5. An introduction to Rock Physics

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ERSE 210 Seismology

Linking Waves to Rocks

Petrophysics/
Rock physics

Geophysics

Rock properties $\longrightarrow$ **Elastic properties** $\longrightarrow$ **Seismic waves**

ϕ: porosity

V_{sh}: shale content

$S_{w/o/g}$: fluid content

V_P:P-wave velocity

V_S: S−wave velocity

ρ: density

$\mathbf{u}$:displacement

$\phi, \mathbf{\Psi}$: potentials

Rock physics: definition

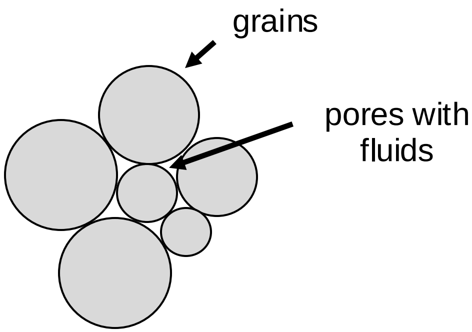
Rock physics is the field of science that aims to characterize **rock properties** based on the behavior of **seismic waves** propagating through them.

→ In a standard seismic interpretation workflow rock physics is used to relate **impedance and elastic parameters derived from seismic data to specific rock properties.**

→ This constrains what **seismic data is physically capable of resolving** and the non-uniqueness associated with a specific interpretation.

History of rock physics

Early days: focus on **physics** → measure wave propagation in the lab under a variety of conditions to create analog acoustic models that describe fluid-filled pores&grains and link them to seismic velocities



Porosity

Fluid types and saturation

$$c_P, c_S, \rho = f\,(V_{matrix}, \phi, geom, S_{w/o/g})$$

Mineralogy and rock types

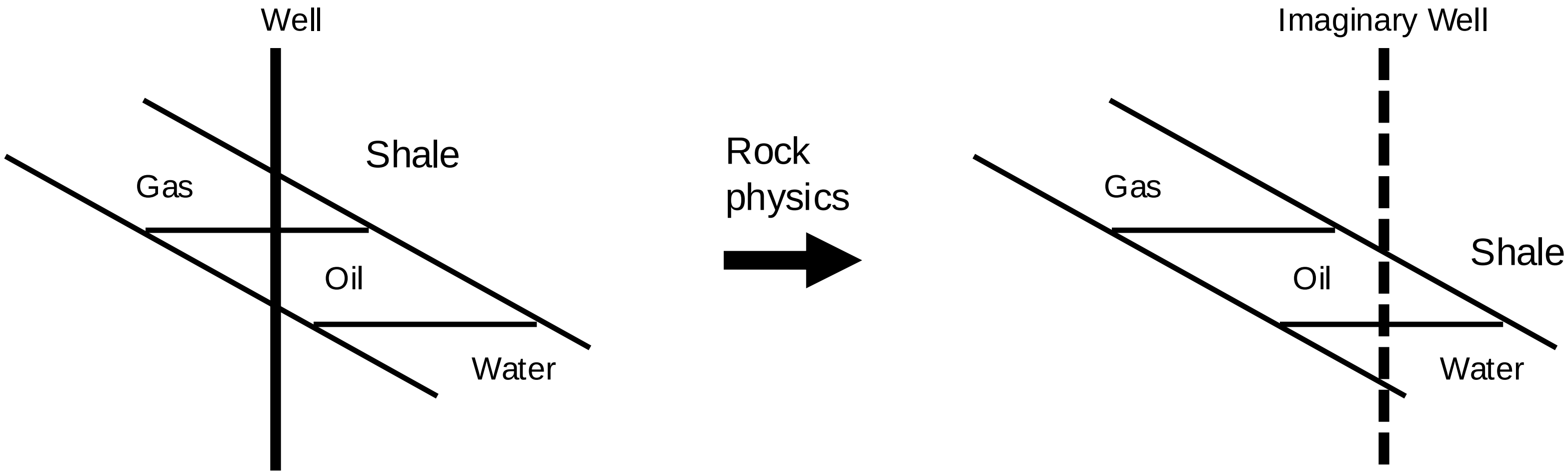
Geometry of grains

History of rock physics

Early days: focus on **physics** → measure wave propagation in the lab under a variety of conditions to create analog acoustic models that describe fluid-filled pores&grains and link them to seismic velocities

