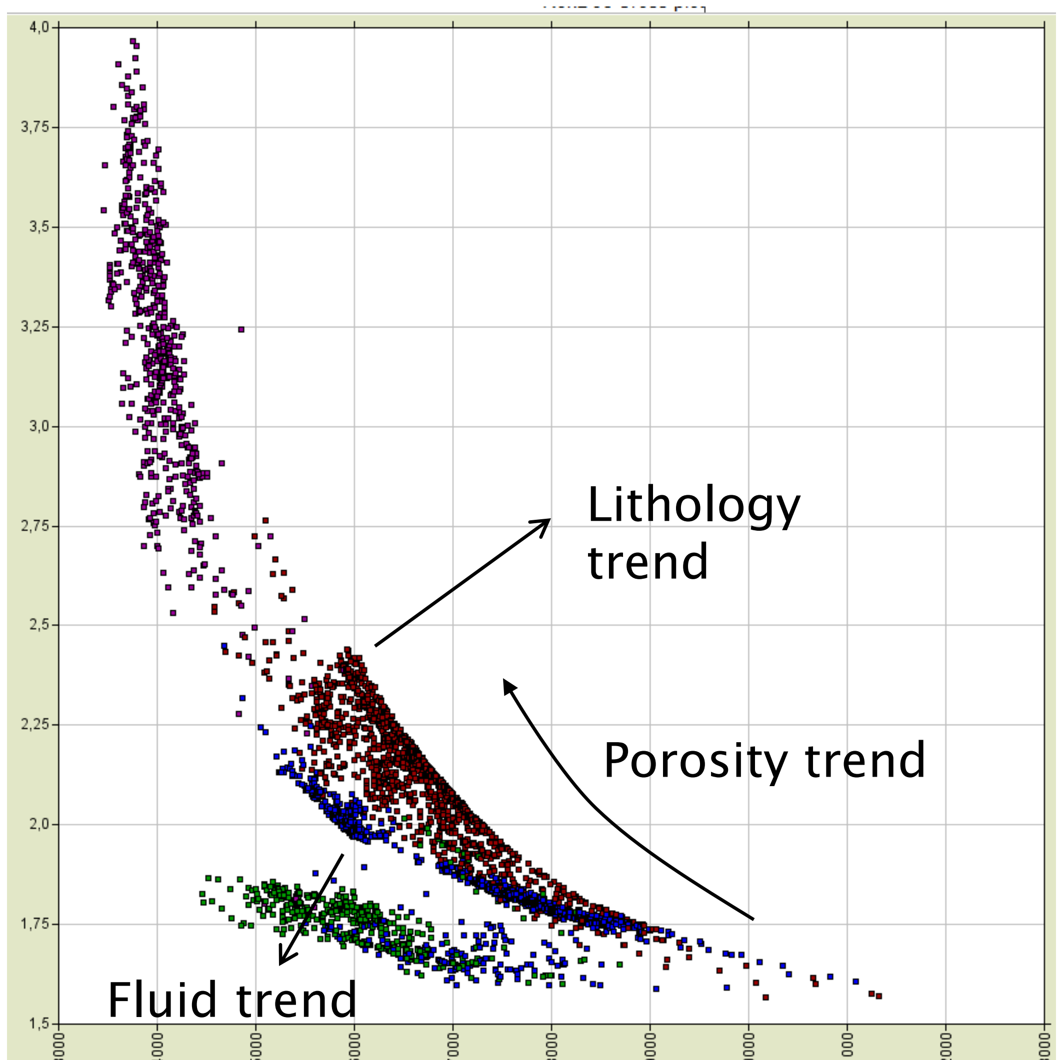
Rock Physics

Peter Harris
Deep Vision Ltd and Sharp Reflections

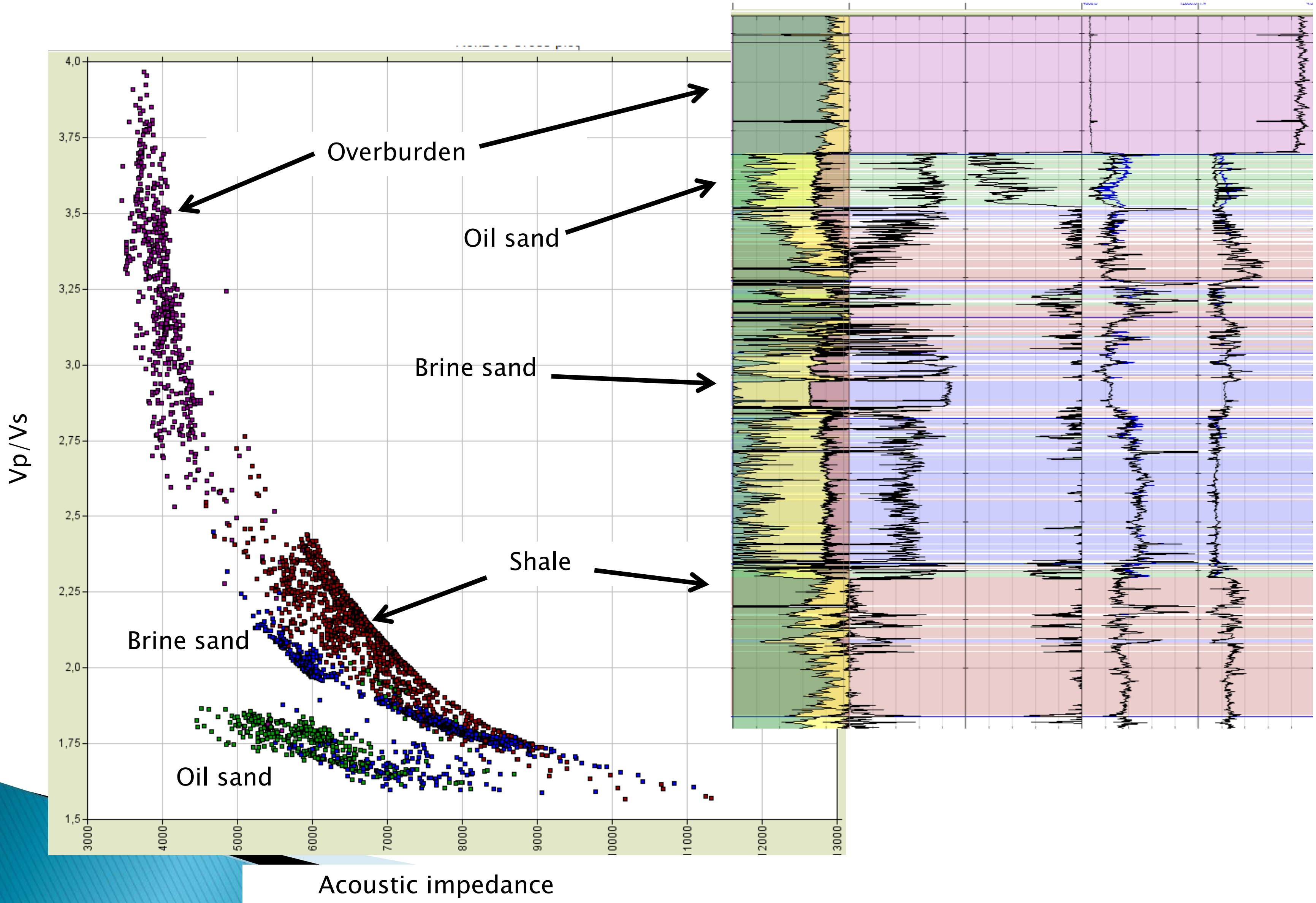
The cross-plot

Vp/Vs



Zp

Popularised by Per Avseth in many publications



Vp/Vs
Acoustic impedance
Overburden
Oil sand
Brine sand
Shale
Brine sand
Oil sand
4,0
3,75
3,5
3,25
3,0
2,75
2,5
2,25
2,0
1,75
1,5
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000

Rock Physics Models

- Theoretical and empirical relationships between different properties.
- Can be used to model rocks or change properties of known ones (eg fluid subs).
- Also useful to check consistency of logs or predict missing data (eg Vs prediction).
- Used to transform seismic inversion results into rock and fluid properties.

