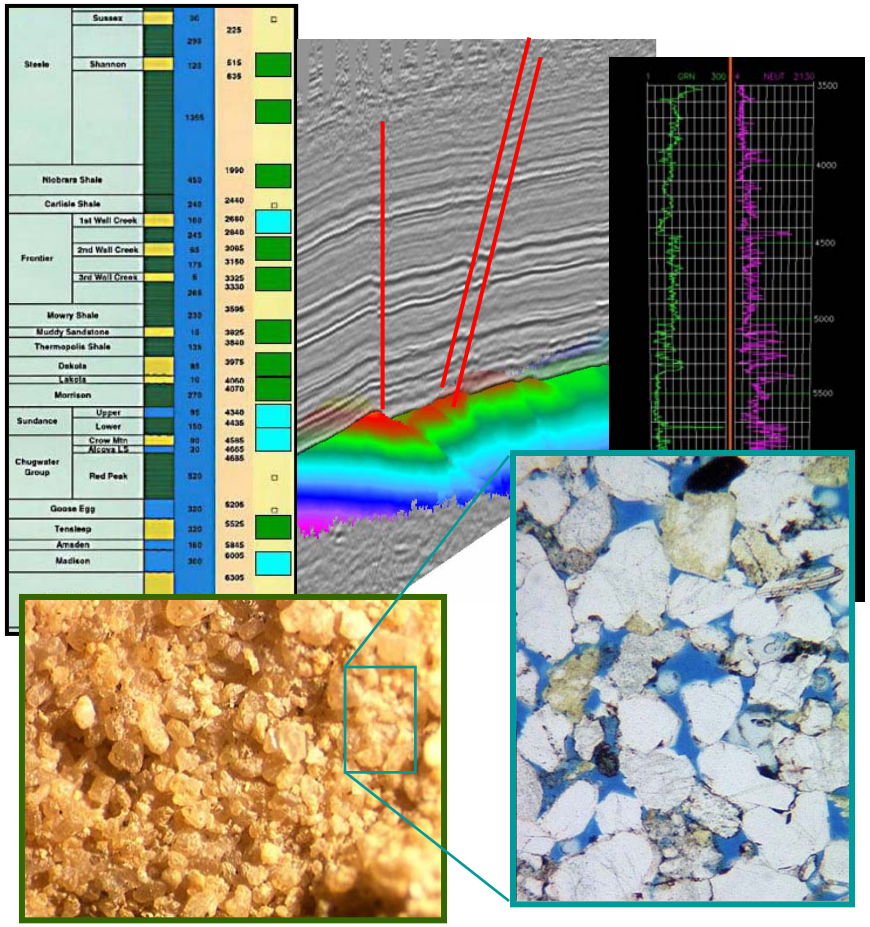
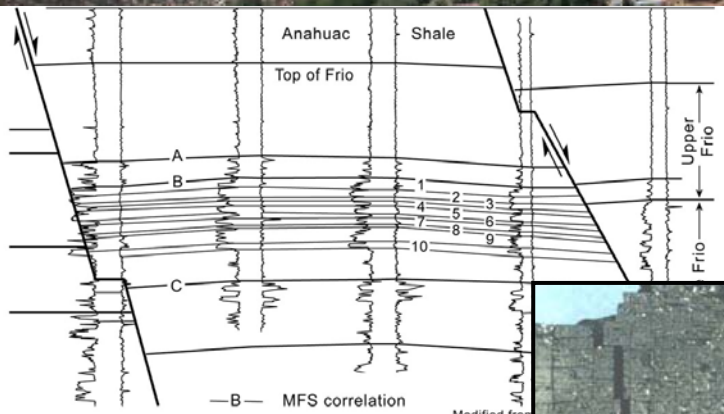
The ICE Framework for Site Selection

And a description of potential due diligence requirements





S. Julio Friedmann

Energy & Environment Directorate, LLNL

Conclusions

Site selection should proceed around three primary characterizations: Integrity, Capacity, and Effectiveness (ICE)

Effectiveness is the most difficult to characterize, but there are many approaches and tools. Wells present the greatest risk but appear manageable.

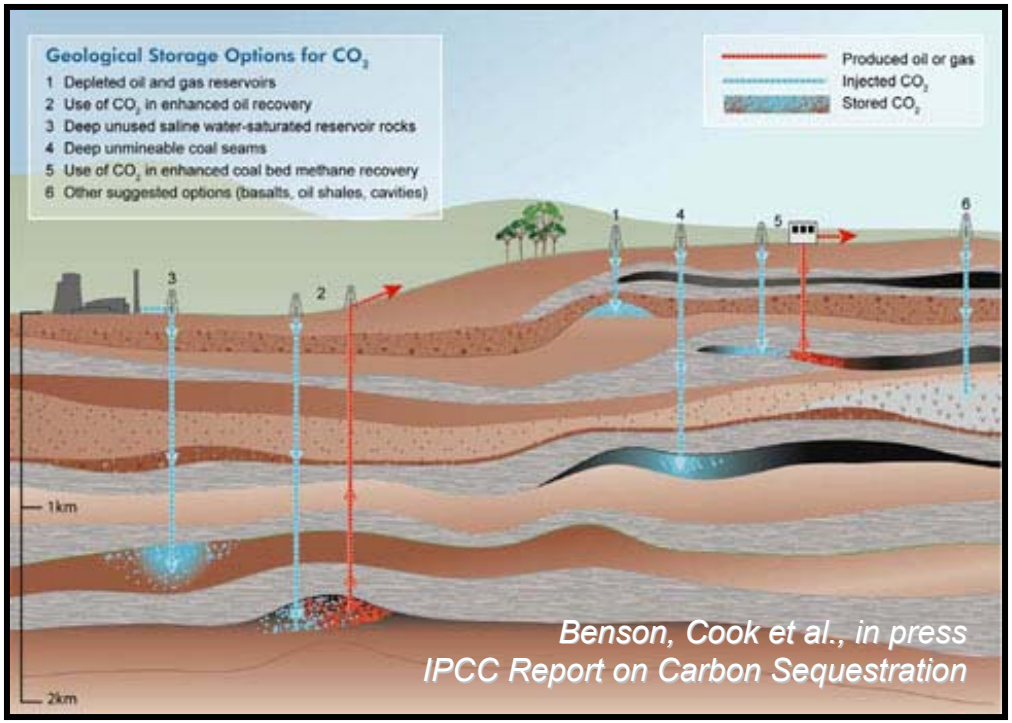
> ***An accelerated research program would help redress ongoing risk concerns.***

What constitutes due diligence will change, but is likely to defined initially around repeatable, defensible, readily obtained measurements

The map is not the territory

Alfred Korzbyski

CO_2 can be stored in several geological targets, usually as a supercritical phase



