SAND2014-18734PE

Geo-engineering Research Challenges in the Age of Climate Change

Dr. Edward Matteo, *Sandia National Labs*
UNM CEE Graduate Seminar
October 15, 2014

Acknowledgements

- Prof. George Scherer – Princeton University
- Wellbore Seal Repair Team
  - John Stormont (PI) – UNM, Mahmoud Taha – UNM, Tom Dewers –SNL, Steve Sobolik – SNL, Steve Gomez – UNM/SNL, Pania Newell – SNL
- SNL CFSES Team
  - Susan Altman, Randy Cygan, Tom Dewers, Craig Tenney
- UFD Natural Systems Team
  - Yifeng Wang, Jessica Kruichak, Melissa Mills, Andy Miller
- UNM CEE

What is Geo-Engineering?

- Connotation vs. denotation
  - Ocean fertilization, aerosol albedo
  - CCS, O&G Exploration, Nuclear Waste Disposal, Mining

Overview – Index of Topics

+ Motivation
+ Carbon Mitigation Strategies and the Wedges Concept
+ Leaky Wellbores – Key Questions
+ Wellbore Seal Repair – 3D Geomechanical Modeling of Seal Repair
+ Subsurface Mineral Surface Properties (Contact Angle Studies)
+ Sorption of radionuclides in clay minerals
+ Conclusions

Overview – Index of Topics

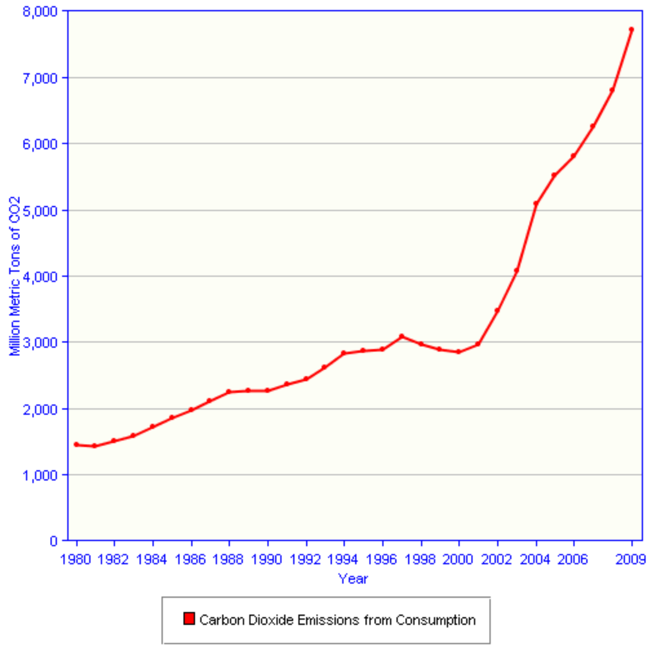
CO_2 Facts and Figures

- Pre-industrial concentration CO_2: 278 ppm
- 2012 concentration: 391 ppm (NOAA GMD)
- 100 ppm CO_2 ~ 770 $GtCO_2$
- World Emissions: 33 $GtCO_2$ / yr (CDIAC for the UN)
  - 13.5 $GtCO_2$ from point sources(IPCC AR3)
- Top 3 emitters >50% of total emissions

Country	CO_2 emissions[11]	Emission per capita[12]
World	33,376,327	4.9
China	9,700,000	7.2
United States	5,420,000	17.3
India	1,970,000	1.6
Russia	1,830,000	12.8
Japan	1,240,000	9.8
International transport	1,040,000	-
Germany	810,000	9.9
South Korea	610,000	12.6
Canada	560,000	16.2

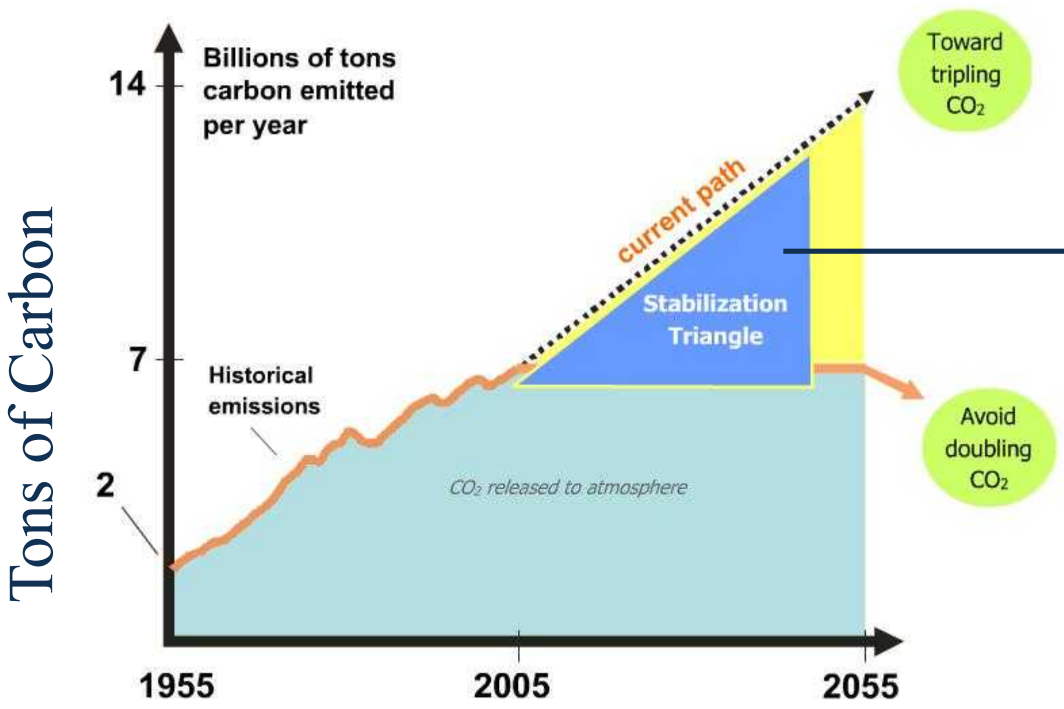
CO_2 Facts and Figures

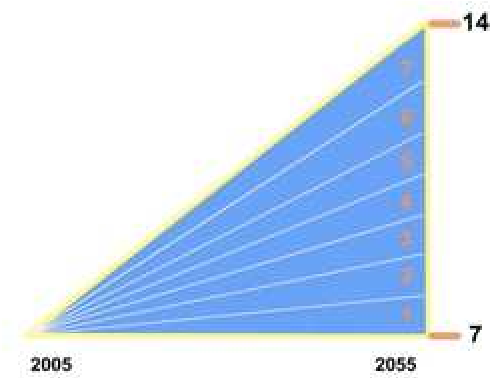
- US Emissions: 5.4 $GtCO_2$/yr (CDIAC for the UN)
- IPCC Projected Total CCS potential (21st century):
  - (Less CCS = 220 $GtCO_2$ stored) -> stabilize at 750ppm CO2
  - (Widespread Deployment CCS = 2200 $GtCO_2$) -> stabilize at 450ppm
- What does carbon storage capacity look like?
  - Depleted oil well vs. saline aquifer



China's growing emissions

An Appreciable Reduction in Carbon Emissions is a "Heavy Lift"





7 Wedges = 1.3 Tt CO2

1 wedge

~ 186 GtCO2

= CCS at 800 coal-fired power plants

S. Pacala and R. Socolow. *Science*, **305**(5686), p.968-972, 2004

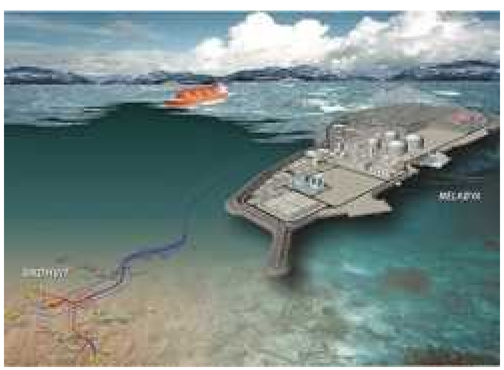
Current CCS projects:

- Sleipner (Norway): 1 MtCO_2 / yr
- In Salah (Algeria): 1.2 MtCO_2 / yr
- Weyburn (Canada): 1.5 MtCO_2 / yr
- Snohvit (Norway): 0.7 MtCO_2 / yr

Sleipner

= 4.4 MtCO_2 / yr

→ Leaving a balance of 185.9956 GtCO_2 to achieve 1 wedge



Snohvit

In Salah

What is Carbon Sequestration or Carbon, Capture , and Storage (CCS)?

