23 Prague Geotechnical Lecture
Praha 2015

A particle-level review of

Soil Behavior

- macroscale implications -

J. Carlos Santamarina
KAUST

Terzaghi (1883-1963)

"… Coulomb… purposely ignored the fact that [soils] consist of individual grains

Coulomb's idea proved very useful as a working hypothesis …. but it developed into an obstacle against further progress

[let's start] again from the elementary fact that [soils] consist of individual grains"

Terzaghi (1920, ENR)

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

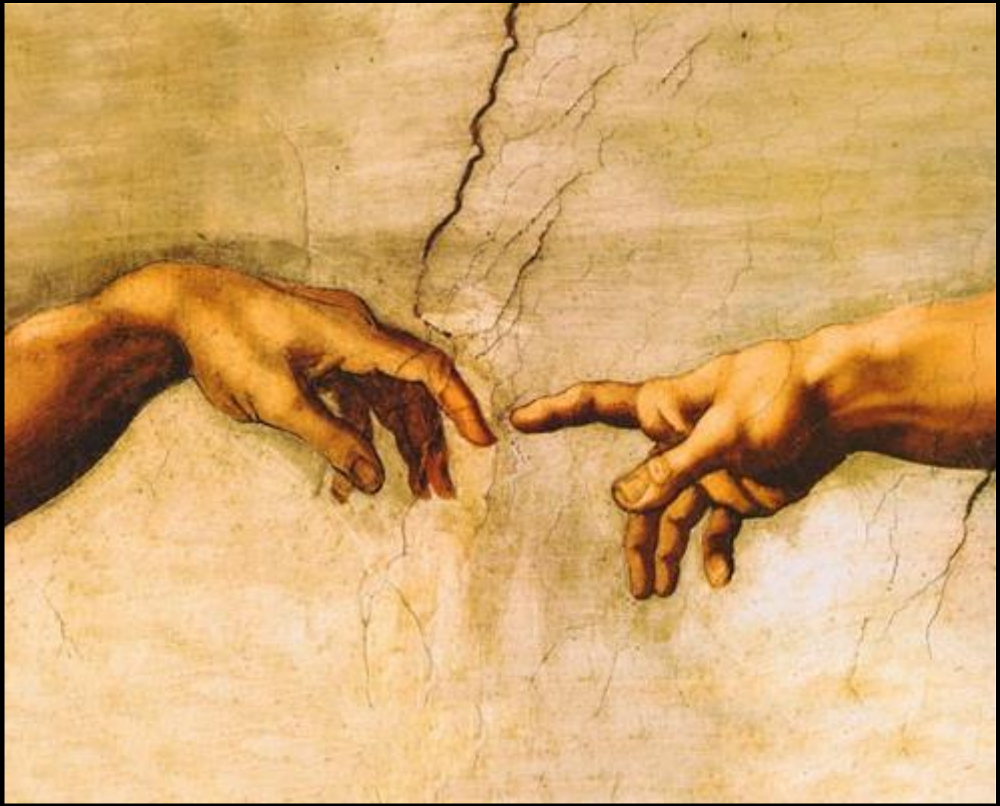
Shear strength

Stiffness

Pores

Permeability

Mixed fluids



Michelangelo

Mechano-Genesis: Gravels, Sands… some Silts

crushed granite

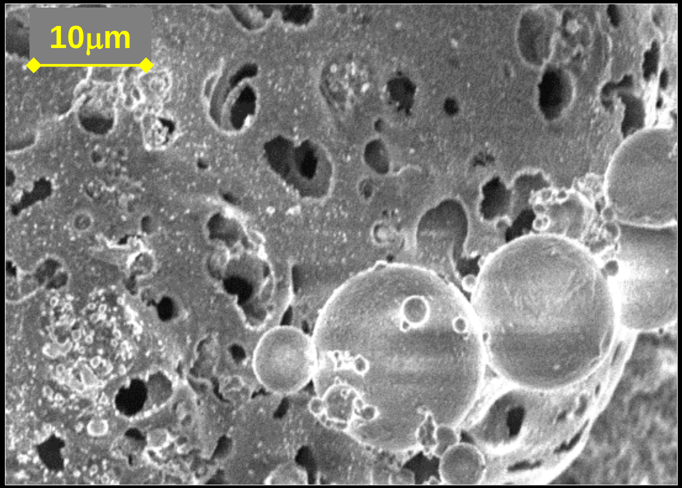
100μm

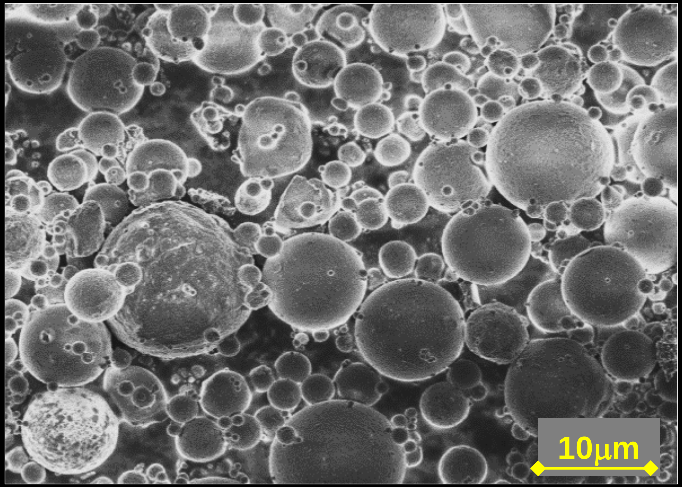
Ottawa sand

100μm

Thermo-Genesis: Ash

fly ash

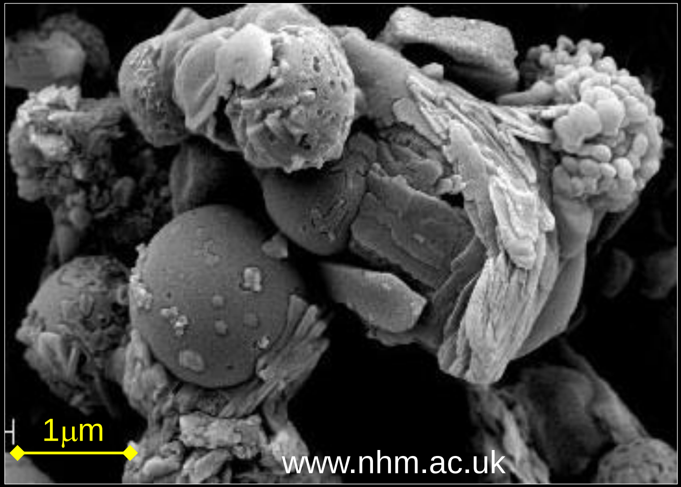


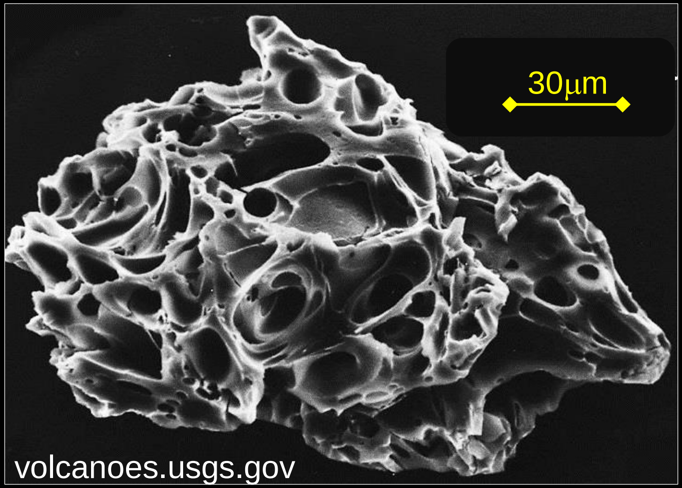


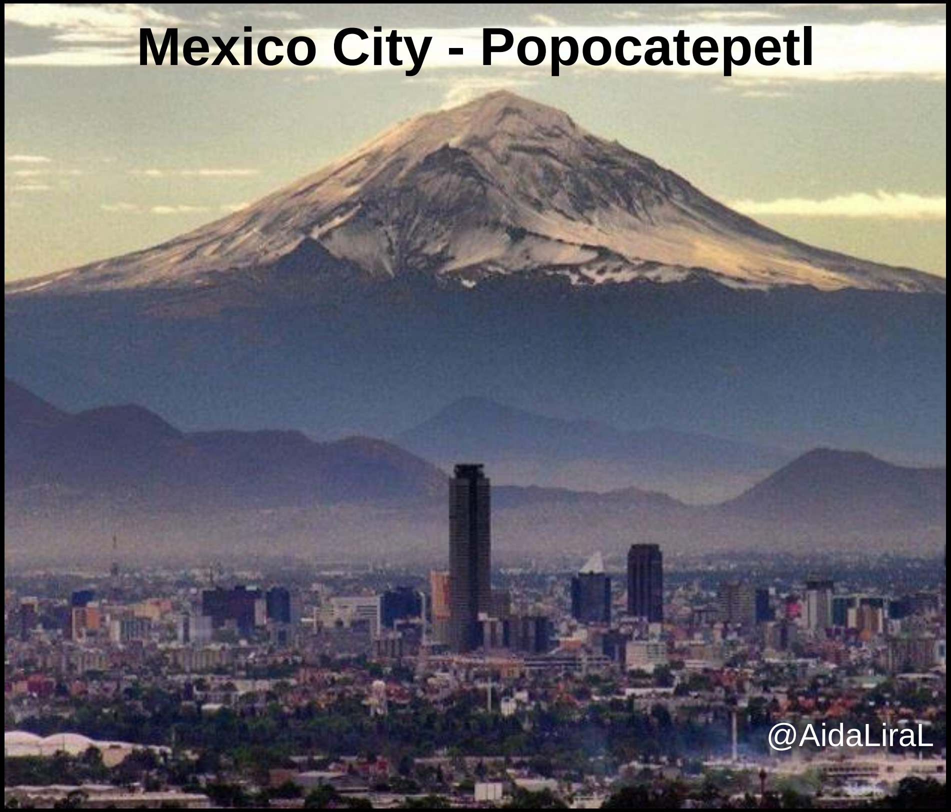
(US EPA)

Thermo-Genesis: Ash

volcanic ash



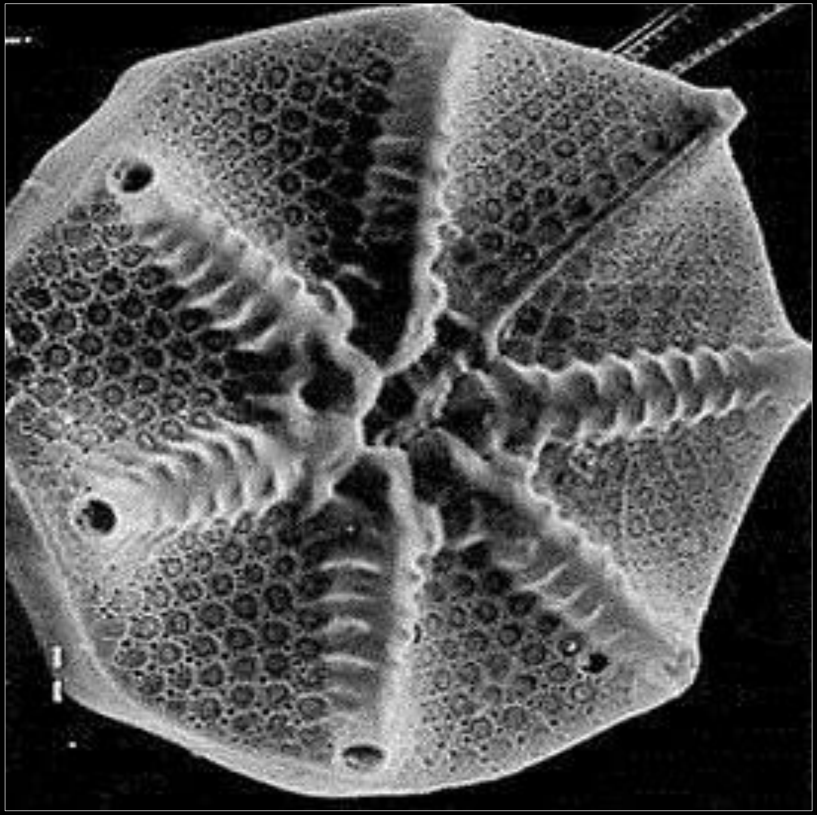




LL> 250

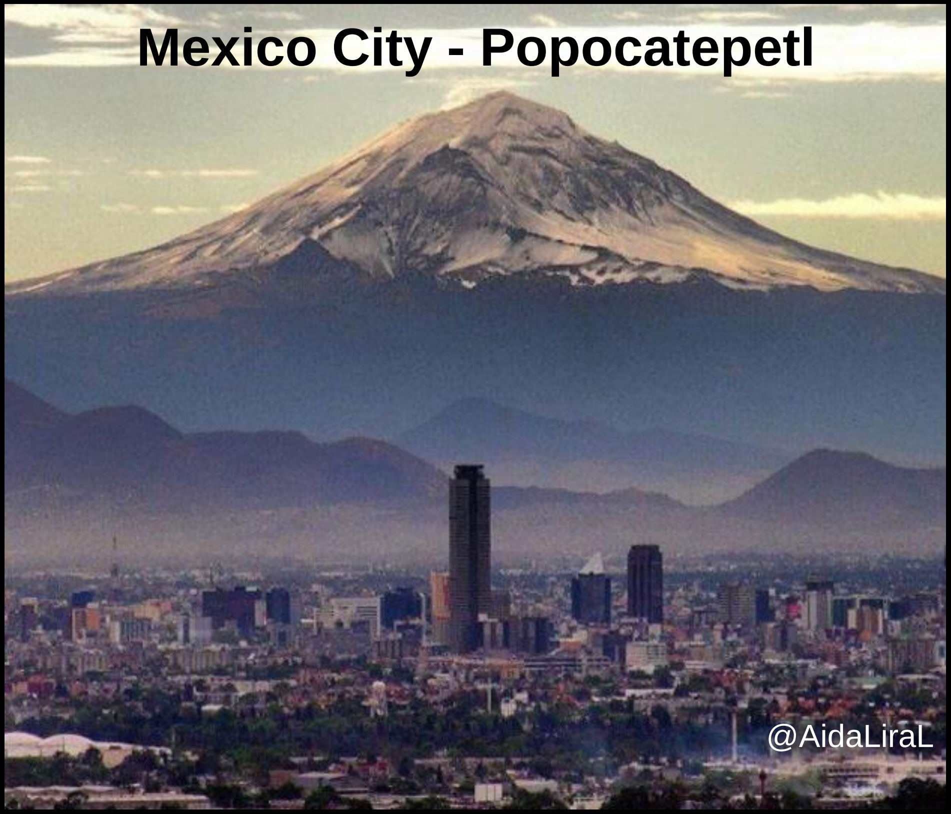
ϕ > 42° ?