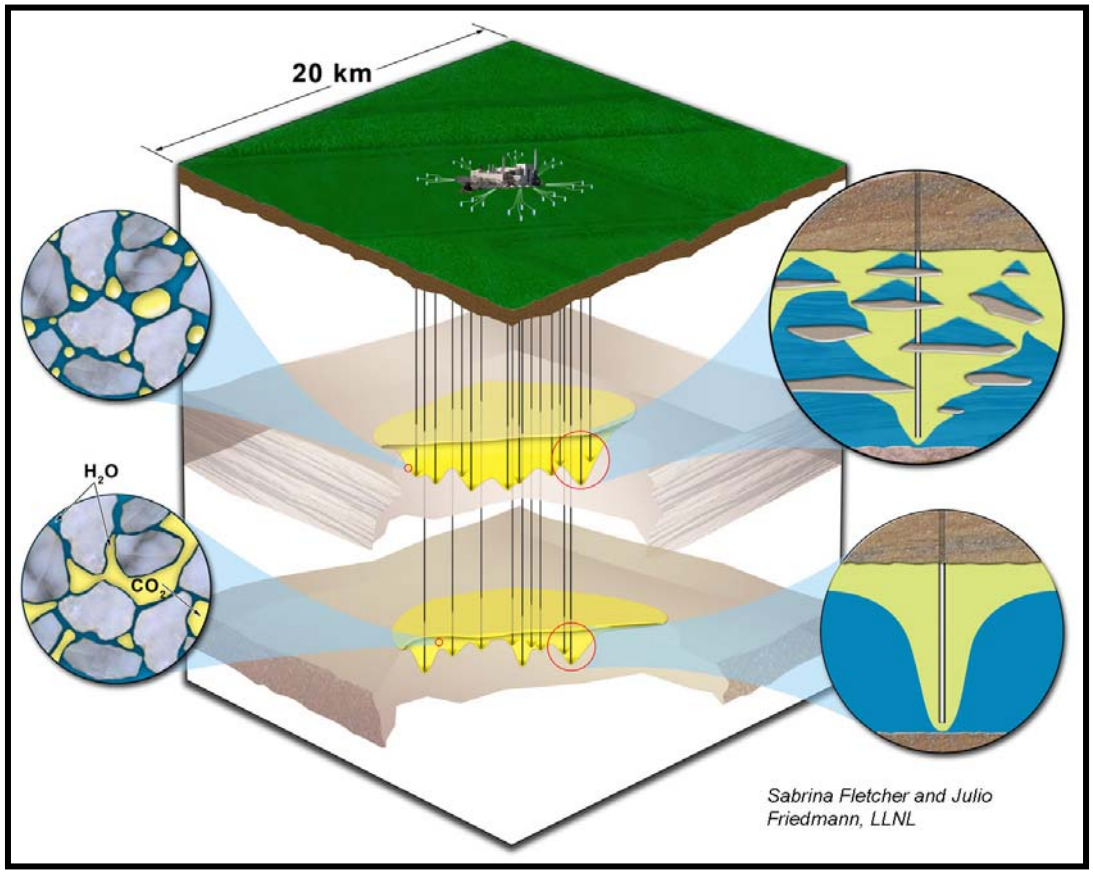
Saline Aquifers
Depleted Oil & Gas fields
(w/ or w/o EOR and EGR)
Unmineable Coal Seams
(w/ or w/o ECBM)
Other options
(e.g., oil shales, basalts)

The storage mechanisms vary by reservoir type

EOR/Depleted Oil & Gas fields are early actors
Saline aquifers hold the largest storage capacity
Both are primarily flow in porous media

The discussion should focus on a real power plant capture case

Let's suggest that by 2020, all new coal plants will be fitted for CO_2 capture and storage. The scope and scale of injection from a single plant must be considered.



One 1000 MW p.c. plant, 85% c.f., 90% capture:

- **6 MM t CO_2/yr**
- **100,000 bbl/d (as supercritical phase)**
- **After 50 year, 2 G bbls**
- **CO_2 plume at 10y, ~10 km radius: at 50 yrs, ~30 km**
- **Many hundreds of wells**
- **Likely injection into many stacked targets**

Sites must receive large volumes of CO_2 at a high rate and contain them for long periods

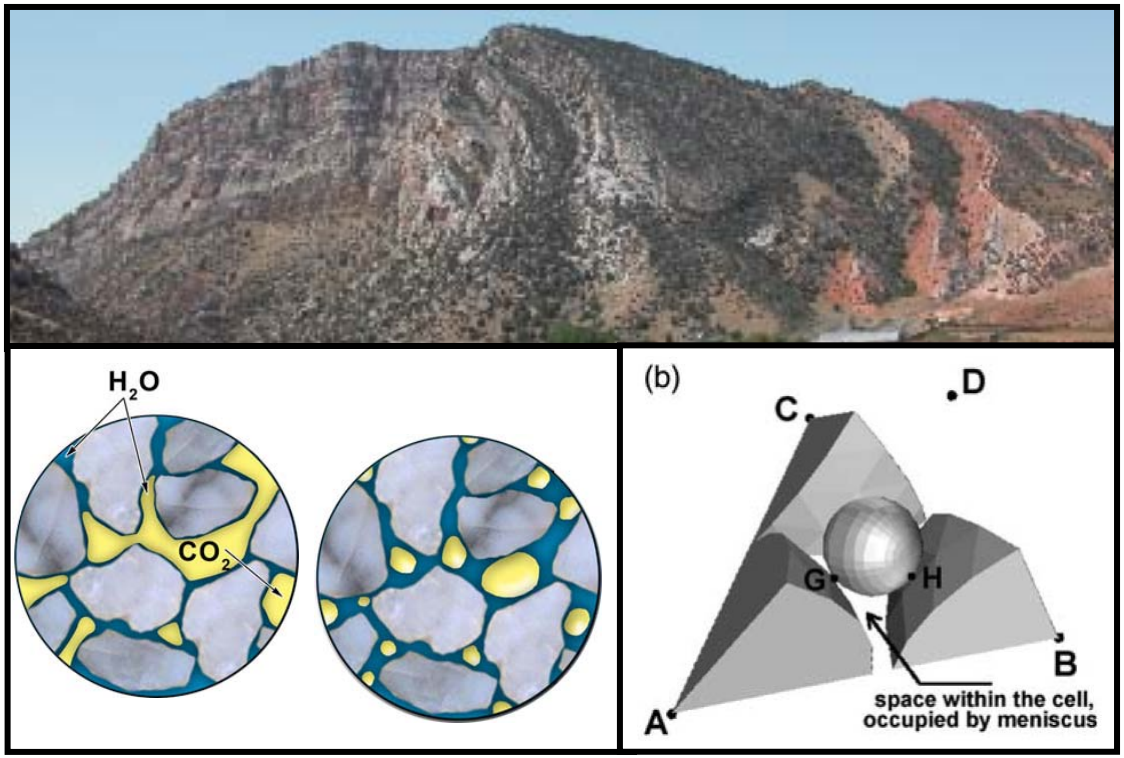
Storage mechanisms are sufficiently well understood to be confident of effectiveness

