British Geotechnical Association
Touring Lecture 2012

Energy Geotechnology

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Georgia Institute of Technology

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References added for further reading
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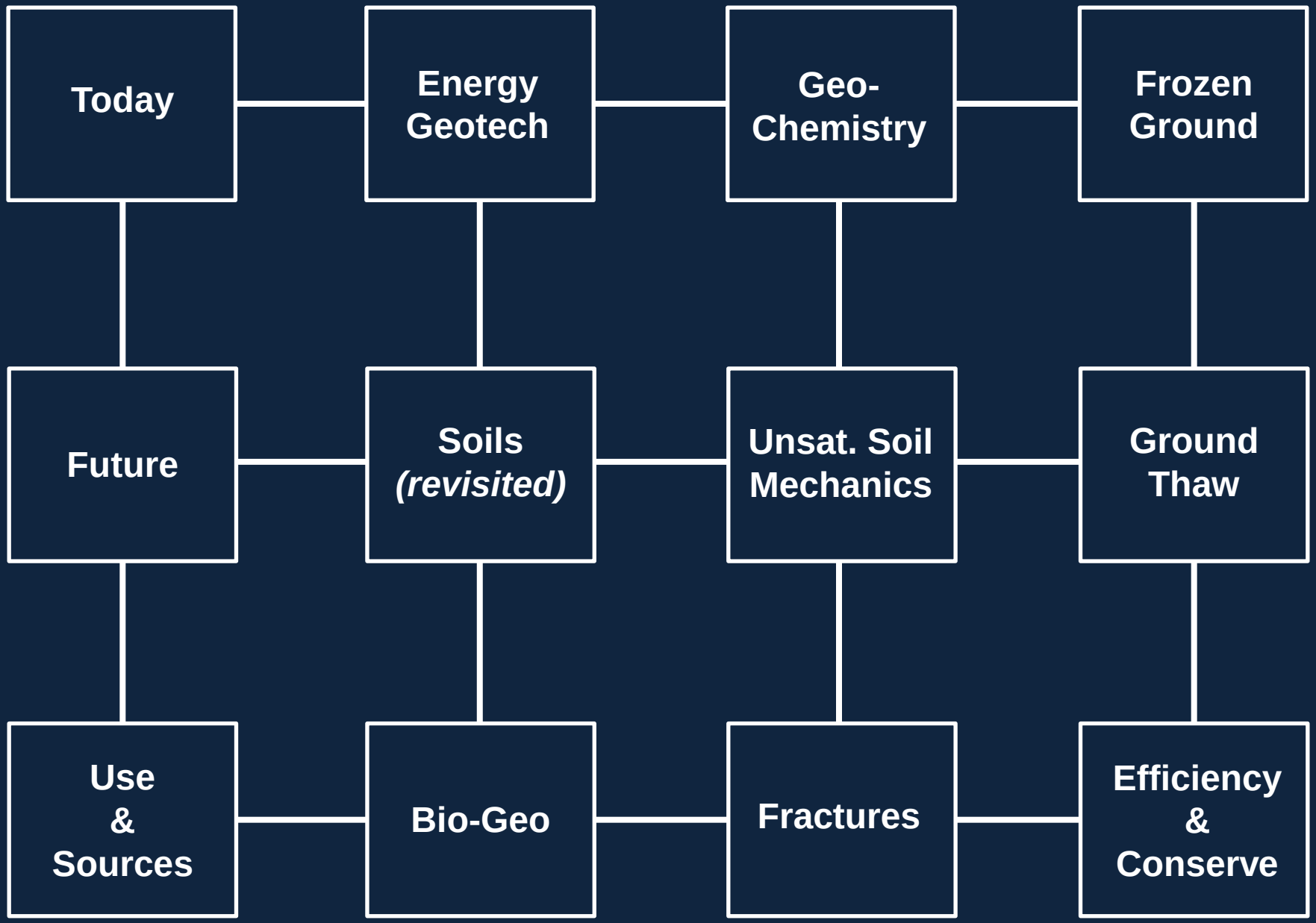
Note: Academic use only


Today
Energy Geotech
Geo-Chemistry
Frozen Ground
Future
Soils *(revisited)*
Unsat. Soil Mechanics
Ground Thaw
Use & Sources
Bio-Geo
Fractures
Efficiency & Conserve

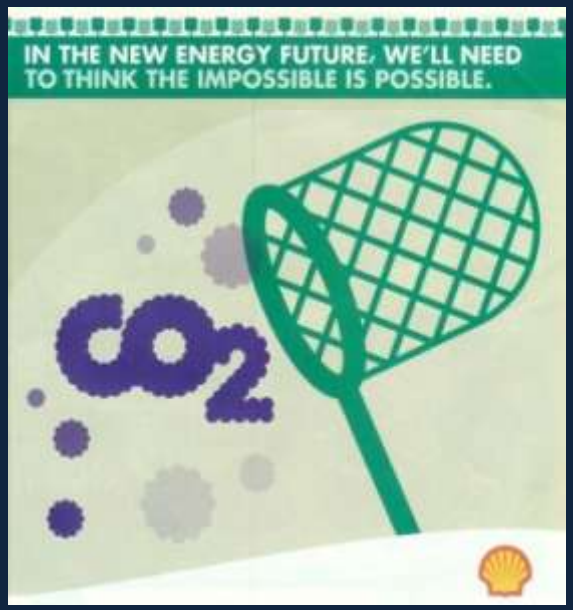
Energy: News

Deepwater Horizon (April 20, 2010)

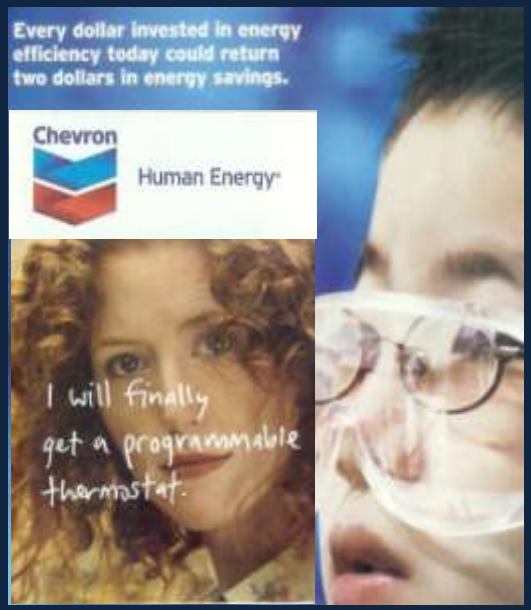
Energy: News

Fukushima I Nuclear Power Plant (March 11, 2011)

Energy: Advertisement



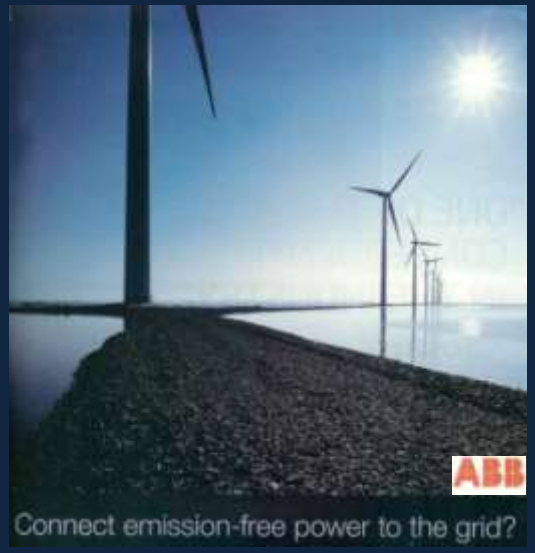
Carbon capture & storage



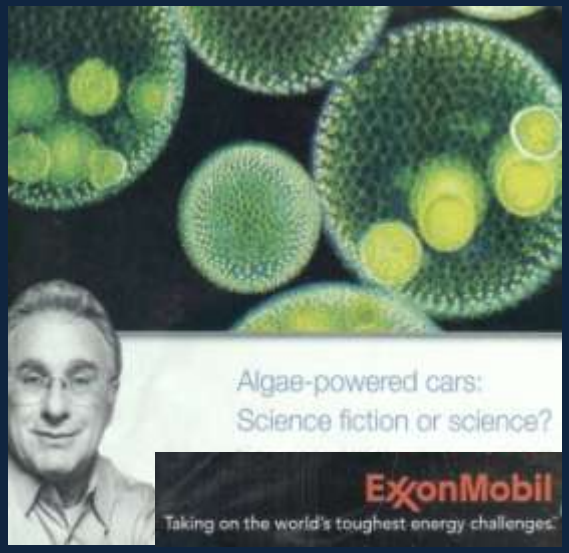
Efficiency and conservation

Alternative sources

Smart grid



C-free energy & the grid



Renewable sources

Energy: Civic Journalism

Energy: Civic Journalism

Energy Geotech

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Future

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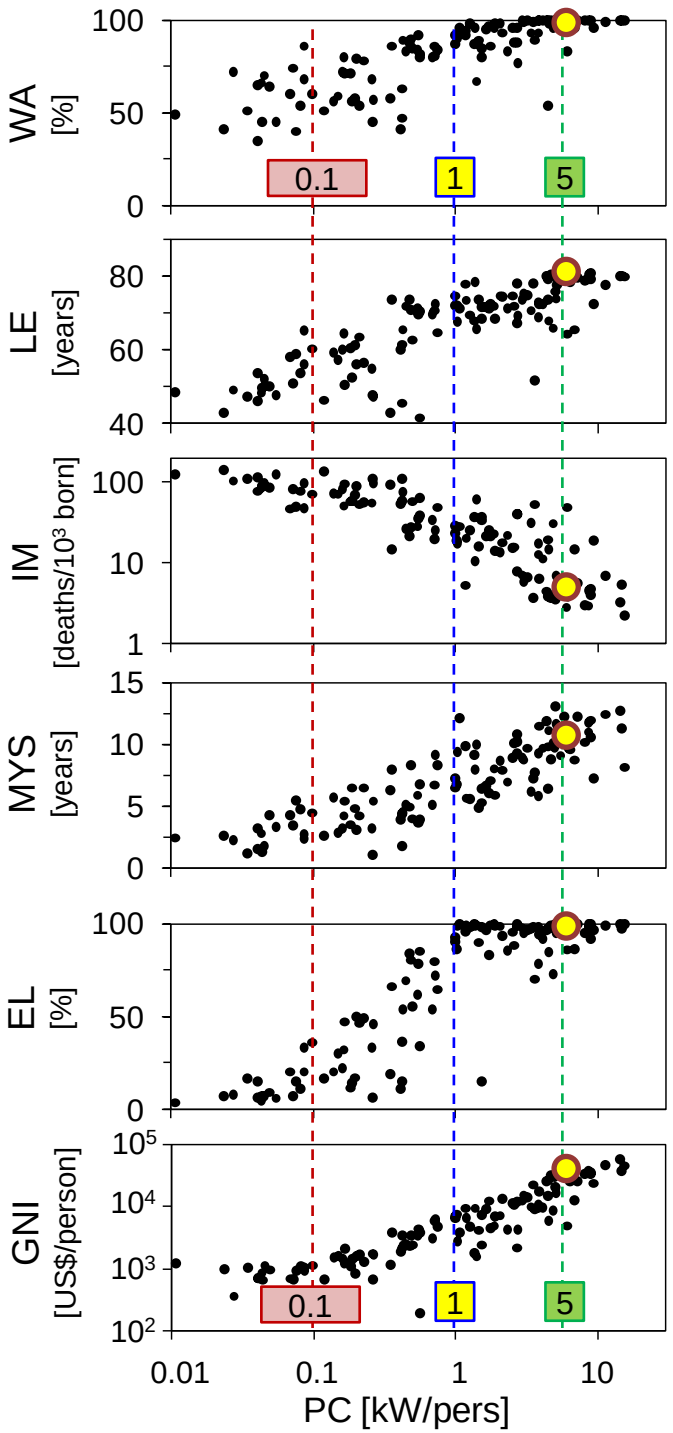
Energy and Life



water
UK: 100%

life expectancy
UK: 79 yr

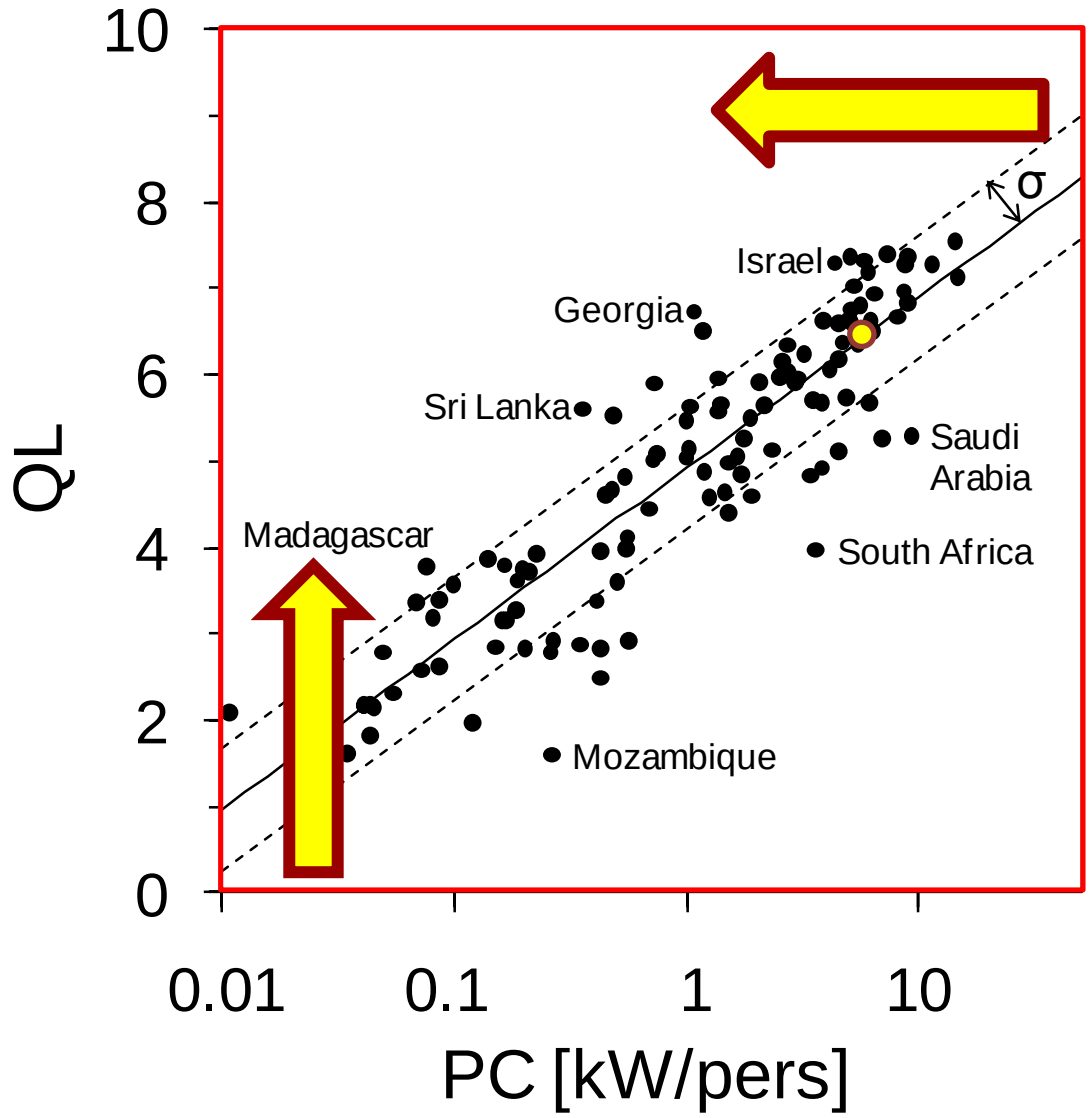
infant mortality
UK: 5/1000

schooling
UK: 9.1

electrification
UK: 99%

income
UK: 34,500 U$A

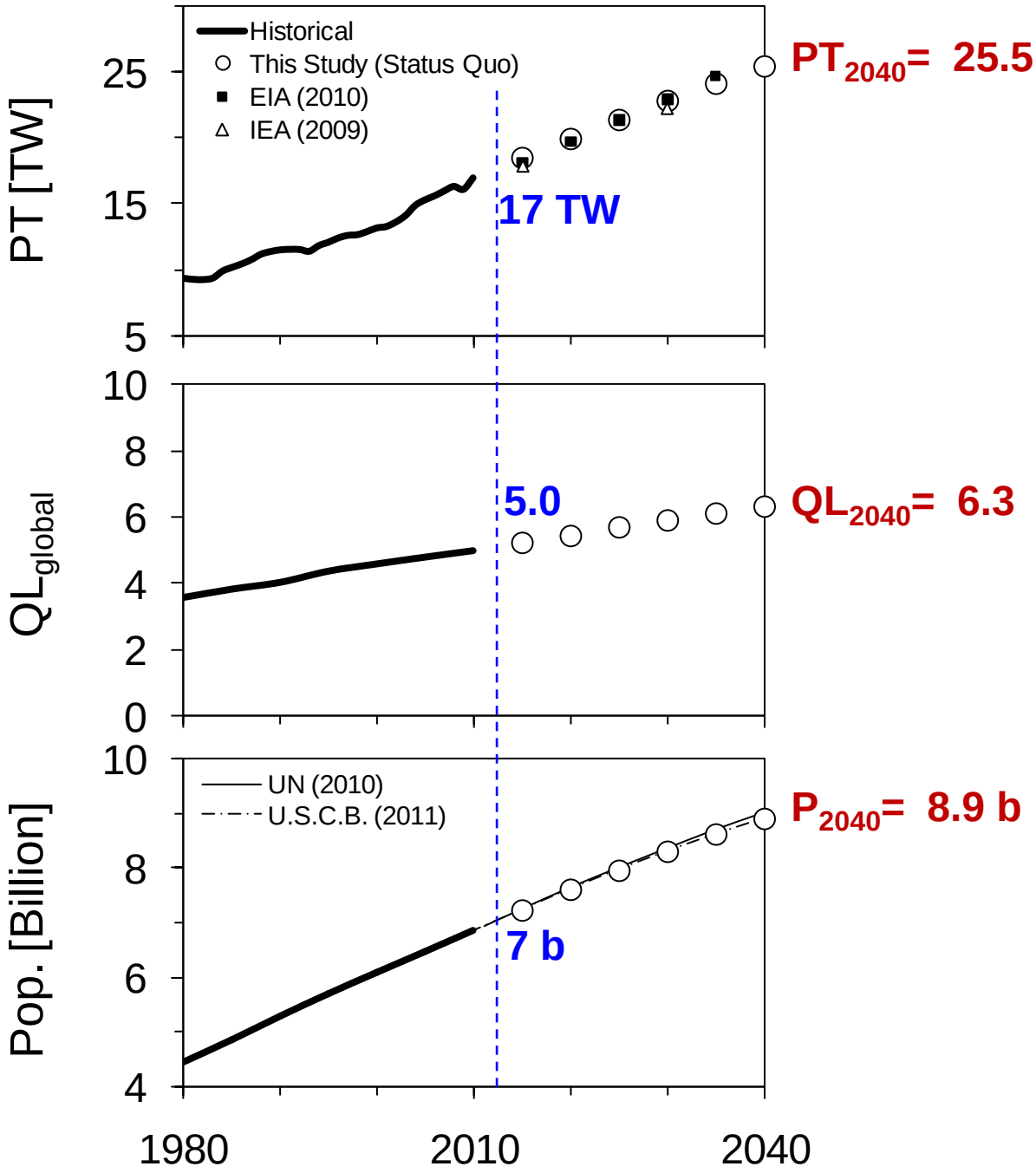
Energy and Life



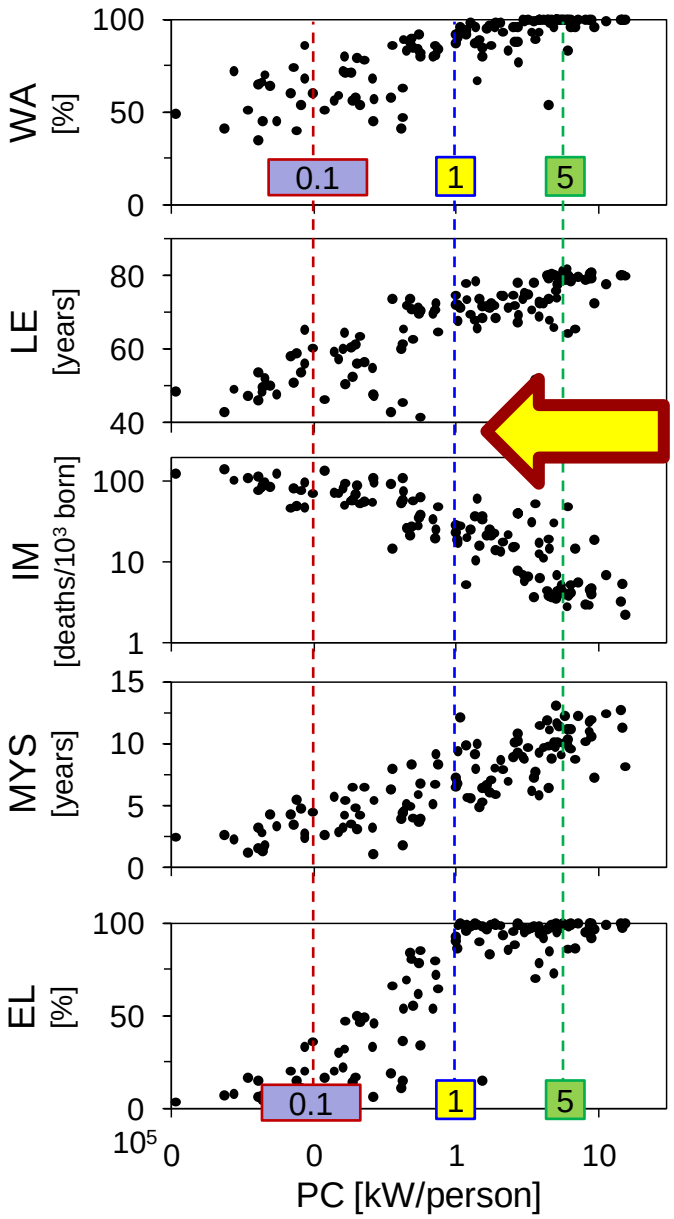
$$QL = 0.072\left(\frac{LE}{yrs}\right) + 0.310\left(\frac{MYS}{yrs}\right) - 2.16$$

