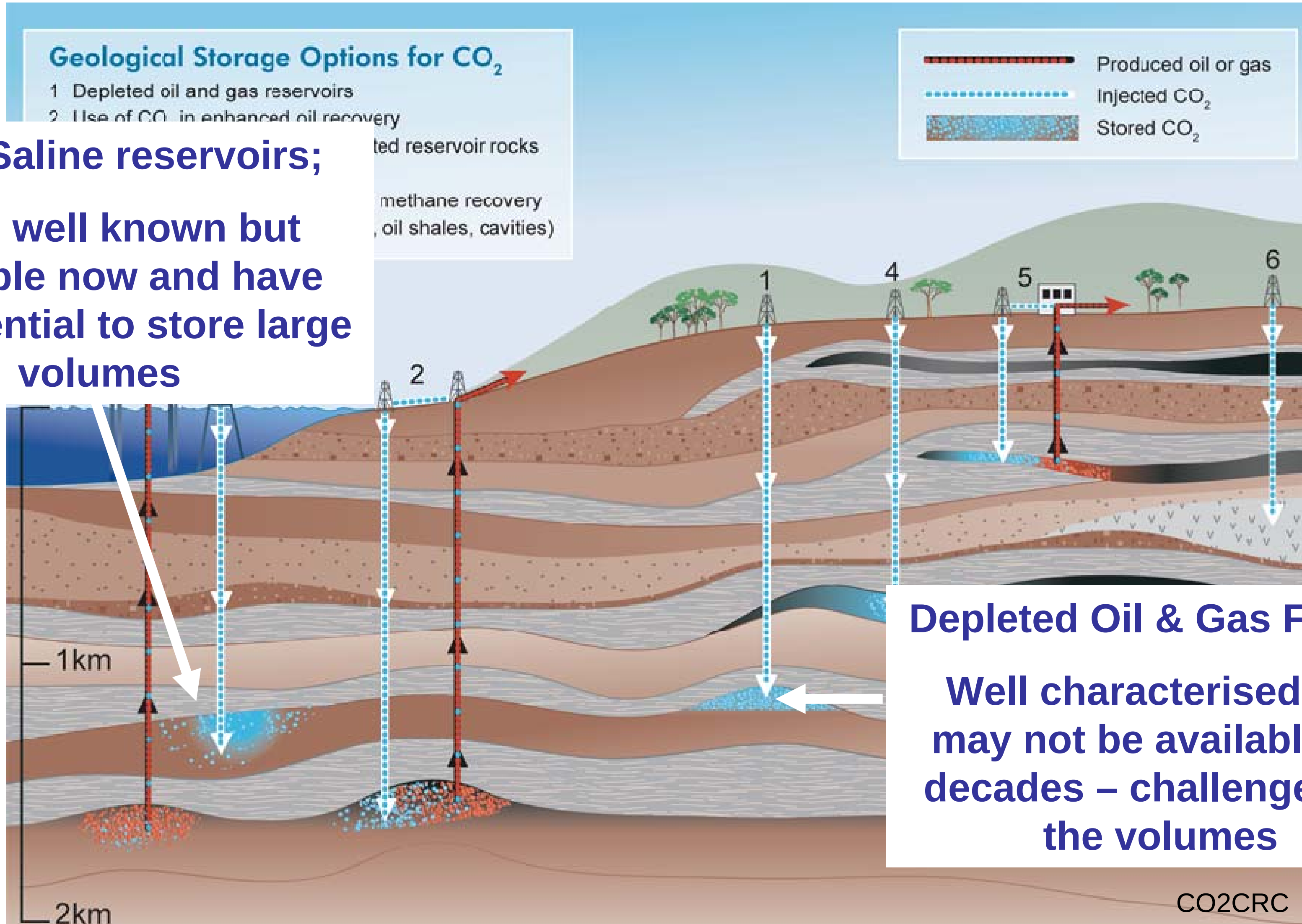
Adapted from CO2CRC

In petroleum exploration we need to be confident that containment continues over the whole structure.

For geological storage in saline reservoirs we need to be confident that containment exists over large geographical areas.

Adapted from CO2CRC

Geological Storage Options



Deep Saline reservoirs;

Less well known but available now and have the potential to store large volumes

Depleted Oil & Gas Fields;

Well characterised but may not be available for decades – challenged by the volumes

cags

China Australia Geological Storage of CO_2

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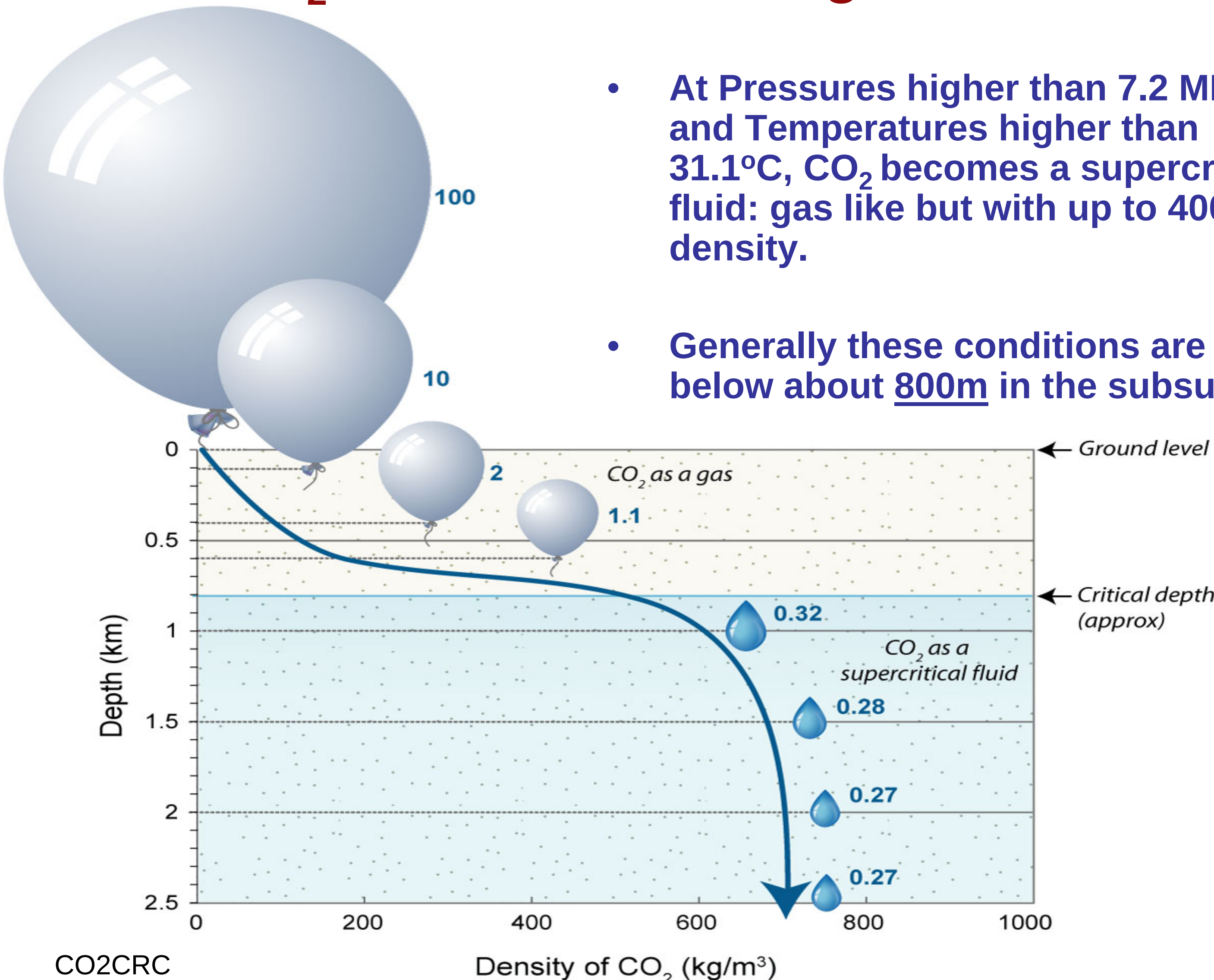
Supercritical CO_2: increased storage effectiveness

- At Pressures higher than 7.2 MPa and Temperatures higher than 31.1ºC, CO_2 becomes a supercritcal fluid: gas like but with up to 400x the density.