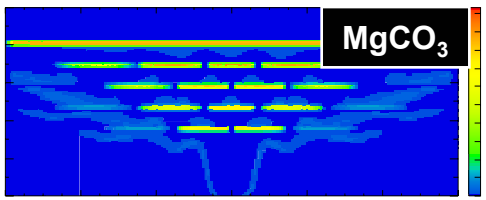
Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

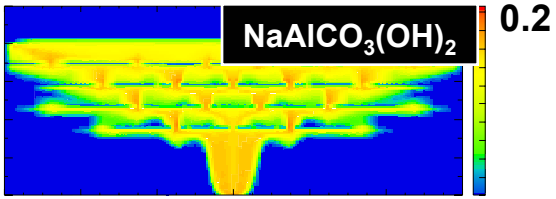
Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)



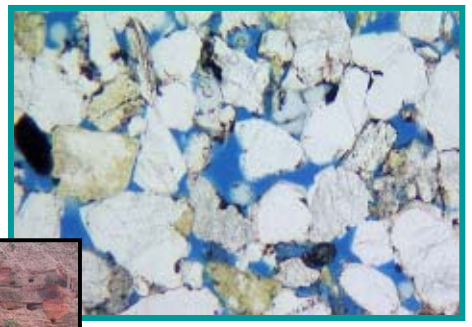




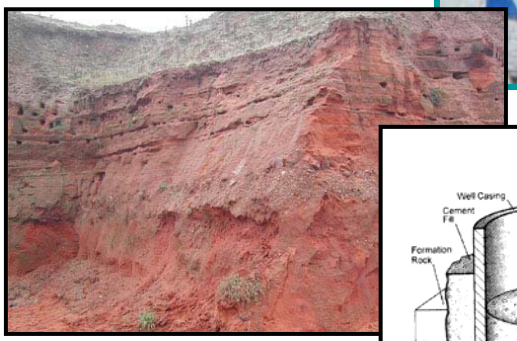
Site selection due diligence requires characterization & validation of ICE

Injectivity ***Capacity*** ***Effectiveness***

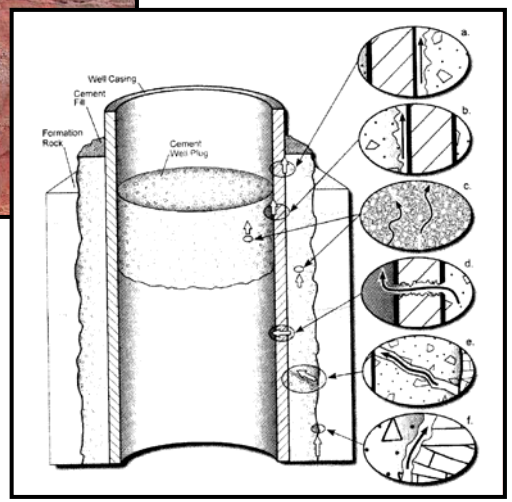
Injectivity
- Rate of volume injection
- Must be sustainable (months – years)



Capacity
- Bulk (integrated) property
- Total volume estimate
- Sensitive to process



Effectiveness
- Ability for a site to store CO_2
- Long beyond the lifetime of the project
- Most difficult to define or defend



Gasda et. al, 2005

The goal of site characterization is NOT to ensure storage integrity

That's a key goal of a successful CO_2 storage project, which requires site characterization

It is to provide a technical basis for decision making for secure storage, including financing & insurance
It is to provide data for planning, including operations, MMV deployment, and risk management
It is to select sites of low overall risk and high chance of success, short- and long-term

Injectivity & Capacity: Operators, insurers, financiers
Effectiveness: Insurers, regulators, public stakeholders

Injectivity

Capacity

Effectiveness

Site selection requires *Injectivity*

A 1000 megawatt p.c. plant will produce 6 MM tons of CO_2 each year. Injectivity must match that load.

Estimated in many ways

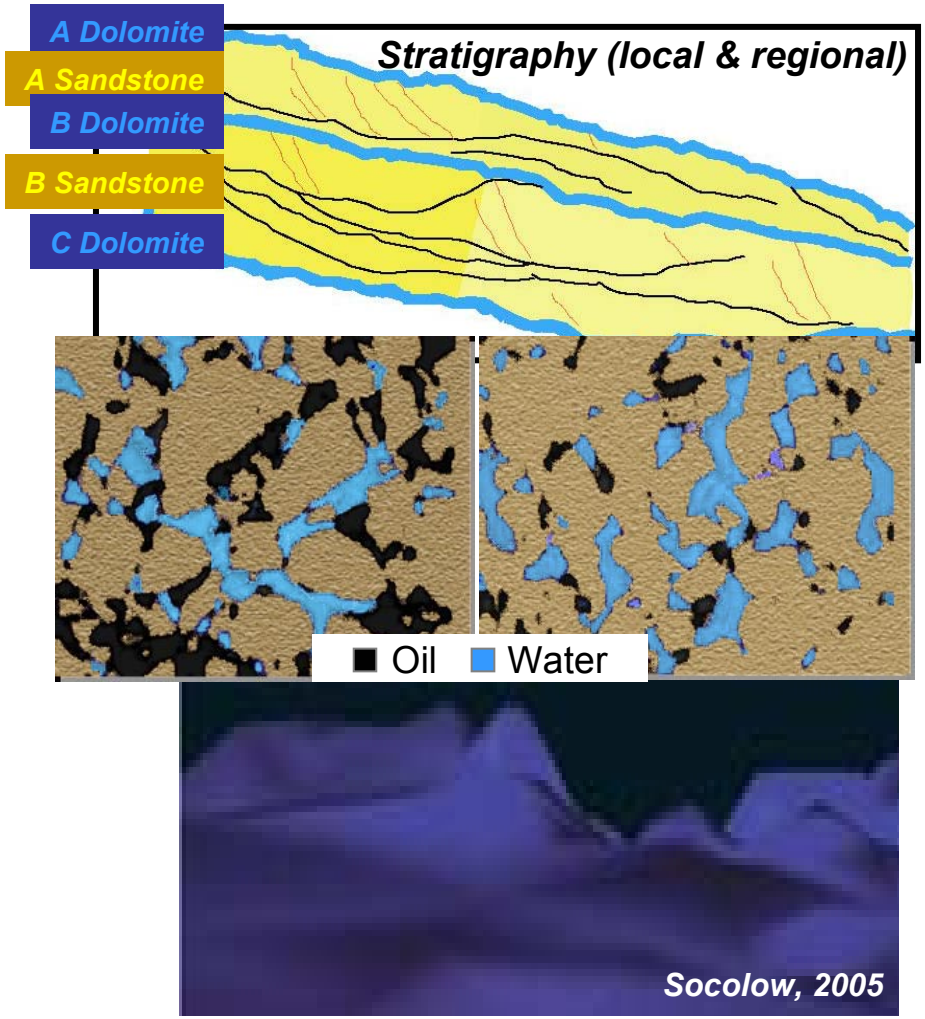
- Permeability tests of core
- Stem, injection, production tests
- Stratigraphic connectivity