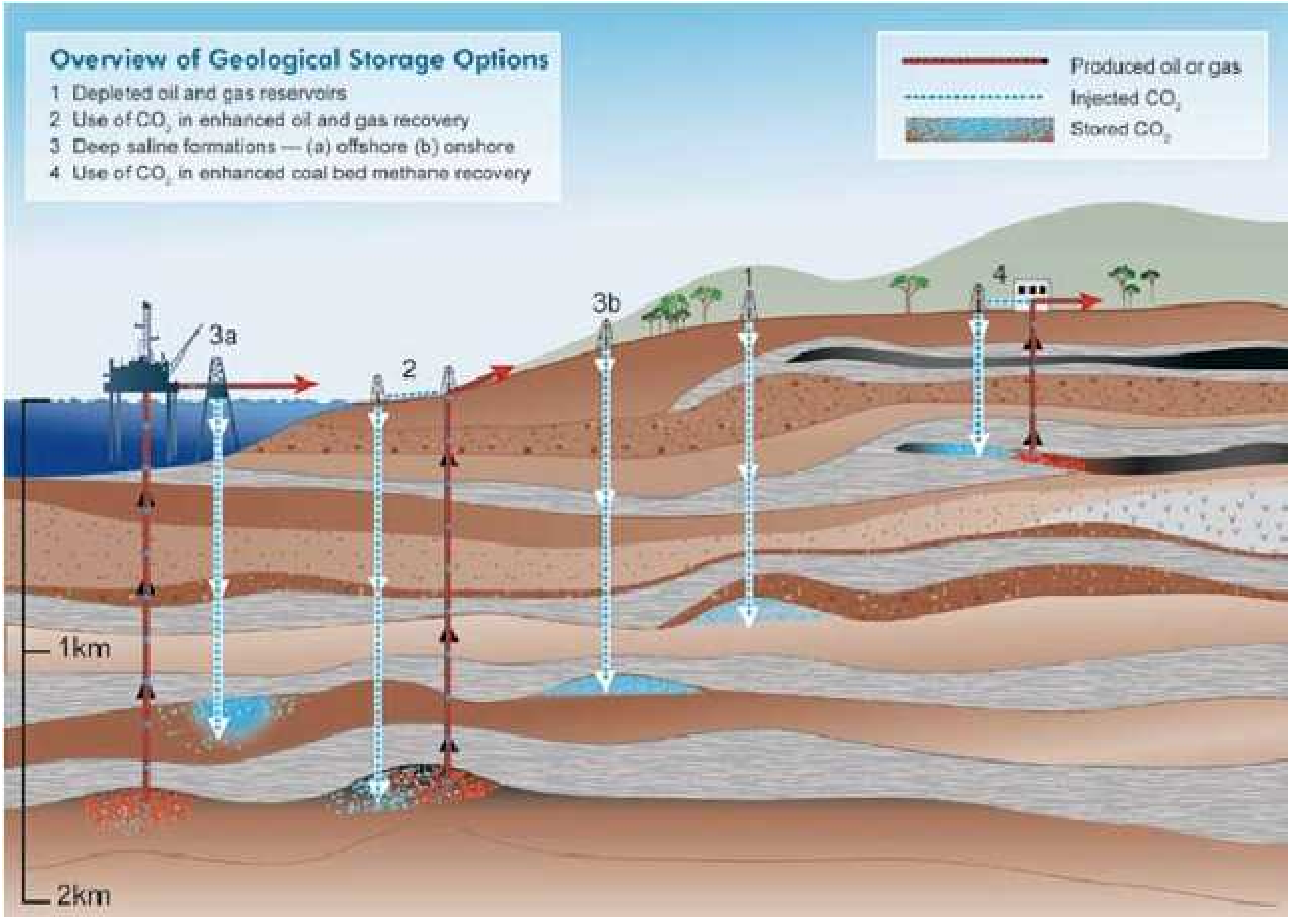


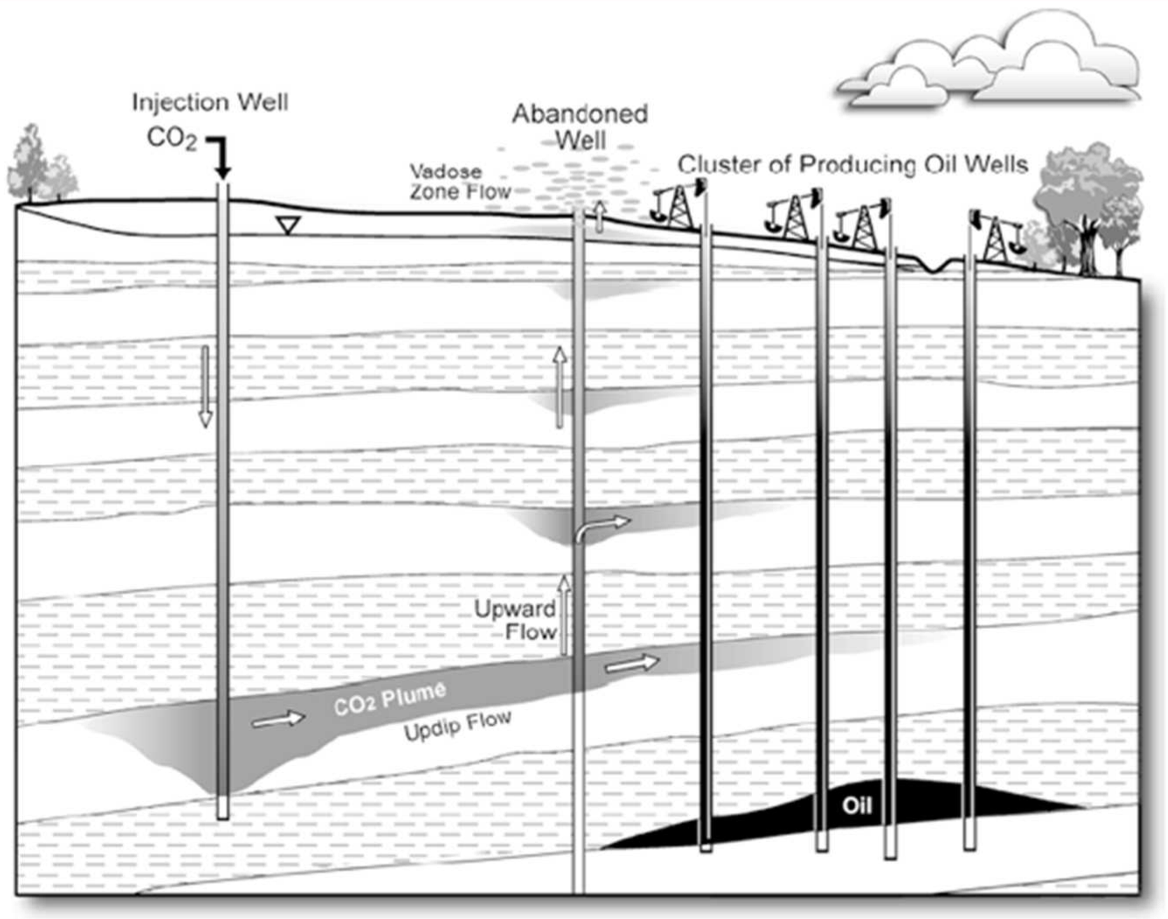
Image from the IPCC Special Report on CCS, 2005

Public Perception may play a significant role

- Fear of the Unknown
  - Less than 5% of US has even heard of CCS
  - Public skepticism, NIMBY-factor
  - The Lake Nyos Effect (Nuclear analogue – 3 Mile Island)
  - Induced seismicity
- How will this effect the regulatory process?
  - CA AB705 – leakage uncertainty central point of debate
  - Regulatory Path exists for CO_2 Storage in Depleted Oil and Gas Reservoirs
  - Without a Global Framework (including $ / tCO2), financial incentive is lacking

Overview – Index of Topics

Injected CO_2 is also buoyant and "wants" to return to the surface



Gasda et al., 2008

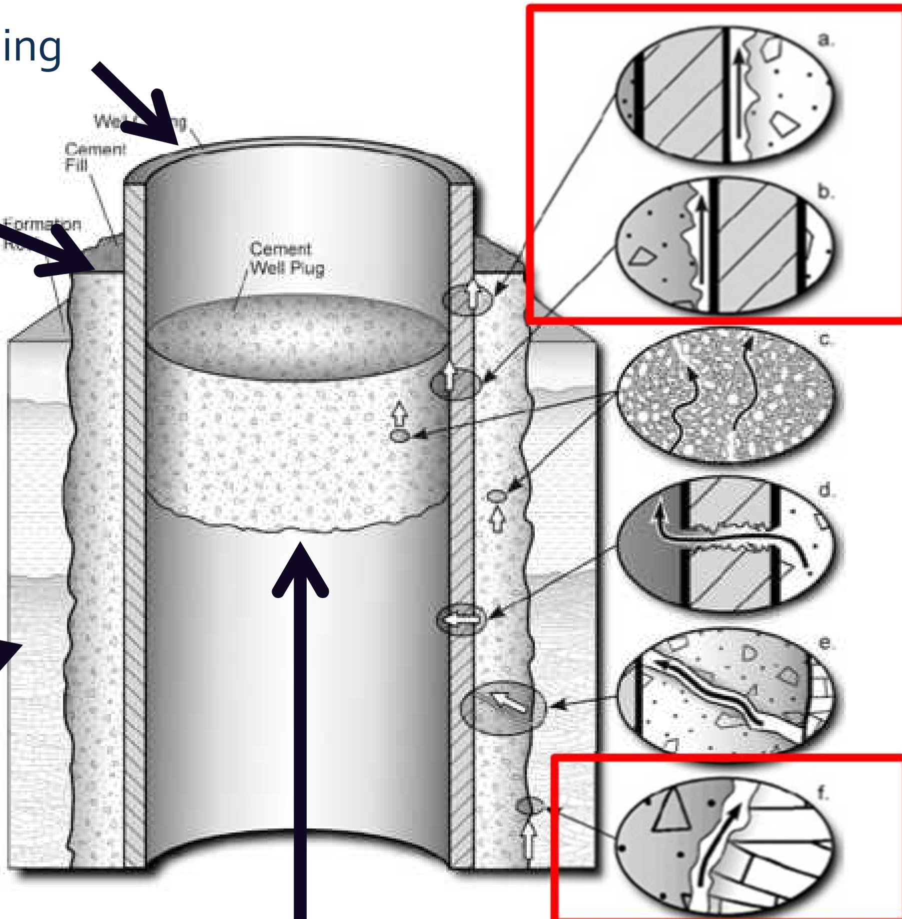
Anatomy of an Abandoned Wellbore

Interfaces between well cement / caprock and well cement/wellbore have high potential as leakage pathways

Well Casing

Well Cement (outer annulus)

Caprock Formation



Well cement / wellbore interface

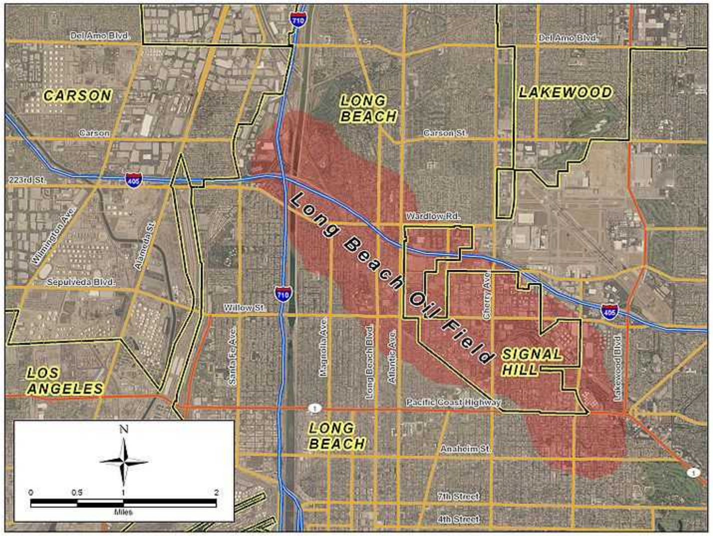
Well cement caprock interface

Well Casing is filled w/ meters of well cement

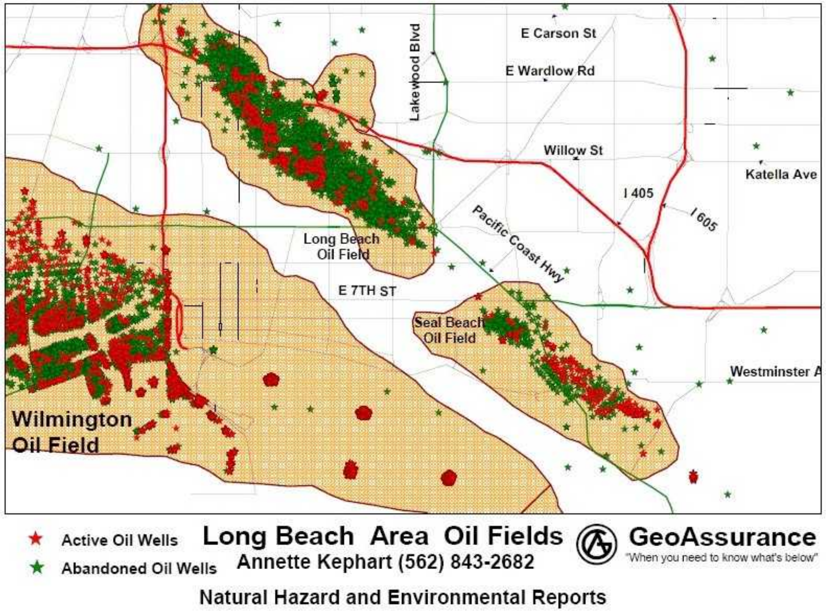
Gasda et al., 2008

Why not replace abandoned wells with acid-resistant cement?