- Generally these conditions are found below about <u>800m</u> in the subsurface



CO2CRC

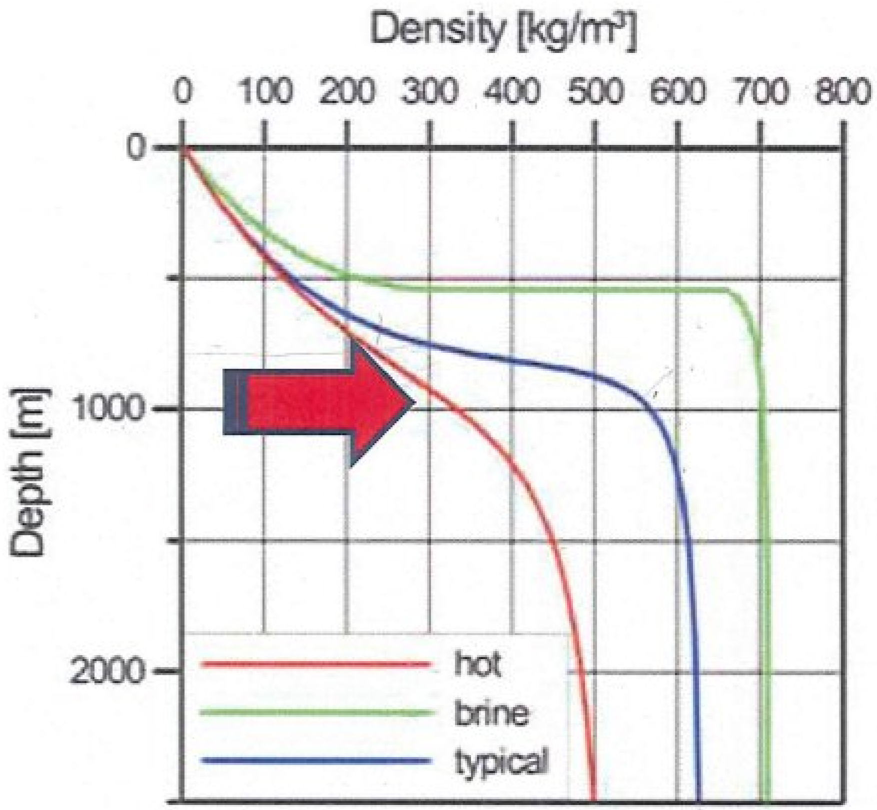
Density of supercritical CO_2

- In the past most capacity estimates of regions or basins have assumed that in the supercritical state the CO_2 will have a density of between 650 -750 kg/m^3.
- But this depends greatly on the geothermal gradient and hydrostatic pressure.
- Recent work in Australia has shown that in basins with a high geothermal gradient ("hot basins") CO_2 may enter the supercritical state at around 200 kg/m^3 and over the zones of interest for storage may never exceed 450kg/m^3.*

This can have a major effect on the assessment of total storage capacity at a regional level

*Queensland Carbon Dioxide Storage Atlas

Effects of Geothermal Gradient and Salinity on CO_2 Density



(From Chadwick et al)

At 1000m the density of the CO_2 can range from around 320 to 700 kg/m^3 depending on the geothermal gradient and the salinity (density) of the formation water

CO_2 Trapping Mechanisms in Porous Rocks

When CO_2 is injected into the subsurface it will rise under buoyancy until it becomes immobilised by a combination of factors:

- **Structural and Stratigraphic**
- **Residual Trapping**
- **Solubility Trapping**
- **Mineral Trapping**

Unless residual storage occurs the buoyant free phase CO_2 will ultimately rise to accumulate under the top seal of the reservoir

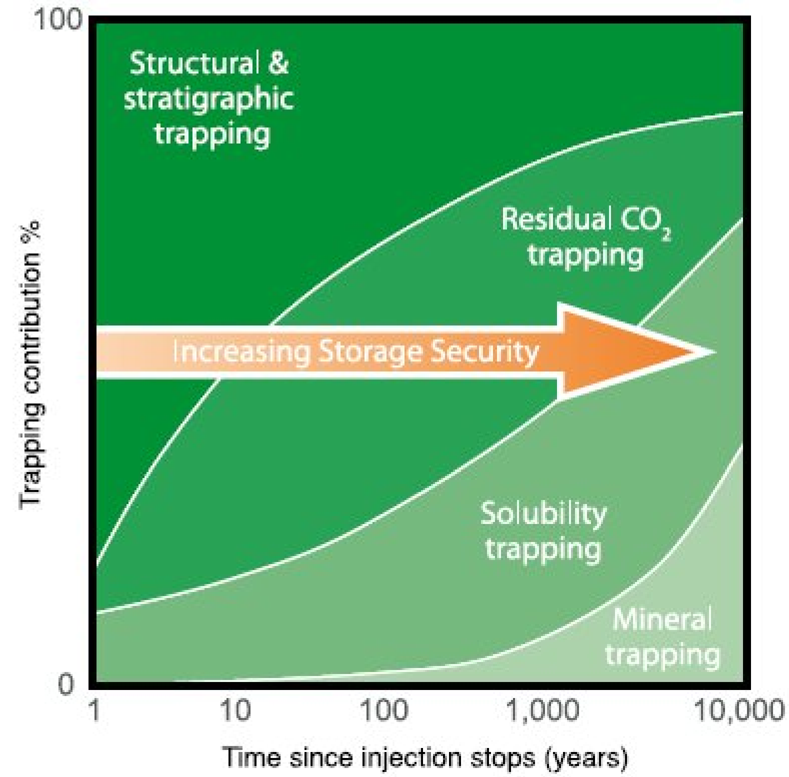
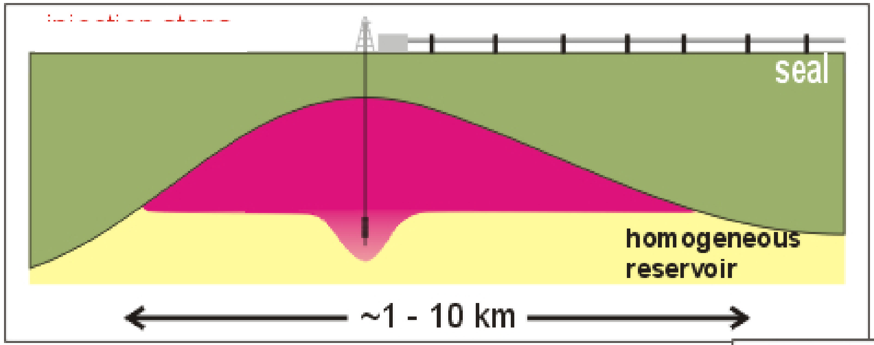
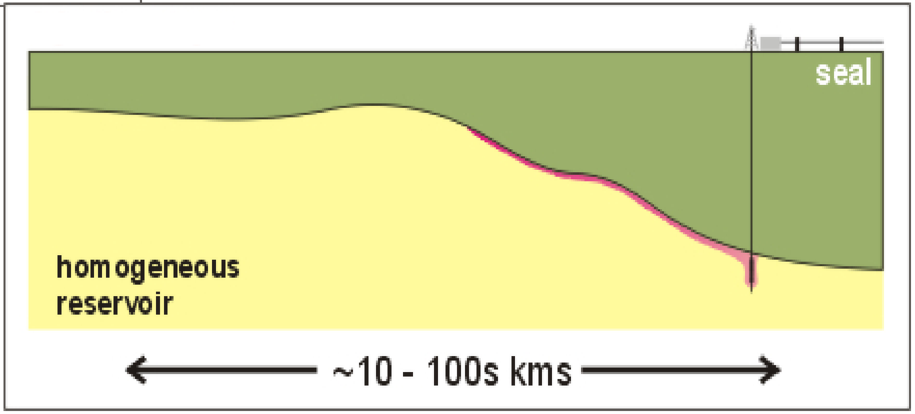


