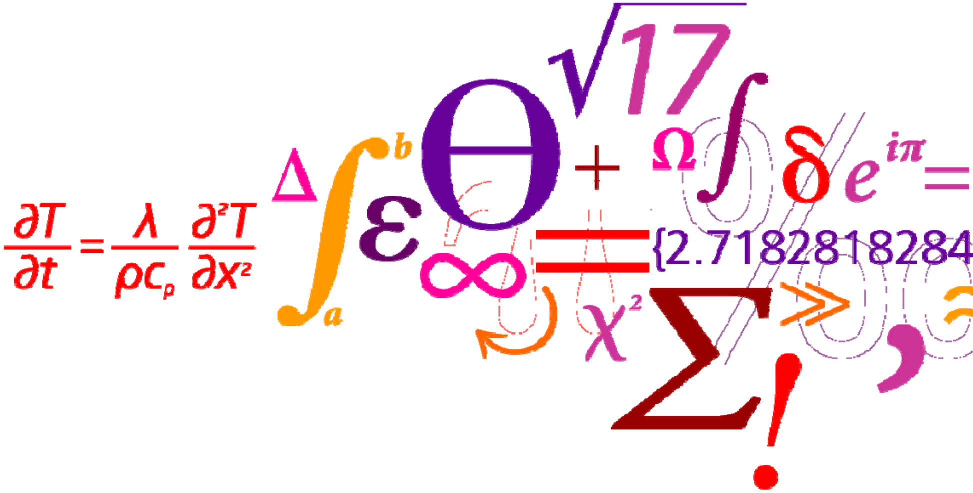
High kinematic viscosity of air may cause dry clay to be stiffer than water saturated clay

Ida Lykke Fabricius
CERE, Department of Civil Engineering,
Technical University of Denmark



DTU Civil Engineering
Department of Civil Engineering

Gassmann, 1951

Gassmann assumed that the shear modulus is independent of pore fluid:

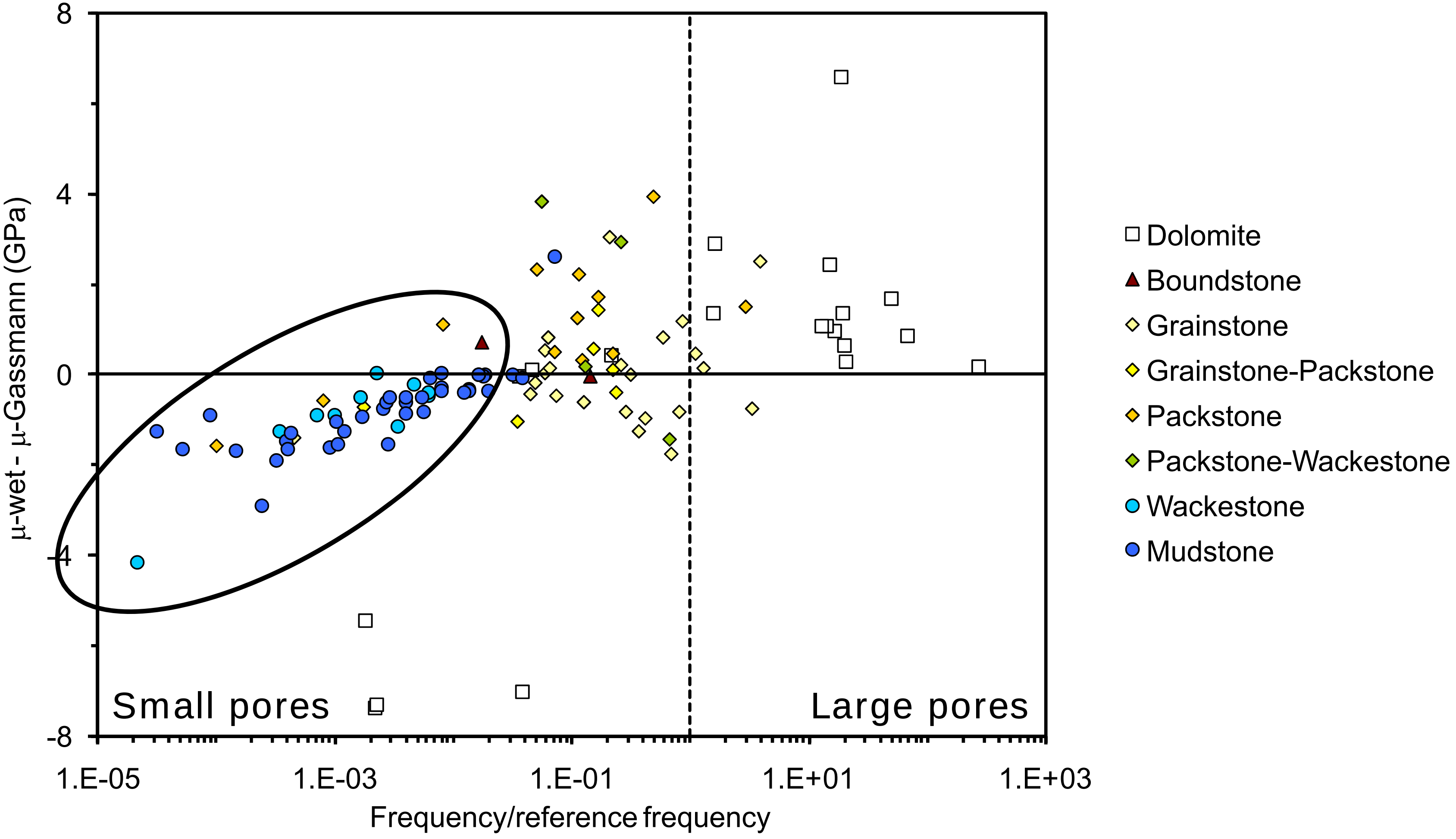
$\mu_{sat} = \mu_{dry}$

Provided:

There is no interaction between solid and fluid.