Bio-Genesis: Diatoms



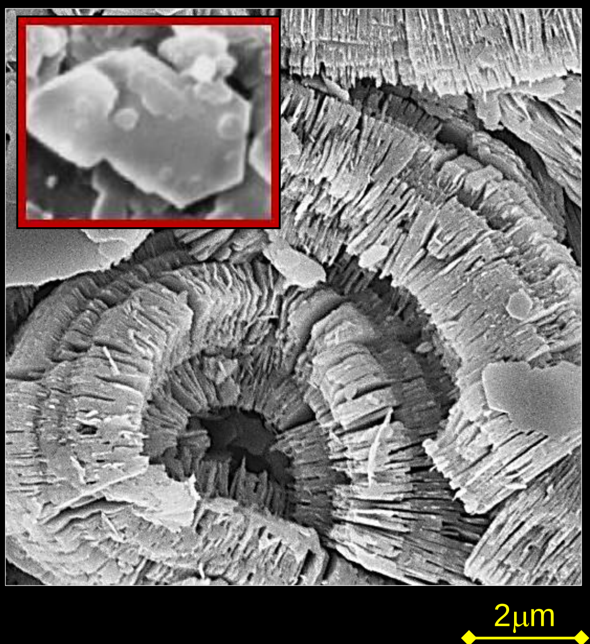
The Diatoms –1990

10μm



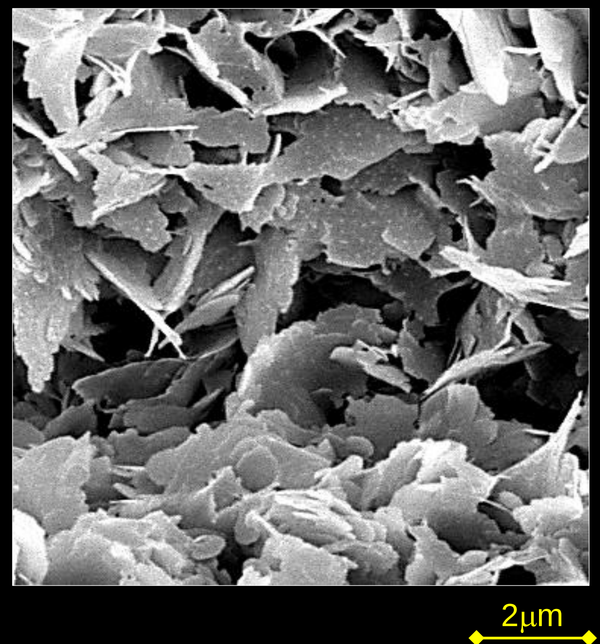
Chemo-Genesis: Clays

kaolinite



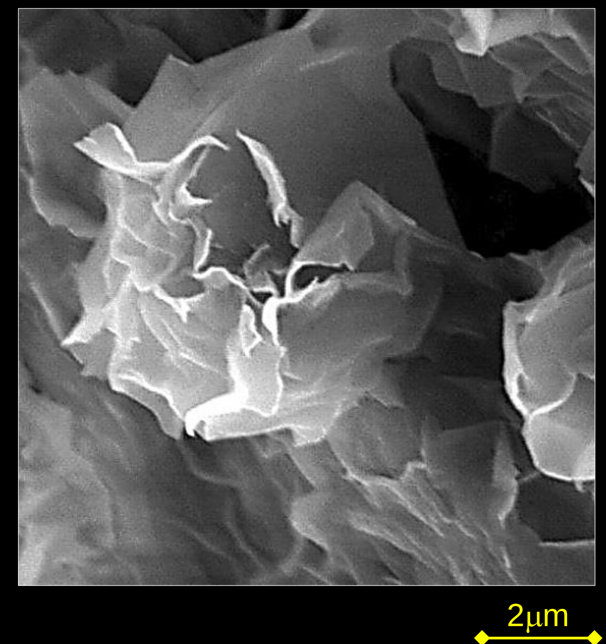
S_s= 10 m^2/g

illite



S_s= 50 m^2/g

smectite



S_s= 300 m^2/g

http://www.minersoc.org

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

Stiffness

Pores

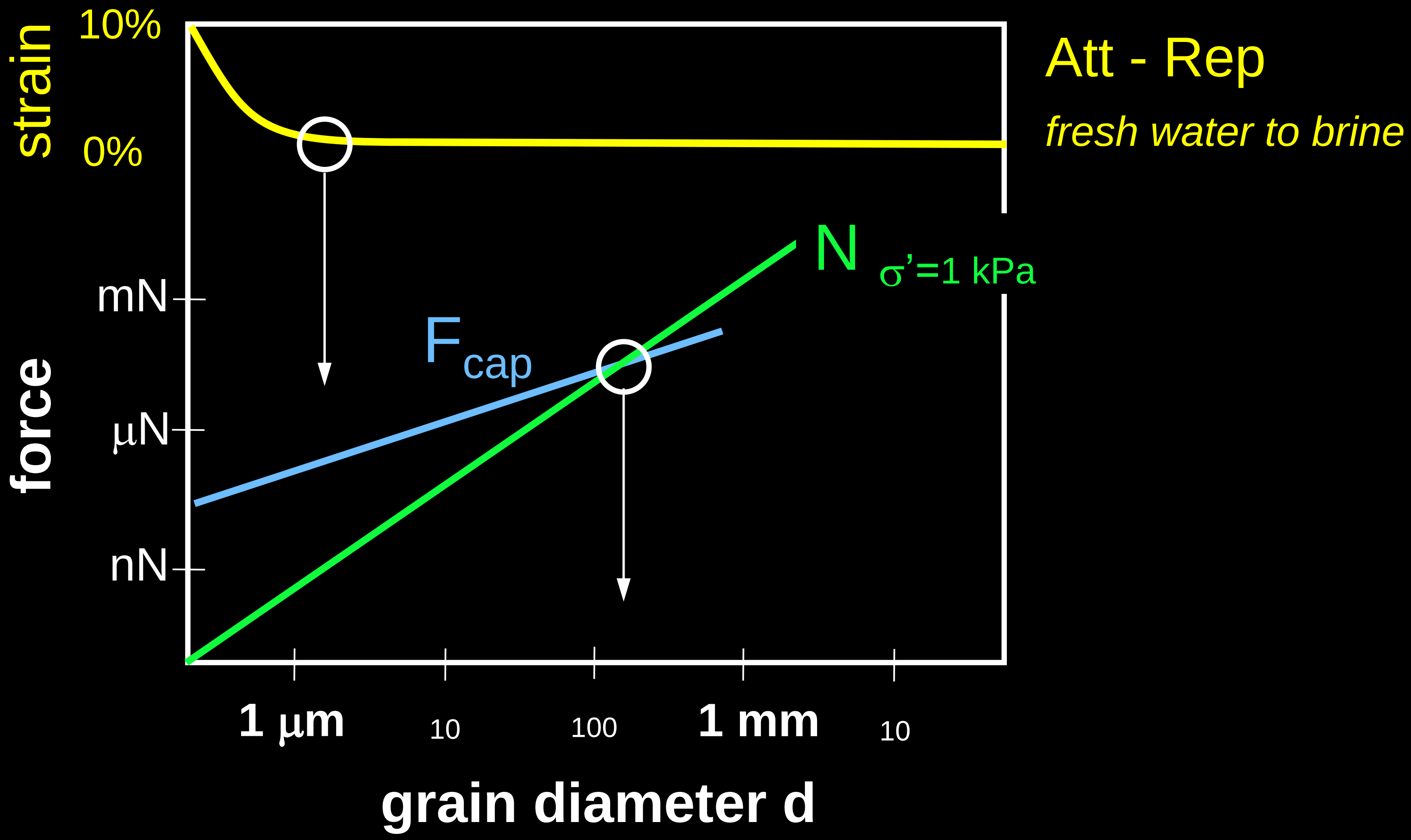
Permeability

Mixed fluids

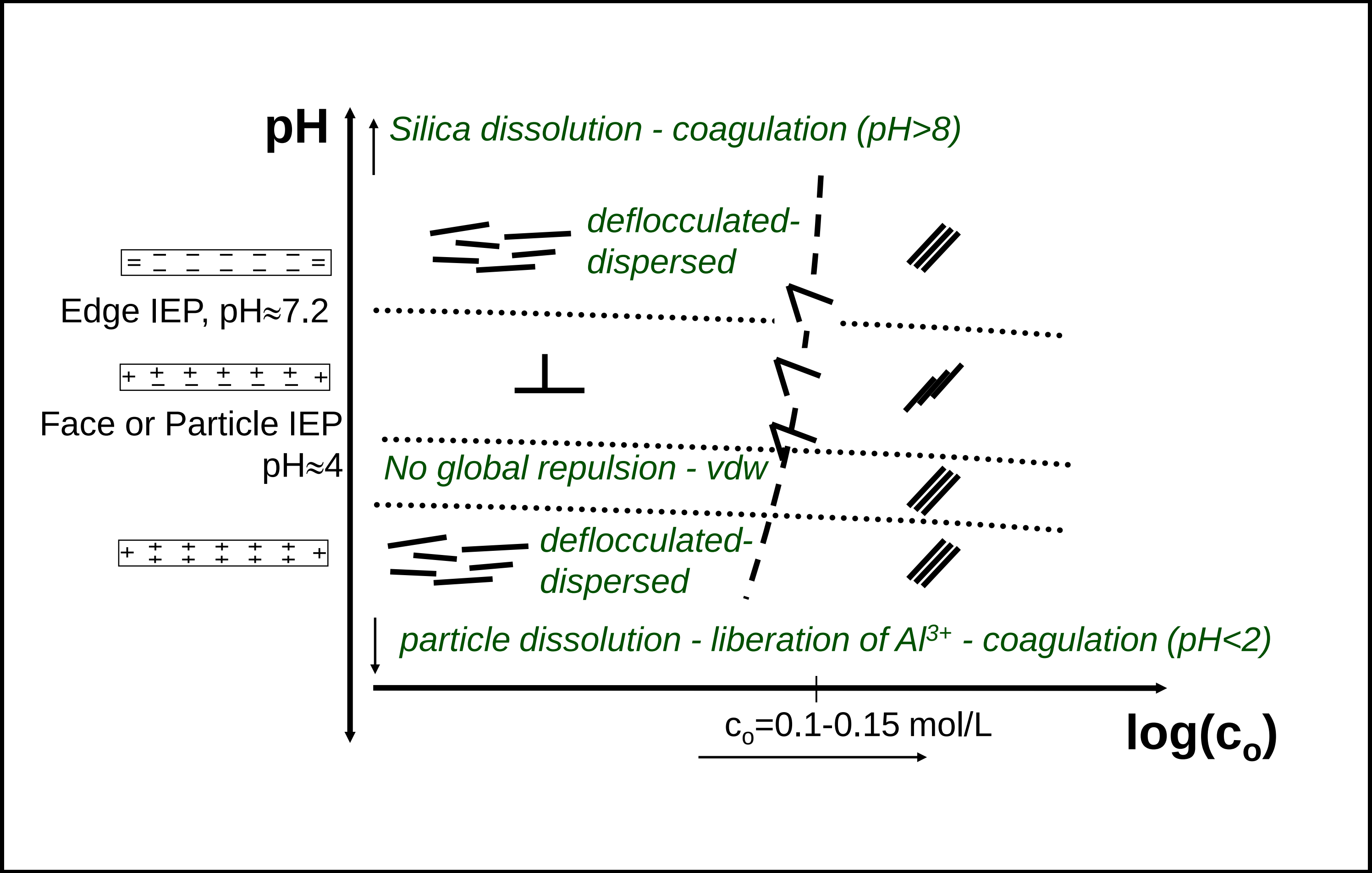
Particle Forces – Spherical Particles

Skeletal	$\underline{N} = \sigma' d^2$
Weight	$W = (\pi G_s \gamma_w / 6) d^3$
Buoyant	$U = Vol \cdot \gamma_w = (\pi \gamma_w / 6) d^3$
Hydrodynamic	$F_{drag} = 3\pi \mu v d$
Capillary	$F_{cap} = \pi T_s d$
Electrical	
attraction	$Att = \frac{A_h}{24t^2} d$
repulsion	$Rep = 0.0024 \sqrt{c_o}\, e^{-10^8 t \sqrt{c_o}} d$
Cementation	$T = \pi \sigma_{ten} t d$

Force Balance: Deformation & Strength



Fine-Grained Fabric: Fluid dependent



kaolinite

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

Stiffness

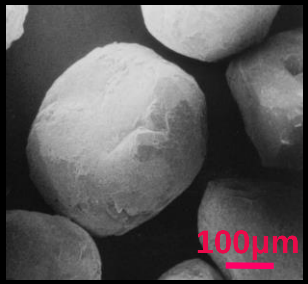
Pores

Permeability

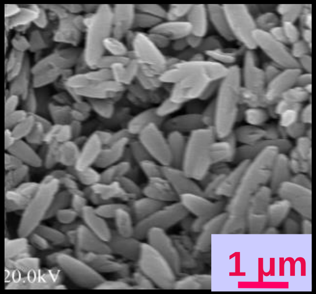
Mixed fluids

Particle Shape

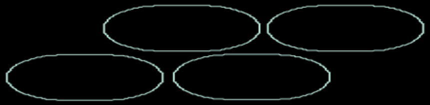
size d



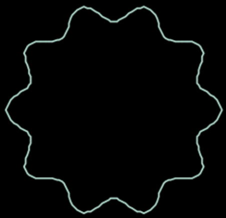
sphericity
ellipticity..platiness

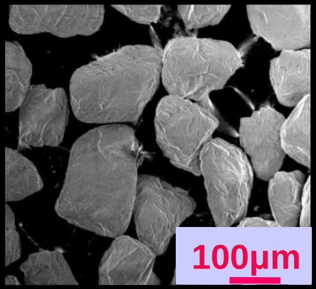


alignment

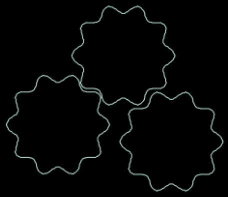


roundness
angularity

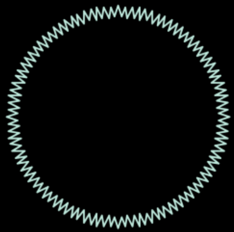


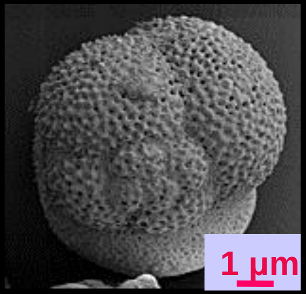


interlocking

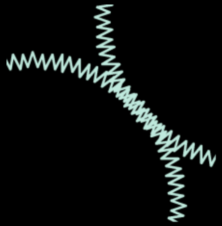


smoothness
roughness



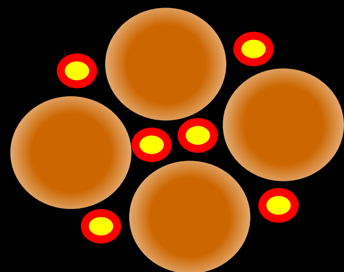


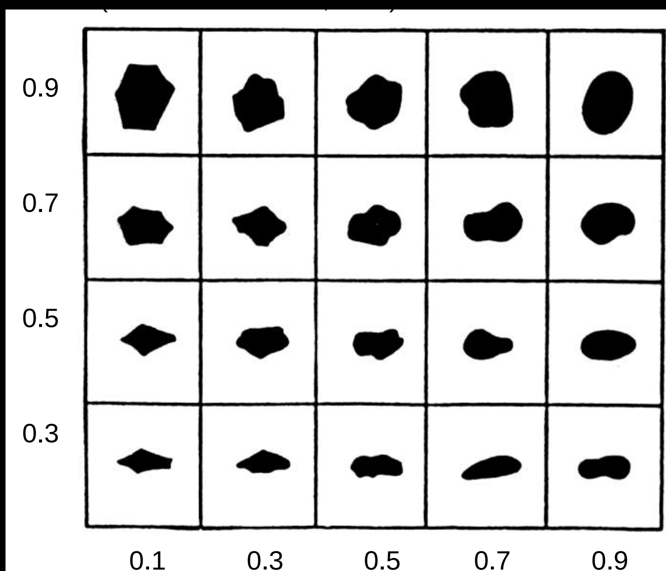
surface μ

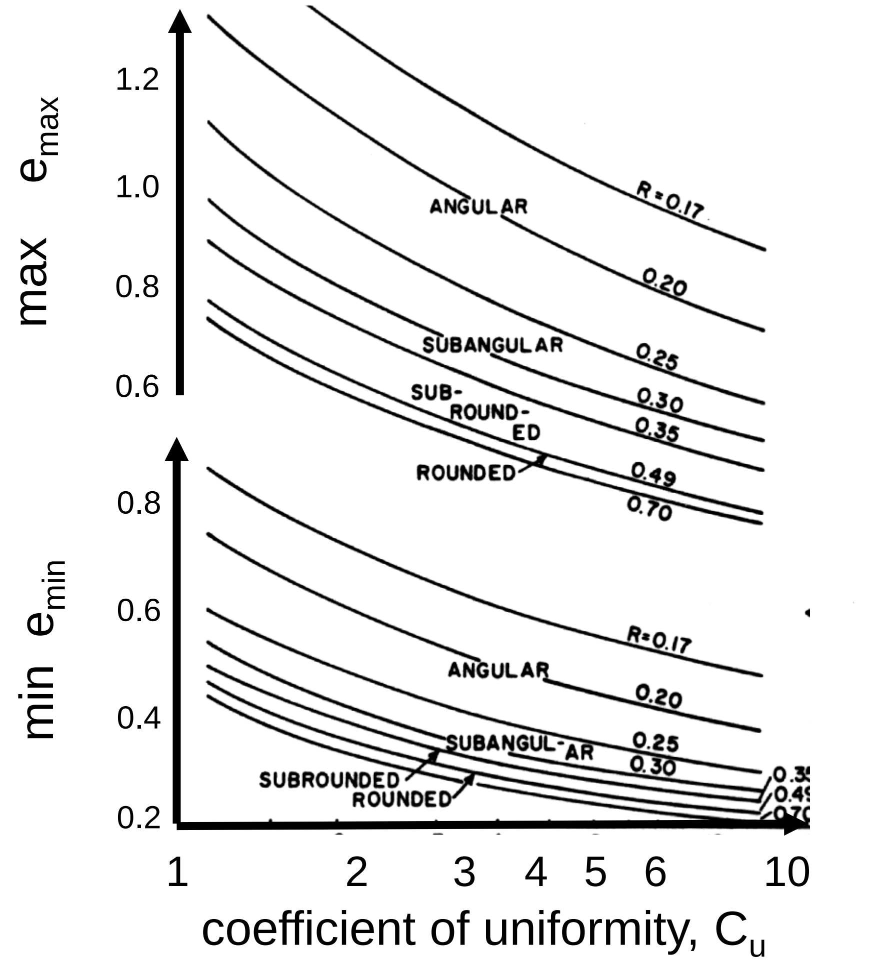


Coarse Grained: Shape + Relative Size

C_u

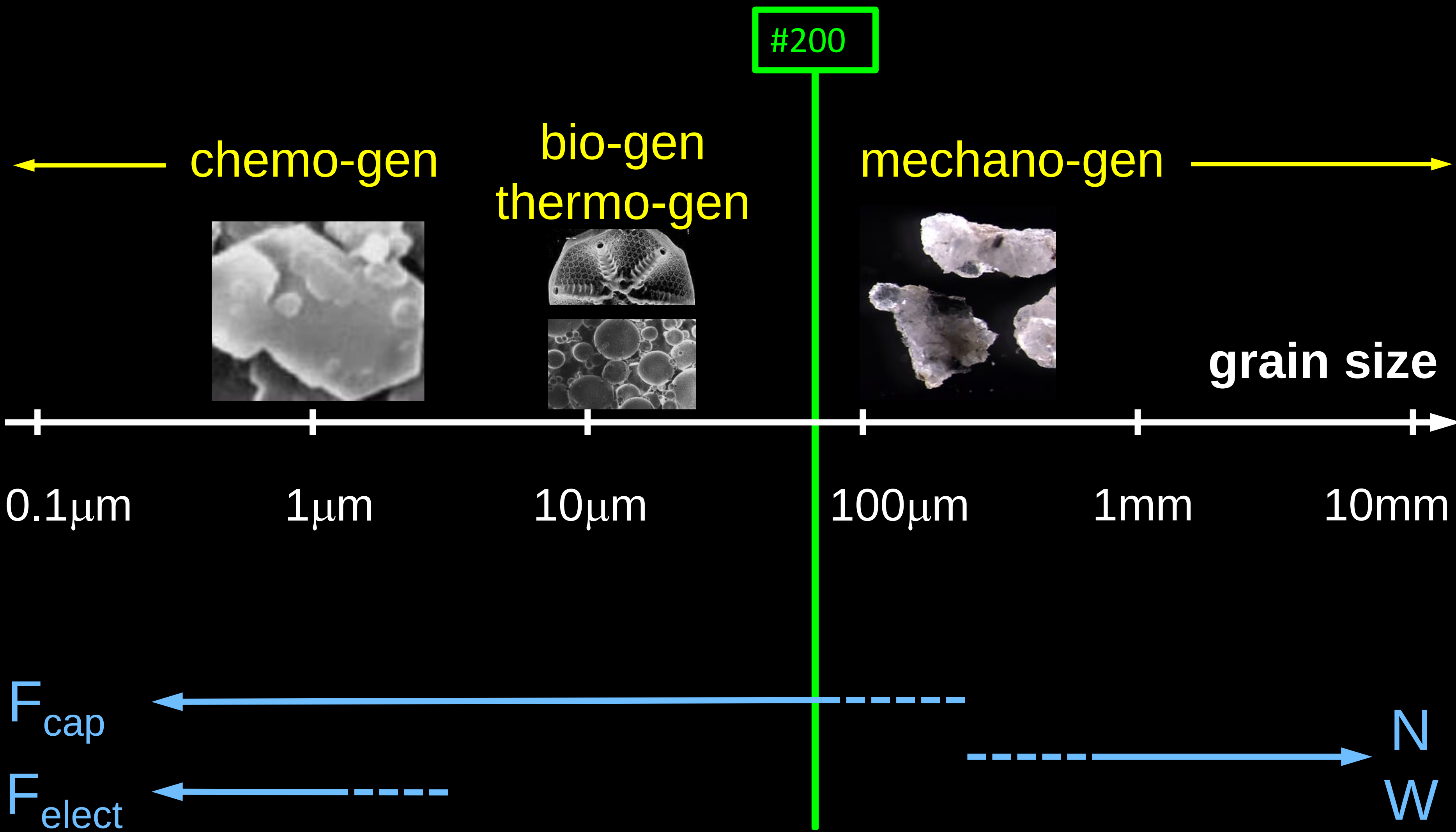






(Youd, 1973; see also Maeda, 2001)

Summary: Genesis → Size – Shape – Forces



Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

Stiffness

Pores

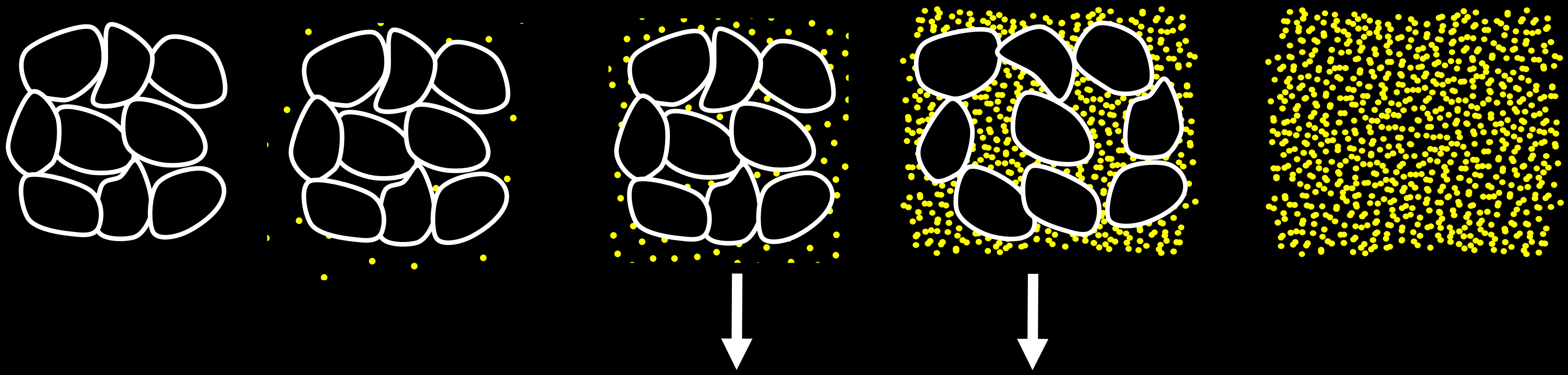
Permeability

Mixed fluids

Casagrande (1902-1981)

Sand + Gravel

sand fraction: $\chi = \frac{M_{sand}}{M_{total}} = \frac{e_G}{1 + e_G + e_s}$

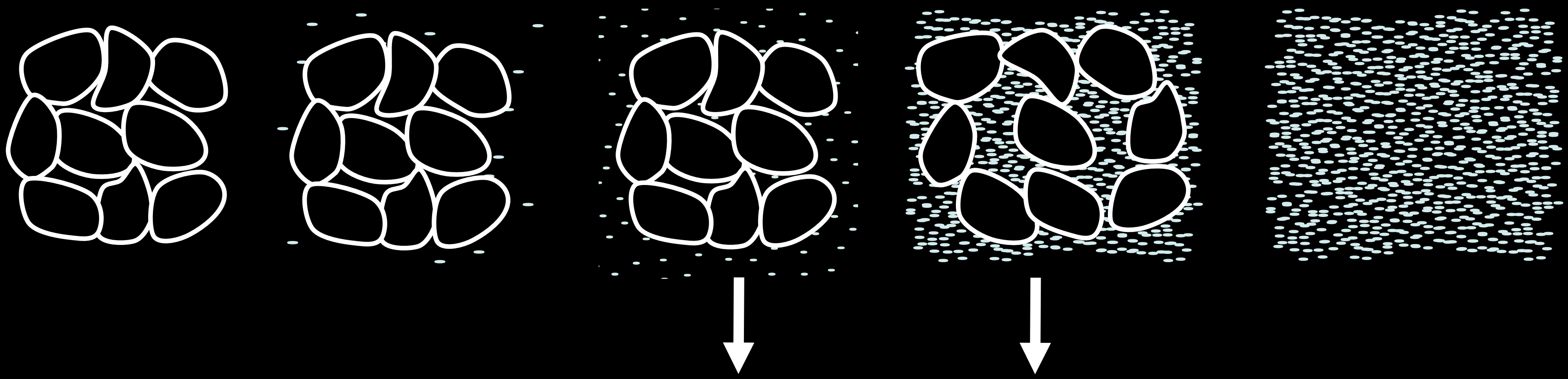


gravel	$e_G = e_{min}$	$e_G = e_{max}$
sand	$e_S = e_{max}$	$e_S = e_{min}$
sand fraction	χ_L = 20-25 %	χ_H = 35-40 %

f(C_u, shape)

Fine + Coarse

fines fraction: $\Phi = \frac{M_{fines}}{M_{total}} = \frac{e_C}{1 + e_C + e_F}$

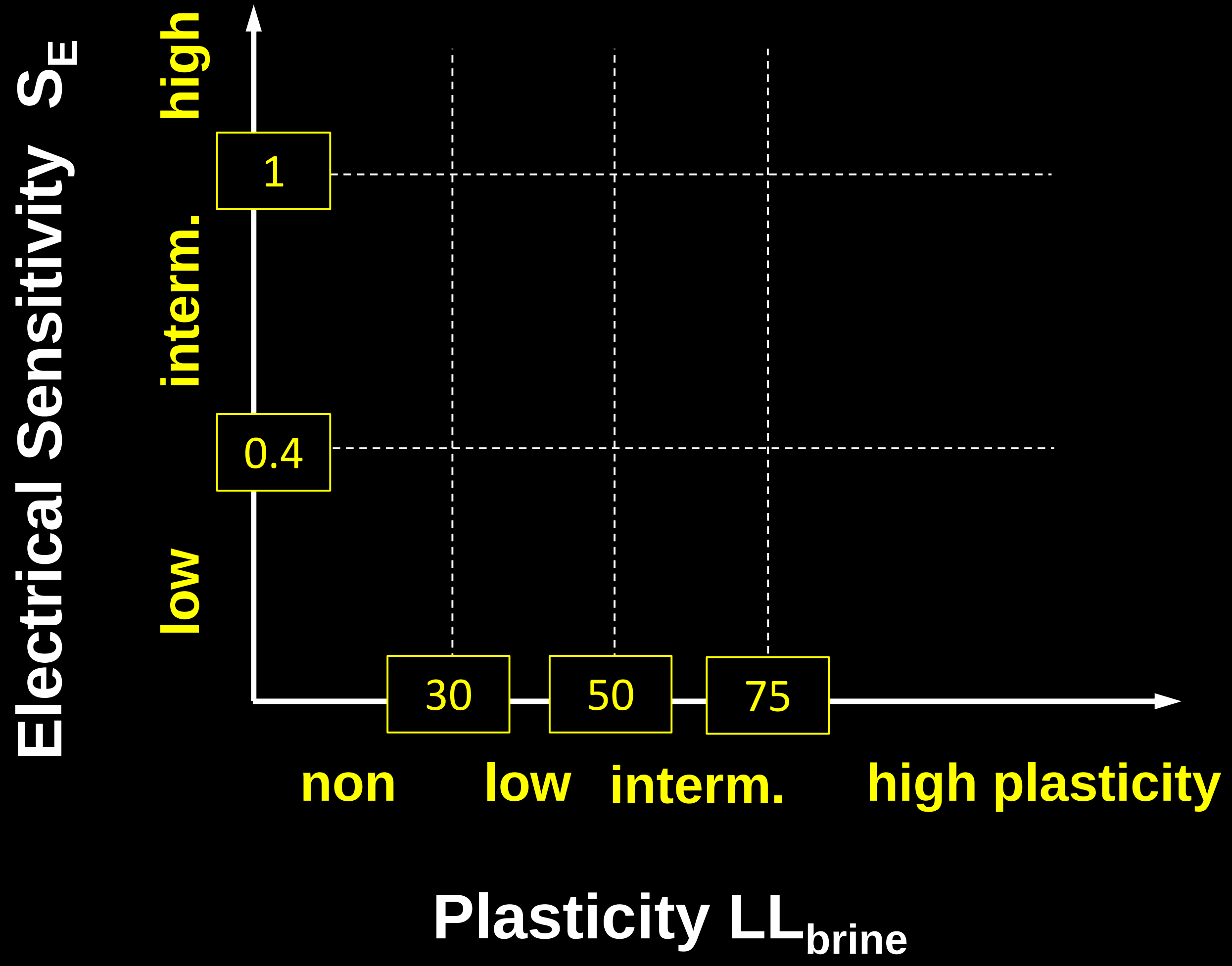


coarse	$e_C = e_{min}$	$e_C = e_{max}$	
fines	$e_F = e_{1kPa}$	$e_F = e_{1MPa}$	
fines fraction	$\Phi_L = 18\ \%$	$\Phi_H = 24\ \%$	kaolin
	$\Phi_L = 8\ \%$	$\Phi_H = 25\ \%$	montmorillonite