Figure 5.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase. IPCC SRCCS 2005

Conventional Traps v Deep Saline Formations



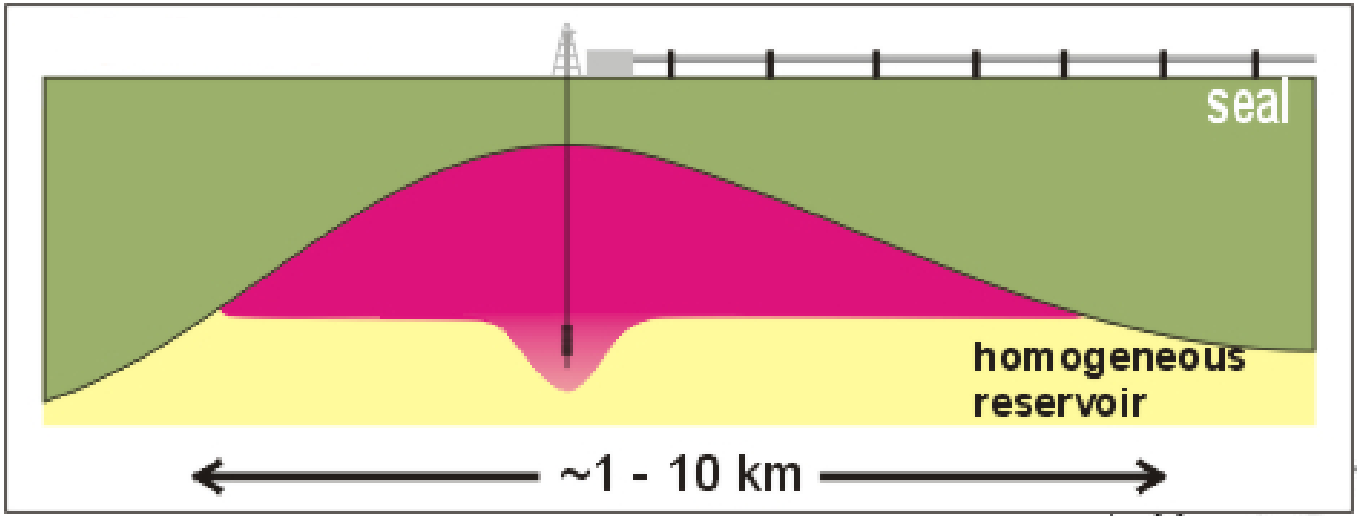
Conventional trap – may be a depleted field or a “dry” structure



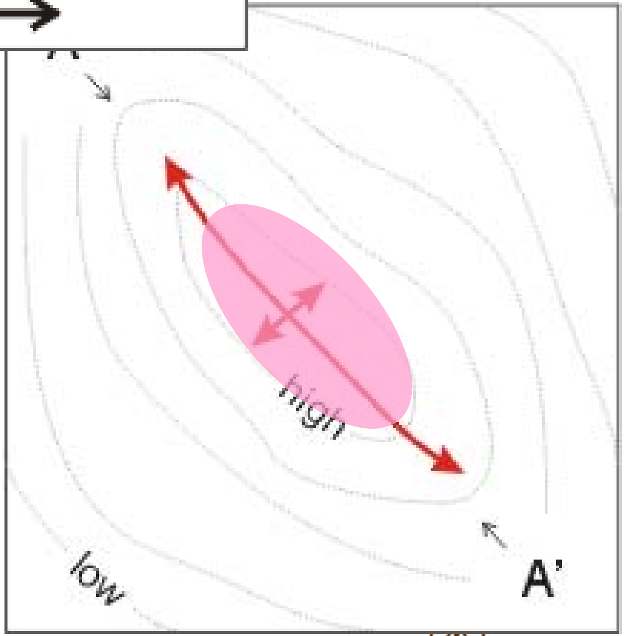
Deep Saline Formation

Conceptual CO_2 Storage Scenario

Depleted field / structural trap



Trap Structure



Conventional Trap / Depleted Field

Can be clearly structurally defined.

Physical trapping causes back pressure to force the CO_2 to fill the structure.

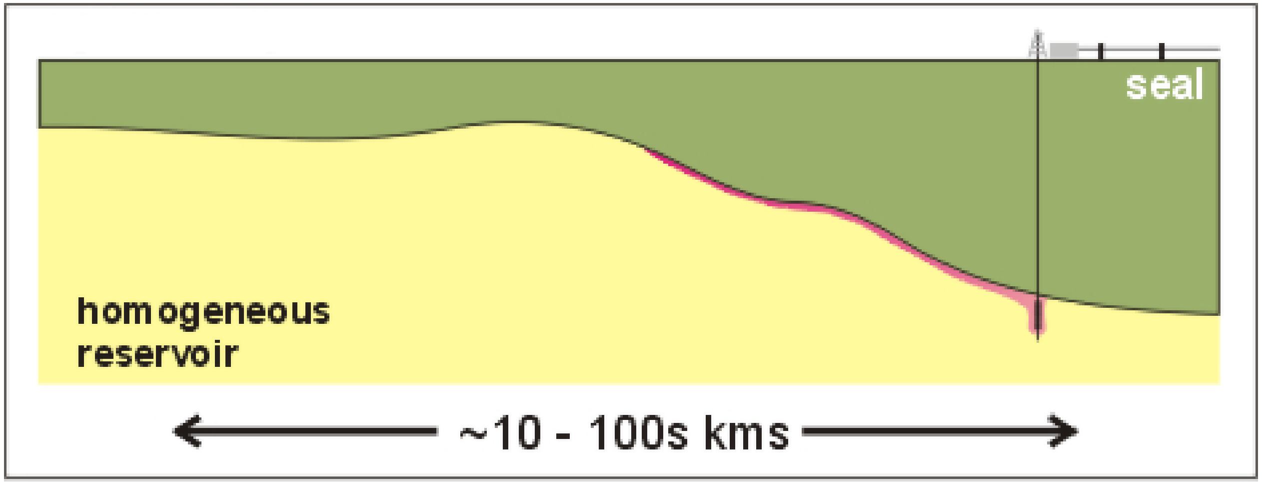
Past oil field experience aids capacity evaluation.