QL= 10 ➔ *LE*= 100yr *MYS*= 16 yr
QL= 0 ➔ *LE*= 30yr *MYS*= 0 yr

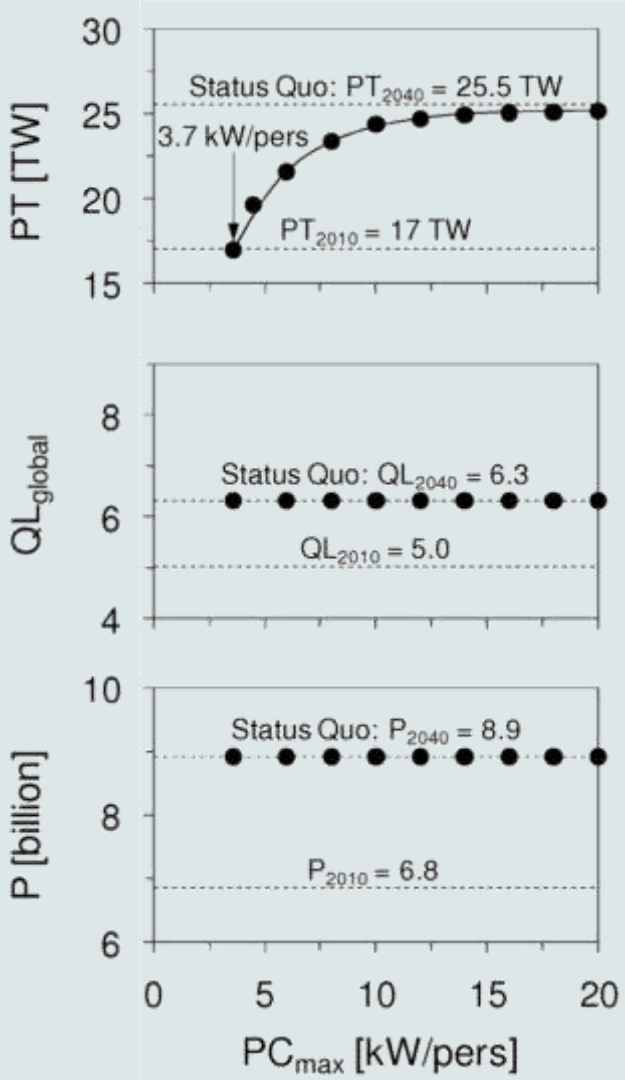
Status Quo


Historical
This Study (Status Quo)
EIA (2010)
IEA (2009)
PT [TW]
25
15
5
17 TW
PT2040= 25.5 TW
QLglobal
10
8
6
4
2
0
5.0
QL2040= 6.3
Pop. [Billion]
UN (2010)
U.S.C.B. (2011)
10
8
6
4
7 b
P2040= 8.9 b
1980
2010
2040

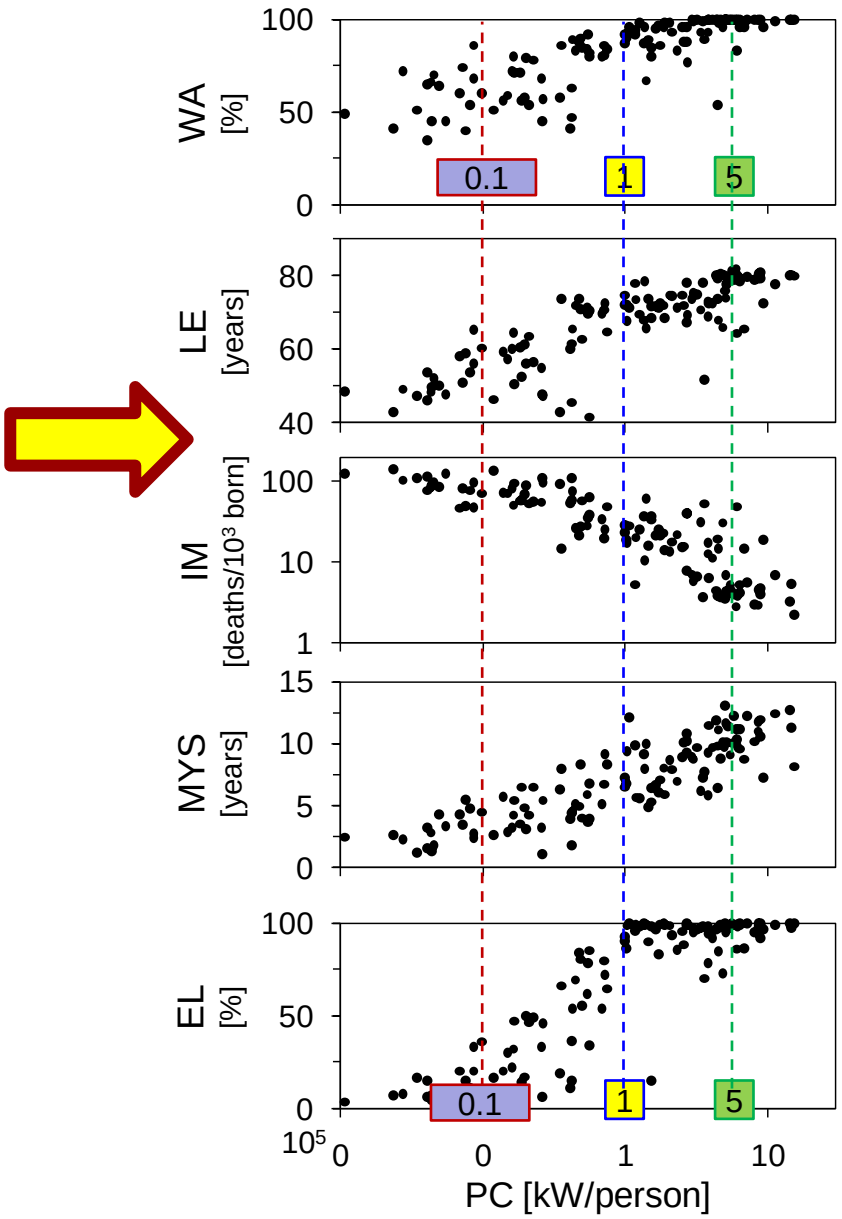
Strategies: 2040 Horizon



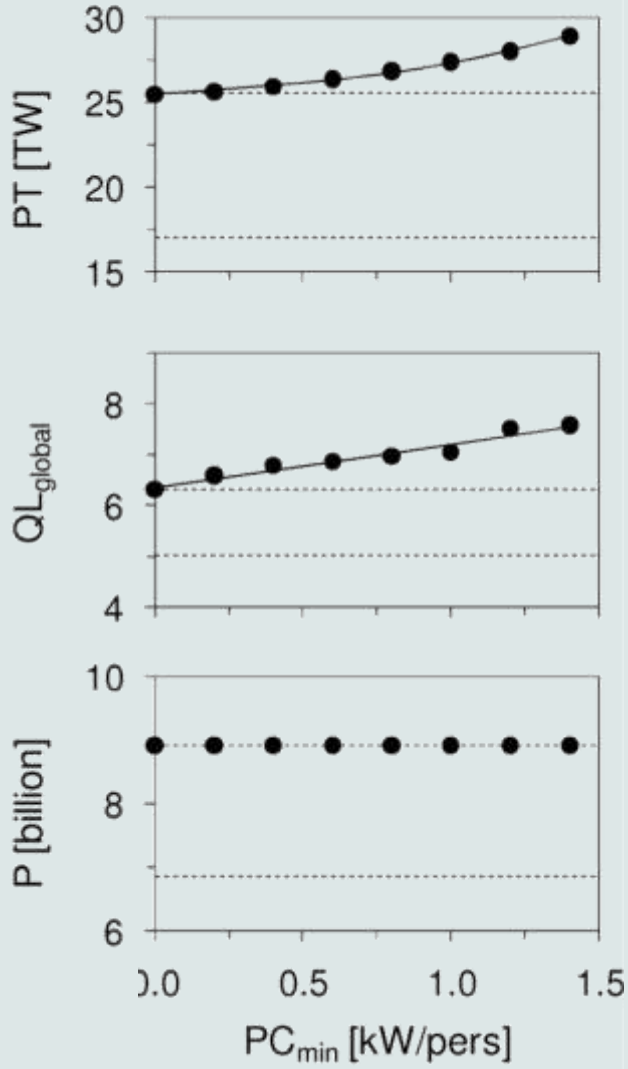
Limit Overspending



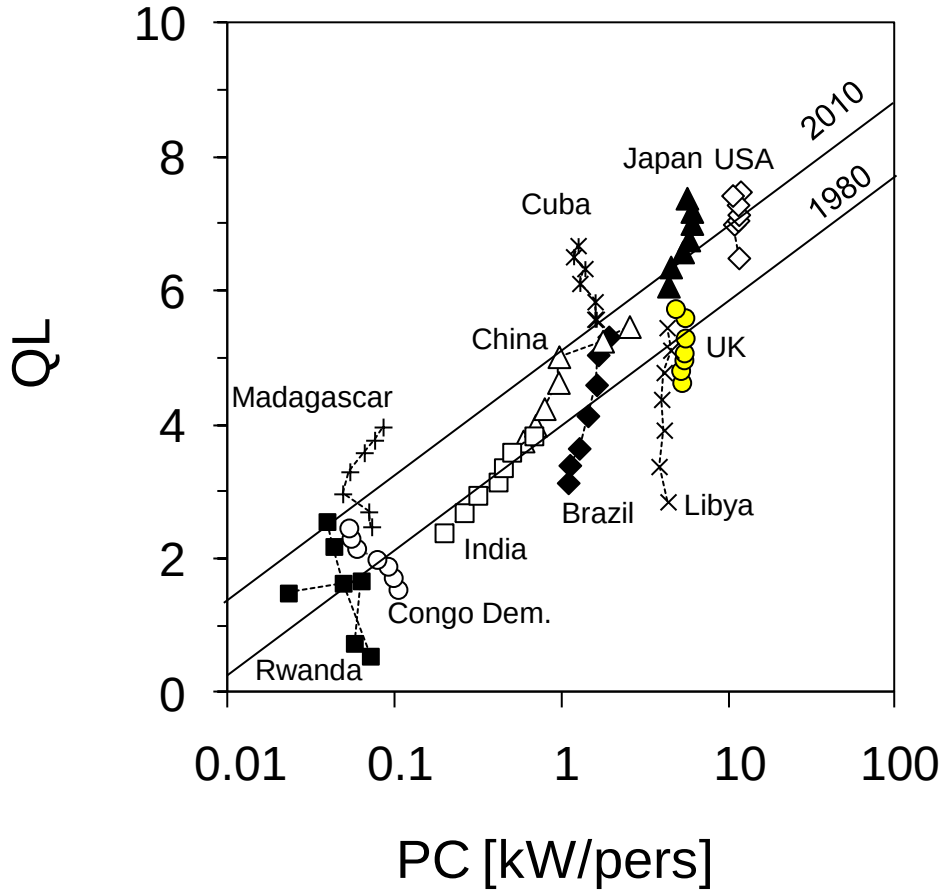
Strategies: 2040 Horizon



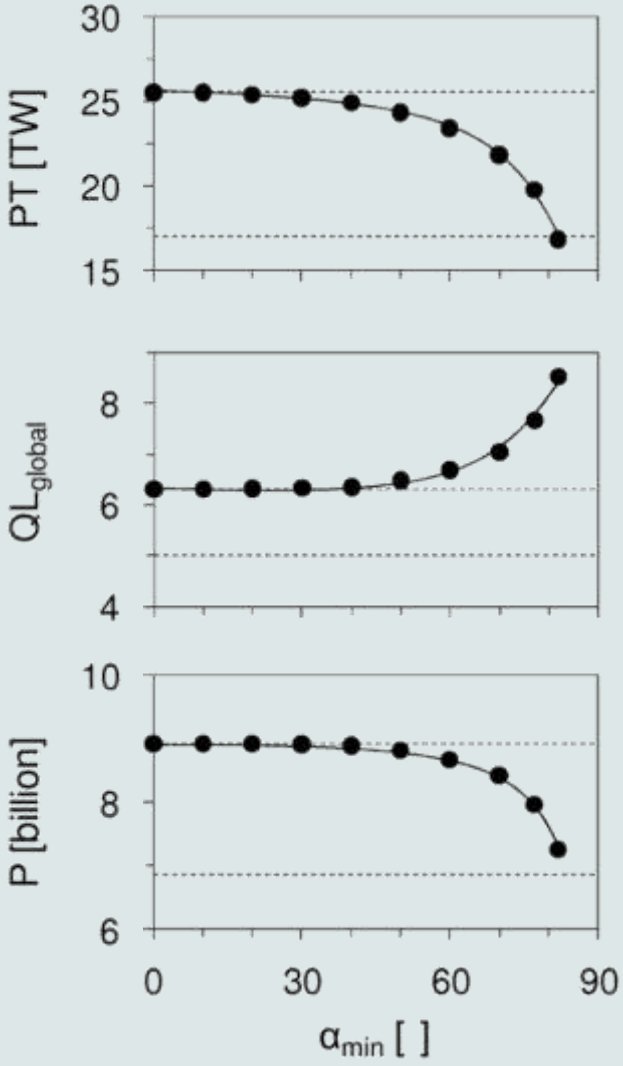
Stimulate Growth in Developing World



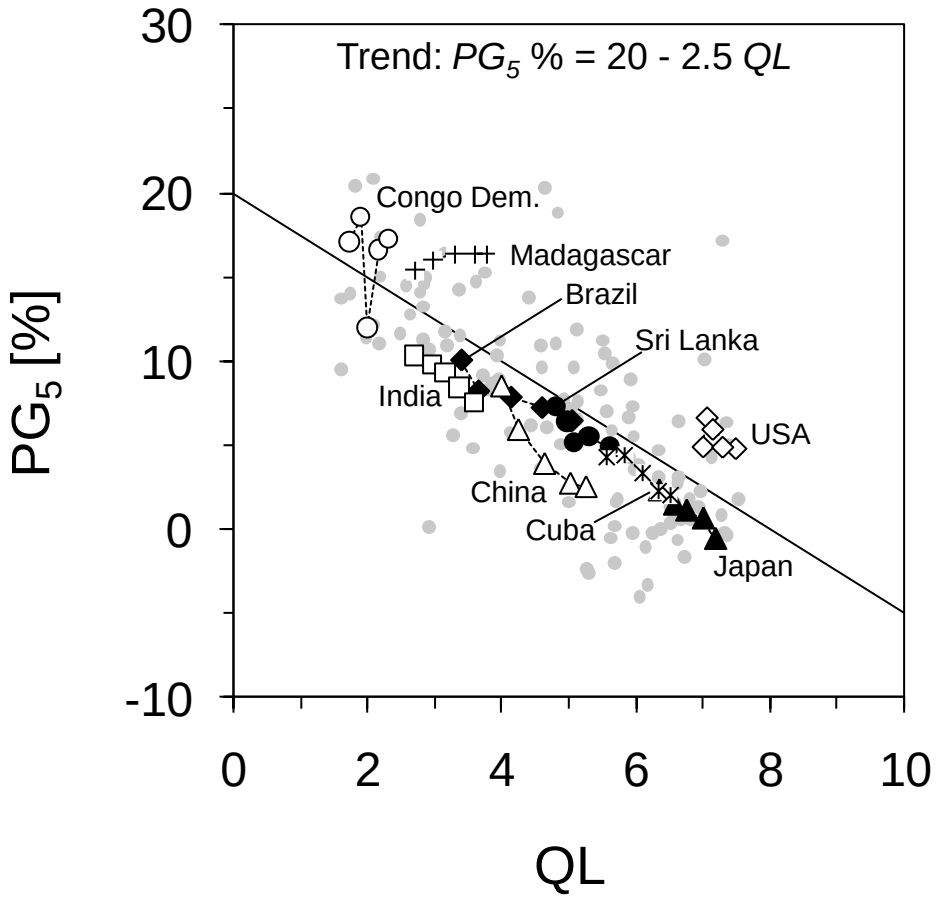
Strategies: 2040 Horizon



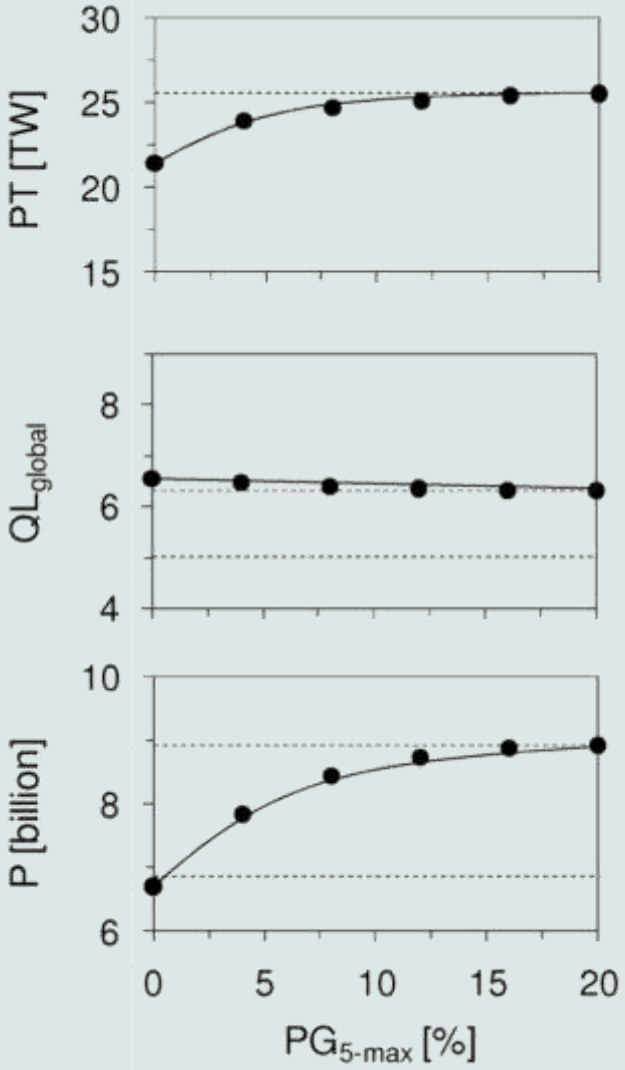
Improved Energy-for-Life Efficiency



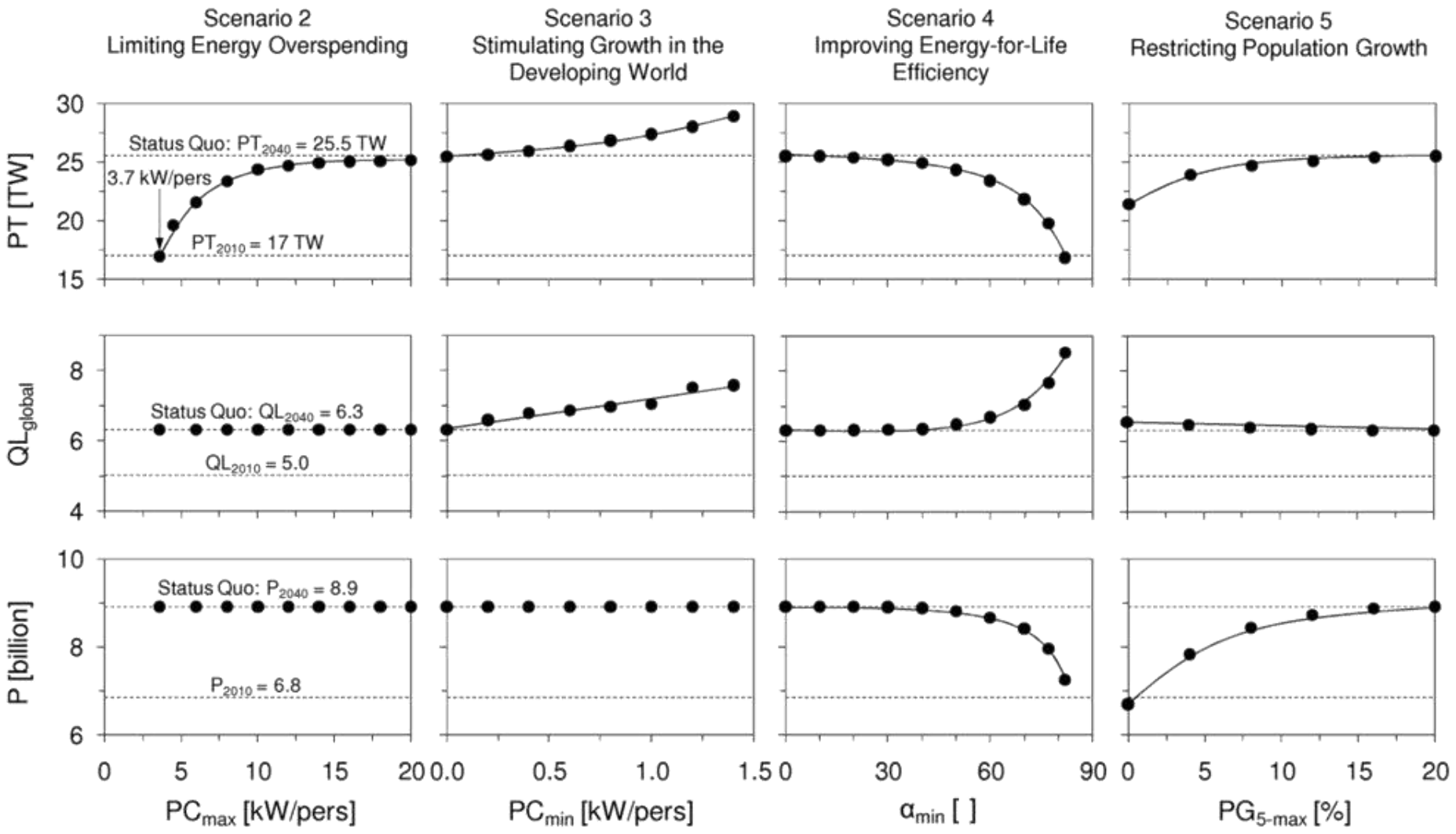
Strategies: 2040 Horizon



Restrict Population Growth



Strategies: 2040 Horizon



Summary: Energy and Life

Quality of life: current development patterns: HDI ↔ Energy

By 2040: Δ-energy ~50%

most of the growth: developing countries

Sustainable energy system:

developing	quality of life > 1 kW/person
	technological leapfrogging
	QL ↑ ➔ population growth ↓
developed	technological breakthroughs
	efficiency and conservation < 4 kW/person
world	energy-for-life efficient governments

http://pmrl.ce.gatech.edu/papers/Santamarina_2006www.pdf
http://pmrl.ce.gatech.edu/papers/Pasten_2012a.pdf