Modern days: link with **geology** → identify connections between rock textural parameters that drive the elastic properties to underlying geological processes (e.g., depositional maturity, compaction and diagenesis)

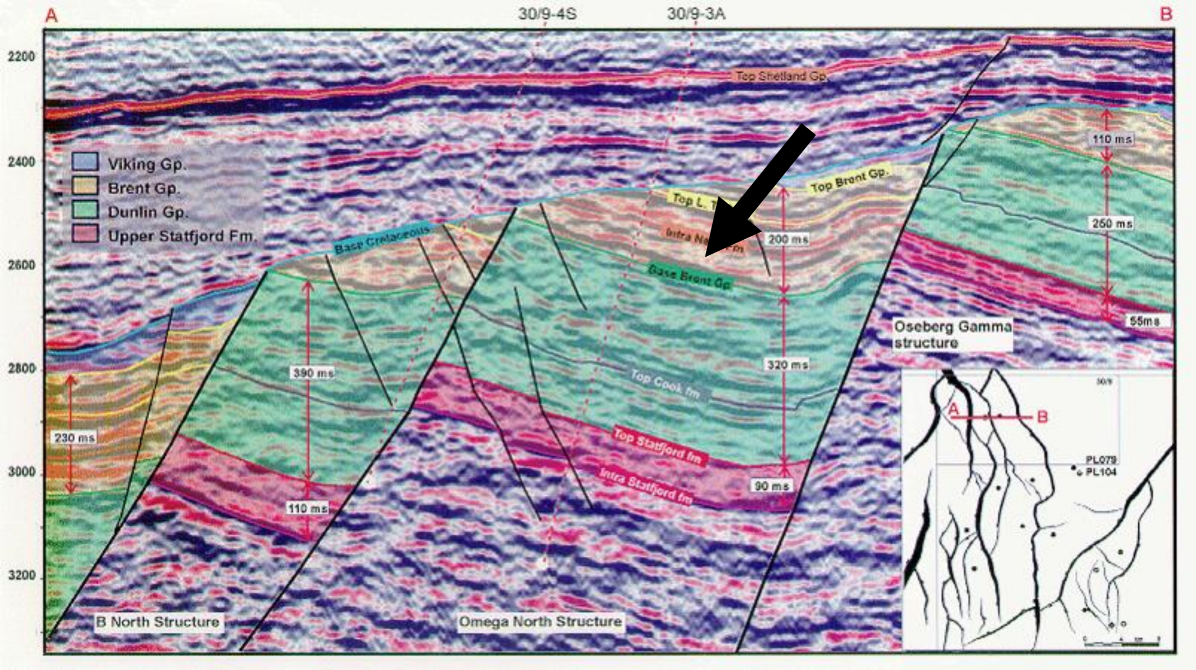
Role of rock physics for geophysicists



Study shale-gas contact

Study shale-oil contact

Role of rock physics for geophysicists



Source: https://www.badleys.co.uk/BGL_analysing_fault_seal_capacities.php

Role of rock physics for geophysicists

Seismic waves → **Elastic properties** → **Rock properties**

Seismic inversion

Petrophysical inversion

Role of rock physics for geophysicists

A general rule holds for the sensitivity of seismic to fluids:

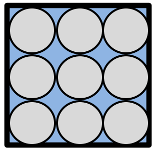
Simplified Gassmann relation

$$\frac{1}{K_{sat}} = \frac{1}{K_{min}} + \frac{\phi}{\widetilde{K}_{\phi}}$$

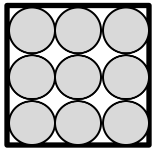
Fluid modulus

$$\widetilde{K}_{\phi} \approx K_{\phi} + K_{fl}$$

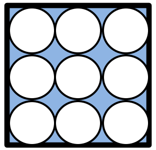
Dry pore modulus (i.e., when fluid is taken out)