(Slide courtesy of Robert Root)

(Slide courtesy of Robert Root)

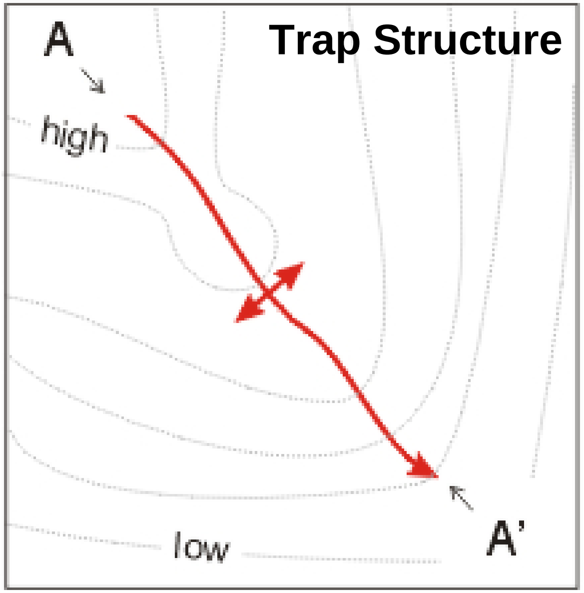
Conceptual Saline Reservoir CO_2 Storage Scenario

Residual and Solubility Trapping



Large, open structure long migration path

- Residual and dissolution the major trapping mechanisms.
- Long term mineral trapping
- Minor structural trapping
- How can the capacity of these reservoirs be assessed?



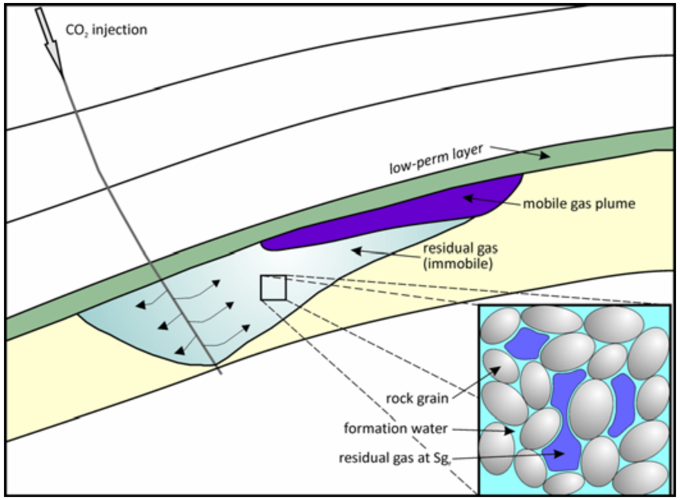
(Slide courtesy of Robert Root)

Saline Reservoir Trapping

- Some percentage of trapping in structural and stratigraphic closures within the body of the rock and beneath overlying seal - may be below seismic resolution.
- Main trapping mechanisms will be residual and dissolution

<u>Critical issues then are:</u>

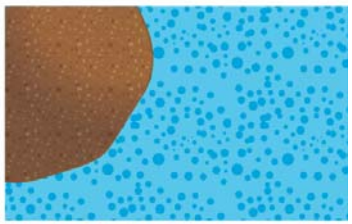
1. how much of the pore space in the path of the migrating plume will ultimately contain residual oil?
2. How much of the total pore space of the rock will the migrating plume “see”, because it will move preferentially through the most permeable zones?



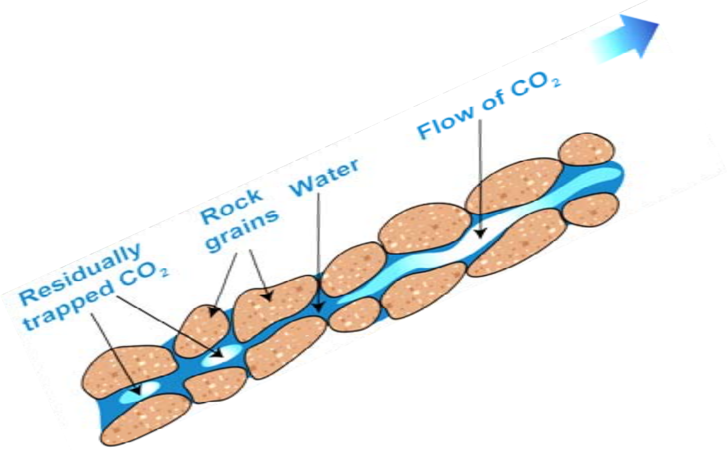
(After Juanes et al, 2006)

Saline Reservoir Trapping – Alternative terms

- Migration Assisted Storage- (CGSS 2009)
- Migration Associated Trapping- (CO2CRC 2010)



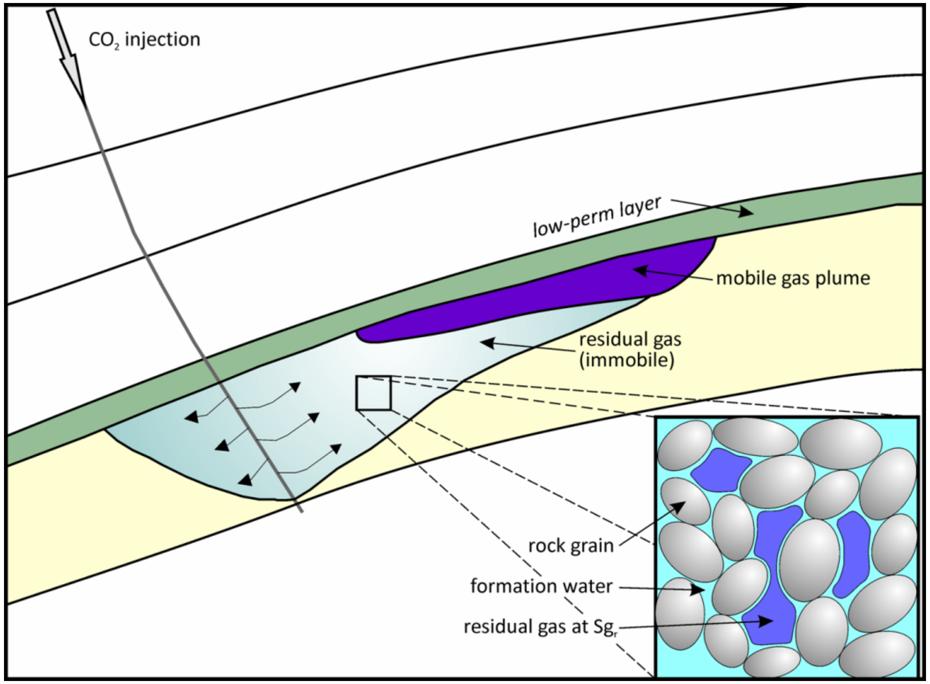
Dissolution



Residual Saturation

Mineralisation

Residual Trapping



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 and CGSS 2010)