- Typically, there are thousands of (known) abandoned wells in a field
- Re-completion is prohibitively expensive



http://en.wikipedia.org/wiki/Long_Beach_Oil_Field



http://en.wikipedia.org/wiki/Long_Beach_Oil_Field

Leaky Wellbores – Key Questions

- What will the leakage flow look like? (i.e., CO_2-staurated brine, humid supercritical CO_2, multiphase flow)?
- How reactive (i.e. what are the rates) is the well cement when it encounters CO_2/brine mixtures?
- Will seal-healing/self-sealing mechanisms occur? e.g., calcium carbonate formation

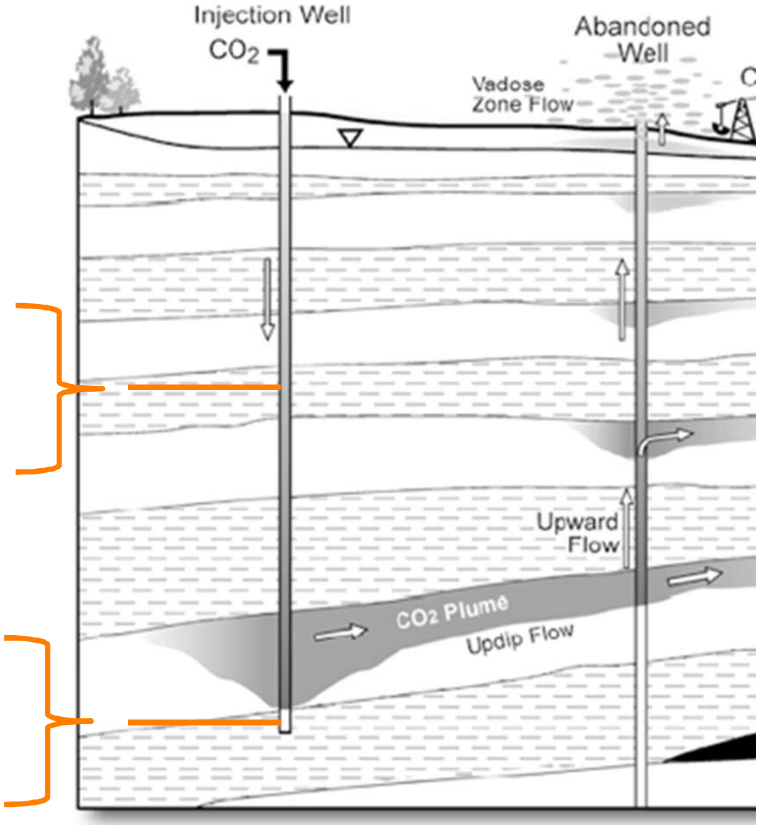
Verticality Matters!

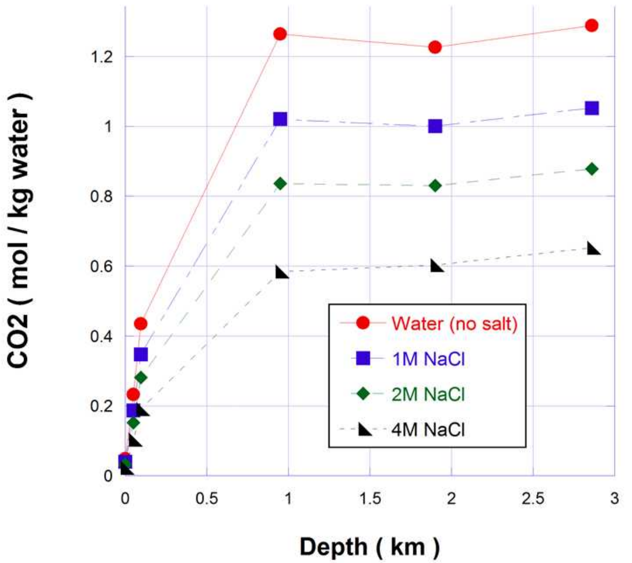
- T, P will effect cement curing
  - Permeability, porosity
- Solubility of CO_2 varies w.r.t. T, P, and brine concentration
- Phase of CO_2 varies with T, P
- Also can affecting mineral wetting properties
  (more on this later)

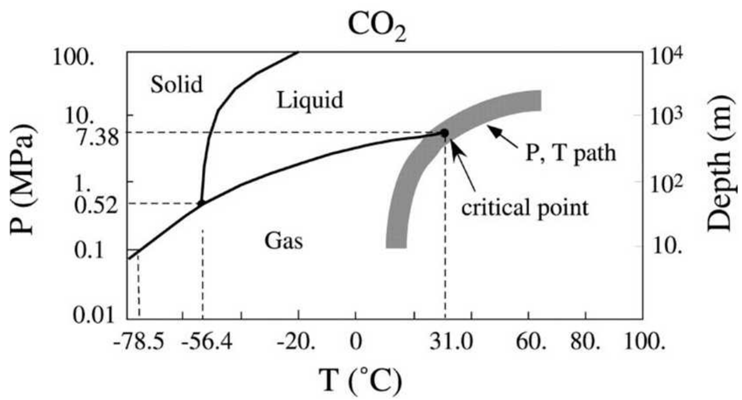
“Verticality” illustrated …

0.5 km
T= 37.5 C
P=5.25
MPa

1 km
T= 50 C
P=10.5
MPa







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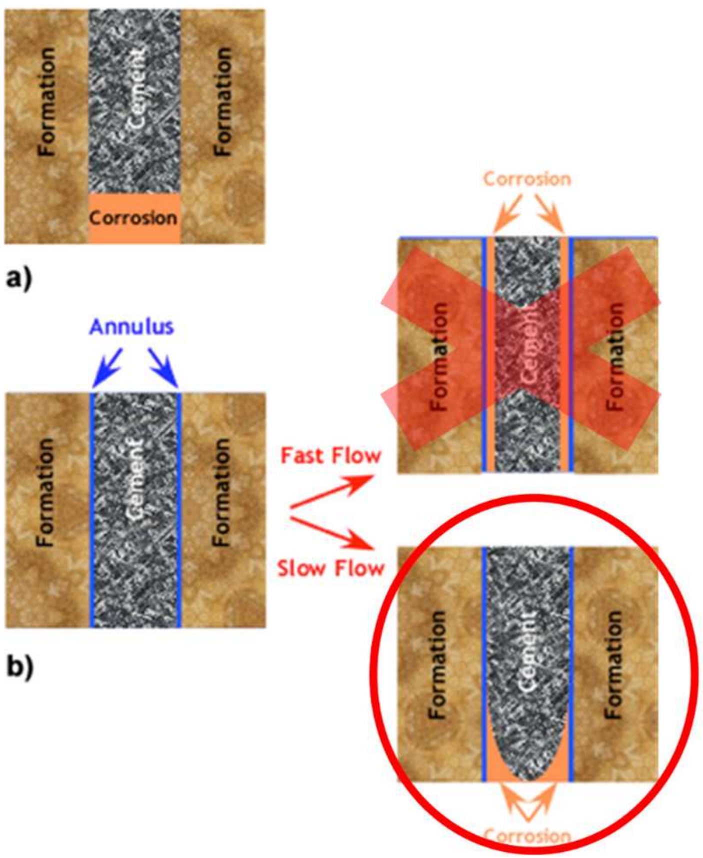
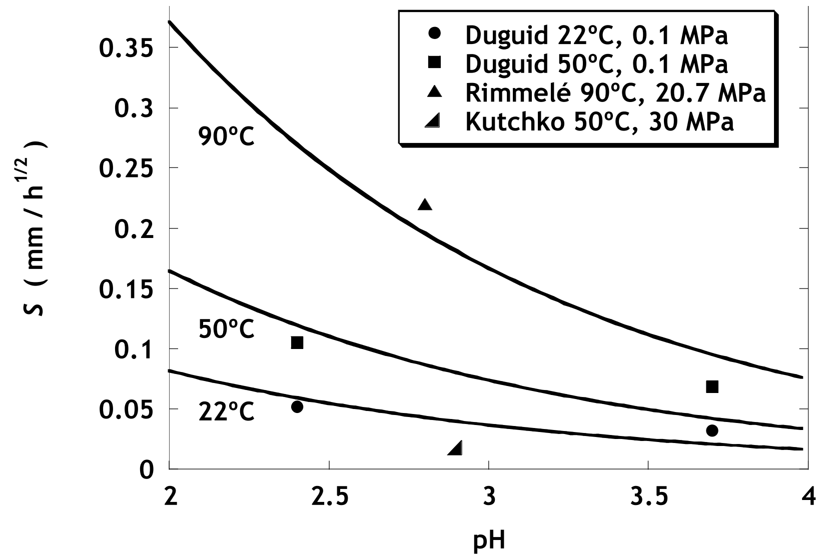
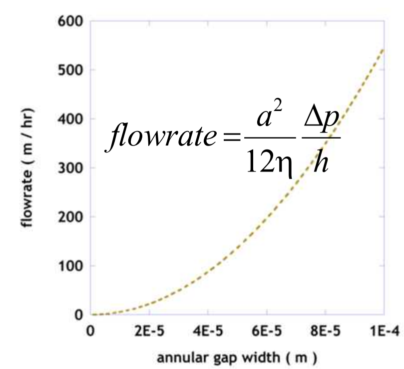
Acid Neutralization Capacity Dominates for Carbonated brine flow in small micro-annuli







Matteo and Scherer. *IJGGC*, 2012.