Energy Geotech

Geo-Chemistry

Frozen Ground

Soils *(revisited)*

Unsat. Soil Mechanics

Ground Thaw

Use & Sources

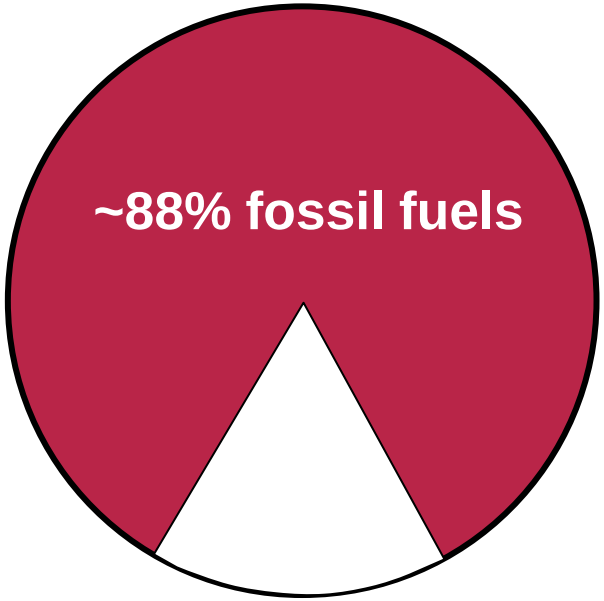
Bio-Geo

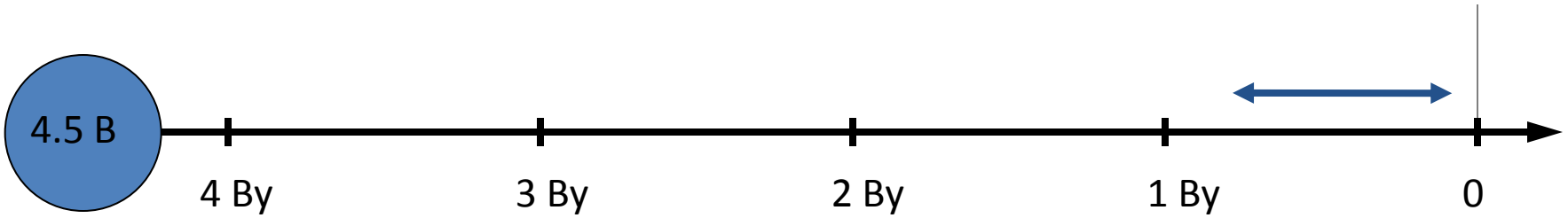
Fractures

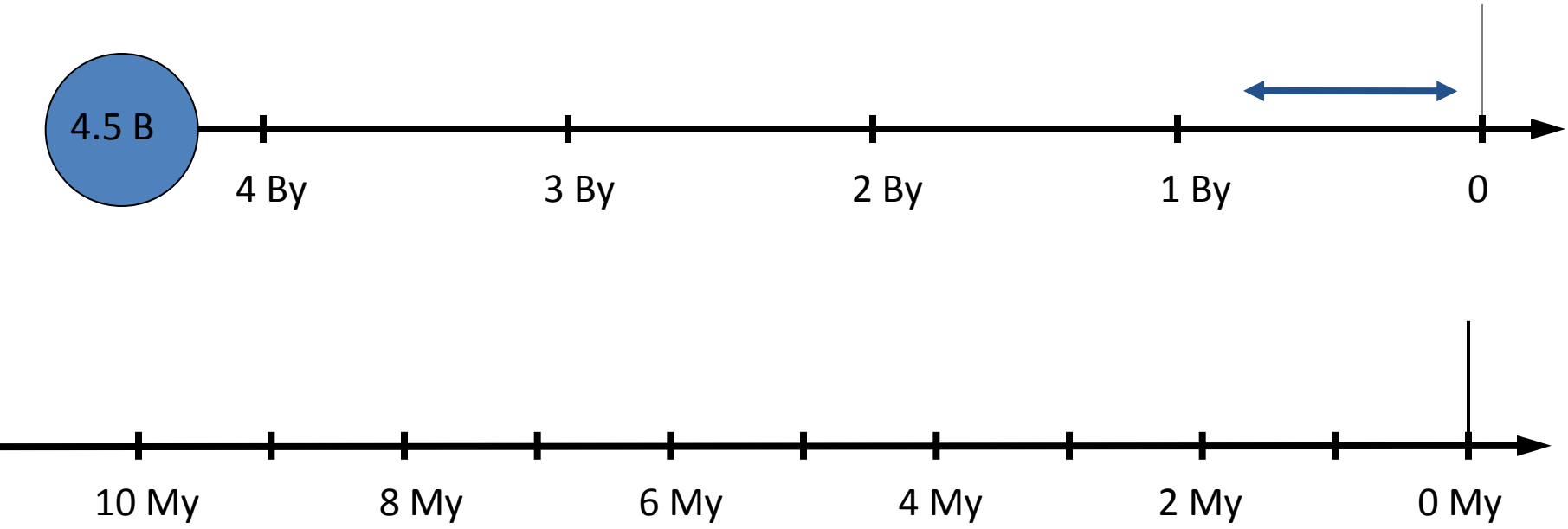
Efficiency & Conserve

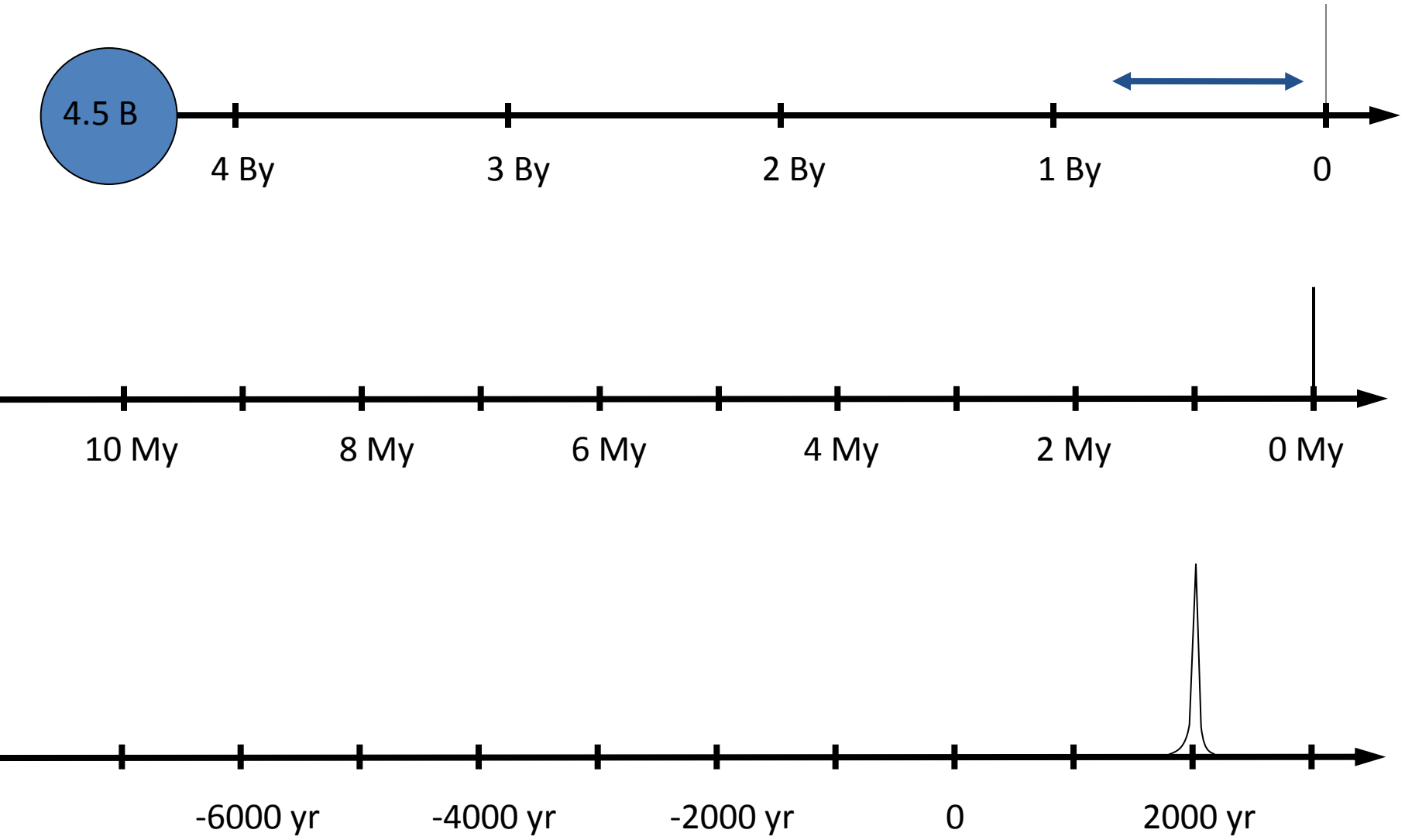
Sources

37%	petroleum	transport
24%	natural gas	heat&power
23%	coal	power
4 %	biomass (renewable)	industrial
8%	nuclear power	power
2%	hydroelectric	power
< 2%	renewable non-hydro	power




4.5 B
4 By
3 By
2 By
1 By
0


4.5 B
4 By
3 By
2 By
1 By
0
10 My
8 My
6 My
4 My
2 My
0 My


4.5 B
4 By
3 By
2 By
1 By
0
10 My
8 My
6 My
4 My
2 My
0 My
-6000 yr
-4000 yr
-2000 yr
0
2000 yr

Fossil Fuel: 88%

Summary: Energy and Life (2)

Resources: **adequate ….**

C-dependency → global warming

Energy Geotech

Geo-Chemistry

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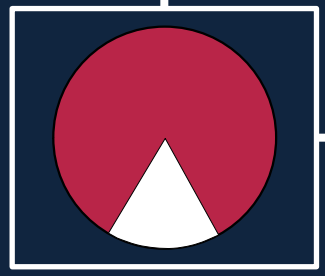

Bio-Geo

Fractures

Efficiency & Conserve

FOSSIL FUELS (C-BASED)			RENEWABLE		Nuclear
Petroleum	Gas	Coal	Wind	Solar	
GEOLOGICAL STORAGE (energy and waste)					
CO_2 sequestration		(Fly Ash)	Energy Storage		Waste storage
GEO-ENVIRONMENTAL REMEDIATION					
CONSERVATION					

- Hydro-electric
- Biofuels
- Geothermal
- Tidal
- Electric grid

FOSSIL FUELS (C-BASED)

Petroleum

- fines & clogging
- sand production
- shale instability
- EOR
- heavy oil & tar sand

Gas

- gas hydrates
- gas storage
- low-T LNG found.

Coal

- characterization
- optimal extraction
- subsurface conv.

- mixed fluid flow, percolation
- contact angle & surface tension = $f(u_a)$

RENEWABLE

Wind

- off/onshore
- periodic load
- ratcheting

Solar

??

Nuclear

- engineered soils
- decommission
- leak detect
- leak repair

GEOLOGICAL STORAGE (energy and waste)

CO_2 sequestration (Fly Ash)

- mineral dissolution ➔ shear faults
- long-term containment
- upscaling geological properties

Energy Storage

- for peak demand (e.g., compressed air)
- pile-exchangers
- phase-change mixtures

Waste storage

10^5 yr BTHCM

GEO-ENVIRONMENTAL REMEDIATION

- Bio-chemo-geo phenomena and methods

CONSERVATION

- Energy efficient construction technology: "Embodied Energy" in infrastructure projects
- Bio-mimetization: ant excavation: tunneling and new infrastructure; tree roots: smart/adaptable foundations

- **Hydro-electric**: capacity almost saturated
- **Biofuels**: strongly geo-related, BUT: water? land? food? energy efficiency?
- **Geothermal**: viable in "hot-spots“ (high T rock performance, tools, monitoring, processes)
- **Tidal**: foundation engineering
- **Electric grid**: critical for renewable sources, CO_2 capture and storage

http://pmrl.ce.gatech.edu/papers/Santamarina_2011a.pdf
http://pmrl.ce.gatech.edu/papers/Santamarina_2012b.pdf

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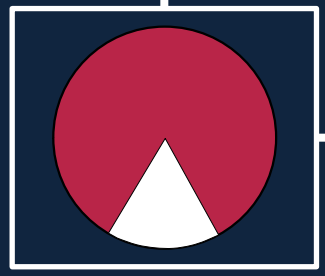
Frozen Ground

Soils *(revisited)* *-pores-*

Unsat. Soil Mechanics

Ground Thaw



Bio-Geo

Fractures

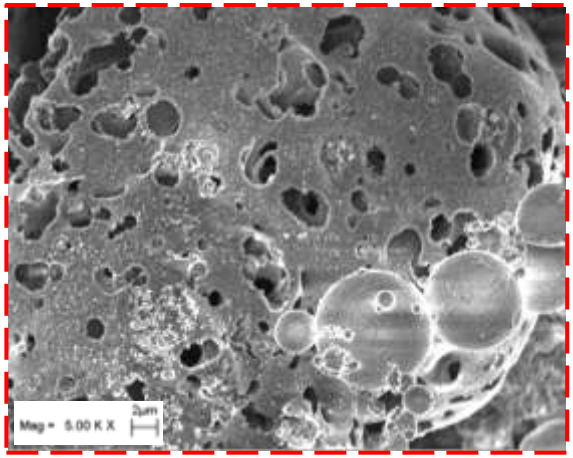
Efficiency & Conserve

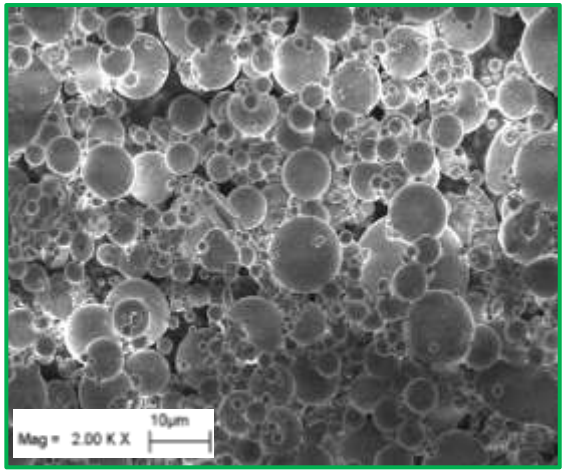
Kingston Fossil Plant (12/22/2008)