Assessing Geological Storage Capacity at Different Scales

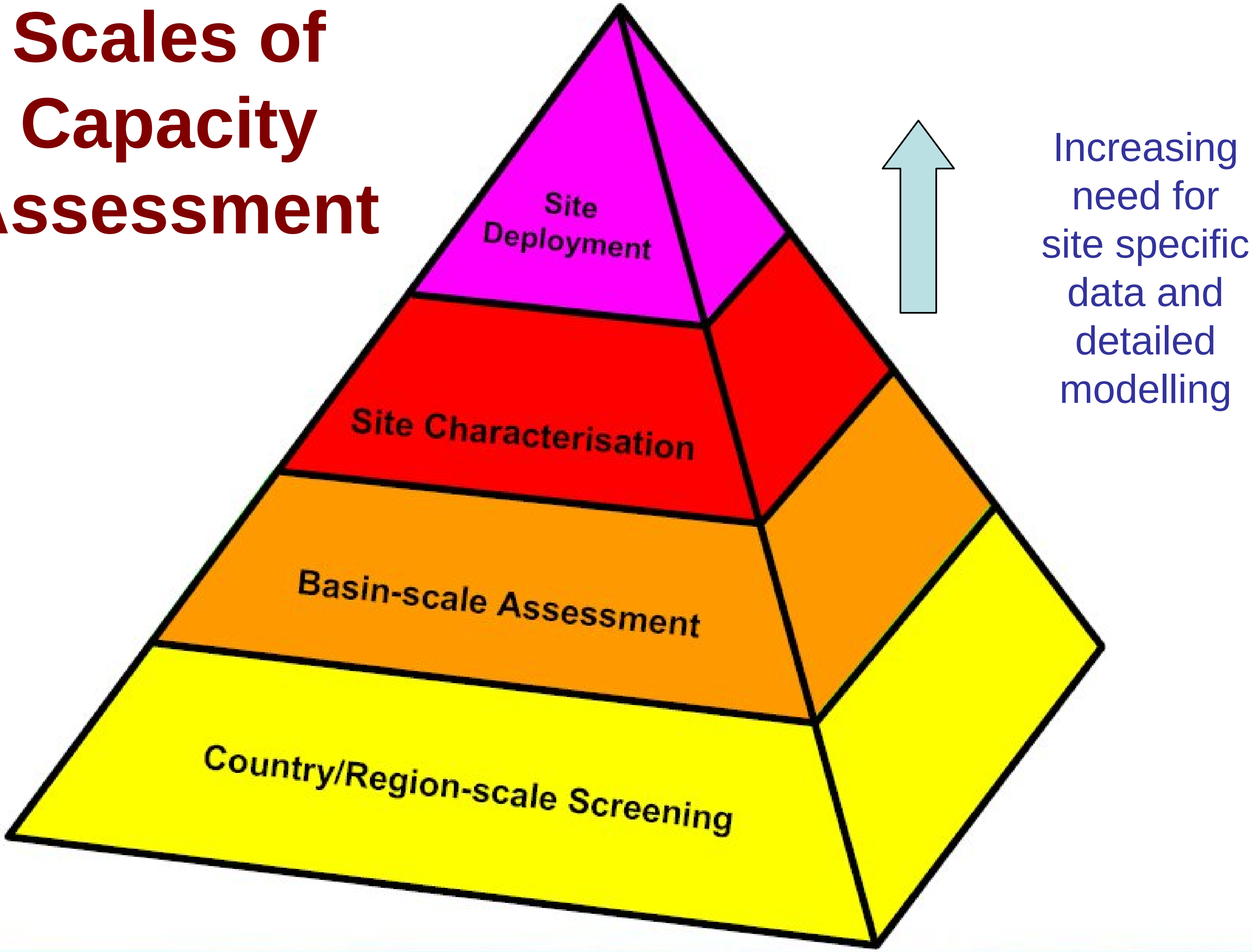
Critical Issues

1. The size of the region to be assessed
2. The amount of subsurface data that is available
3. The time frame over which the assessment must be made

Some critical parameters

- Area of the reservoir formation
- Area of the seal
- Efficiency of the seal
- Porosity of the reservoir
- Geothermal Gradient
- Heterogeneity of the reservoir (net/gross ratio)
- Efficiency with which the carbon dioxide will fill the reservoir (E Factor).

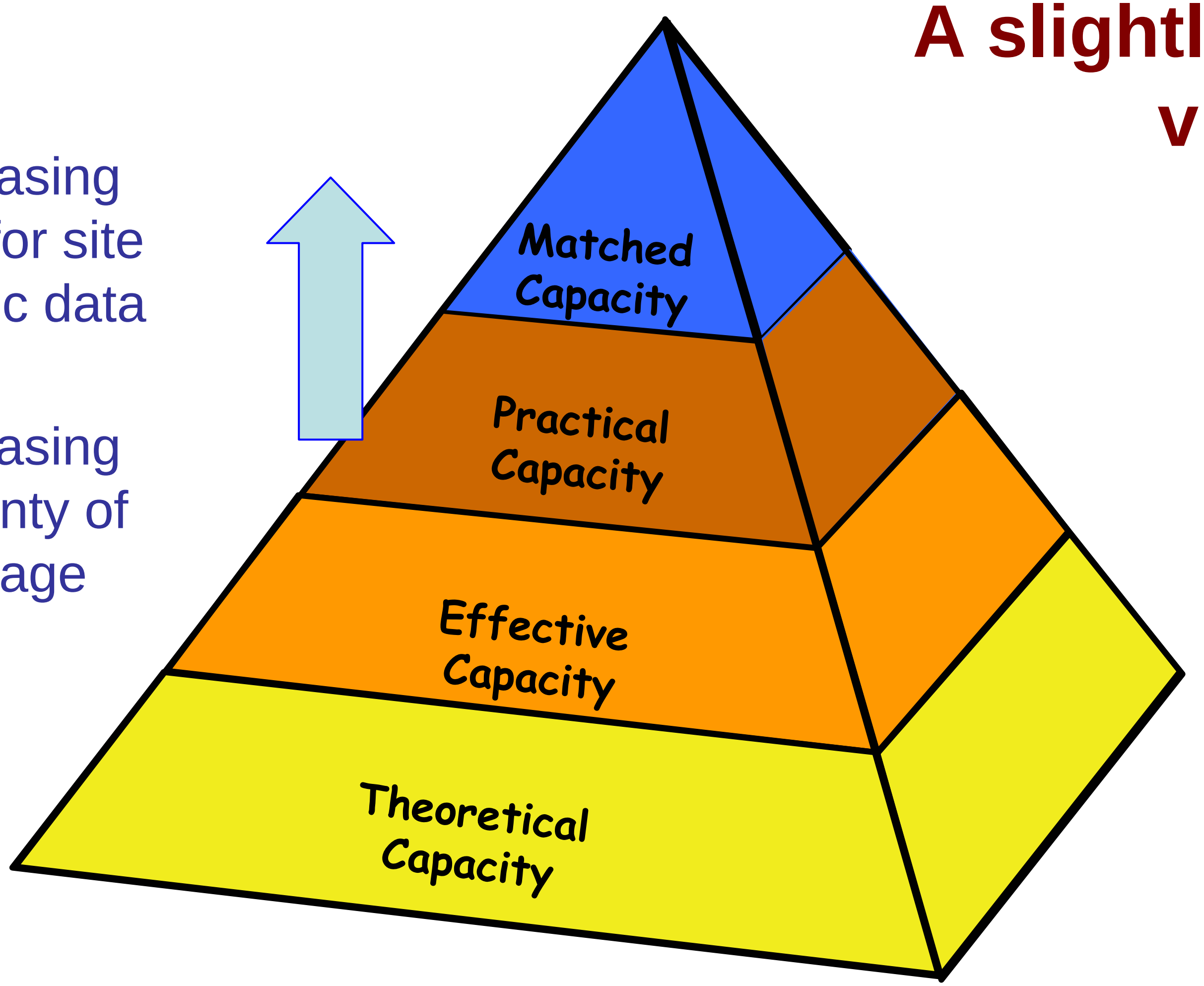
Scales of Capacity Assessment



A slightly different view

Increasing need for site specific data

Increasing certainty of storage



CSLF Techno-Economic Resource Pyramid (2005/2007)

Basin Scale Assessment versus Site Characterisation

- Ideally capacity assessments should be made on the basis of detailed geological and geophysical analysis and modelling.