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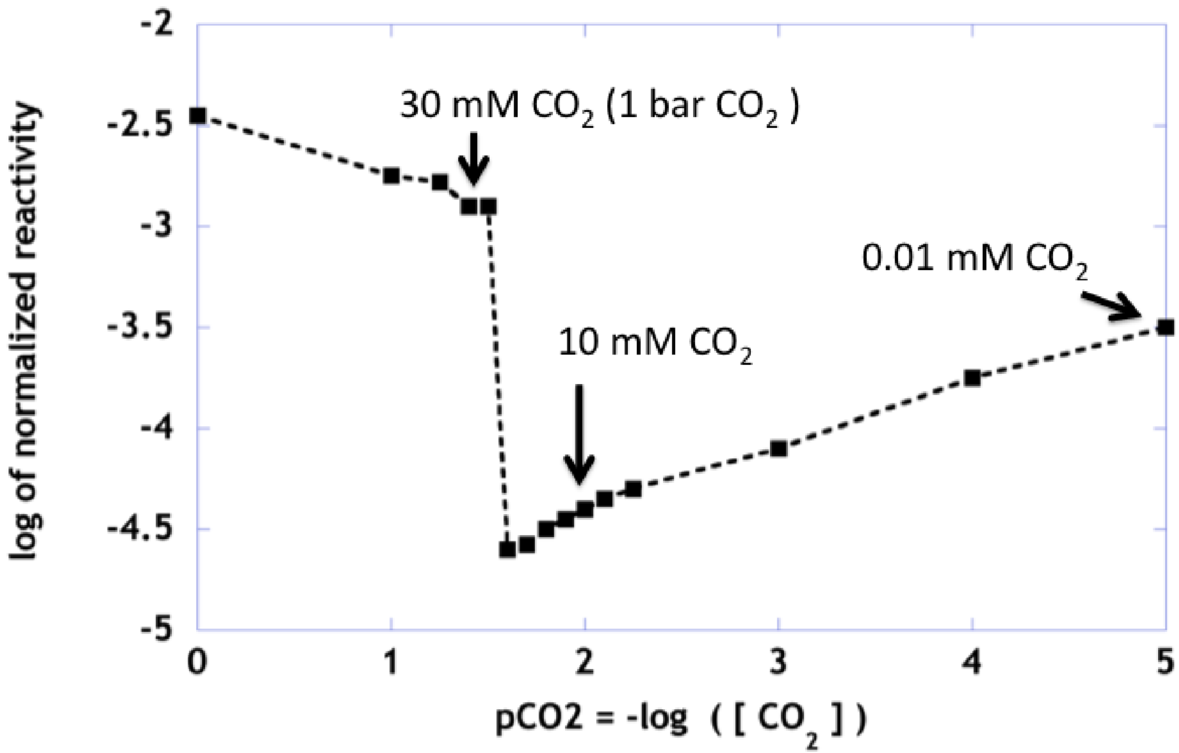
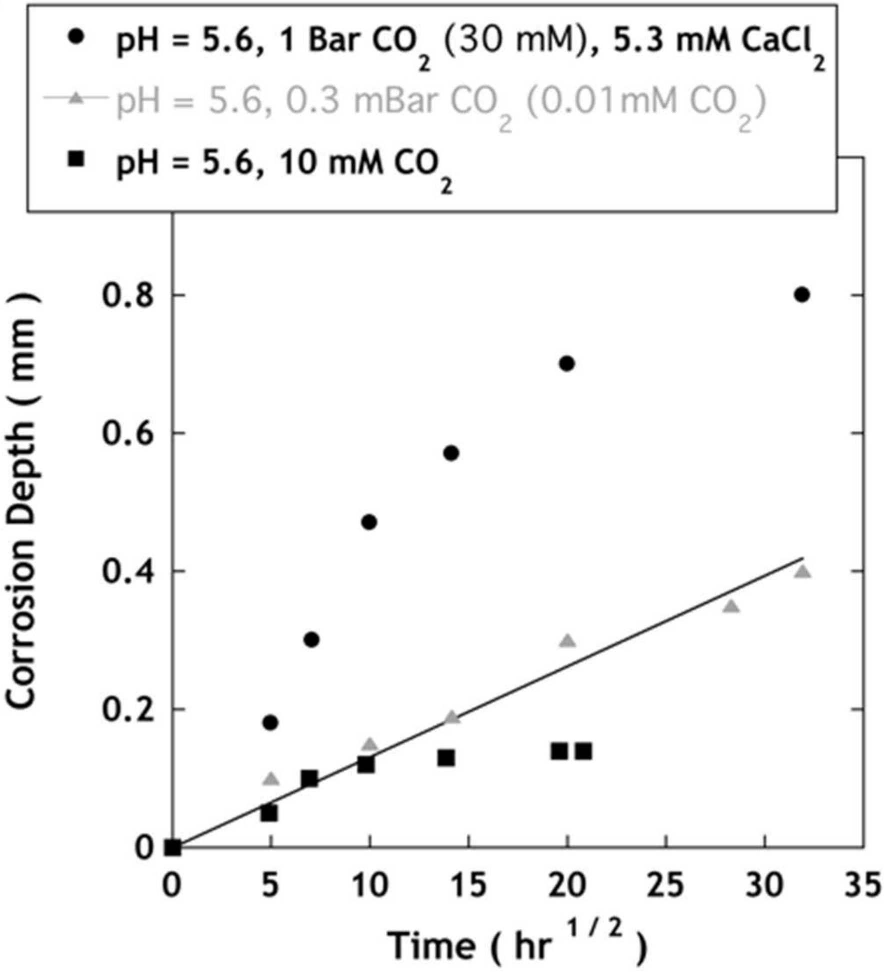
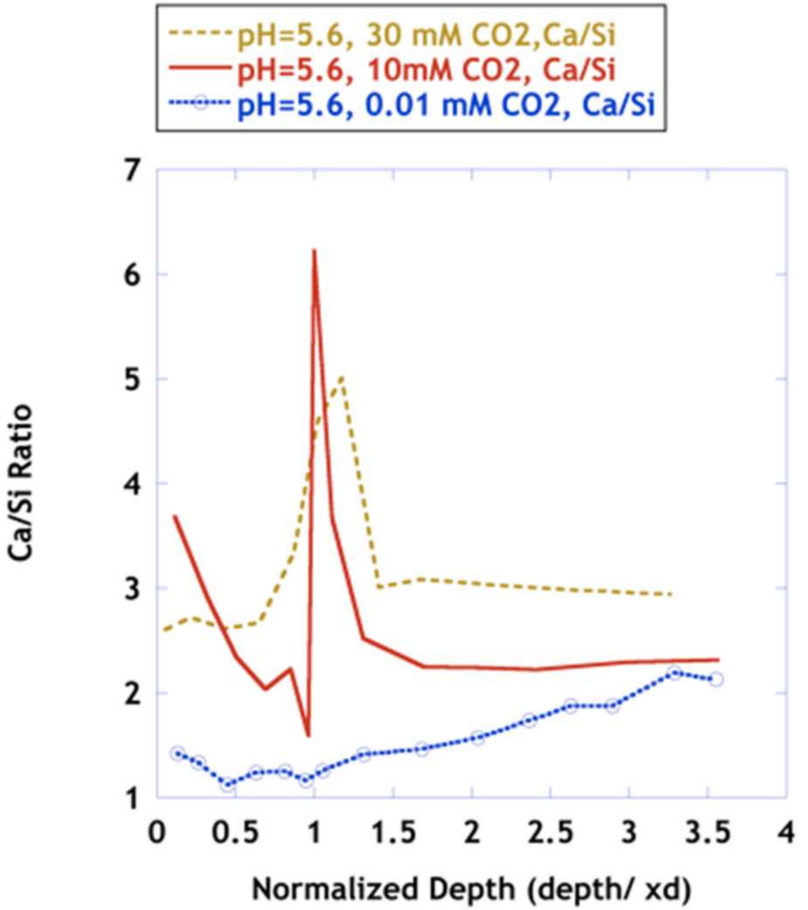
Simulations imply possible kinetic slow-down due to self-sealing



Data courtesy of Dr. Bruno Huet, Lafarge

Pore-Plugging Experiments





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Wellbore Seal Repair Project

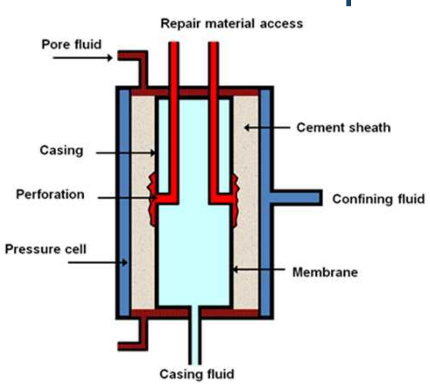
DOE NETL funded in collaboration with UNM

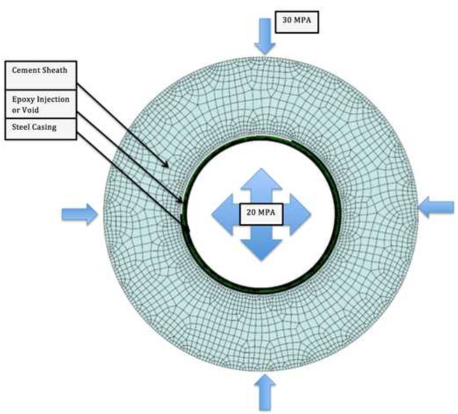
Novel Materials Development Test Matrix

Polymers	Nanomaterials					
	Neat	CNTs	Nanoclay	Nanosilica	Nanoalumina	Graphene NP
Polysulfide siloxane epoxy	C	C	C	C	C	U
Novolac epoxy	C	C	U	C	C	U
Siloxane epoxy	P	P	P	P	P	P
SBR latex/cement	P	P	P	P	P	P
Reference repair material (Microfine cement)	P (without nanomaterials)					

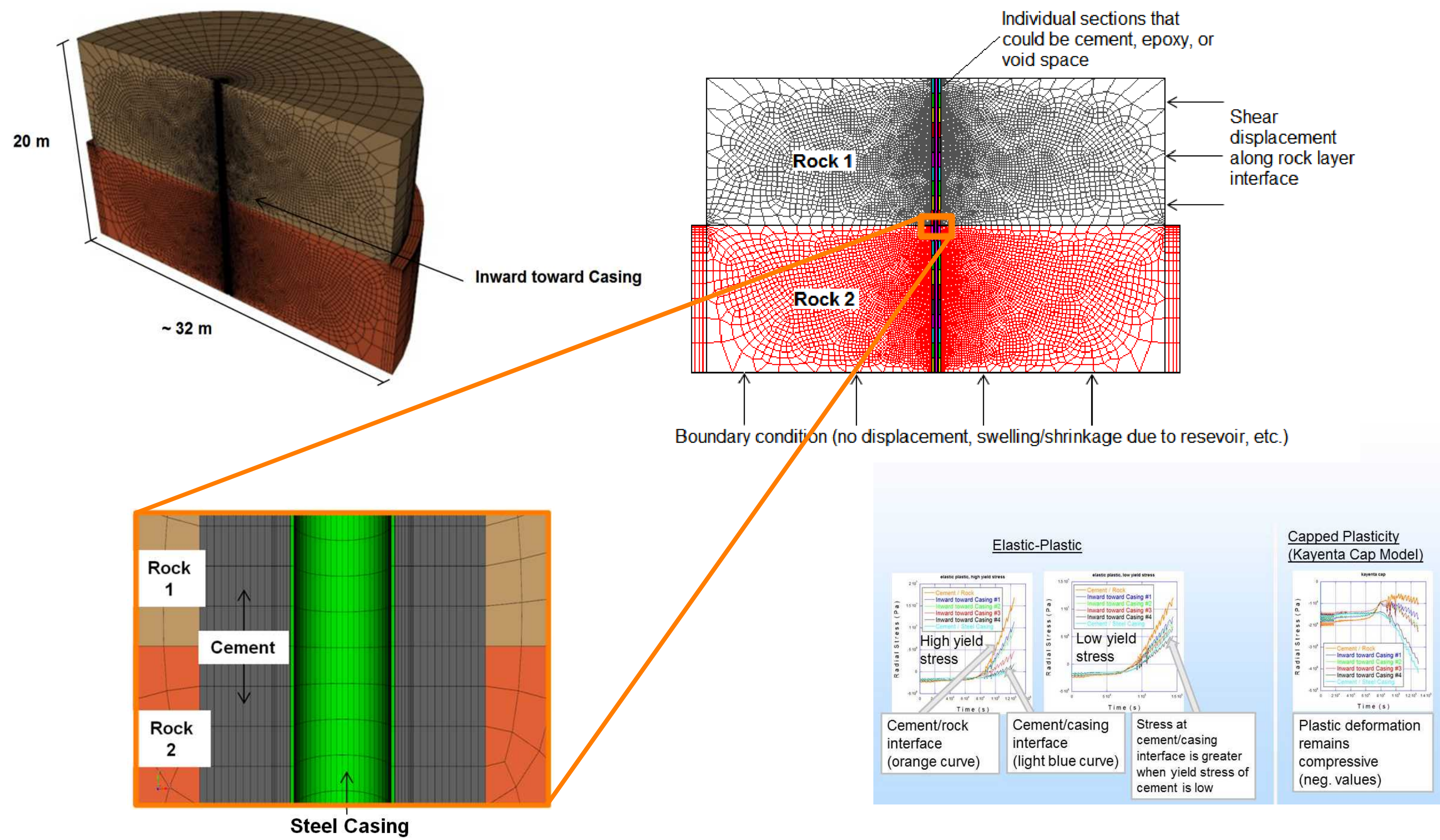
C: Completed testing **U: Undergoing testing** **P: Planned testing in coming quarter**