Ultimately a function of difficult to predict or measure key terms

- Pore throat diameter (local)
- Cap rock yield strength
- Relative permeability

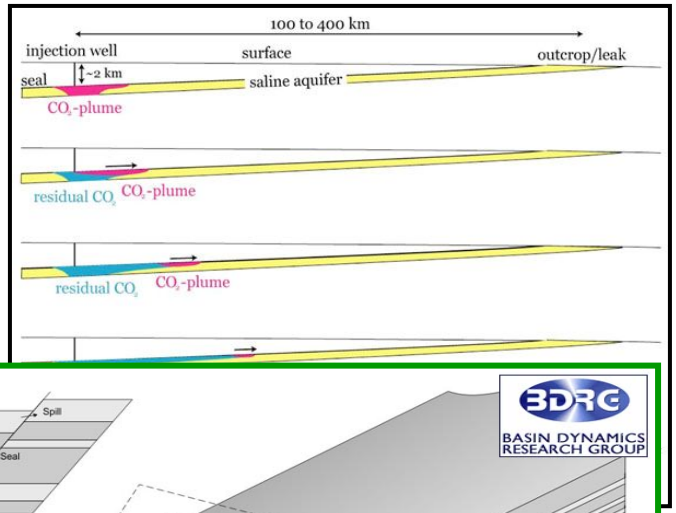
Ultimately, can be engineered

- Increased injection length (deviated wells)
- Stimulation (hydrofracture)



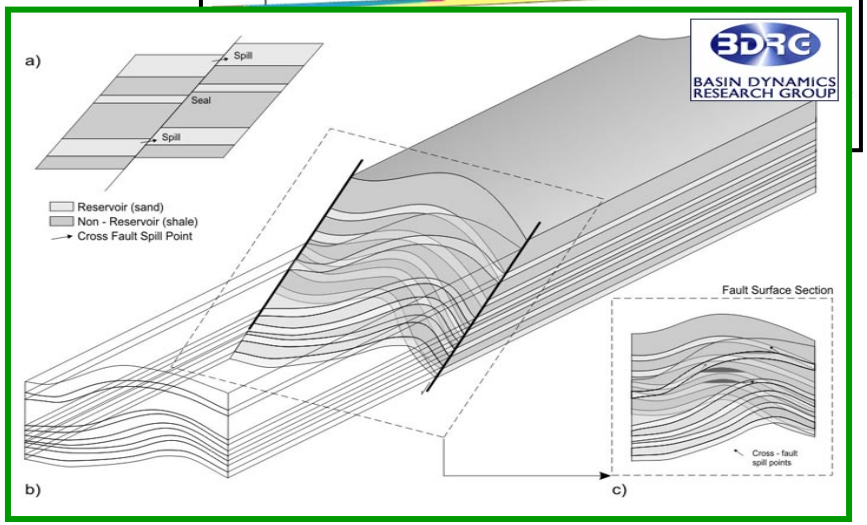
Site selection requires **Capacity**

A 1000 megawatt p.c. plant will produce 300 MM tons of CO_2 in 50 years. Capacity must match that volume.



Estimation requires pore volume estimates: conventional mapping & conventional tools

- **Unit thickness and extent (rock volume)**
- **Net:gross (sand percent)**
- **Porosity/effective porosity**



Ultimately a function of pore-scale process *over functional injection duration and area*

- **Physical trapping; saturation**
- **Conventional simulation to define extent of plume relative to rock volume**
- **The rest (residual, dissolved, mineralized fractions)**

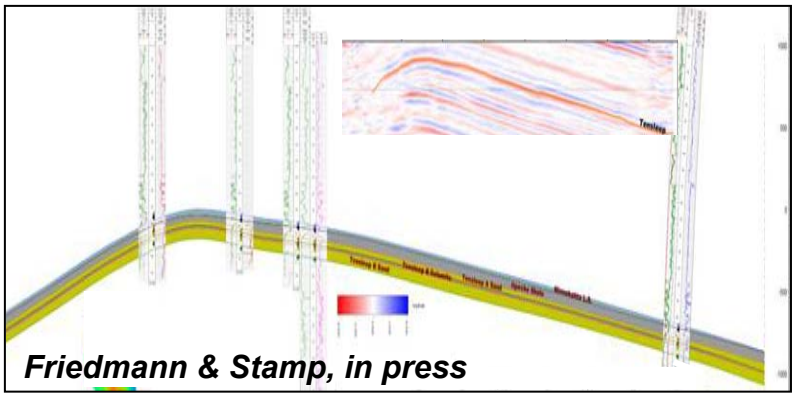
While "the rest" may be difficult to estimate precisely, reasonable estimation can be done with conventional tools

Site selection requires **Effectiveness**

Emissions from a 1000 megawatt p.c. plant should reside in the crust a long time for CO_2 storage to be effective

Initial characterization is simple

- **Does it close? (structurally, stratigraphically, hydrodynamically?**
- **Is there one of more good seals?**
- **Are there high permeability conduits out that will leak**

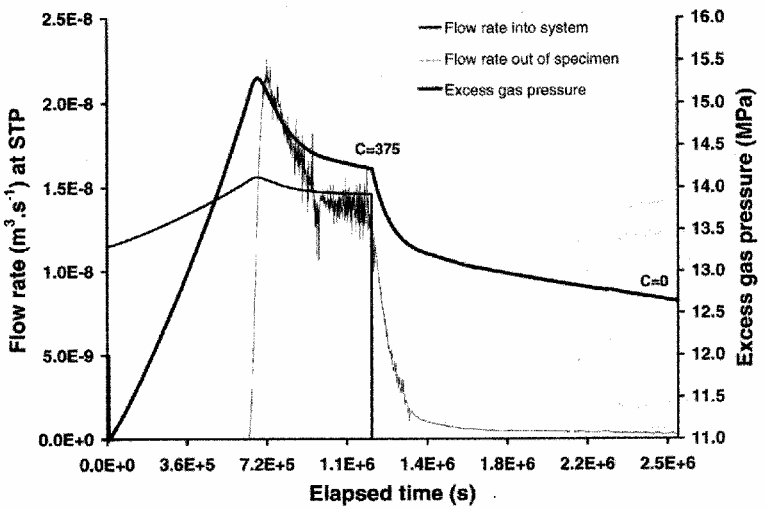


Friedmann & Stamp, in press

Hmmm… not so simple

Multiple initial screening tools, multiple supporting tools

- **Geological mapping, characterization and correlation**
- **Capillary entry pressure**
- **Stress tensor estimation**



