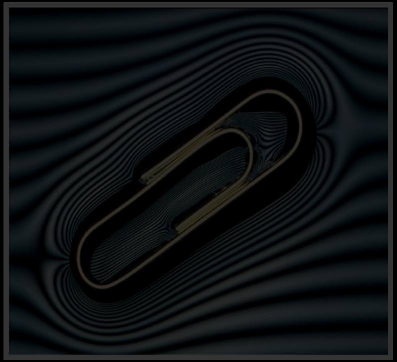
UNSAT 2010 - Barcelona

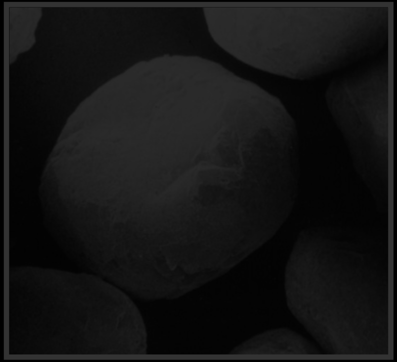
ENERGY GEOTECHNOLOGY

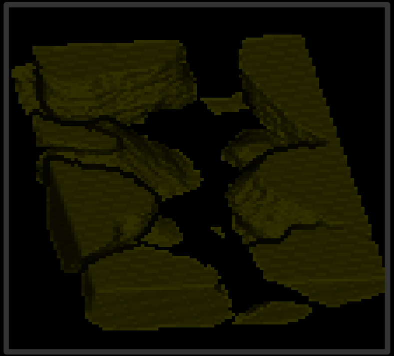
Mixed Fluid Conditions

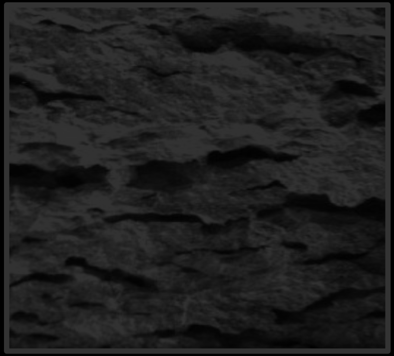
J. Carlos Santamarina and Jaewon Jang

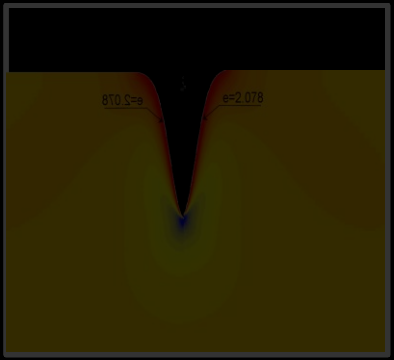
energy geotechnology

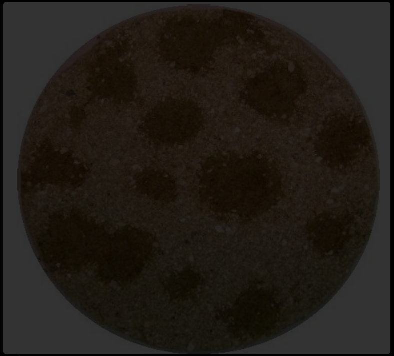








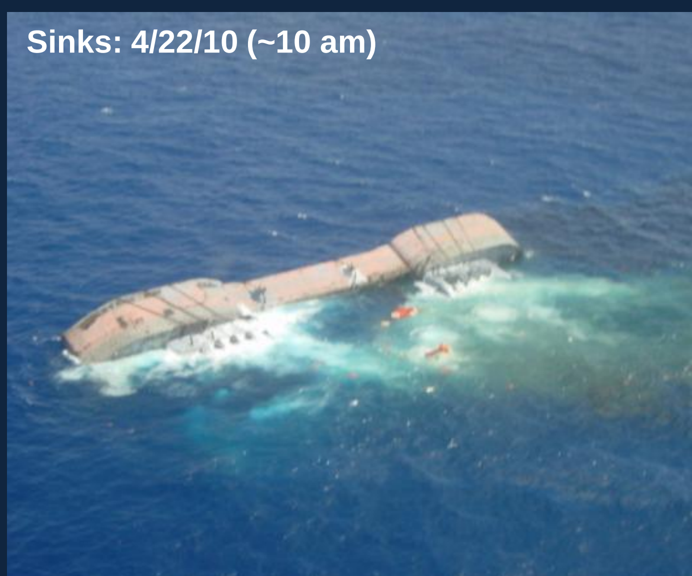




Energy in the News

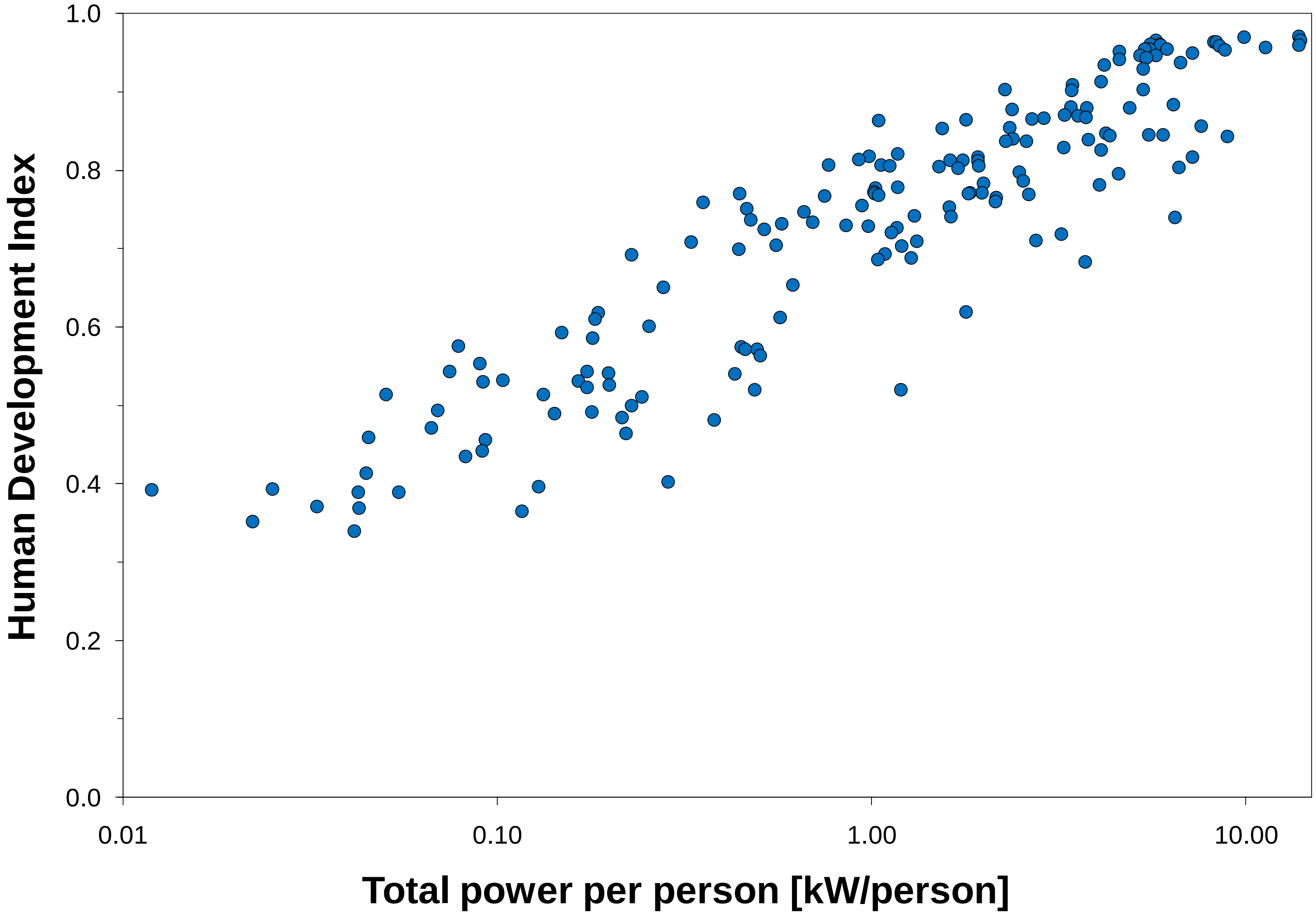

Deepwater Horizon


Explosion: 4/20/10 (@10 pm)


Sinks: 4/22/10 (~10 am)

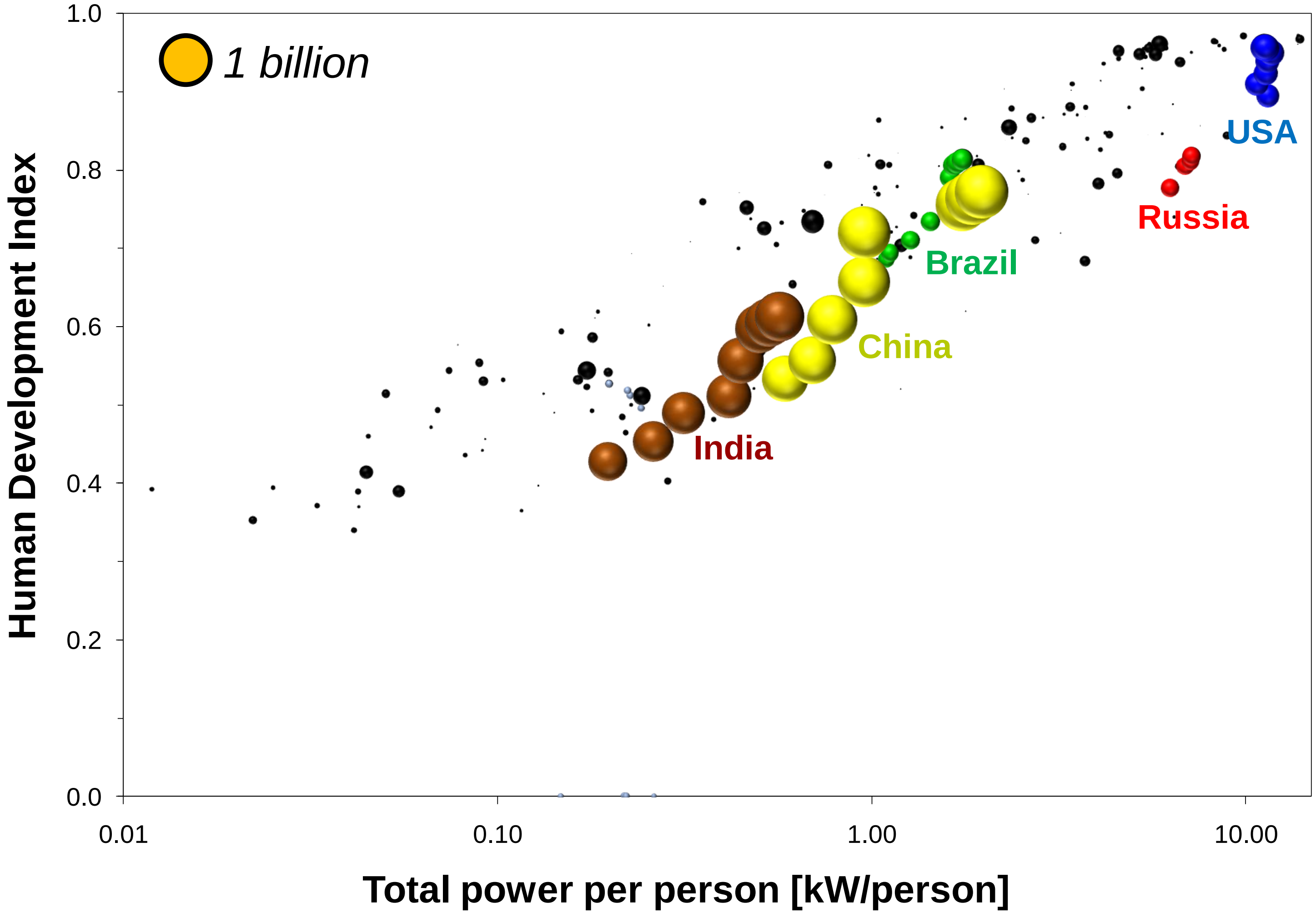
Oil slick: 5/6/10

Energy and Life (Global: 2008)



CIA, UN, EIA

Energy and Life (Global: 2008 – BRIC trends: 1980-2007)

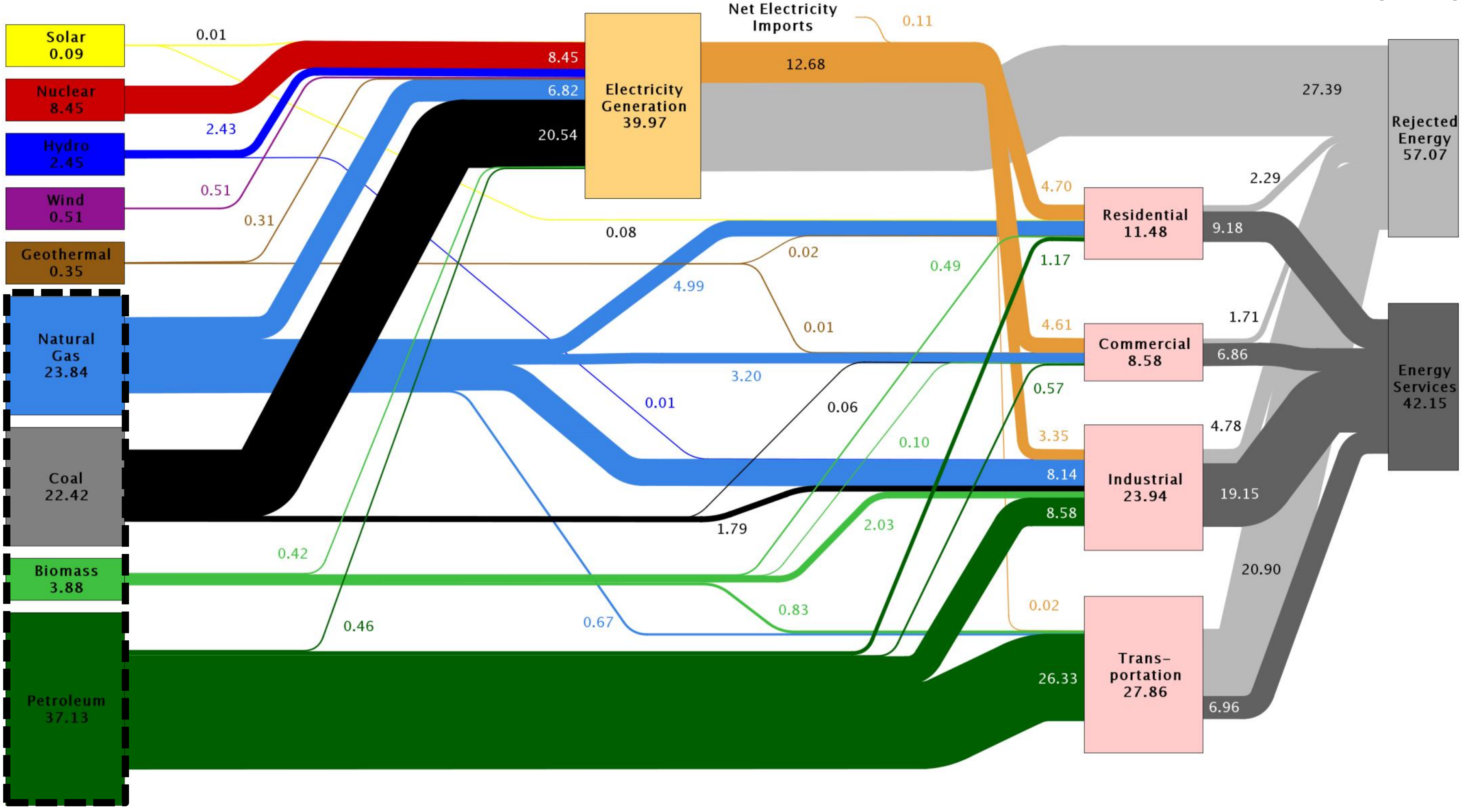


CIA, UN, EIA

Countries following the same trend: P↑ ➔ HDI ↑

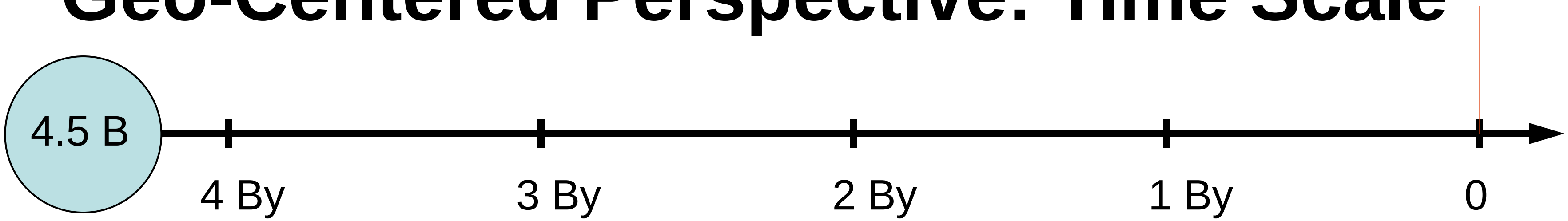
Sources – Case: USA

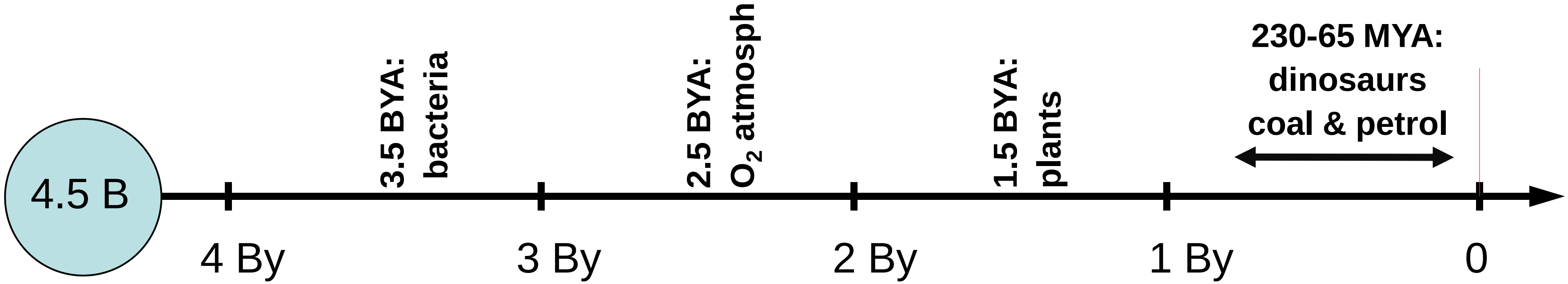
2008 LLNL – DOE
Units: [QUADS]



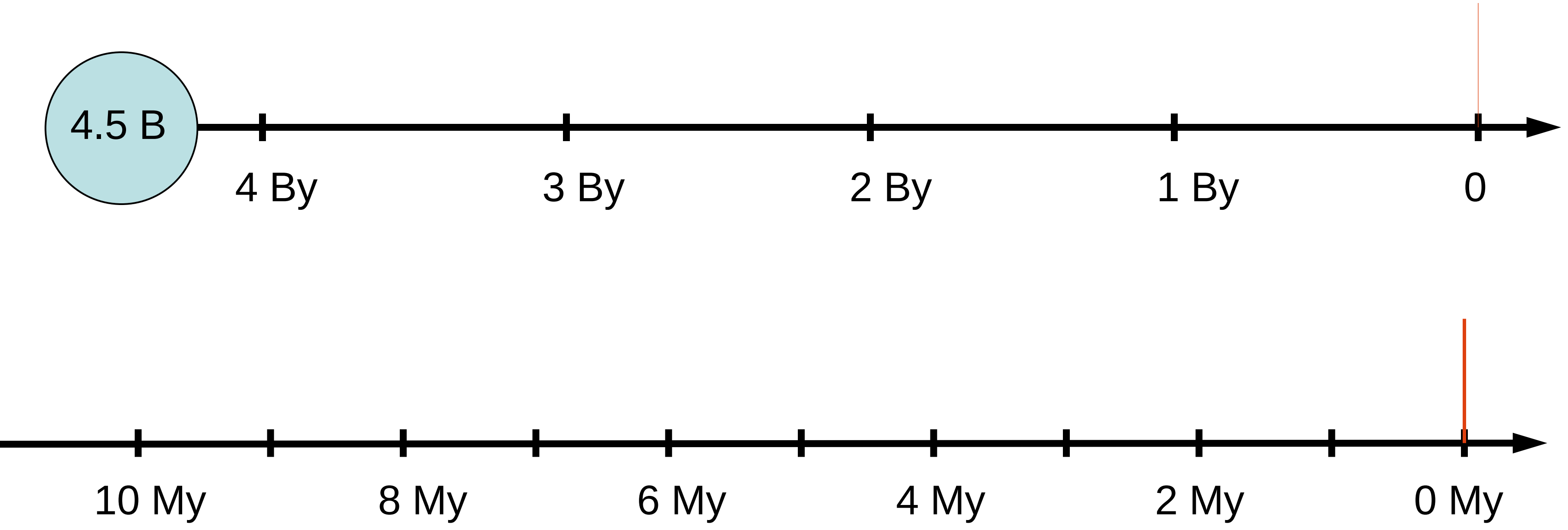
Efficiency in geotechnology? crushing<5% tunneling<< ants!