Wellbore Mock-up Bench-scale Testing





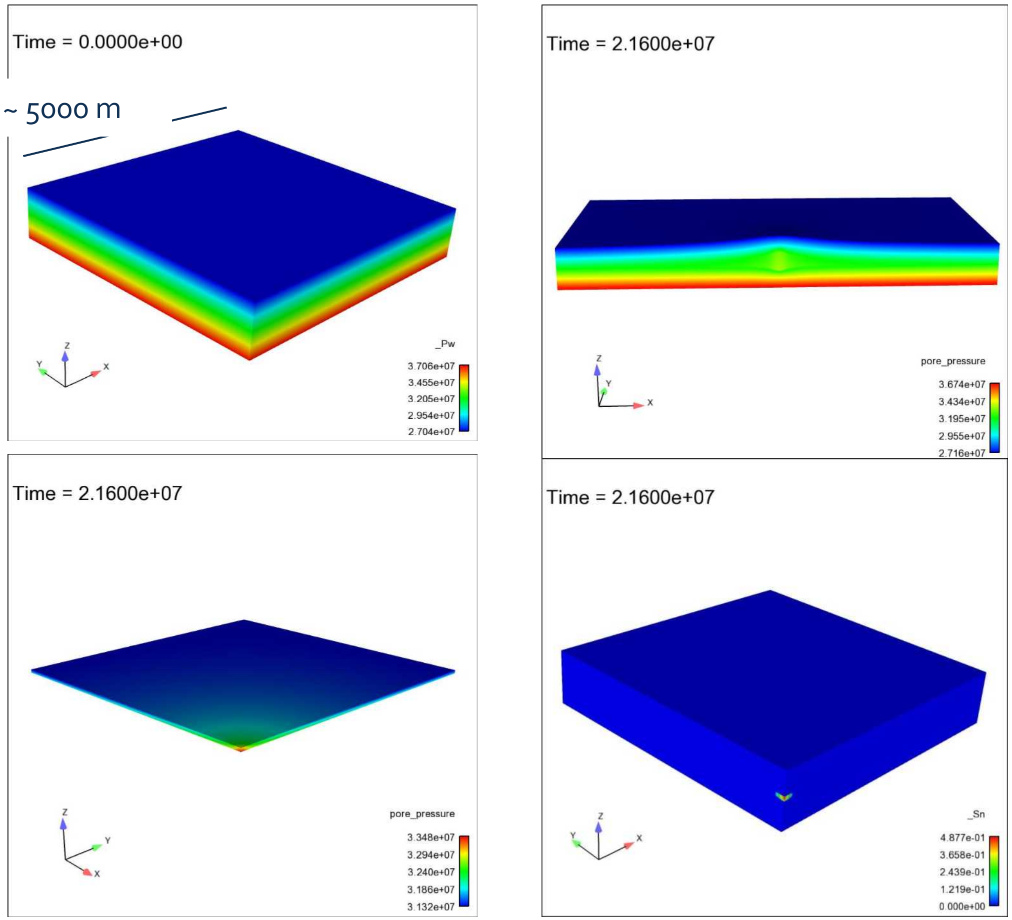
3D Geomechanical Wellbore Modelling

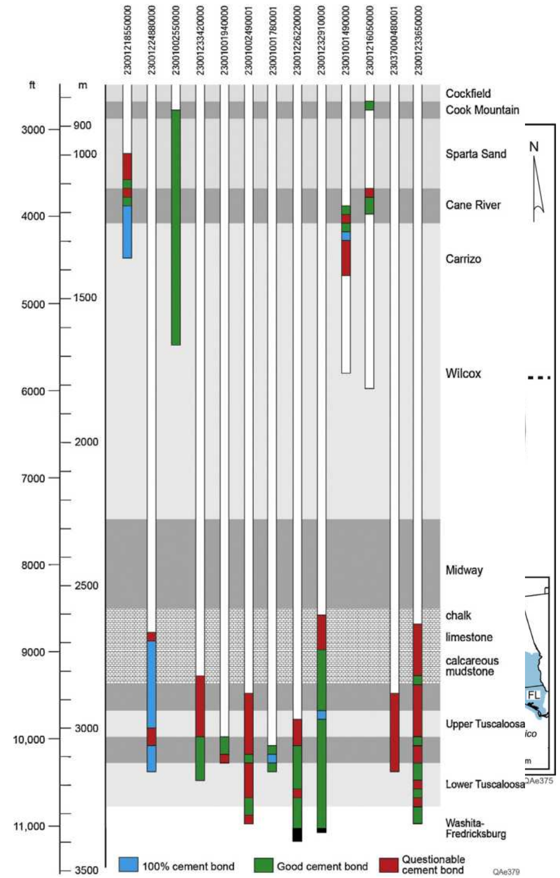


Intregrating Wellbore Modeling with Field Scale Modeling

~ 5000 m

~ 1000 m





Nicot et al., *IJGGC, 18, 2013*

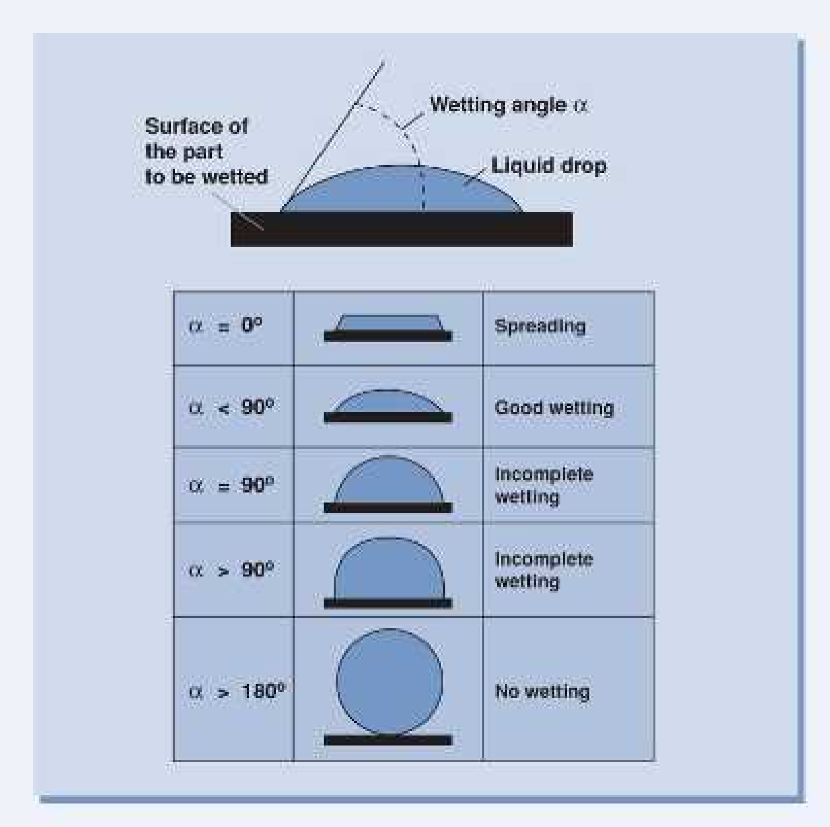
Overview – Index of Topics

3 Trapping Mechanisms during Geologic Storage of CO_2

- Structural
  - Top seal counteracts buoyant force
  - Wetting directly related to seal integrity esp. in caprocks with smaller pore throats (Wang et al. *ES&T* 2012)
- Capillary/ Residual Trapping
  - CO_2 "left behind" in pore space
  - Important for predicting plume distribution and total storage capacity
- Solubility
  - CO_2 dissolved in brine

Dependent on wetting properties (Structural; Capillary/ Residual Trapping)

Q: How are wetting properties measured? A: Contact angles



http://soft-matter.seas.harvard.edu

Chemical and Physical Effects of Secondary Mineralization on Contact Angle

- Chemical
  - pH_{pzc} – pH of point of zero charge is f (P, T, ionic strength)
    - Surface hydroxyl functional groups control surface chemistry of minerals and, in turn, wetting properties
- Physical
  - Surface topography (esp. surface roughening) can lead to changes in wetting behavior
  - Cassie Baxter
  - Wenzel