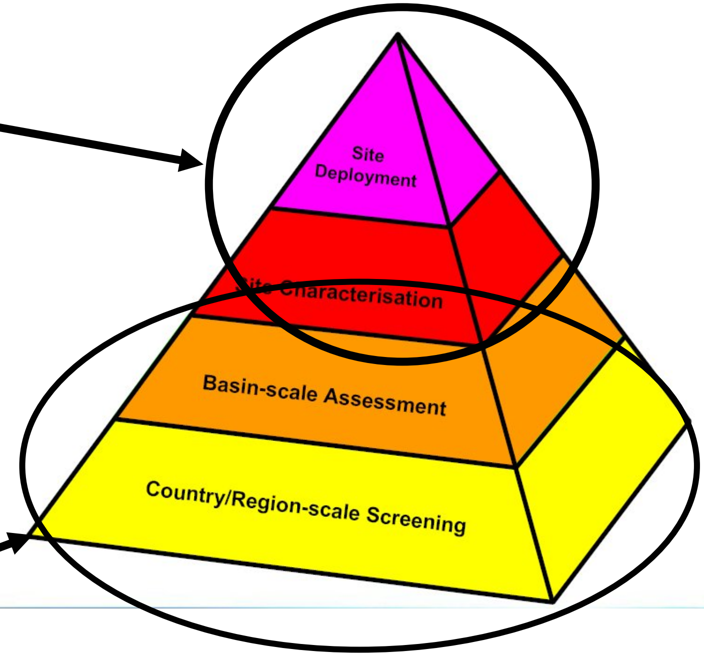
- But frequently high level assessments are required for political, strategic or financial reasons.

- It may then be necessary to carry out a high level assessment of a particular basin, region or country.

Basin Scale Assessment versus Site characterisation

- **Site characterisation or assessment requires detailed geological and reservoir simulation modelling to determine if the site has the capacity to contain the volumes which it is proposed to inject.**

- **Basin or regional scale may require a general formula to allow high level assessment of total potential capacity if data availability or time for assessment is limited**

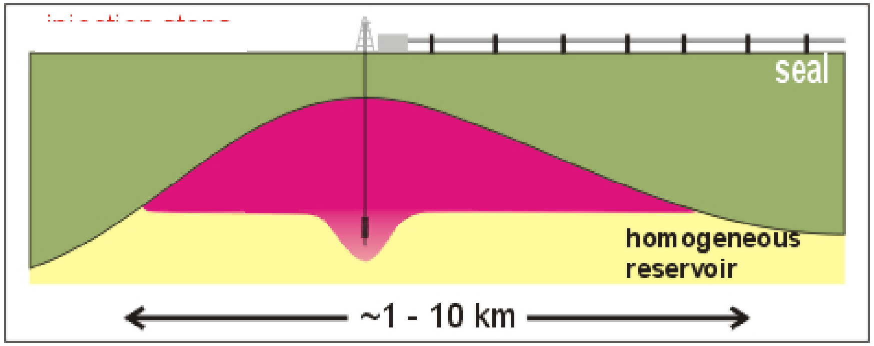


Structural Traps
Depleted Fields and Dry Structures

- General agreement on capacity estimations for physical structures.
- If it is a depleted field can assume that capacity will be related volume of petroleum extracted, less any constraints from injection pressure versus fracture pressure and from seal capacity differences between CO_2 and petroleum.

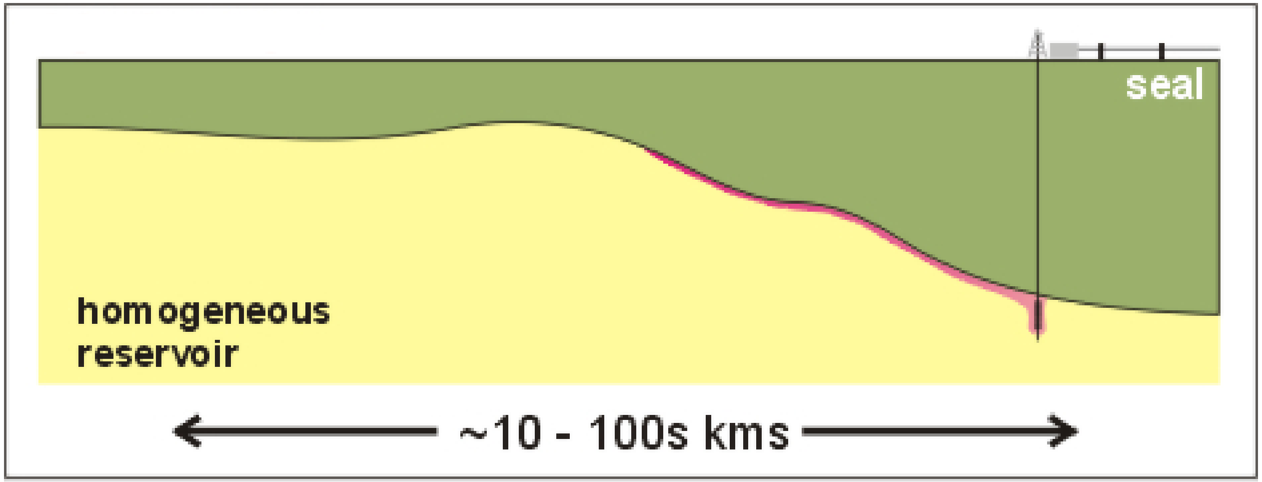
“Dry” Structure

- If a “dry” structure capacity can be estimated by conventional methods:
  - Area * av net thickness *av porosity*(1-Sw)*structural correction
- Again this may be reduced due to fracture pressure or seal capacity constraints.
- “Dry” structures can be considered a subset of saline aquifers.