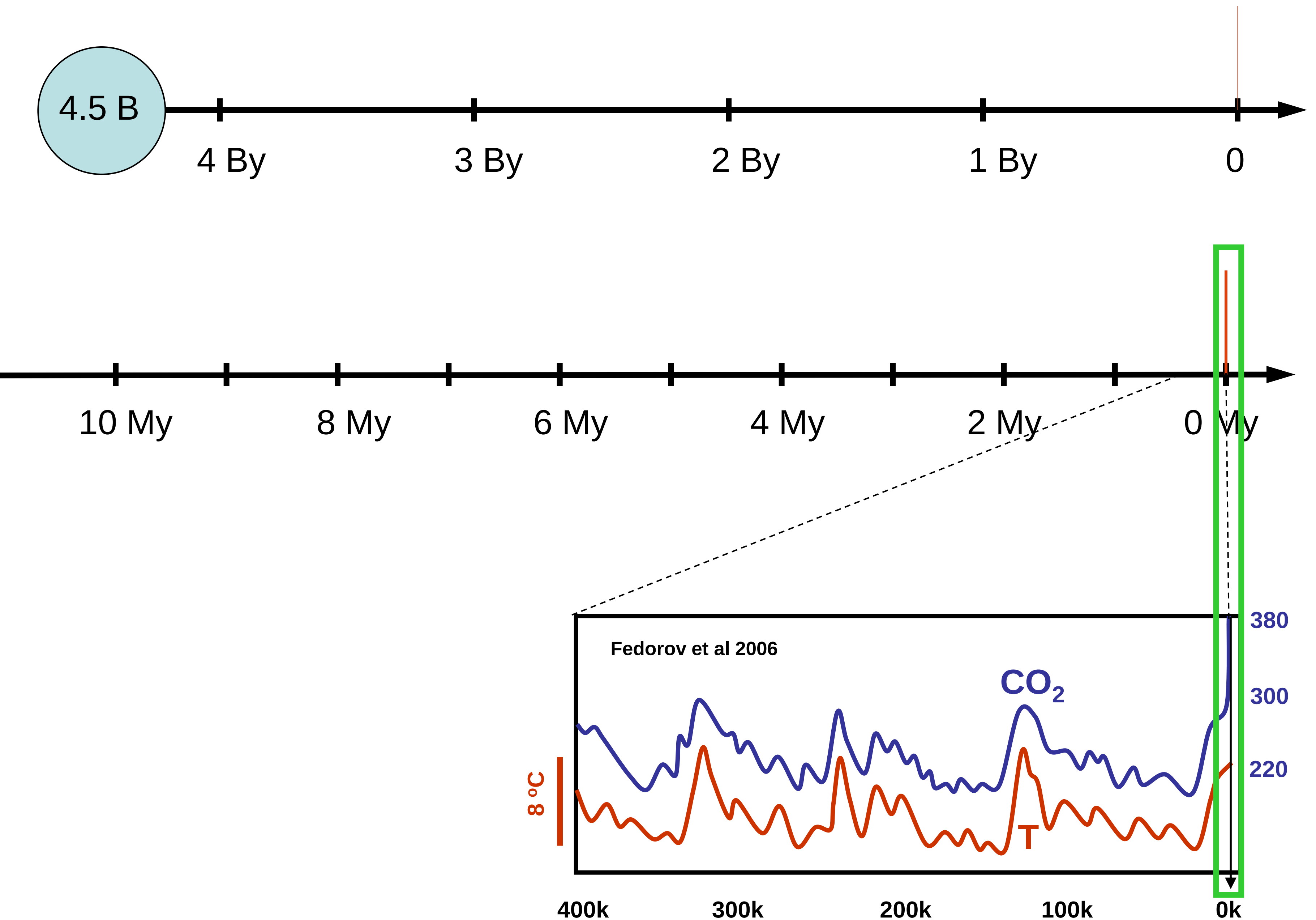
Geo-Centered Perspective: Time Scale

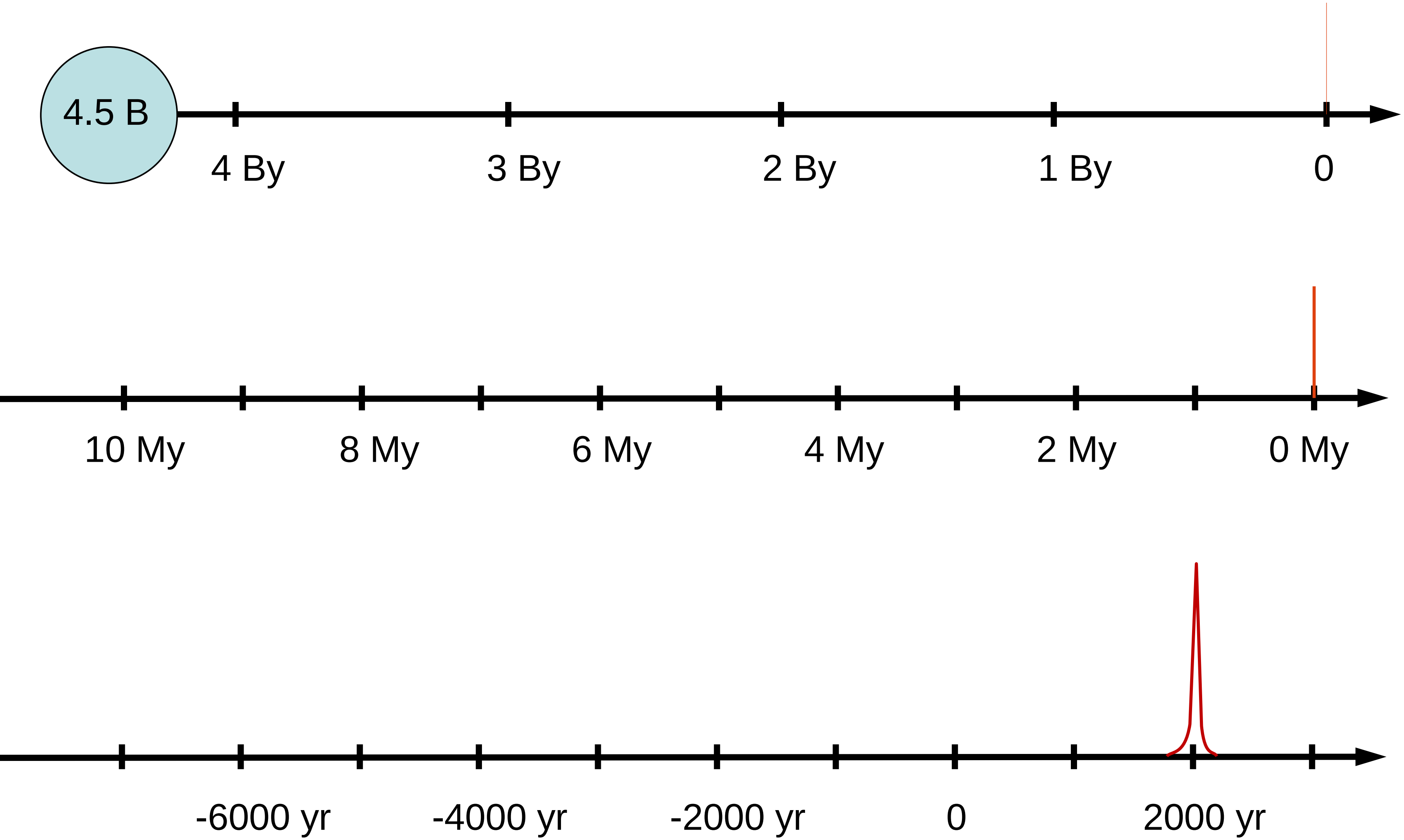




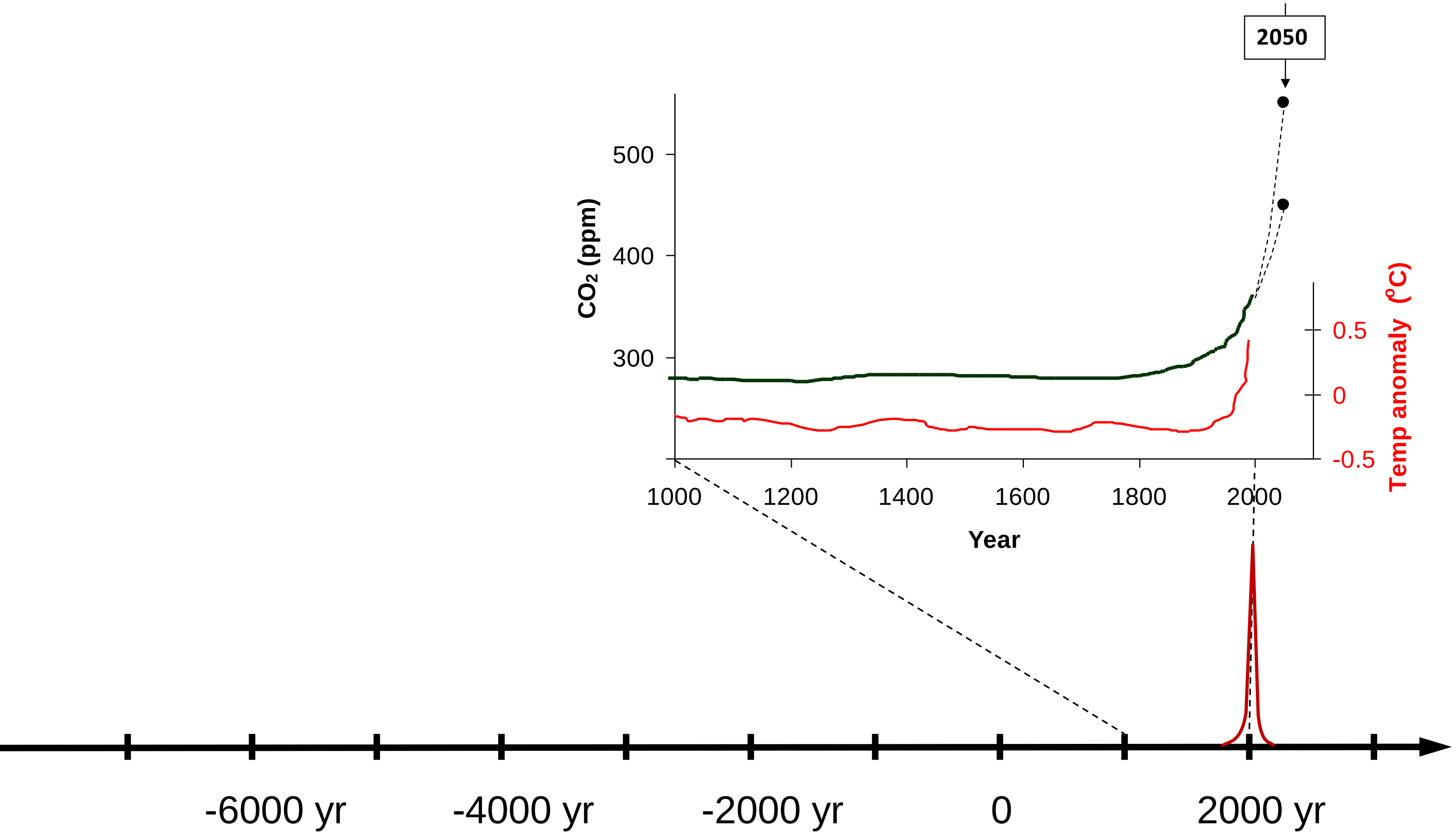
4.5 B
3.5 BYA: bacteria
2.5 BYA: O_2 atmosph
1.5 BYA: plants
230-65 MYA: dinosaurs coal & petrol
4 By
3 By
2 By
1 By
0


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
Fedorov et al 2006
CO2
T
8 °C
380
300
220
400k
300k
200k
100k
0k



History of fossil fuels: a δ-function


2050
500
400
300
CO2 (ppm)
0.5
0
-0.5
Temp anomaly (oC)
1000
1200
1400
1600
1800
2000
Year
-6000 yr
-4000 yr
-2000 yr
0
2000 yr

Geo-Centered Perspective: Spatial Scale

Energy Geotechnology

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.

Petroleum & Gas:

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

Coal

- characterization
- optimal extraction
- subsurface conv.

RENEWABLE

Wind Solar Biofuels Geo-T Tidal

- periodic load
- ratcheting

Nuclear

- engineered soils
- decommission
- leak detect
- leak repair

GEOLOGICAL STORAGE

CO_2 sequestration

10^4-10^5 yr BTHCM

mineral dissolution ➔ shear faults, pipes

Energy Storage

CAES, phase-change

Cyclic HTCM

Waste storage

10^5 yr BTHCM

GEO-ENVIRONMENTAL REMEDIATION

CONSERVATION

- **Hydro-electric:** capacity almost saturated

Energy Geotechnology: Phases

Gas

water vapor
CO_2
CH_4

supercritical CO_2

Liquid

water
CO_2
oil

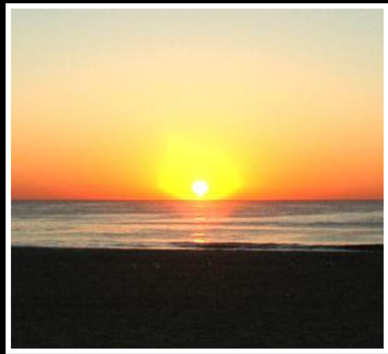
Solid

mineral
ice
CO_2 hydrate
CH_4 hydrate

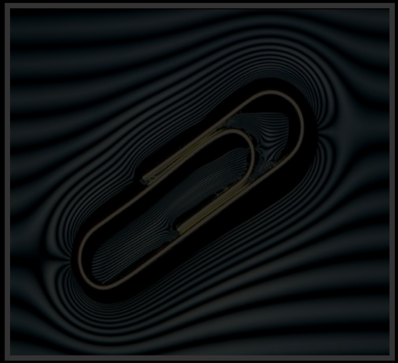
Summary: Energy Geotechnology

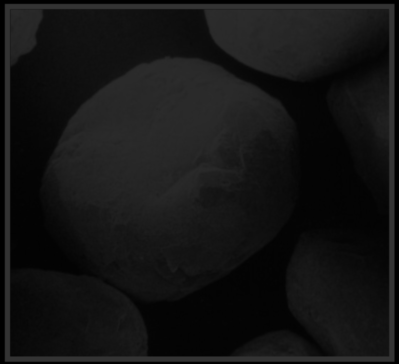
Quality of life	**Current development patterns: HDI ↔ Energy**
Current	**15.6 TW – increasing at ~1% per year**
Fossil fuels	**Stored solar energy (1 billion years in the making)** **C-Economy: ~300 years** **Short-term: C-emissions → Climate (global)**
CO_2 storage	**Fossil fuels more sustainable … but…**
Energy Geotechnology	**resource recovery — production** **energy storage — waste storage** **efficiency**

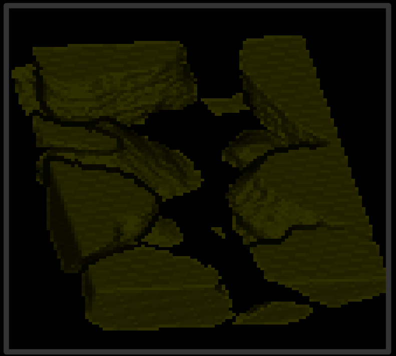
Wide range of multi-phase conditions

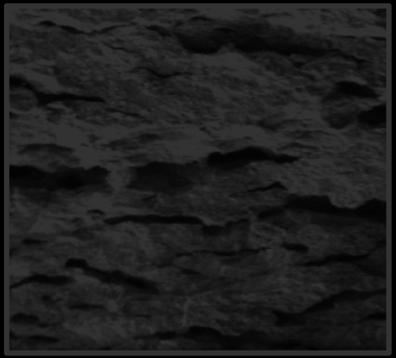


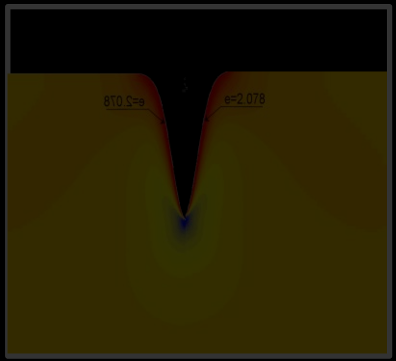
CH_4 hydrates

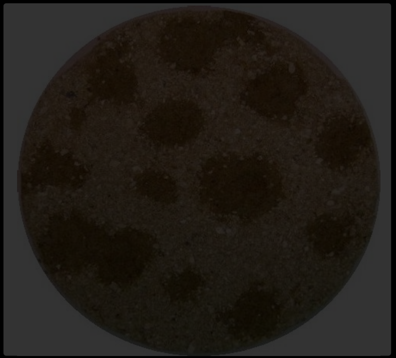






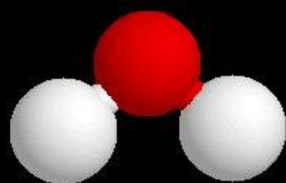




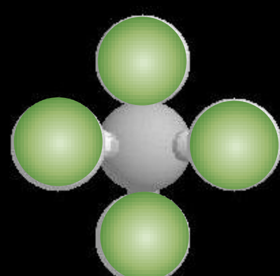


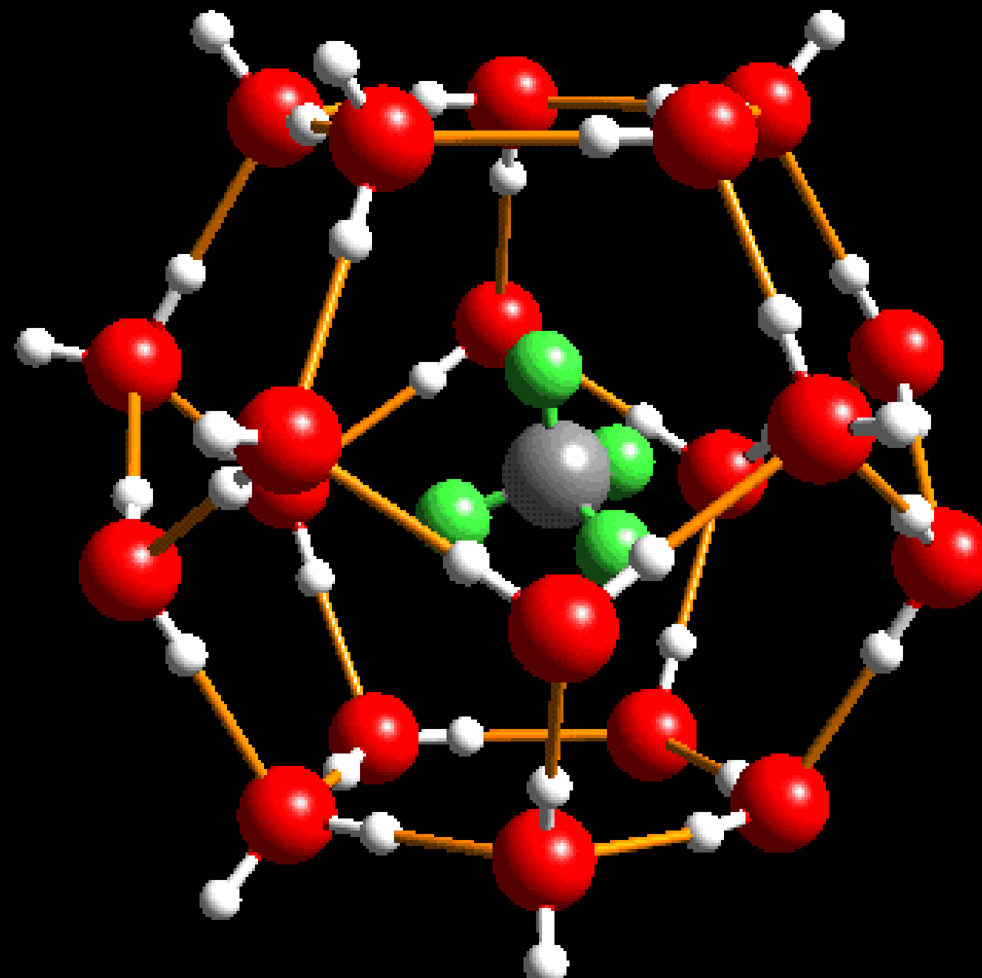
Hydrates (clathrate = cage)