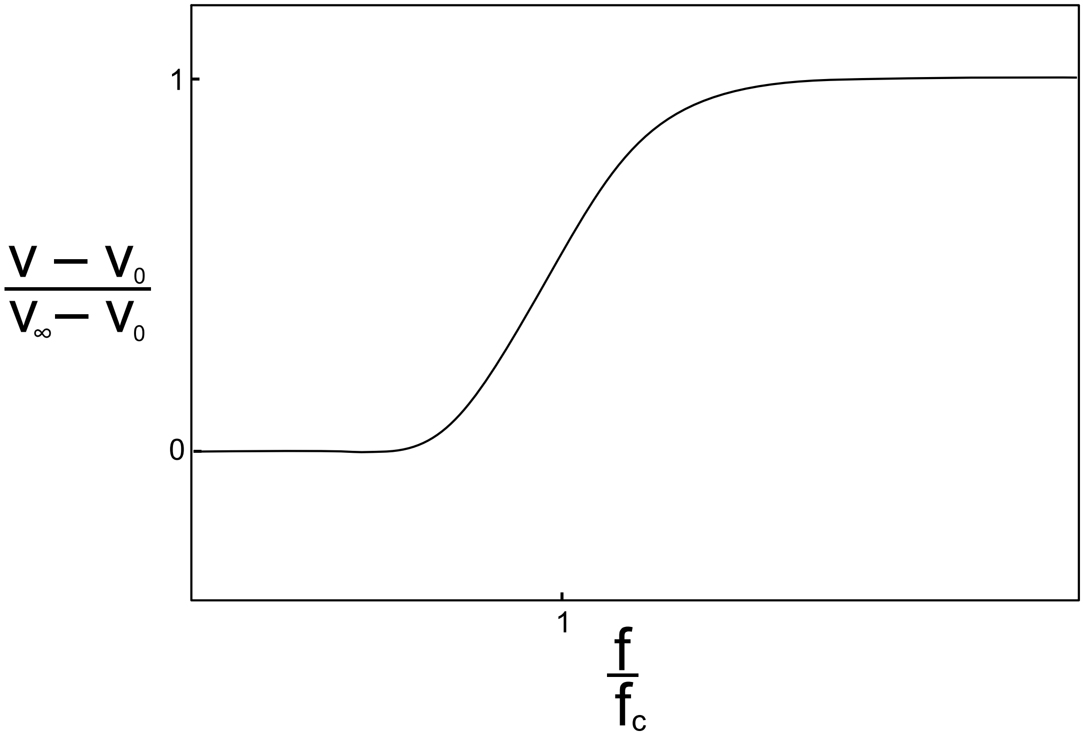
There is local pressure equilibrium among pores.