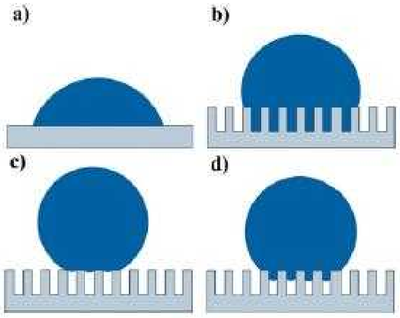
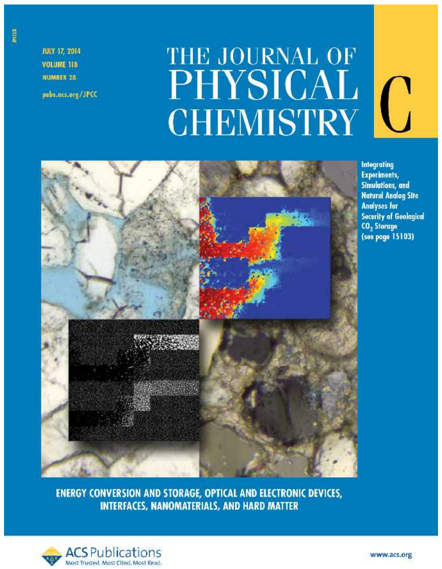
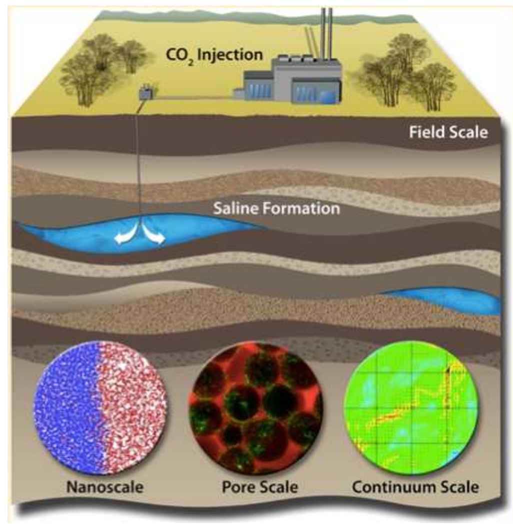


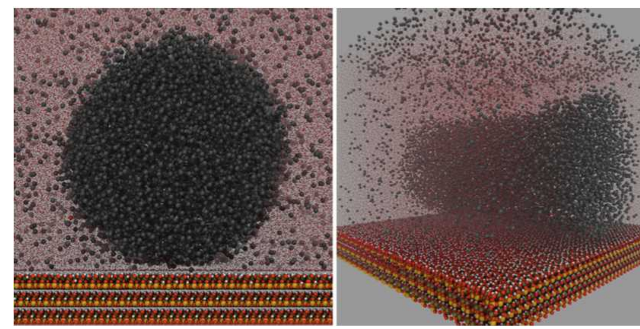
Figure 2. Effect of surface structure on the wetting behavior of solid substrates. a) A liquid drop on a flat substrate (Young's mode). b) Wetted contact between the liquid and the rough substrate (Wenzel's mode). c) Non-wetted contact between the liquid and the rough substrate (Cassie's mode). d) Intermediate state between the Wenzel and the Cassie modes.

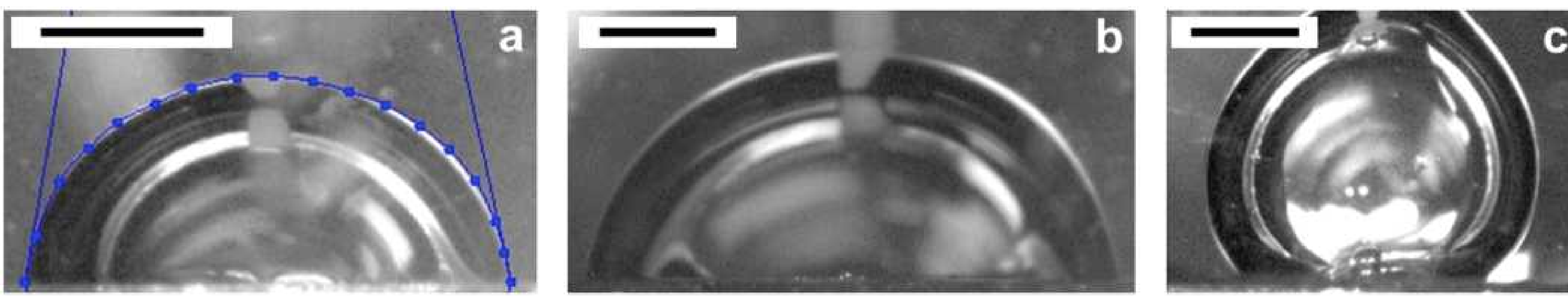
Feng et al., *Adv. Mater.*, **18** (2006), 3036-3078

Contact Angle Measurements across scales









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+ Sorption of radionuclides in clay minerals
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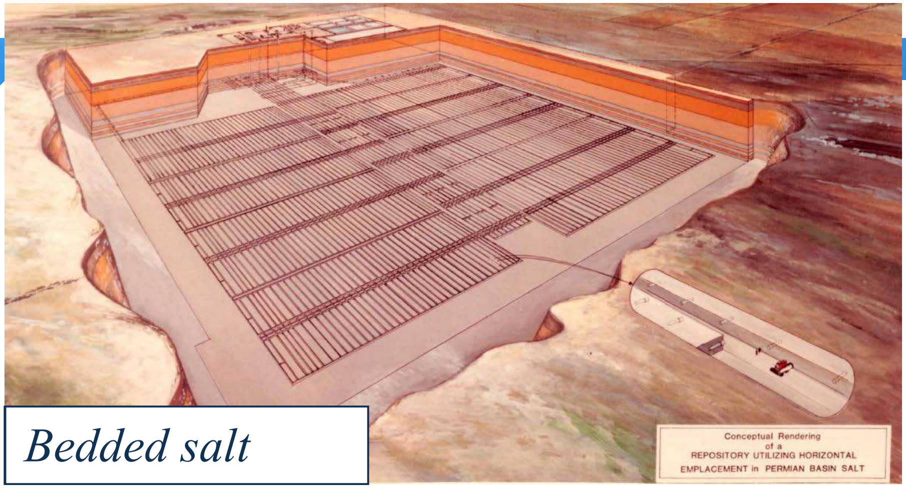
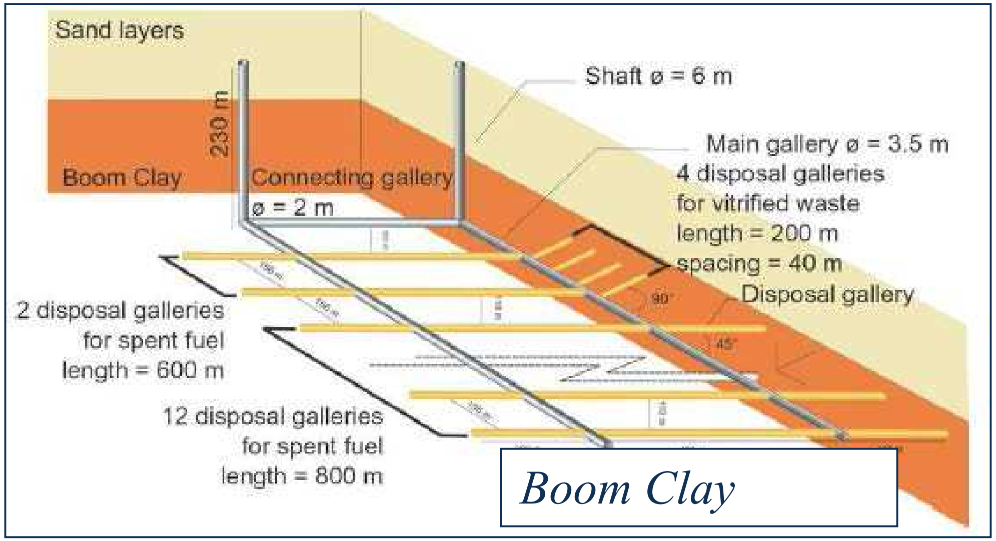
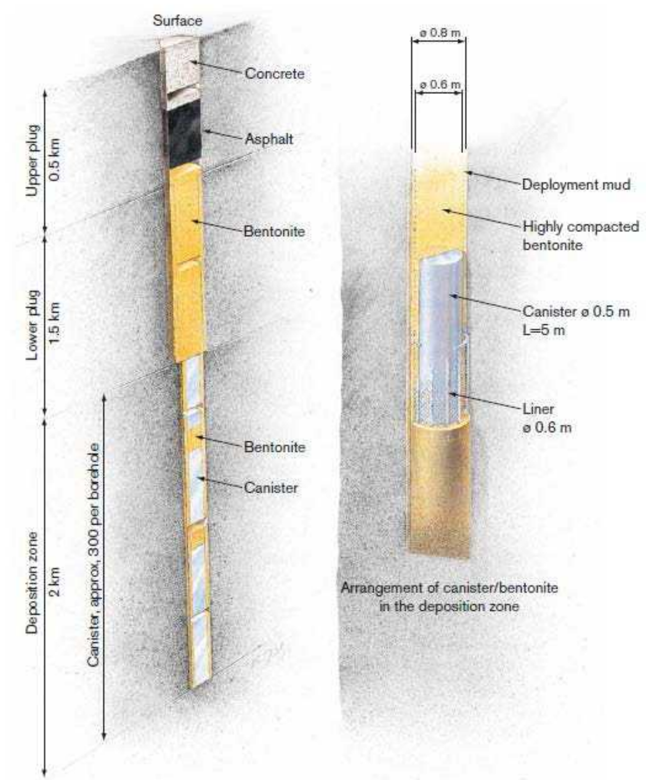
Repository Designs contain Clay Minerals either as the host formation or in Engineered Barriers and Seals



Bedded salt



Boom Clay

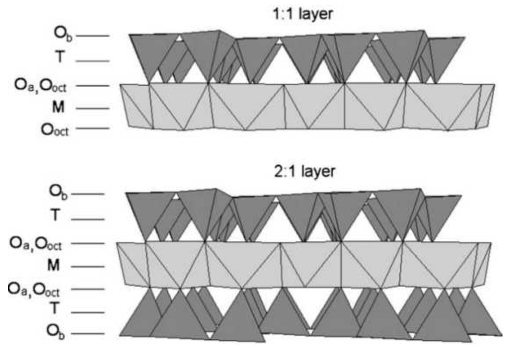


Deep Borehole in Crystalline Basement

(images courtesy of E. Hardin)

Radionuclide sorption behavior in clay minerals

Clay mineralogy

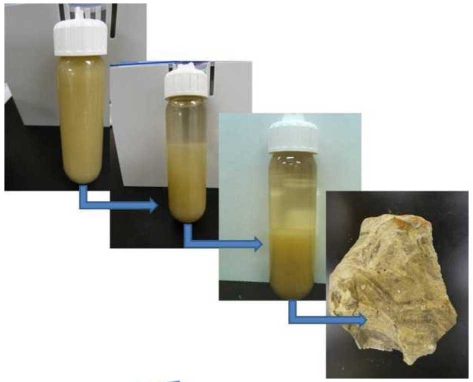


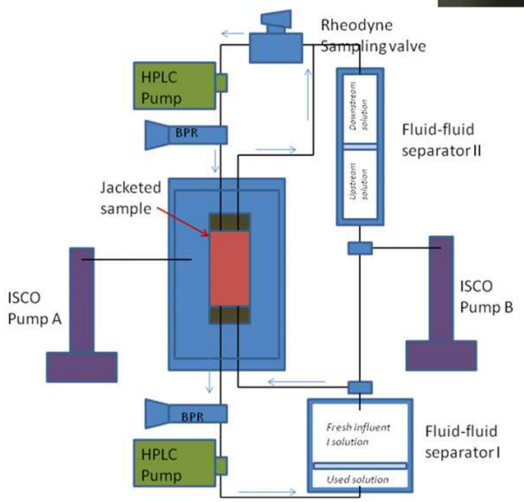
Handbook of Clay Science, Eds.: Bergaya, F., Theng, B.K.G., Lagaly, G.; Elsevier, 2006.