H_2O

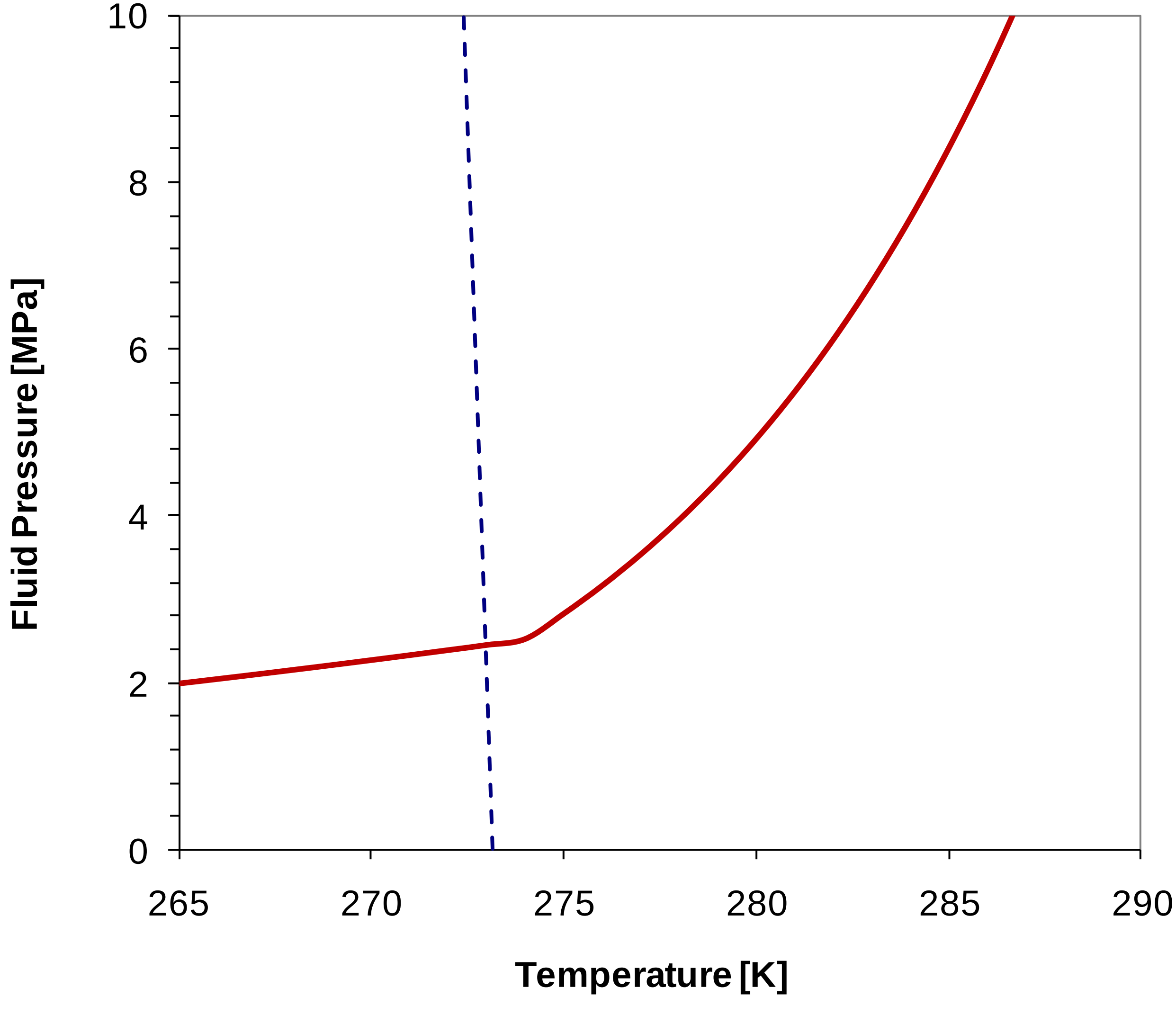


CH_4

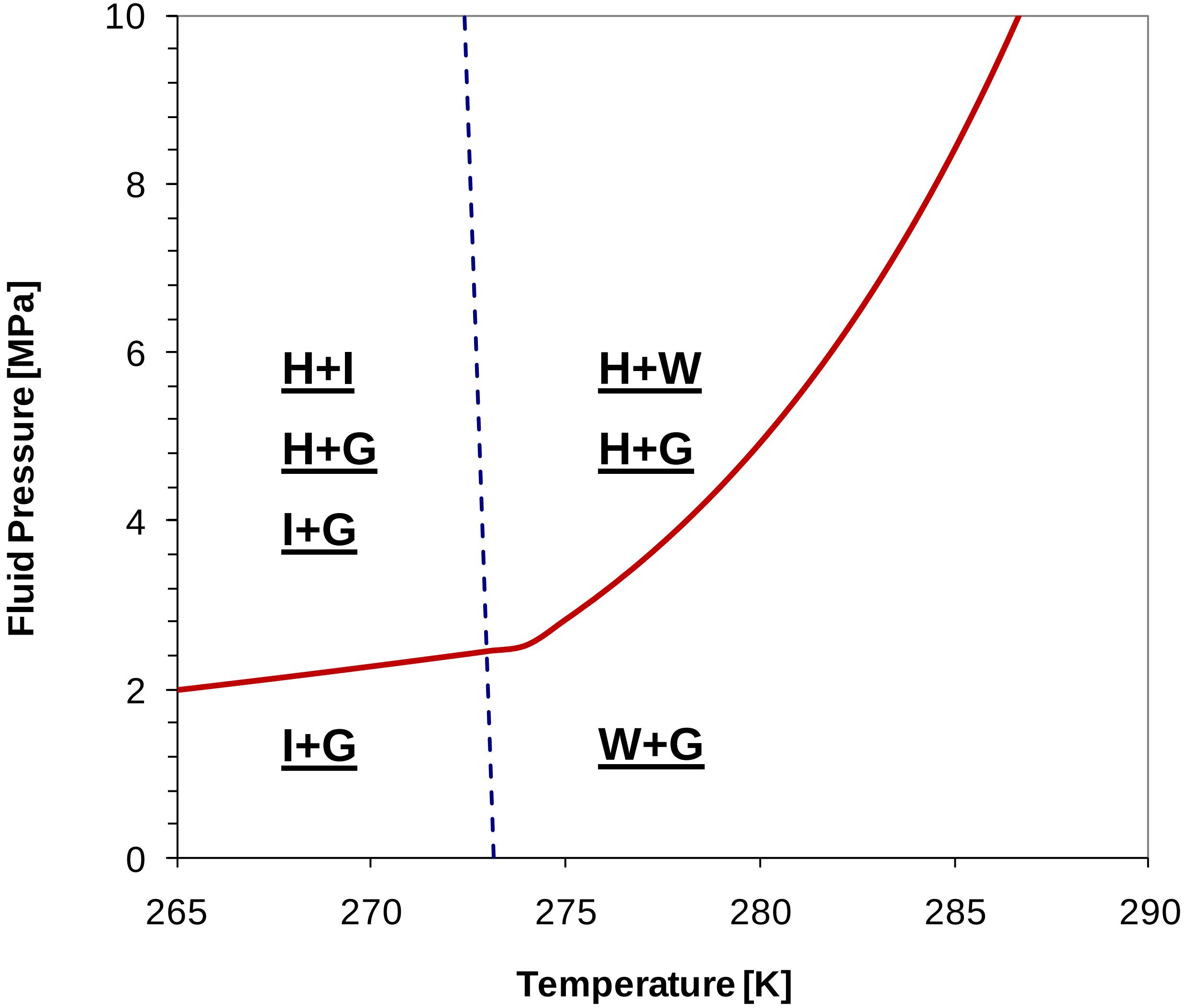




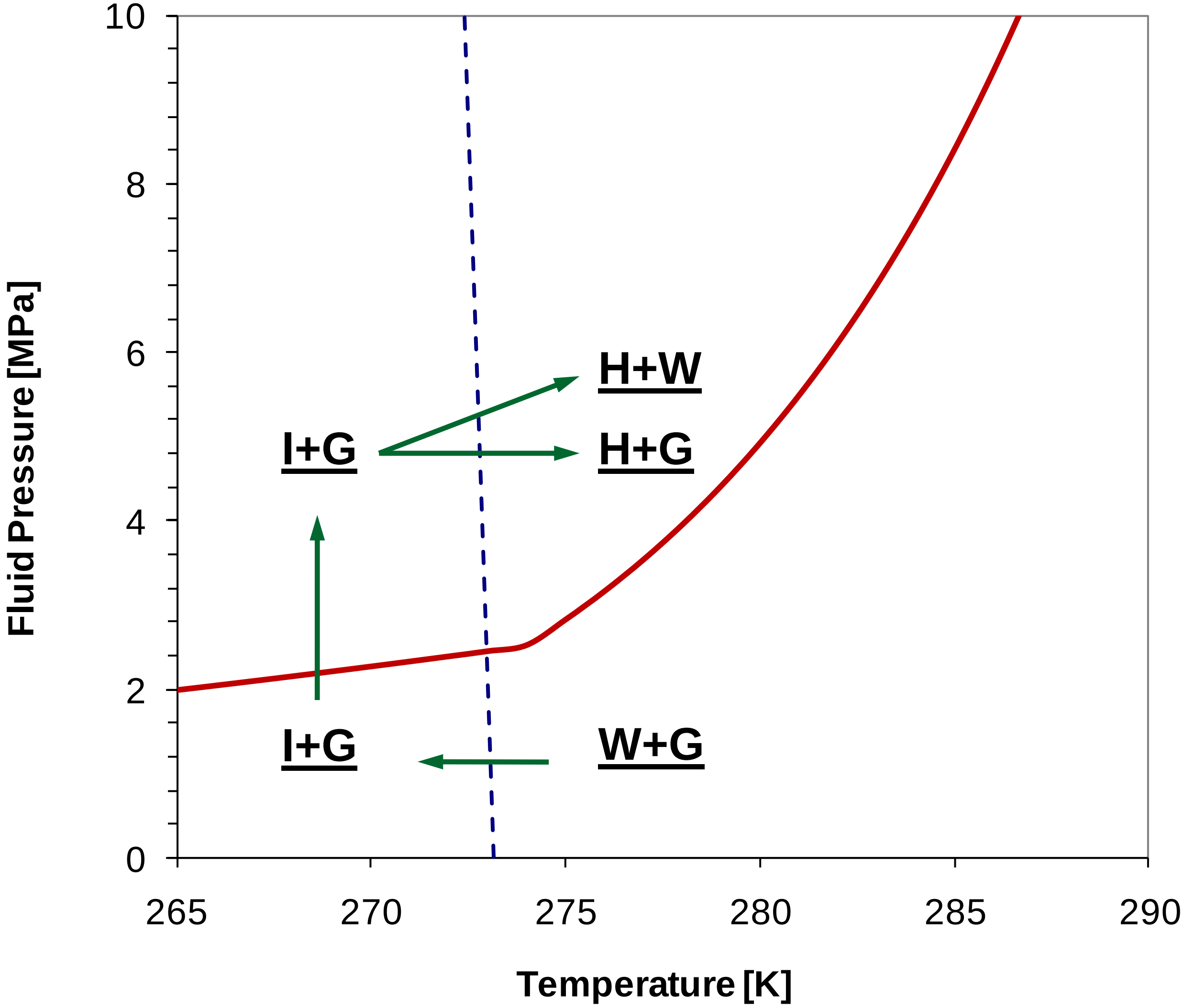
Methane Hydrate



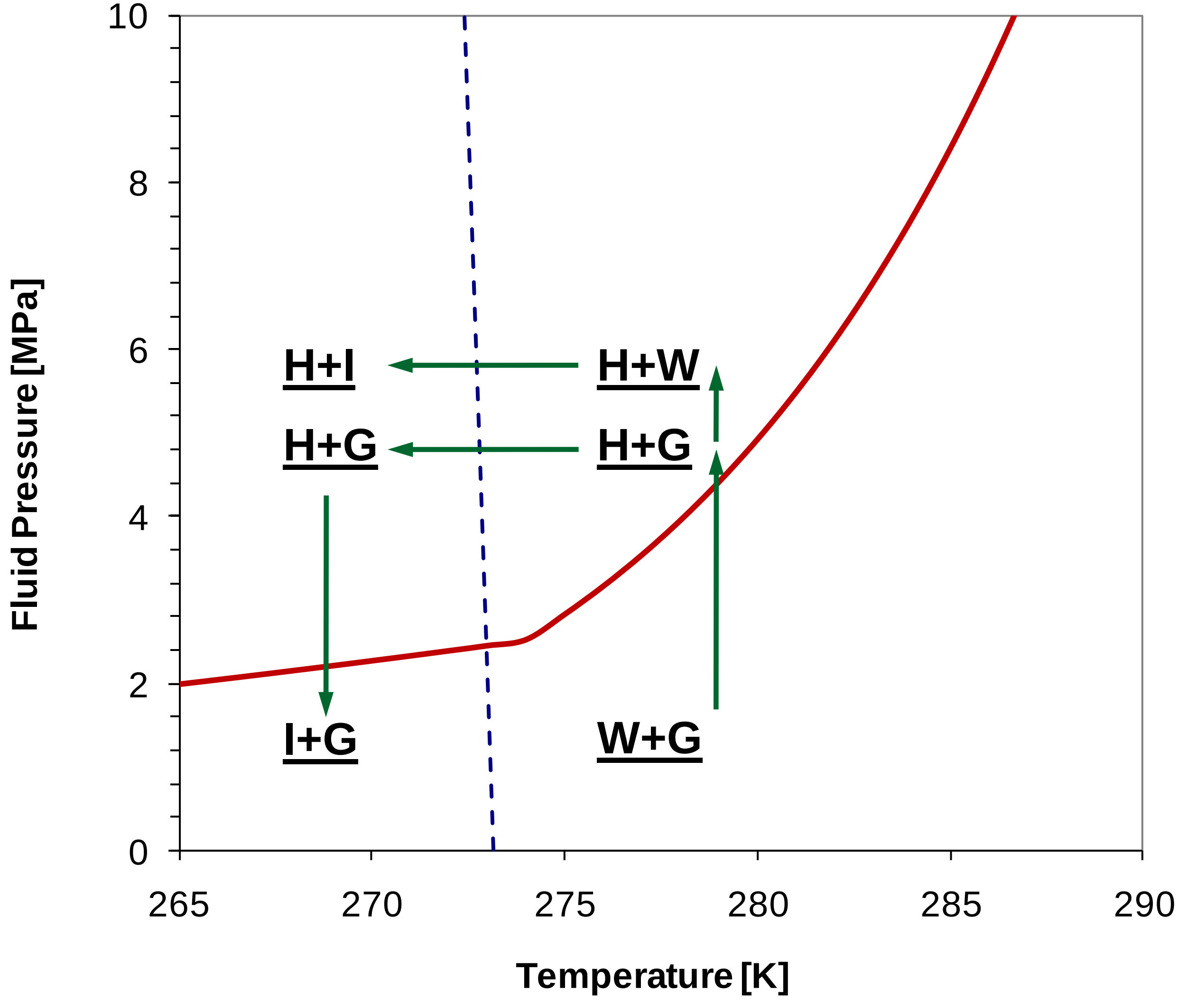
Methane Hydrate



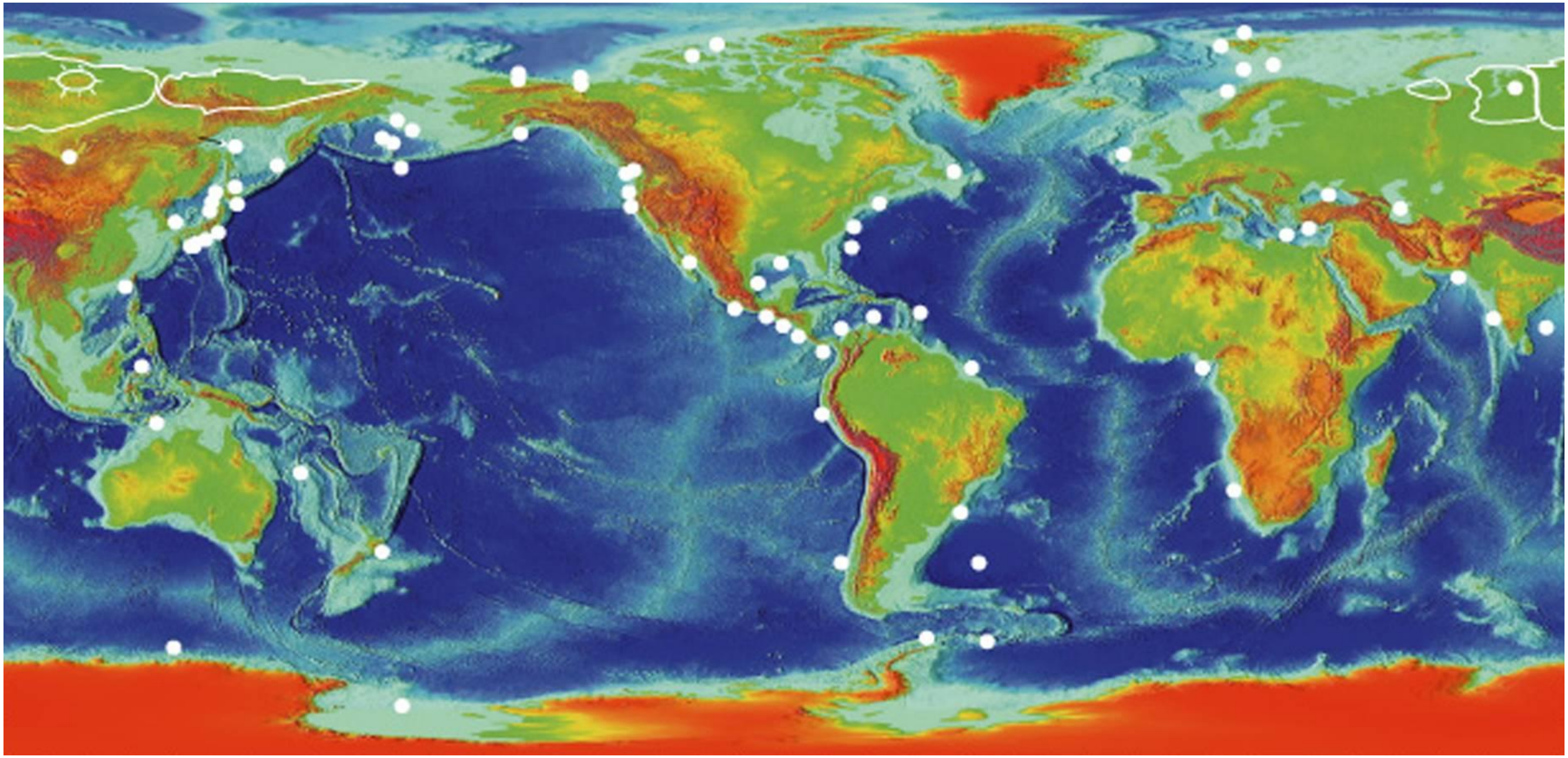
Methane Hydrate



Methane Hydrate



Methane Hydrate - Occurrence



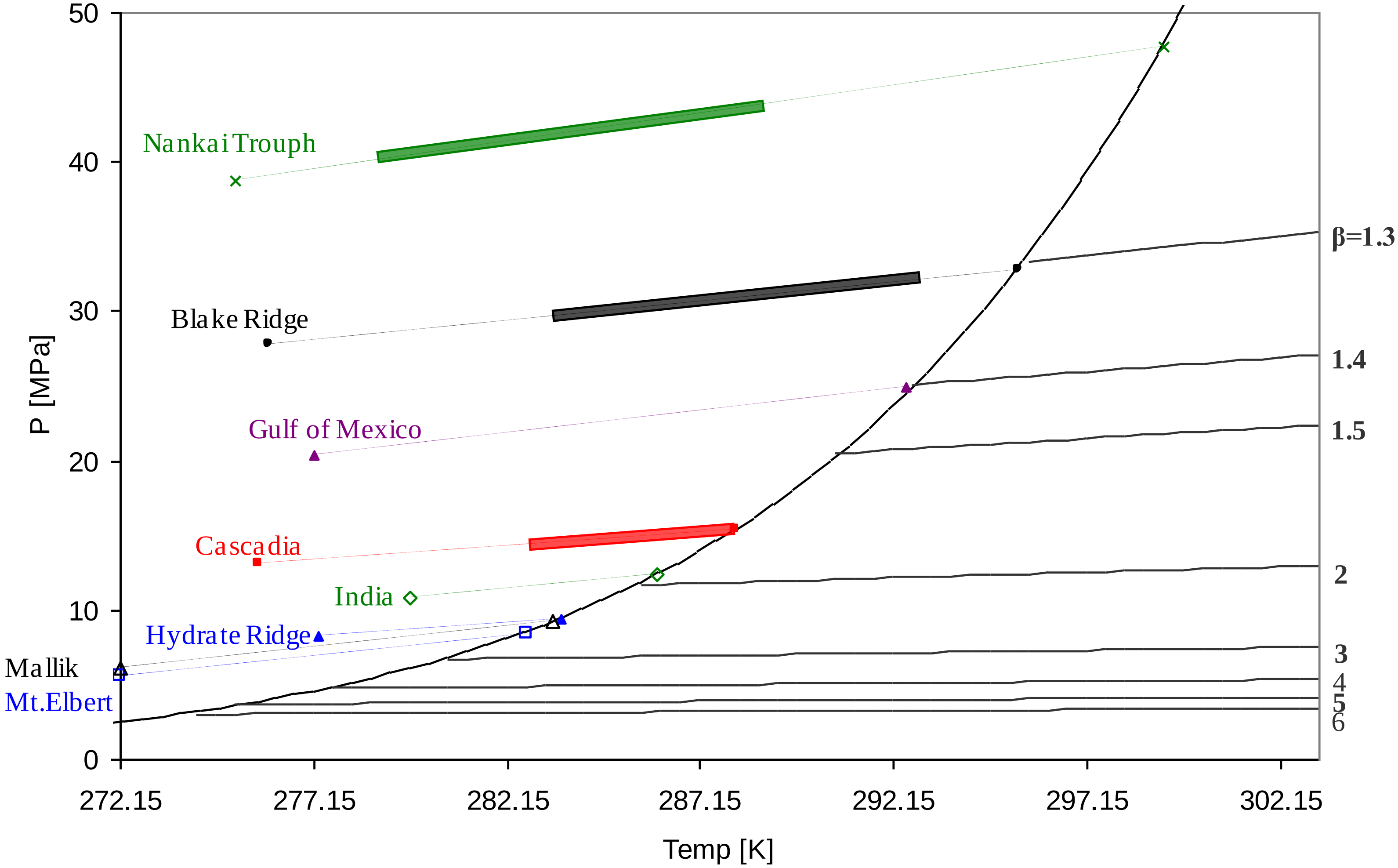
(Kvenvolden and Lorenson, 2001)

Hydrate – Key Observations

CH_4 solubility in H_2O		CH_4 : 750 H_2O	
CH4 concentration in hydrate		CH_4 : 6 H_2O	*formation: CH_4 diffusion*
Diffusivity CH_4 in	*water*	~1 x 10^{-9} m^2/s	
	hydrate	~5 x 10^{-13} m^2/s	
Ice ➔ water		V_w/V_{ice}=0.92	*production*
Hydrate ➔ (water+CH_4^{gas})		V_{w+g}/V_{hyd}= 1 to >6	

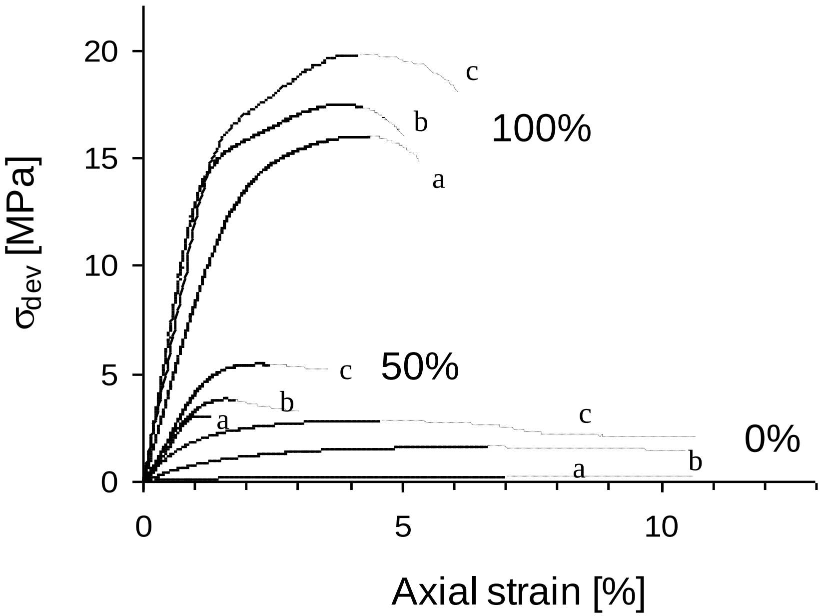
Fluid Volume Expansion

$$\beta = \frac{V_W + V_G}{V_{hyd}}$$

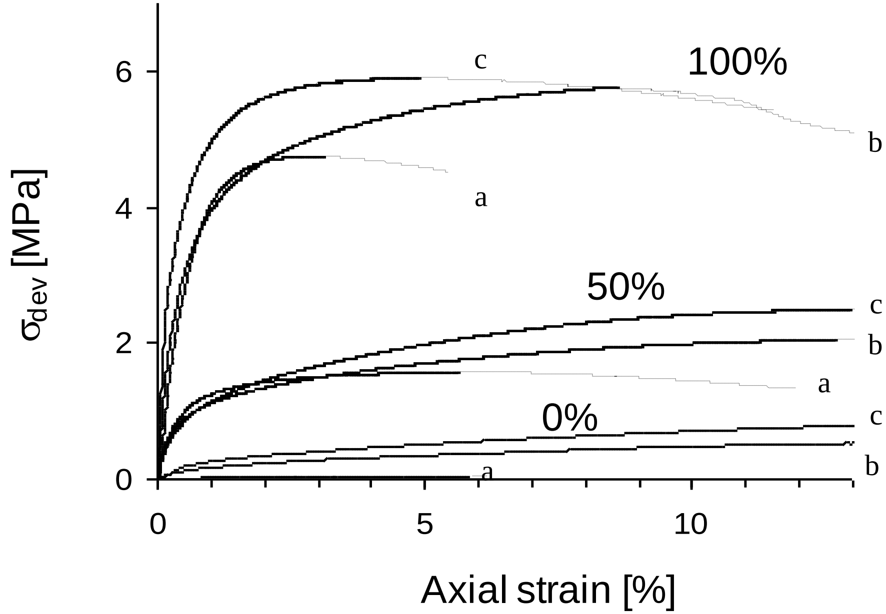


Hydrate-bearing Sediments

Sand



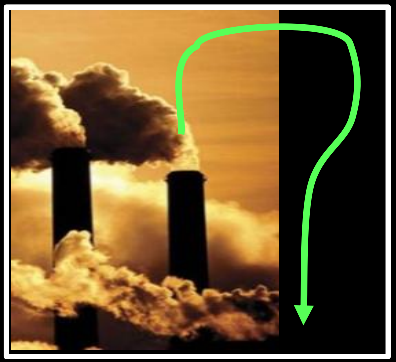
Kaolinite



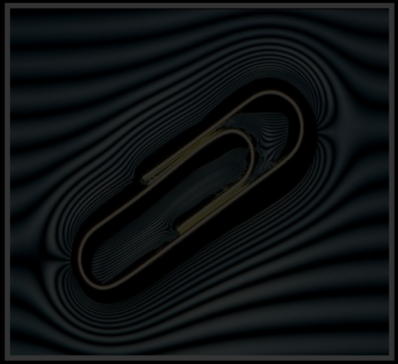
all THCEM properties = non lineal functions of S_{hyd}

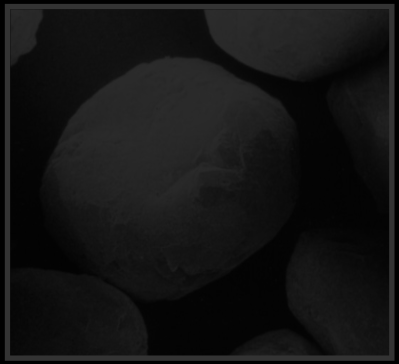
Summary: Methane Hydrates

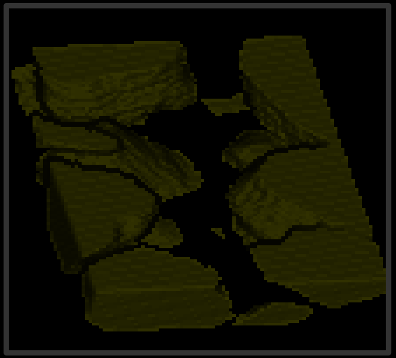
Relevance:	C-reserves climate change instability
Formation	PT history dependent S_{hyd} is CH_4-limited (typically)
Multi-phase	Hydrate Water Gas Ice Mineral (not all at once)
Pore habit	Patchy (coarse grained sediments) Lenses (fine grained sediments)
THCEM properties	Non linear functions of S_{hyd}
Gas Production	Endothermic (may be heat-limited) Very large volume expansion Production from sands? from clayey sediments?