Shear softening



Fabricius et al. 2010

Biot, 1956



$$f_c = \frac{\phi\eta}{2\pi\rho_{fl}k}$$

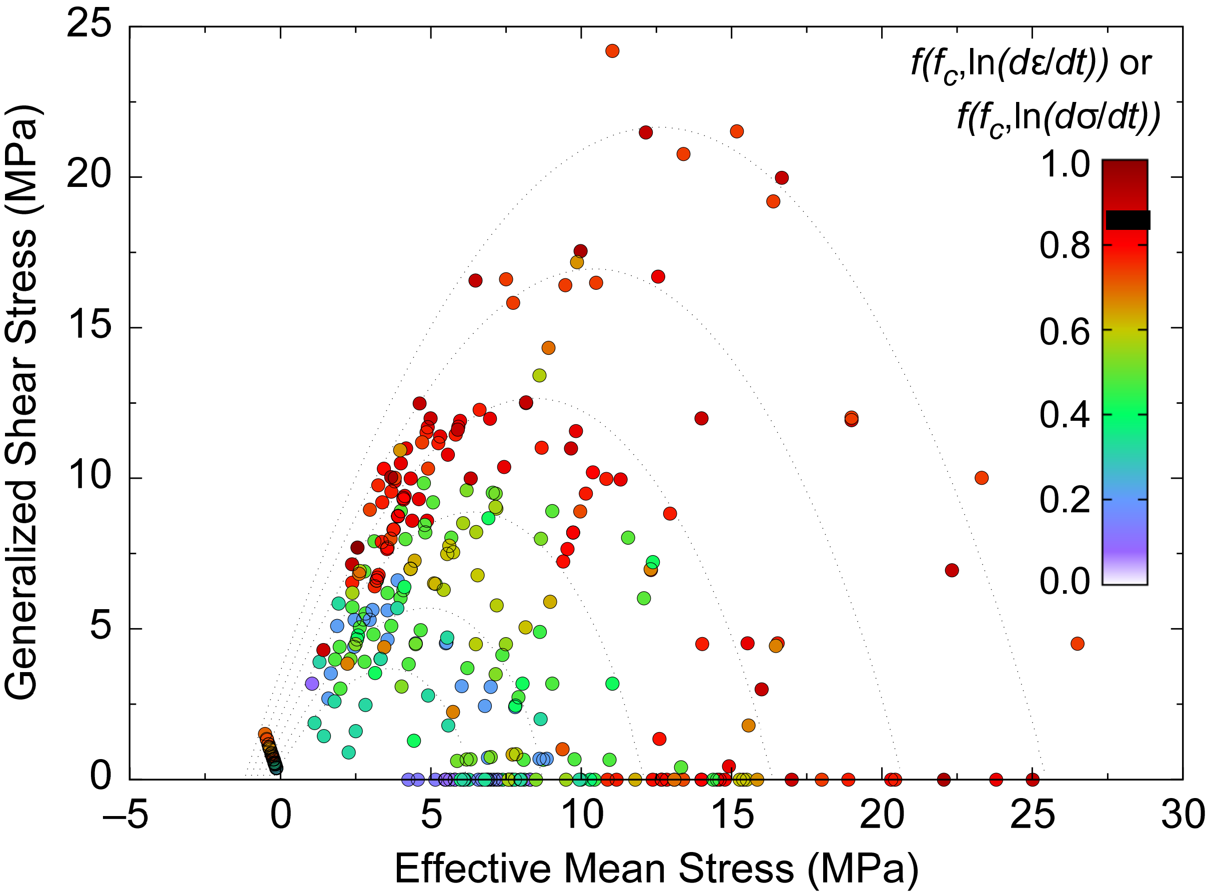
ϕ: porosity,

η: viscosity,

ρ_{fl}: fluid density,

k: permeability

Geotechnical experiments on highly porous chalk

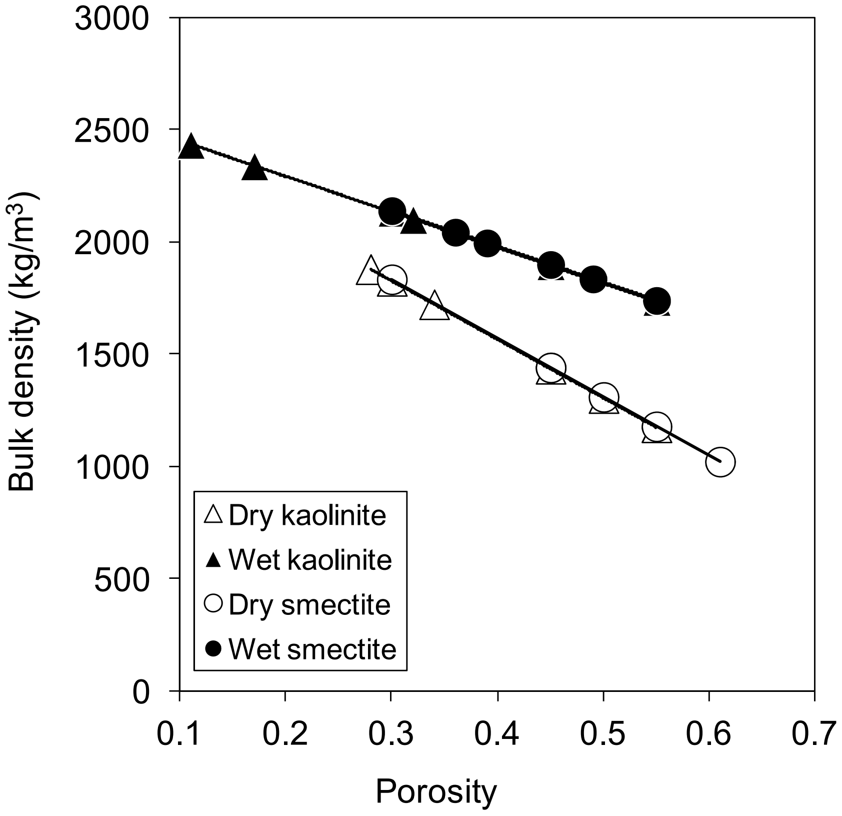


Andreassen & Fabricius 2010

Drying pottery

http://pottery.about.com/od/temperatureandmaturation/ss/drypottery.htm

Mondol et al., 2007



Clay powder and air;