Harrington & Horseman, 1999

Site selection due diligence requires characterization & validation of ICE

The uncertainty in ICE can be delineated characterized, and managed

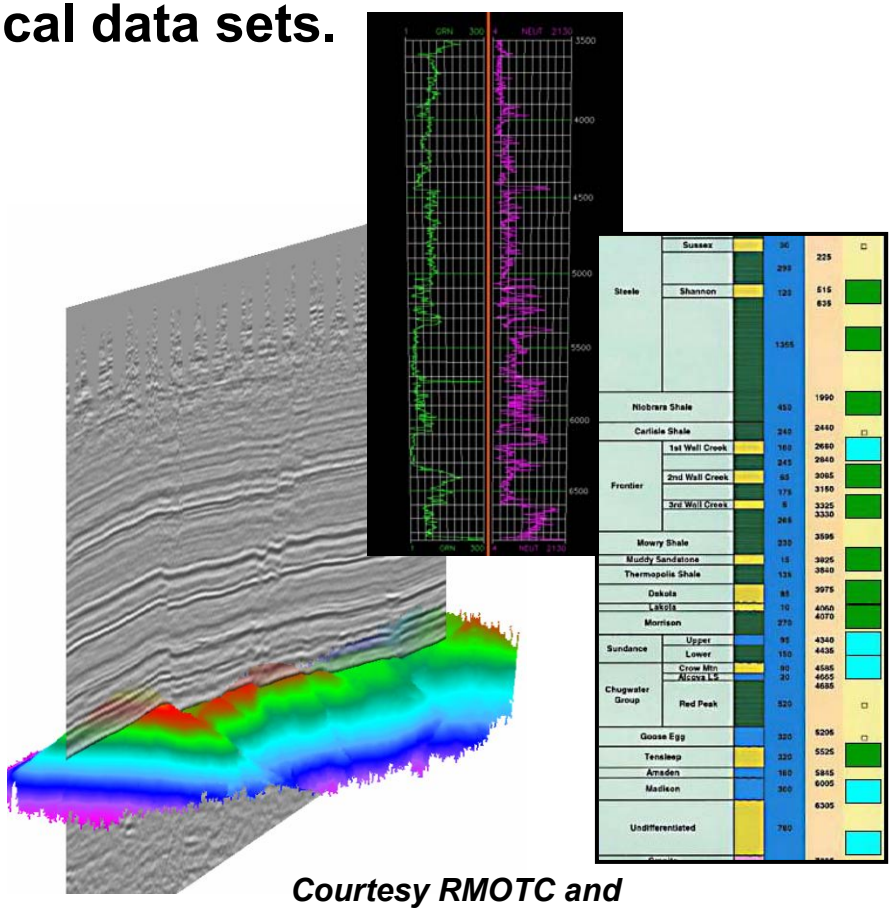
Ideally, any site selection and certification process will involve detailed characterization. In some cases, this will require new geological and geophysical data sets.

For Depleted Oil & Gas Fields:

- **Injectivity & capacity well established**
- **Objective measures of effectiveness exist**

For Saline Aquifers:

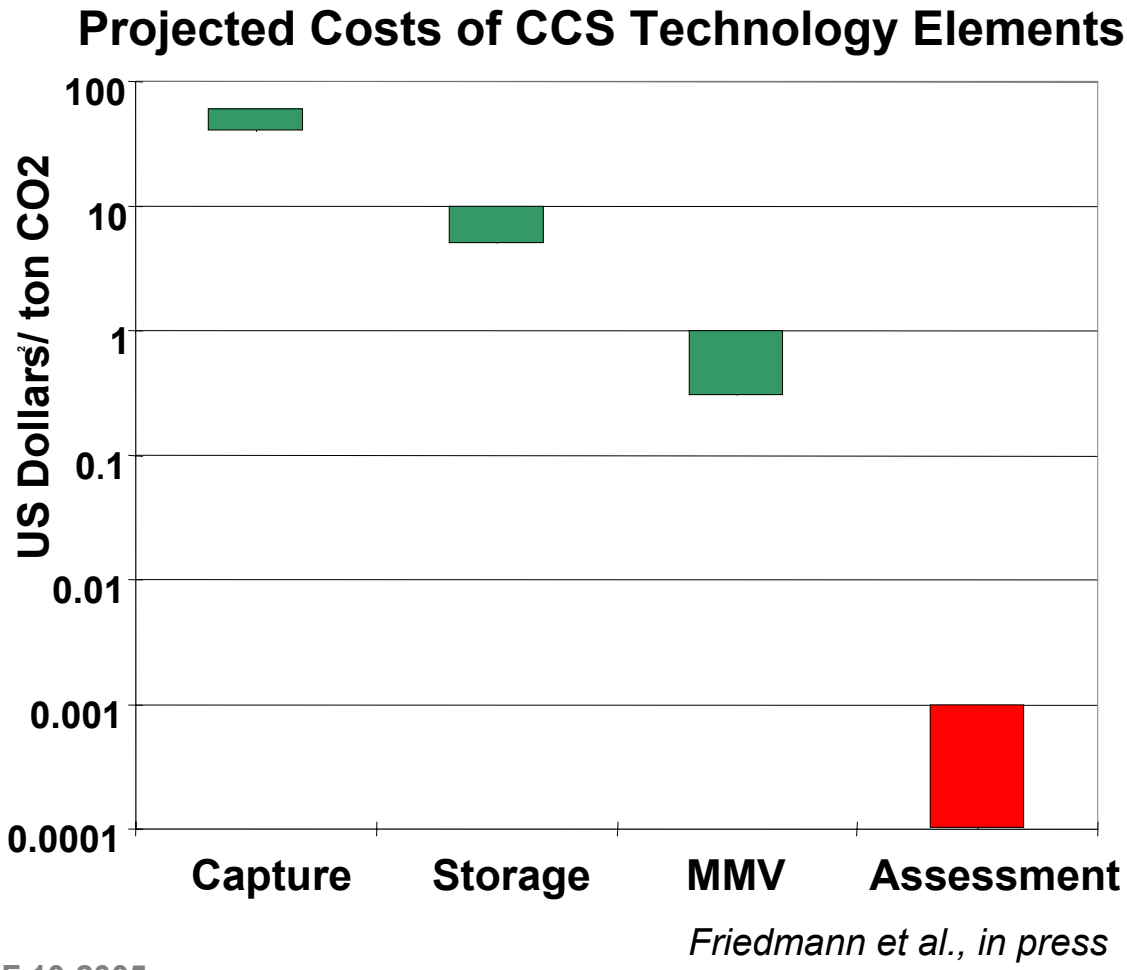
- **ICE can be estimated; would probably require exploratory wells**
- **Include cores, followed by lab work.**
- **May need 3D seismic**



Courtesy RMOTC and McChutcheon Energy

Assessments represent the lowest cost, highest impact step in CCS

For any large injection volume, local assessment is extremely low in cost and can be executed with conventional technology



Friedmann et al., in press

On a national level, assessments should proceed through geological surveys or in partnerships with the oil and gas industry

Site assessments may be paid for by the site operator, the CO_2 owner, or through bonds.

This step is vital, and should be supported fully.