Classification: Fines

(Pass #200)

$$S_E = \sqrt{\left(\frac{LL_{DW}}{LL_{brine}} - 1\right)^2 + \left(\frac{LL_{ker}}{LL_{brine}} - 1\right)^2}$$



Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

Stiffness

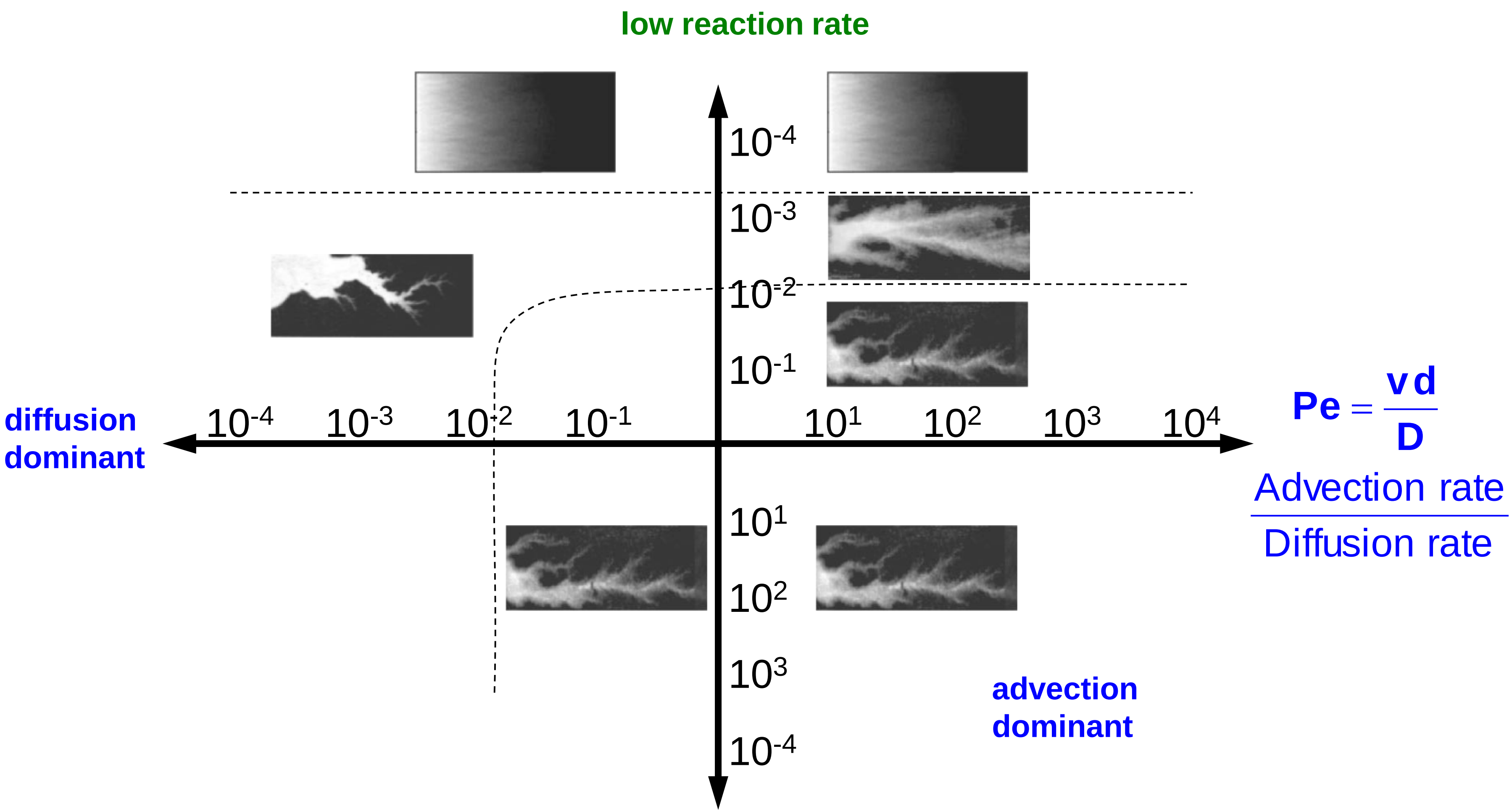
Pores

Permeability

Mixed fluids

National Corvette Museum
Bowling Green, Kentucky

Reactive Fluid Transport

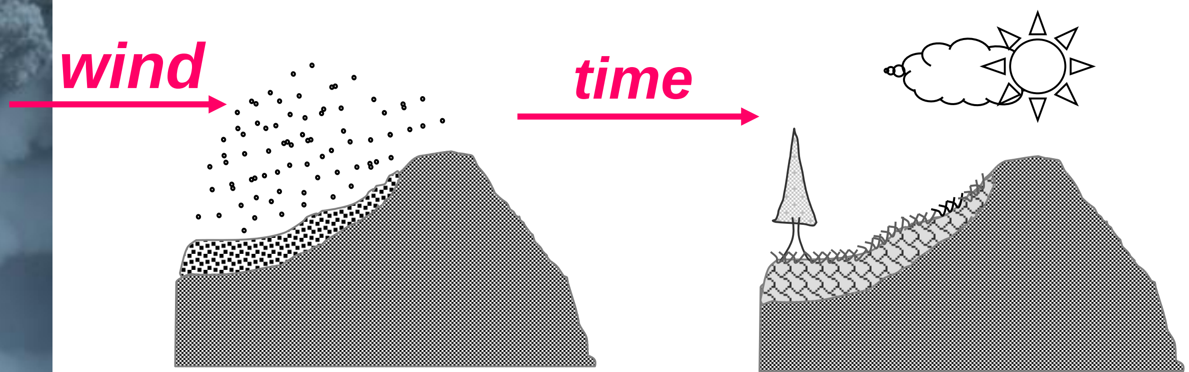


$$Da = \frac{\alpha l}{v}$$

Reaction rate / **Advection rate**

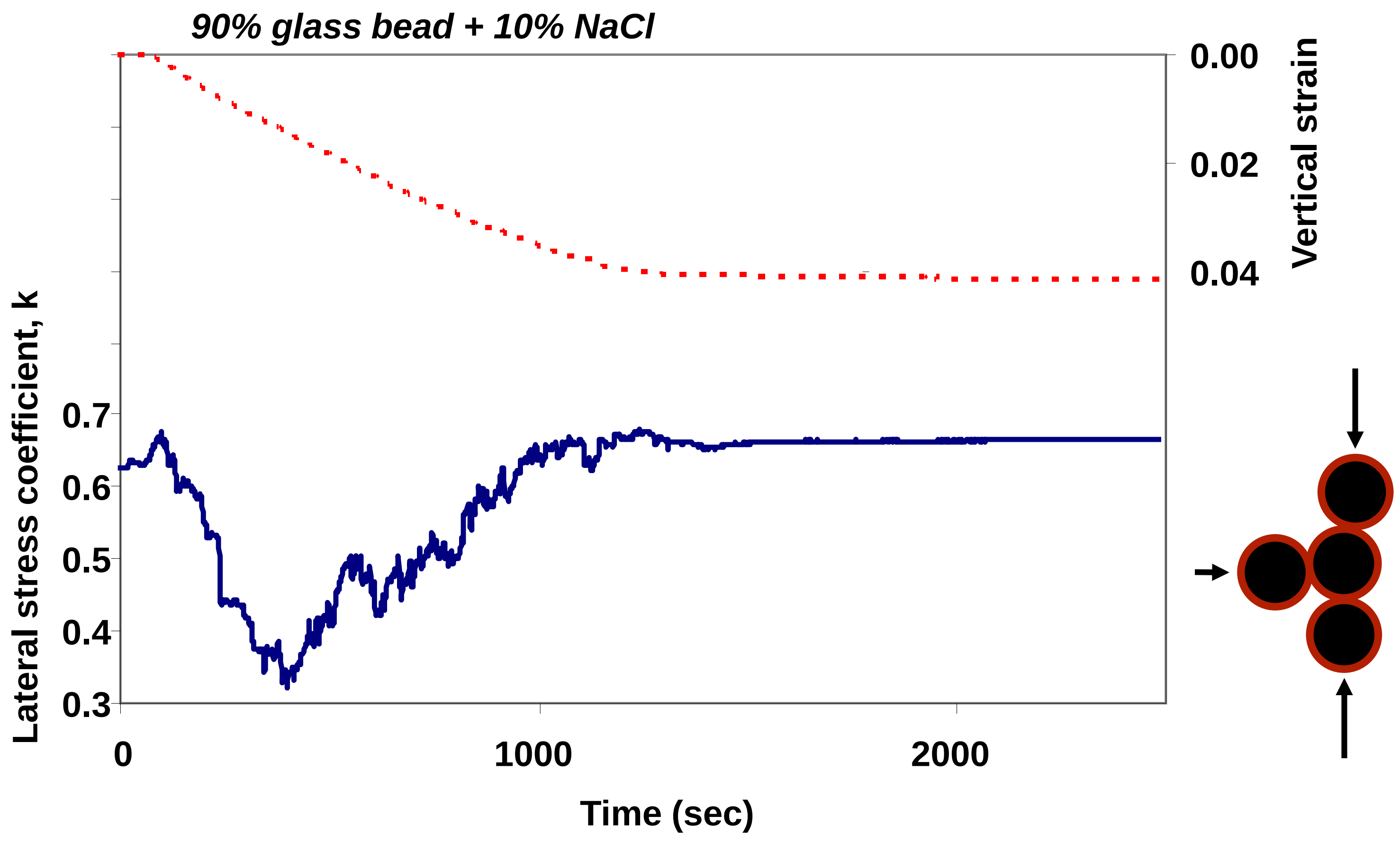
Fredd & Fogler 1988, 1998
Fredd & Miller's 2000
Golfier et al. 2002

Volcanic Ash Soils: Formation

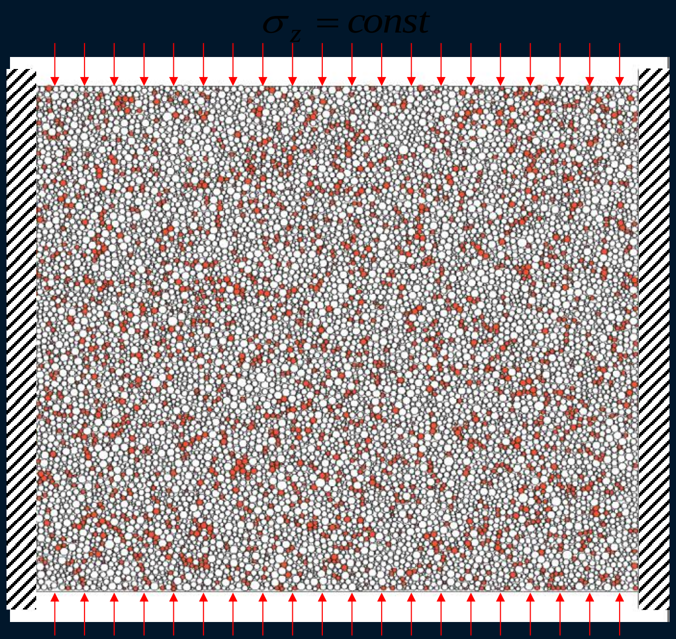


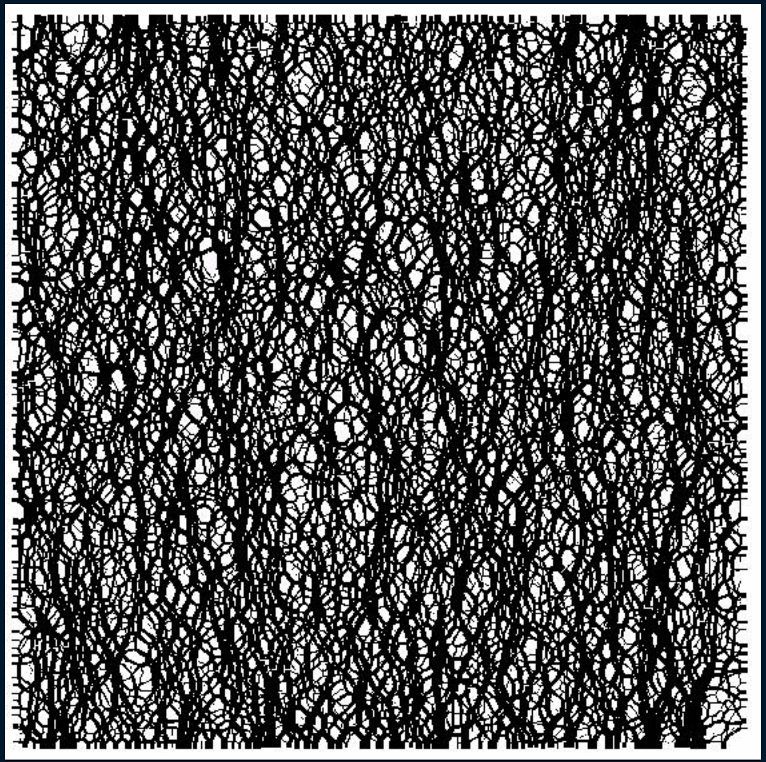
e= 0.8-1.5	e= 2.0-7.0
S_s~0.1-1 m^2/g	S_s=50-to-200 m^2/g
volcanic glass	hallosite imogolite alophane
$k_o=1-\sin\varphi$	k_o= ??

Experimental Results

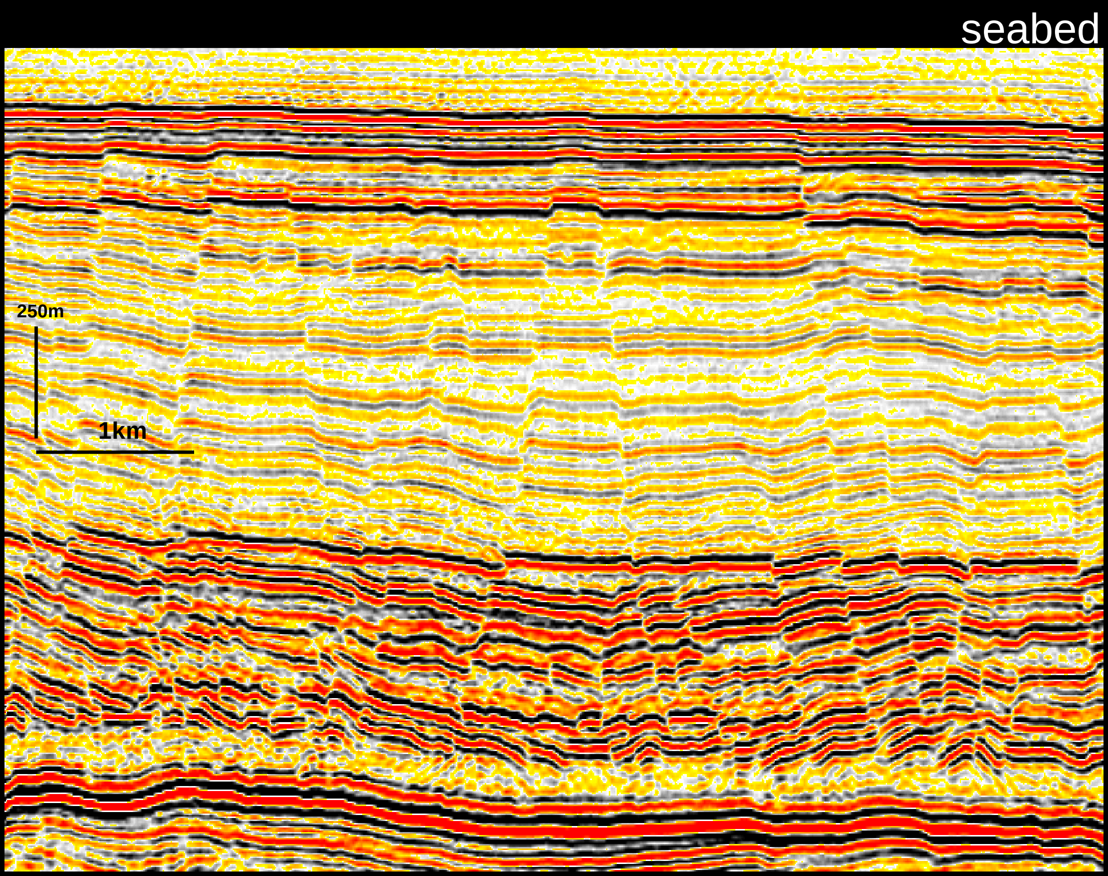


DEM Simulation dR/dt=f(N)



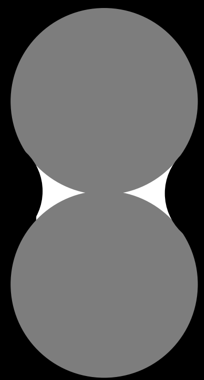


Natural Sediments

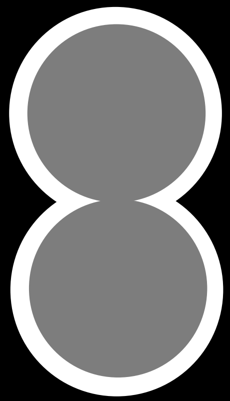


Cartwright (2005)

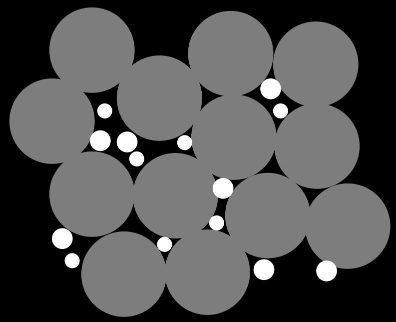
Precipitation – Pore Habit



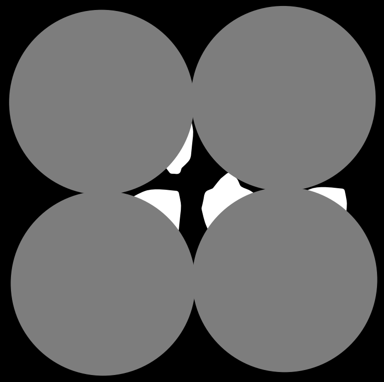
at contact



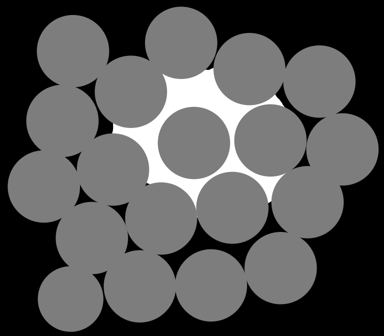
surface coating



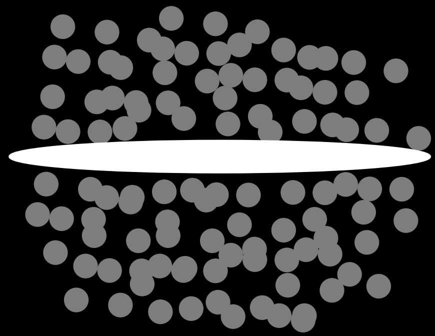
homogeneous nucleation



heterogeneous nucleation

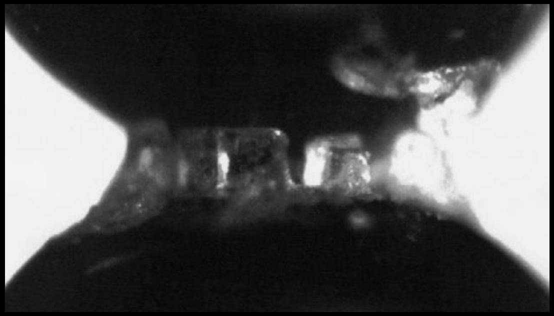


patchy (ripening)

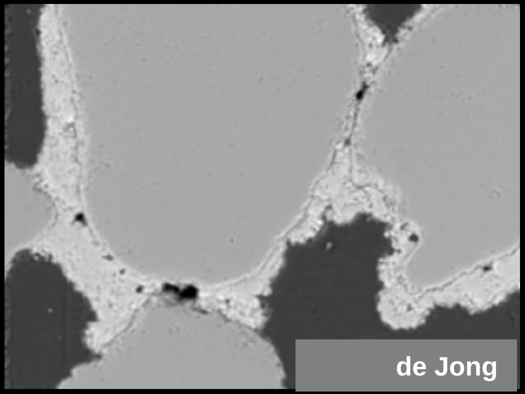


segregated (lenses)

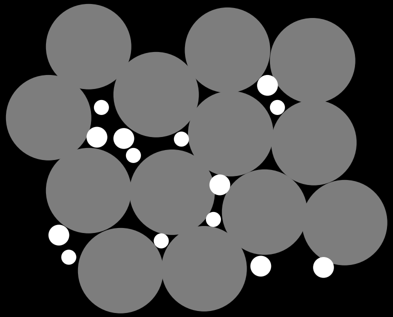
Precipitation – Pore Habit



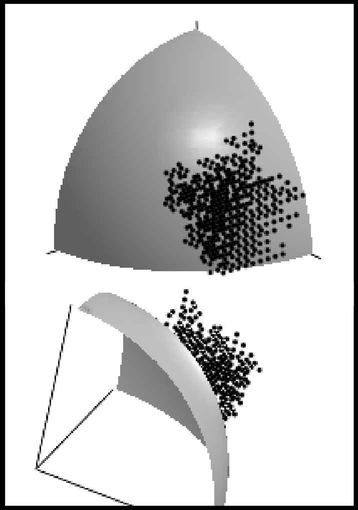
at contact



surface coating



homogeneous nucleation



heterogeneous nucleation

patchy (ripening)

segregated (lenses)