Saturated rock



Mineral part of the rock



Saturated pore spaces

Role of rock physics for geophysicists

A general rule holds for the sensitivity of seismic to fluids:

$$\frac{1}{K_{sat}} \alpha \frac{\phi}{K_\phi + K_{fl}}$$

→ Stiff rock (K_ϕ is large): small sensitivity to fluids

→ Soft rock (K_ϕ is small): large sensitivity to fluids

Main principle of AVO analysis and 4D seismic

Mixing Laws

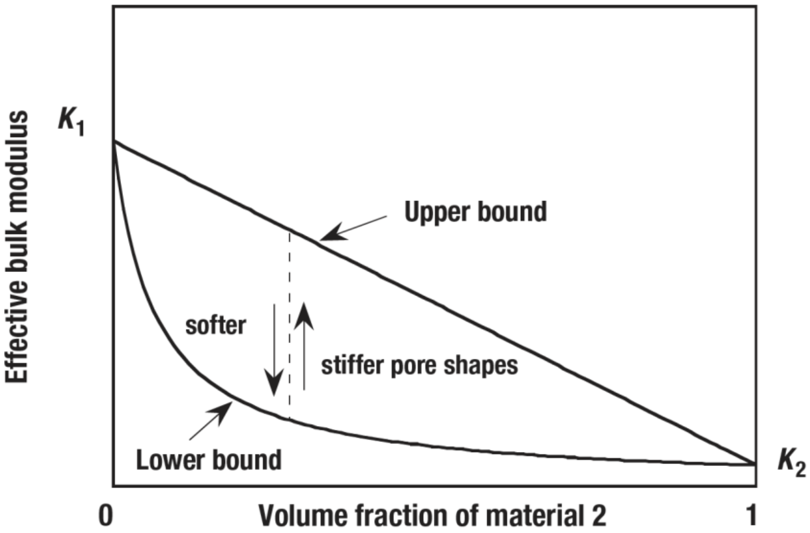
In rock physics we want to mix:

- 2 minerals in a rock: e.g., sand and clay with different %
- 2 fluids: e.g., water and oil with different %
- 1 mineral and 1 fluid: e.g., sand and oil with different %

→ How to get K_{min}, K_{fl}, or K_{sat}? **Effective medium theory**

(Can predict upper and lower bound but not exact value!)

Mixing Laws

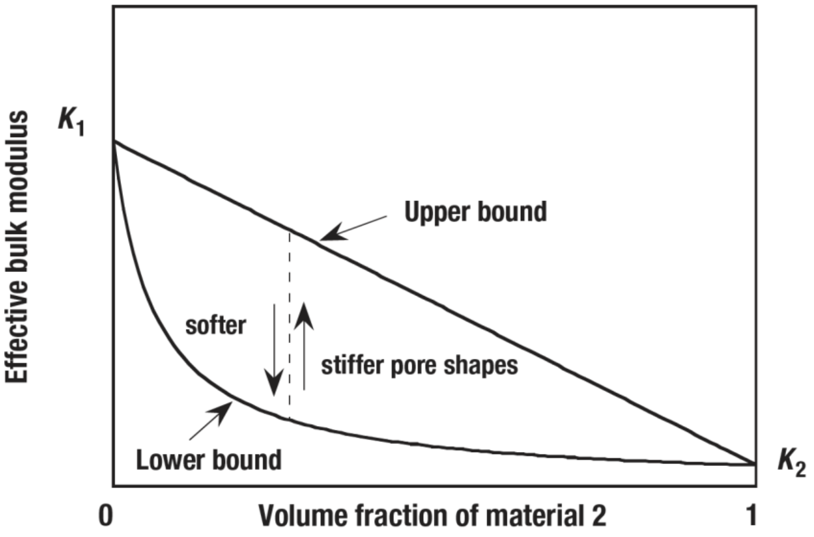


UB -> **Voigt** (arithmetic average): $M = \sum_i \; f_i M_i$

LB -> **Reuss** (geometric average): $1/M = \sum_i \; f_i / M_i$

Source: Avseth, P., Mukerji, T., and Mavko, G., Quantitative Seismic Interpretation