Conceptual Saline Reservoir CO_2 Storage Scenario

Residual and Solubility Trapping



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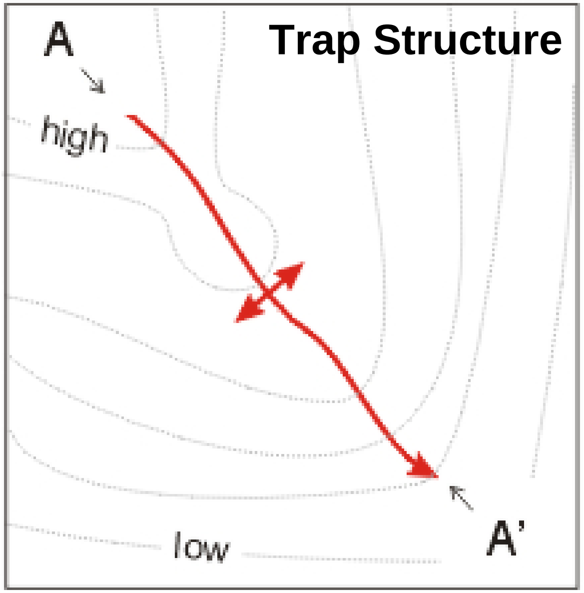
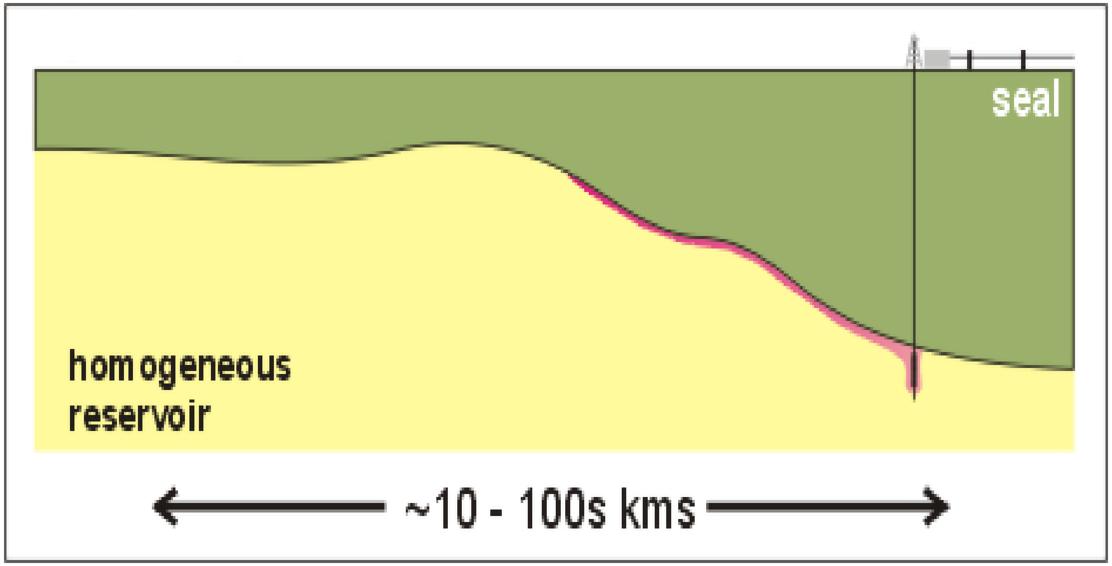


(Slide courtesy of Robert Root)

The Efficiency or Capacity Factor

In this simple model the CO_2 is moving along under the base of the seal so it does not contact the main mass of the rock.



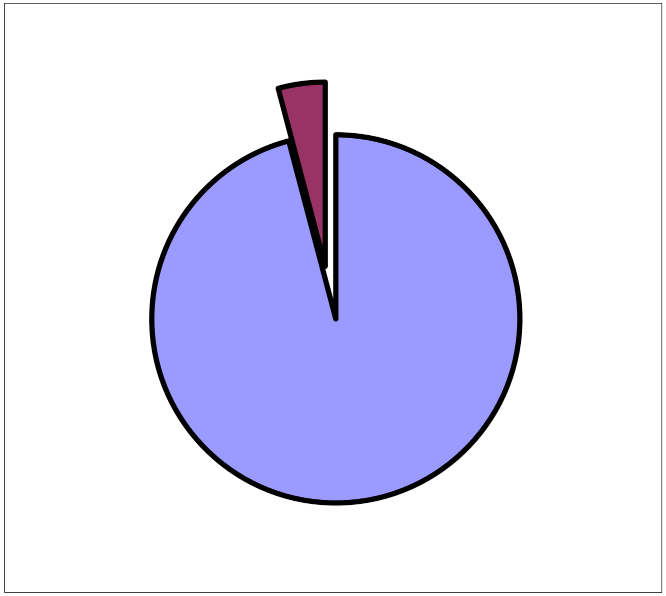
How much of the rock does the CO_2 "see"?

Key Recent Published Methodologies

DOE 2006	USDOE Capacity and Fairways Sub-group – Regional Carbon Sequestration Partnerships
CSLF 2007	CSLF Task Force for Review and Development of Standard Methodologies for Storage Capacity Estimation
CO2CRC 2008	Generally based on the DOE methodology
USGS 2003/2006	Specific sequestration Volumes. A useful tool for CO_2 Storage Capacity Assessment
USGS 2009	Development of a Probabilistic Assessment Methodology for Evaluation of Carbon Dioxide storage – needs detailed knowledge of basin
IEA/EERC 2009	Summary and overview of CSLF, DOE and other methodologies, Calculation of storage coefficients in the context of the resource pyramid.
CGSS 2010	Methodology developed for the 2009 Queensland CO_2 Geological Storage Atlas. Requires depth of data from basin

How much of the reservoir is available?

- Essentially the two most widely used methods calculate the volume of the pore space in the area under consideration then apply a discount factor to allow for the pore space that realistically cannot be accessed for a variety of reasons, both large and small scale.
- Generally accepted that less than 4% of pore space is available even under optimum conditions.



Capacity of saline formations
The DOE Formula

$$G_{CO2} = A\ h_g\ \phi_{tot}\ \rho\ E$$

Parameter	Units*	Description
G_{CO2}	M	Mass estimate of saline-formation CO_2 storage capacity
A	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage-capacity calculation
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A
ϕ_{tot}	L^3/L^3	Average porosity of entire saline formation over thickness hg. Total porosity of saline formations within each geologic unit's gross thickness divided by hg
ρ	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over hg
E	L^3/L^3	CO_2 Storage Efficiency Factor that reflects a fraction of the total pore volume that is filled by CO_2

- 1-4% or less?

Methodology for Development of Carbon Sequestration Capacity Estimates – Appendix A., DOE 2006

The CSLF Formula

In the CSLF methodology this formula is only applied to the structural and stratigraphic traps that exist within the body of the reservoir and at the base of the seal. Requires a greater level of knowledge than the DOE method.

$$V_{CO2t} = V_{trap} \times \phi \times (1 - S_{wirr}) \equiv A \times h \times \phi \times (1 - S_{wirr}) \quad (10)$$

where A and h are the trap area and average thickness, respectively.

The effective storage volume, V_{CO2e}, is given by:

$$V_{CO2e} = C_c \times V_{CO2t} \quad (11)$$

where C_c is a capacity coefficient that incorporates the cumulative effects of trap heterogeneity, CO_2 buoyancy and sweep efficiency.

Capacity Coefficient is - this the same as the E Factor?

DOE or CSLF - What is the difference?

- "The methodologies proposed by the CSLF Task Force and the USDOE Subgroup are basically identical, with minor differences in computational formulation" (Bachu 2008)

- "Fundamentally, the CSLF and DOE methods are the same Method" (Gorecki (EERC) 2009)

$$\text{“}V_{CO_2,DOE_e} = V_{CO_2,CSLF_e}\text{”}$$

Assessment Methodologies requiring more data

Specific Sequestration Volumes

- Brennan and Burruss (2006)
- Does not assess the capacity of a basin as a whole but determines what amount of pore space would be required to store a given volume of CO_2 at a specific temperature and pressure.

Specific Sequestration Volumes

For instance:

- At 60^{o}C and 15 Mpa CO_2 has a density of 604 Kg/m^{3}.
- Therefore: 1 tonne CO_2 requires a pore space of 1.7 m^{3} to contain it.
- If a reservoir sandstone has a porosity of 10% and a residual water saturation of 75%, it will require 60m^{3} of rock to hold 1 tonne of CO_2.
- Therefore a power station emitting 8.7 million tonnes annually would require 0.519 km^{3} of this reservoir rock to store 1 years emissions.