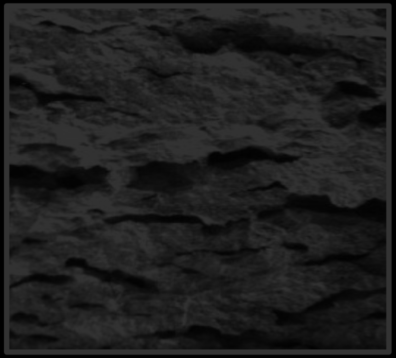


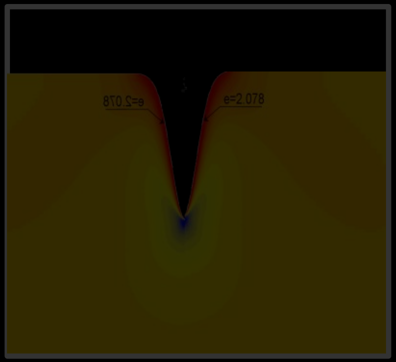
CO_2 geo-storage

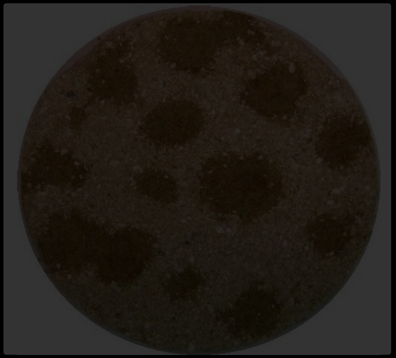




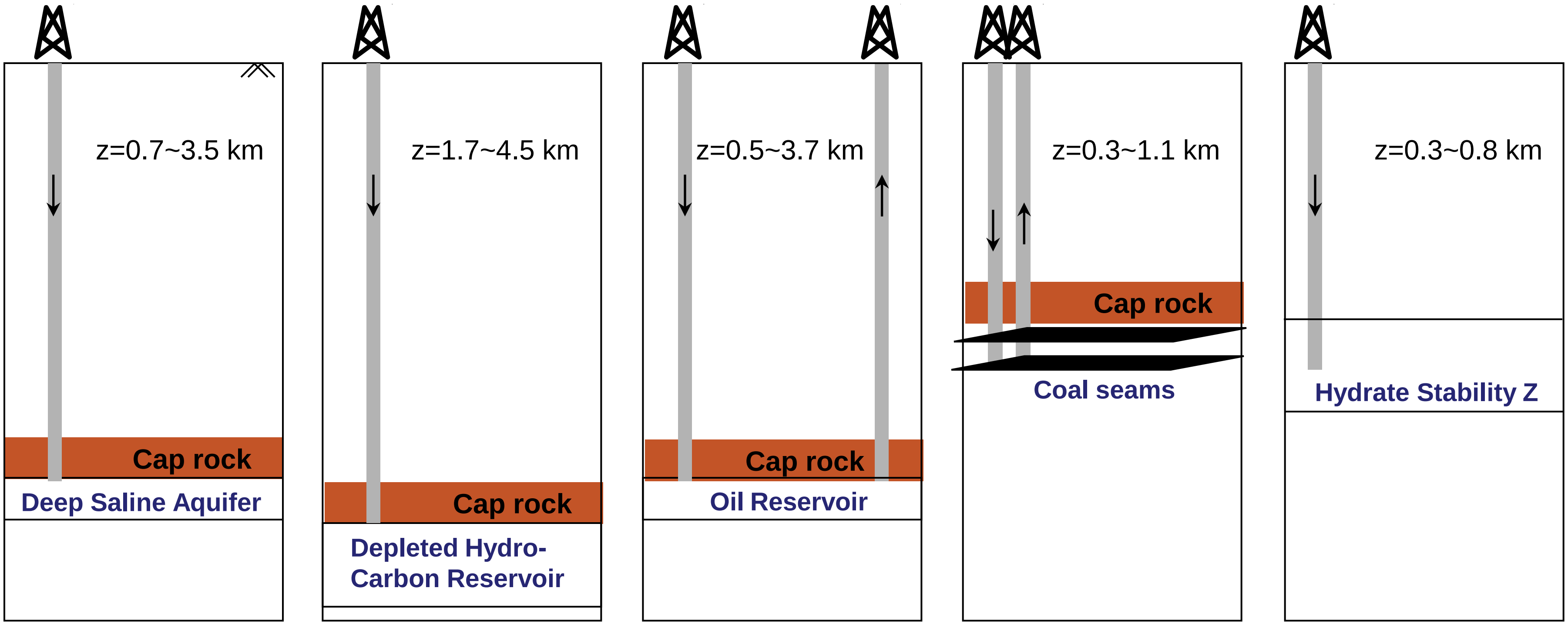




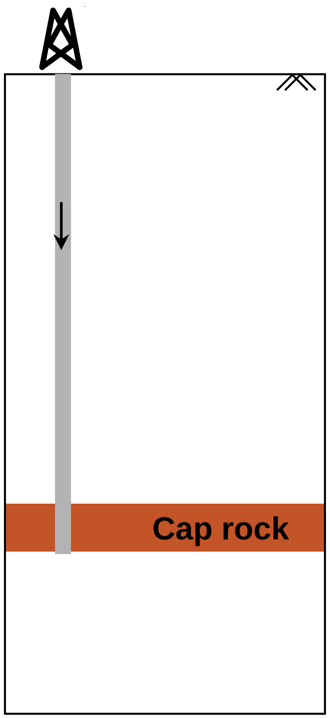


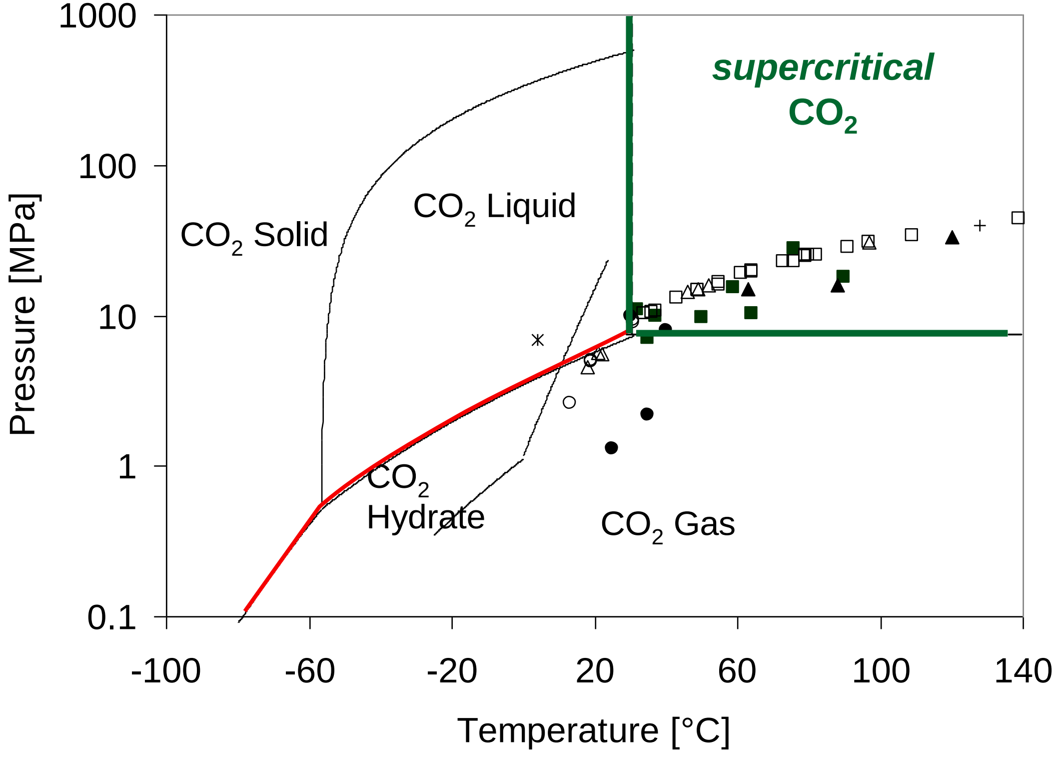


Geological Storage of CO_2



CO_2 Properties

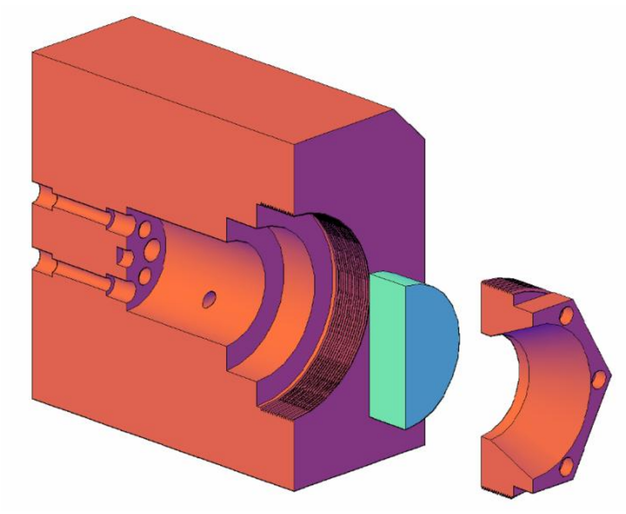


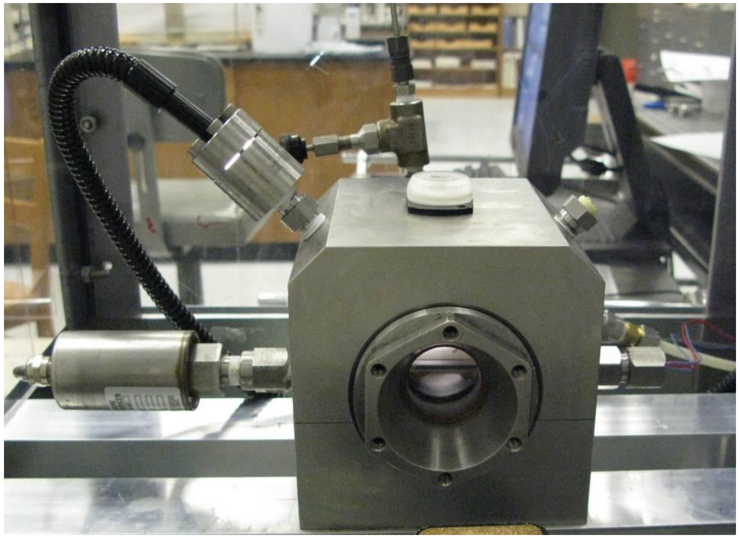


Water and Liquid CO_2 Properties

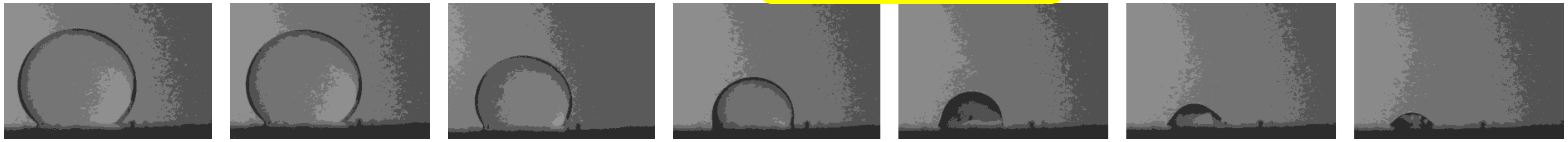
Property	[units]	CO_2 liquid	H_2O liquid
Heat capacity c_p	$[kJ \cdot kg^{-1} \cdot K^{-1}]$	2.3	4.2
Thermal cond. λ	$[W \cdot m^{-1} \cdot K^{-1}]$	~0.13	0.56
Thermal Diff. κ	$[m^2 s^{-1}]$	6.1×10^{-8}	1.3×10^{-7}
Viscosity μ	[Pa·s]	(2-to-8)$\times10^{-5}$	~1.5×10^{-3}
Density ρ	$[kg \cdot m^{-3}]$	~938-to-800	1003
Bulk Modulus	[GPa]	0.1-to-0.3	2.1-to-2.3
V_P	[m/s]	~400-to-600	1450-to-1520
Electrical cond.	[S/m]	< 0.01	f(c) - seawater: ~5
Dielectric permit.	[ ]	~ 1.5	~79

Diffusion of CO_2 in H_2O

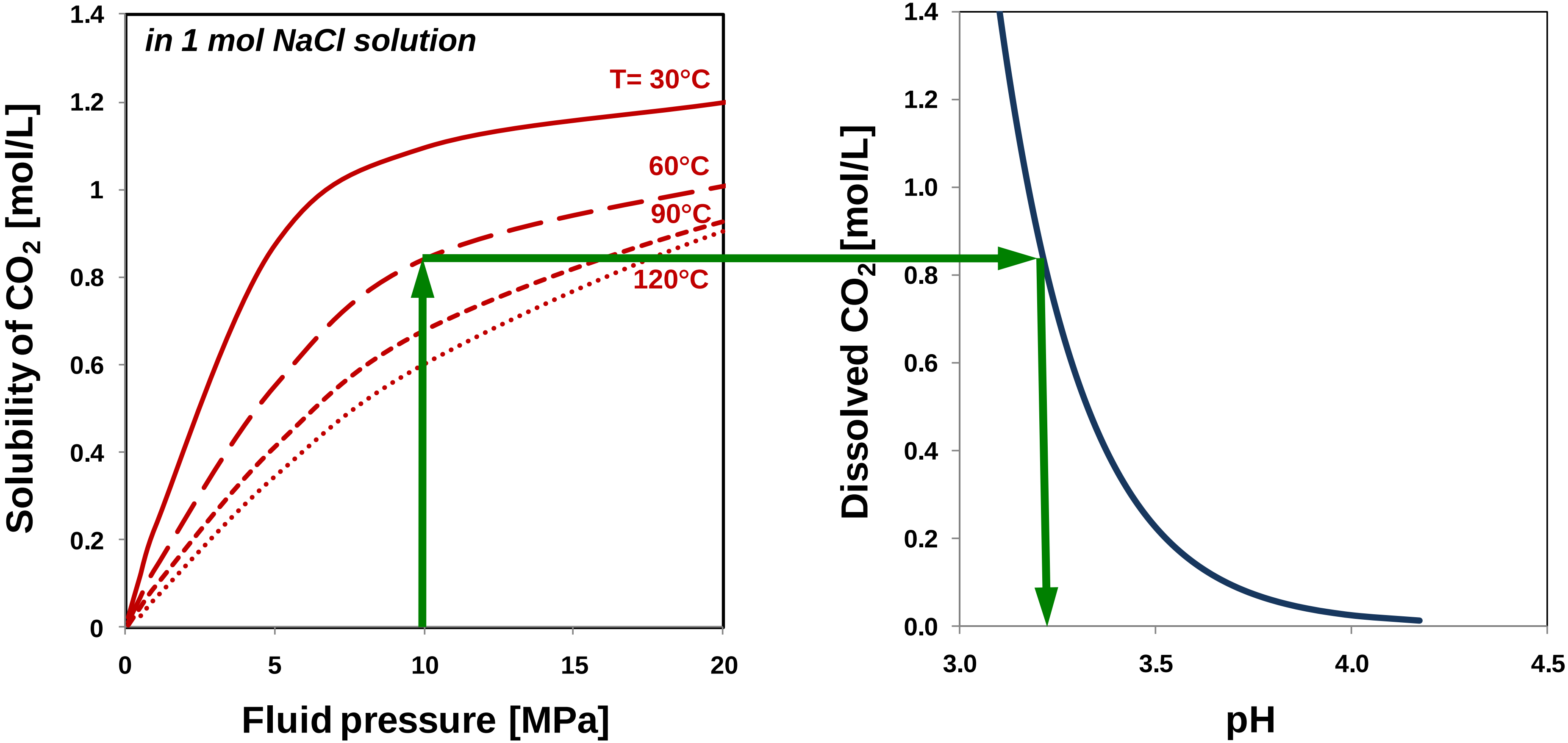




Water diffusion into liquid CO_2: $D \sim 10^{-7}\ m^2/s$

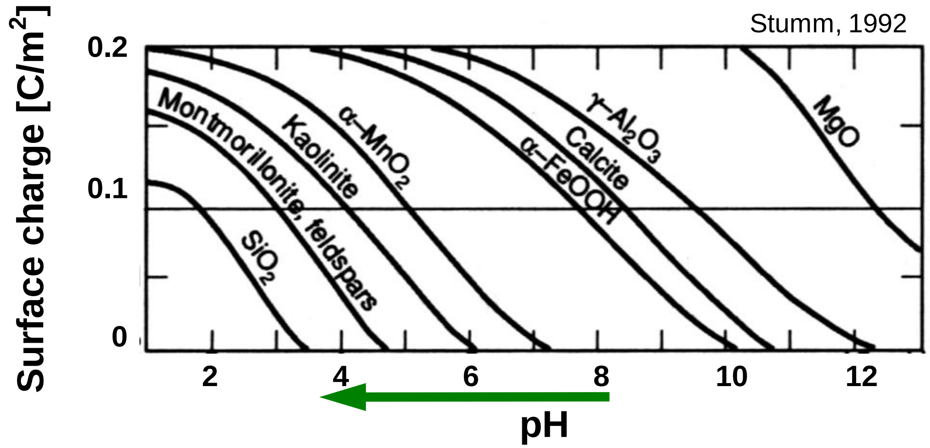


Solubility of CO_2 in Water - pH

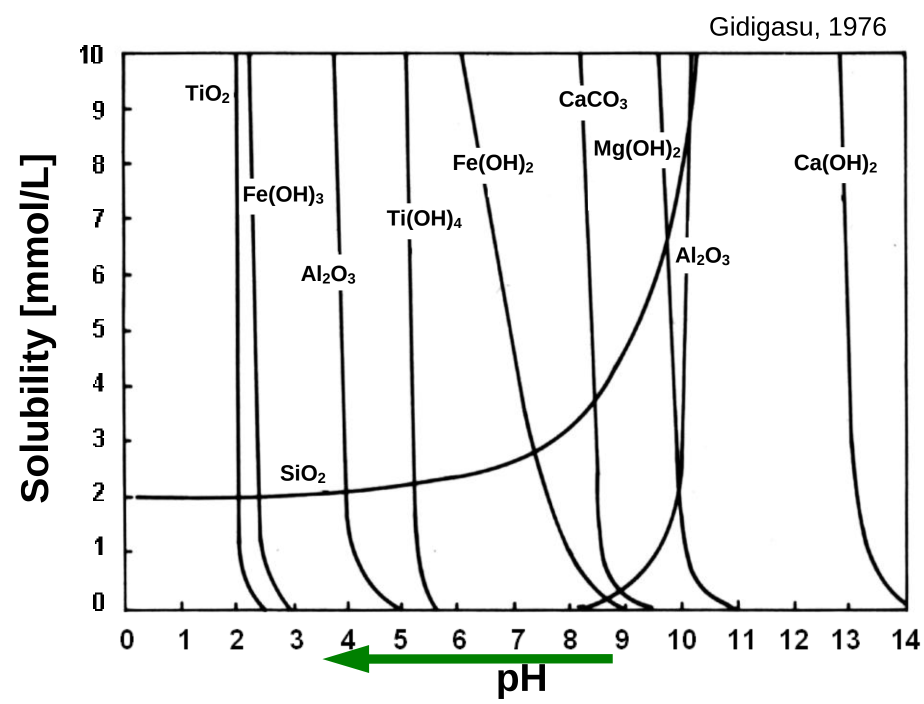


(1) change in surface charge ➔ change in fabric *(2) mineral dissolution*

pH and Minerals



➔ *change in fabric*



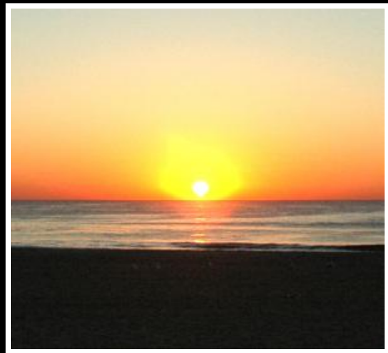
➔ *mineral dissolution*

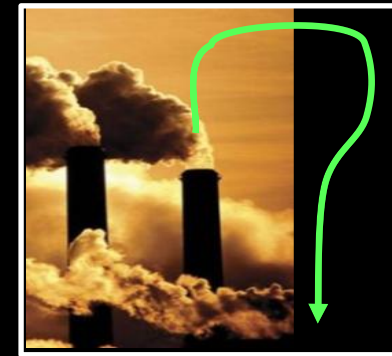
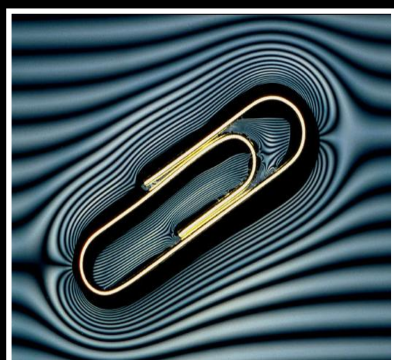
Summary: CO_2 Geological Storage

More sustainable use of fossil fuels

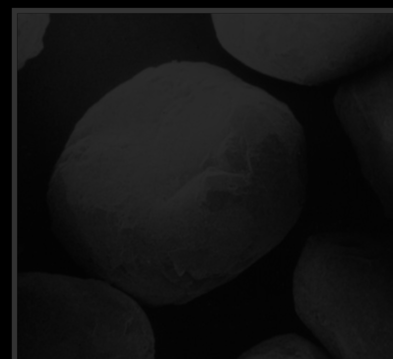
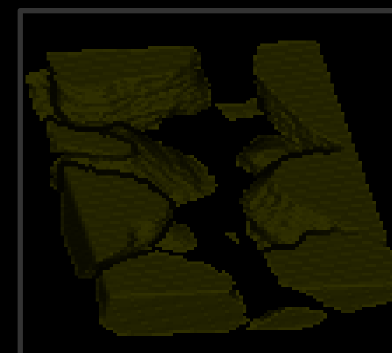
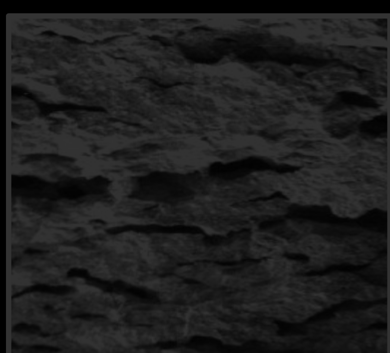
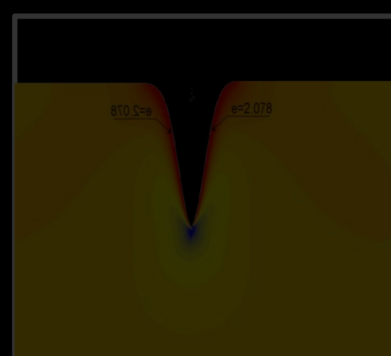
PT: typically in supercritical regime

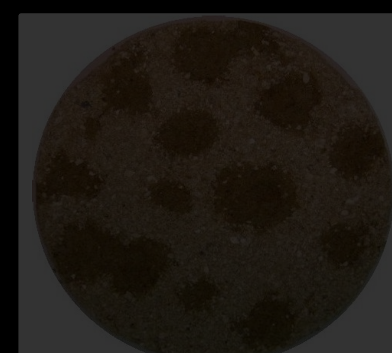
Liquid CO_2	➔ **low viscosity**	➔ **invasion pattern?**
	➔ **low B, κ', σ_{el}**	➔ **geophysical monitoring**
Acidifies water	➔ **surface charge (+)**	➔ **clay fabric in shale cap rock?**
	➔ **mineral dissolution**	➔ **stress field? permeability?**



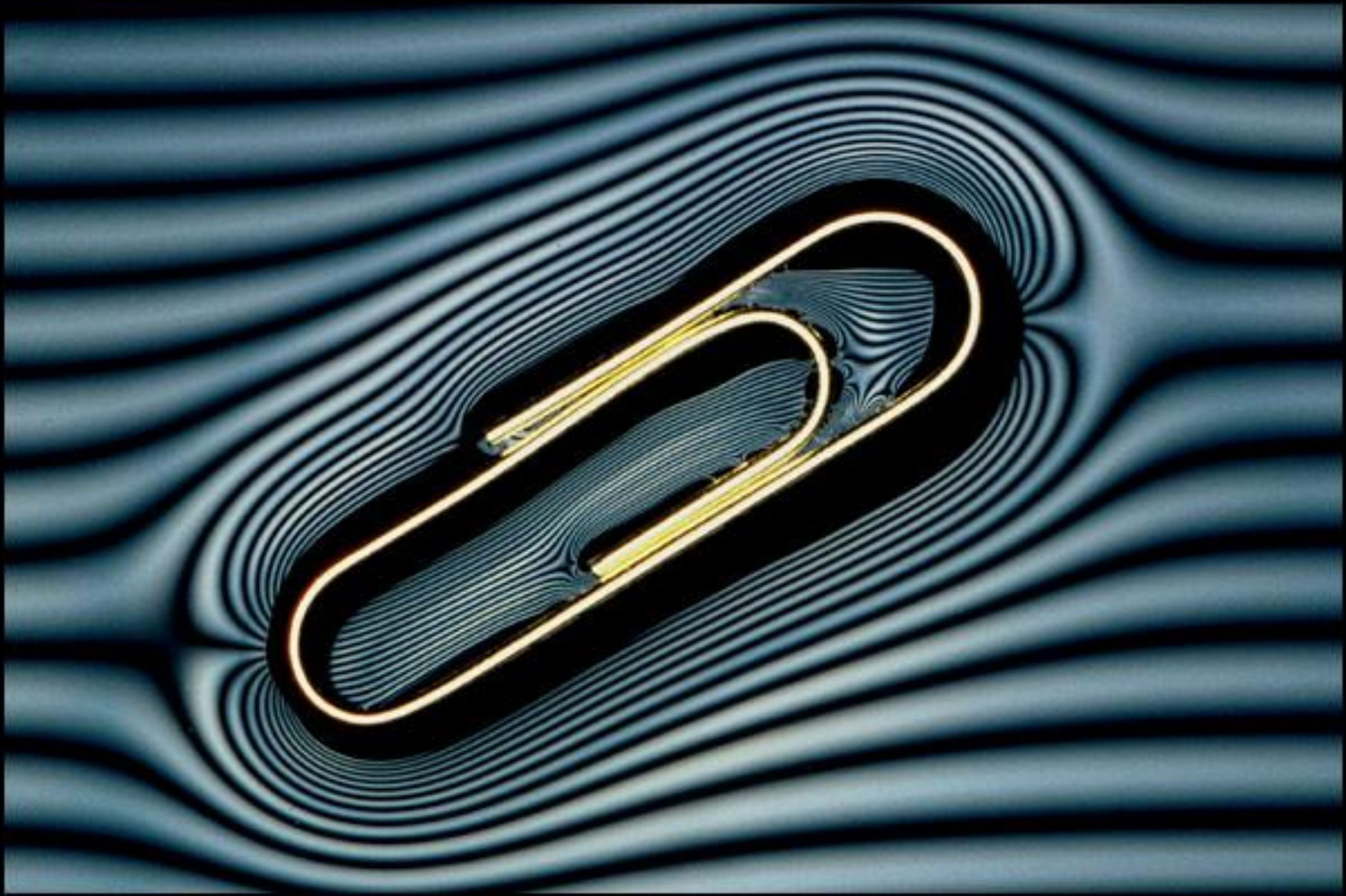



interfaces



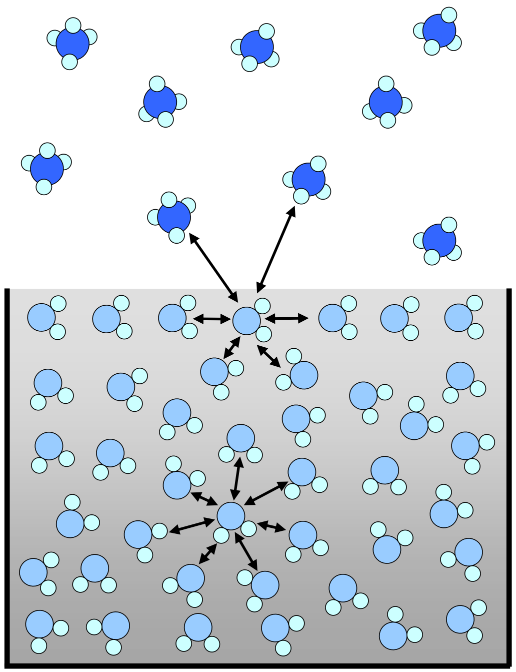
Surface Tension



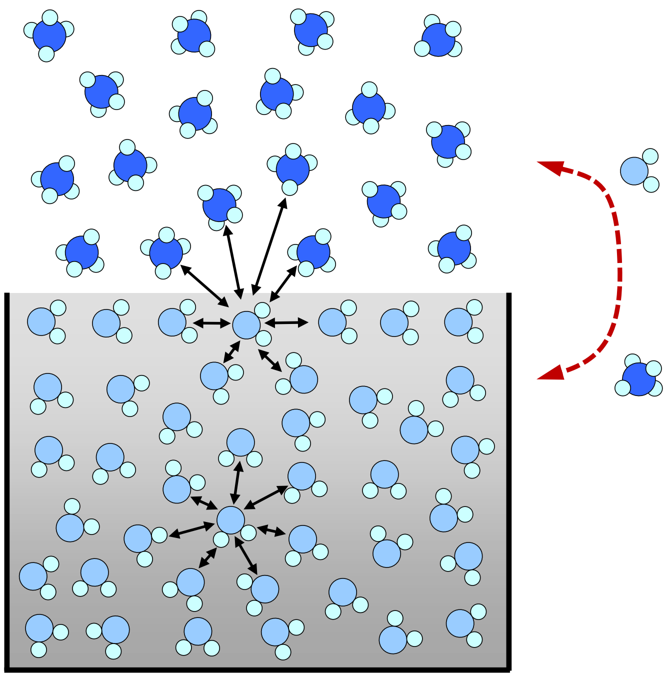
BBC News In pictures Visions of Science.jpg

CO_2-H_2O: Interfacial Interaction

Low P



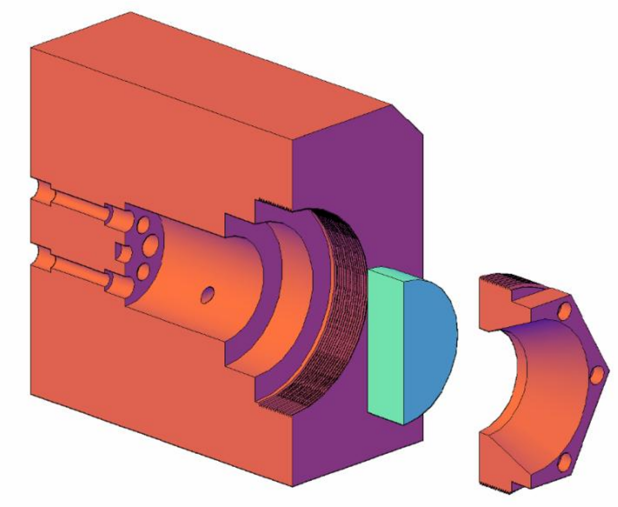
High P

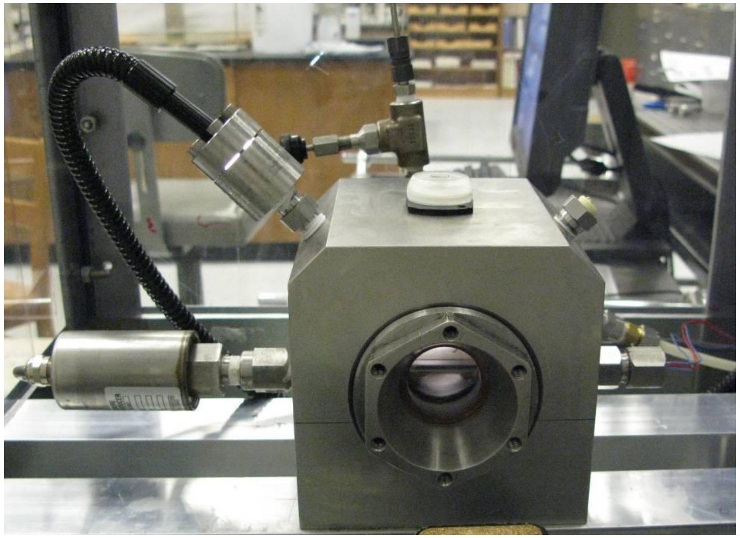


(1) mutual diffusion of CO_2-H_2O

(2) interfacial tension=f(P)