Clay powder and sea water from Oslo fjord

Ambient conditions

Kaolinite, BET: S = 11 m^2/g

Smectite, BET: S = 25 m^2/g

Air: $\eta/\rho_{fl} = 1.6\ 10^{-5}\ m^2/s$

Water: $\eta/\rho_{fl} = 1.0\ 10^{-6}\ m^2/s$

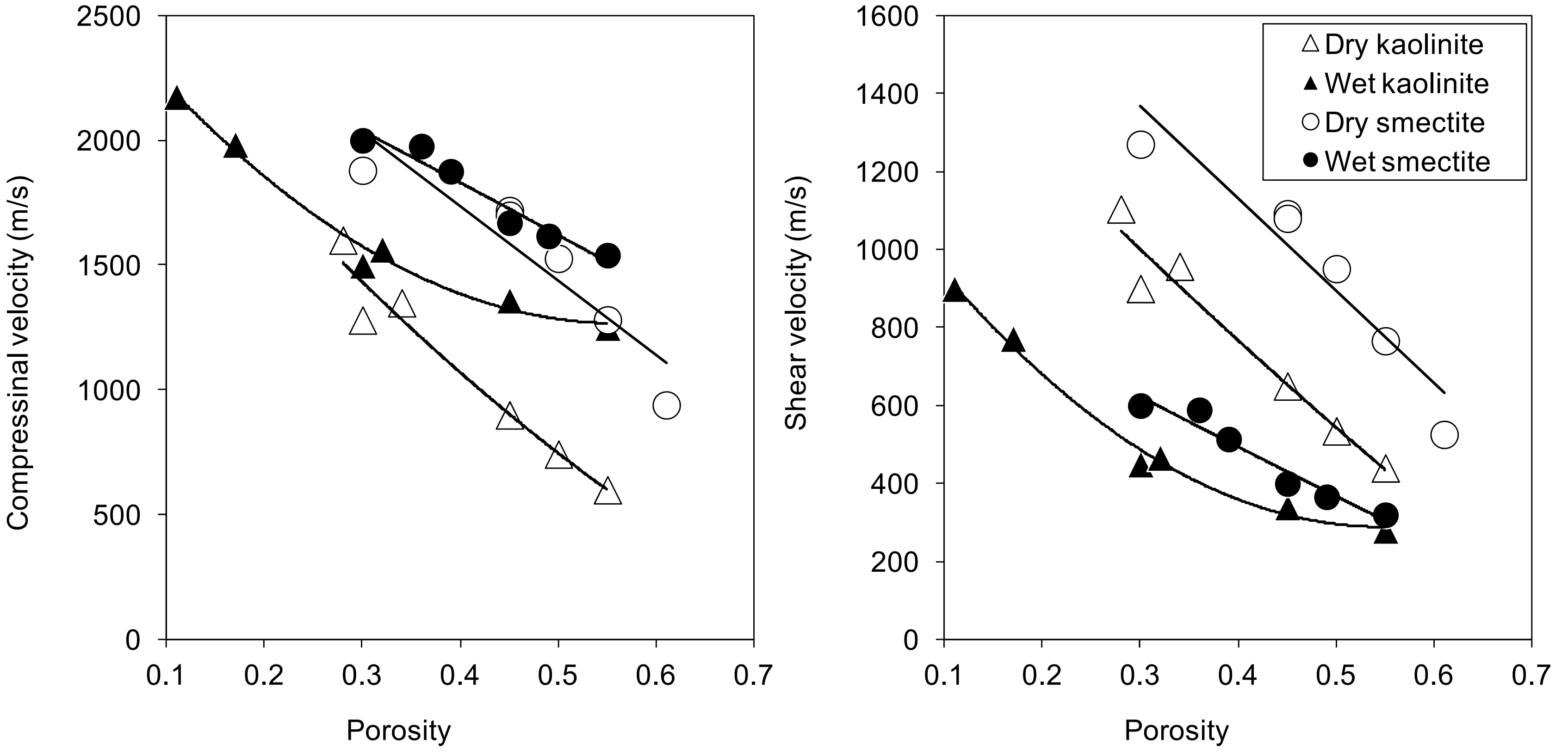
Uniaxial confined drained loading

Ultrasonic velocities (50 kHz)

Mondol et al. 2007

Elastic wave velocity vs. porosity

For a given porosity:



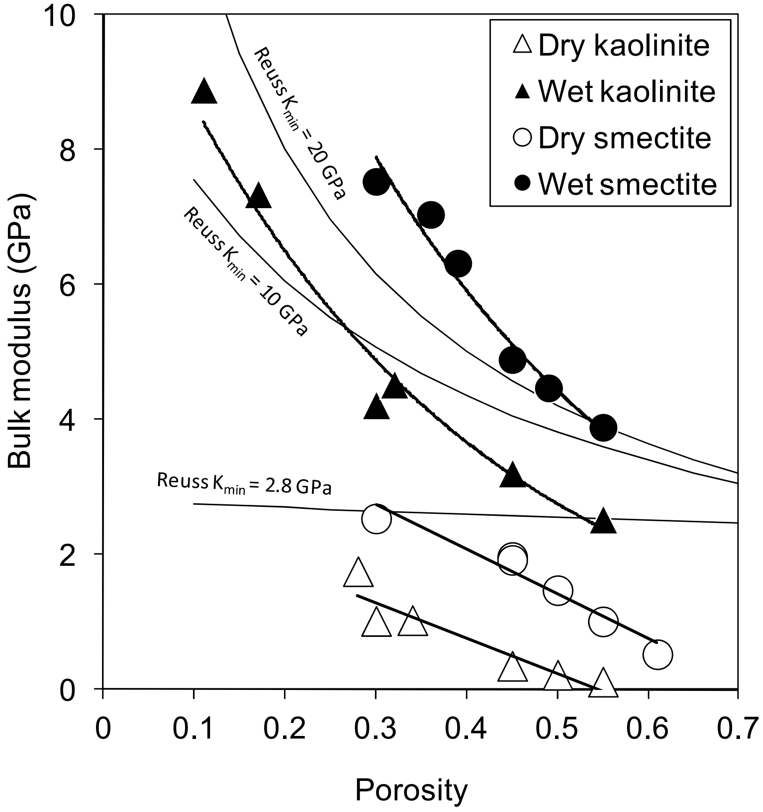
Smectitic samples have higher velocities