Specific Sequestration Volumes

- From this the volume of rock required over the life of a power plant can be calculated, and if the thickness of the reservoir is known the areal extent of the plume can be calculated.
- Again, although not specifically stated, the concept that the CO_2 is stored within the body of the rock implies residual storage.
- This methodology also includes an equation to calculate the volume of CO_2 that can be dissolved in the saline water within the reservoir.

Specific Sequestration Volumes

- This methodology is very good for rapidly assessing if a basin or sub-basin has the capacity to deal with the emissions from a specific point source or group of point sources.
- However it will not easily give total potential storage capacity if that is what is asked for.

USGS Probabilistic Assessment- 2009

- Develops methodology similar to natural resource assessments in the USGS National Oil and Gas Assessment.

- Regards the “geological commodity” of “pore space in the subsurface” as a resource that can be assessed in a similar way to other natural resources.

- Uses “ Monte Carlo” analysis to define Minimum, maximum and most likely values.

USGS Probabilistic Assessment- 2009

- This methodology is probably the most rigorous proposed has a well established precedent in the National Oil and Gas Assessment.

- However in many cases it requires a level of knowledge and data that may not be available in the saline formation proposed for storage.

CGSS – “Queensland Methodology”

- A rigorous methodology was developed for the assessment in the “Queensland Carbon Dioxide Geological Storage Atlas 2009”
- Deterministically based, requiring detailed geological database to be most efficiently used.
- Probably most realistic assessment of basin capacity if data available.
- May tend to result in less optimistic storage capacities than other methods.

The Critical Question

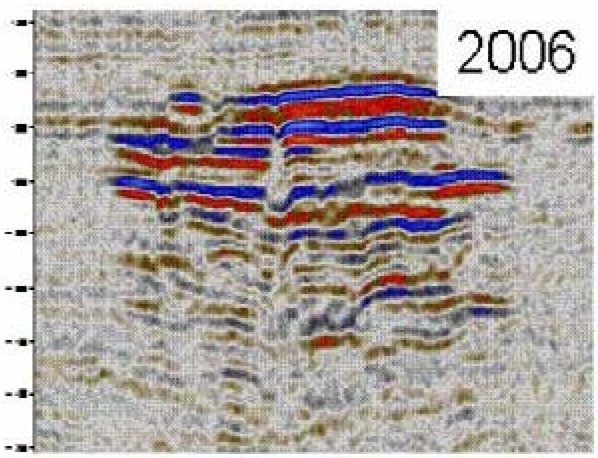
- What is the appropriate E or Cc or Cce value to use?
- The IEA/EEC Report has calculated a series of site-specific coefficients for 3 different lithologies and ten different depositional environments.
- These range from 4% to 15%
- However extrapolating site-specific coefficients over a larger area must take into account probable geological heterogeneity and compartmentalisation.
- Other studies suggest that ranges 1%-4% is more likely.

Where is the Empirical Data?

- Almost all of the E factor quoted are based on expert assessments from oil field experience and computer modelling.
- There is only one long running saline reservoir storage project in the world – Sleipner.

And at Sleipner we are still very unsure of what CO_2 saturation is being reflected in the seismic image.

Only when we have a portfolio of real storage projects will we be able to approach this number with any certainty



Questions?

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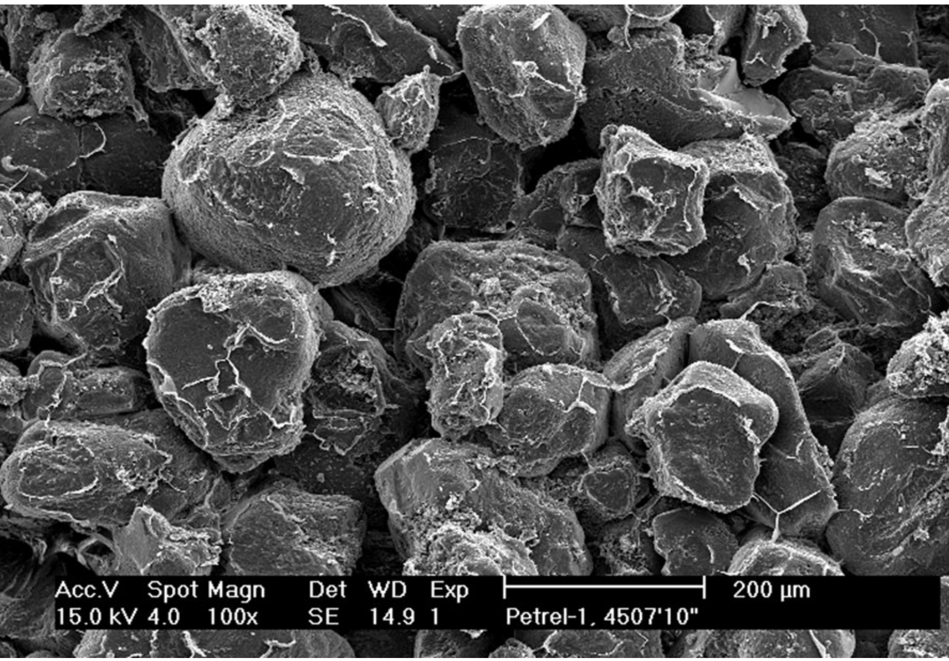
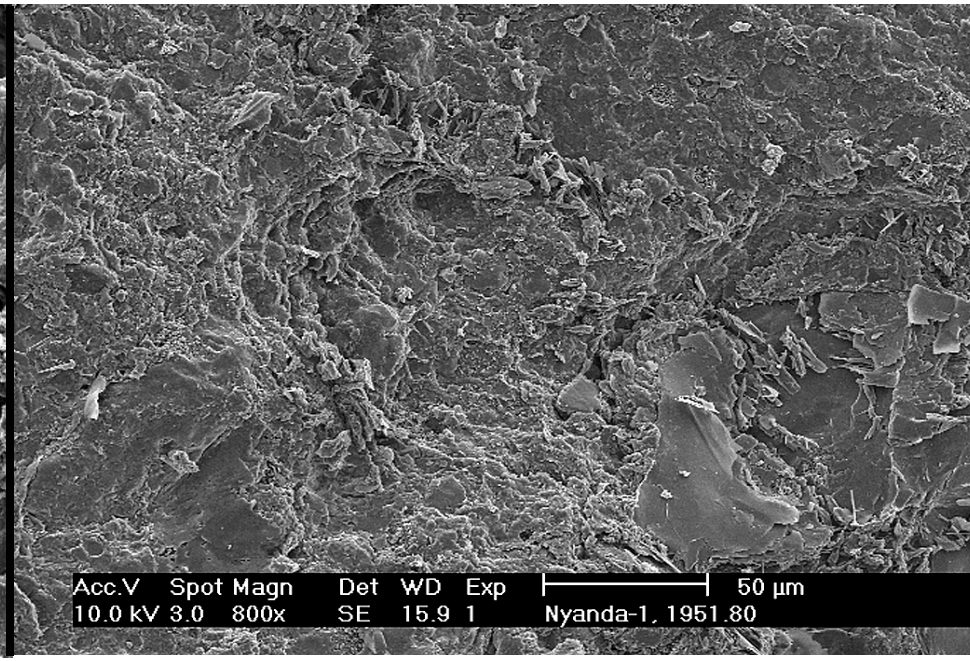
Reservoir v Seal





~1 millimetre

(Container)

~¼ millimetre

(Lid)