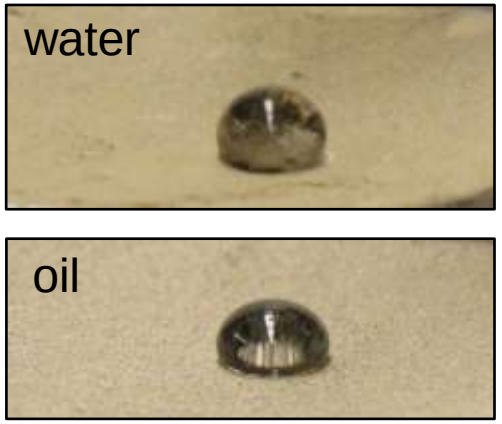
with R. Bachus - Geosyntec

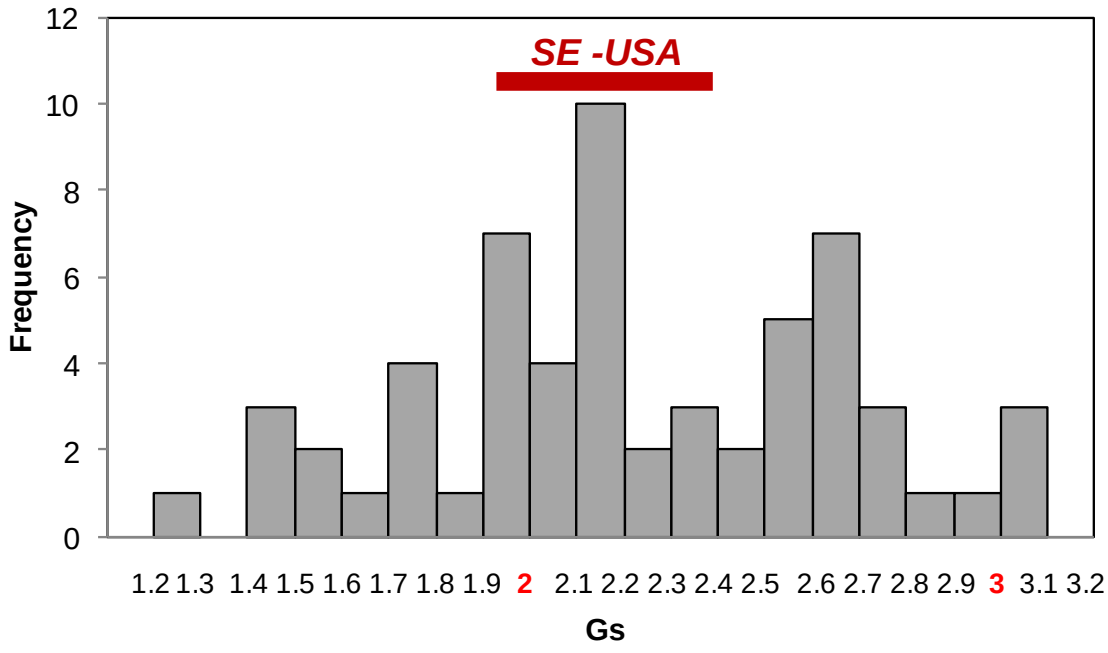
US EPA

Specific Gravity



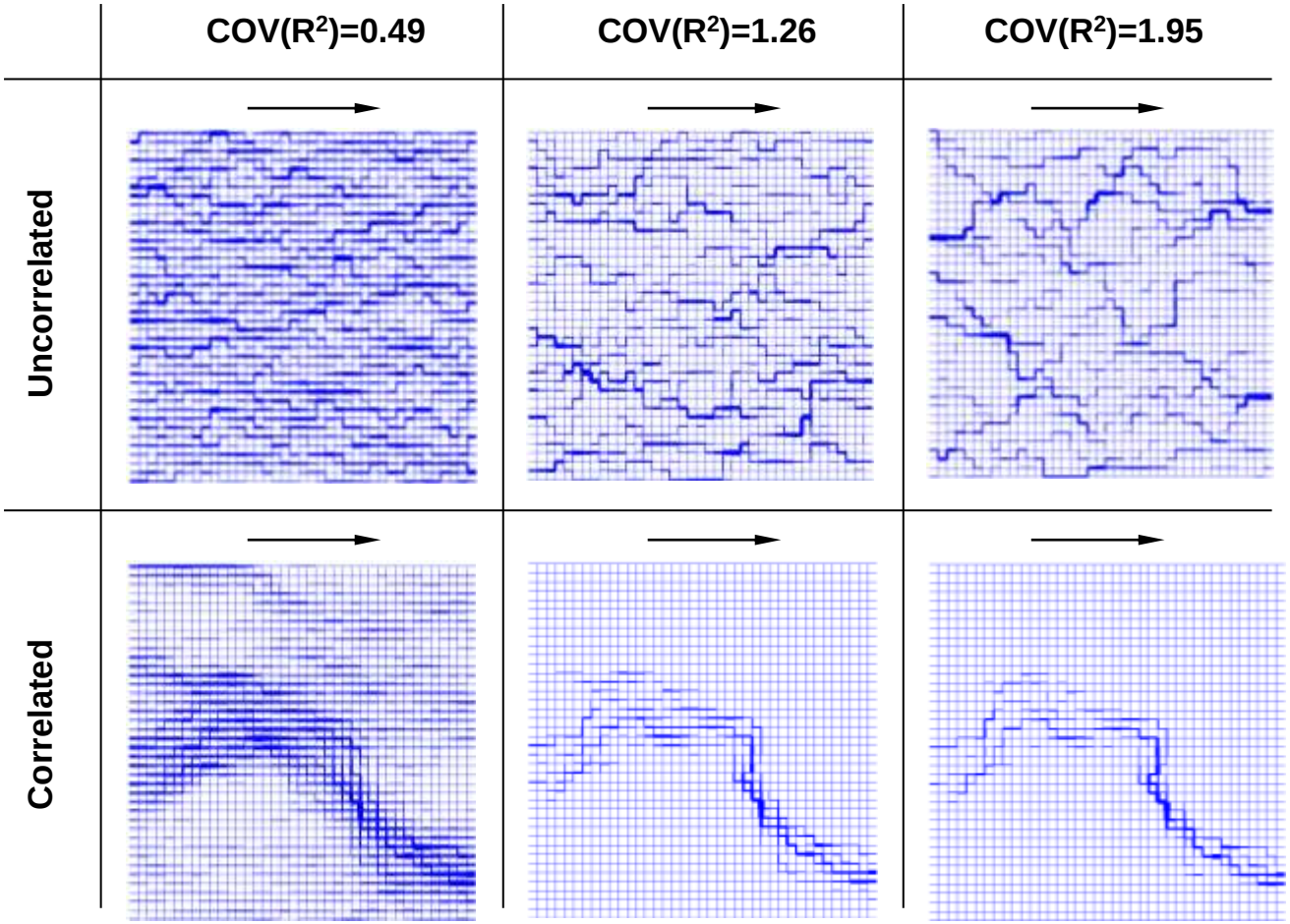






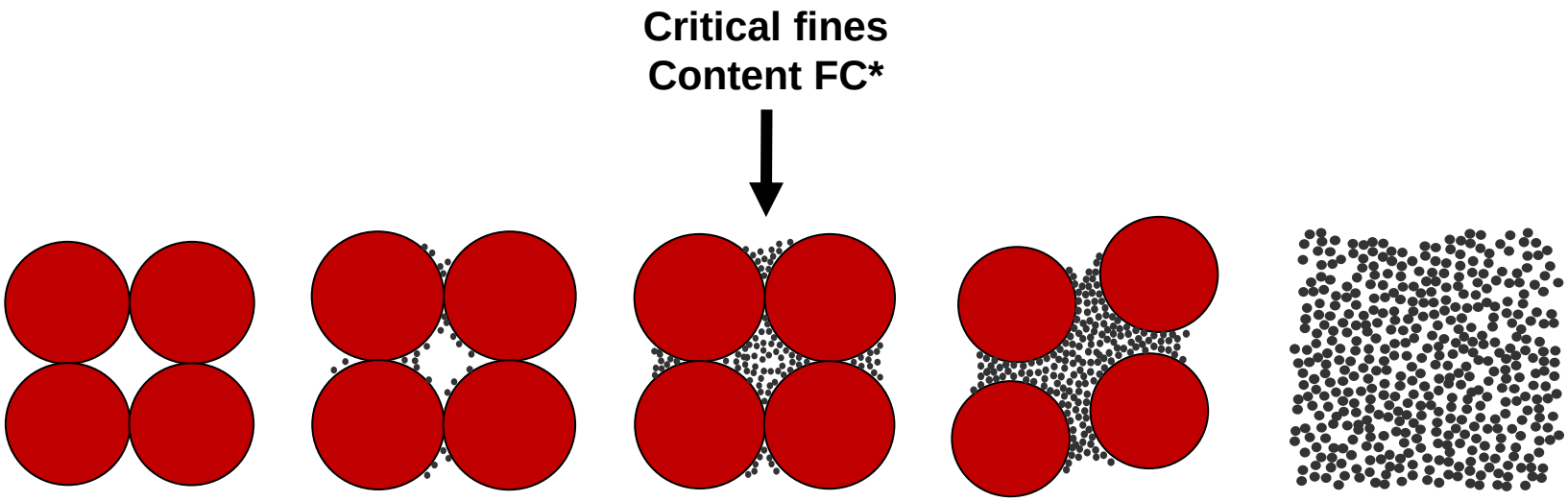
Hydraulic Conductivity – Spatial Variability

Flow Focusing



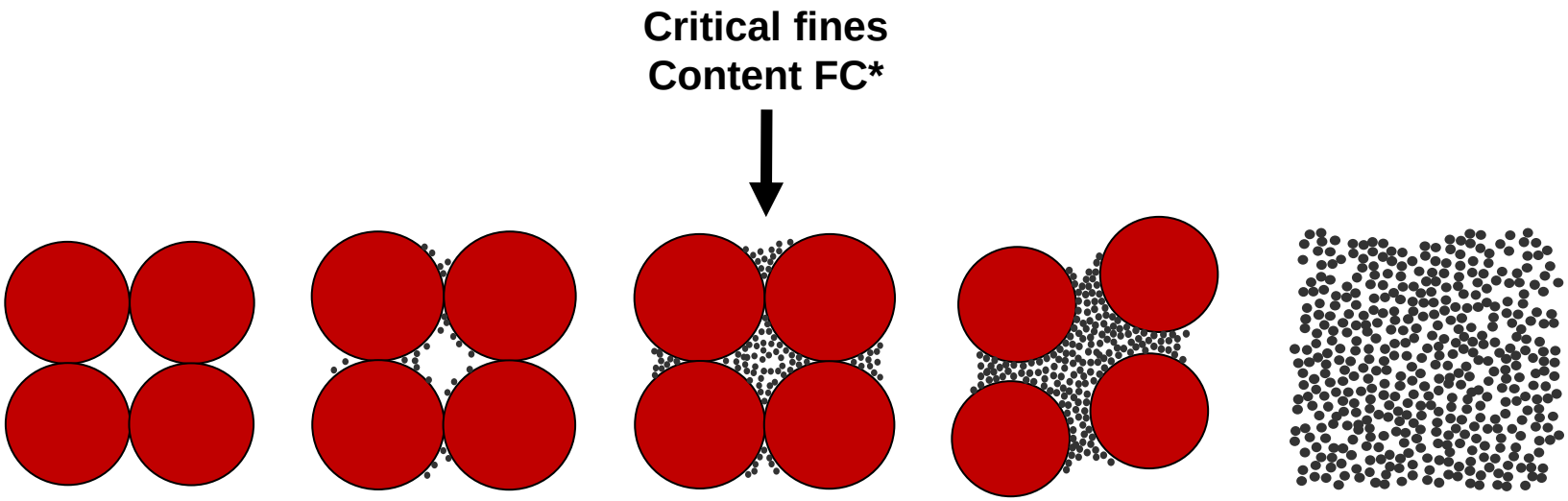
http://pmrl.ce.gatech.edu/papers/Jang_2011a.pdf

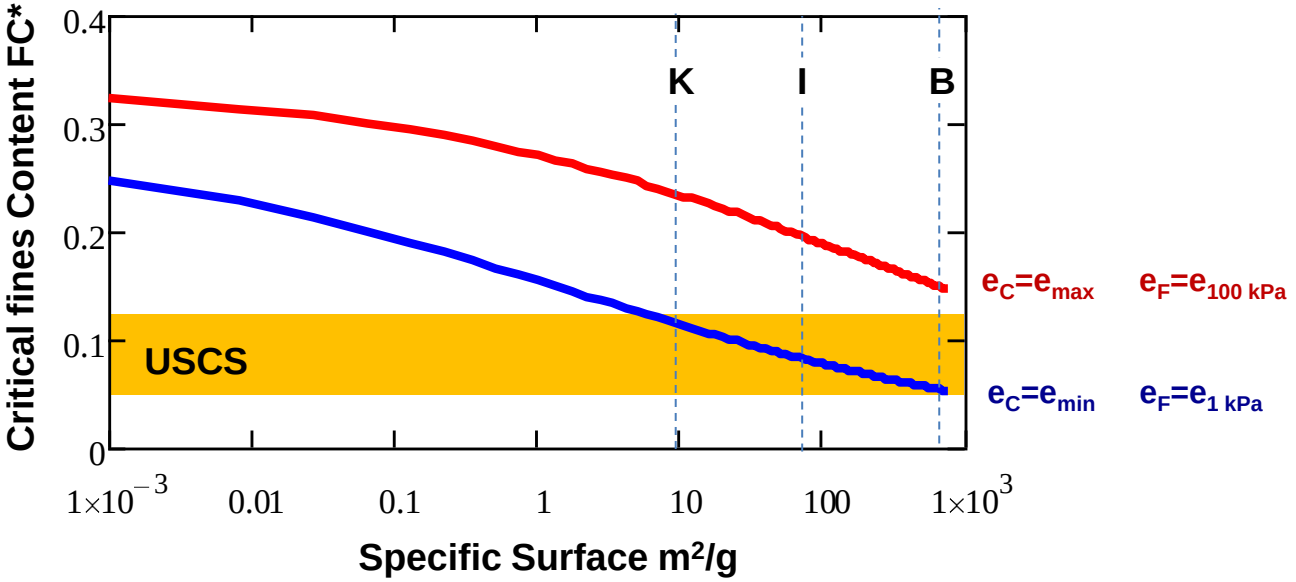
Grain Size Distribution: The Role of Fines



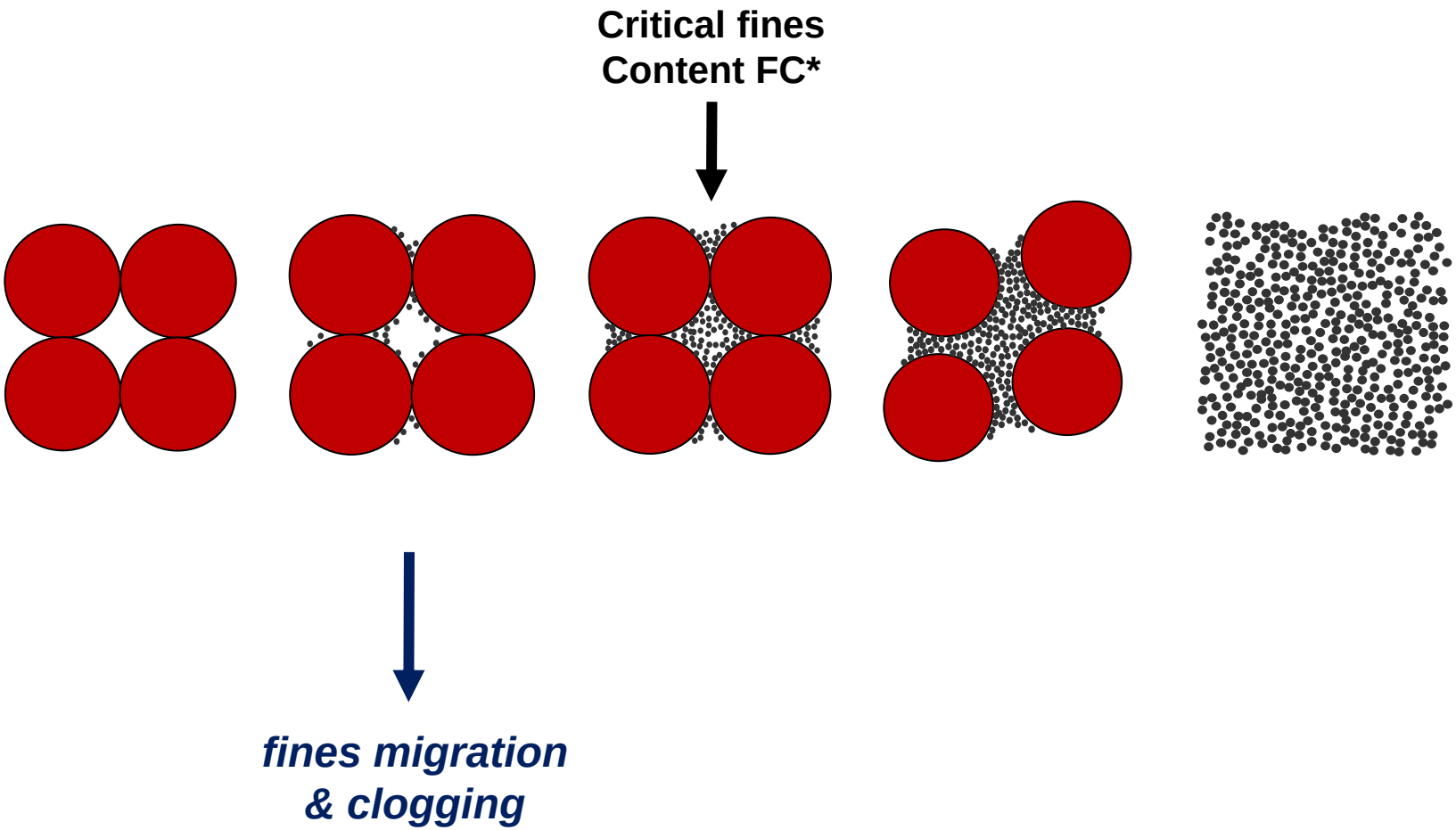
$$FC^{*} = \frac{M_{fine}}{M_{total}} = \frac{e_{coarse}}{1 + e_{coarse} + e_{fine}}$$