Open issues in site selection

For Depleted Oil & Gas Fields:

- **Incremental cost concerns in most cases**

For Saline Aquifers:

- **Approximation of potential fast-paths to surface**
- **Accurate rendering of reservoir heterogeneity and residual saturation**
- **Understanding of local stress tensor and geomechanics**

The threshold for validation is different for each site and reservoir class.

Policy is needed to establish a regulatory framework aimed at appropriate validation of selected sites for certification

Due diligence will evolve around practical approaches, operations, and measurements

In the following examples, potential sites have a small number of wells nearby with conventional wireline logs. None have 3D seismic.

Not to worry! You're only trying to characterize three things:

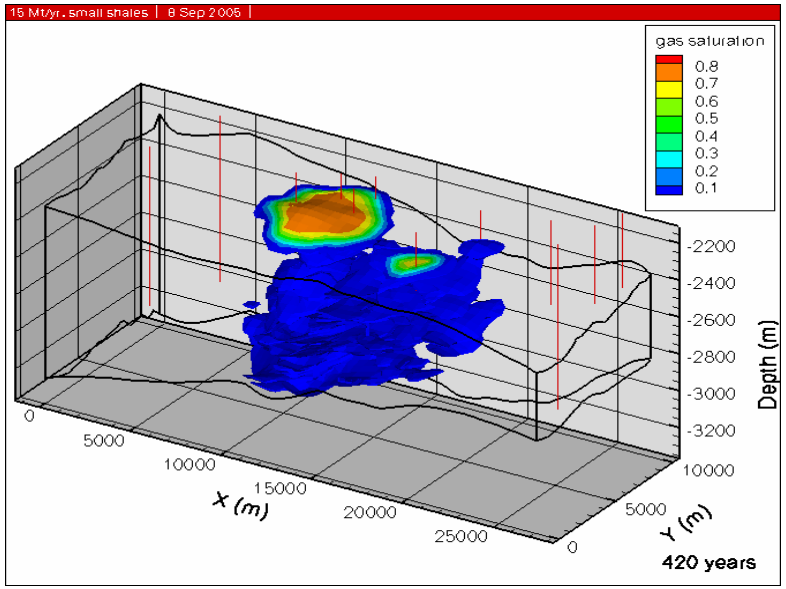
Injectivity	*Capacity*	*Effectiveness*

Depleted Oil/Gas field

- **Injectivity is well circumscribed**
- **Capacity is easily assessed**
- **Effectiveness centers on wells**

Saline Aquifer

- **Injectivity may be poorly defined**
- **Capacity may be difficult to define depending on simulations and available pore-volume data**
- **Effectiveness will rely largely on analog information**



Courtesy Latrobe Valley Project & CO2CRC

Possible due diligence: Depleted Oil/Gas Field

Multiple penetrations, production records, cores from the field or neighboring fields, saturation data, HC composition and gravity.

Injectivity

- Equal to producibility (bbl/day/psi/ft)
- Limited by perf length and maximum injectiton pressure

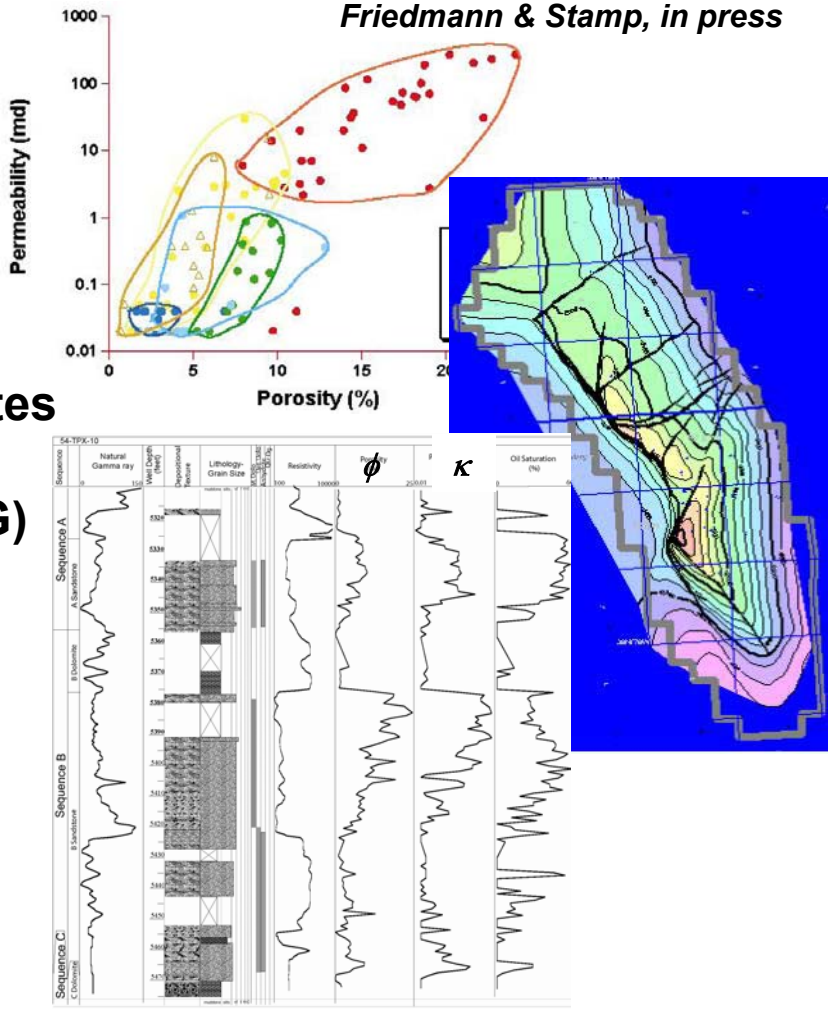
Capacity

- Defined by spill point/column height
- Reserves come from pore vol. estimates
- HC composition, P, T define process (miscibility vs. displacement; EOR/EOG)

Effectiveness

- Cap rock is effective, prob. multiple
- Wells require review of locations & drilling records; some remediation & monitoring
- Structure maps inform fault leakage risk; some stress data & analysis may be required

Friedmann & Stamp, in press



More odious due diligence: Depleted Oil/Gas Field

This kind of analysis may be needed to satisfy state regulators, stakeholders, nervous financiers; esp. for early large projects