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

Stiffness

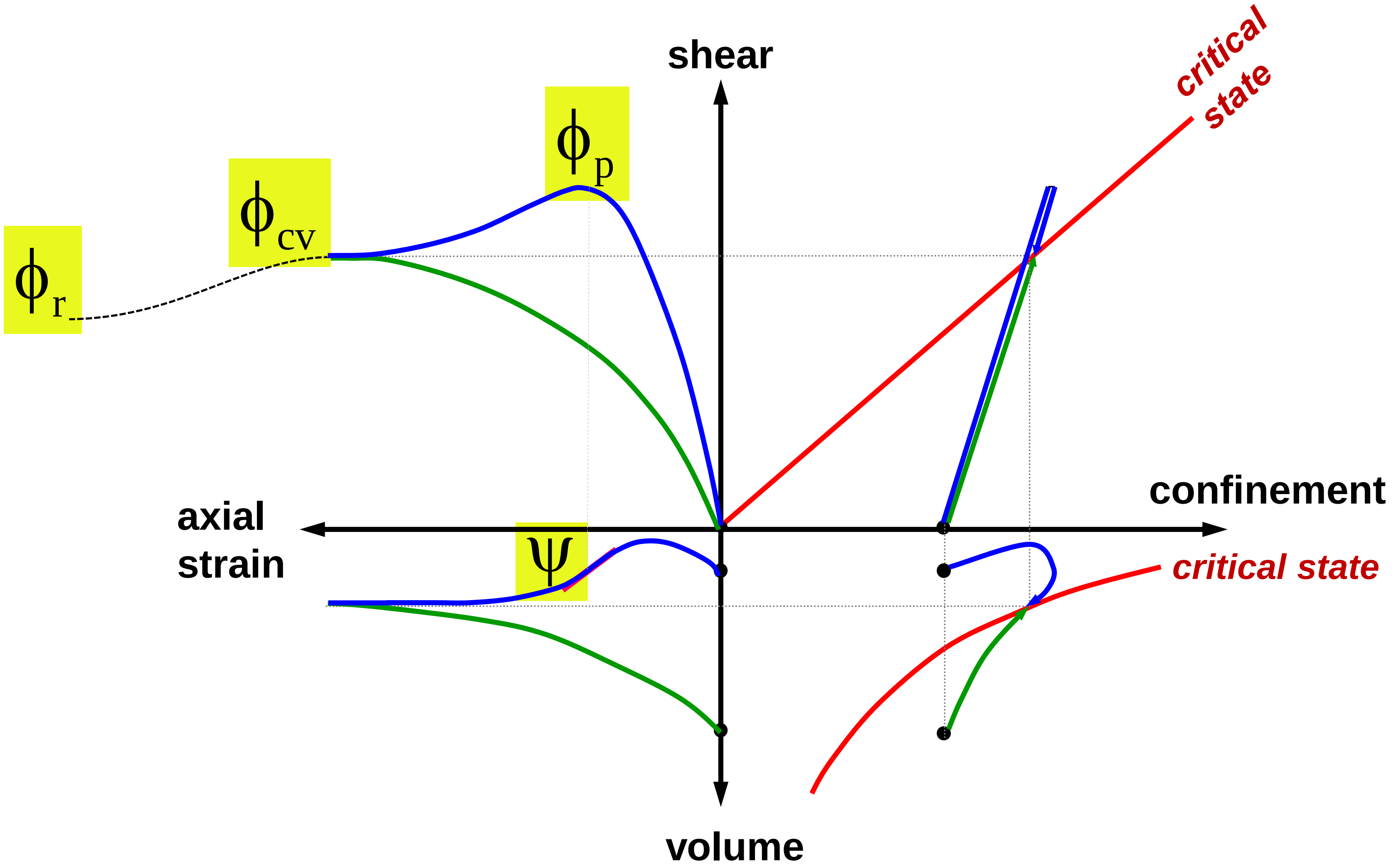
Pores

Permeability

Mixed fluids

coal mine – Australia – guardian.co.uk

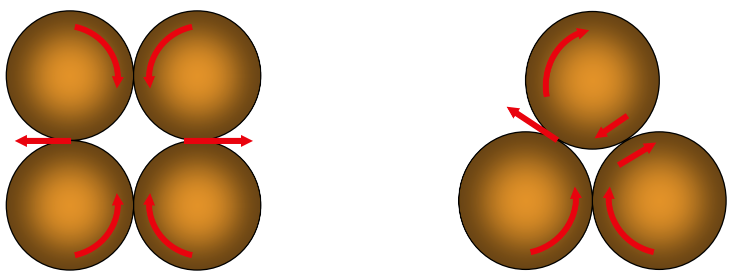
Sediment Response During Shear



Constant Volume Shear: "*Critical State*"

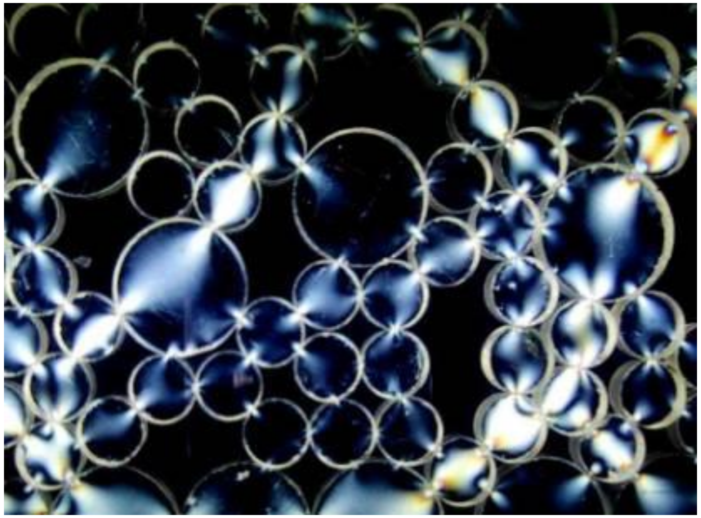
ϕ_{cv}

Rot. frustration: Coordination ↓ **Chain Buckling: Coordination↑**



Free
(high e)

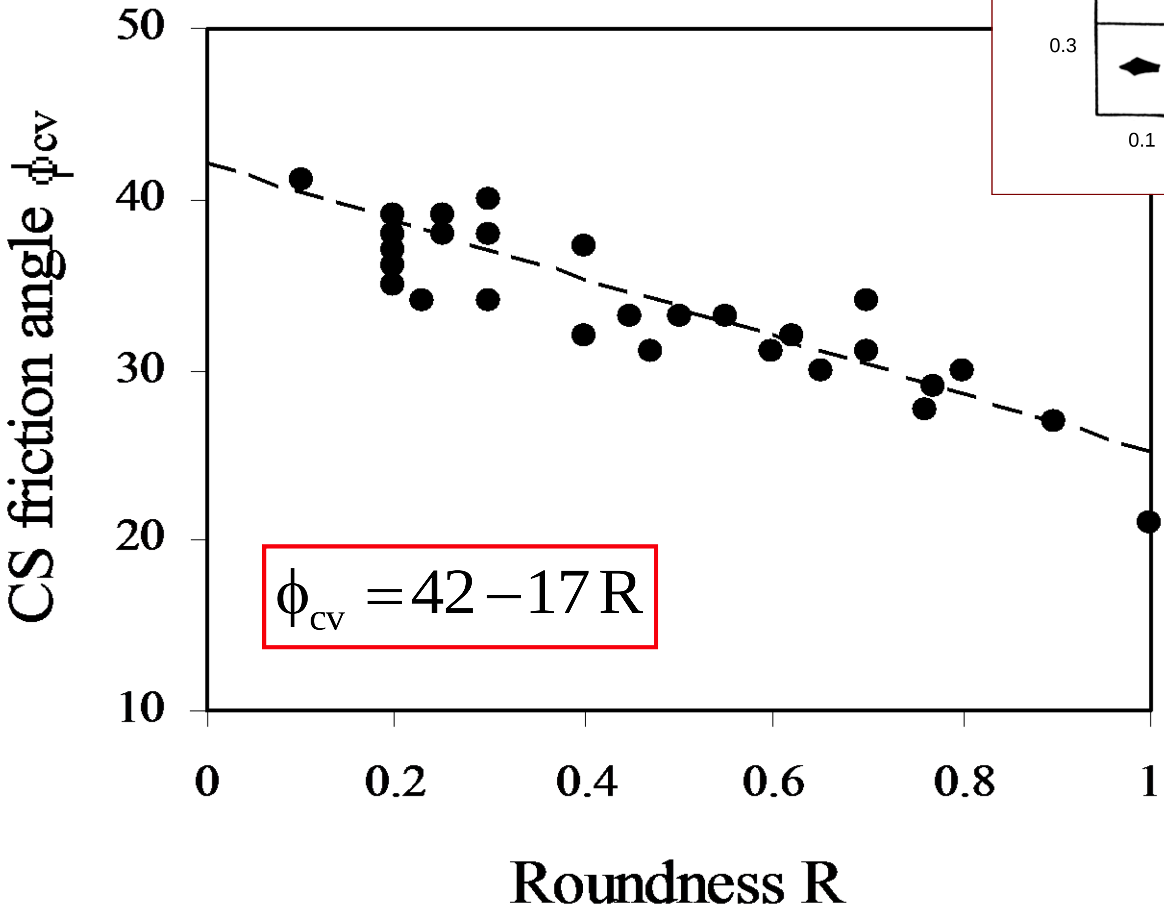
Frustrated
(low e)

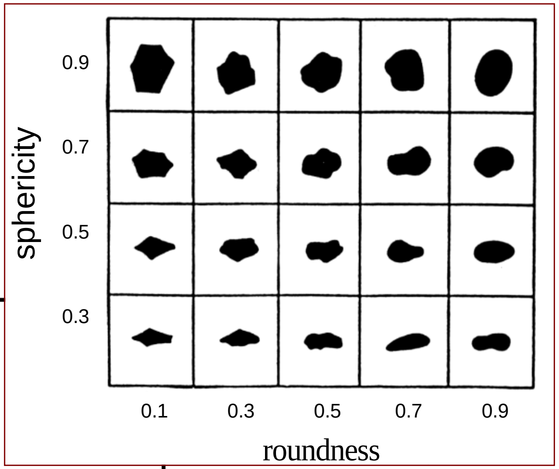


reduce rotational frustration
avoid contact slip

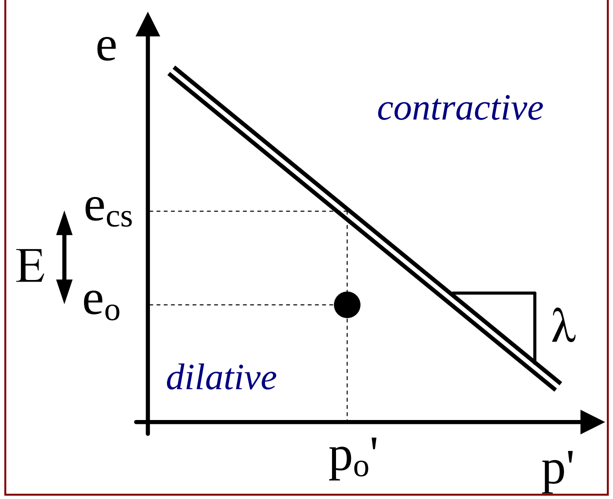
Constant Volume Friction vs. Roundness

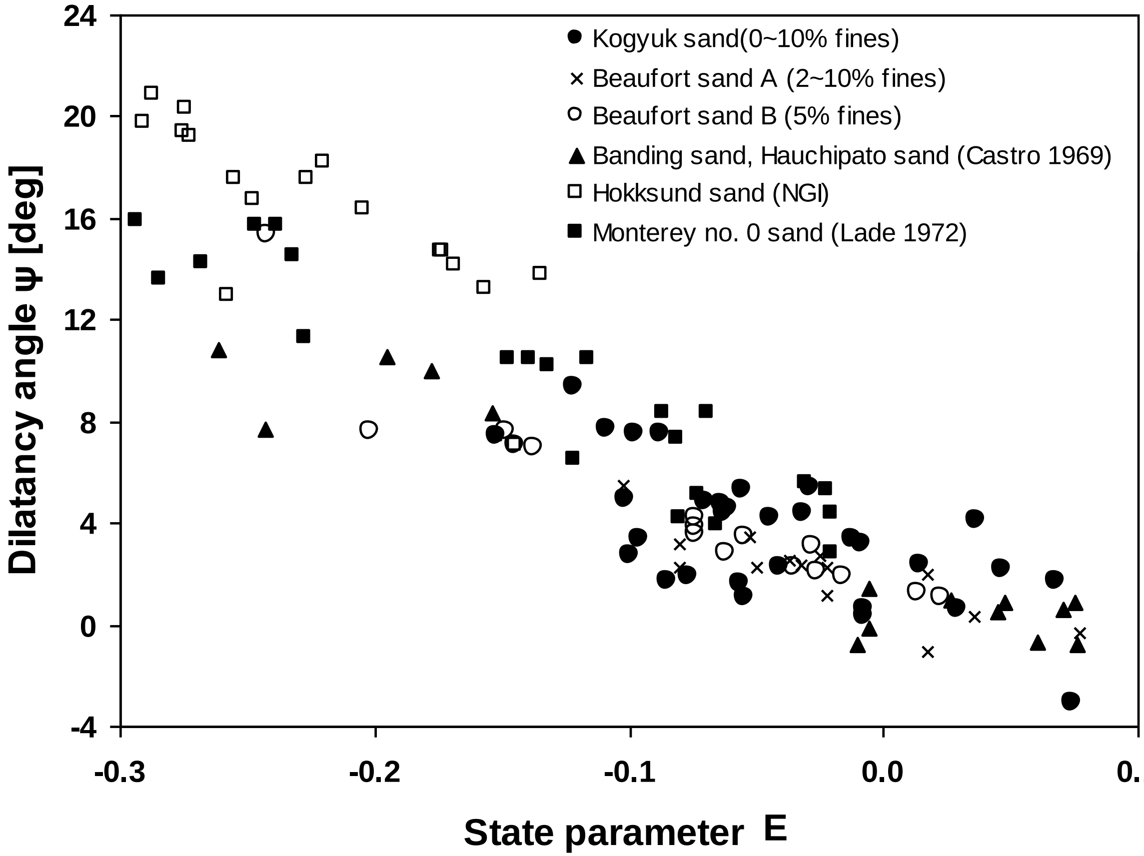
ϕ_{cv}





Dilatency Angle





(Been and Jefferies 1985)

Peak Friction Angle

ϕ_p

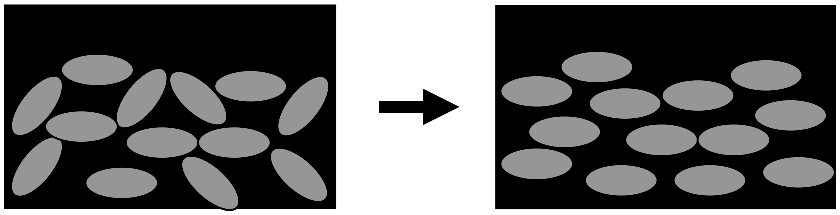
Taylor 1948: $$\tan\phi_p = \tan\phi_{cv} + \tan\psi$$

Bolton 1986: $$\phi_p = \phi_{cv} + 0.8\psi$$

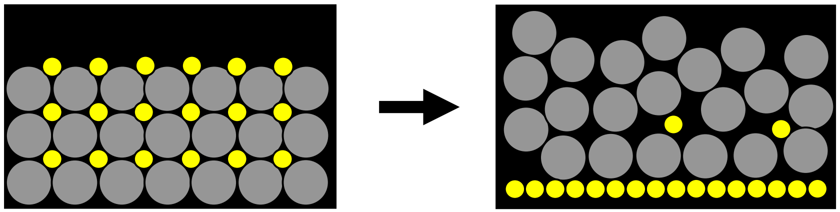
Residual Friction Angle - very large strains

ϕ_r

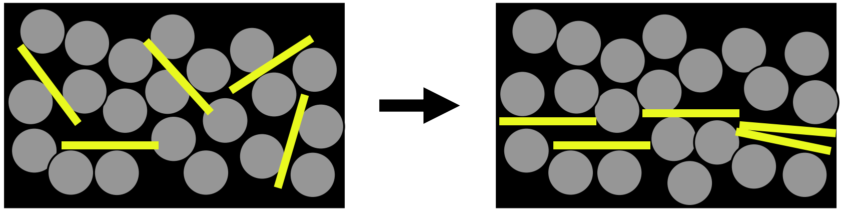
particle alignment



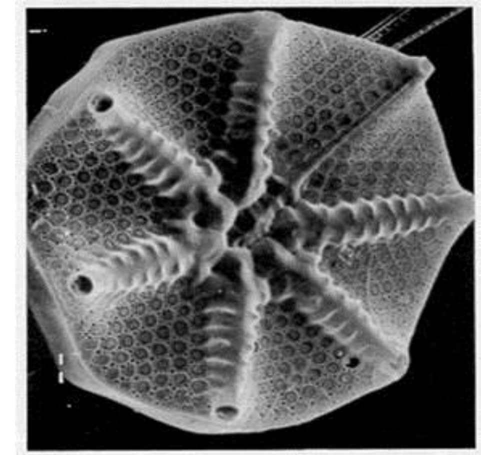
size segregation

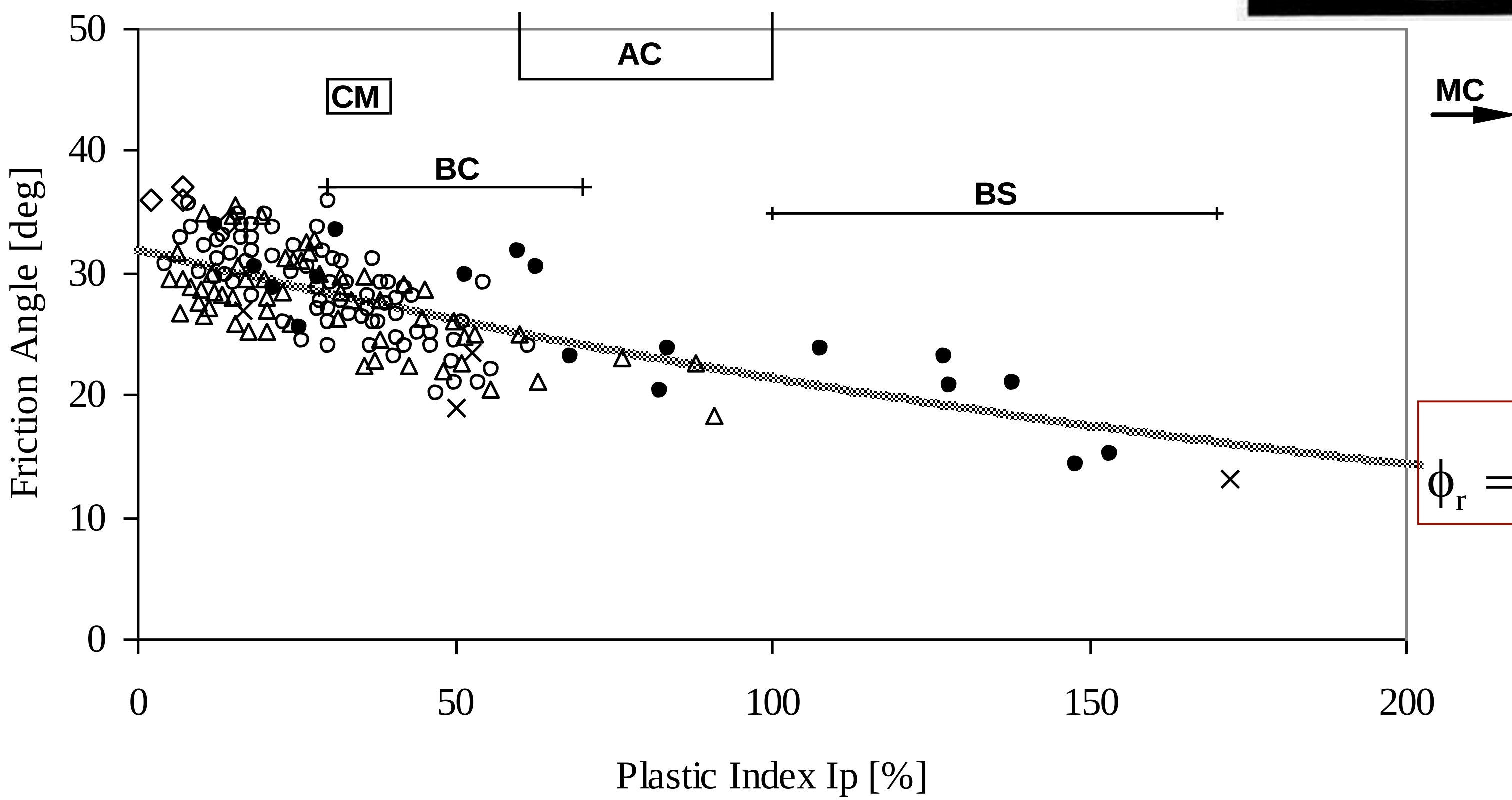


shape segregation



Residual Friction Angle ϕ_r

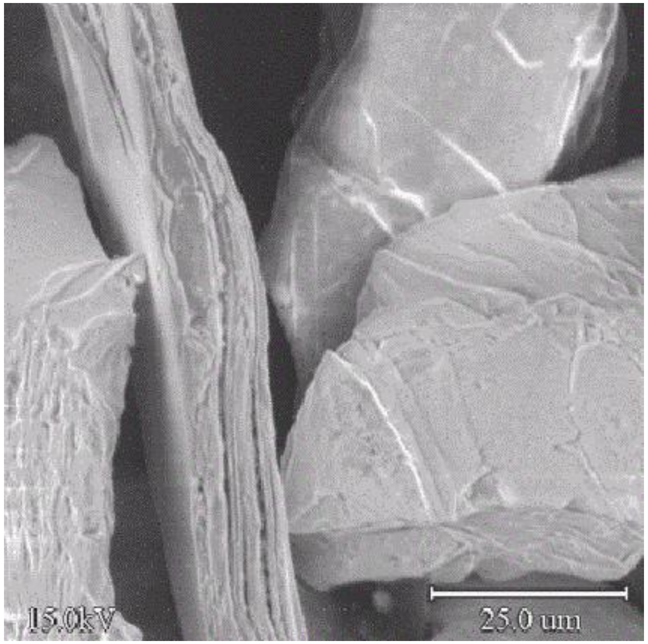


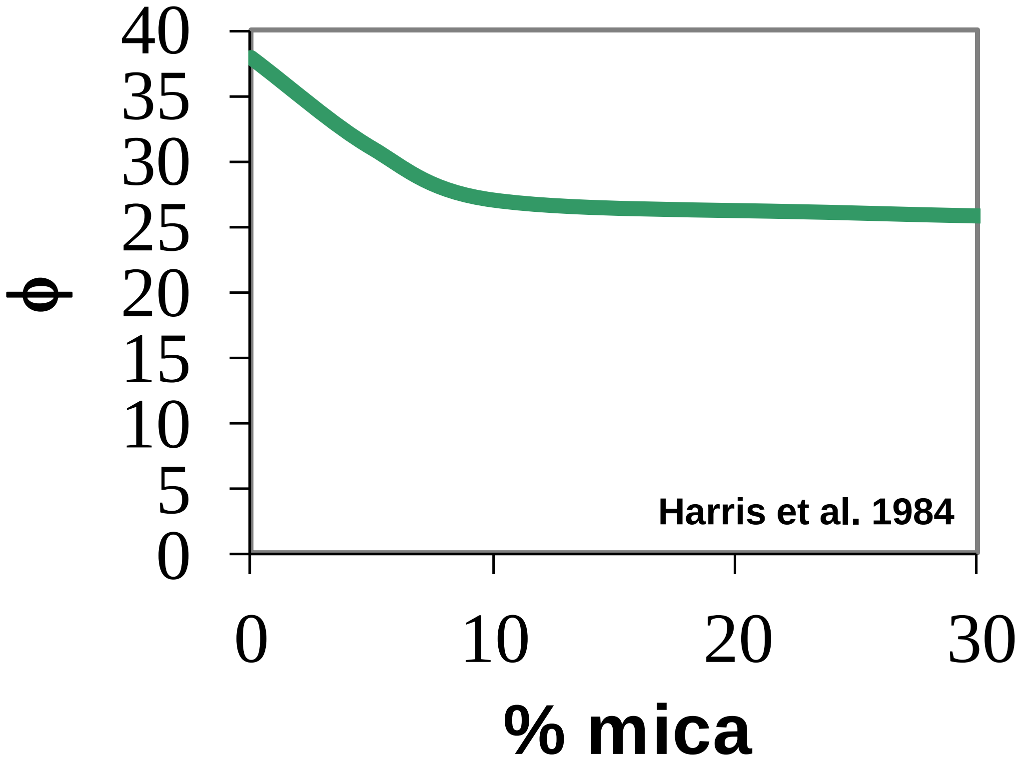


$$\phi_r = 32\, e^{\frac{-IP}{250}}$$

Ariake Clay "AC" Bangkok Clay "BC" Bogota Soil "BS" Cooper Marl "CM" Mexico City "MC"