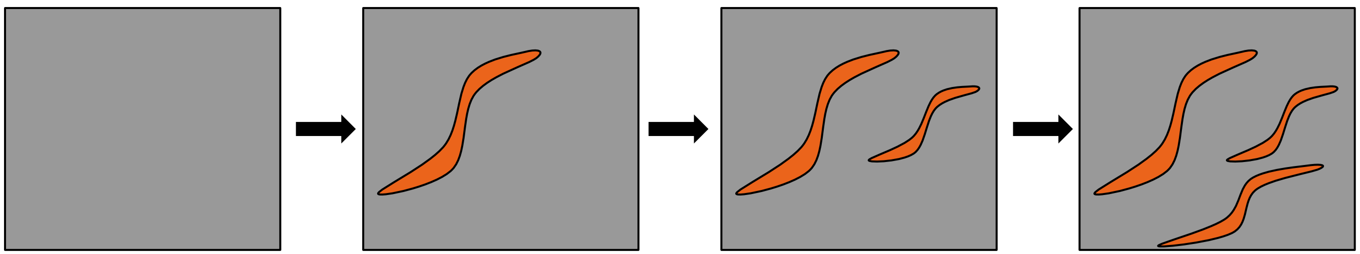
Examples
- Gassmann for fluid substitution
- Hashin-Shtrickman bounds
- Voigt-Reuss bounds
- Contact cement model

Read Mavko et al for lots more

Rock Physics Models

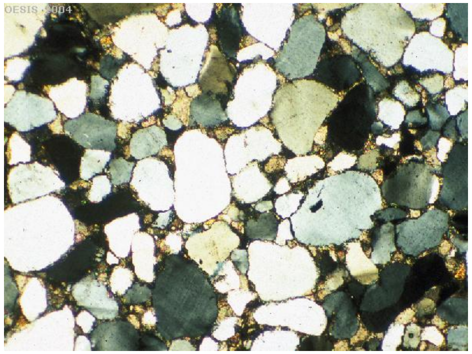
There are two common classes of rock physics models:

Inclusion models start with a solid and gradually add pore space or fractures. They are used to model carbonates (eg Kuster-Toksöz), fractured rocks (Hudson), and clastics.

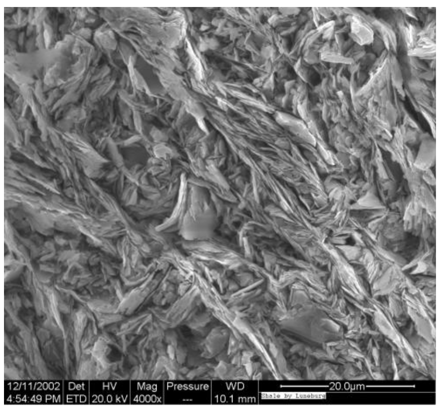


Grain models model a rock as a packing of grains, and add material into the pore space. They are commonly used to model clastics.

Rock Description



http://www.earth.ox.ac.uk/~oesis/micro/index.html



http://www.westga.edu/~geosci/webdata/wgmc/Images/Gallery%20Pictures/Minerals%20and%20Rocks/Shale2.jpg