Critical Fines Content

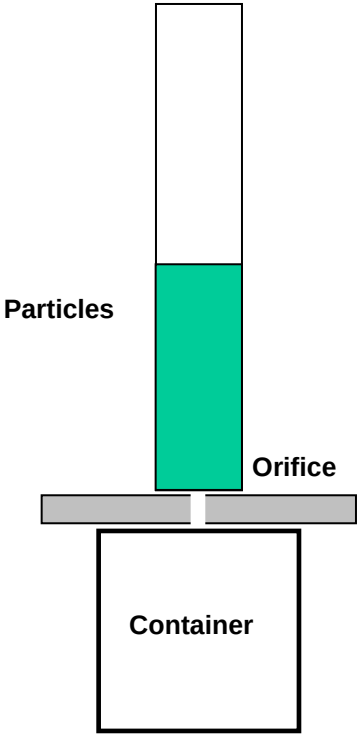


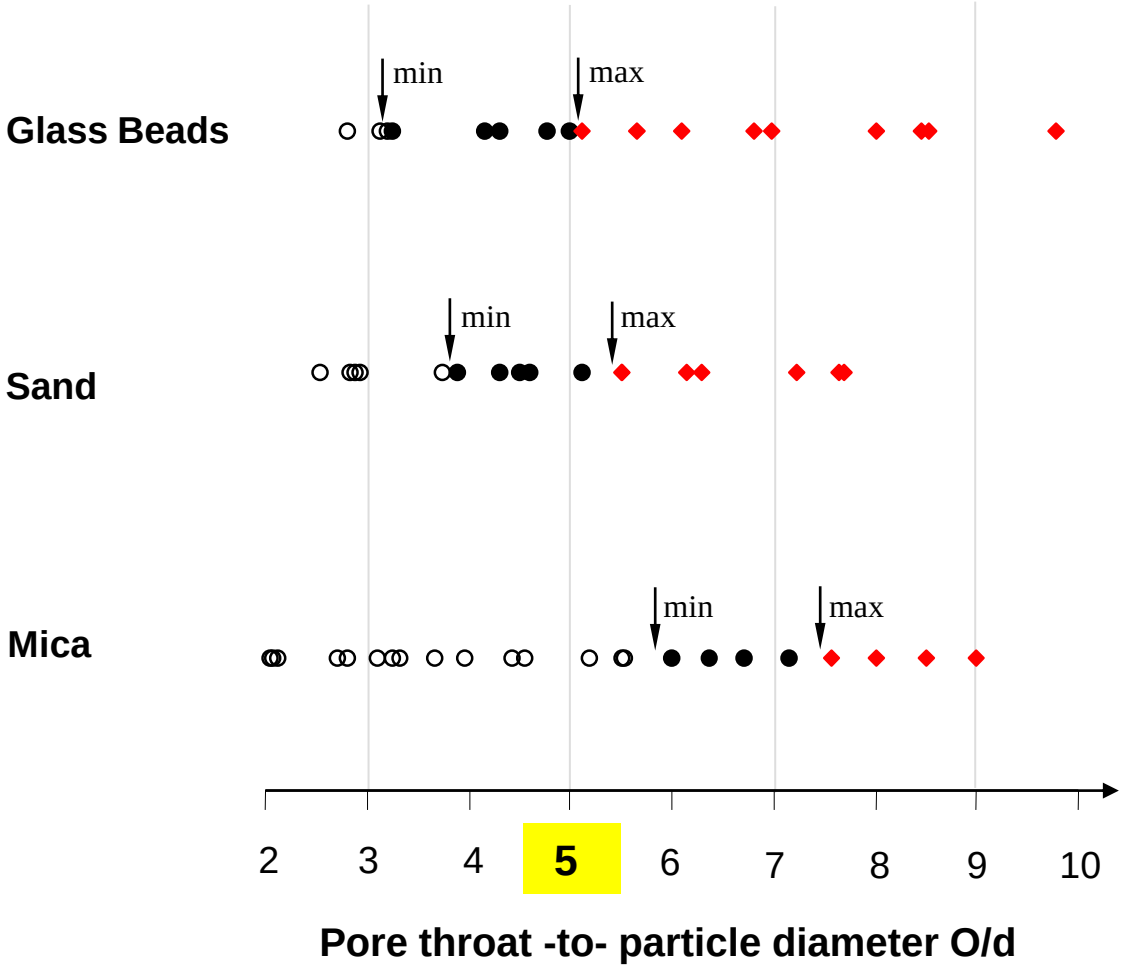


Fines Migration and Clogging

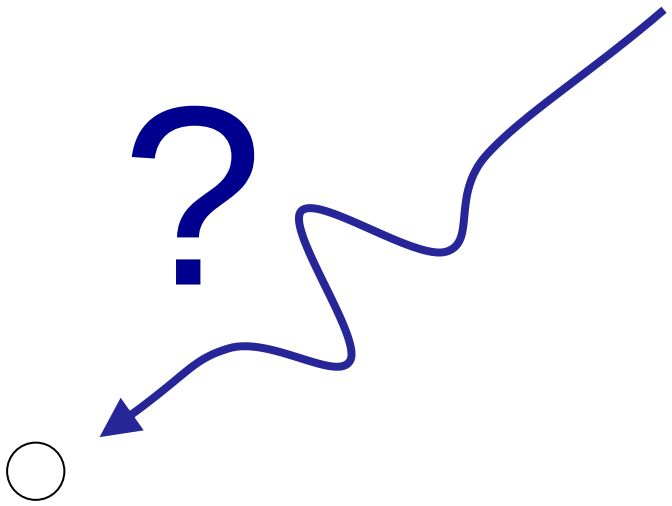


Bridges at Pore Throats



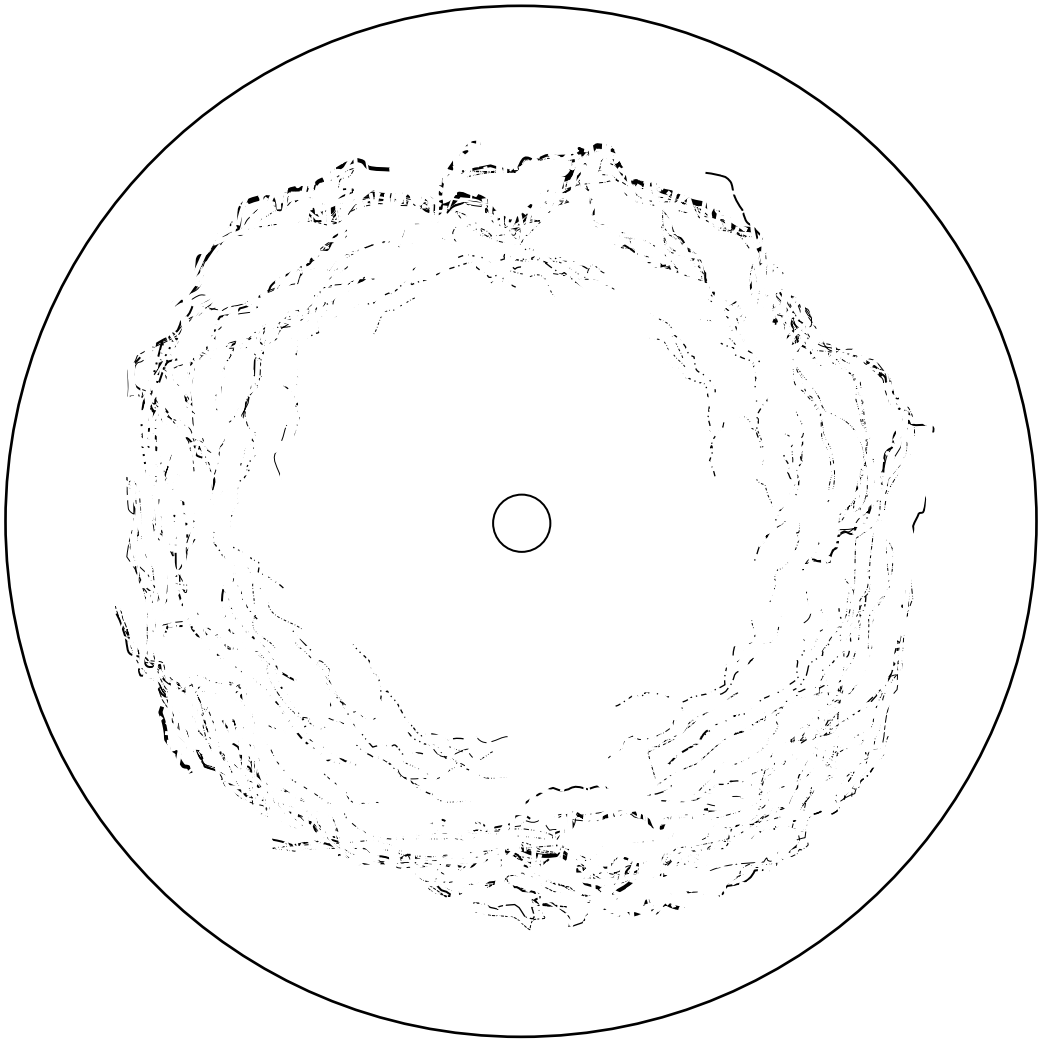


Clogging in radial flow

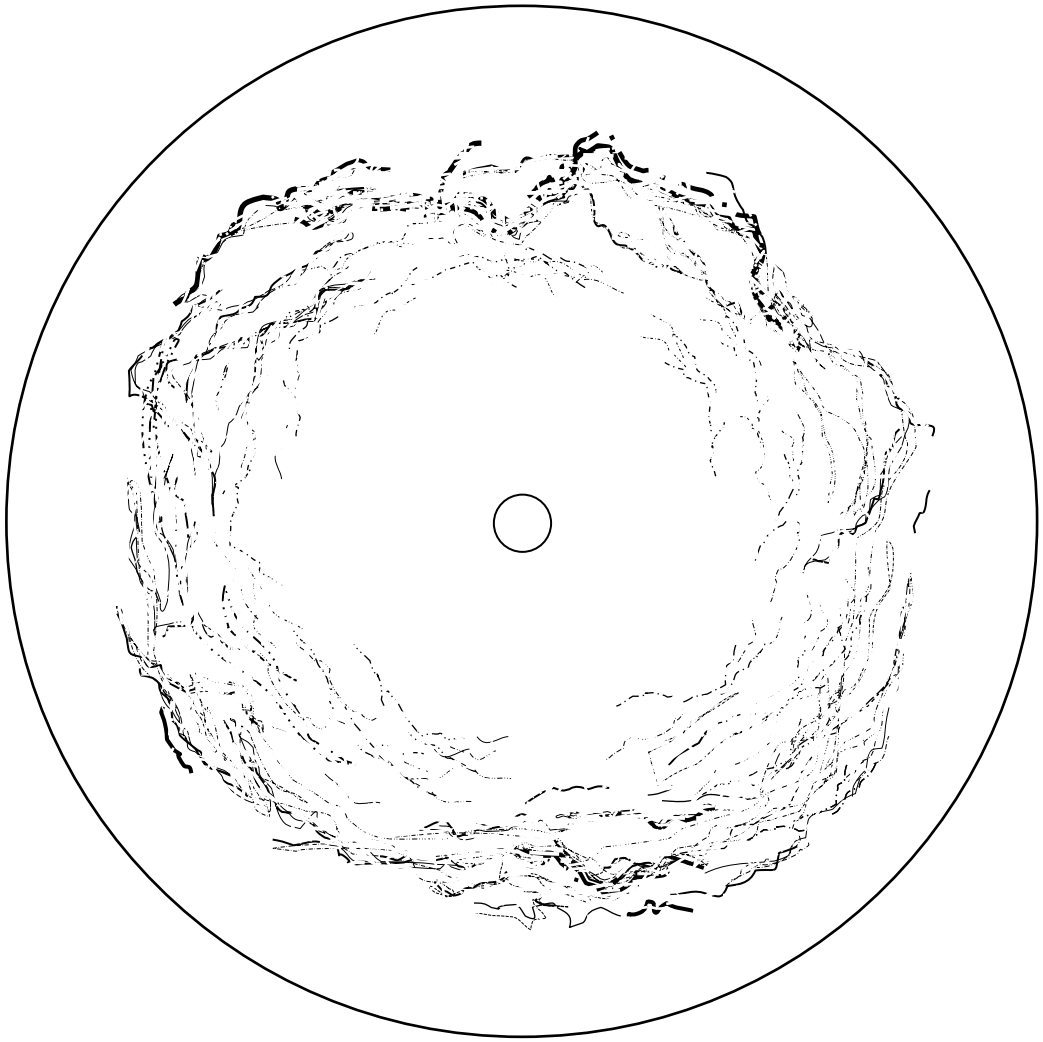


http://pmrl.ce.gatech.edu/papers/Valdes_2008c.pdf
http://pmrl.ce.gatech.edu/papers/Valdes_2008c.pdf
http://pmrl.ce.gatech.edu/papers/Valdes_2006b.pdf
http://pmrl.ce.gatech.edu/papers/Valdes_2006b.pdf

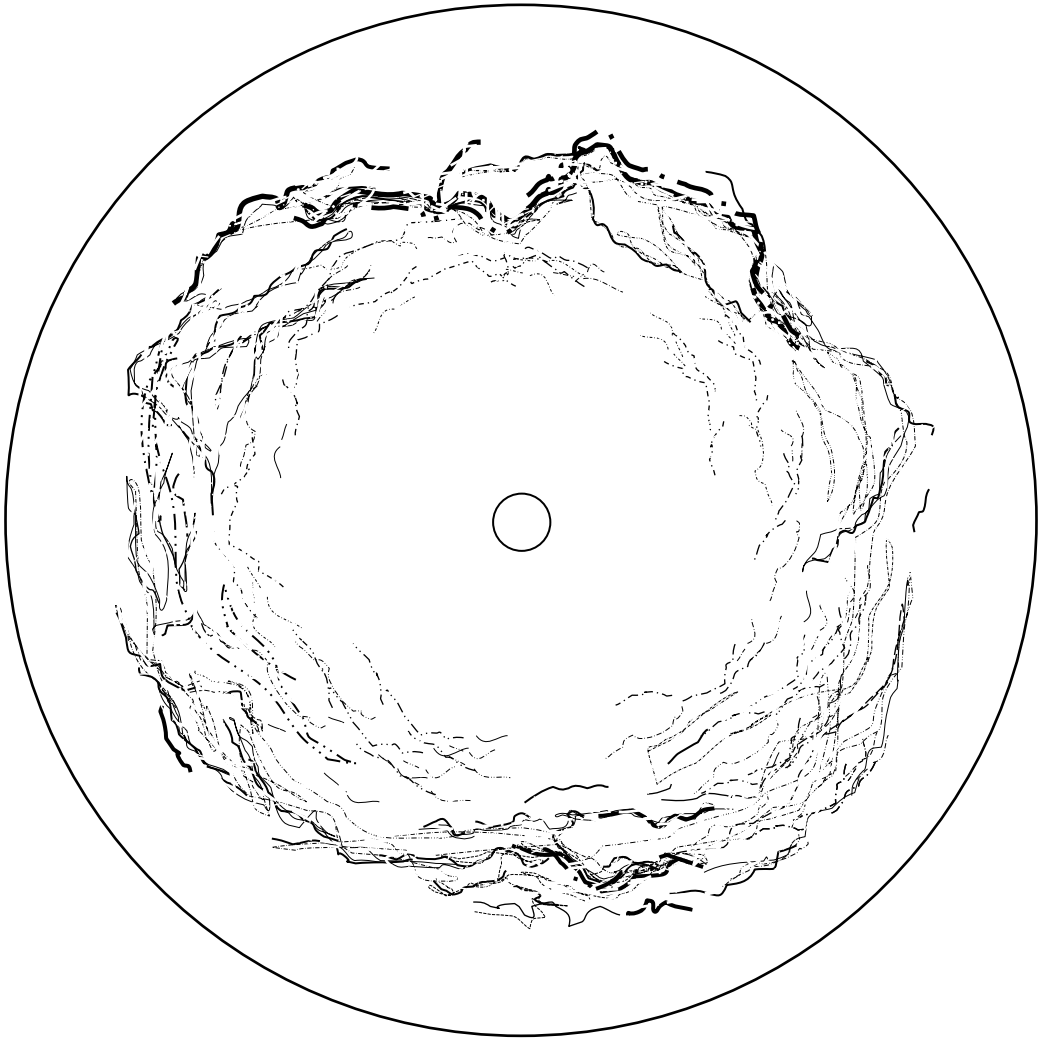
Clogging in radial flow



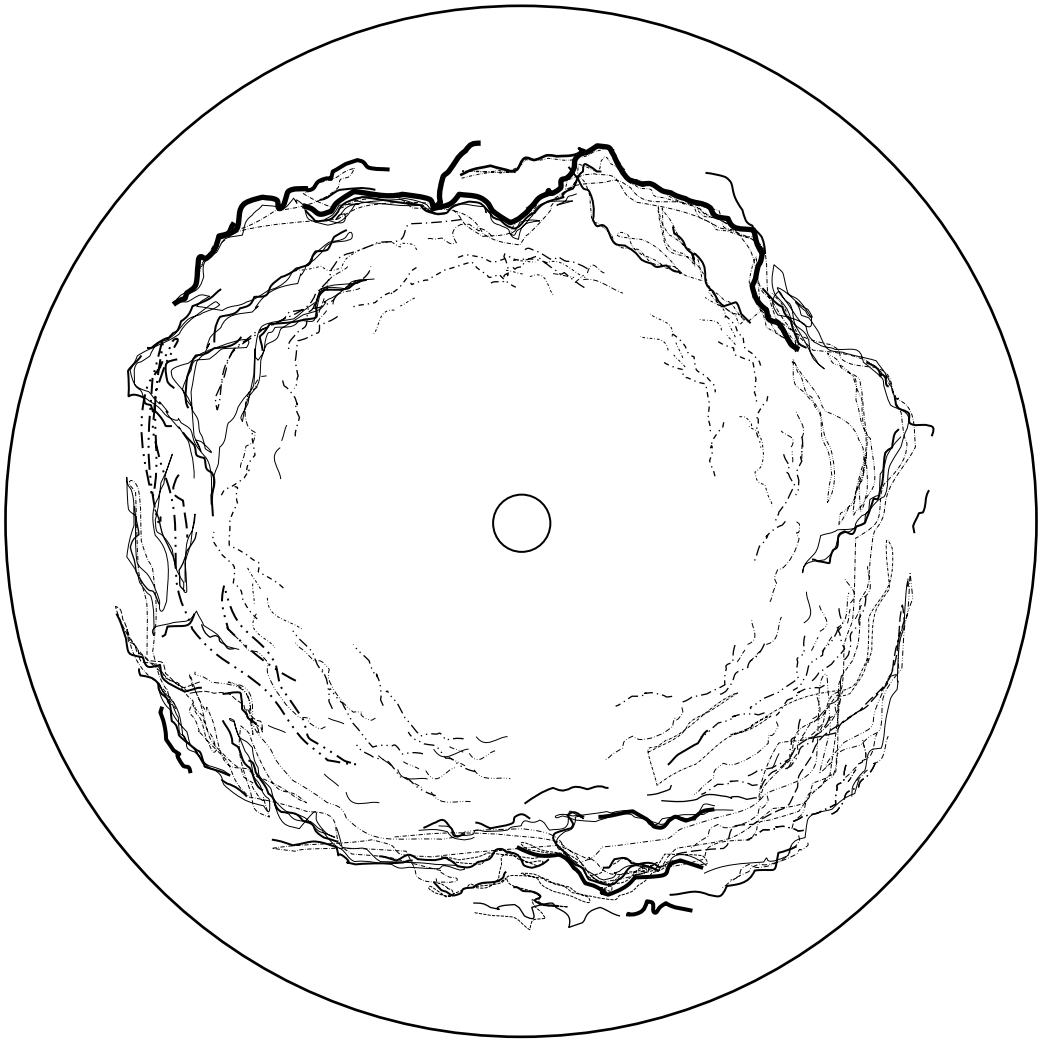
Clogging in radial flow



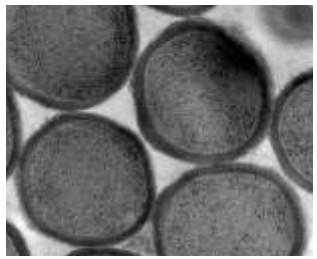
Clogging in radial flow

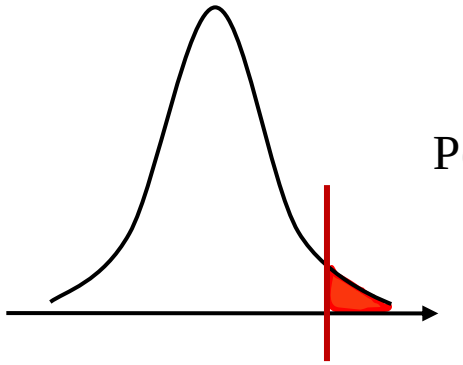


Clogging in radial flow

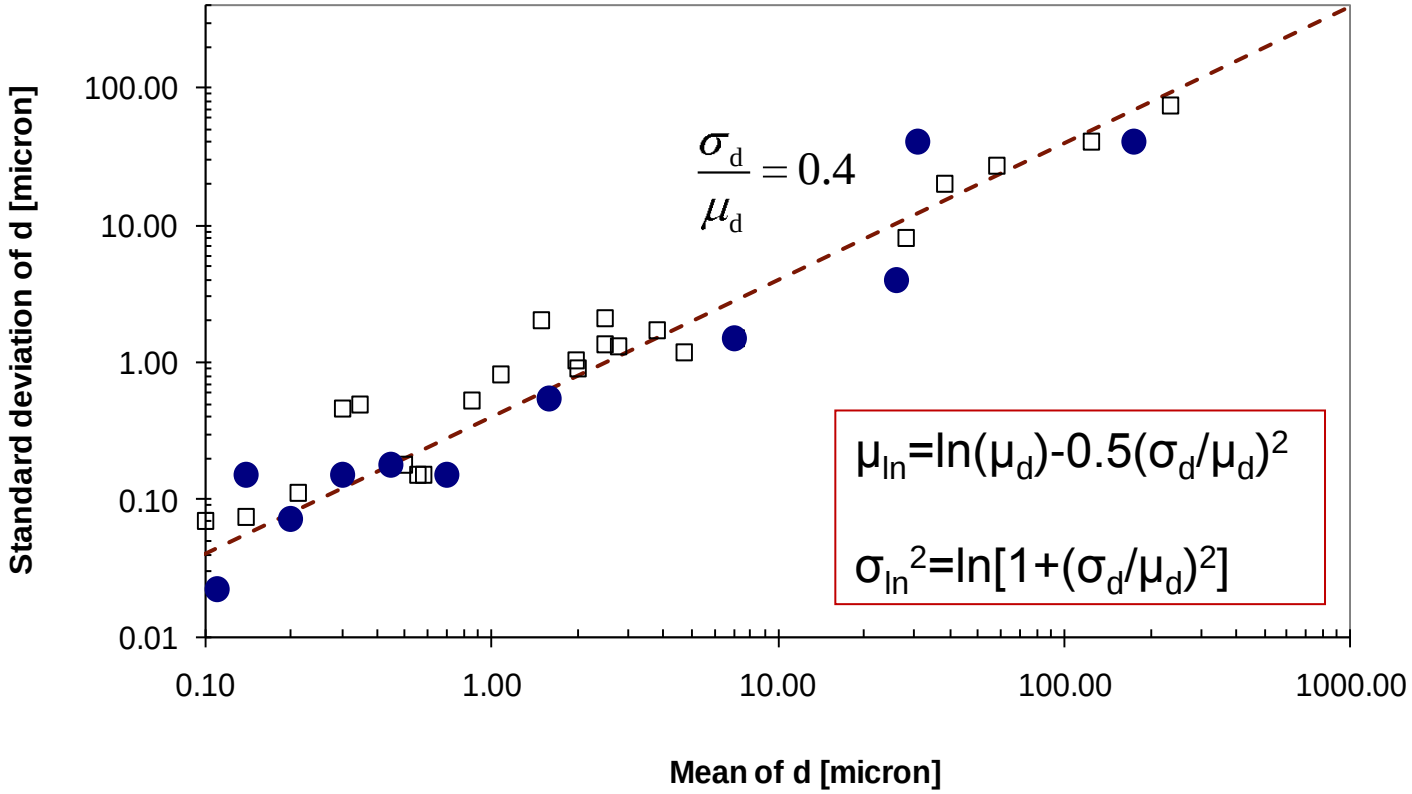


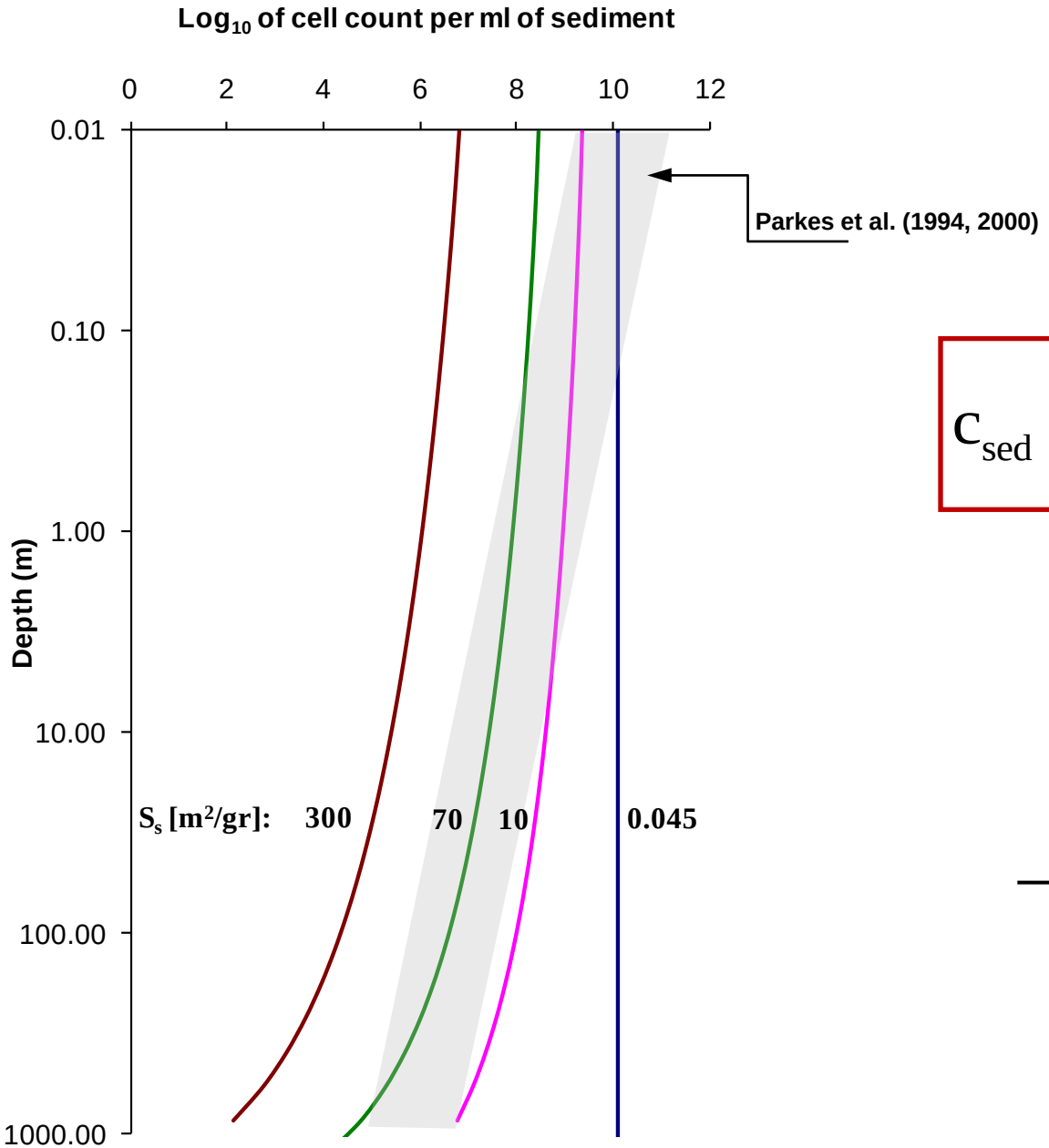
Bioactivity - Probabilistic



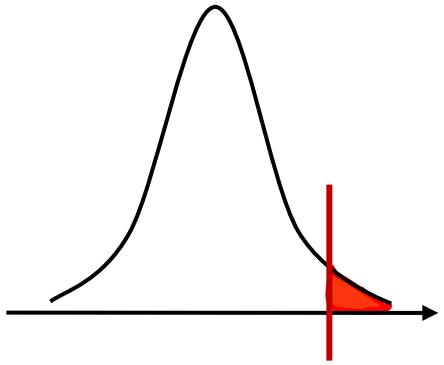


$$P(d \geq b) \cong \int_{\ln(b)}^{\infty} \exp\left\{-\left[\frac{2.5}{4}\ln\left(\frac{d}{\mu_d}\right)+0.05\right]^2\right\} dd$$



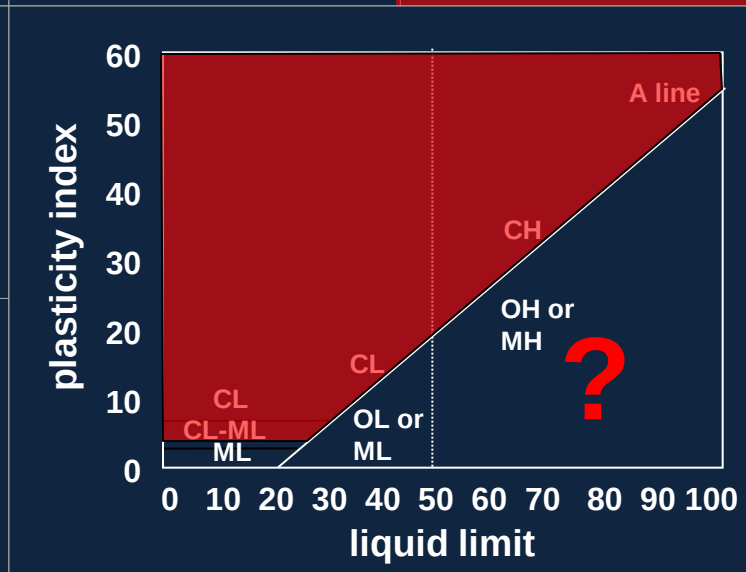


$$c_{sed} = c_{fl} \cdot n \cdot P(d \geq b)$$



$P(d_{pore}>b)$

http://pmrl.ce.gatech.edu/papers/Rebata-Landa_2006b.pdf

COARSE > 50% retained sieve #200	Gravel: > 50% retained sieve #4	< 5% fines	$C_u>4,\ 1\le C_c\le 3$	GW
			else …	GP
		> 12% fines	Below 'A' line	GM
			Above 'A' line	GC
	Sand: < 50% retained sieve #4	< 5% fines	$C_u>6,\ 1\le C_c\le 3$	SW
			else …	SP
		> 12% fines	Below 'A' line	SM
			Above 'A' line	SC
FINE < 50% retained sieve #200	LL<50			ML CL OL
	LL>50			MH CH OH