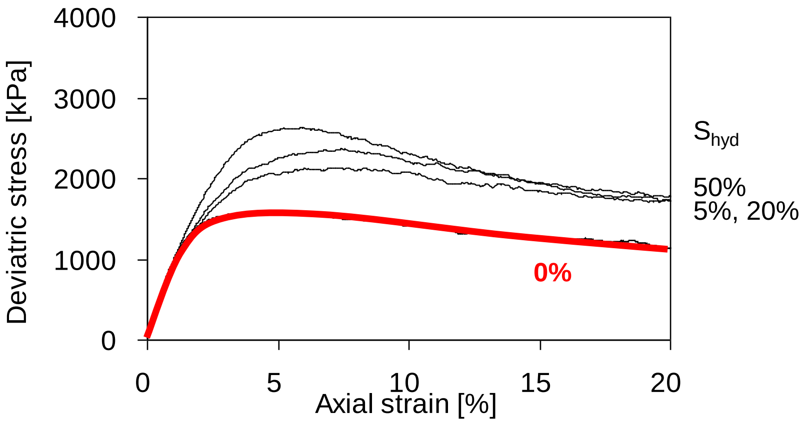
Platy particles

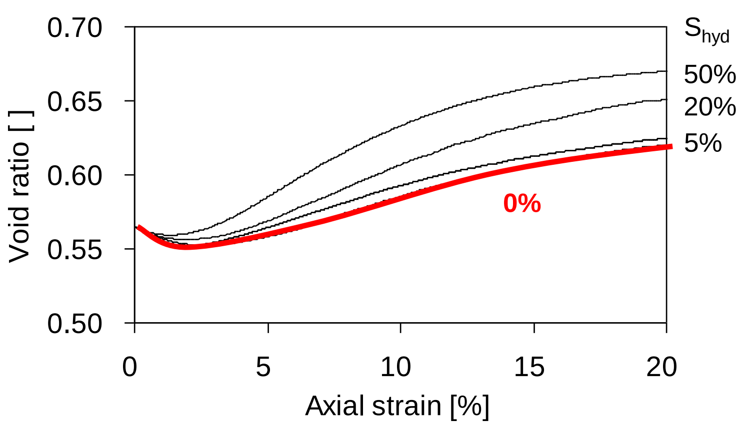




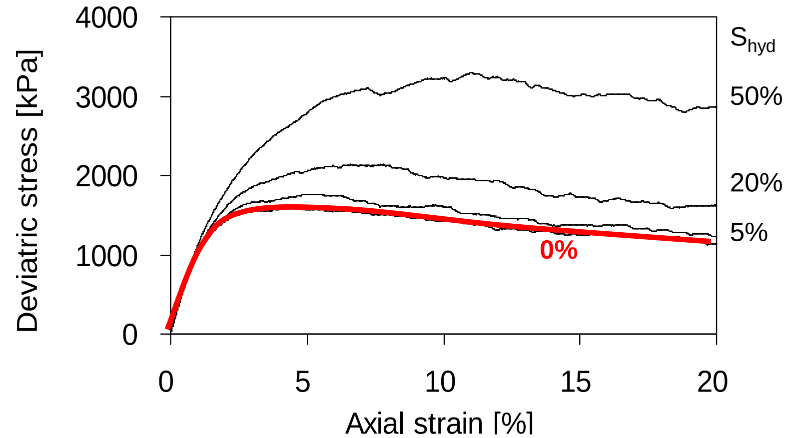
Precipitation ➔ ?

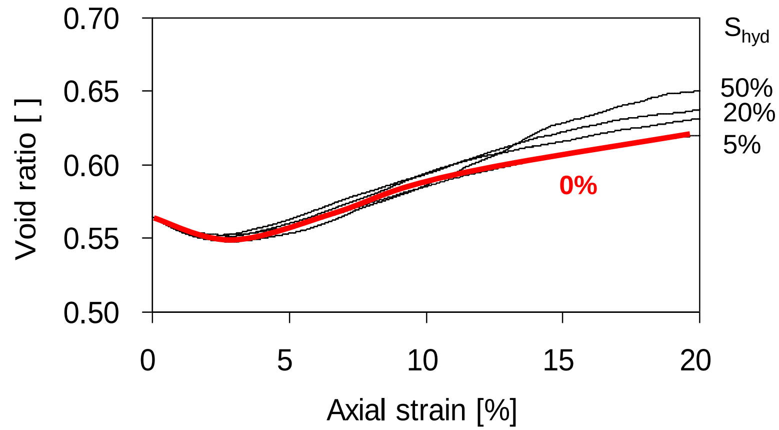
distributed cementation





patchy cementation

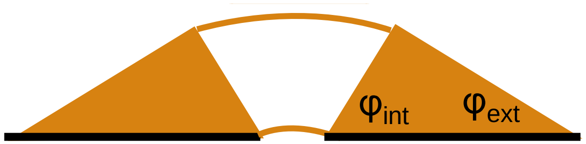


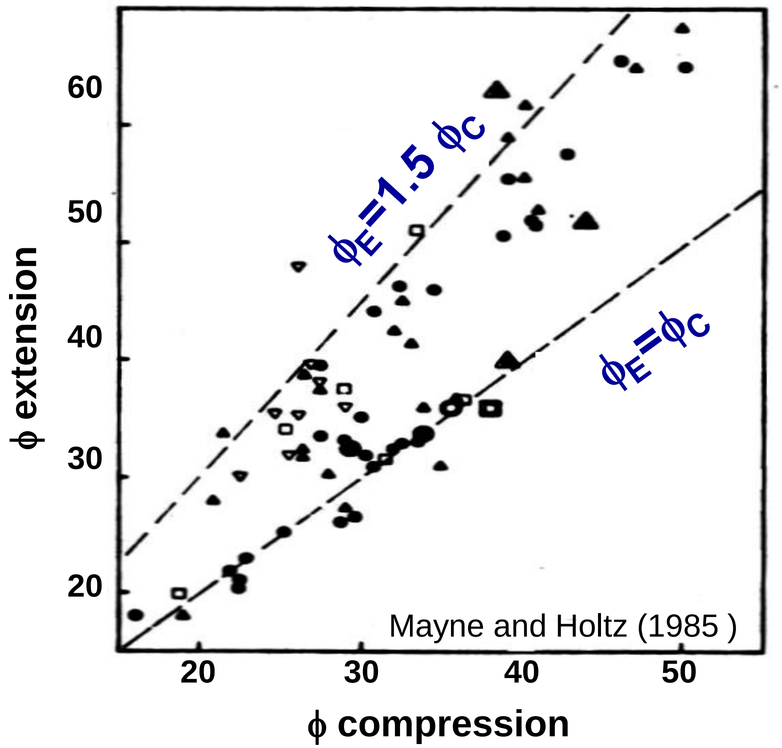


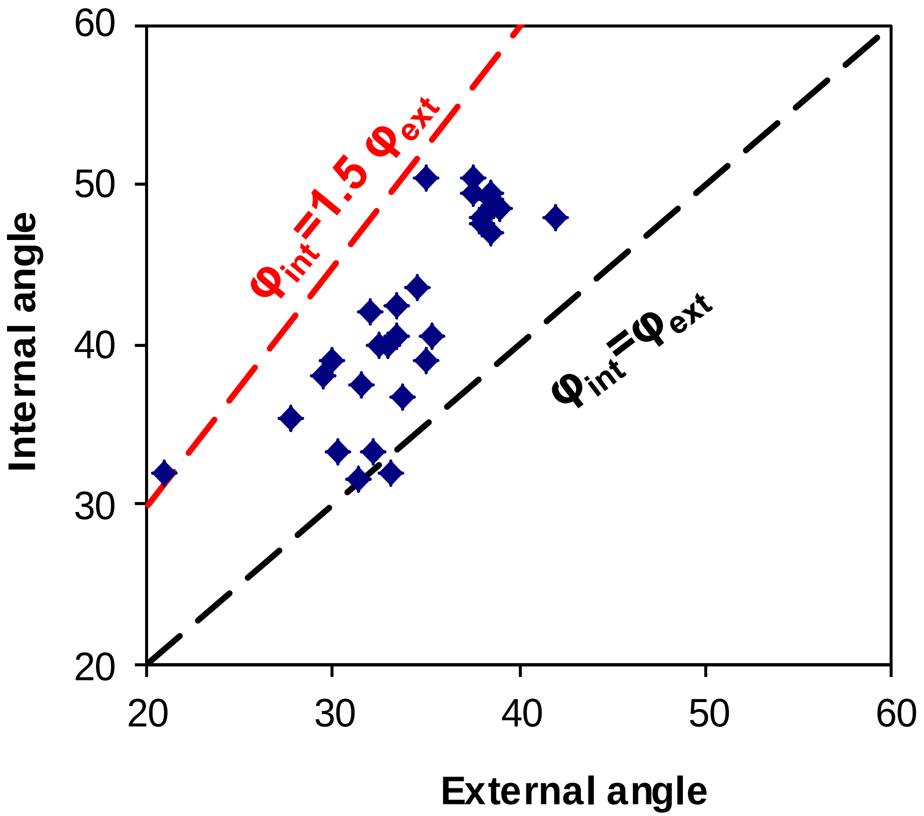
Note: increase in stiffness , strength, dilation with S_{hyd} - pore habit affect dilation

Frictional strength anisotropy

$\phi_E = 1.0 \text{ to } 1.5\ \phi_C$







Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

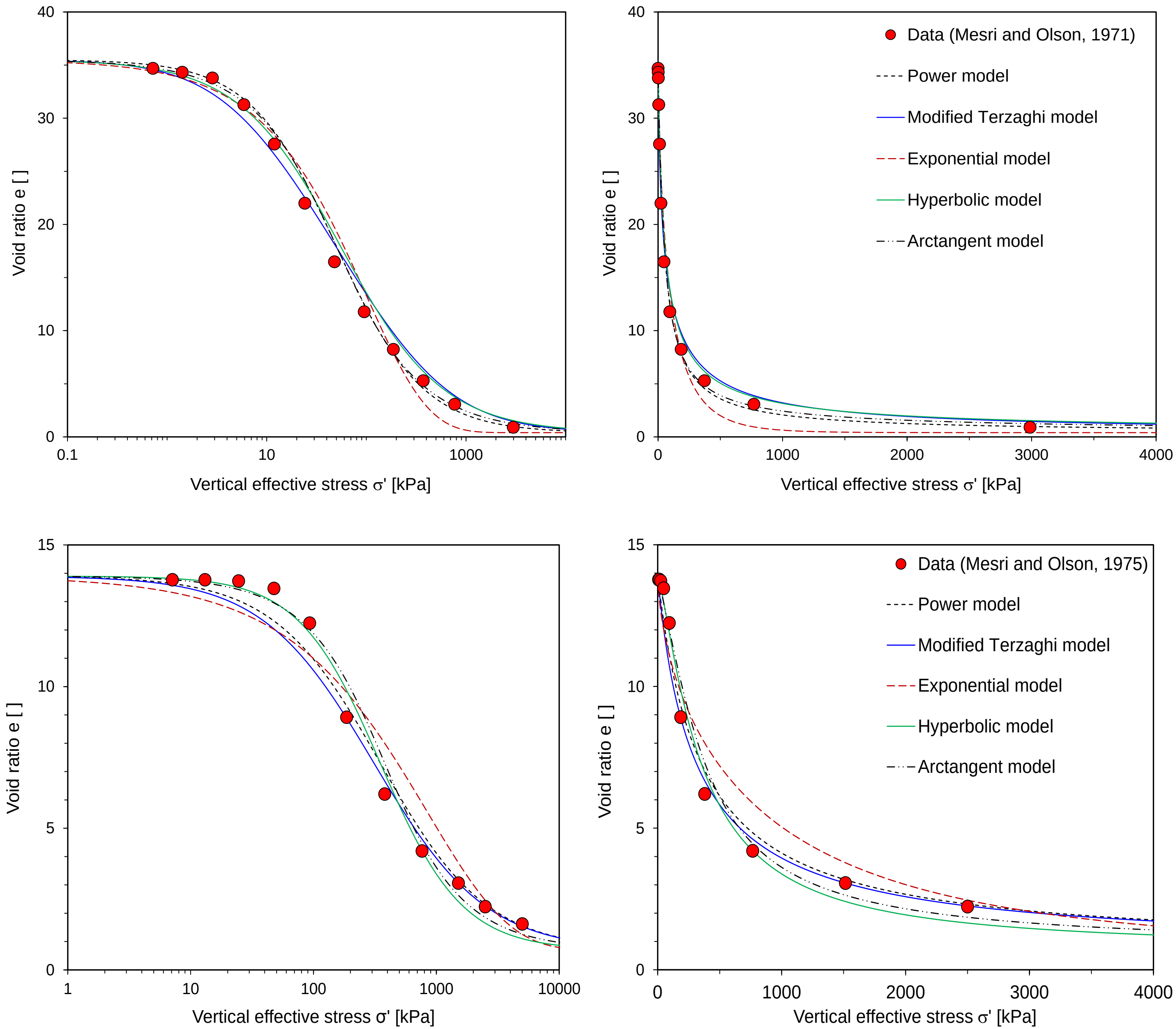
Stiffness

Pores

Permeability

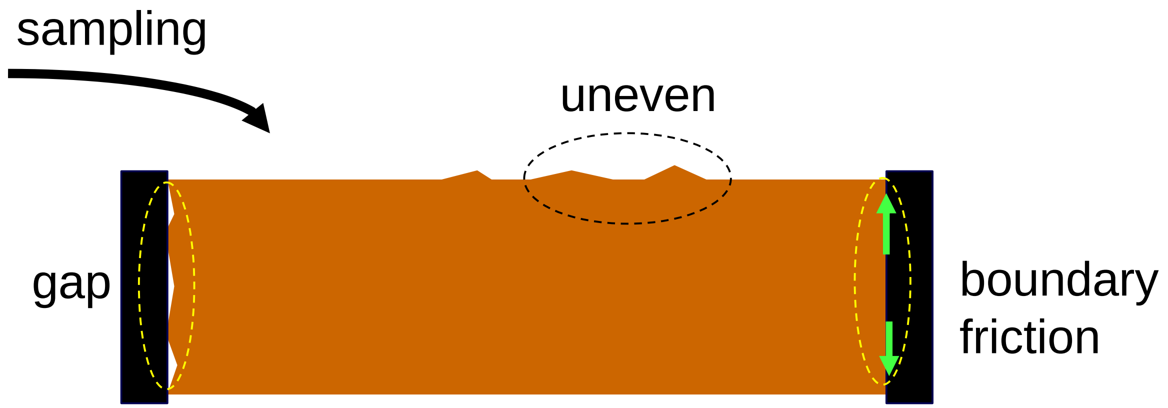
Mixed fluids

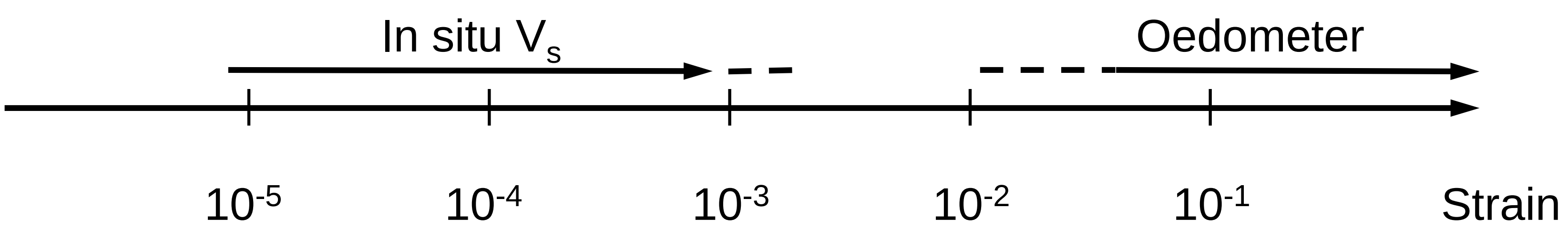
Semi-log	*Classical (1st order)* Terzaghi & Peck (1948) Schofield & Wroth (1968)	$e = e_{1kPa} - C_c \log\left(\frac{\sigma'}{1kPa}\right)$
	Cubic (3rd order) *(high-stress correction)* Burland (1990)	$e = e_{ref} - \alpha \cdot \log\left(\frac{\sigma'}{\sigma'_{ref}}\right) + \beta \cdot \left[\log\left(\frac{\sigma'}{\sigma'_{ref}}\right)\right]^3$
	Modified *(low and high stress asymptotes*	$e = e_c - C_c \log\left(\frac{1kPa}{\sigma'+\sigma'_L} + \frac{1kPa}{\sigma'_H}\right)^{-1}$
Power	*From gas to soil* Hansen (1969); Butterfield (1979); Juárez-Badillo (1981); Houlsby & Wroth, (1991); Pestana & Whittle (1995)	$e = e_H + (e_L - e_H)\left(\frac{\sigma'+\sigma'_c}{\sigma'_c}\right)^{-\beta}$
Exponential	*Gompertz function* *(classical exp: β=1)* Gregory et al. (2006) Cargill (1984 – β=1)	$e = e_H + (e_L - e_H) \cdot \exp^{-\left(\frac{\sigma'}{\sigma'_c}\right)^{\beta}}$
Hyperbolic	*Ramberg-Osgood* *(classical hyperbolic: β=1)*	$e = e_L - (e_L - e_H)\frac{1}{1+\left(\frac{\sigma'_c}{\sigma'}\right)^{\beta}}$
Arctangent	*S-shaped function* G. Goldsztein	$e = e_L + \frac{2}{\pi}(e_L - e_H)\arctan\left[-\left(\frac{\sigma'}{\sigma'_c}\right)^{\beta}\right]$



Data (Mesri and Olson, 1971)
Power model
Modified Terzaghi model
Exponential model
Hyperbolic model
Arctangent model
Data (Mesri and Olson, 1975)
Void ratio e [ ]
Vertical effective stress σ' [kPa]
0
10
20
30
40
5
15
0.1
1
100
1000
10000
2000
3000
4000

Oedometer?