Mixing Laws



Source: Avseth, P., Mukerji, T., and Mavko, G., Quantitative Seismic Interpretation

UB -> **Voigt** (arithmetic average): $M = \sum_i \; f_i M_i$

LB -> **Reuss** (geometric average): $1/M = \sum_i \; f_i / M_i$

→ Other (tighter) bounds exist: e.g., **Hashin-Shtrikman**

Fluid Relations

At the core of any AVO/4D study, one must understand how *changes in elastic properties (and seismic responses) related to changes in pore fluids*

2 effects to consider:

- *changes in rock bulk density: very simple,* $\rho = \phi\rho_{fl} + (1-\phi)\rho_{min}$

- *changes in rock compressibility: more complicated*

$$\frac{1}{K_{dry}} = \frac{1}{K_{min}} + \frac{\phi}{K_{\phi}} \qquad \frac{1}{K_{\phi}} = \frac{1}{v_{pore}} \frac{\partial v_{pore}}{\partial \sigma}$$

Pore volume

Hydrostatic pressure

Fluid Relations

$$\frac{1}{K_{sat}} = \frac{1}{K_{min}} + \frac{\phi}{K_\phi + K_{fl}K_{min}/(K_{min} - K_{fl})} \approx \frac{1}{K_{min}} + \frac{\phi}{K_\phi + K_{fl}}$$

Eliminating K_ϕ from the two previous relations:

$$\boxed{\frac{K_{sat}}{K_{min} - K_{sat}} = \frac{K_{dry}}{K_{min} - K_{dry}} + \frac{K_{fl}}{\phi(K_{min} - K_{fl})}}$$

Gassmann relation

And:

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

no fluid effect on shear modulus

Petro-elastic modelling

Given a rock composed of some minerals with properties $(K/\mu/\rho_{min,1}, K/\mu/\rho_{min,2}, \dots, K/\mu/\rho_{min,N})$ and proportions $(f_{min,1}, f_{min,2}, \dots, f_{min,N})$, a fluid composed of different fluids with properties $(K/\rho_{fl,1}, K/\rho_{fl,2}, \dots, K/\rho_{fl,N})$ and and proportions $(f_{fl,1}, f_{fl,2}, \dots, f_{fl,N})$, and given a certain porosity ϕ

$$\rho_{min} = \sum_i f_{min,i}\rho_{min,i} \qquad \rho_{fl} = \sum_i f_{fl,i}\rho_{fl,i}$$

$$1/K_{min} = \sum_i \frac{f_{min,i}}{K_{min,i}} \qquad 1/K_{fl} = \sum_i \frac{f_{fl,i}}{K_{fl,i}} \qquad 1/\mu_{min} = \sum_i \frac{f_{min,i}}{\mu_{min,i}}$$

$$K_{dry}, \mu_{dry} = f(\phi, \dots)$$

From theoretical or empirical models (discusses later…)

$$\rho_{sat} = \phi\rho_{fl} + (1-\phi)\rho_{min} \qquad \mu_{sat} = \mu_{dry} \qquad K_{sat} = K_{dry} + \frac{\left(1 - K_{dry}/K_{min}\right)^2}{\phi/K_{fl} + (1-\phi)/K_{min} + K_{dry}/K_{min}^2}$$

Gassmann fluid substitution

Given a single material with the following properties

$$K_1, \mu_1, \rho_1, \phi_1, (S_{w,1}, S_{o,1}, S_{g,1}), f_{min,i} \qquad +(K, \mu, \rho)_{fl}, (K, \mu, \rho)_{min}$$

$$\Big\downarrow \quad \text{Change fluid proportions} \quad (S_{w,2}, S_{o,2}, S_{g,2})$$

$$\boldsymbol{K_2, \mu_2, \rho_2} \; ?$$

We first equate the dry term of the Gassmann relation for the two fluids

$$\frac{K_{dry,1}}{K_{min,1} - K_{dry,1}} = \frac{K_{dry,2}}{K_{min,2} - K_{dry,2}}$$

$$K_{dry,1} = K_{dry,2}$$

$$K_{min,1} = K_{min,2}$$

Gassmann Fluid substitution

We now insert the other two terms from the Gassmann relation

$$\frac{K_1}{K_{min} - K_1} - \frac{K_{fl,1}}{\phi(K_{min} - K_{fl,1})} = \frac{K_2}{K_{min} - K_2} - \frac{K_{fl,2}}{\phi(K_{min} - K_{fl,2})}$$