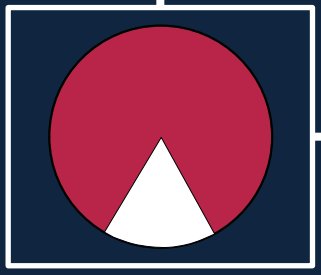
Energy Geotech

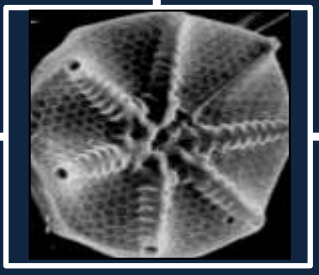
Geo-Chemistry

Frozen Ground

Unsat. Soil Mechanics

Ground Thaw

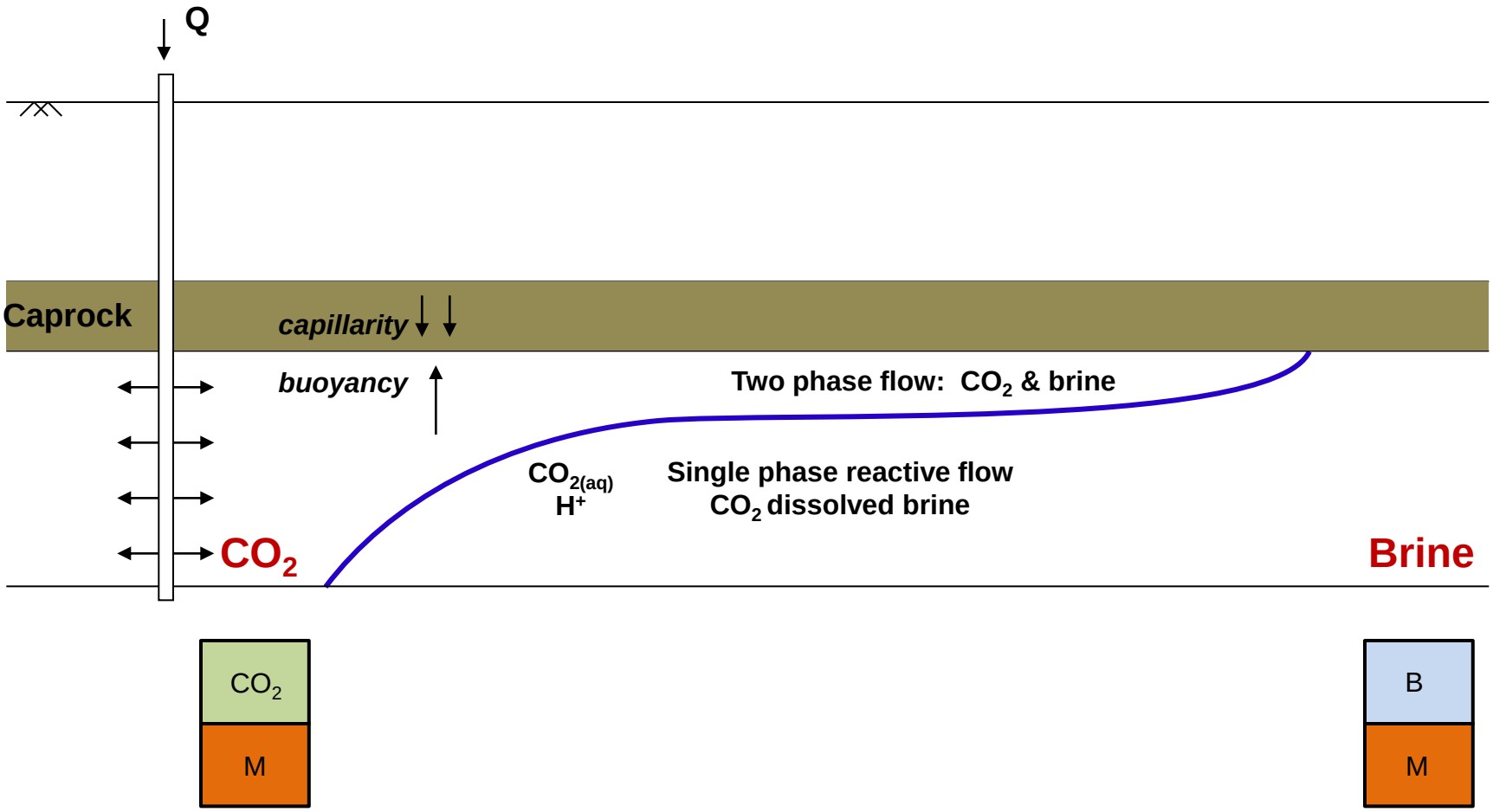




Fractures

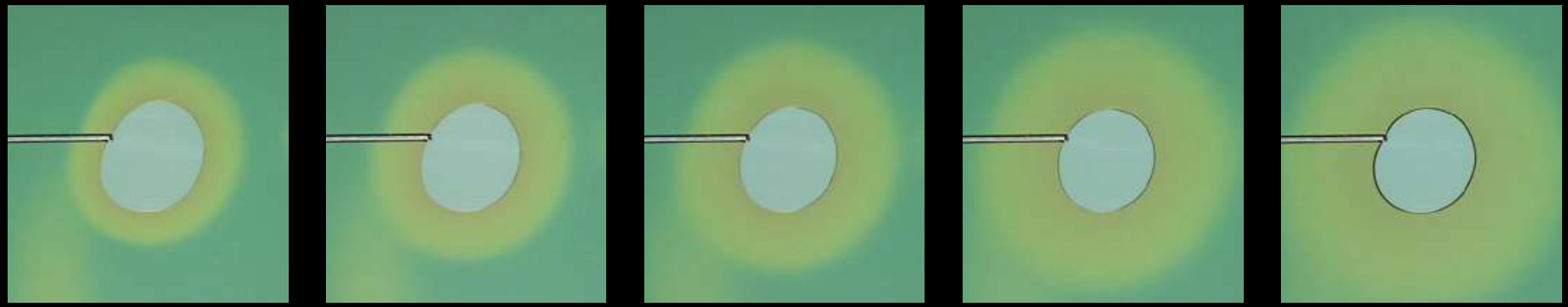
Efficiency & Conserve

CO_2 Storage



http://pmrl.ce.gatech.edu/papers/Espinoza_2011a.pdf
http://pmrl.ce.gatech.edu/papers/Espinoza_2012a.pdf
Kim and JCS – Several publications – Contact authors

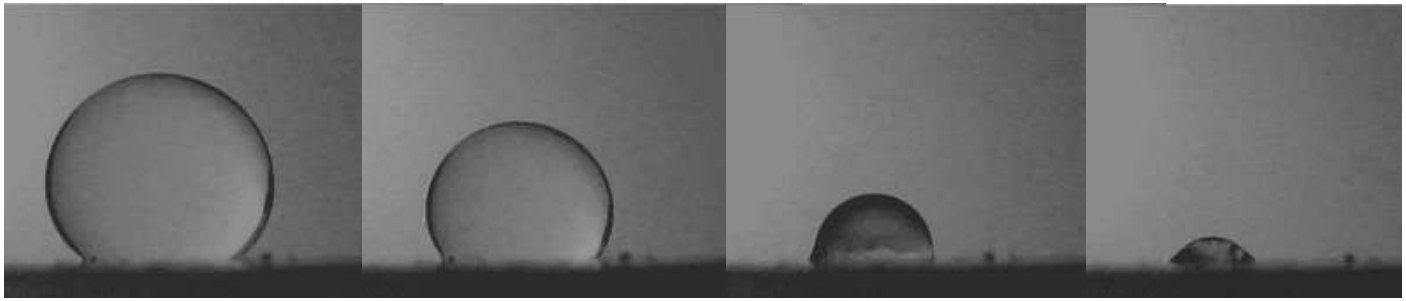
CO_2 Dissolution and H_2O Acidification



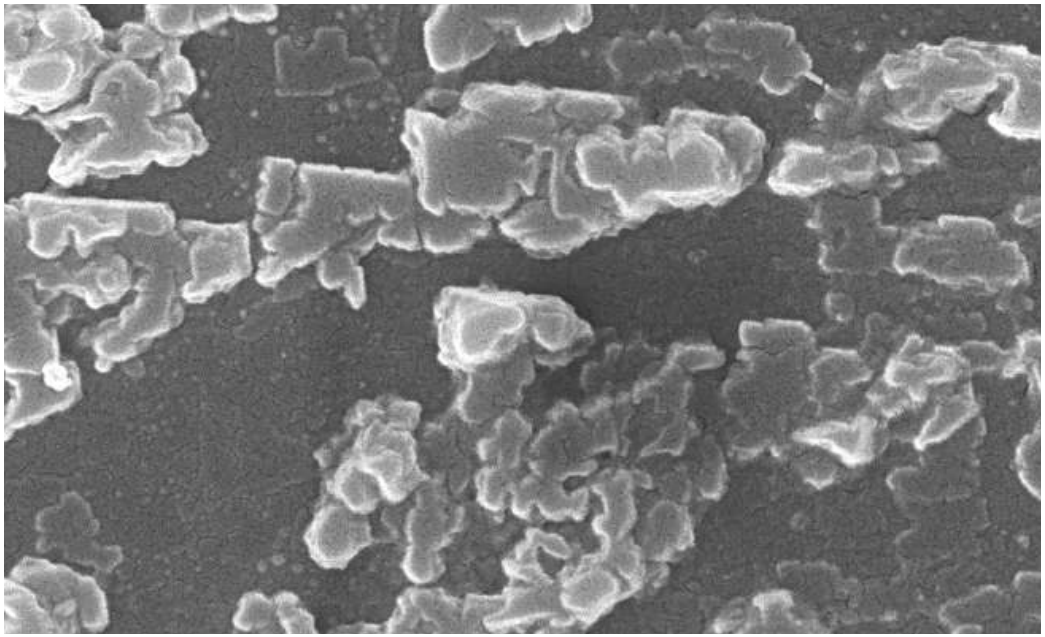
http://pmrl.ce.gatech.edu/papers/Santamarina_2012b.pdf

Water in CO_2

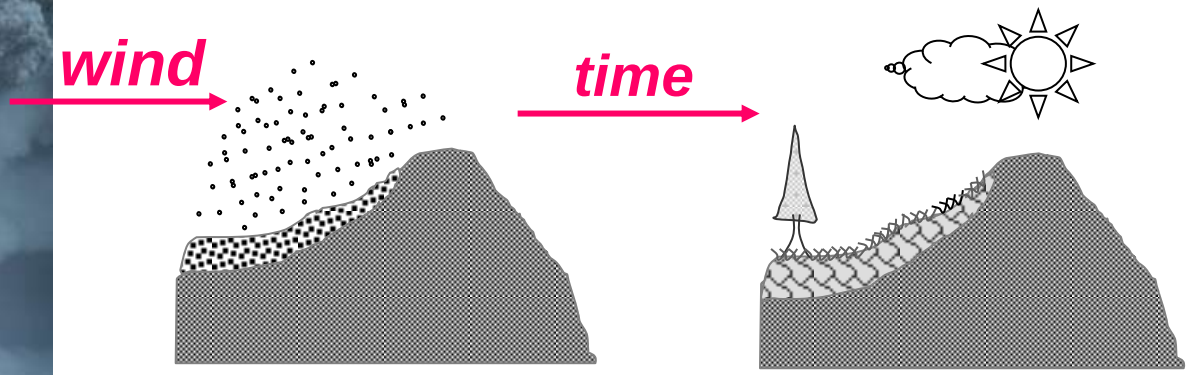
acidification ➔ dissolution ➔ drying ➔ precipitation



Calcite substrate



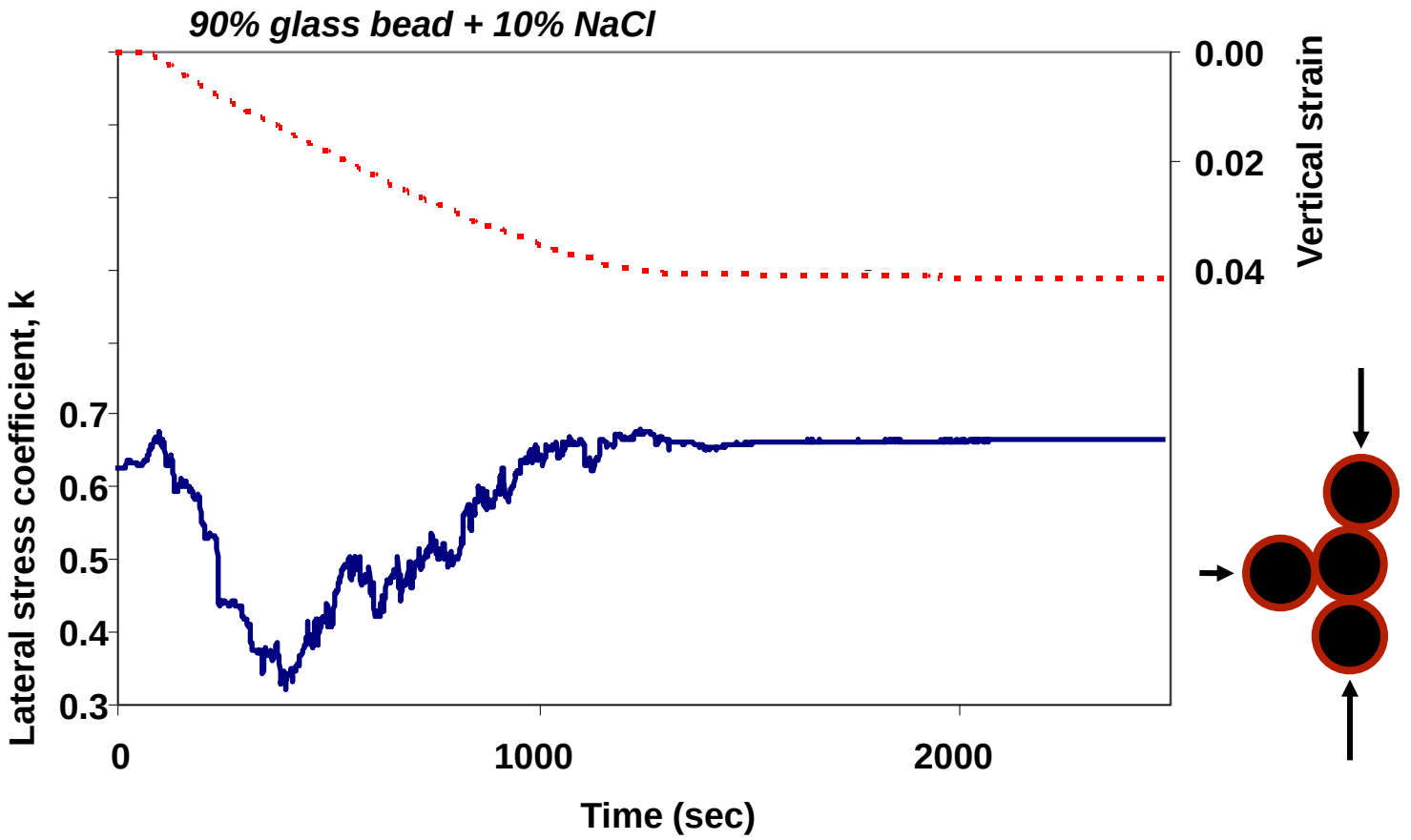
Volcanic Ash Soils: Formation



e= 0.8-1.5	e= 2.0-7.0
S_s~0.1-1 m^2/g	S_s=50-to-200 m^2/g
volcanic glass	hallosite imogolite alophane
$k_o=1-\sin\varphi$	k_o= ??

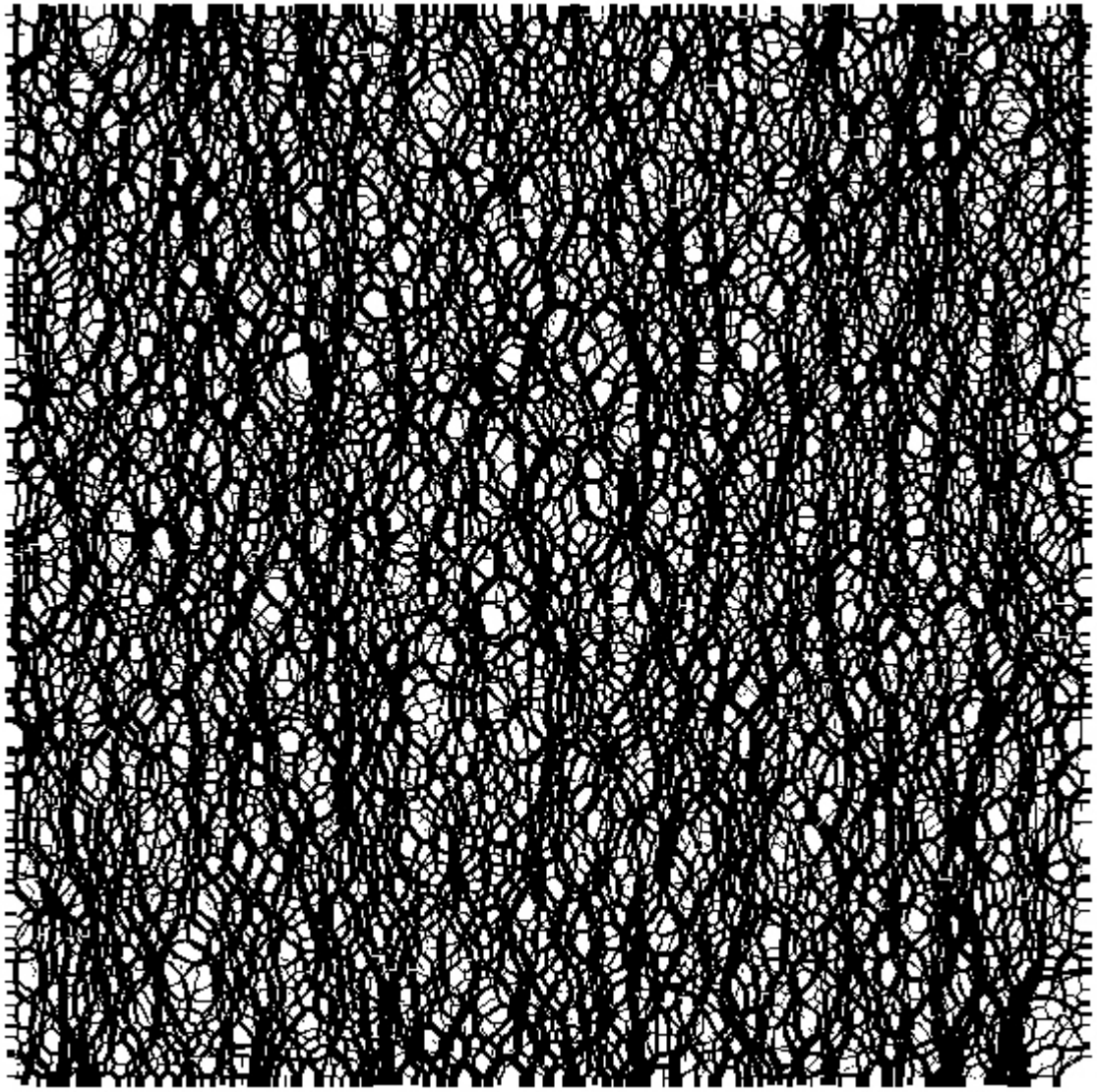
zhttp://pmrl.ce.gatech.edu/papers/Herrera_2007a.pdf