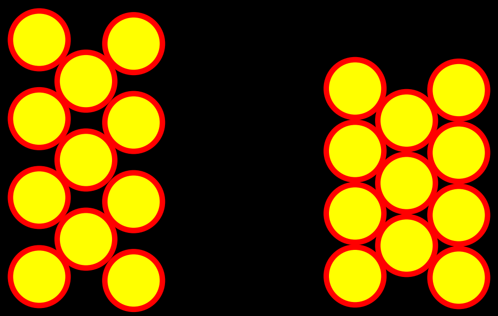




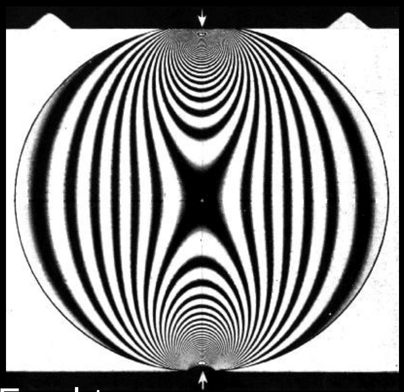
$$\frac{\Delta e}{1+e_o} = C_c \log\left(\frac{\sigma_o' + \Delta\sigma'}{\sigma_o'}\right)$$

Small Strain Stiffness

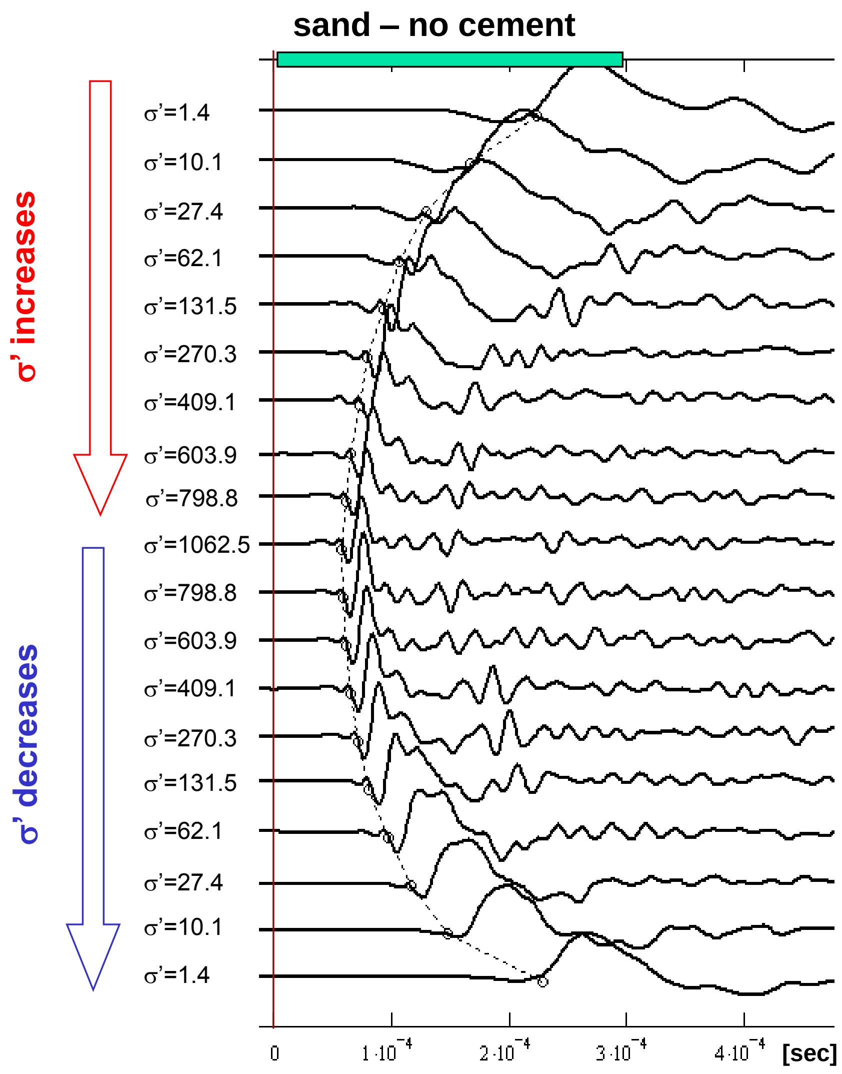
1: Fabric change



2: Contact deformation

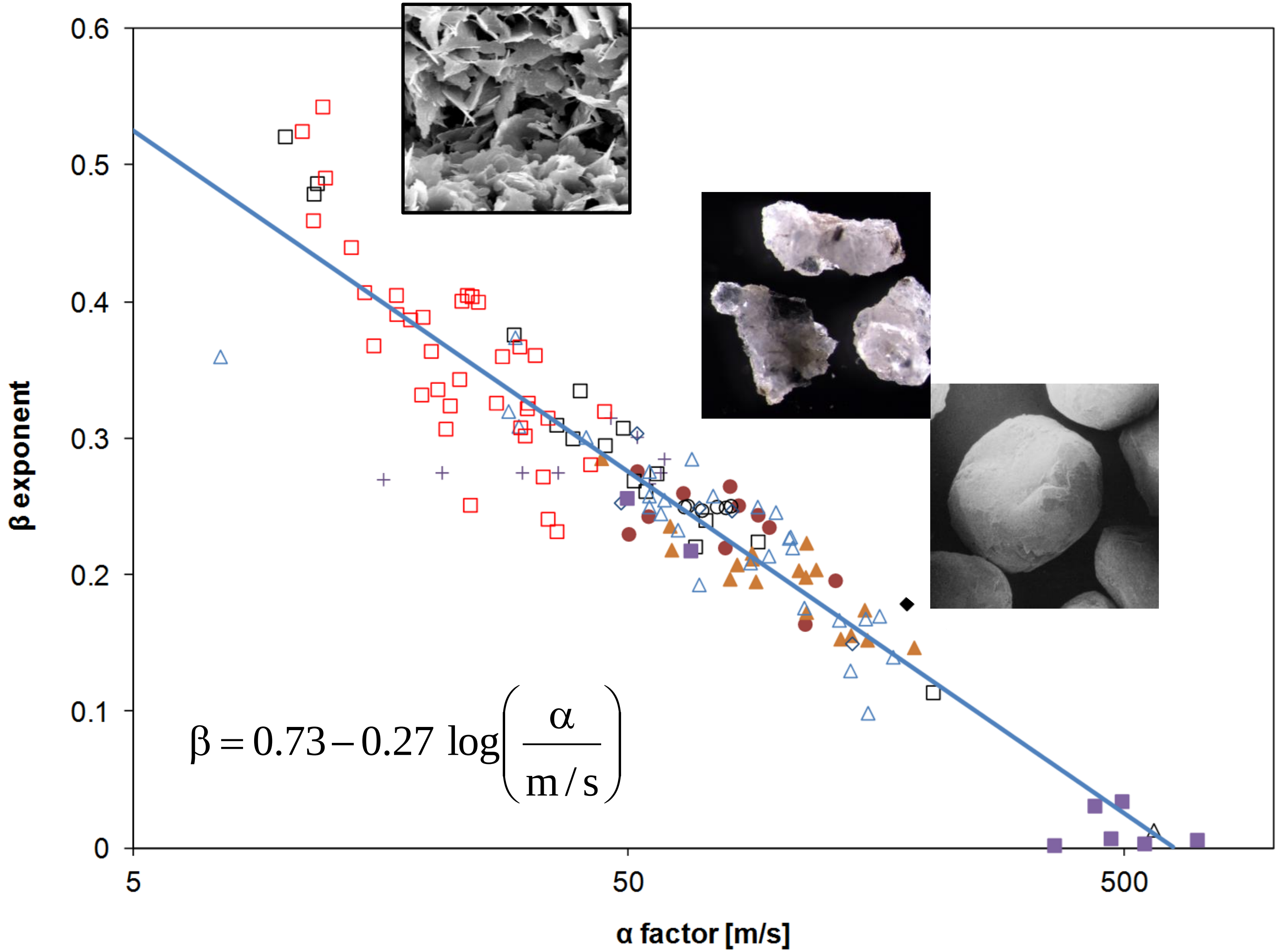


Frocht



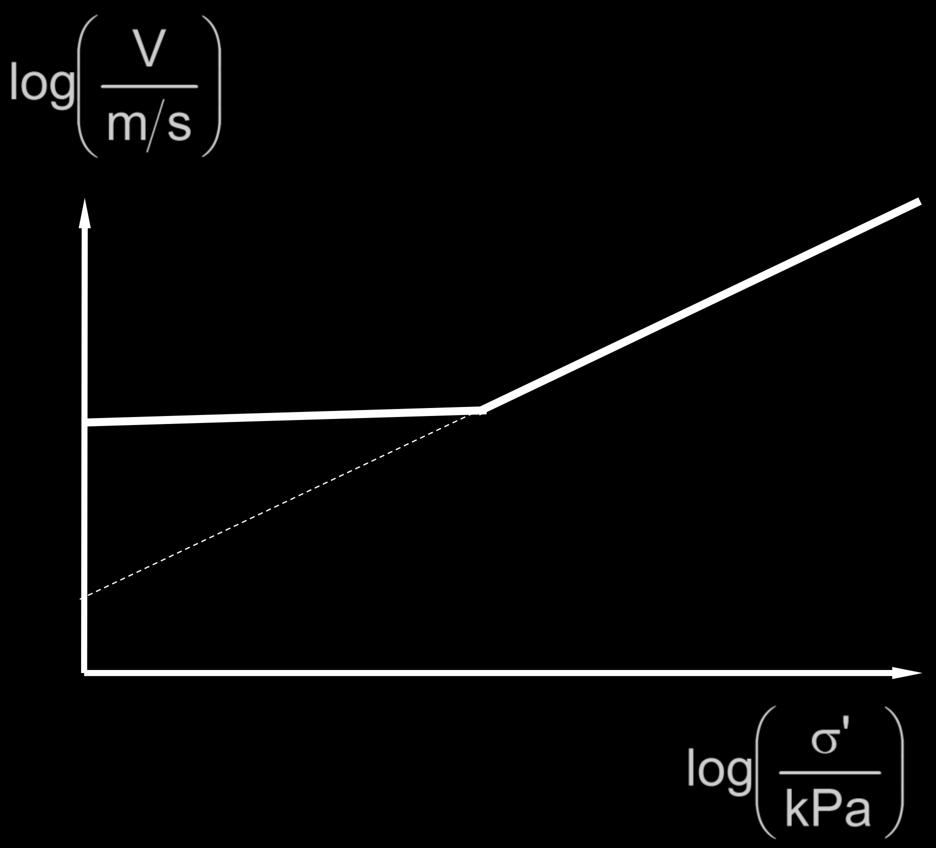
Velocity-Stress: Contact + Fabric

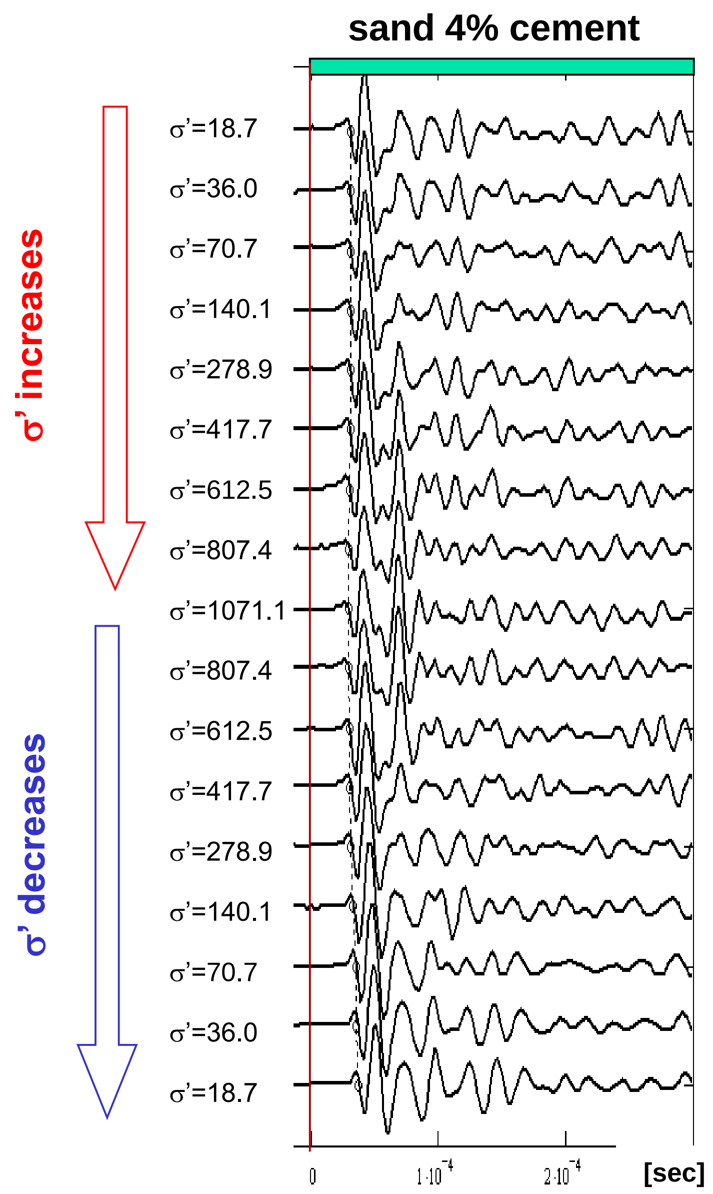
$$V_s = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2P_a} \right)^{\beta}$$



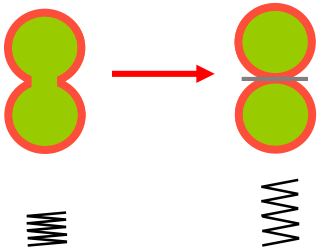
$$\beta = 0.73 - 0.27\ \log\left(\frac{\alpha}{m/s} \right)$$