Injectivity

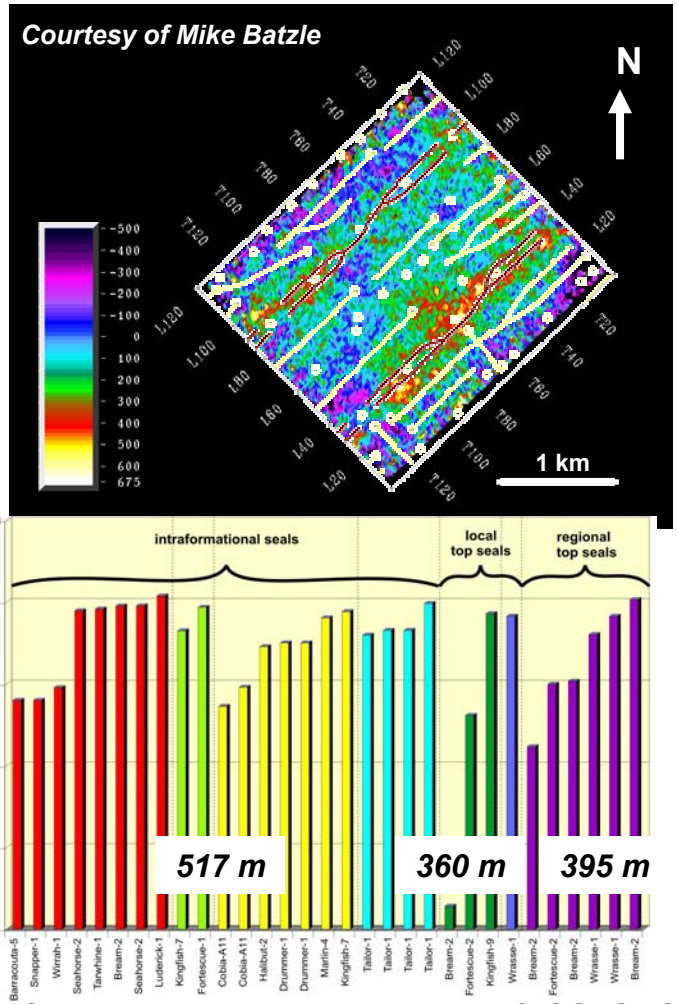
- Limited CO_2 injection test with operational monitoring
- One new well possible w/ analysis

Capacity

- New geological analysis (well correlation)
- Possible additional tests
- Conventional simulation

Effectiveness

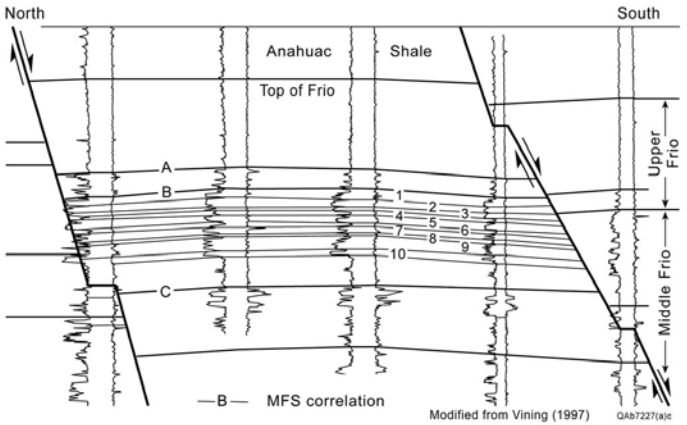
- Capillary entry pressure measurements
- Recompletion of any old wells, perhaps all wells (Salt Creek)
- Limited monitoring program (may or may not require seismic)
- Stress characterization & risk analysis



Courtesy Latrobe Valley Project & CO2CRC

Possible due diligence: Saline Formation

Limited well logs and cores; poor rock-volume and porosity estimation; limited brine composition or hydrological data



Injectivity: New well required

- Injection test, possible extra special core analyses
- Decent local/regional reservoir maps
- Credible drilling strategy; poss. 3D seismic

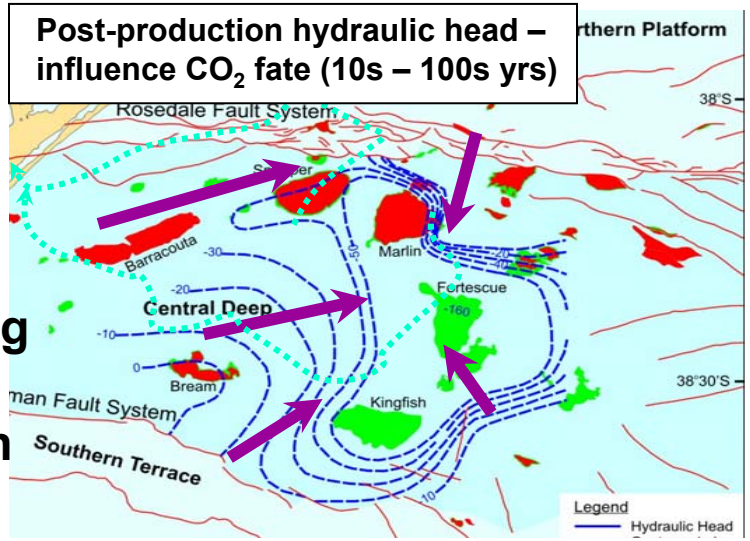
Capacity

- Pore volume may have large uncertainties to be represented; superabundance required
- Brine composition; special core analysis
- Conventional simulation

Effectiveness

- Credible caprock maps; if no secondary seals, petrol./mech. study may be needed
- Wells requires review of locations & drilling records; some remediation & MMV
- Closure mechanisms must be defended; in hydrol. case; some regional data required

Post-production hydraulic head – influence CO_2 fate (10s – 100s yrs)



More odious due diligence:

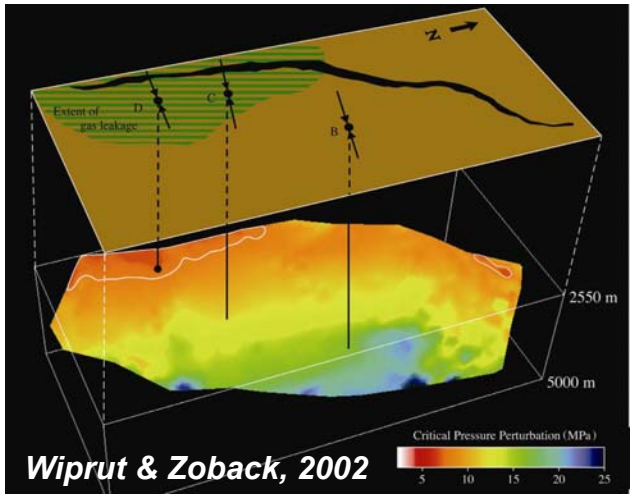
Saline Formation

This kind of analysis may be needed to satisfy state regulators, stakeholders, nervous financiers; esp. for early large projects

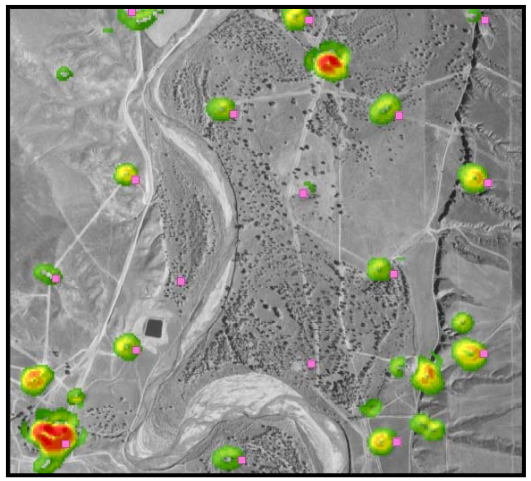
Injectivity: More than one new well required
- Injection test, possible extra special core analyses
- Decent local/regional reservoir maps
- Credible drilling strategy; possible 3D seismic