Experimental Results

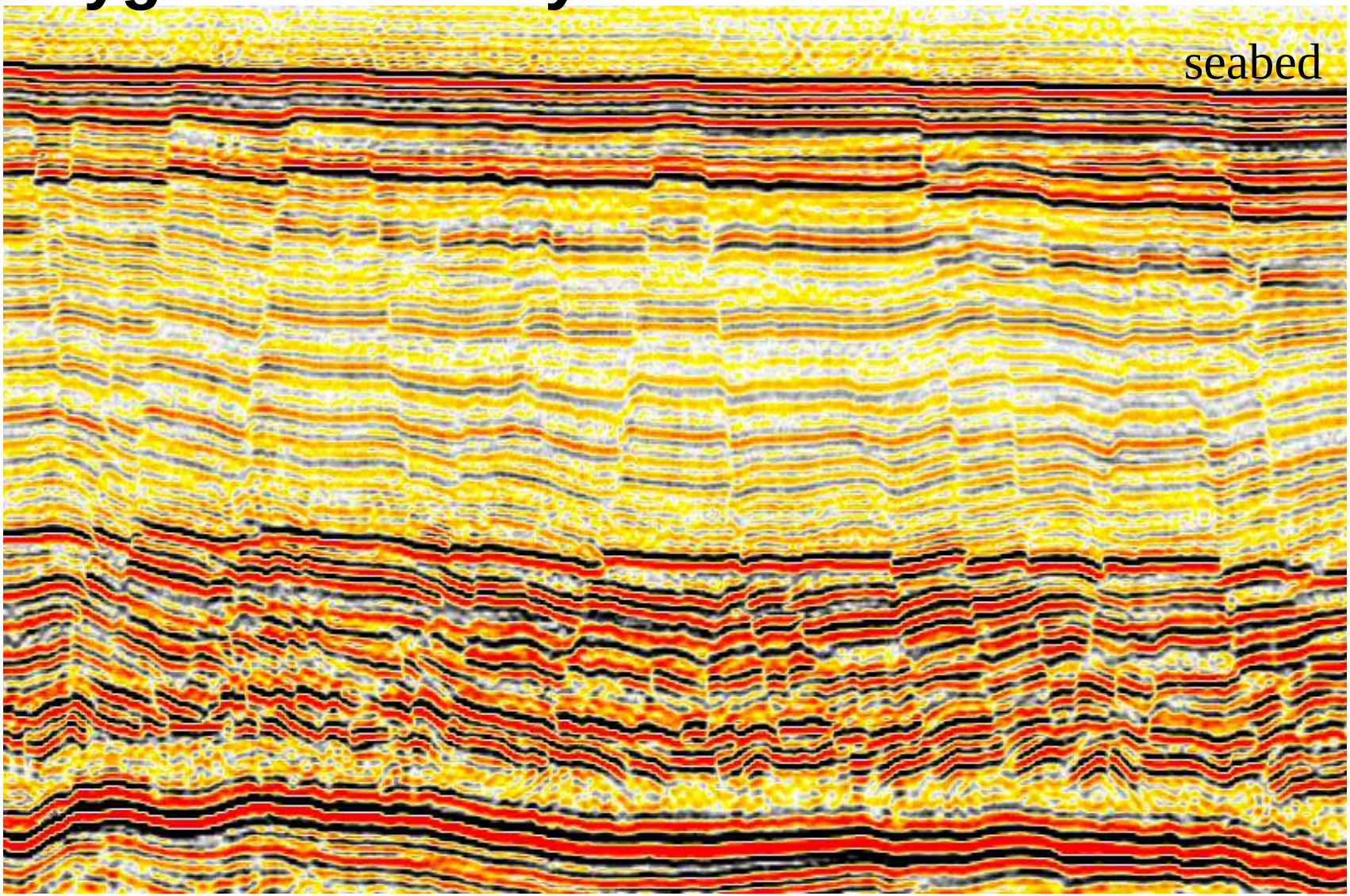


http://pmrl.ce.gatech.edu/papers/Shin_2009b.pdf
http://pmrl.ce.gatech.edu/papers/Shin_2008d.pdf

Emergent: Shear Localization



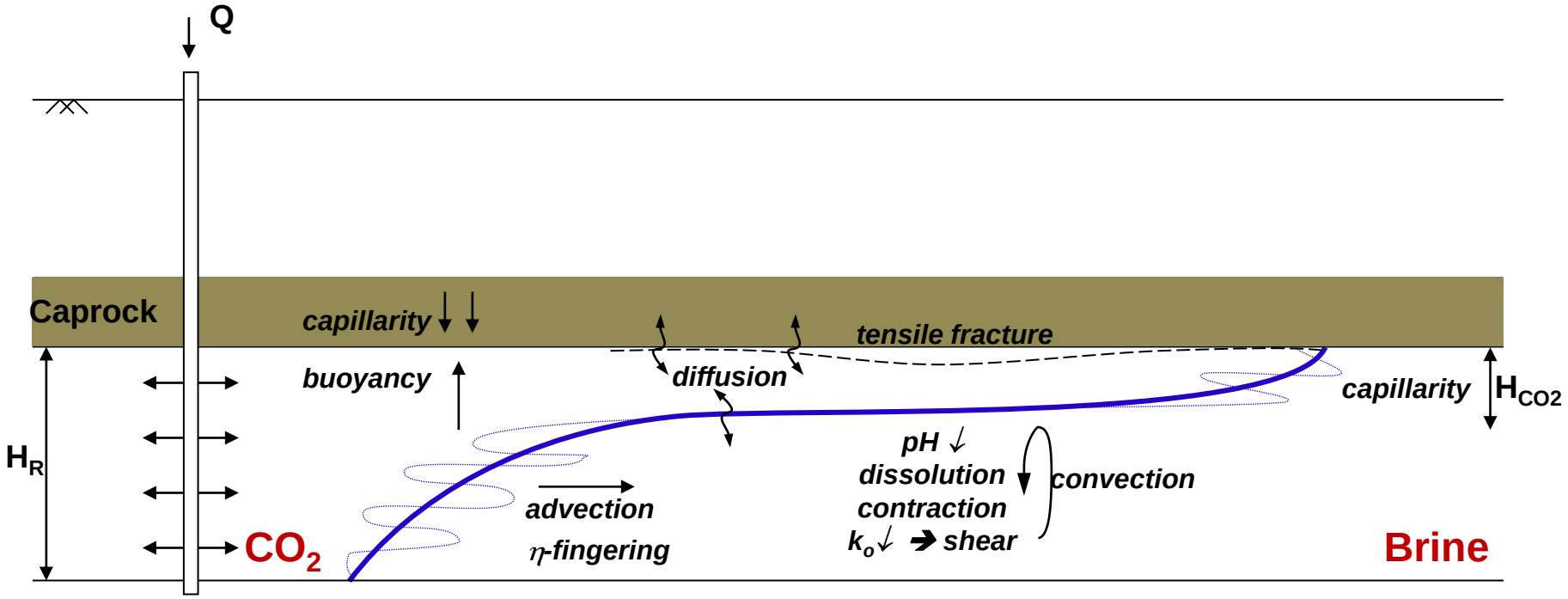
Polygonal Fault Systems



Cartwright (2005)

CO_2 Storage ?


CO2
C

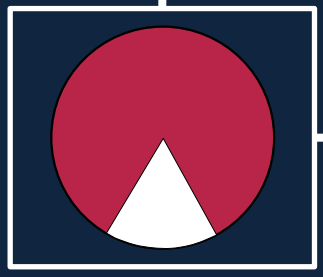

Q
Caprock
capillarity
buoyancy
tensile fracture
diffusion
capillarity
HCO2
HR
pH ↓
dissolution
contraction
convection
advection
η-fingering
ko↓ ➔ shear
CO2
Brine

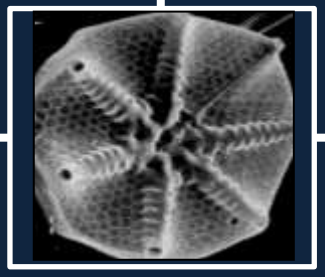
Energy Geotech

Frozen Ground

Unsat. Soil Mechanics

Ground Thaw





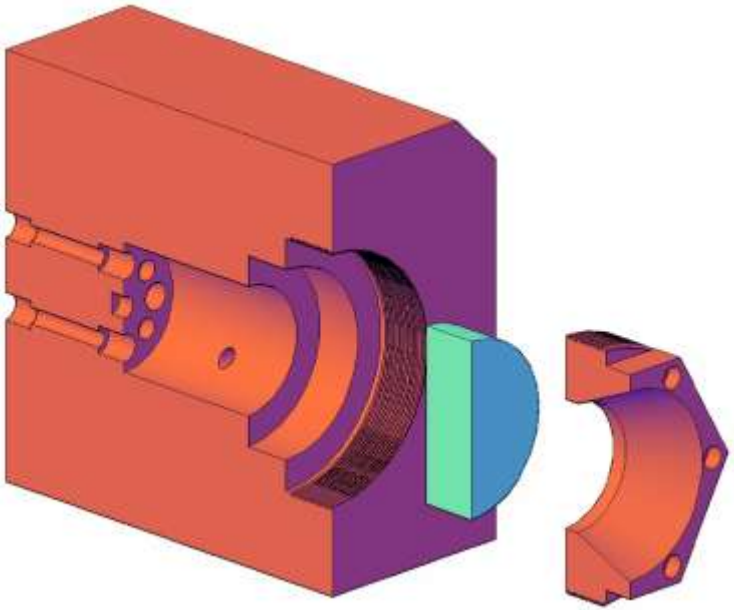
Fractures

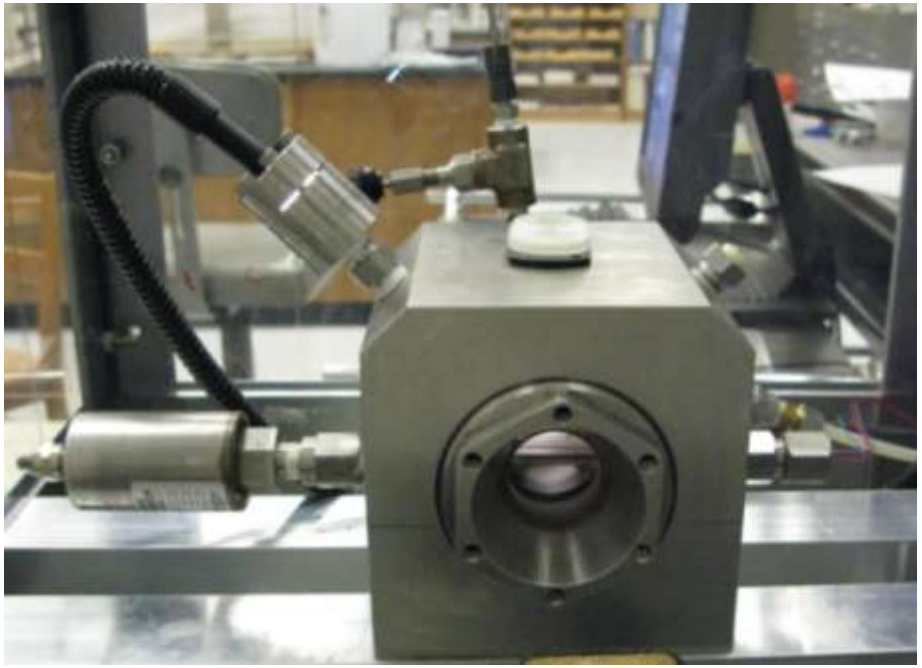
Efficiency & Conserve

Mixed Fluids

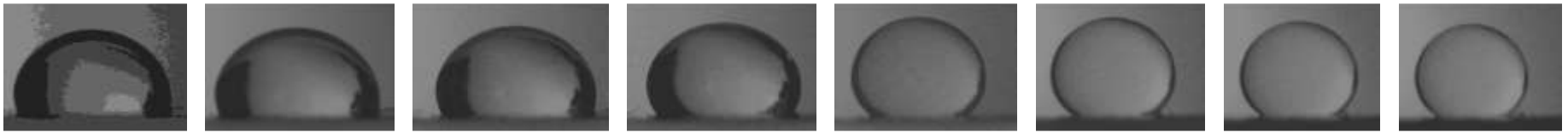
BBC News In pictures Visions of Science.jpg

Surface Tension & Contact Angle: H_2O-CO_2



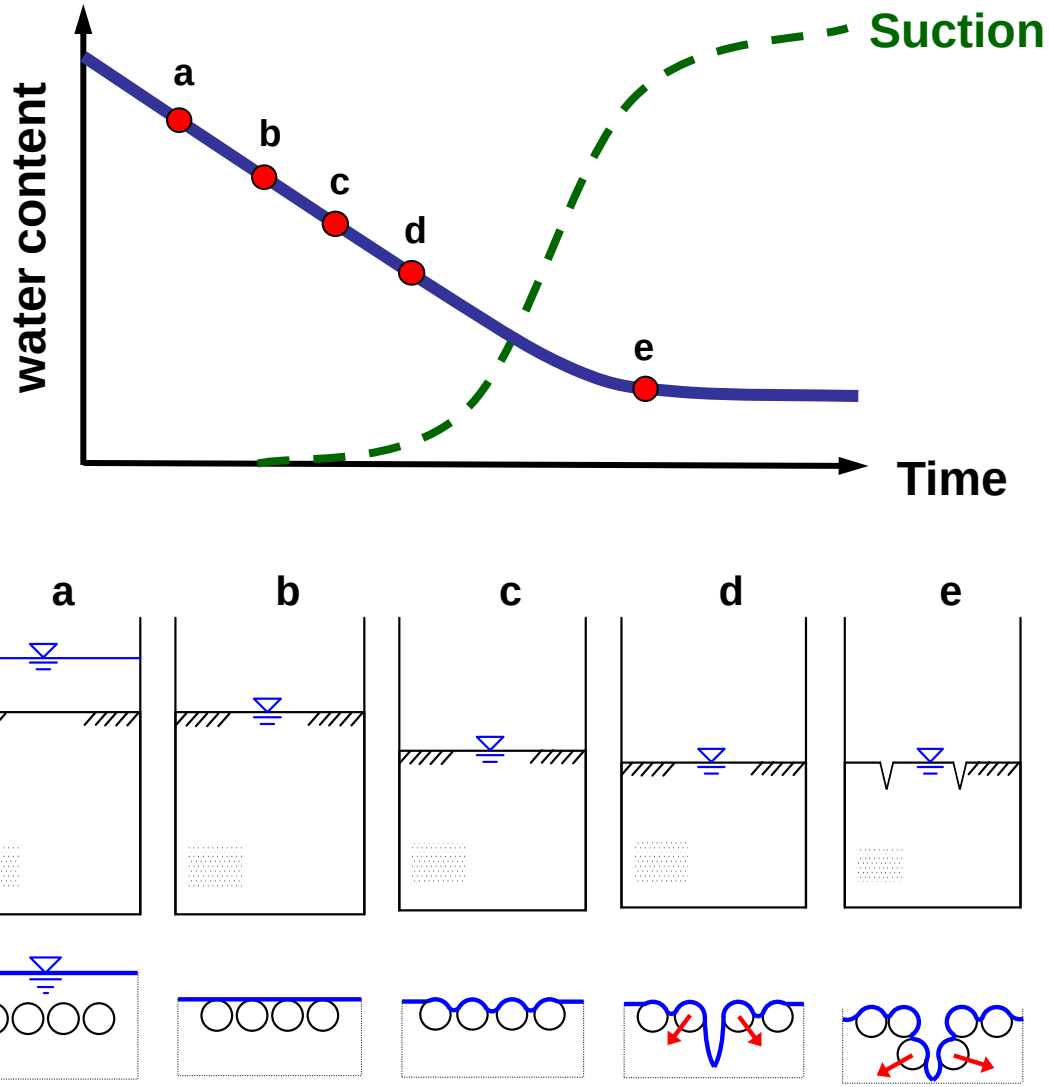


water droplet in CO2



atm ***gas*** ***liquid*** **20 MPa**

Crack initiation



http://pmrl.ce.gatech.edu/papers/Shin_2011b.pdf
http://pmrl.ce.gatech.edu/papers/Shin_2011a.pdf
http://pmrl.ce.gatech.edu/papers/Shin_2010e.pdf

Shale: structured rock

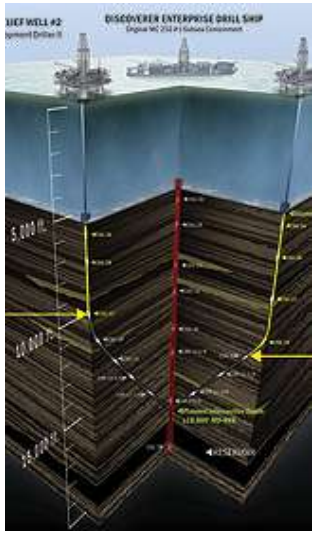
Thermogenic

$z_{history}$ > 5000 m

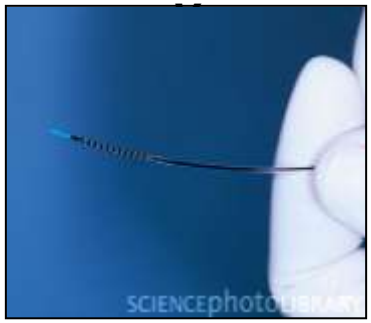
z_{today}≈ 1000-3000 m

Step 1: Drill

Directional Drilling



Catheter Angioplast



Laparoscopy

L/D= 1 **10** **100** **1,000** **10,000** **100,000**

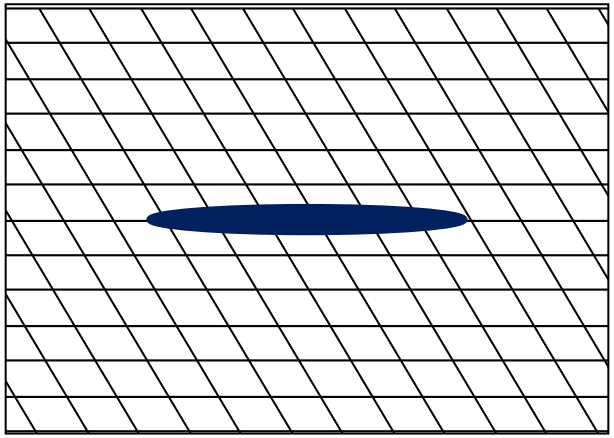
rigid tool ***within artery***

known body

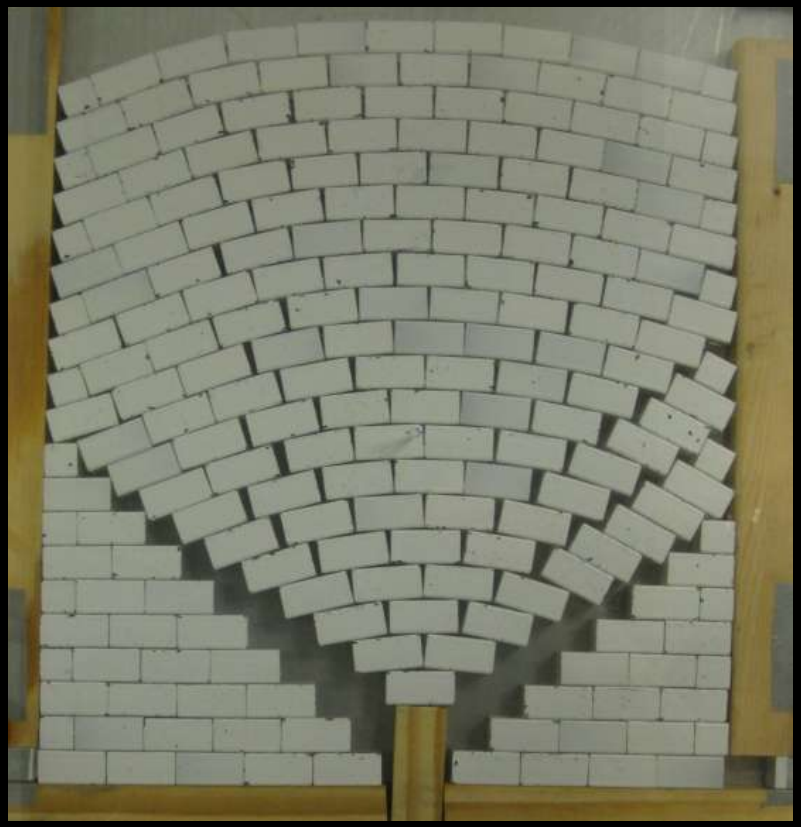
unconstrained terra incognita

Step 2: HF "fracking"

But shales…
structured rock

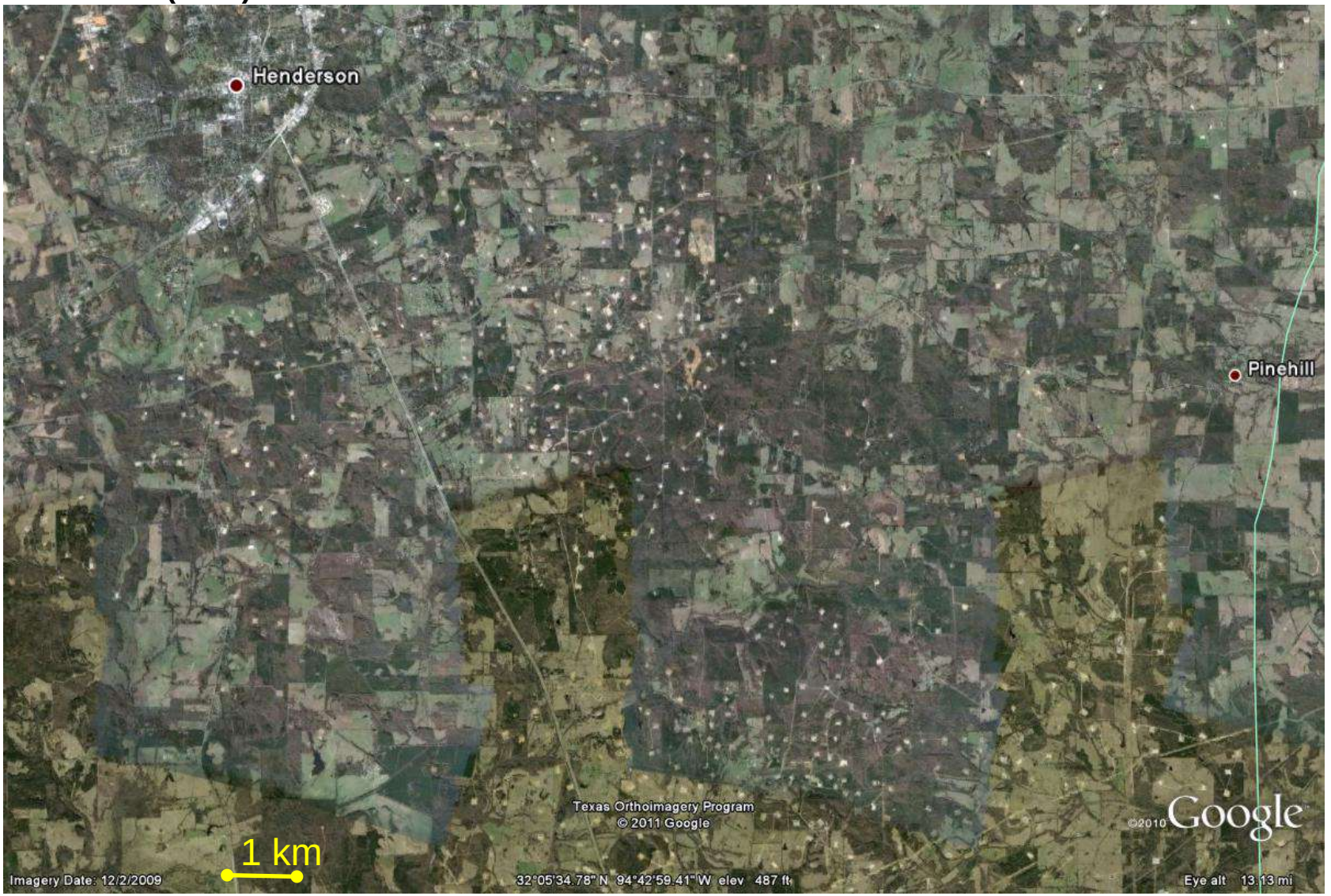


Kirsch (1898)
Griffith (1921)
Irwin (1957) ???