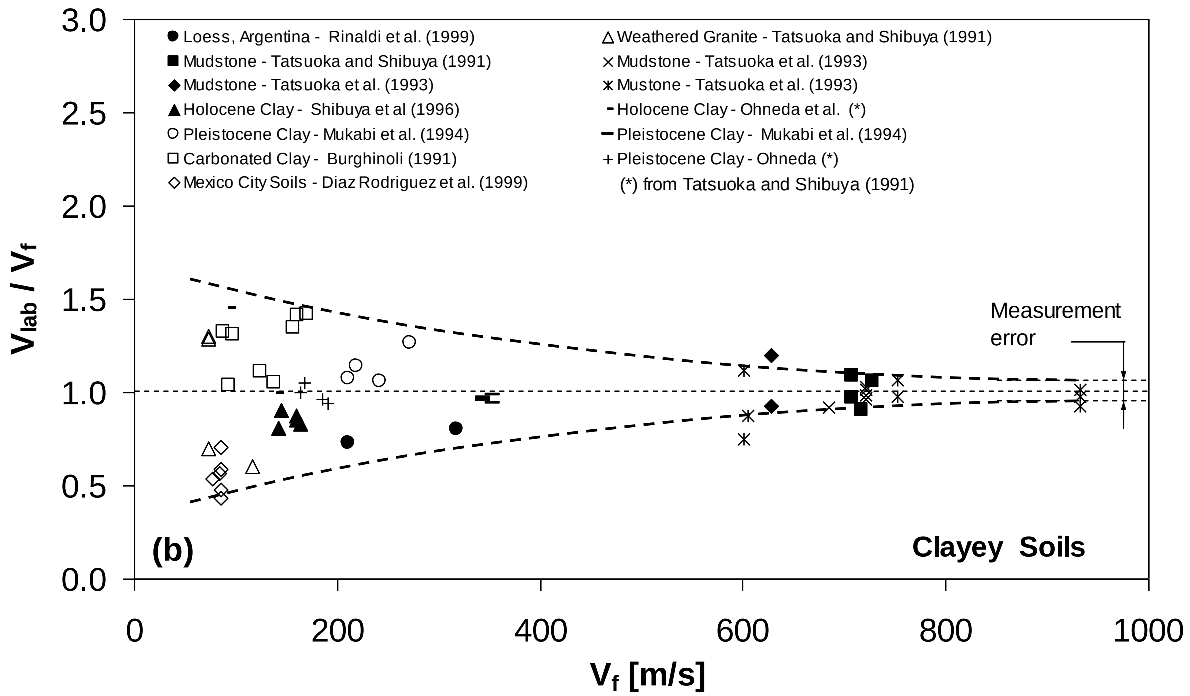
Cementation Controlled Stiffness

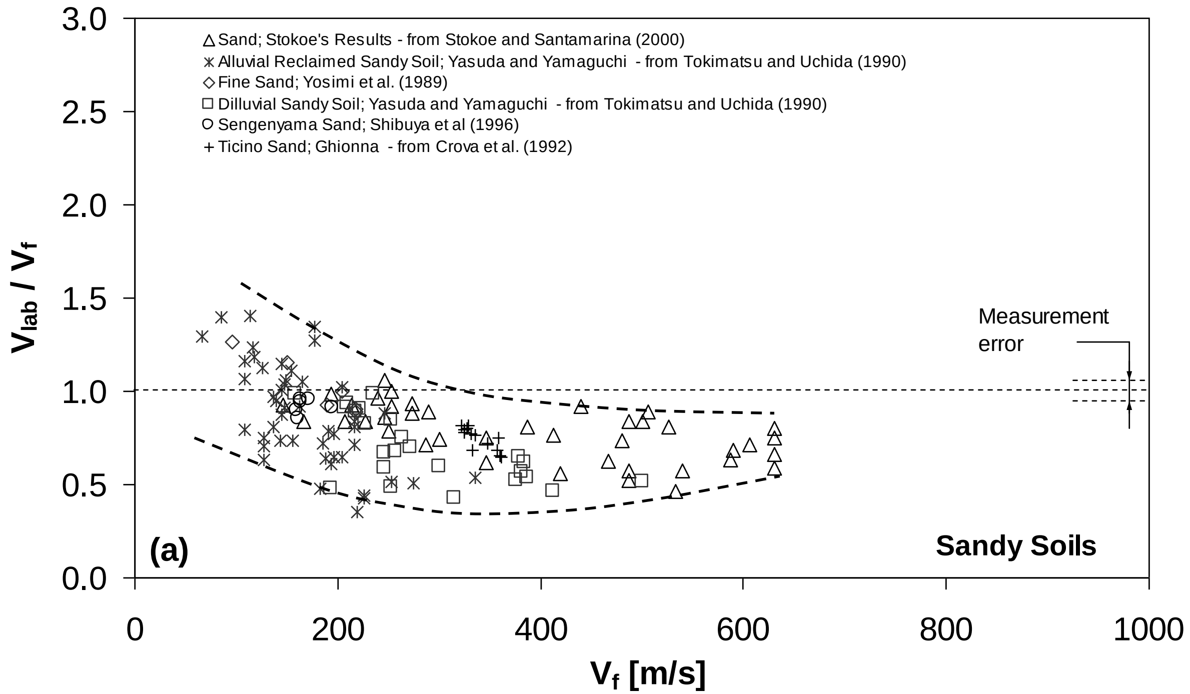




Sampling effect







Formation

Size → Forces

Shape

Soil Classification

Diagenesis

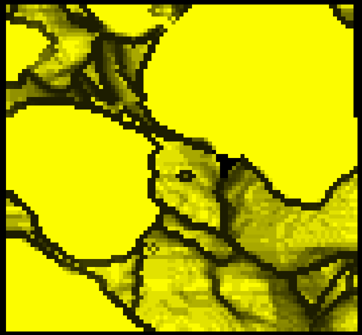
Shear strength

Stiffness

Pores

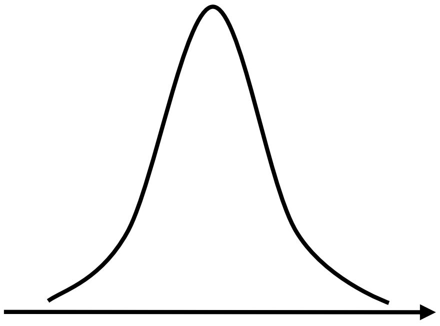
Permeability

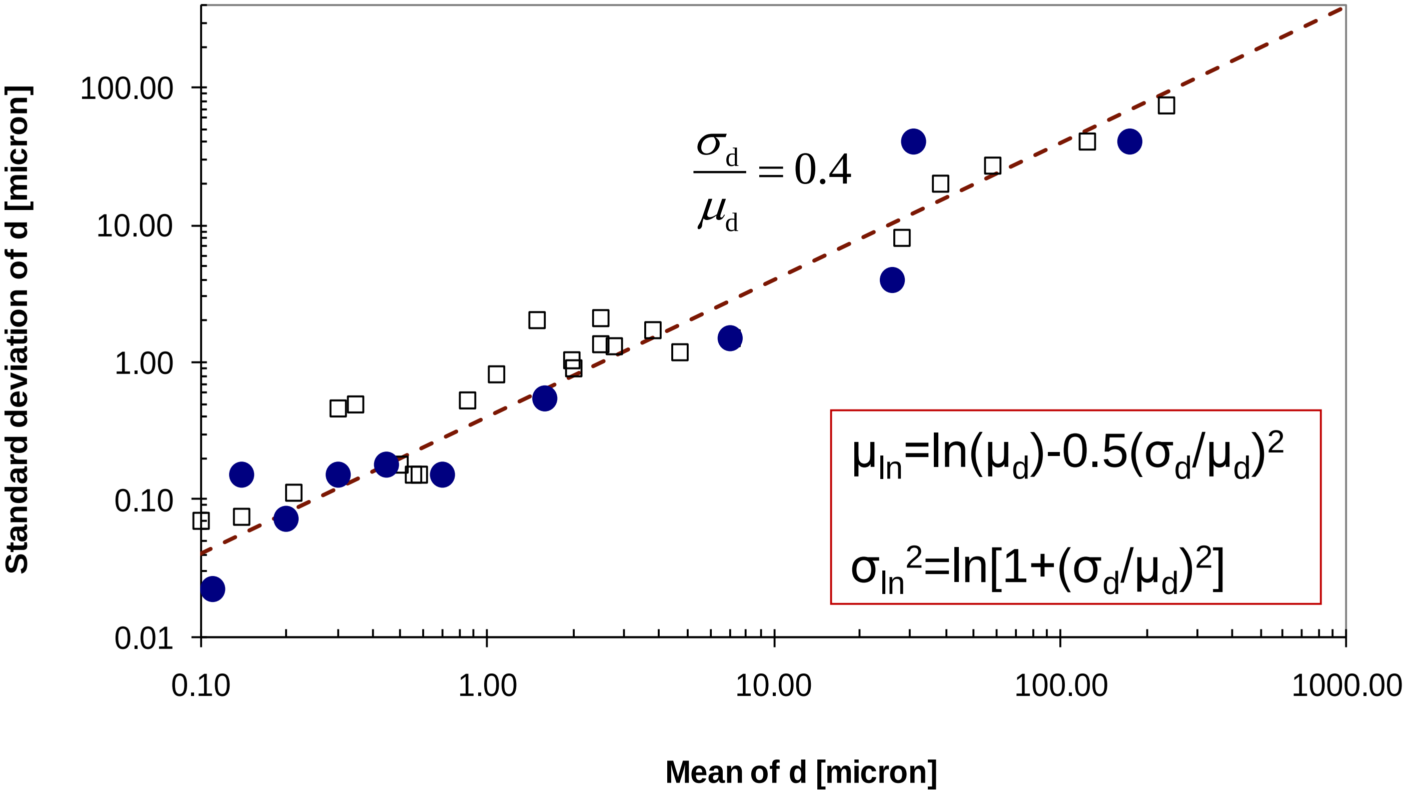
Mixed fluids



D. Frost

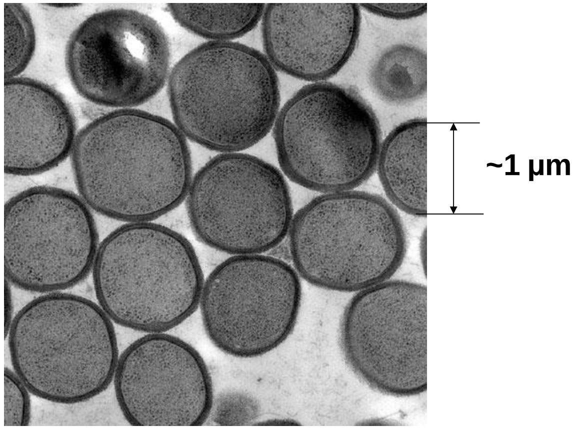
Pore Size Distribution

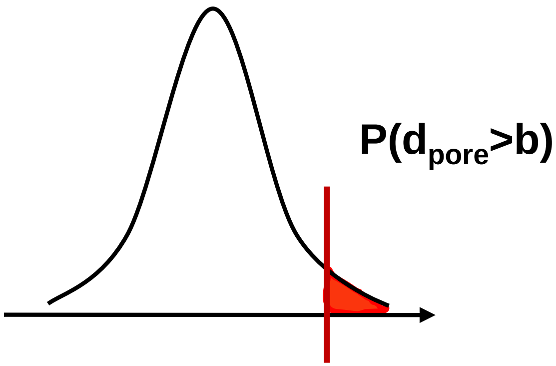




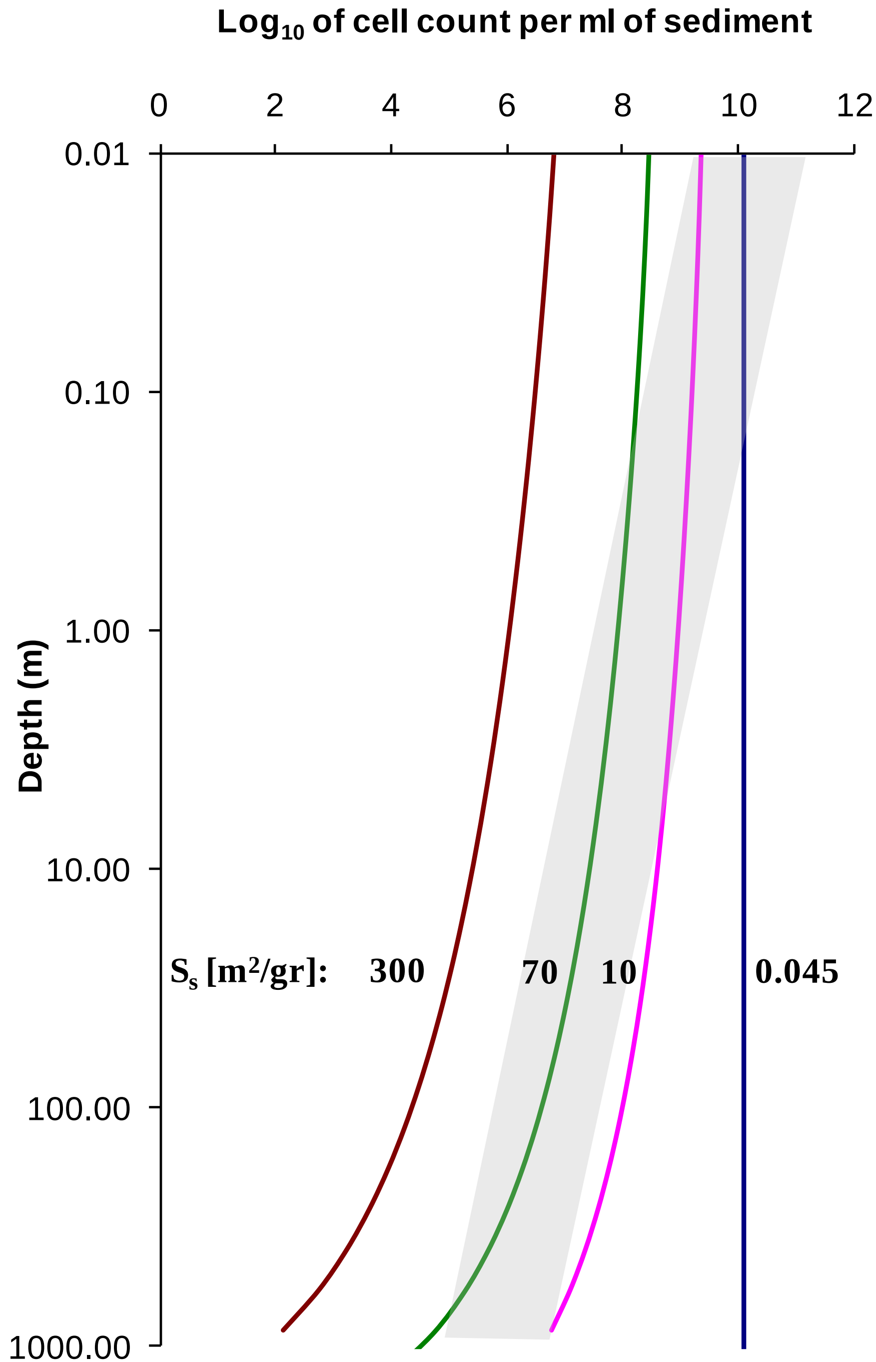
Bioactivity?

Bacillus subtilis





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



Formation

Size → Forces

Shape

Soil Classification

Diagenesis

Shear strength

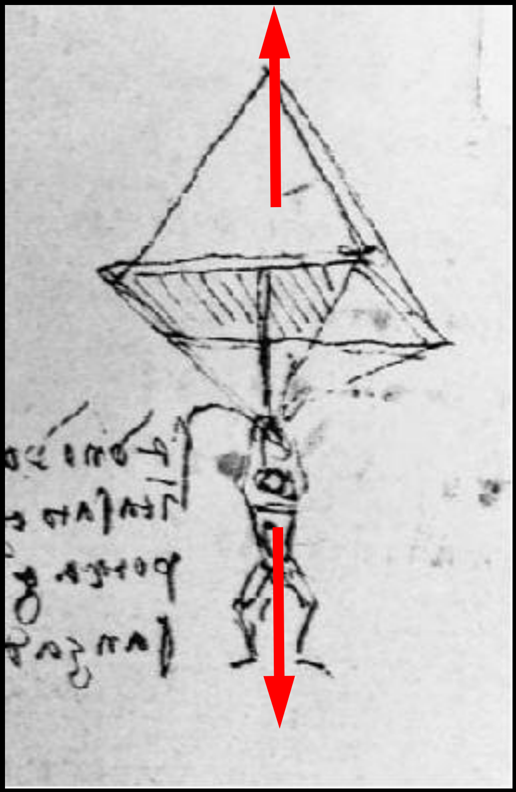
Stiffness

Pores

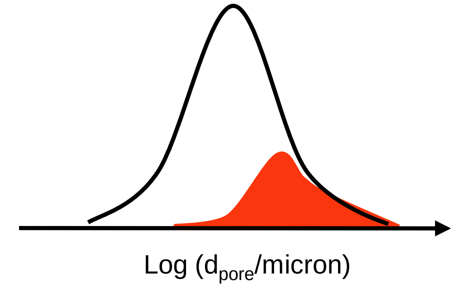
Permeability

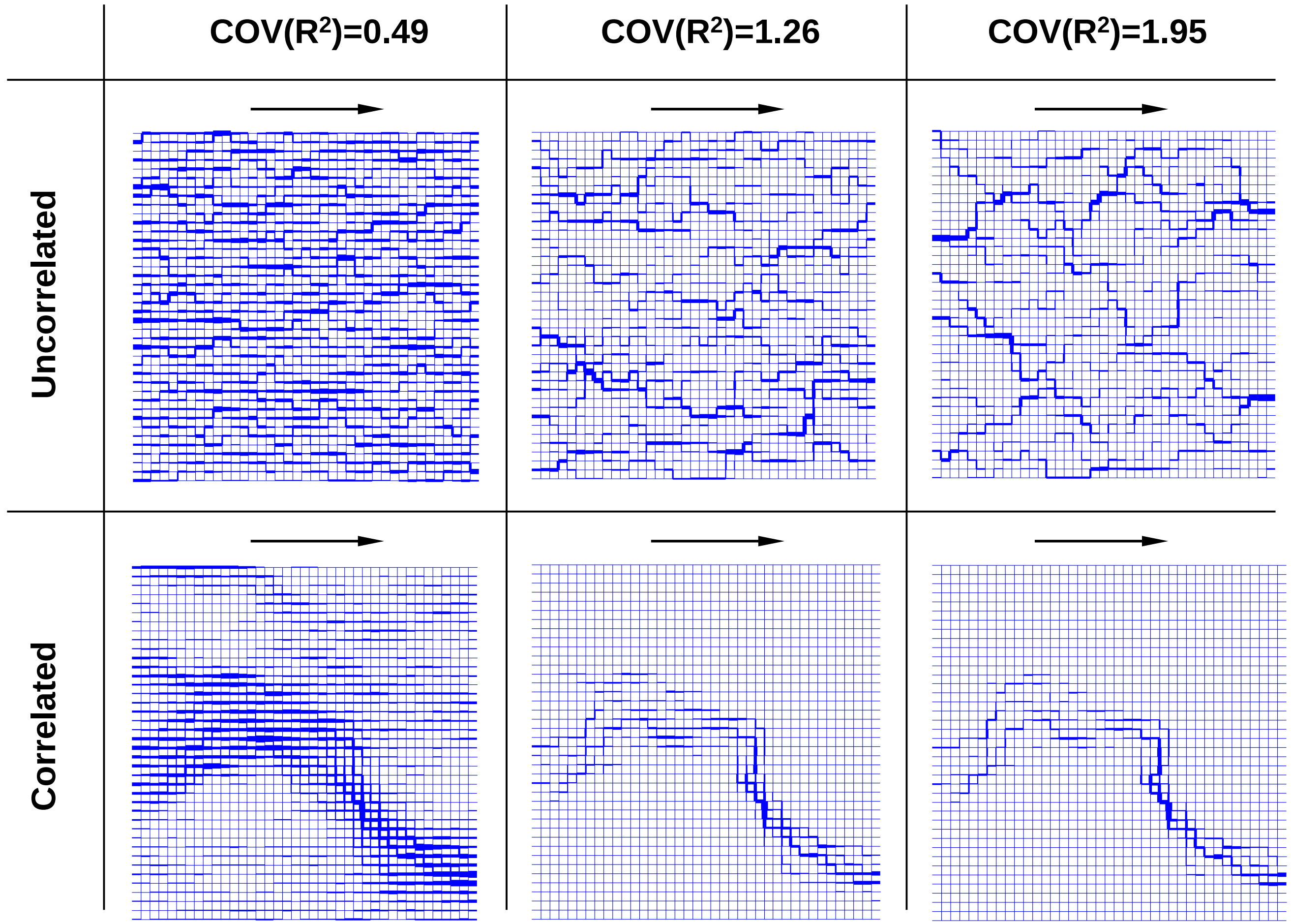
Mixed fluids

Leonardo's Parachute



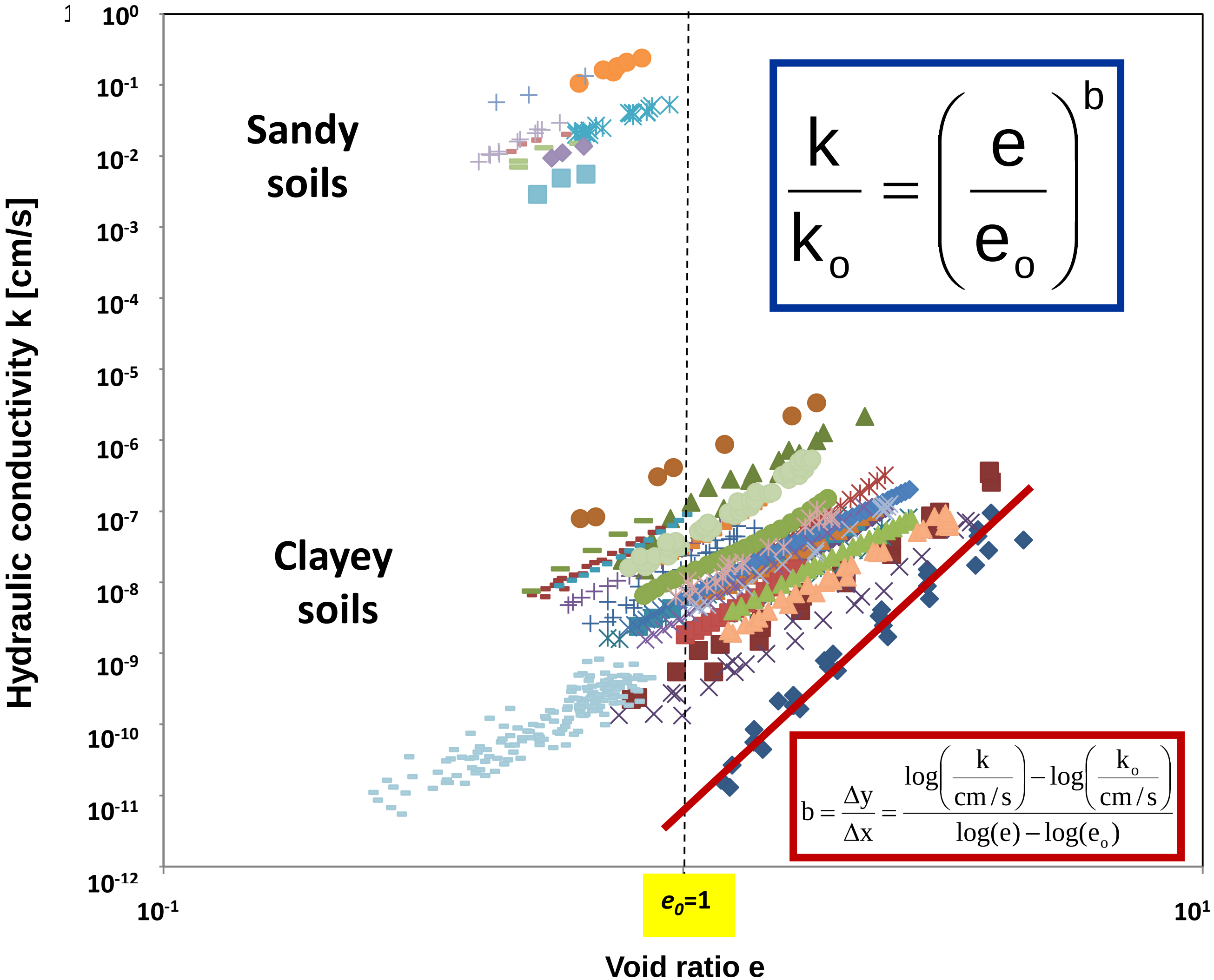
Pore Network (Poiseuille flow)

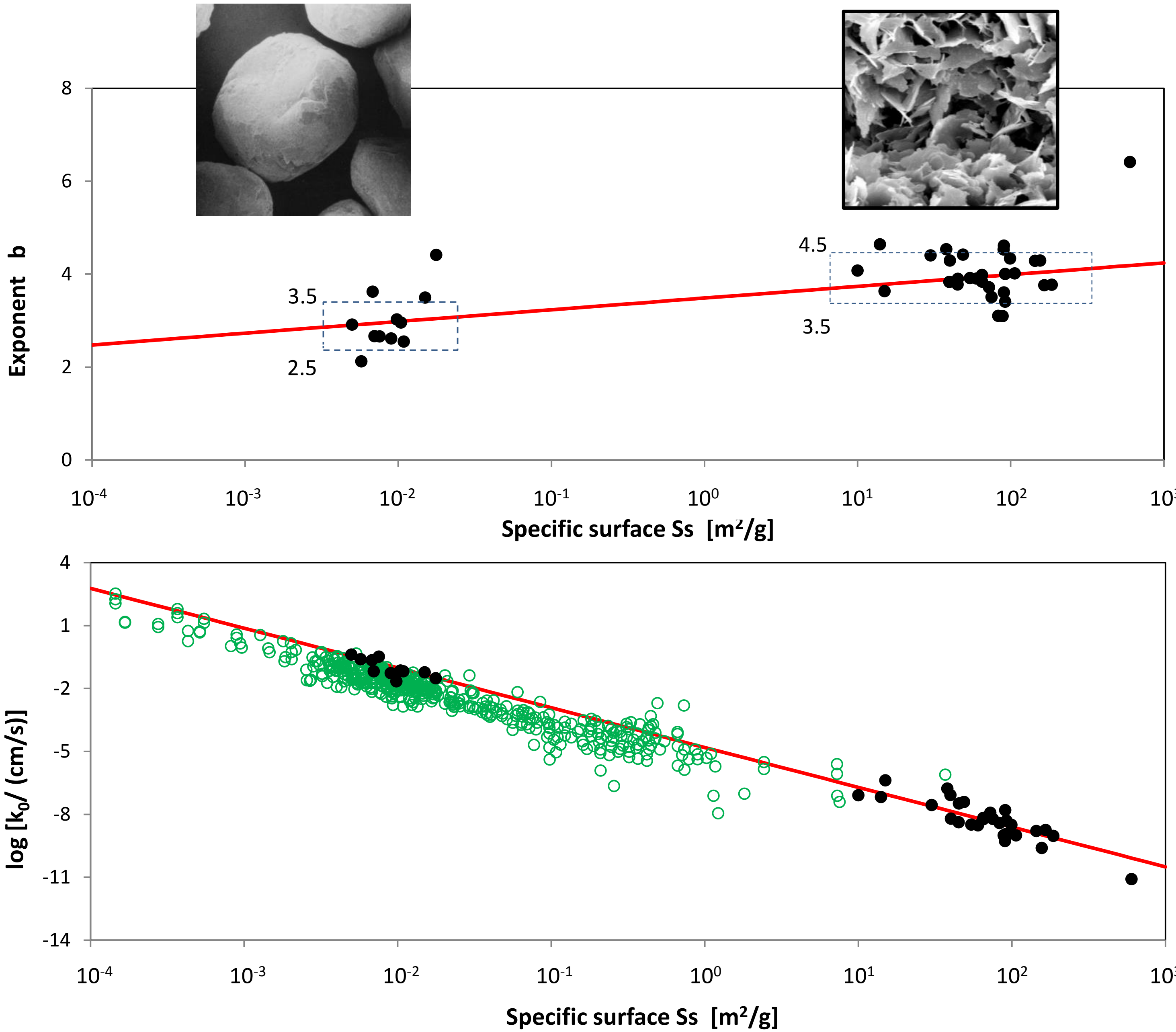




preferential flow along interconnected large pores

Permeability during compression





8
6
4
2
0
Exponent b
3.5
2.5
4.5
3.5
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Specific surface Ss [m²/g]
4
1
-2
-5
-8
-11
-14
log [k_0/ (cm/s)]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Specific surface Ss [m²/g]