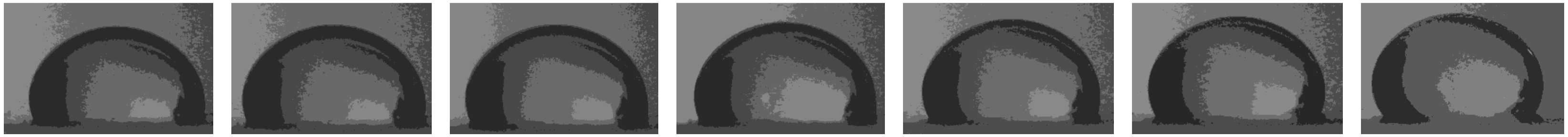
Surface Tension and Contact Angle



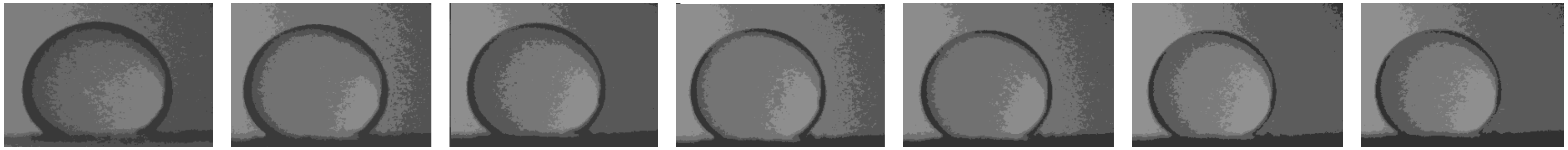


Water droplet in

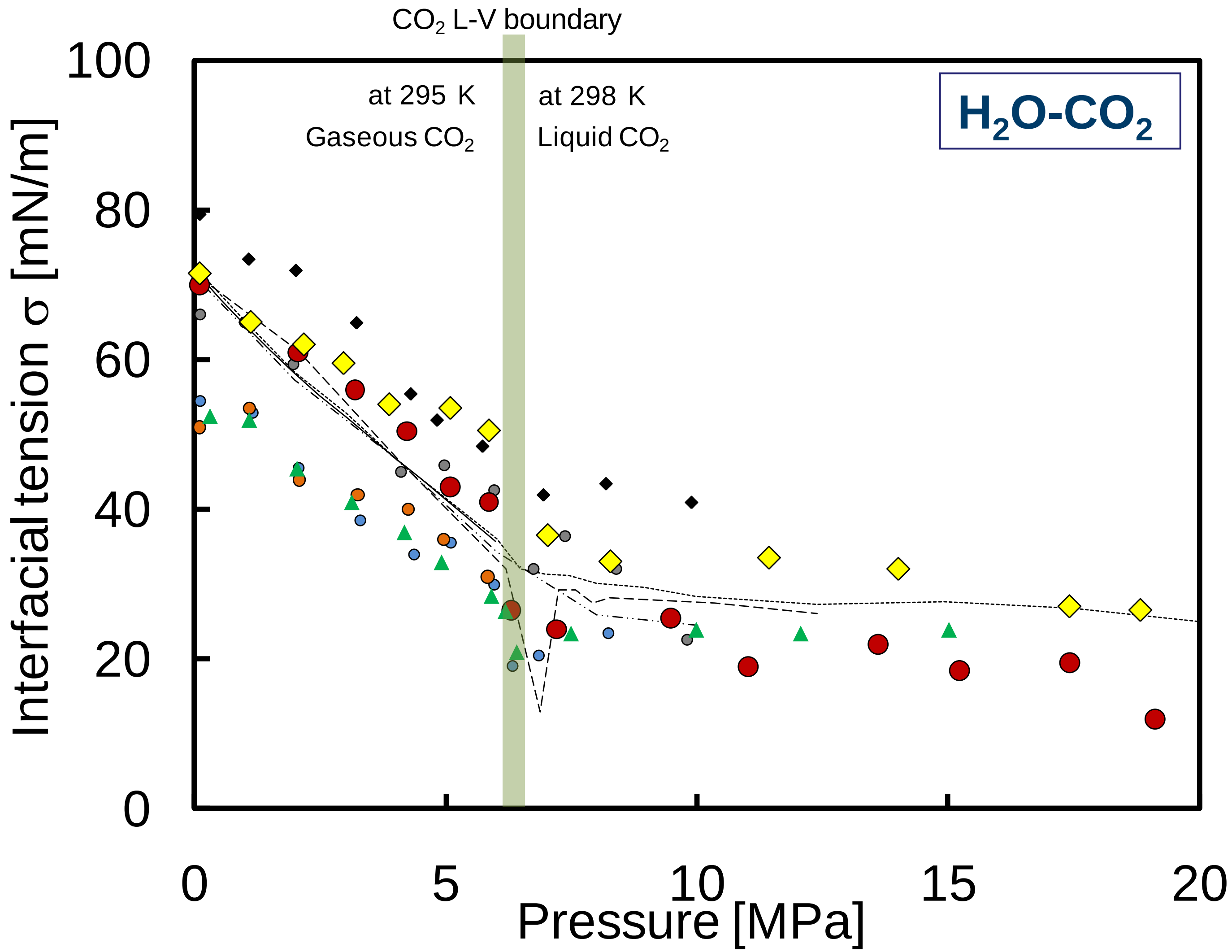
CO_2 gas



CO_2 liquid

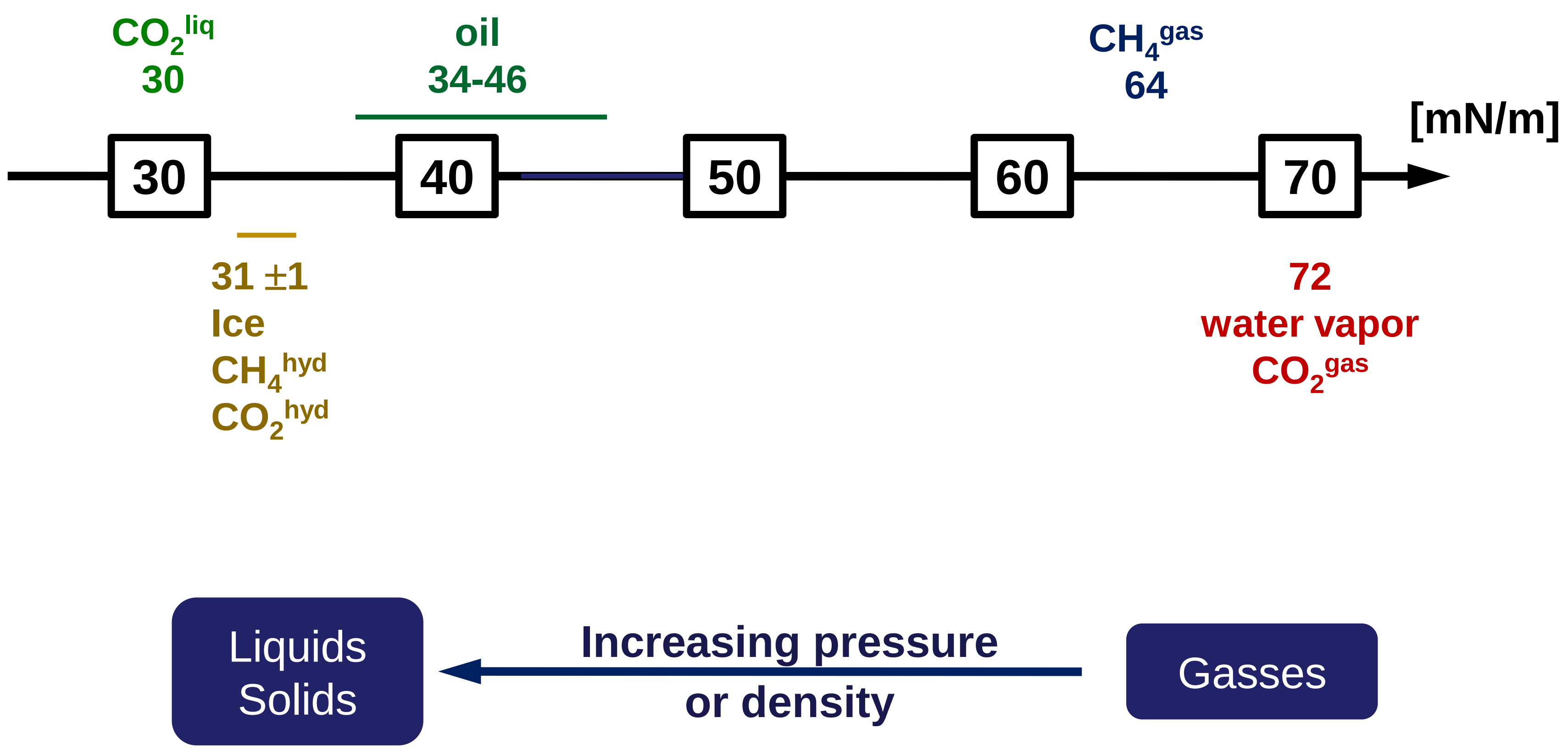


Surface Tension = f(P)



Interfacial Tension

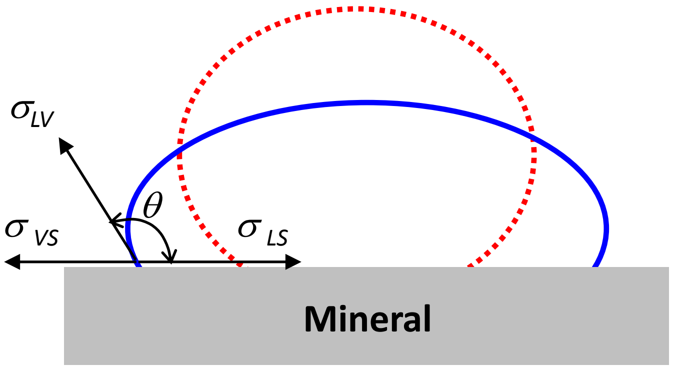
water and …



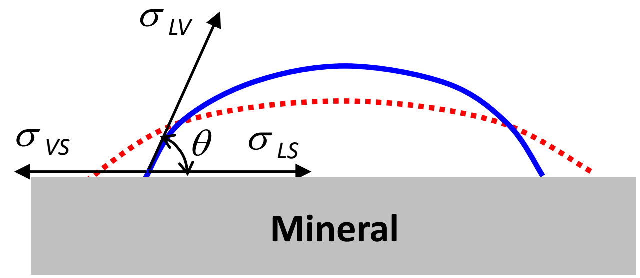
Contact Angle

$$\cos\theta = \frac{\sigma_{VS} - \sigma_{LS}}{\sigma_{LV}}$$

Non-wetting droplet



Wetting droplet

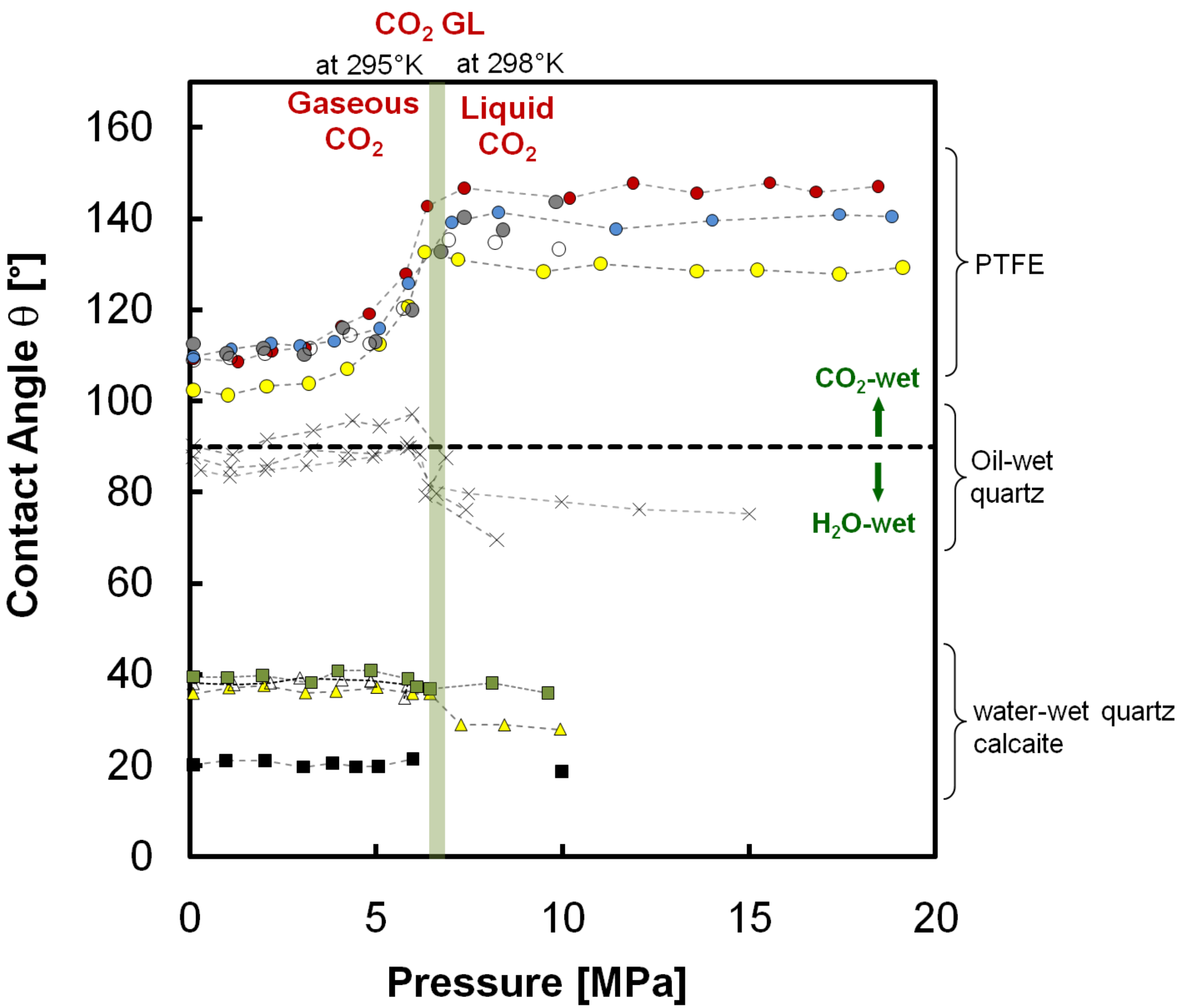


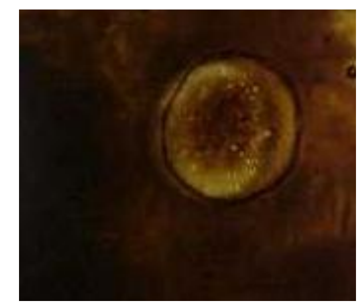
$\boldsymbol{\sigma}_{LV}\downarrow \rightarrow \boldsymbol{\theta}\uparrow$

$\boldsymbol{\sigma}_{LV}\downarrow \rightarrow \boldsymbol{\theta}\downarrow$

Contact Angle = f(P_{gas})

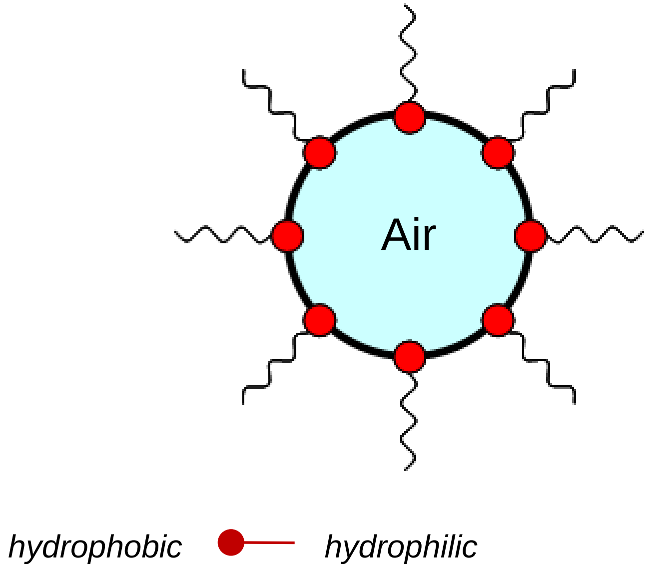
$$\cos\theta = \frac{\sigma_{VS} - \sigma_{LS}}{\sigma_{LV}}$$

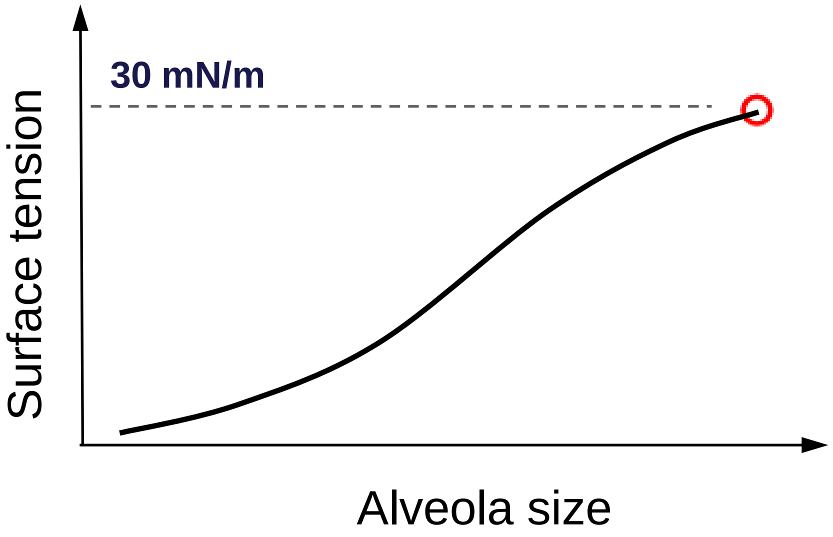




Other Effects - Surfactants

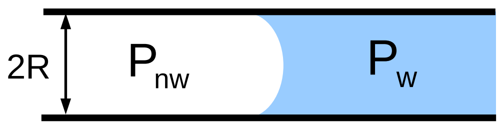
Pulmonary self-regulation:





Surfactant ➔ Surface tension = f(pore size) ➔ S-u data interpretation

Capillary Pressure - Laplace



$$\left(P_{nw} - P_w\right)\pi R^2 = 2\pi R\,\sigma\cos\theta$$

$$\Delta P = \frac{2\sigma}{R}\cos\theta$$

$$\Delta P = \frac{2\sigma}{R}\cos\theta$$

$$\Delta P = \frac{\rho}{M}\underline{R}T\ln\left(\frac{1}{h_r}\right) \rightarrow R = 2\,\sigma_{LV}\cos\theta\frac{M}{\rho\underline{R}T\ln\left(\frac{1}{h_r}\right)}$$

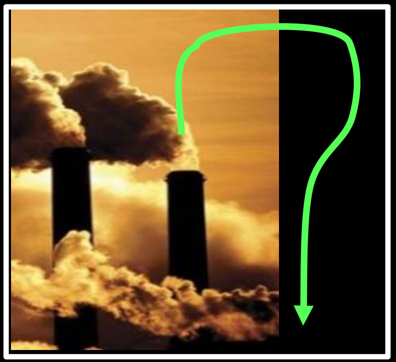
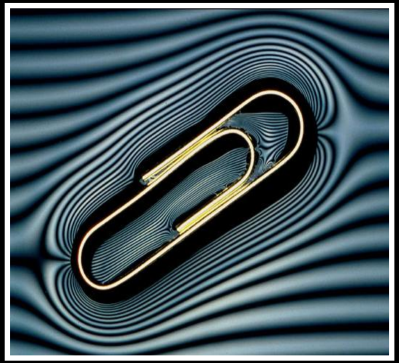
$$\Delta P = \Sigma_m\left(T_m - T\right) \rightarrow R = 2\sigma_{wi}\cos\theta\frac{1}{\Sigma_m\left(T_m - T\right)}$$

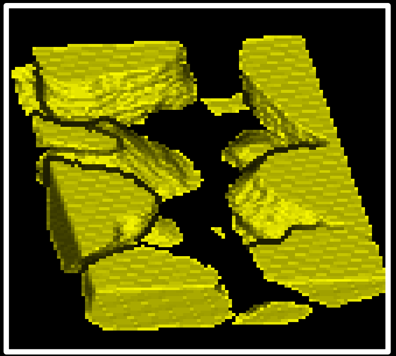
Characteristic curves Δu-S for: *water -gas* *water-oil* *gas-oil* *water-ice* *water-hydrate*

Summary: Interfacial Phenomena

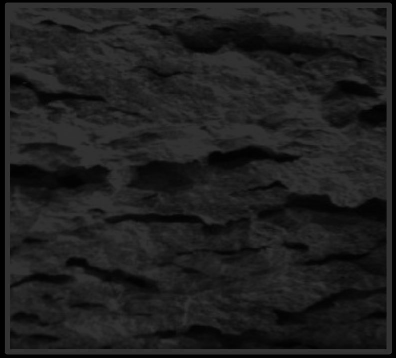
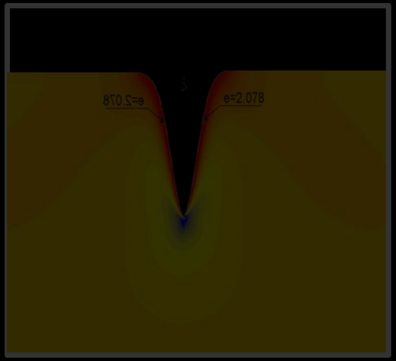
Interfacial tension:	**participating molecules and PT (or density)**
Contact angle:	**varies with interfacial tensions**
Implications:	**capillarity** **characteristic curves** **resource recovery**