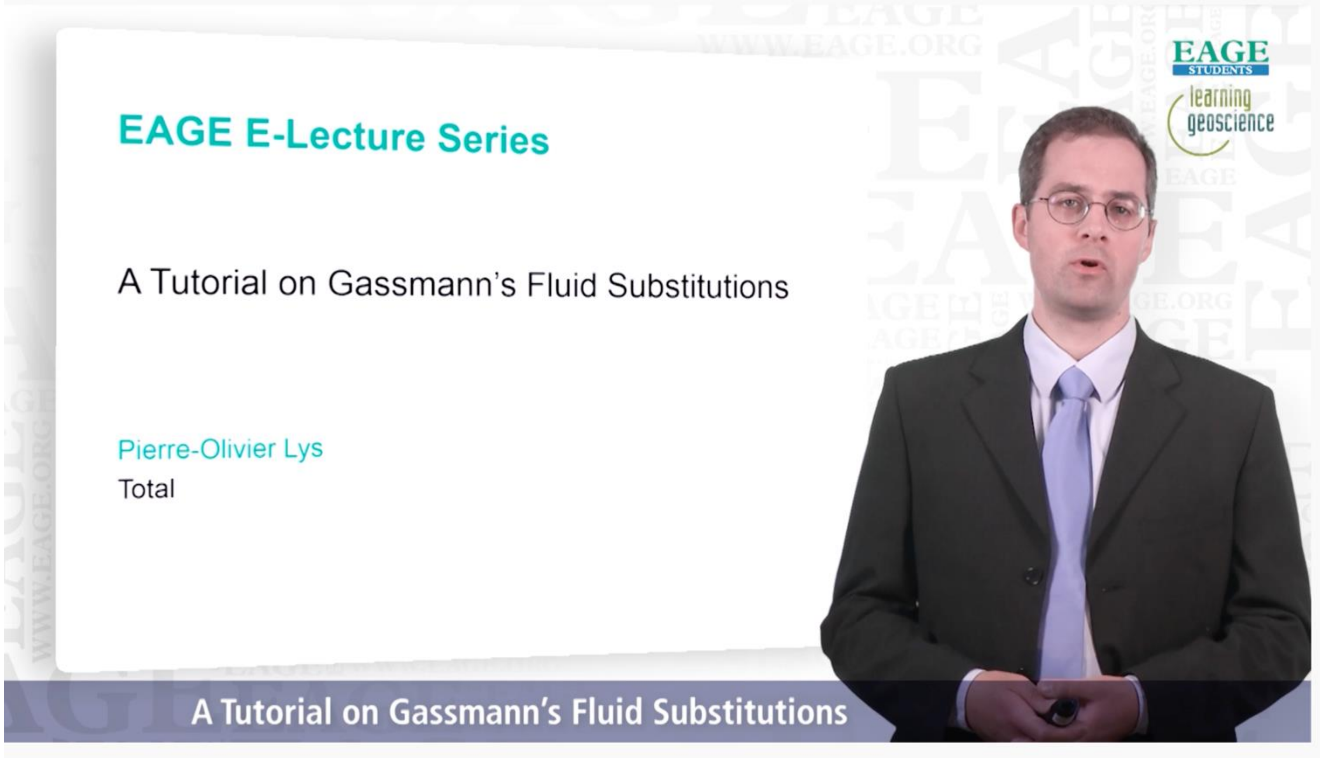
And solve for K_2:

$$K_{dry} = \frac{K_1\left(\frac{\phi K_{min}}{K_{fl,1}} + 1 - \phi\right) - K_{min}}{\frac{\phi K_{min}}{K_{fl,1}} + \frac{K_1}{K_{min}} - 1 - \phi}$$

$$K_2 = K_{dry} + \frac{(1 - K_{dry}/K_{min})^2}{\frac{\phi}{K_{fl,2}} + \frac{1-\phi}{K_{min}} - \frac{K_{dry}}{K_{min}^2}}$$