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

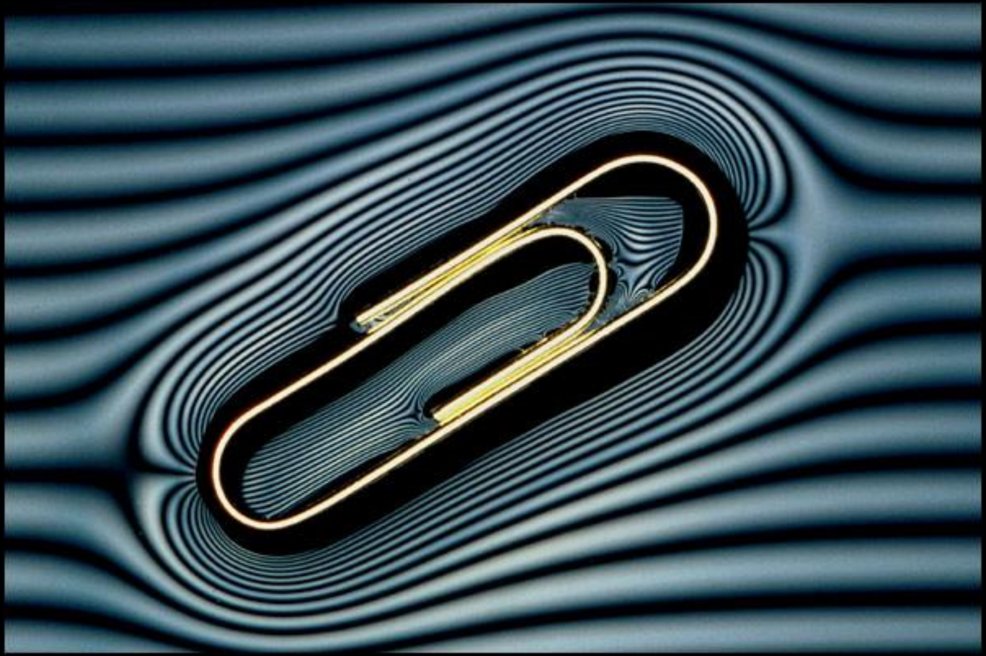
Shear strength

Stiffness

Pores

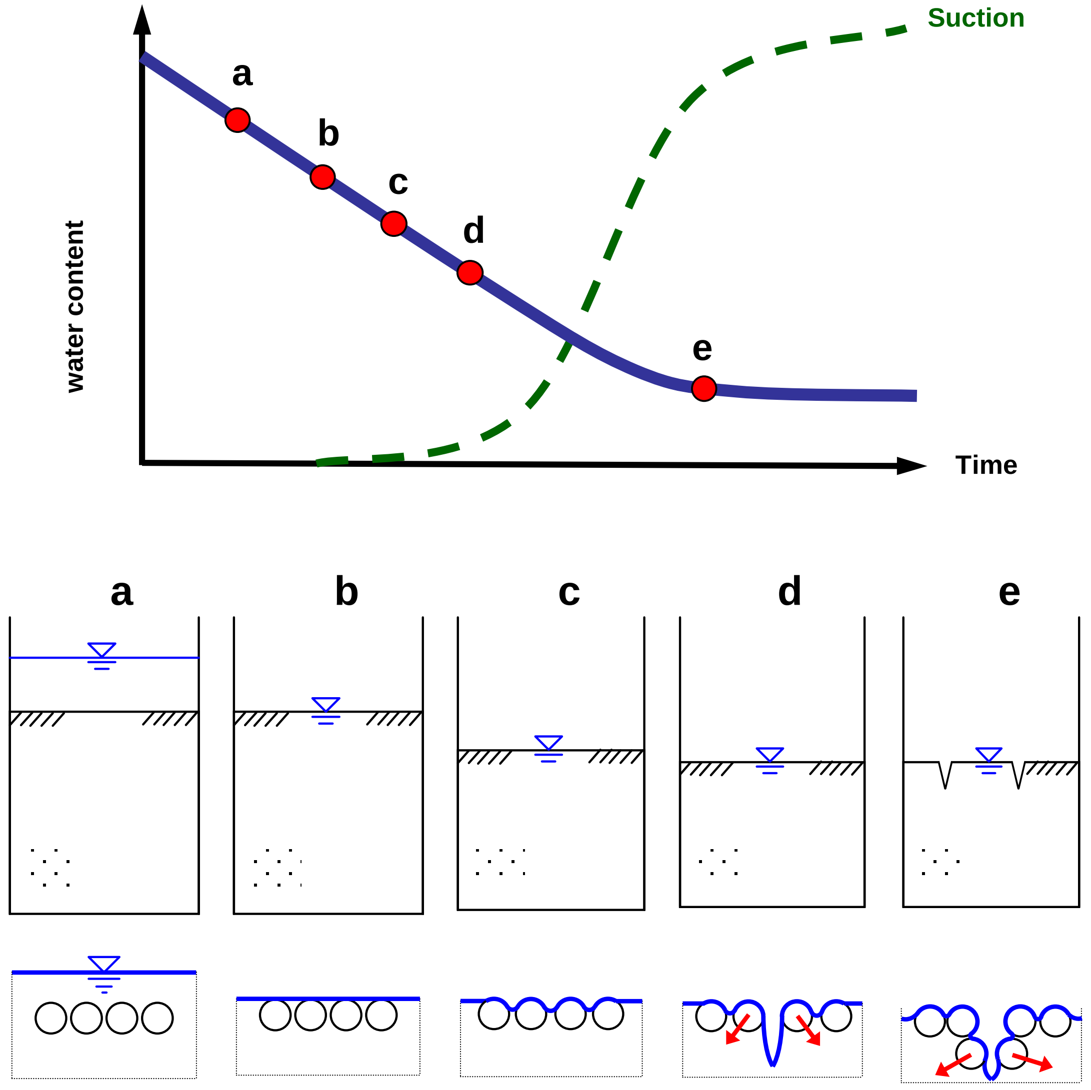
Permeability

Mixed fluids

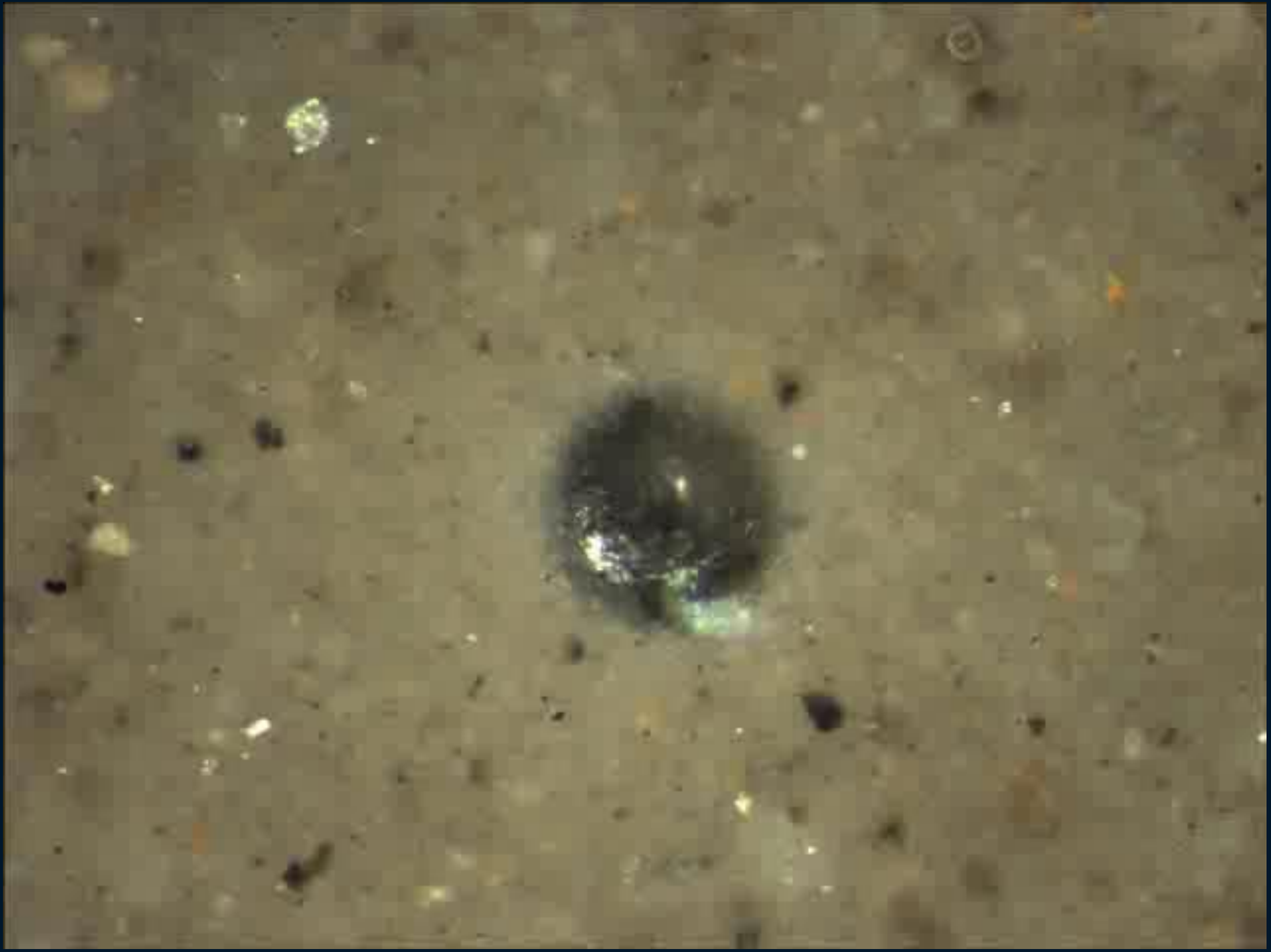


BBC News In pictures Visions of Science.jpg

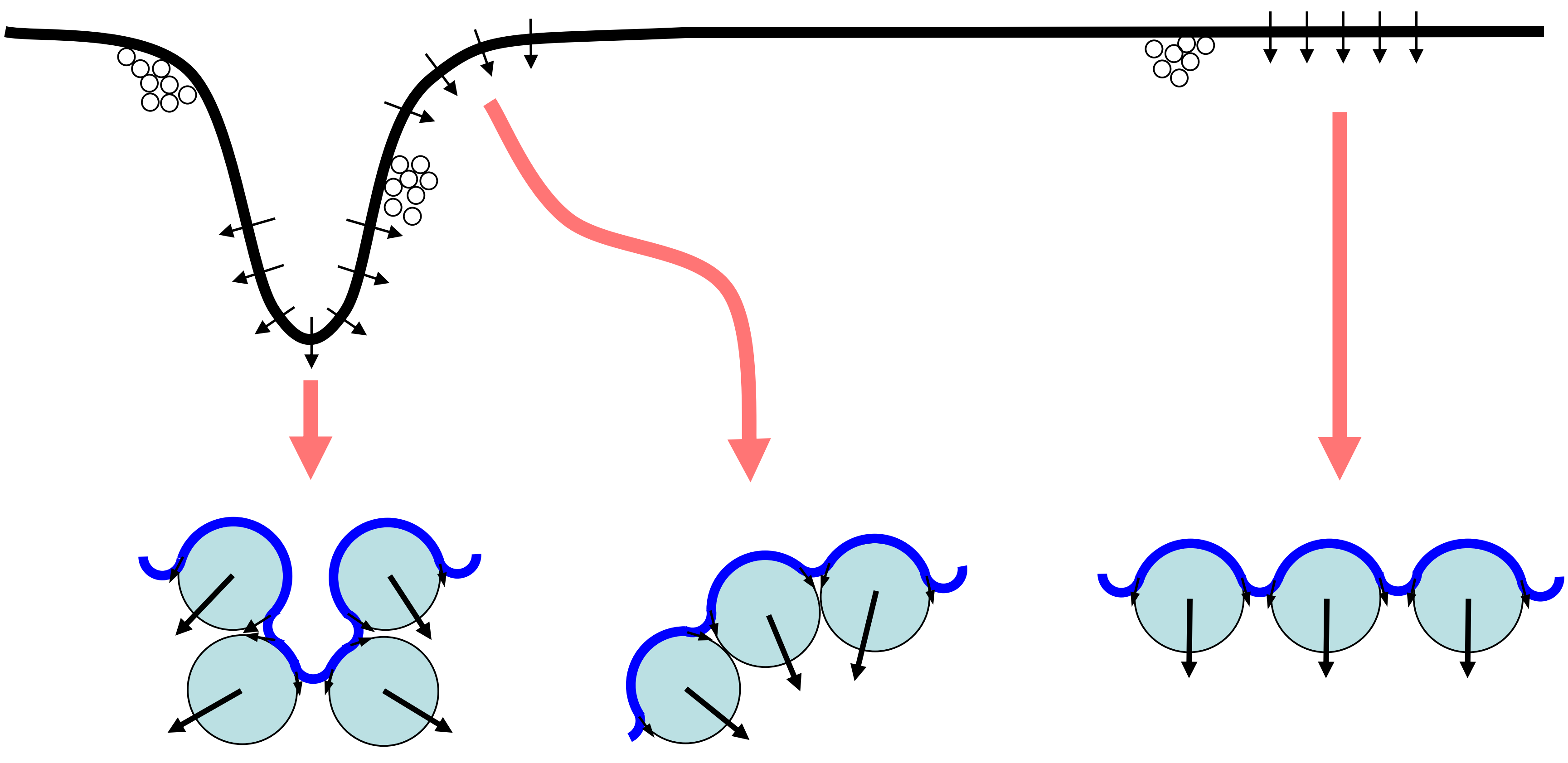
Evolution



Forcing Gas Into Sediment



Gas-Driven Fracture

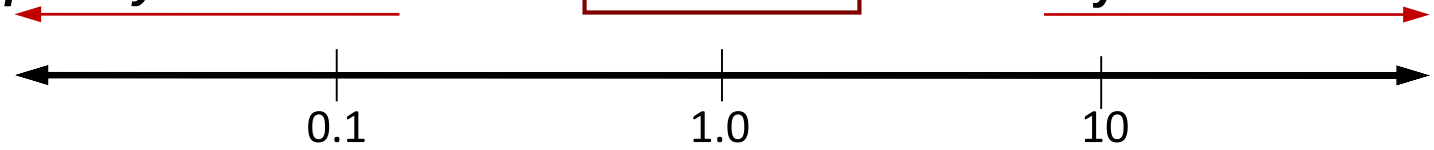


Invasion vs. Localization

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

Formation

Size → Forces

Shape

Soil Classification

Diagenesis

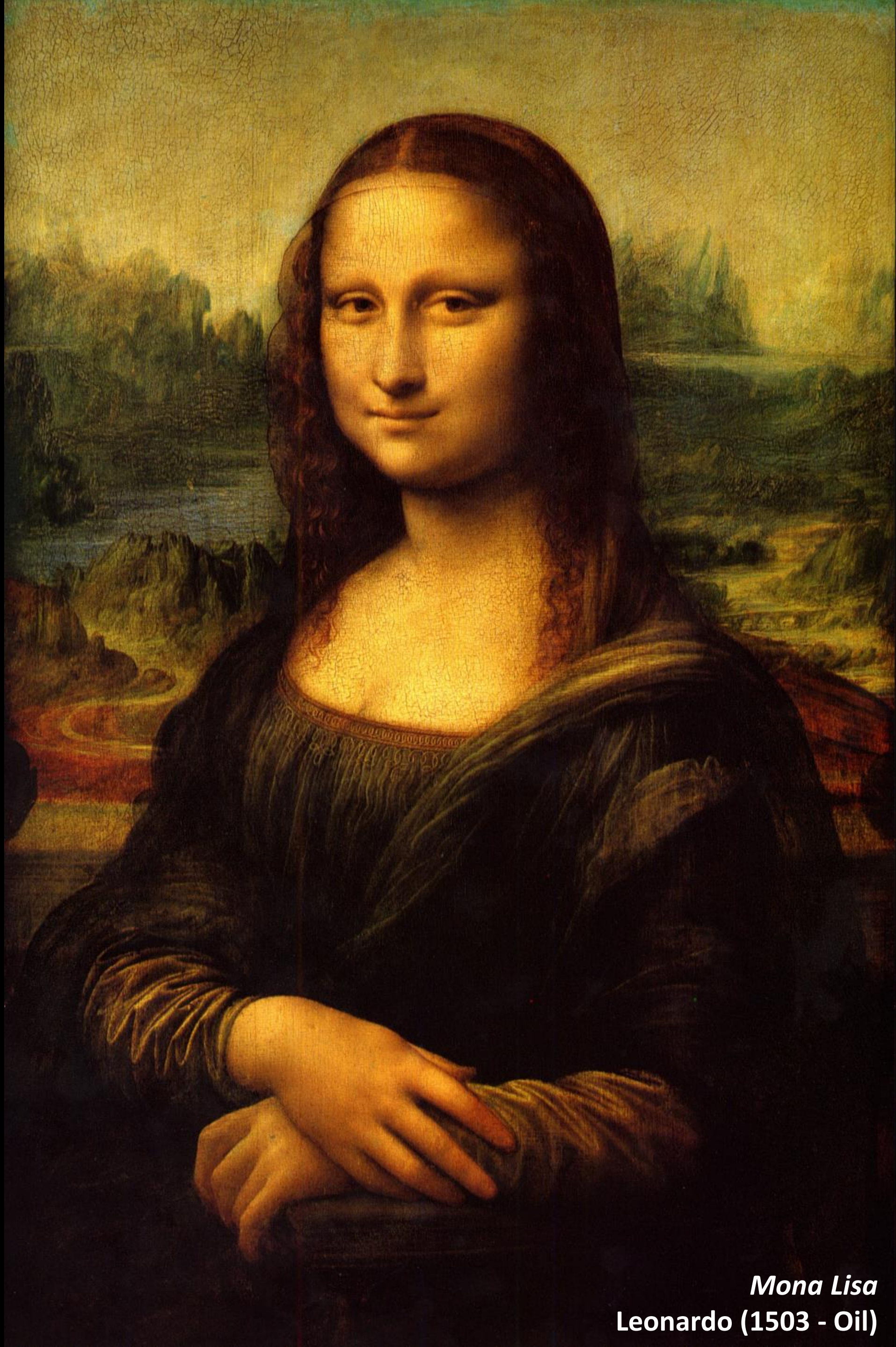
Shear strength

Stiffness

Pores

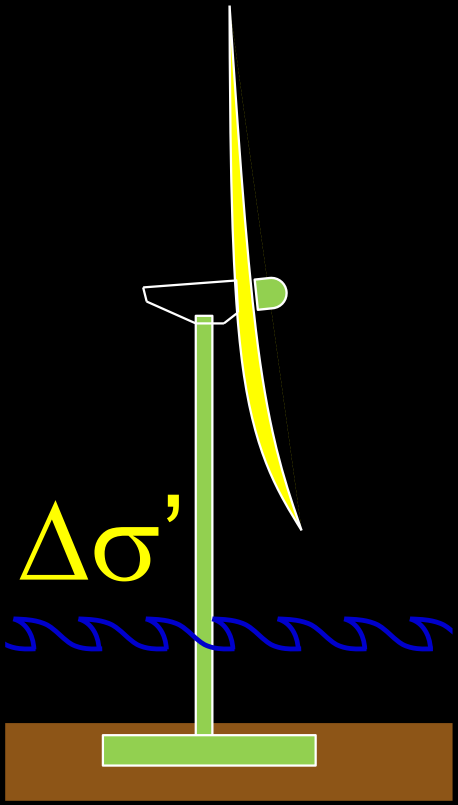
Permeability

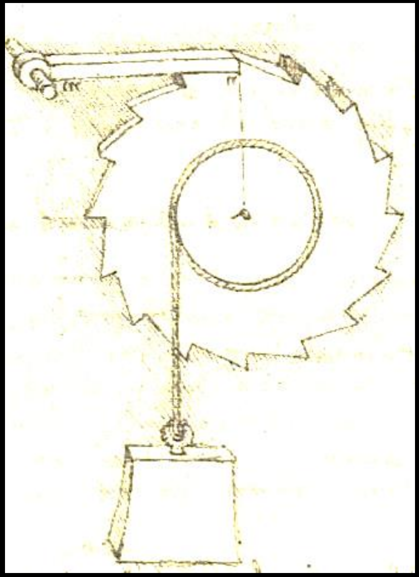
Mixed fluids



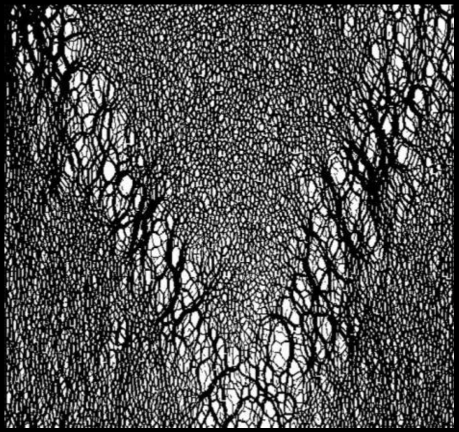
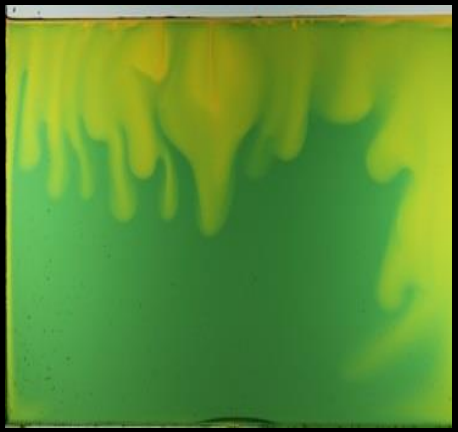
Mona Lisa
Leonardo (1503 - Oil)

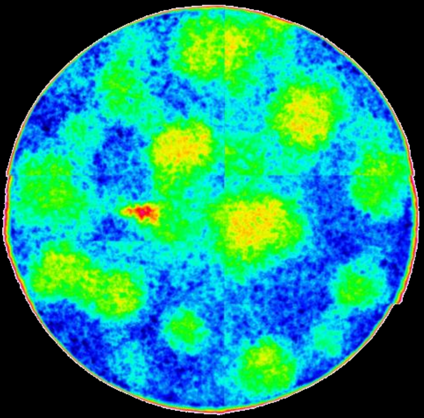
Repetitive Loads

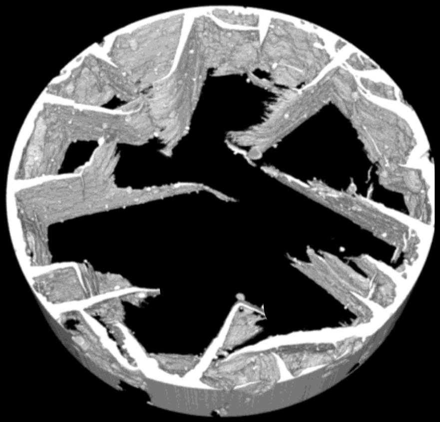




Instability → Localization





Strain localization
shear band
compaction band

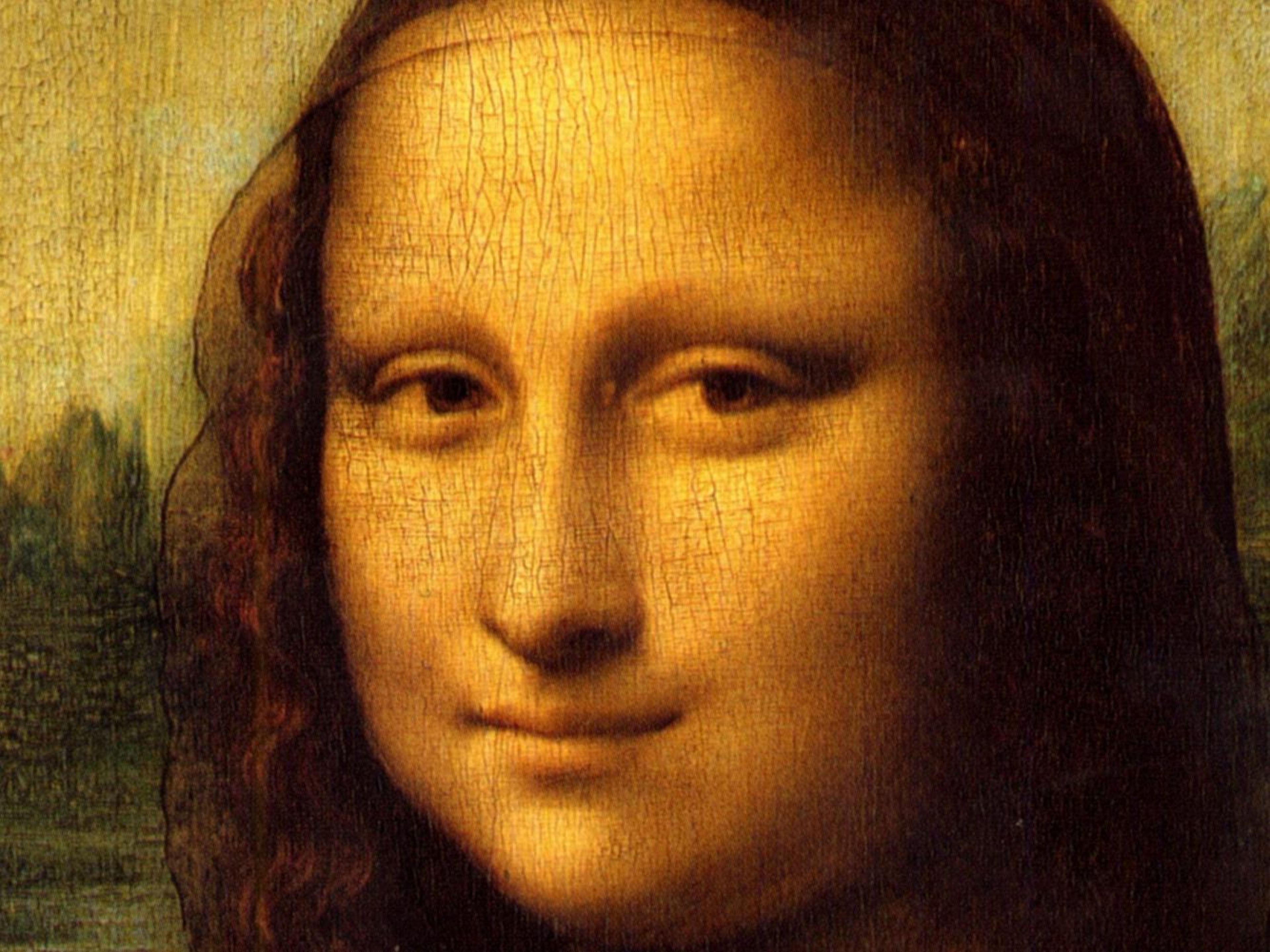
Grains migration
clogging
piping erosion
sand production

Fluids
viscous fingering
density tears

Fluid-driven
desiccation cracks
gas or oil-driven
hydraulic fracture

Lenses
ice & hydrate

Dissolution
shear in contraction
piping & wormholes




Thank you