Potential reasons for anion interactions

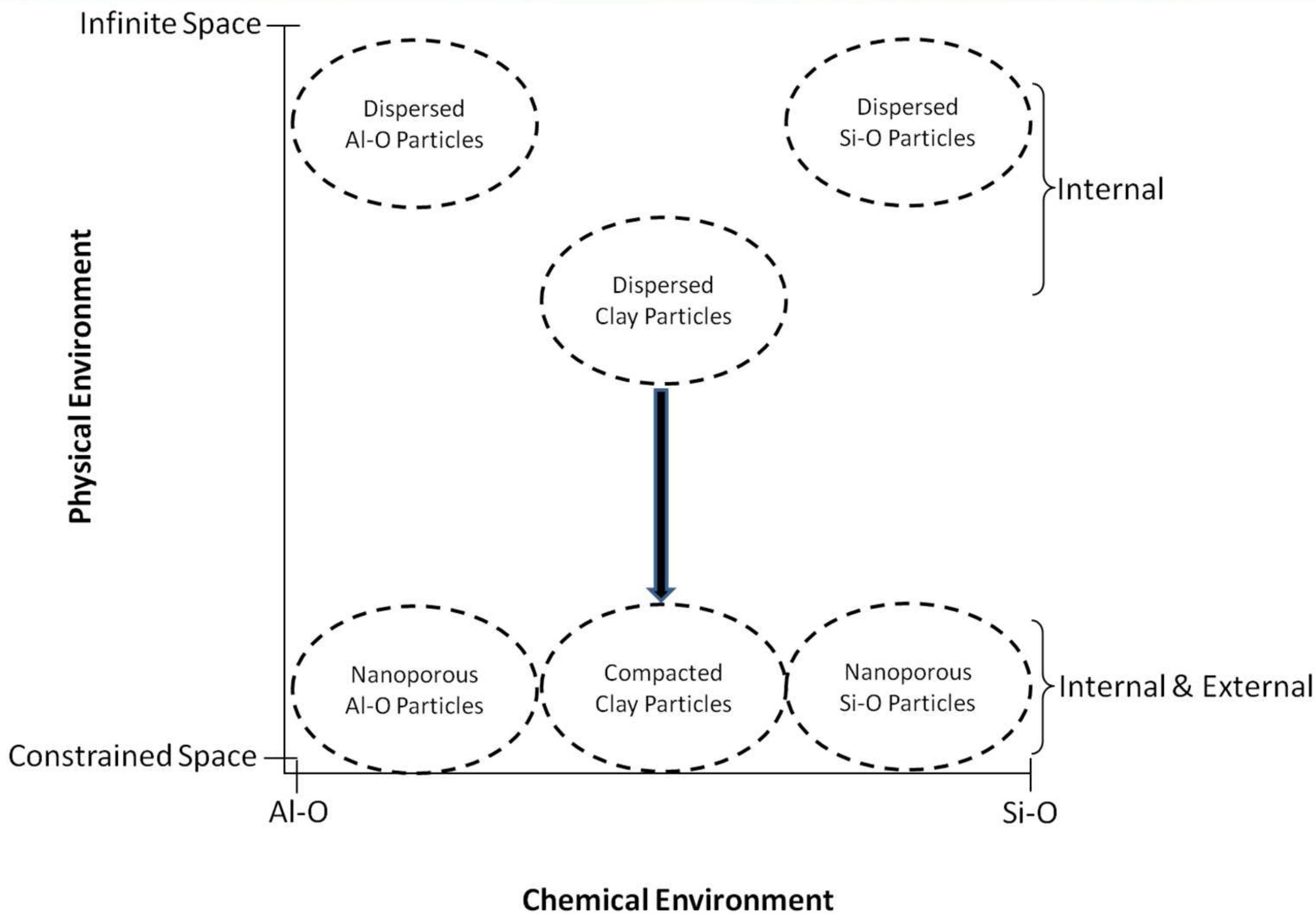
1. Interactions?... what interaction?
2. Iodine redox -> oxyanions
3. Clays impurities
4. Nano-environments

Experimental conditions/results





Clay particle proximity has the potential to change observed reactivity



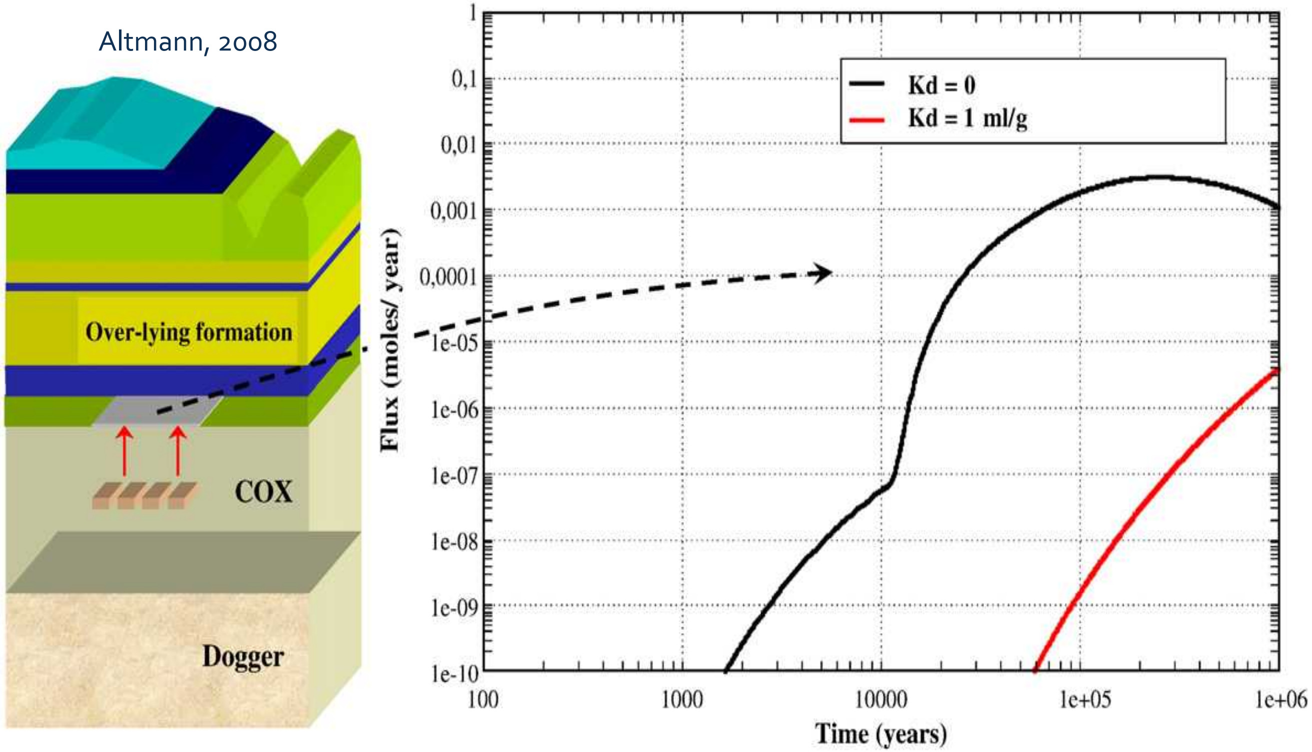
Miller, A.W., Wang, Y. (2012). *Environ.Sci. Technol.* **DOI:** 10.1021/es203025q.

Is Iodide interacting with negatively charged interlayers?

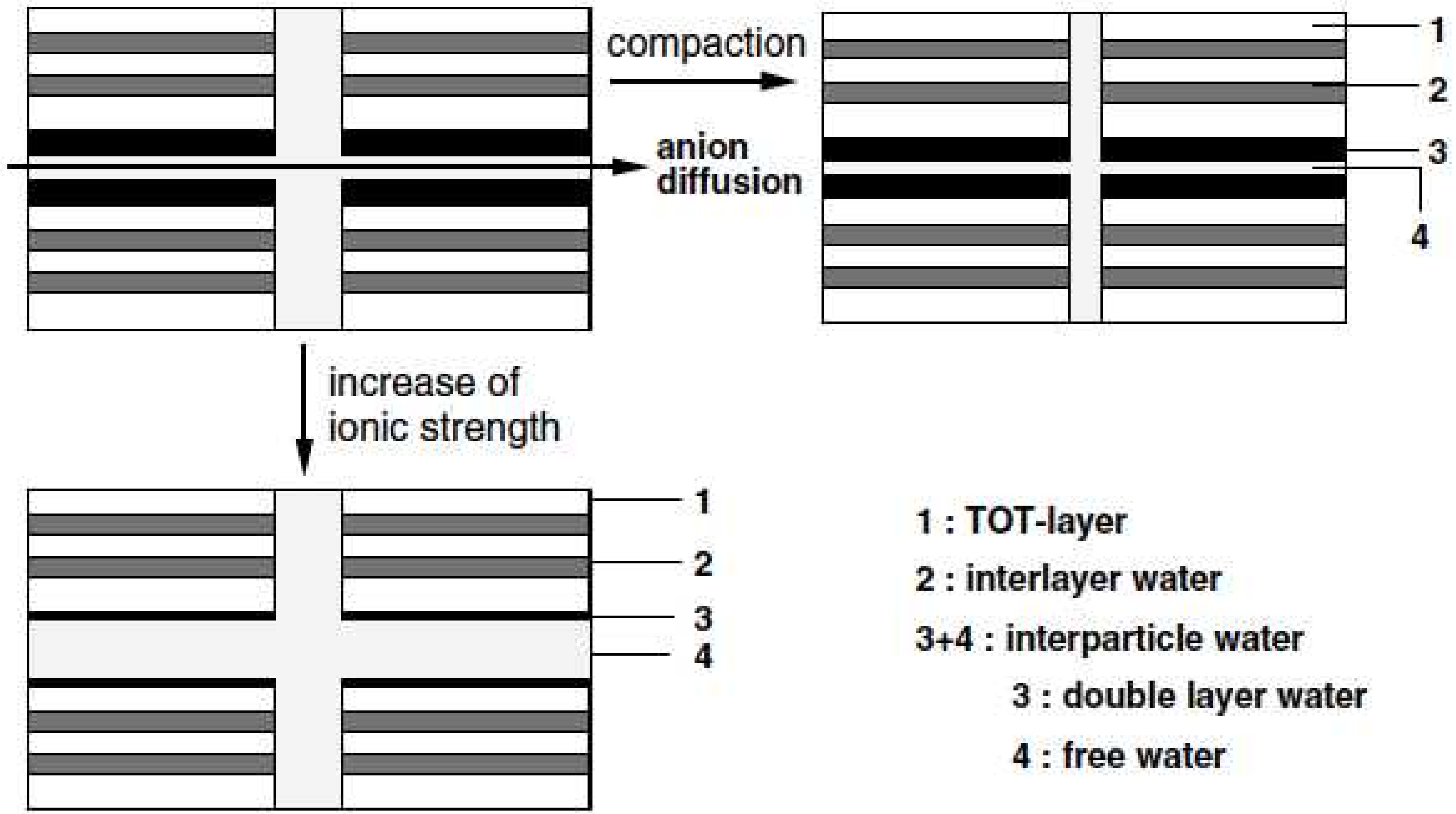
Q: Who cares?