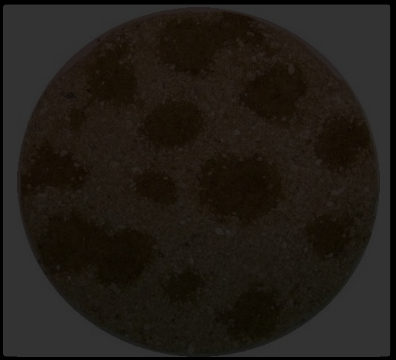




grains and pores

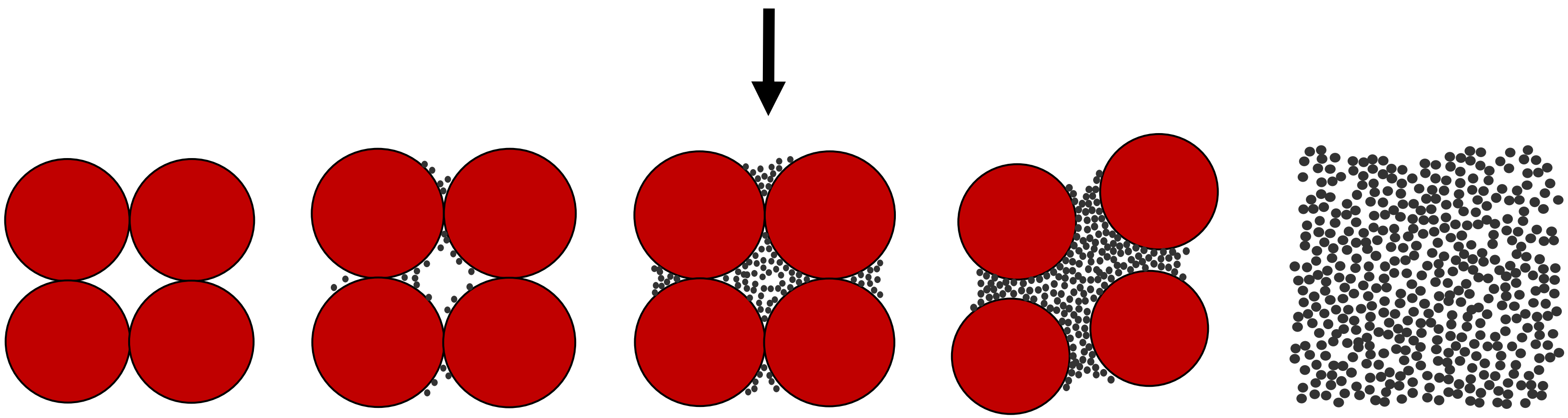





Grain Size Distribution: The Role of Fines

Critical fines Content FC*

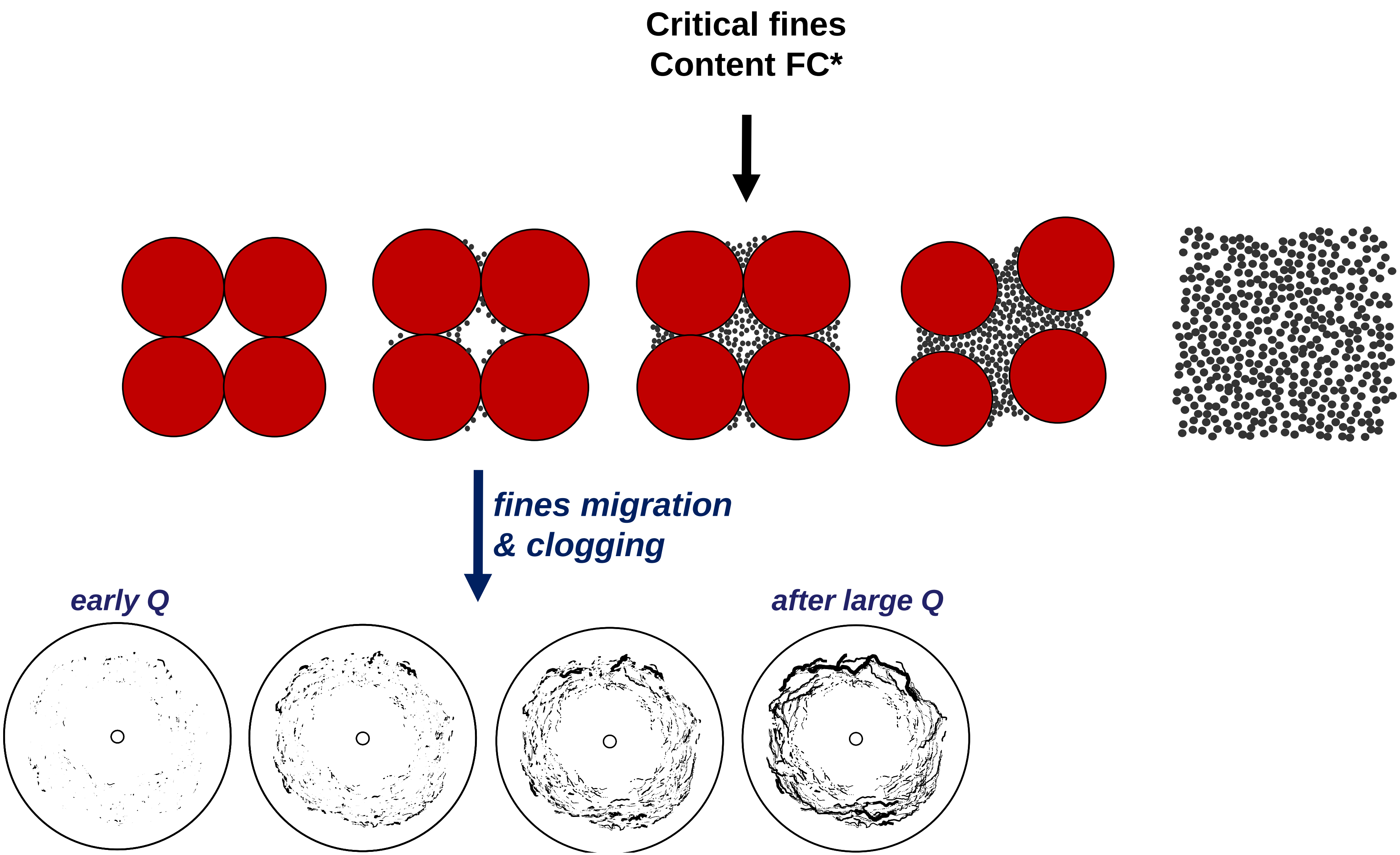
(for mechanical properties …)



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

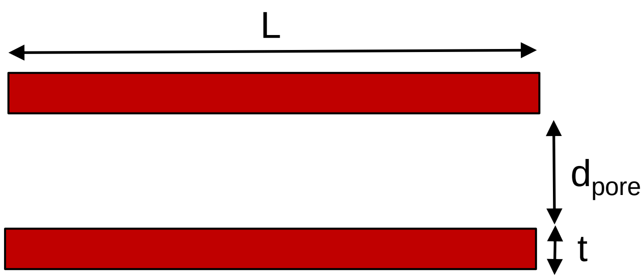
Sediment	e_{1kPa}	FC*
Silt	~0.7	~ 25 %
Kaolinite	~1.5	~ 20 %
Illite	~3.7	~ 11 %
Montmorillonite	~5.4	~ 8 %

Fines Migration and Clogging



J. Valdez

Grains and Pores: Clays



$$d_{pore} = \frac{2\,e}{S_s\,\rho}$$

MEAN PORE SIZE

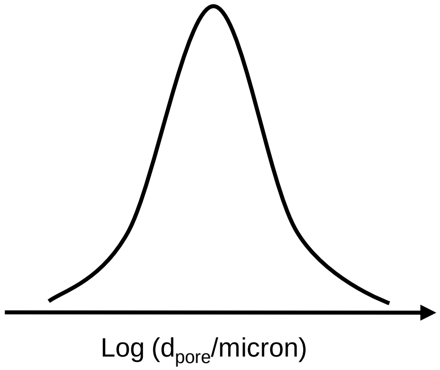
Sediment compaction

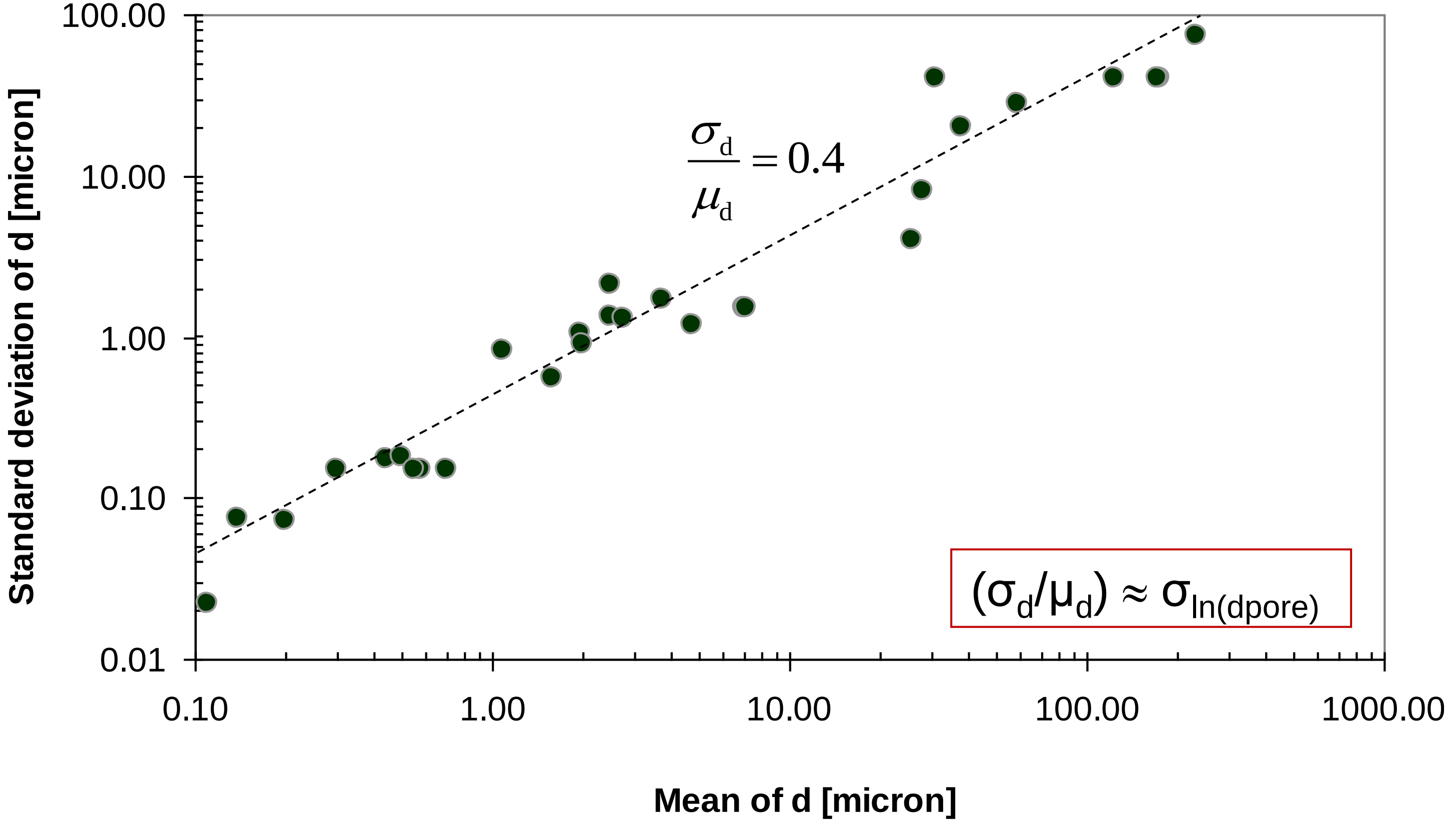
$$e = e_{1kPa} - C_c \log\left(\frac{\sigma'}{1kPa}\right)$$

Sediment	e_{1kPa}	C_C	S [m^2/g]	mean d_{pore}	ΔP [Mpa]
Silt	~0.7	0.02-0.09	0.045-1	5 μm	0.05
Kaolinite	~1.5	0.19-0.3	10-20	0.5 μm	0.5
Illite	~3.7	0.5-1.1	65-100	0.05 μm	5
Montmorillonite	~5.4	1-2.6	300-780	0.005 μm	50

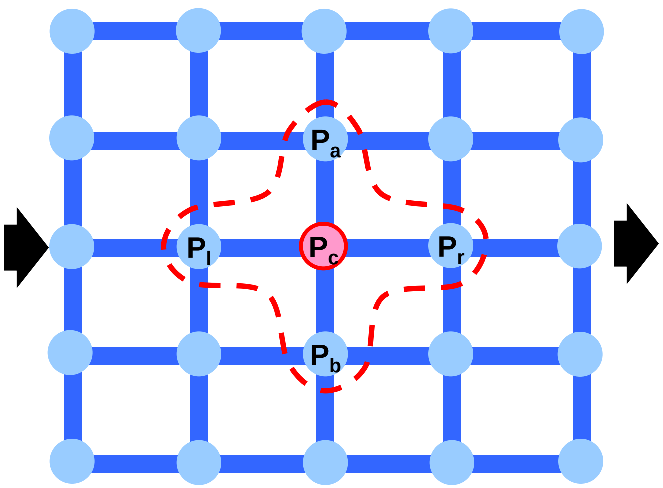
@ σ'=100 kPa σ_{LV}=70 mN/m

Pore Size Distribution





Network Models – Upscaling



Poiseuille's Eq.

$$q = \frac{\pi R^4}{8\eta \Delta L} \Delta P \quad \left(\alpha = \frac{\pi R^4}{8\eta \Delta L} \right)$$

Mass Balance at Nodes

$$0 = \sum q_c$$

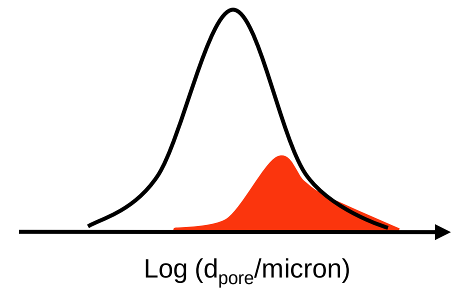
$$0 = \alpha_a (P_a - P_c) + \alpha_b (P_b - P_c) + \alpha_r (P_r - P_c) + \alpha_l (P_l - P_c)$$

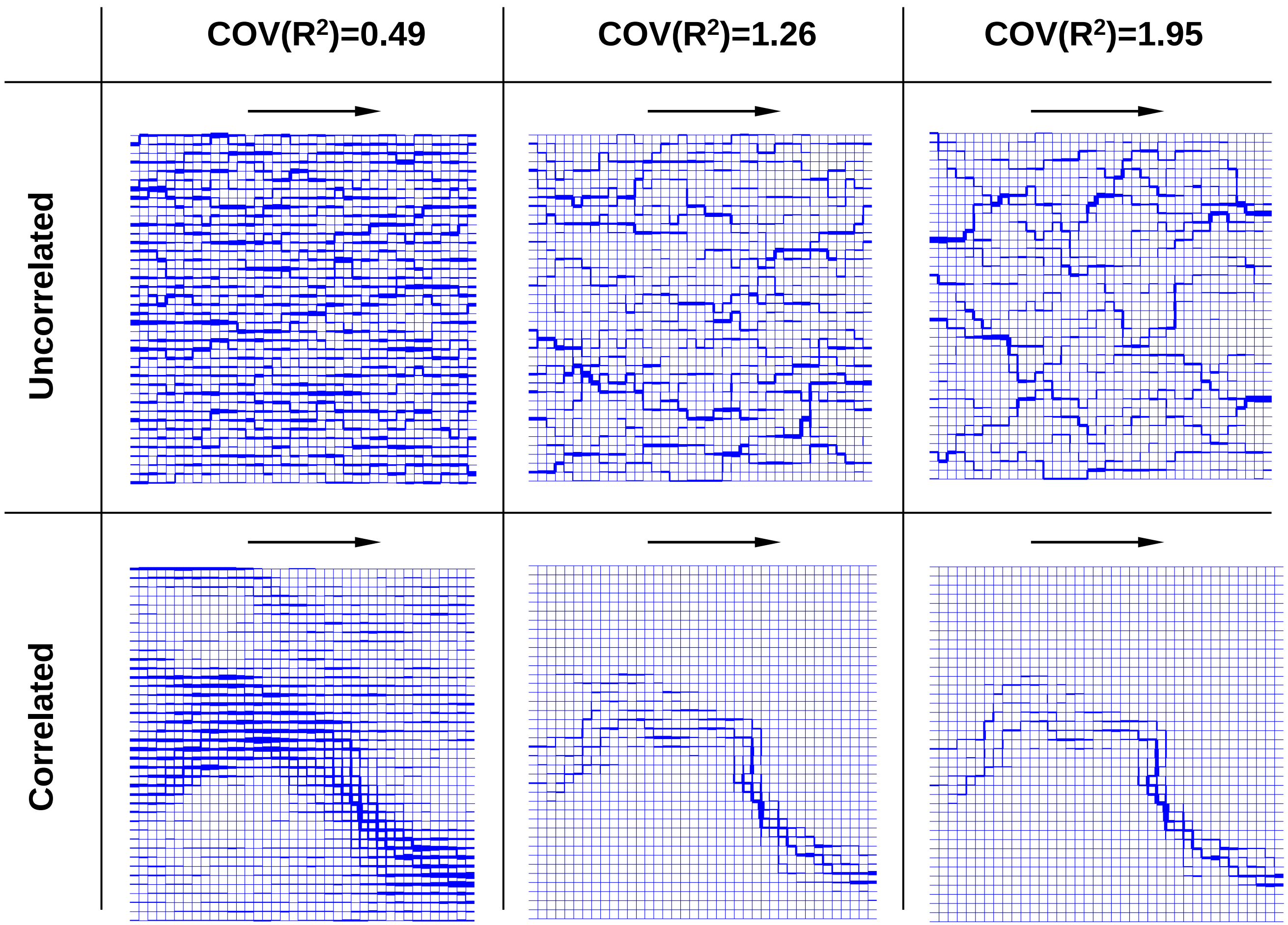
$$P_c = \frac{\alpha_a P_a + \alpha_b P_b + \alpha_r P_r + \alpha_l P_l}{(\alpha_a + \alpha_b + \alpha_r + \alpha_l)}$$

System of Equations

$$\underline{B} = \underline{\underline{A}}\, \underline{P} \quad \text{then} \quad \underline{P} = \underline{\underline{A}}^{-1} \underline{B}$$

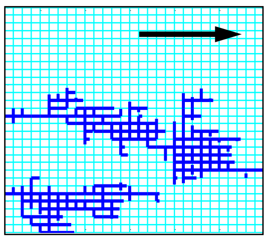
Spatially Correlated Porosity



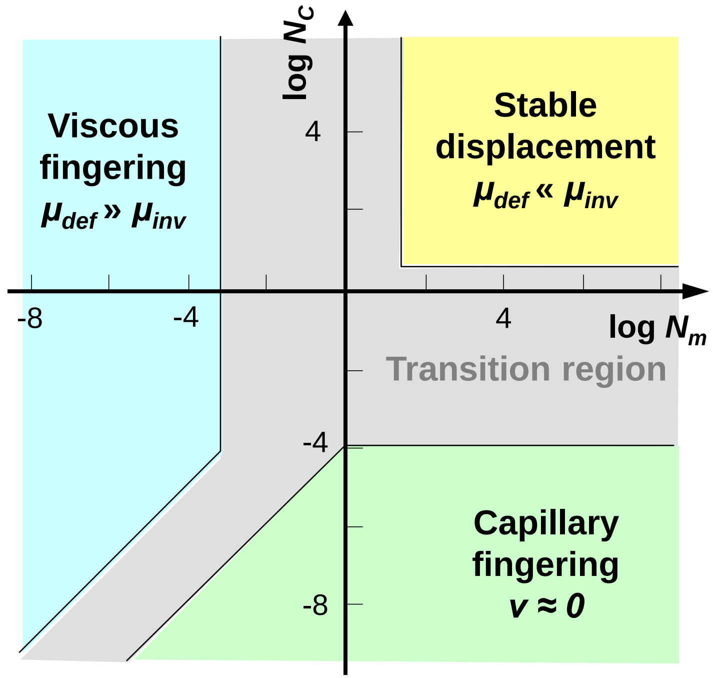


Immiscible Fluids: Invading vs. Defending

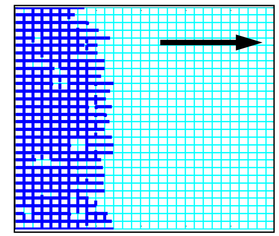
$$N_C = \frac{F_d}{F_c} = \frac{3\mu_{inv} v}{\sigma \cdot \cos\theta}$$