Pads (several wells per pad)

East Texas (2009)



Observations

Surface tension and contact angle: f(u_a)

Fracture **no tensile strength (uncemented soils)**

soil in compression *everywhere*

follows the invasion of immiscible fluid

Geo-Energy Relevance:

residual oil saturation

relative permeability (gas, petroleum)

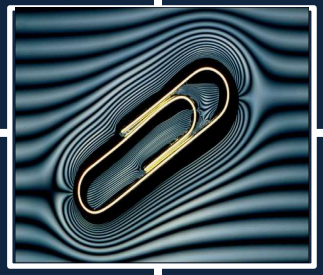
desiccation cracks in liners

gas & oil storage (CO_2 sequestration)

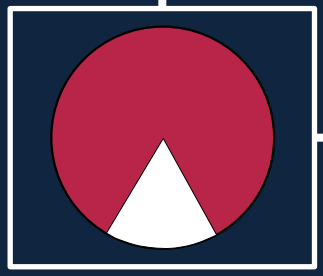
hydraulic fractures (EOR, gas recovery)

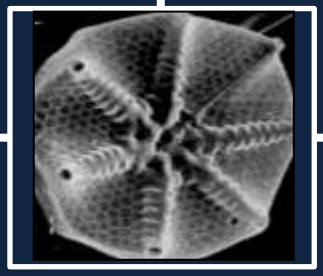
Energy Geotech

Frozen Ground

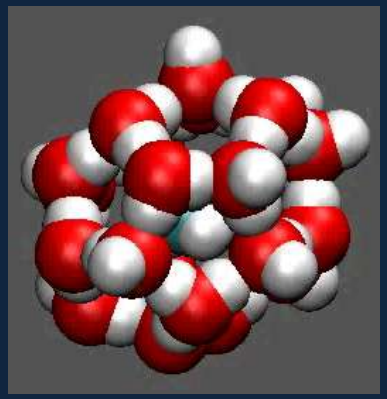


Ground Thaw





Efficiency & Conserve



Multiple articles. Please, visit http://pmrl.ce.gatech.edu ➔ go to publications ➔ then, search for "hydrate"

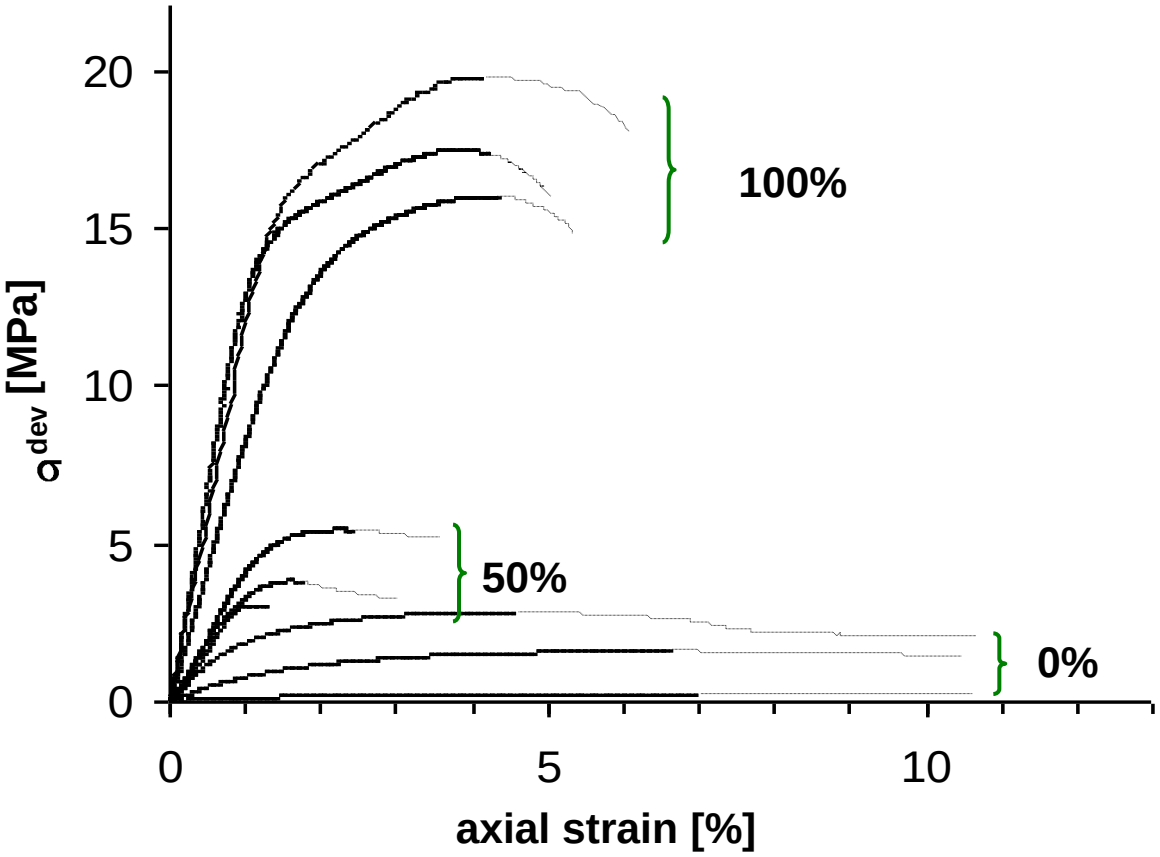
Load-Deformation

$$S_u = a\sigma'_o + bq_h \left(\frac{S_h}{n} \right)^2$$

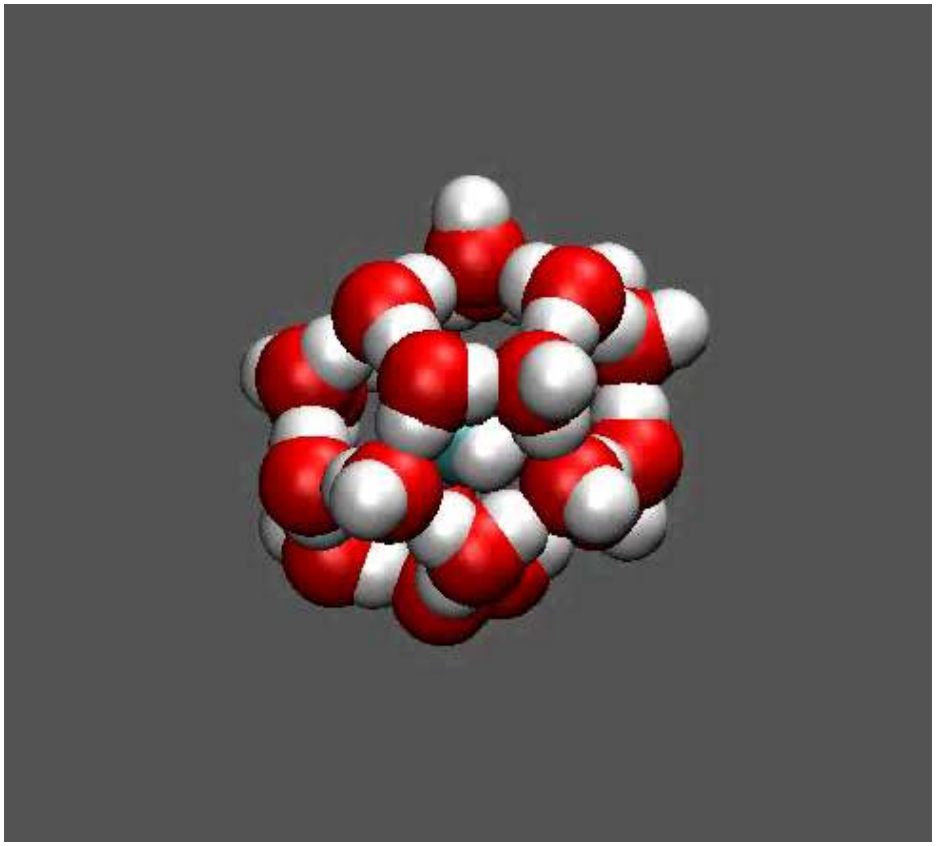
Sand | **σ'_c= 1 MPa**

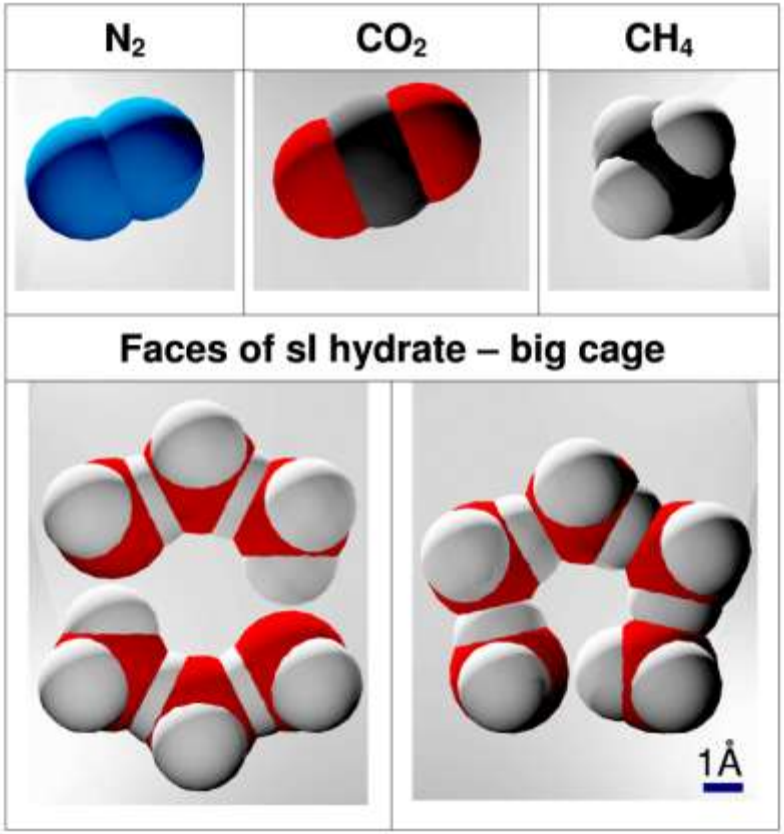
σ'_c= 0.5 MPa

THF | **σ'_c= 0.03 MPa**



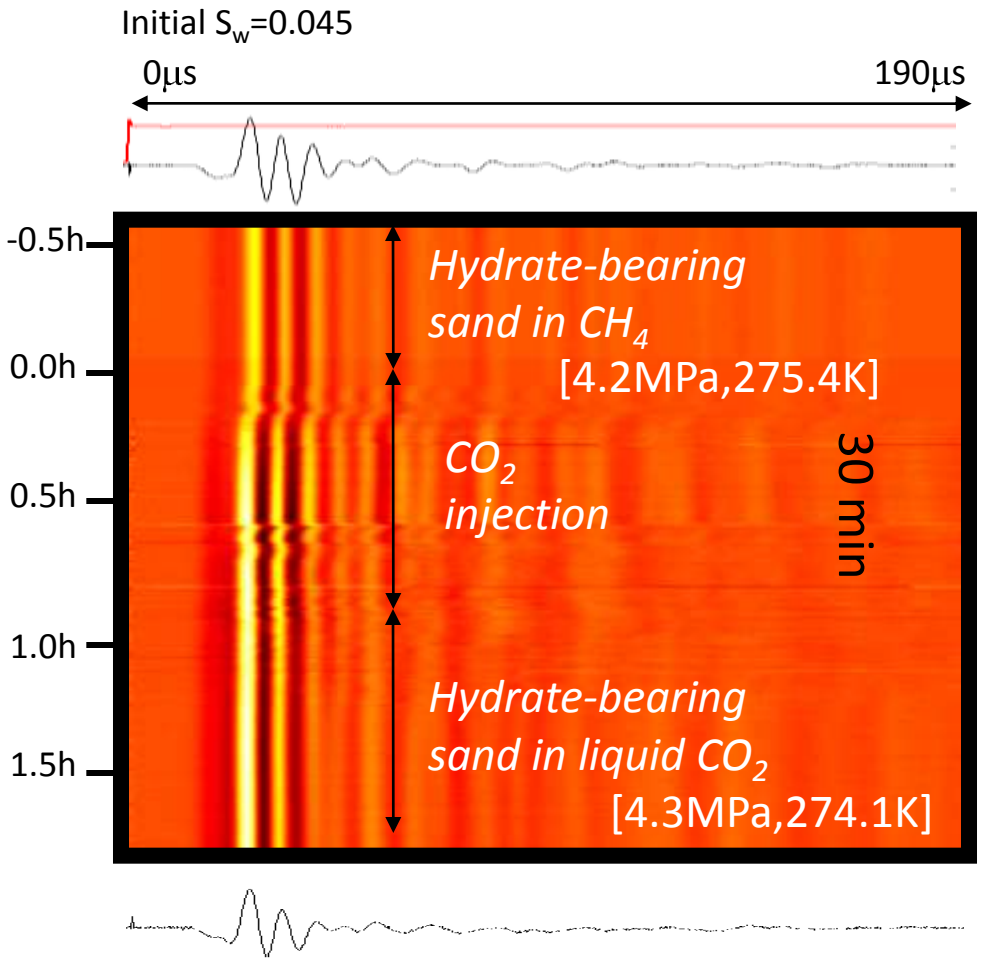
Gas replacement in hydrates





J Karl Johnson – NETL

Gas replacement in hydrates



Observations

***In situ*:** **mineral + water + hydrate**

***Production*:** **mineral + water + hydrate + gas**

Stiffness, strength, hydraulic conductivity = f(S_{hyd})

Coupled THCM

Localizations: lensing, gas-driven fractures

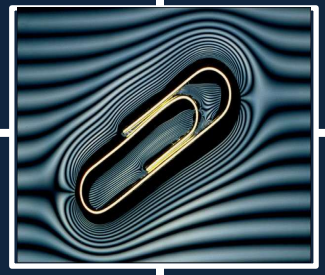
Geo-Energy Relevance:

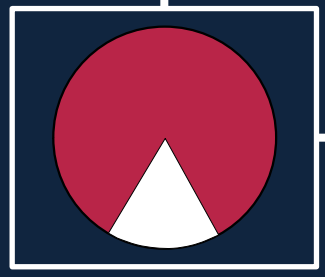
instability (boreholes, slopes, foundations)

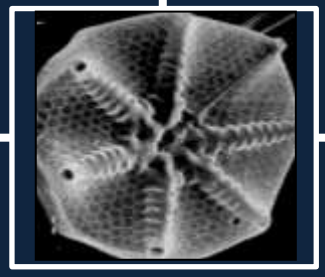
methane production

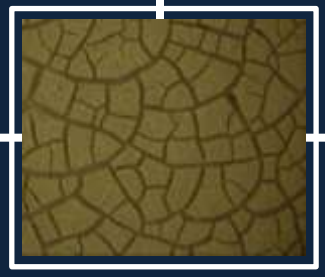
CO_2 sequestration

Energy
Geotech



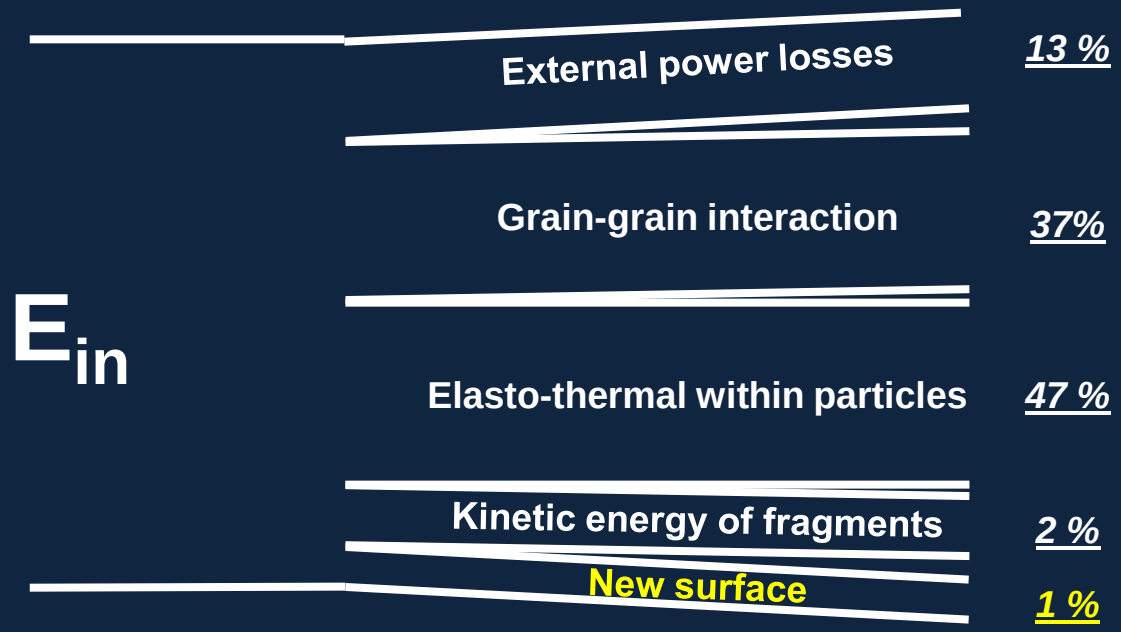






Efficiency
&
Conserve

Rock Crushing

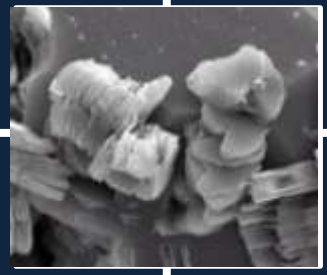


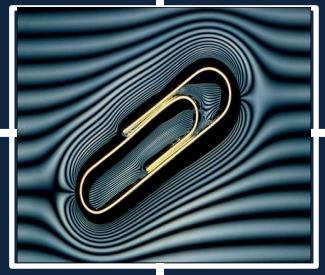
Kim and JCS – Please, contact authors.

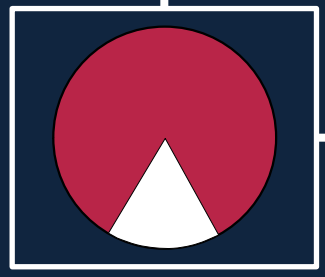
Tunneling: Ants

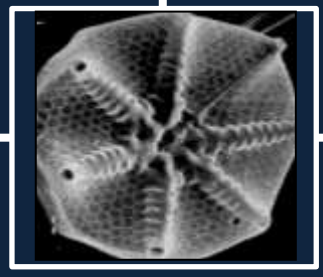
http://pmrl.ce.gatech.edu/papers/Espinoza_2010a.pdf

Energy Geotech









Energy: critical for development

high increase in demand in next decades

resources: sufficient – but inadequate spatial distribution

C-economy → global warming

efficiency and conservation (primarily: top consumers)

Further developments in geotechnology: Rich & Complex

enhanced understanding of soil behavior

coupled processes

spatial variability and emergent phenomena

discontinuities

long time ➔ many repetitions ➔ ratcheting & terminal density

Geotechnology: central role

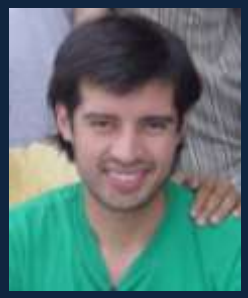
urgency …. fascinating !

Collaborators:

M.S. Cha

G Narsilio

J Valdes



C Pasten

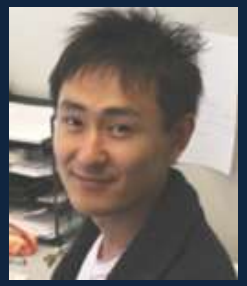
V Rebata

S. Dai

F. Francisca

T.S. Yun

J.Y. Lee



SH Kim

D. Cortes

T.H. Kwon

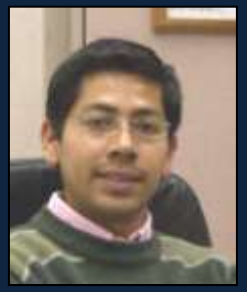
S. Roshankhah

C.H. Lee

J.W. Jung

J.W. Jang

H. Shin



N. Espinoza

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University of Birmingham

Cardiff University

Imperial College

Queen’s University Belfast

Thank you !