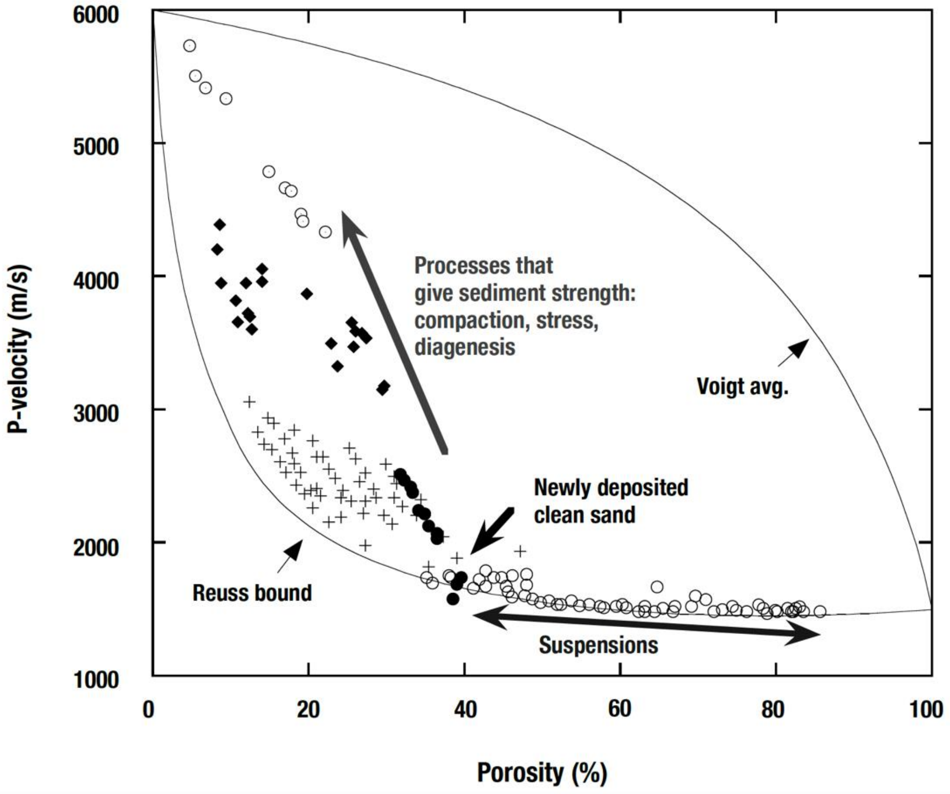
To which we add: $\mu_2 = \mu_1$ $\quad\quad \rho_2 = (1-\phi)\rho_{min} + \phi\rho_{fl,2}$