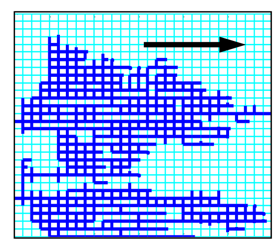
log N_m = -4.2
log N_c = 0.2



$$N_m = \frac{\mu_{inv}}{\mu_{def}}$$



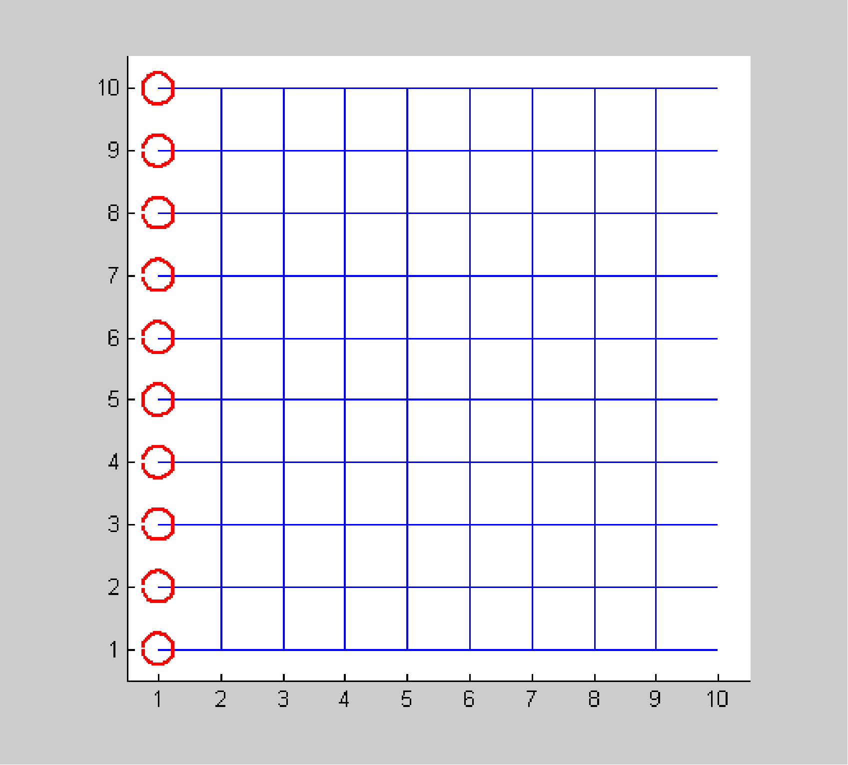
log N_m = 1.8
log N_c = 3.2



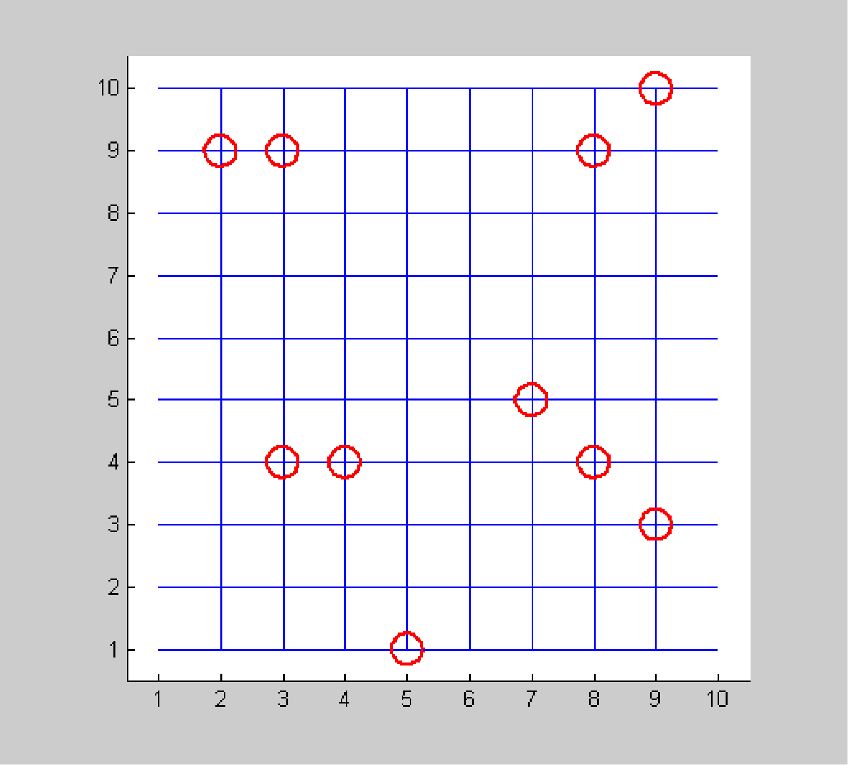
log N_m = 1.8
log N_c = -8.5

Gas Invasion vs. & Gas Nucleation

invasion

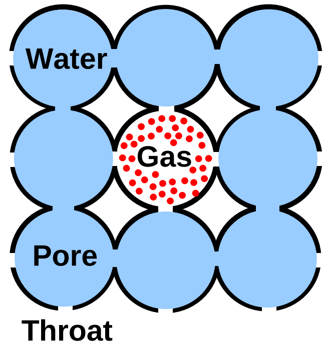


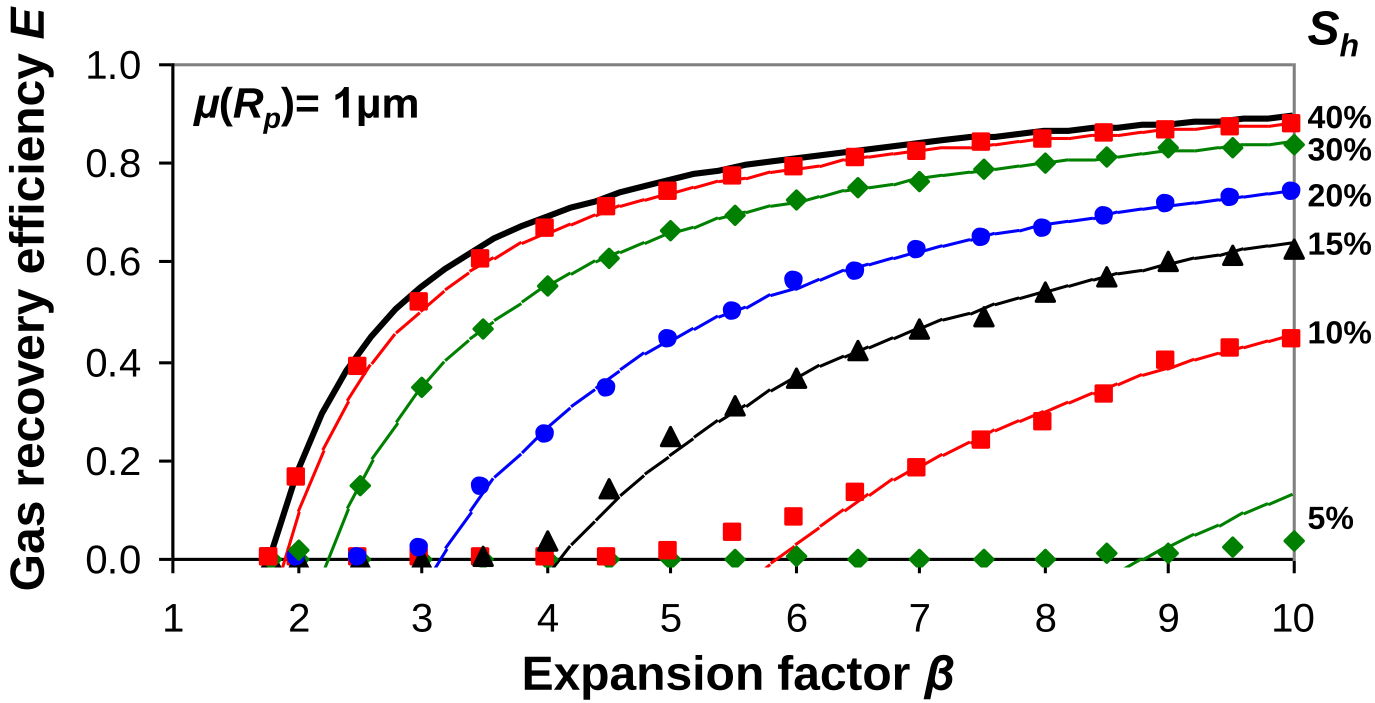
nucleation



Characteristic Curve ➔ Recovery Efficiency

Methane Hydrates





Summary: Grains and Pores

CAUTION — **fines content !**

Invasion — **pore size distribution and connectivity**

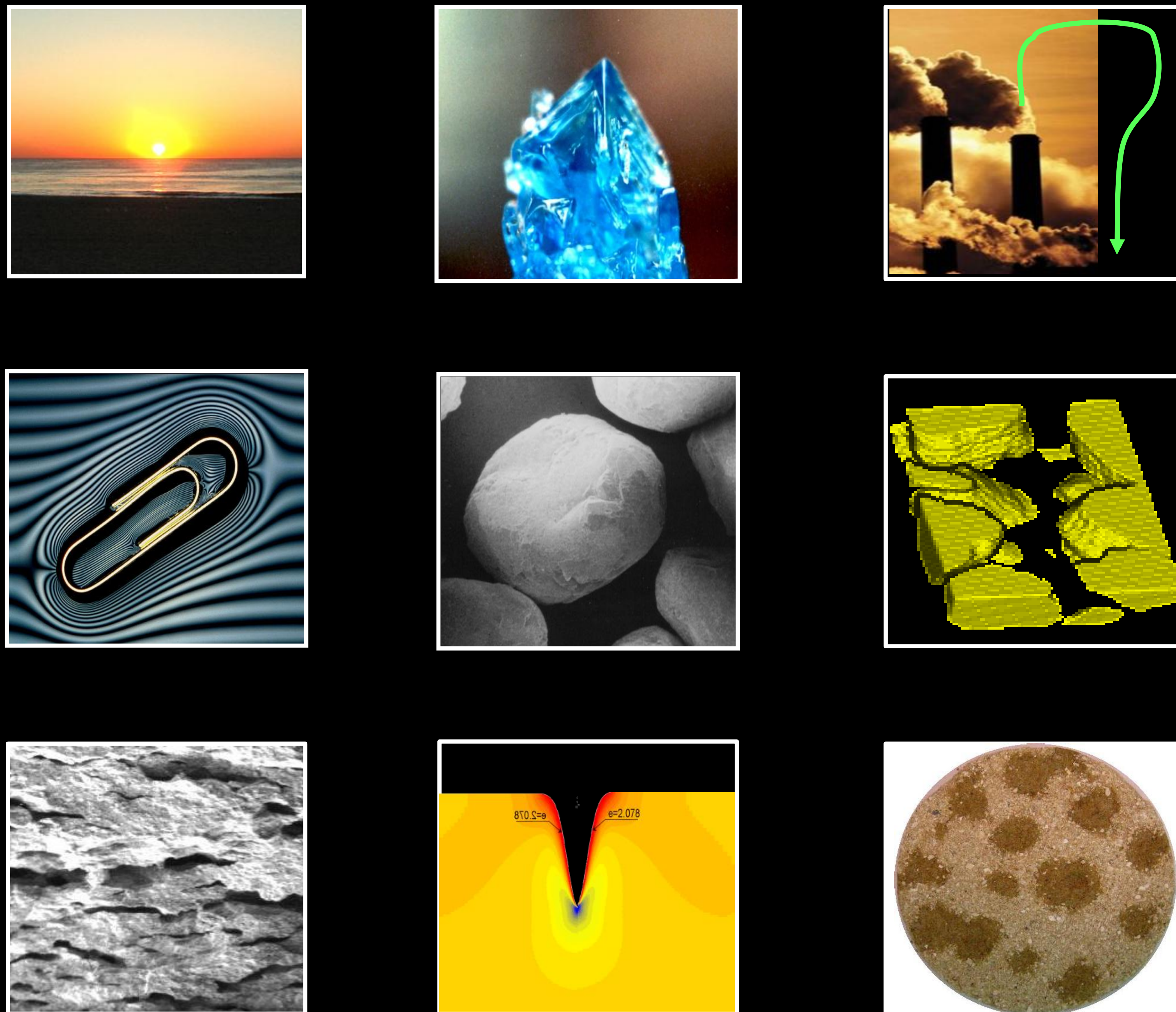
patterns: flow velocity and rel. viscosities

Gas invasion ≠ Gas nucleation

similar characteristic curve

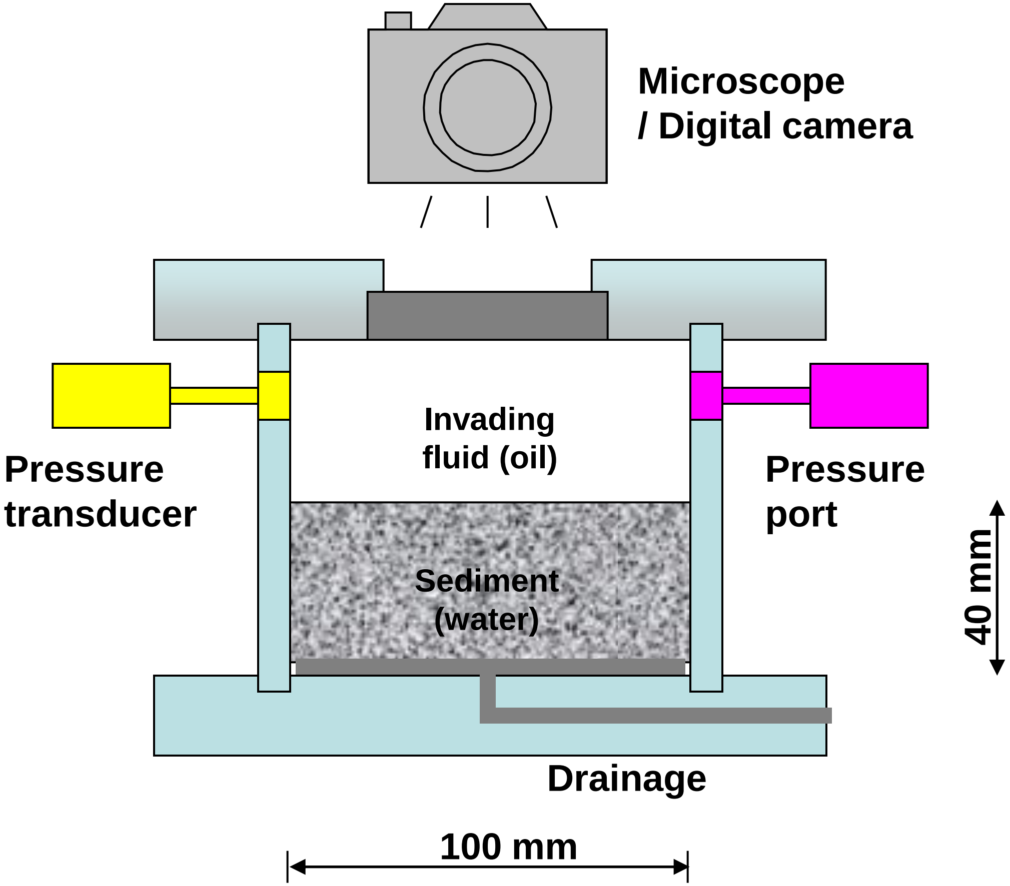
different relative permeabilities

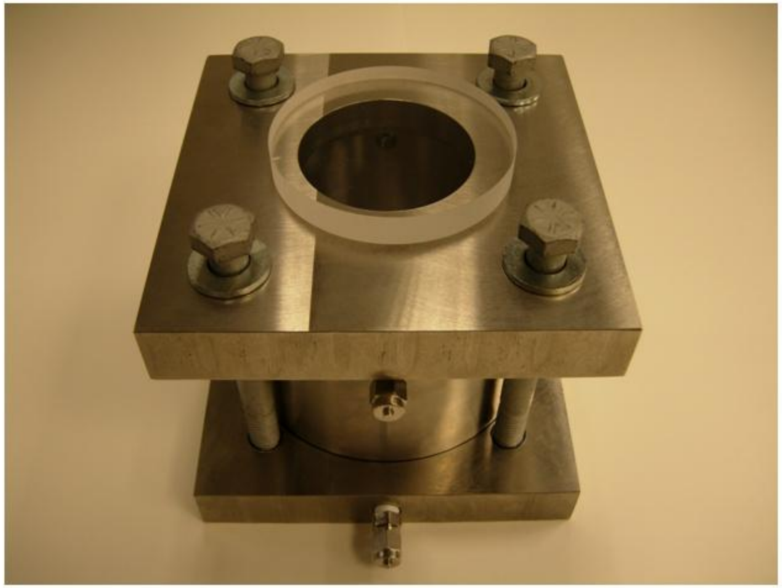
Characteristic curve ➔ Recovery efficiency



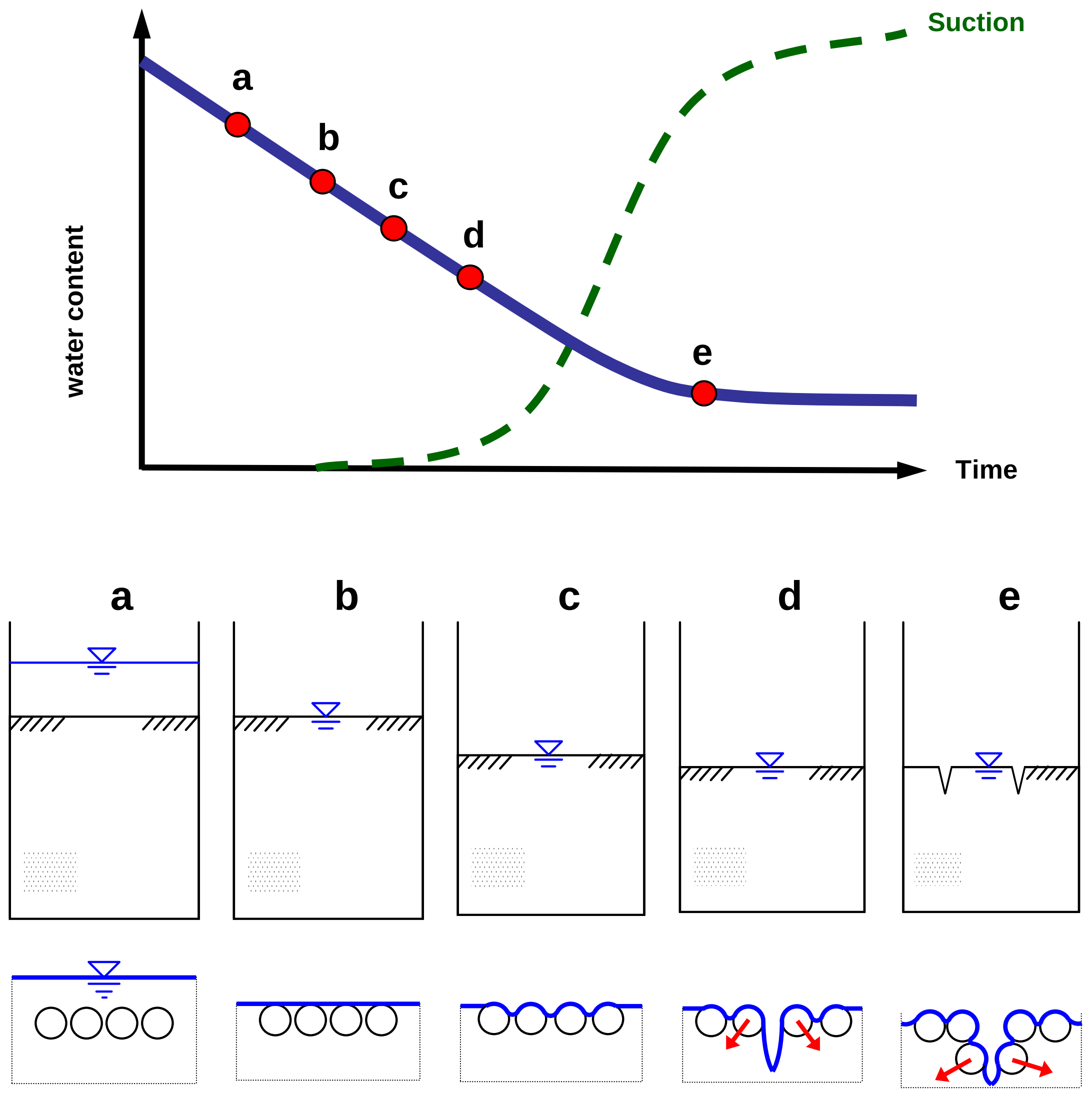
positive feedback in coupled THCM processes ➔ localizations