Description of rocks

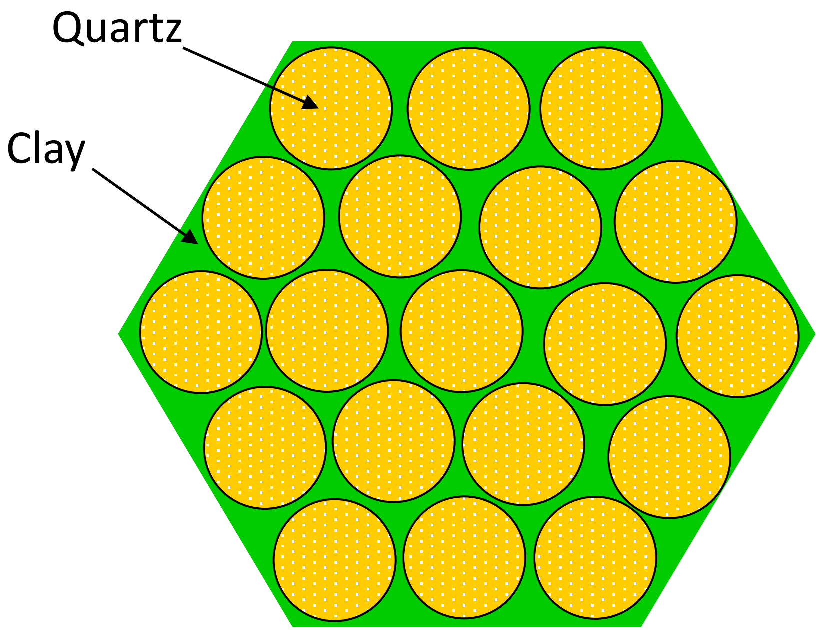
Grains:
Properties: mineralogy
Geometry: size, shape, sorting, angularity, orientation

Cement:
Properties: mineralogy
Geometry: volume, distribution

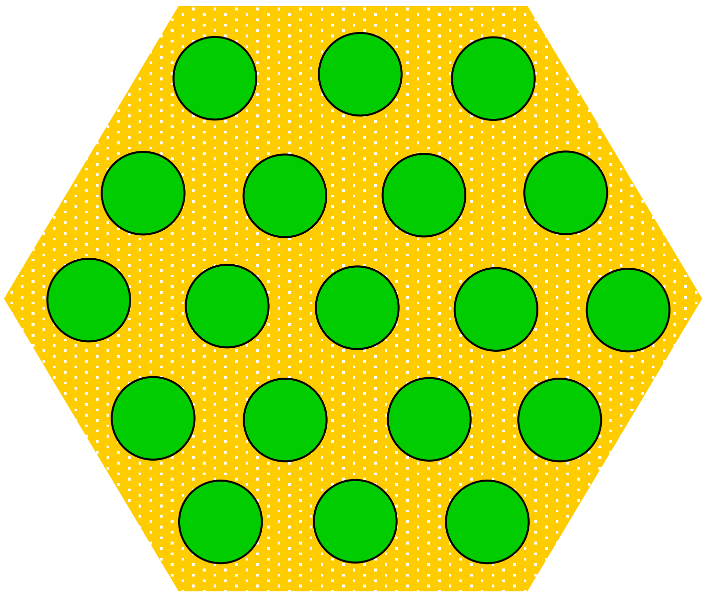
Pore space:
Properties: fluid types
Geometry: volume, connectivity, orientation