Dry samples have higher v_S

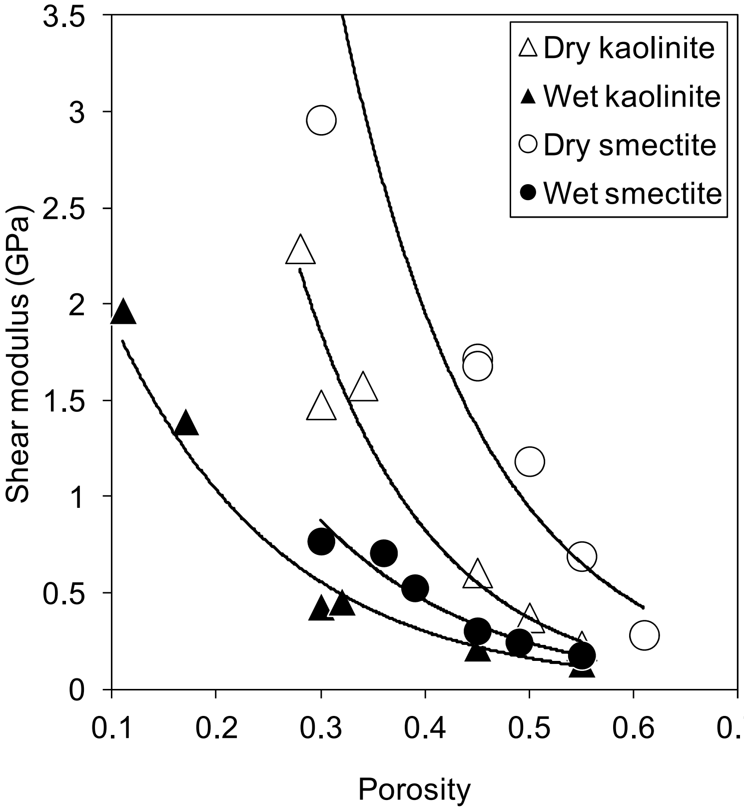
Mondol et al. 2007

Elastic moduli vs. porosity

For decreasing porosity:



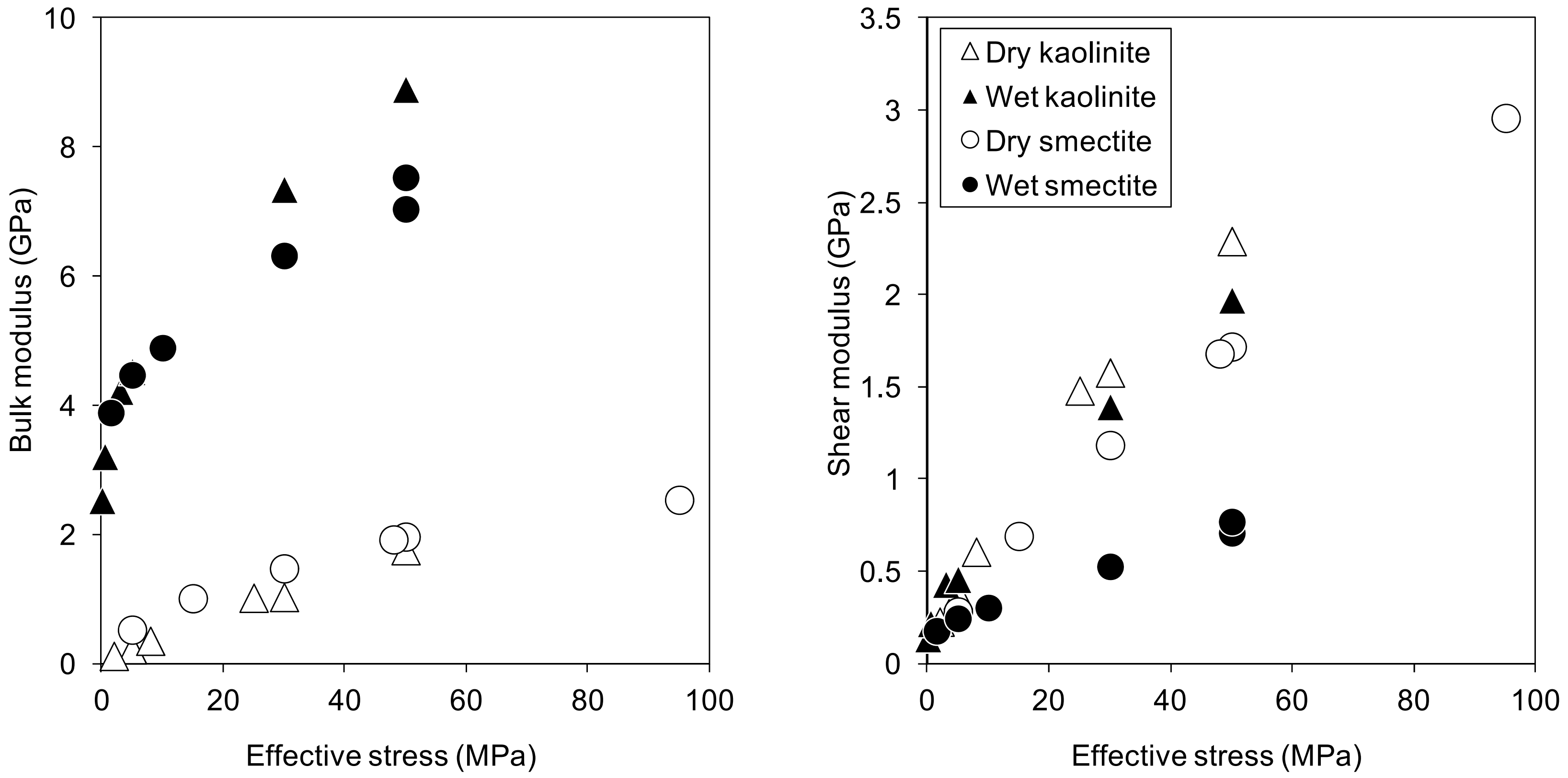
Bulk moduli increase more than Reuss bound



Shear moduli of dry and wet samples deviate

Elastic moduli vs. axial effective stress (Terzaghi)

For a given effective stress:

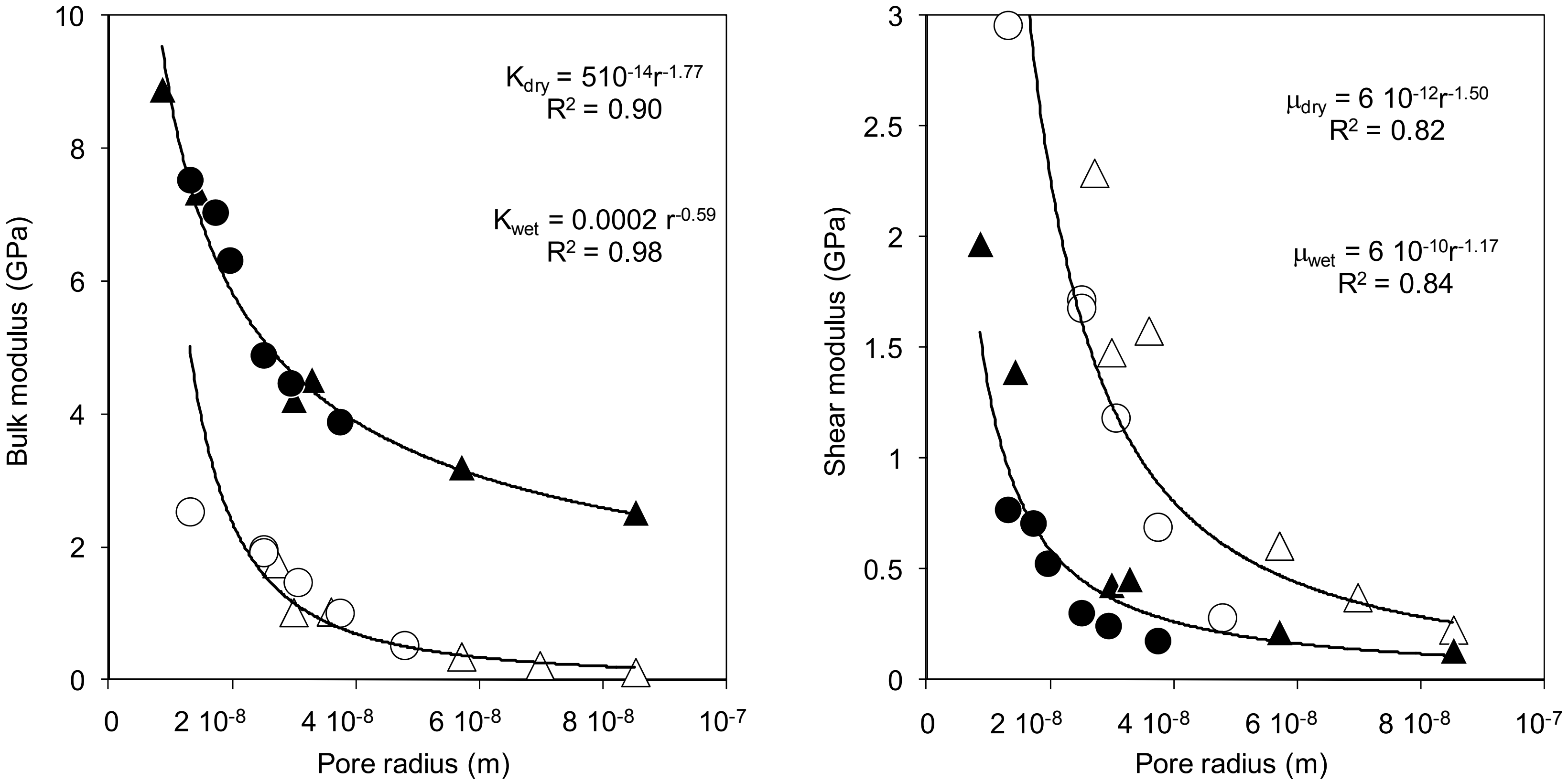


Bulk modulus depends on pore fluid

Shear modulus is high for dry samples

Pore radius: $r = (2\phi)/(S\ \rho_g\ (1-\phi))$

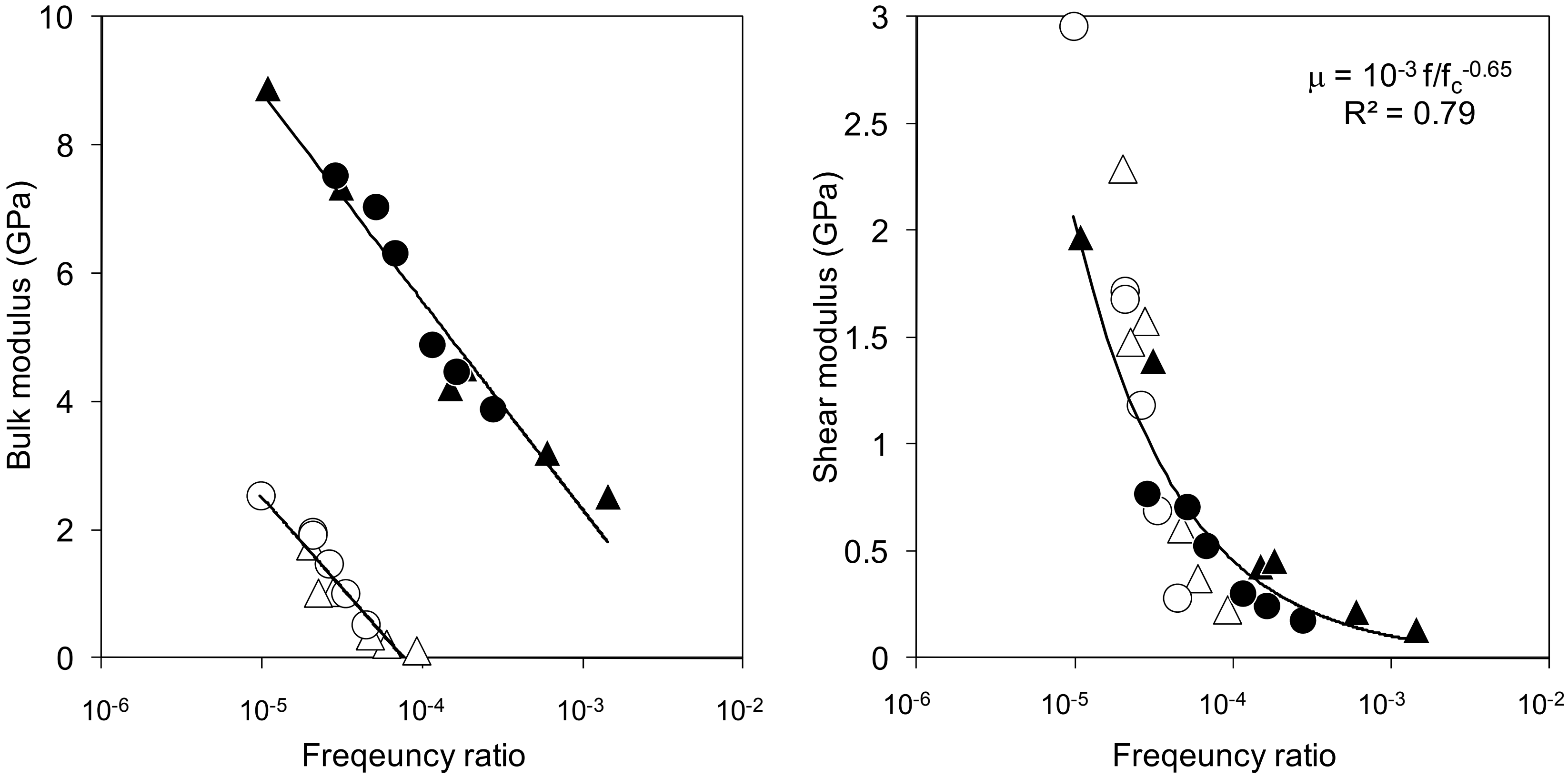
For a given pore radius:



Moduli are controlled by pore fluid, not by mineralogy

Frequency ratio: $f/f_c = f/((2\eta)/(\rho_{fl}\ \pi\ r^2\ c))$

For a given frequency ratio:



Bulk modulus ~ $-\log(f/f_c)$

Small fluid effect on shear modulus

What breaks the rules of Gassmann, 1951?

Gassmann assumed that the shear modulus is independent of pore fluid:

$\mu_{sat} = \mu_{dry}$

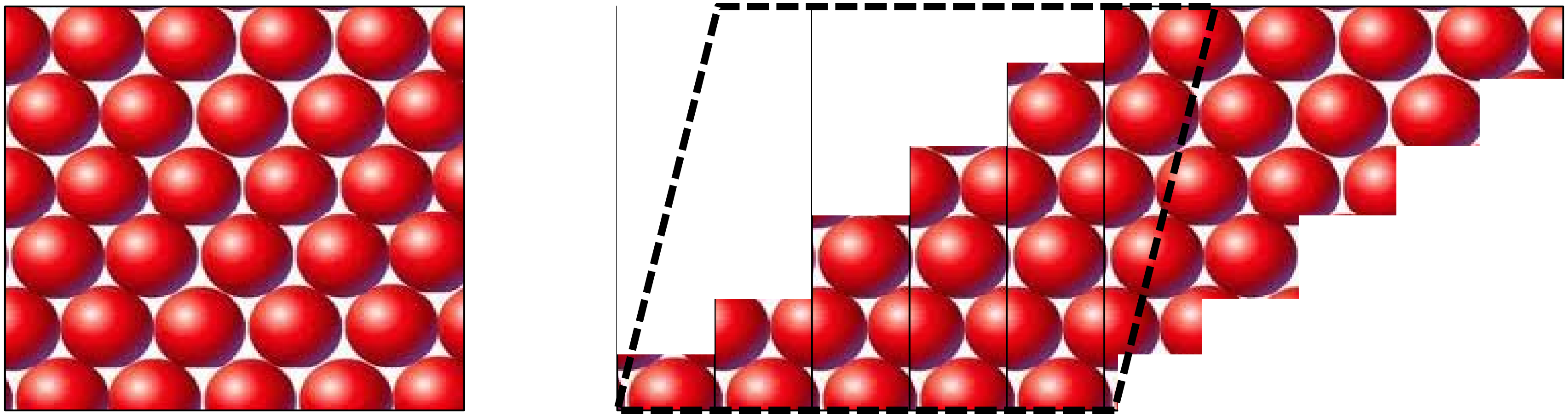
Provided:

There is no interaction between solid and fluid. ? ←

There is local pressure equilibrium among pores. ? ←

Shear

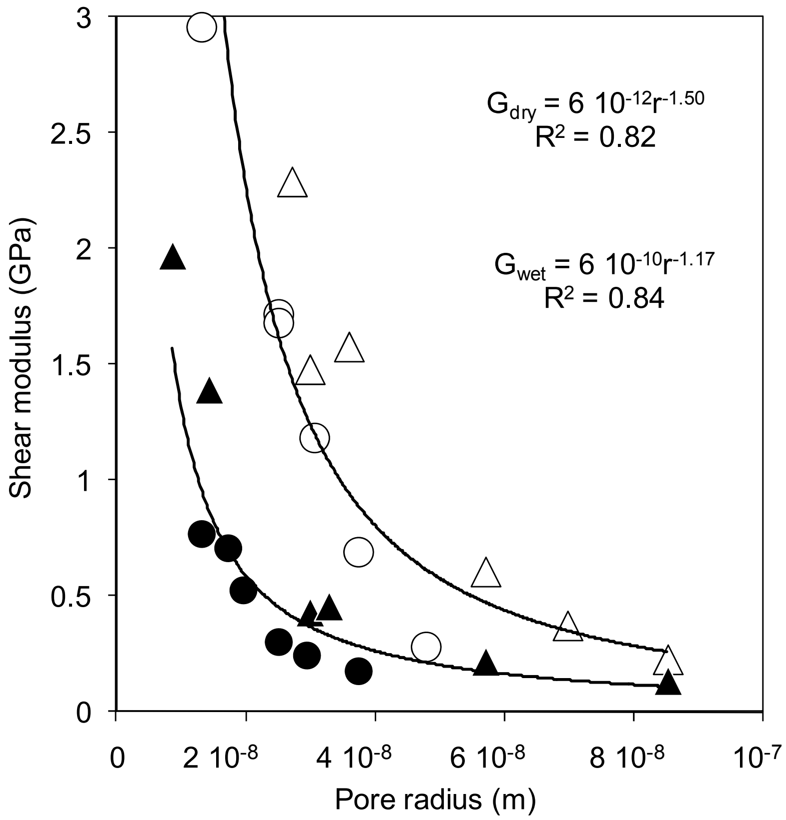
Fluid may lag behind solid



Provided wave length is significantly larger than pore size

and kinematic viscosity is high.

Amplitude > Pore radius?



$G_{dry} = 6\ 10^{-12} r^{-1.50}$
$R^2 = 0.82$

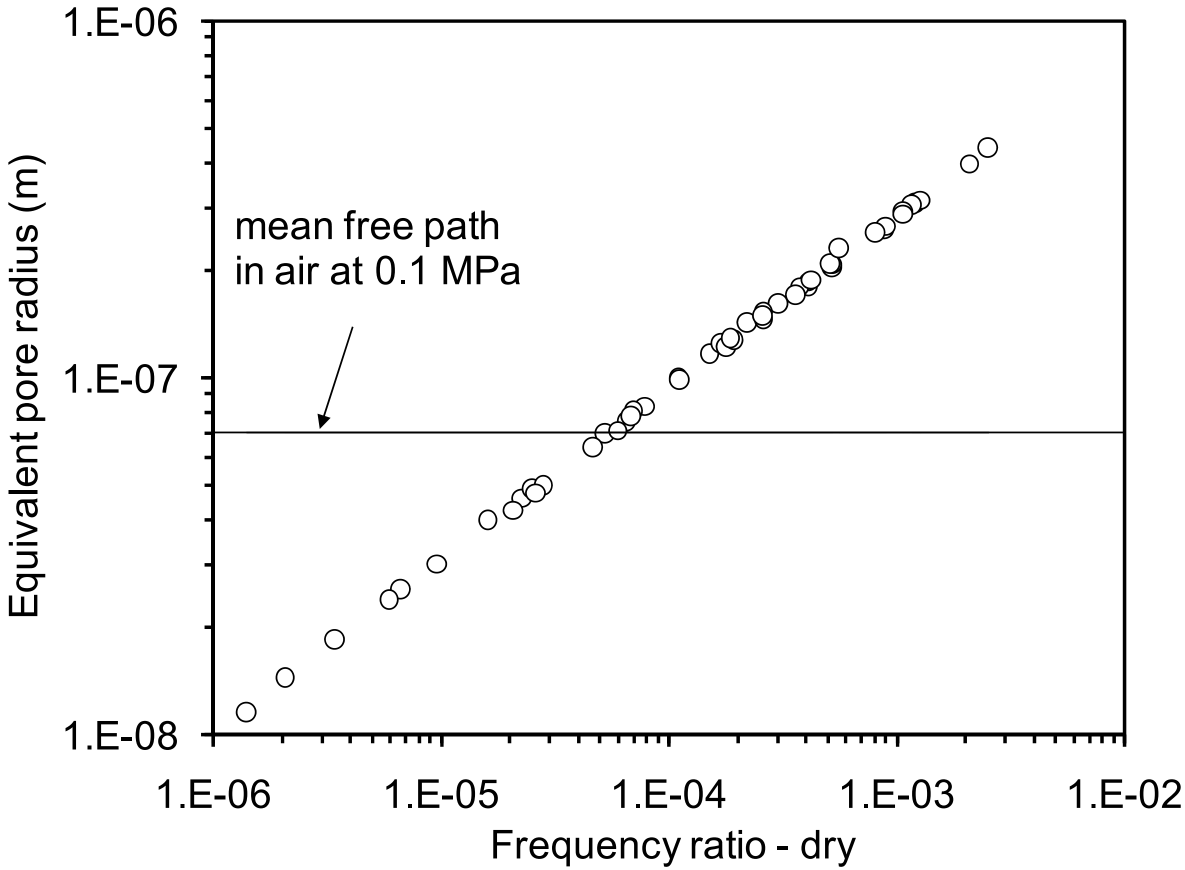
$G_{wet} = 6\ 10^{-10} r^{-1.17}$
$R^2 = 0.84$

Wave length: 10^{-2} m

P-wave amplitude: ≈ 10^{-8} m

How large is shear wave amplitude?

The effect of high kinematic viscosity of air



Fabricius 2010

Conclusion

- Clay and chalk may be soft in the water saturated state due to the same mechanism.

- Maybe the anomaly is due rather to the air than to the water.

- The anomaly correlates with Biot's frequency ratio pointing to the kinematic viscosity.

- Maybe the effect arises when the wave amplitude is large relative to pore radius.
  - This could cause violation of Gassmann's and Biot's assumption of pressure equilibrium at low frequency.