A: Performance Assessment (PA).

Altmann, 2008

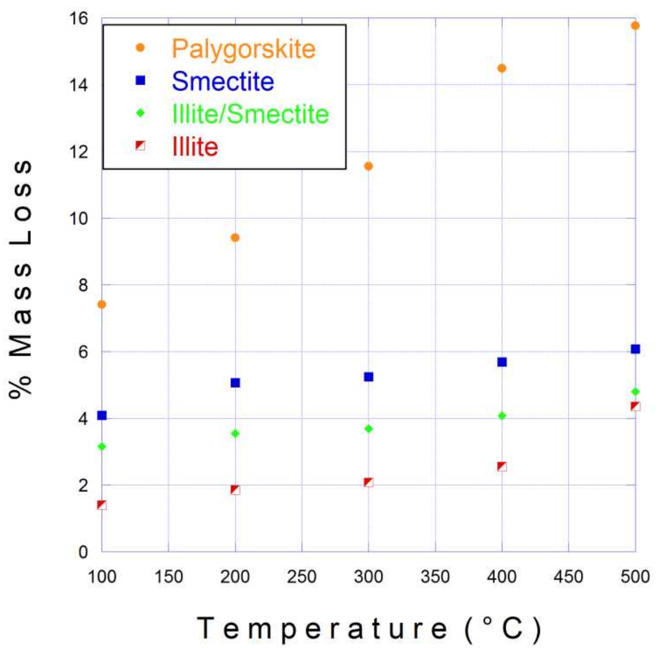


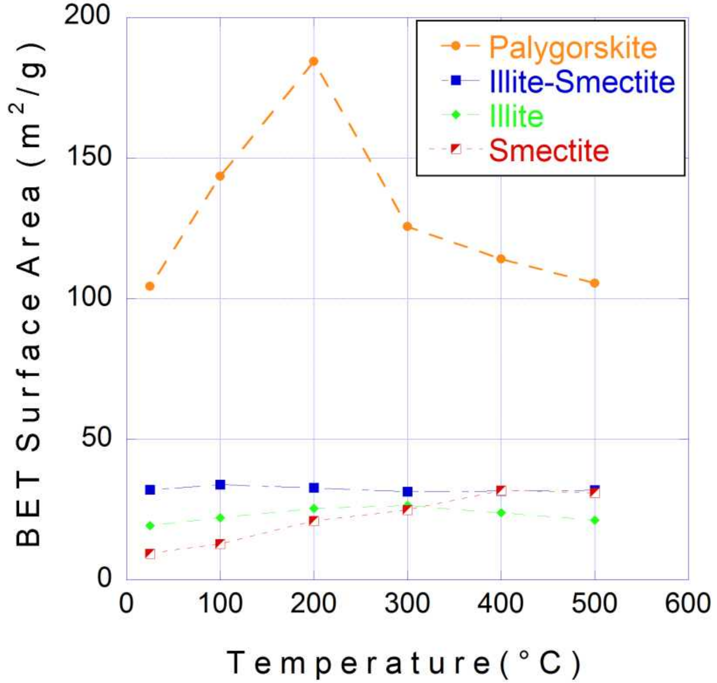
Anion Exclusion in Clays



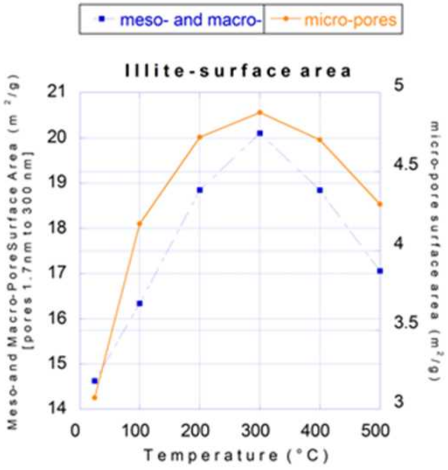
L.R. Van Loon et al. / Applied Geochemistry 22 (2007) 2536–2552

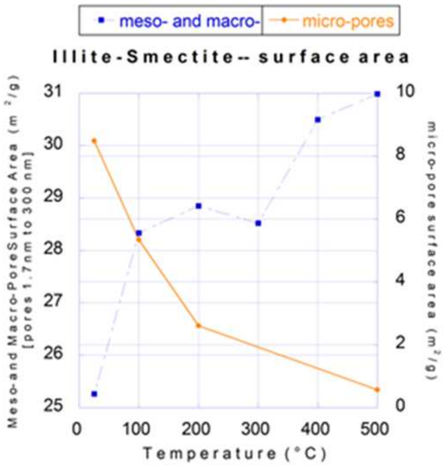
Results I -- Mass Loss on Heating
Clay morphology matters

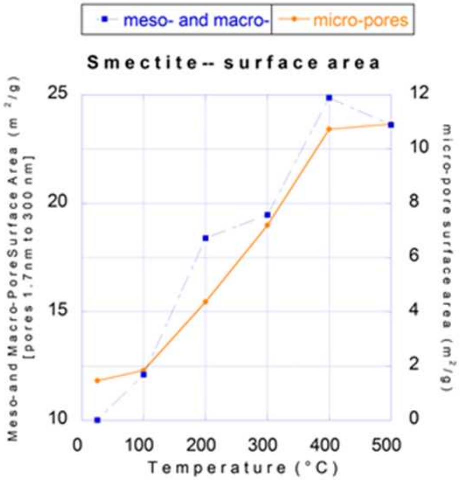


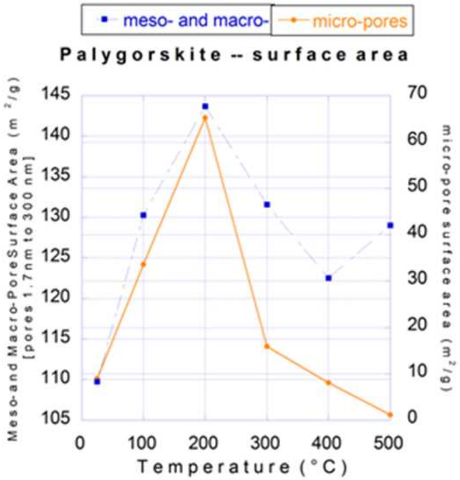


Results II – Pore Size Distributions



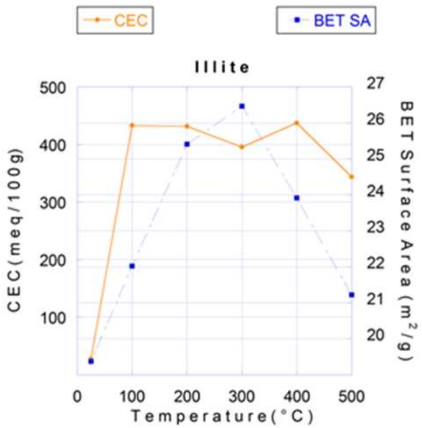


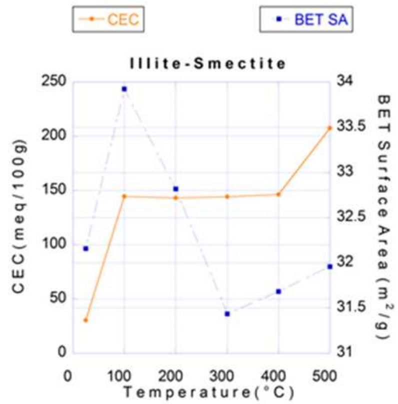


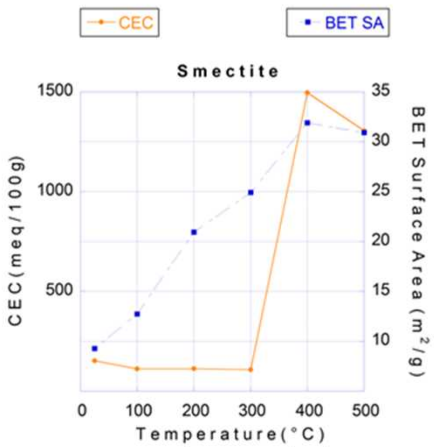


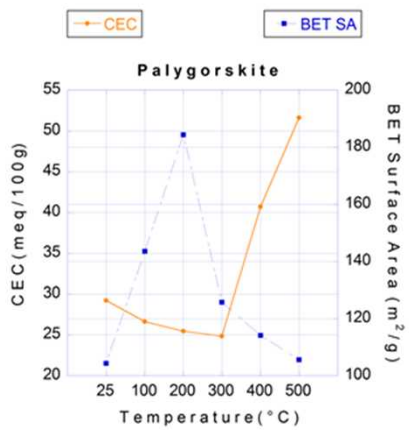
Results III – CEC / SA vs. Temperature

Again, morphology matters









Illite

– 20X increase in CEC 100C

Illite-Smectite

– 10X increase in CEC 100C

Ongoing / Future Work, Pt. 1

- Well cement durability
  - Degradation rates in cases where $scCO_2$ flows through brine
- Wellbore Seal Repair using Nanocomposite Materials
  - UNM -> Materials development – choose "winners" from experimental matrix
  - SNL -> Wellbore and test modeling, geomechanical testing at *in-situ* conditions

Ongoing / Future Work, Pt. 2

- Contact Angle Measurement
  - Various brine conditions/ compositions relevant to carbon storage
- Sorption on Heated Clays
  - Mechanical properties of heated, compacted systems
  - Diffusion behavior through heated and compacted clay systems

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- Wellbore Seal Repair – 3D Geomechanical Modeling of Seal Repair
- Subsurface Mineral Surface Properties (Contact Angle Studies)
- Sorption of radionuclides in clay minerals
- Conclusions

Conclusions

- Carbon constrained paradigm would necessitate a diverse portfolio of low carbon energy solutions (Truly effective carbon mitigation is a heavy lift!!!)
- Wellbore leakage in the case of carbonated brine flow and $scCO_2$ is understood and in many cases predictable
- Multi-phase wellbore leakage represents a complex problem, and is potentially important to truly understanding the risk posed by leakage along wellbores
- Wellbore seal material properties are key to mechanical behavior
- Mineral wetting properties play an important role in seal integrity and plume distribution
- Understanding mechanical behavior and sorption properties of heated of clays is critical to nuclear waste repository design

Backup Slides

Secondary minerals are more widespread on surfaces exposed to humid supercritical CO2