Gassmann Fluid substitution



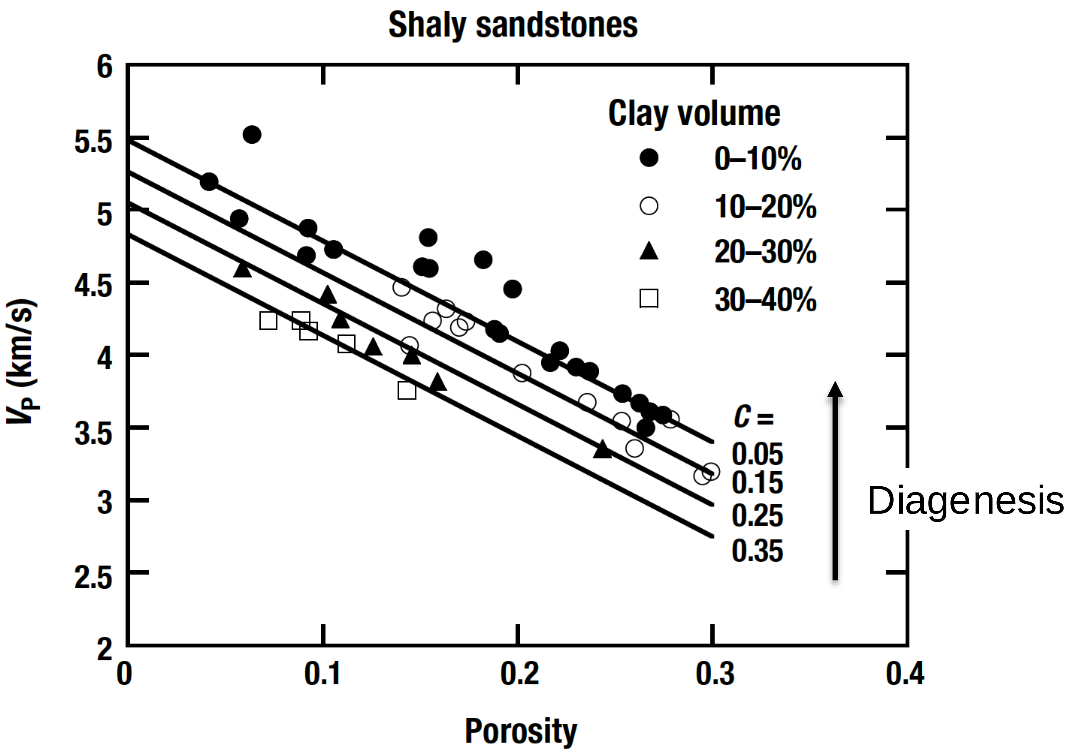
EAGE E-Lecture: https://www.youtube.com/watch?v=C6LOsvCjyw8

Velocity-Porosity relation – field evidence



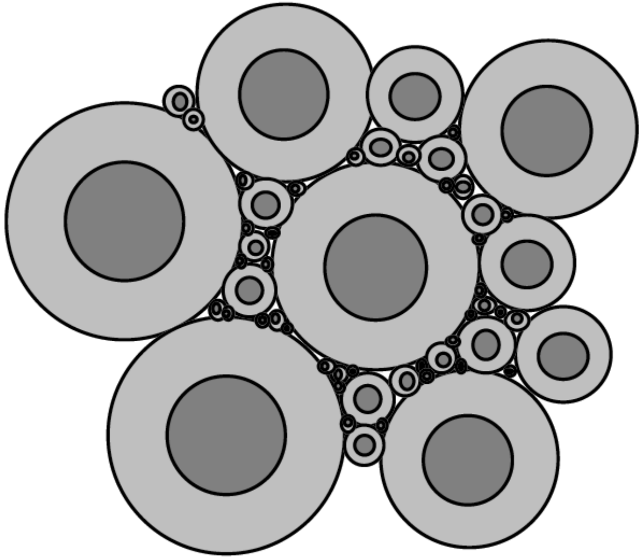
Source: Avseth, P., Mukerji, T., and Mavko, G., Quantitative Seismic Interpretation

Velocity-Porosity relation - empirical



Source: Avseth, P., Mukerji, T., and Mavko, G., Quantitative Seismic Interpretation

Velocity-Porosity relation - theoretical



Friable Sand Model

At high porosity ($\phi > 0.4$), the relations are given by contact theory (Hertz-Mindlin theory):

$$K_{\mathrm{dry}} = \left[\frac{\phi/\phi_{\mathrm{c}}}{K_{\mathrm{HM}} + 4\mu_{\mathrm{HM}}/3} + \frac{1 - \phi/\phi_{\mathrm{c}}}{K + 4\mu_{\mathrm{HM}}/3} \right]^{-1} - \frac{4}{3}\mu_{\mathrm{HM}}$$

$$\mu_{\mathrm{dry}} = \left[\frac{\phi/\phi_{\mathrm{c}}}{\mu_{\mathrm{HM}} + z} + \frac{1 - \phi/\phi_{\mathrm{c}}}{\mu + z} \right]^{-1} - z$$