Forced Immiscible Fluid Invasion - Device

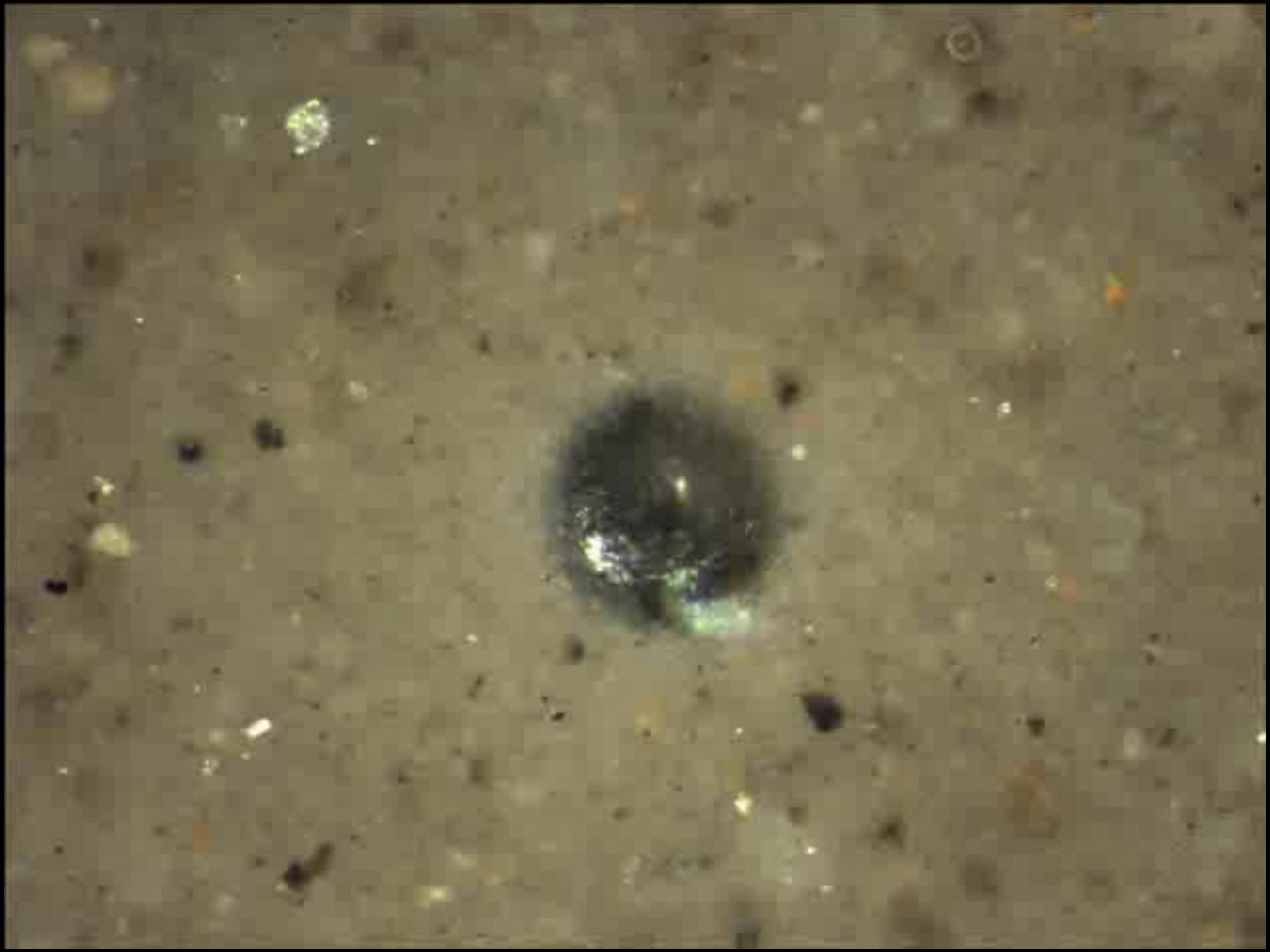




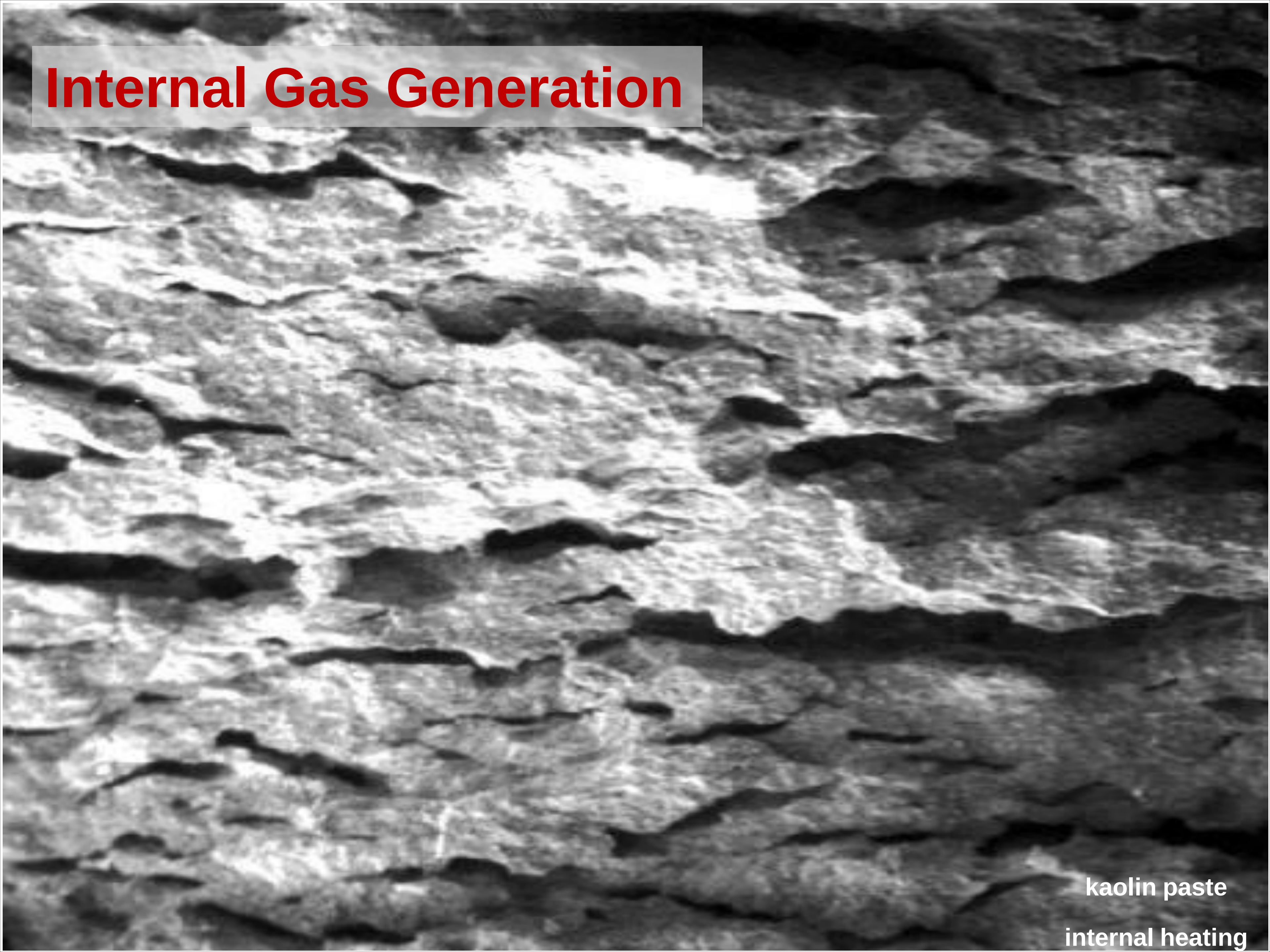
Evolution



Forcing Gas Into Sediment



Internal Gas Generation



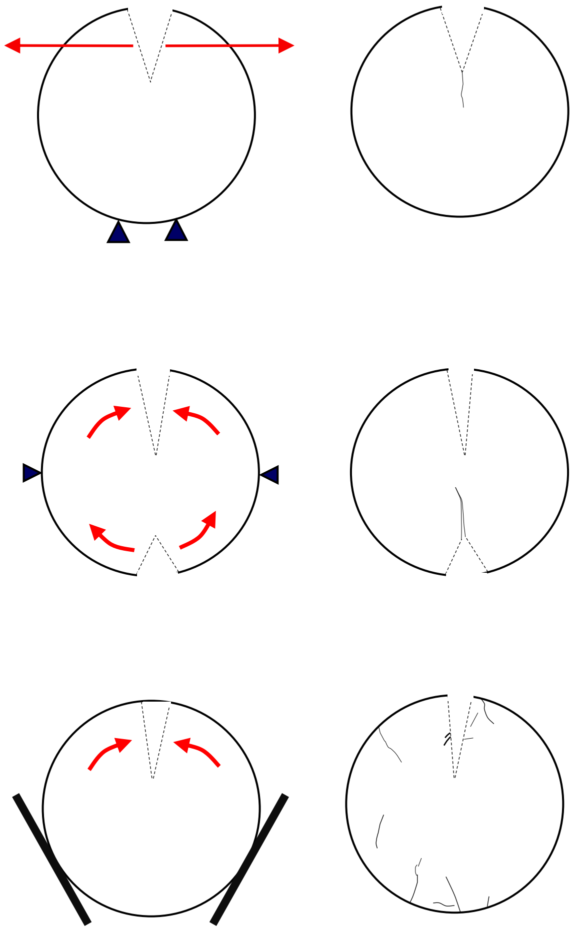
Ice Lenses

Ice Lens Formation Under Stress Boundary

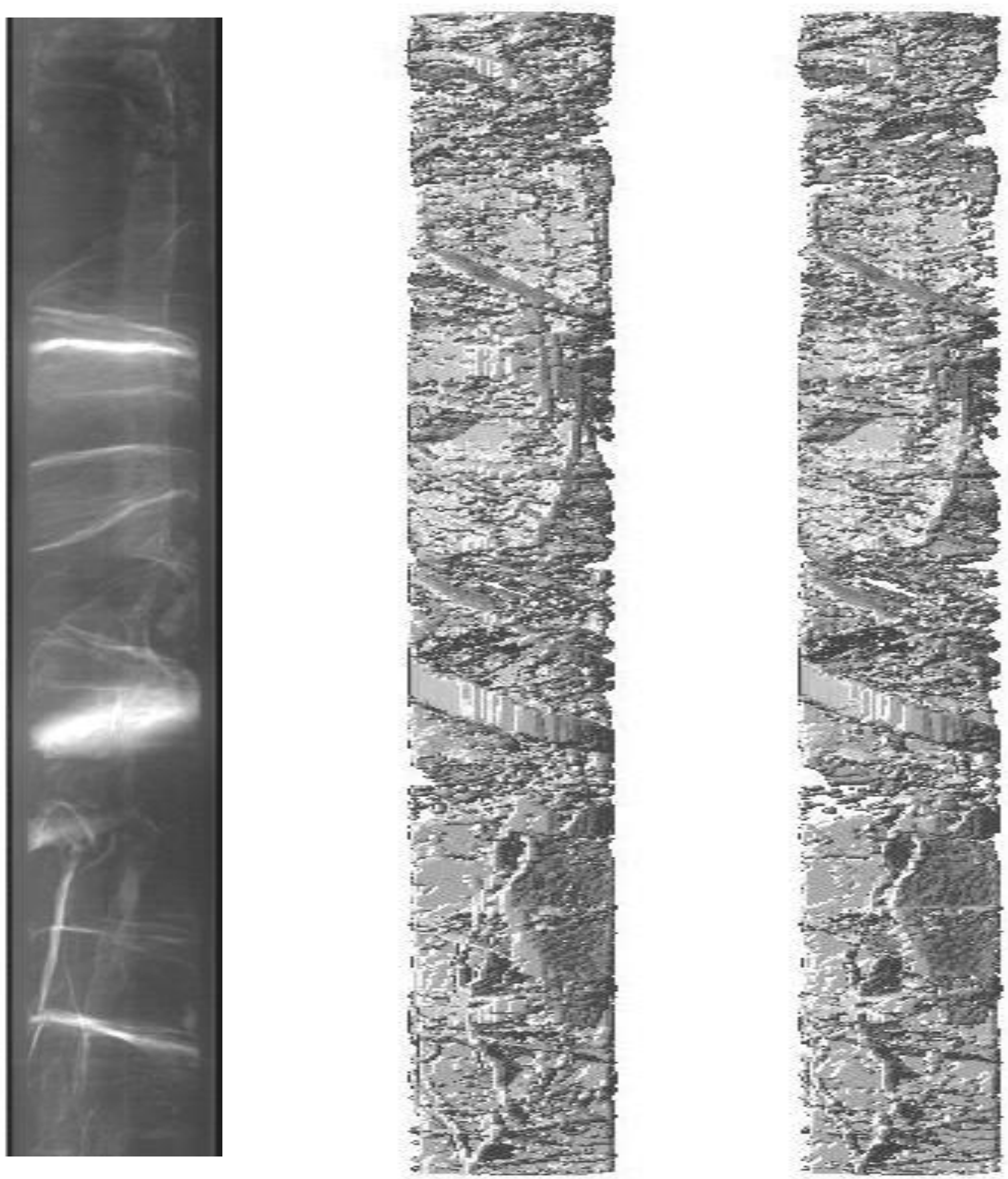
Tension

Tension / compression

Compression



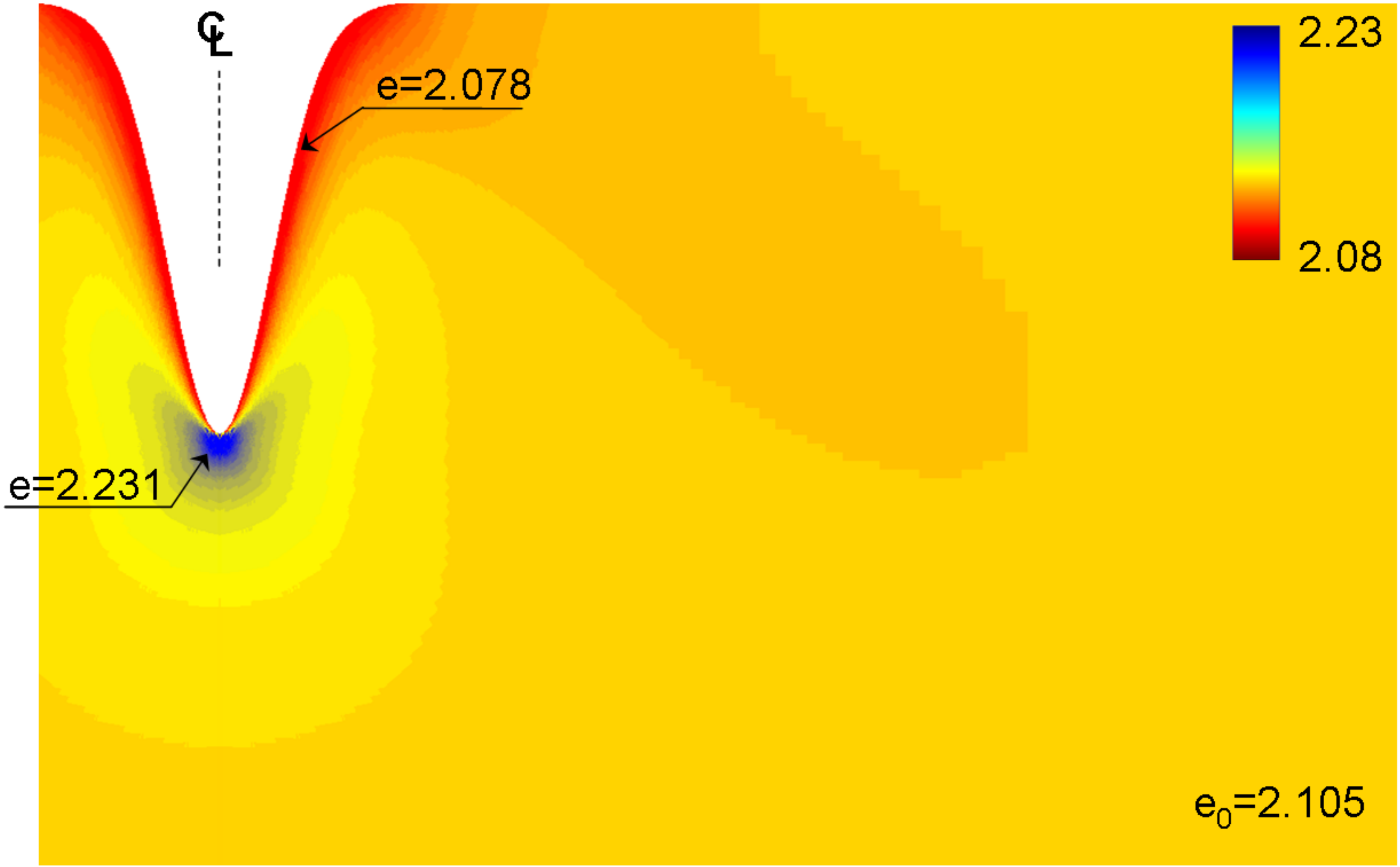
Hydrate lenses – Pressure cores



Percussion Core - KUB

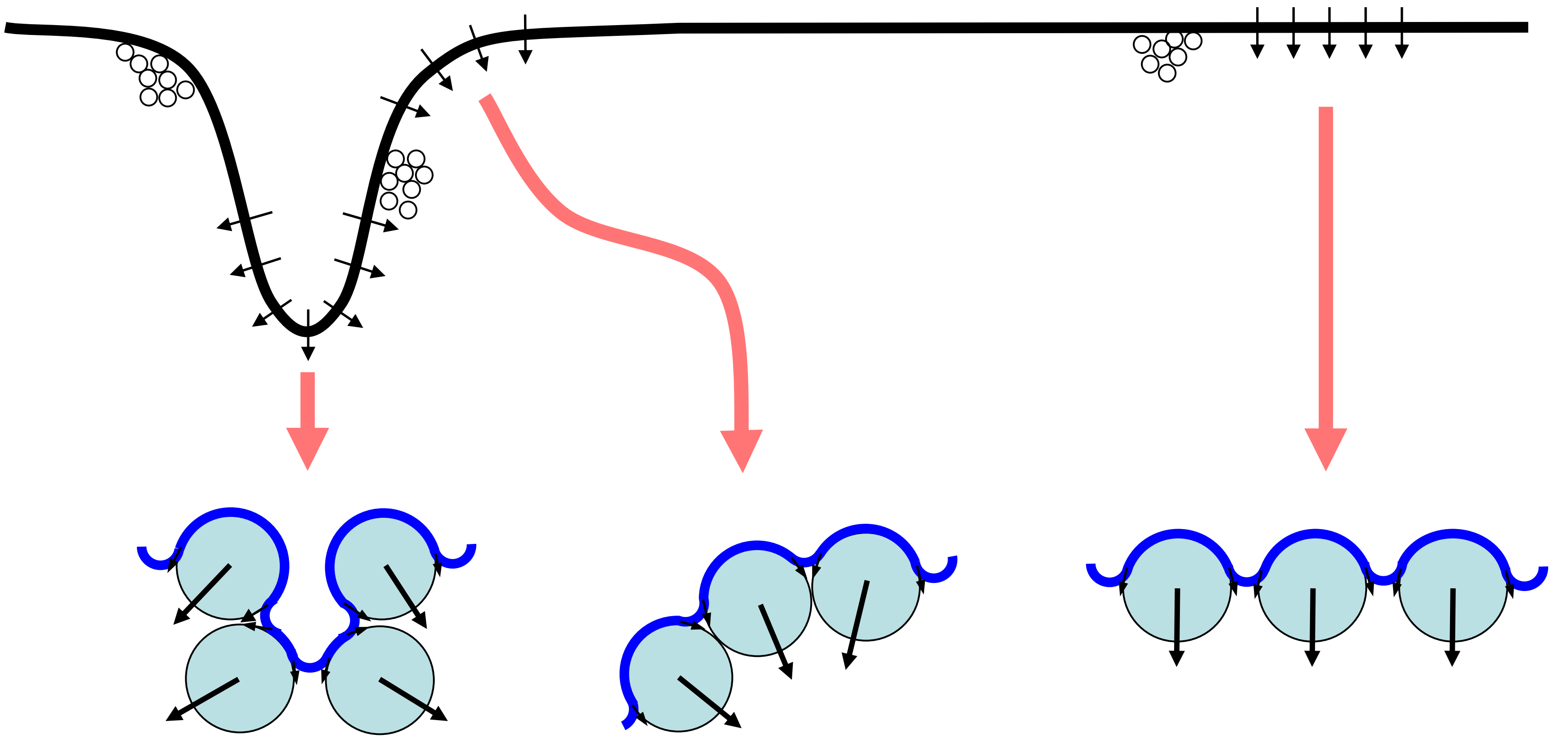
Tip Conditions

$$\Delta P = \frac{\rho \sigma_s S_s}{e}$$



Sediment in compression EVERYwhere

Gas-Driven Fracture

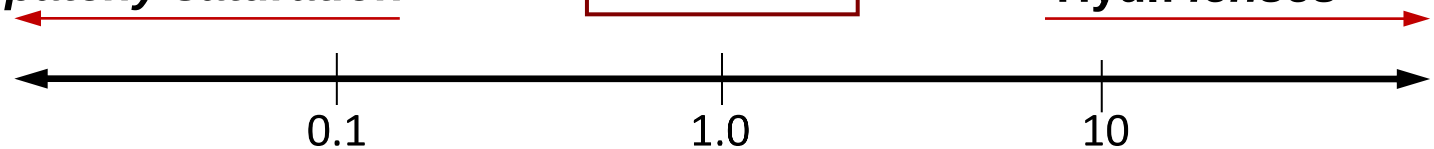


Invasion vs. Localization

INVASION
Fluid invasion
Crystal growth in pores
Hyd.: *patchy saturation*

$$\frac{F_c}{N} = \frac{2\pi\sigma_{LV}}{\sigma' d}$$

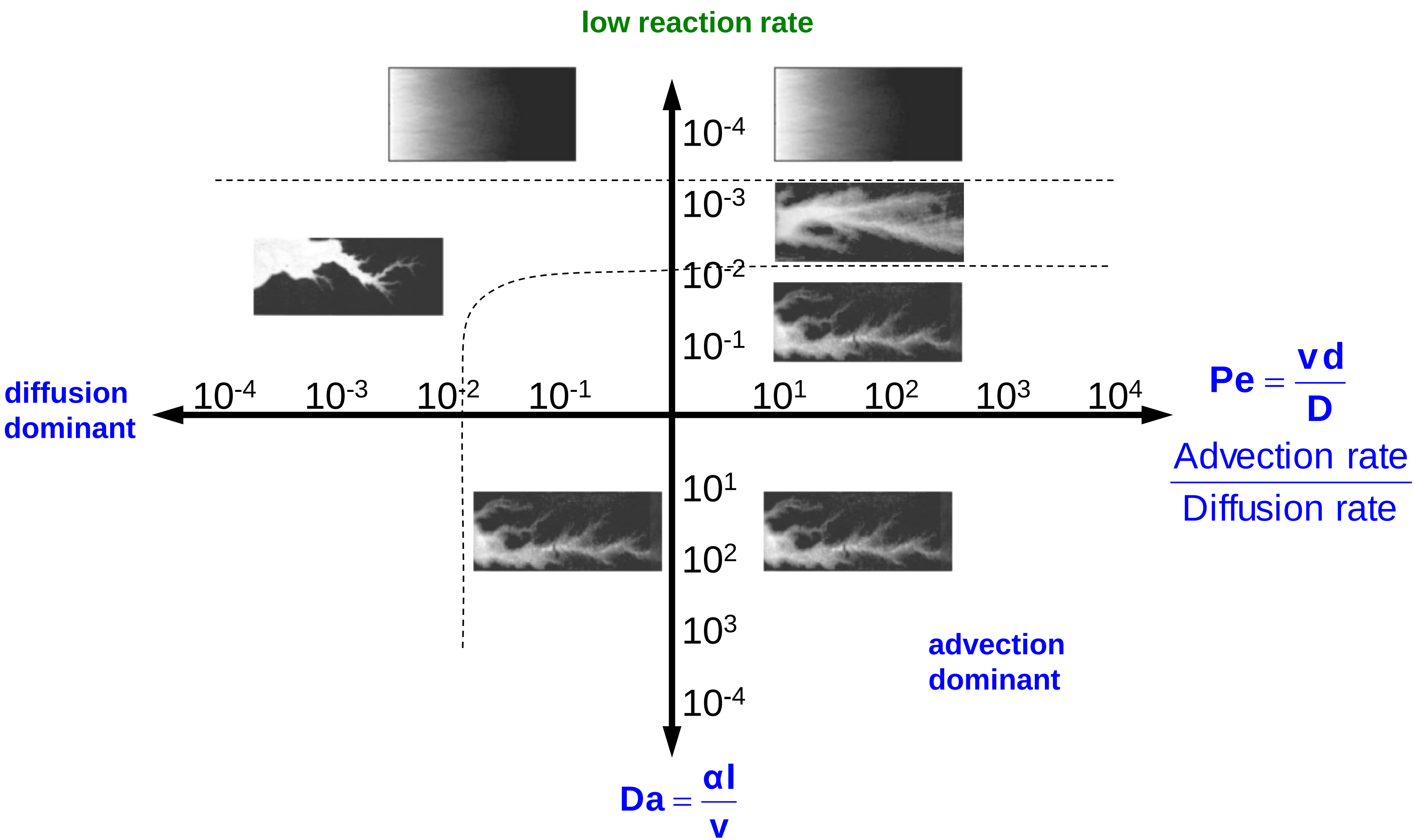
LOCALIZATION
Lenses
Fractures
Hyd.: *lenses*



coarse grained soils
high effective stress

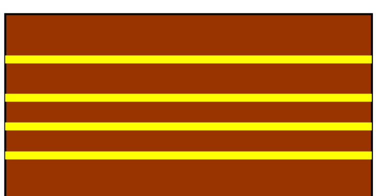
fine grained soils
low effective stress

Acidification: Reactive Transport

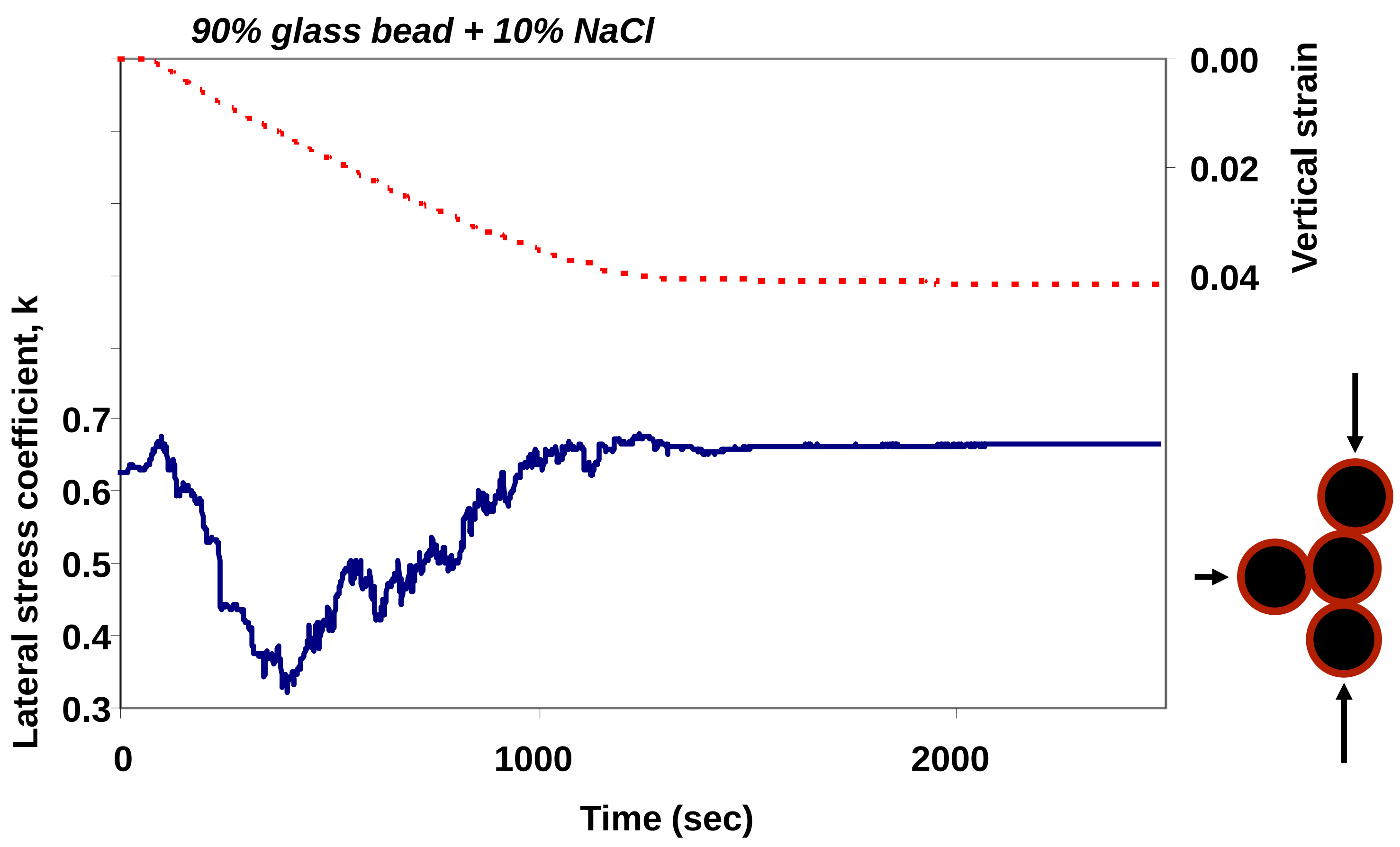


Fredd & Fogler 1988, 1998
Fredd & Miller's 2000
Golfier et al. 2002

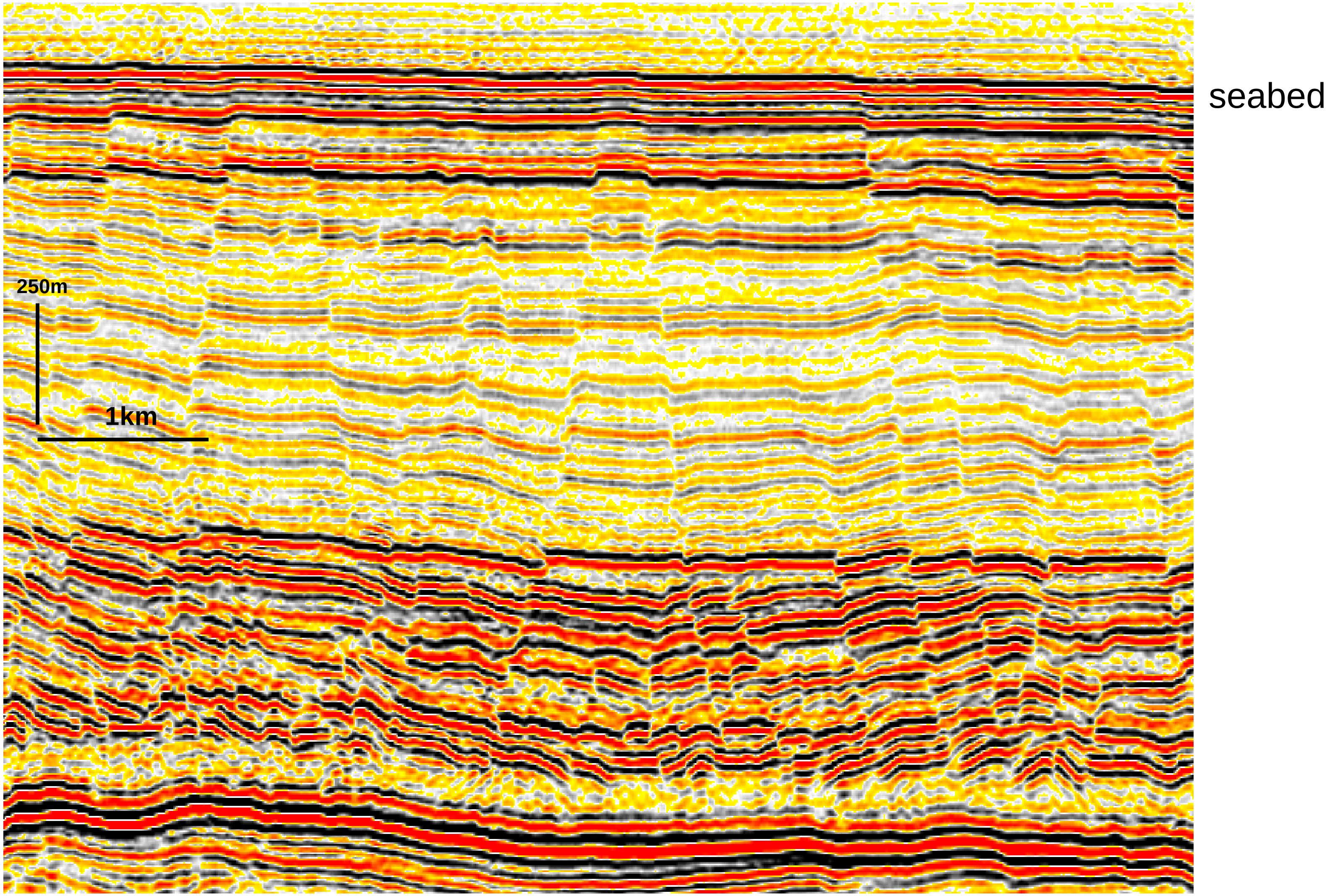
Dissolution + k ↑ + q ↑: Localized Flow



Dissolution ➔ k_o ↓



$k_o \rightarrow k_a$: Possible Shear Localization



Cartwright (2005)

Summary: Localizations

F_c/N explains hydrate formation habit

Various possible positive-feedbacks in coupled THCM

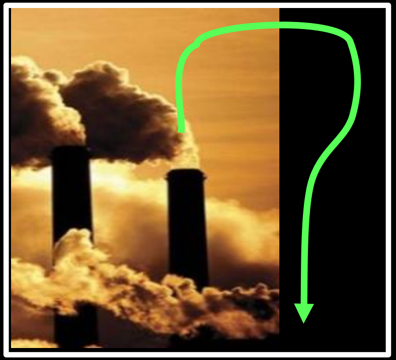
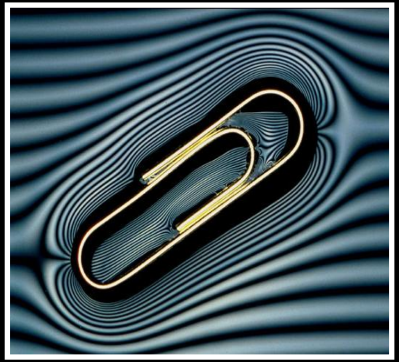
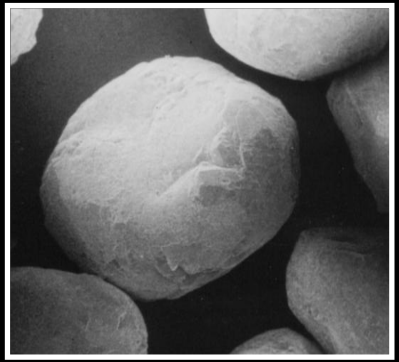
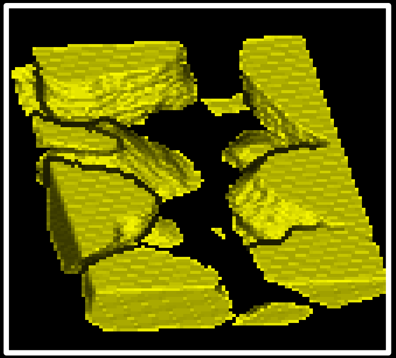
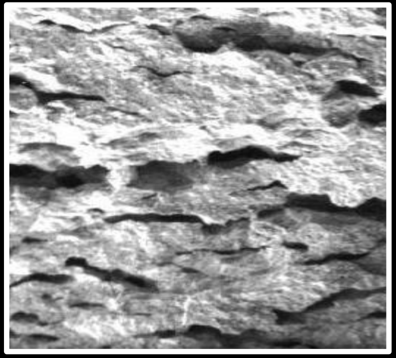
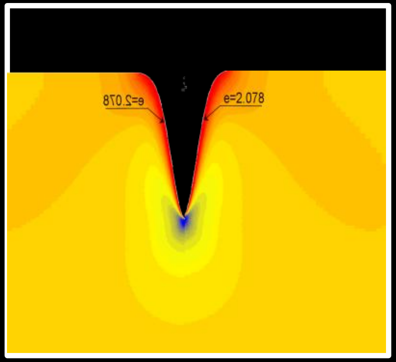
- Fluid-driven fractures: desiccation cracks, gas or oil-driven
- Lenses: ice, hydrate
- Dissolution: Shear fractures in contraction, wormholes

May hinder long-term CO_2 geological storage

Can be used to enhance recovery

In all cases: CAUTION









e=2.078


Closing Thoughts

Energy: critical to life

Energy geotechnology: fascinating BTHCEM coupled problems

Unsaturated soil mechanics: great framework but careful "extension"

Methane hydrates:

C-fuel + climate + hazard

Challenging: multi-physics, testing… production

CO_2 geological storage = C-economy + climate change

Must be reliable in the long time scales

Complex geo-plumbing

***Faustian bargain* ?**

Emergent phenomena & unanticipated coupled processes

Caution: positive feedback in coupled processes

Various localizations can be anticipated

F. Francisca

T.S. Yun

J.Y. Lee

A.I. Martin

D. Cortes

T.H. Kwon

P. Taboada

C.H. Lee

J.W. Jung

H. Shin

N. Espinoza

S. Dai

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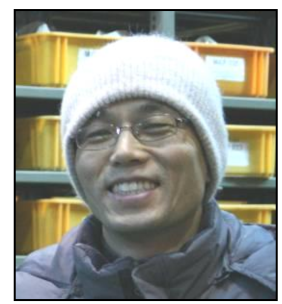

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