Capacity
- Pore volume may have large uncertainties to be represented; superabundance required
- Brine composition; special core analysis
- Conventional simulation; ~20yr post-injection

Effectiveness
- Petrological/mechanical study may be needed
- Aeromagnetic well survey; recompletion of all wells (not many); other shallow geophysics (GPR)
- 3D survey required for structural risk analysis
- Commitment to short term monitoring; ~5yr review



Wiprut & Zoback, 2002


Courtesy NETL

Monitoring can always be used to support effectiveness in tough cases

3D seismic will remain preferred method, but not always necessary

- **Define cap-rock extent; tie to well**
- **Identify faults & perm. fast paths**
- **Defend rock-volume estimates**

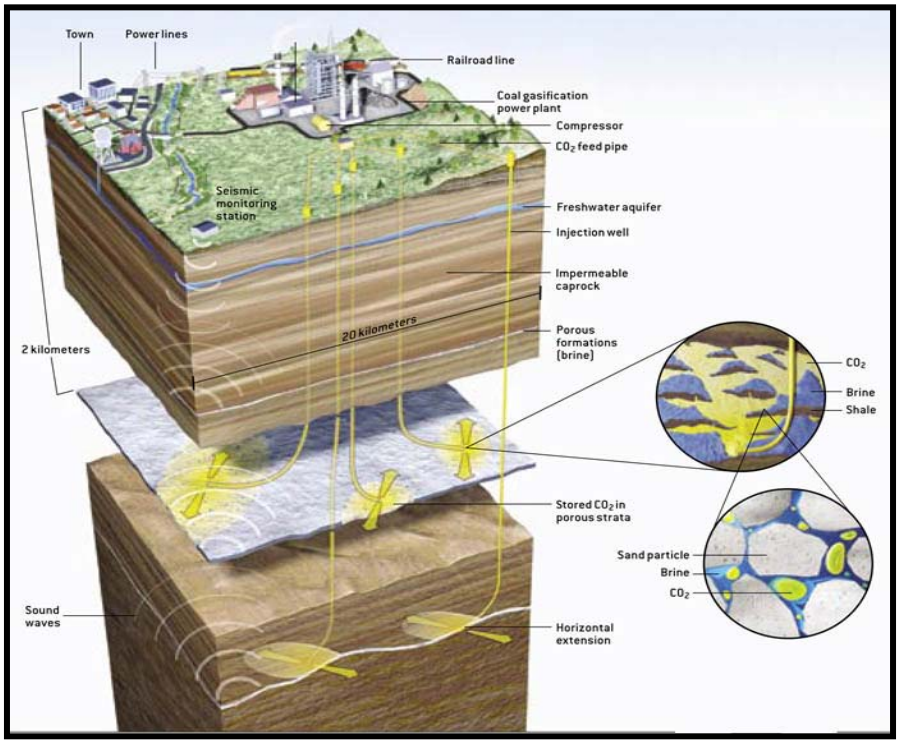
2D seismic or cross-well techniques may suffice

- **if substantial reservoir definition is not needed**
- **if in cratonal area with limited faulting**

Operational monitoring during injection

Formal integration worthwhile

Monitoring for site characterization programs should (1) be minimal (2) define and improve understanding of local geology and geography (3) aimed at constraining effectiveness



Socolow, 2005

To quantify risk, numerical models must integrate complex processes

Currently, there is no package that satisfies the full complement of simulation needs.

- **Reactive transport, including full geochemistry and dynamic permeability**
- **Coupled geomechanics/fracture dynamics, including seismic hazard & fault reactivation**
- **Well components, including plugs, cements, and annulus**
- **Vadose-zone transport & other environmental hazards**
- **Outputs usable for risk assessment**

In order to resolve these key questions, an intensive, accelerated program to develop and deploy the simulation capabilities is needed

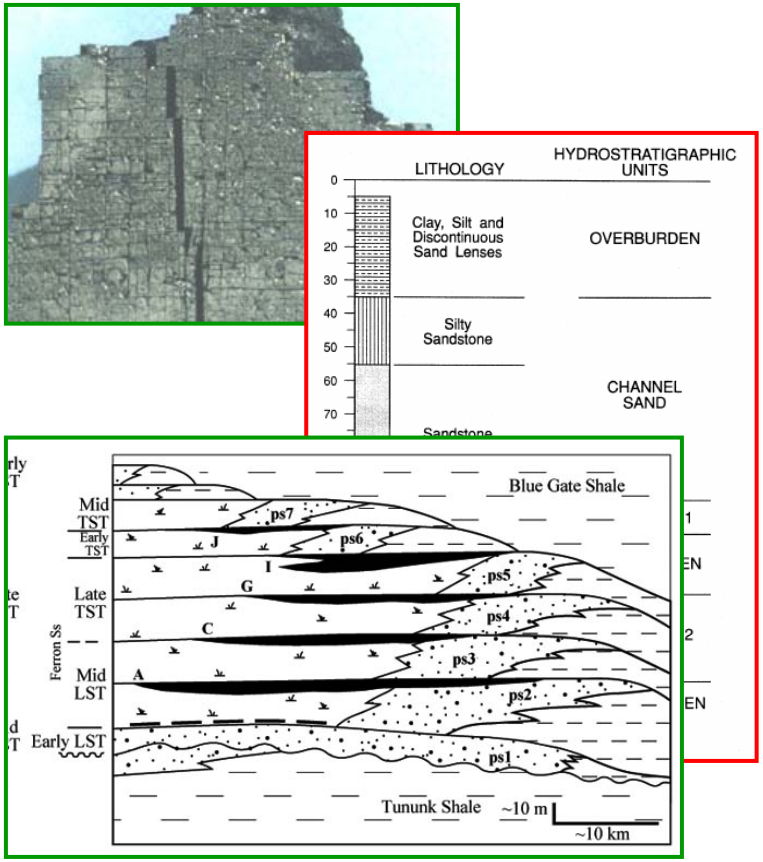
Site characterization and due diligence for coal seam storage remains a challenge

The nature of the rocks, the CO_2 storage mechanism, fluid flow uncertainty, and lower industrial maturity make SC extremely difficult.

Injectivity
- ***Often requires years to test***
- ***Some coals (bituminous) are low perm.***
- ***Fracture injectivity, not bulk***
- ***Time dependent (swelling, plasticization)***

Capacity
- ***Not clear that adsorption isotherms show capacity (surface area/volume)***
- ***Conventional simulators?***

Effectiveness
- ***Many coals interbedded with permeable, flow-prone zones (thiefs)***



From an ICE perspective, coals require more research

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