Fluids:
Properties: salinity, GOR
Geometry: distribution in pore space

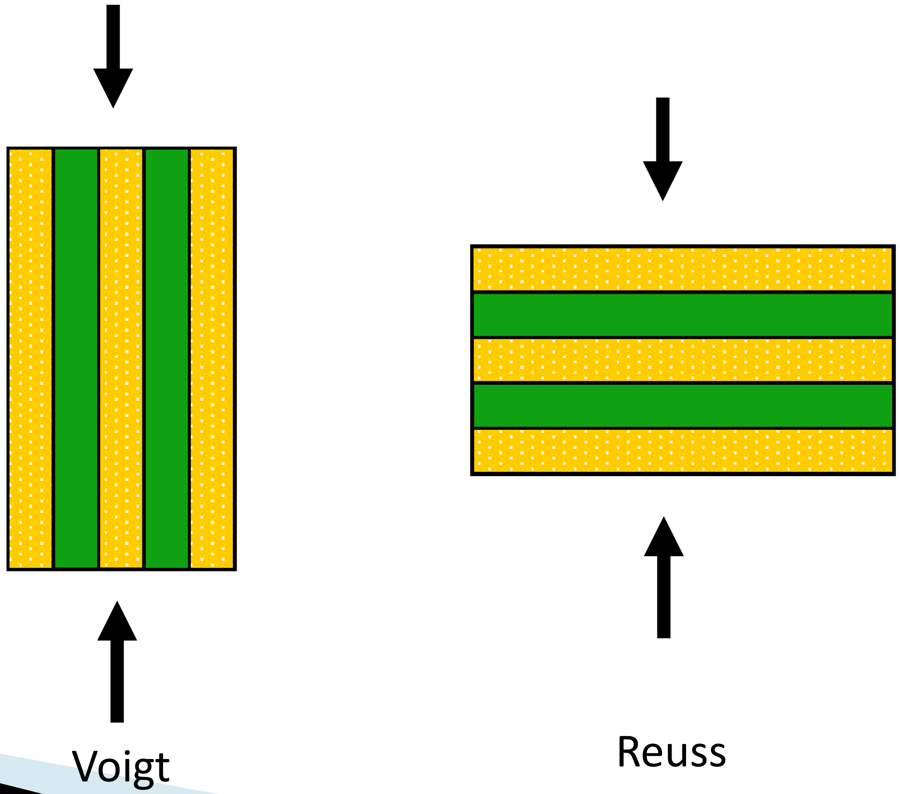
Voigt–Reuss

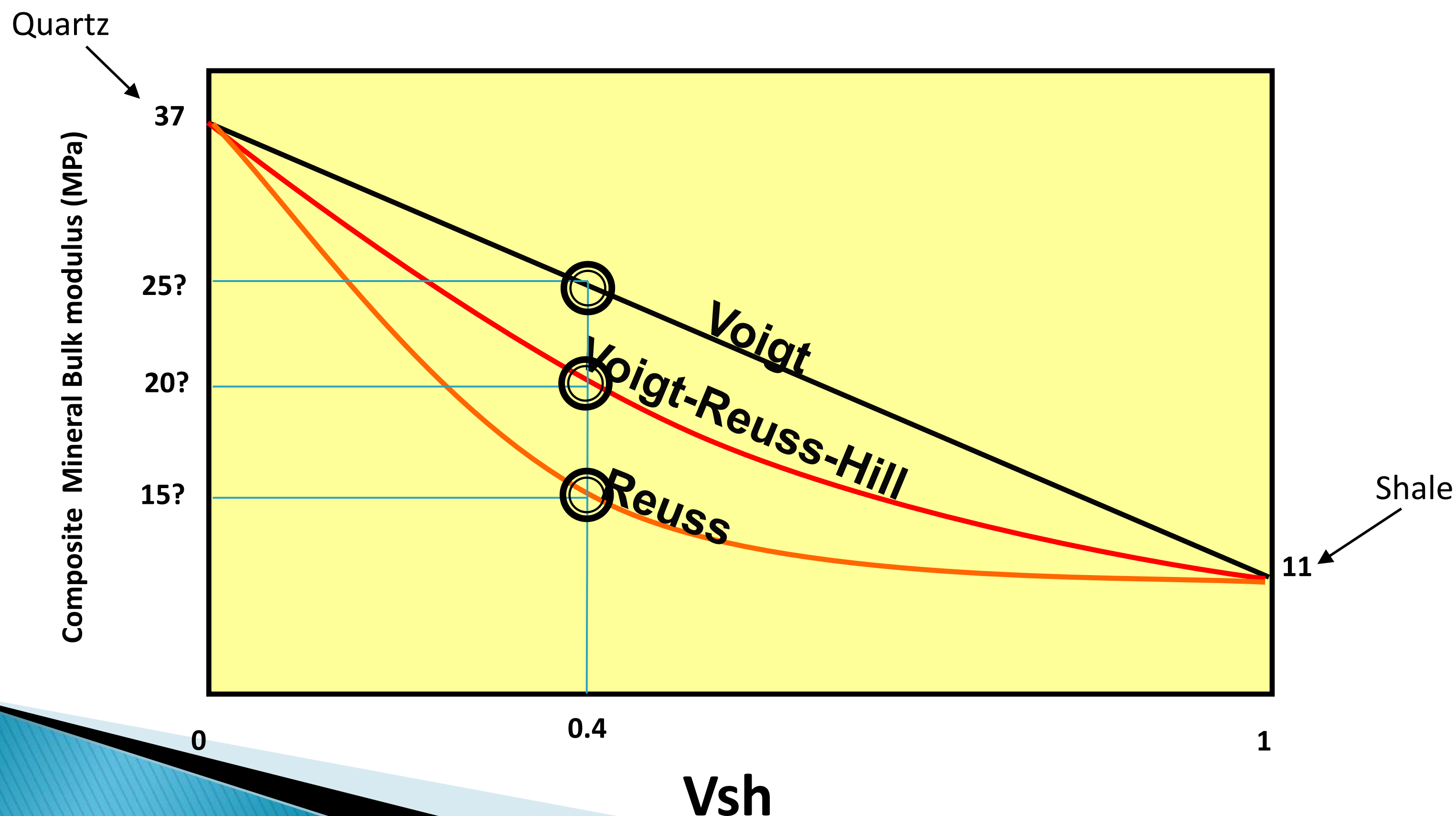


Reuss



Voigt


Voigt
Reuss


Quartz
37
25?
20?
15?
Composite Mineral Bulk modulus (MPa)
Voigt
Voigt-Reuss-Hill
Reuss
Shale
11
0
0.4
1
Vsh

Voigt modulus
(upper bound)

$$K_v = \left(K_{qtz} Vol_{qtz}\right) + \left(K_{cl} Vol_{cl}\right)$$

Reuss modulus
(lower bound)

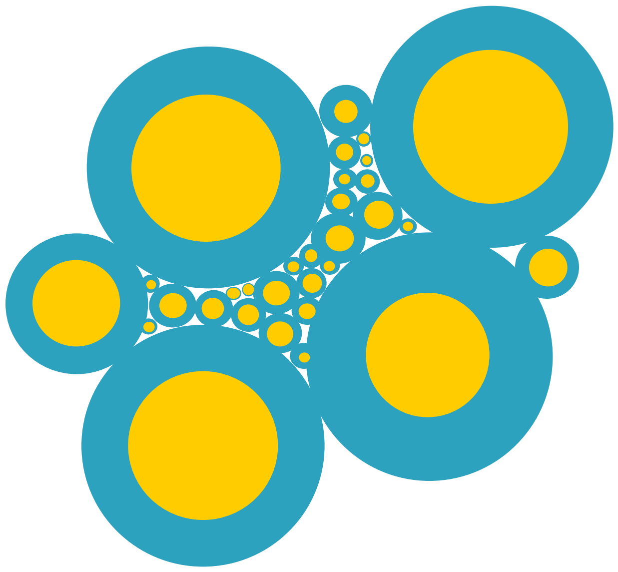
$$K_r = \frac{1}{\dfrac{Vol_{qtz}}{K_{qtz}} + \dfrac{Vol_{clay}}{K_{clay}}}$$

V-R-H modulus
(arithmetic average)

$$K_{vrh} = \frac{K_v + K_r}{2}$$

Hashin-Shtrikman

- **Hashin-Shtrikman Bounds**
  - The physical interpretation of this type of mixture is two materials forming concentric spheres. The upper bound is reached when the stiffer material forms the shell, the lower bound when it is the core
  - The separation of the bounds depends on how elastically different the constituents are
  - When solids are mixed the bounds are close (usually within a factor of two to each other)
  - When one constituent is a fluid, the bounds are further apart, so their predictive value is reduced
  - In practice use a mineral modulus equal to one of the bounds, or an average of the two



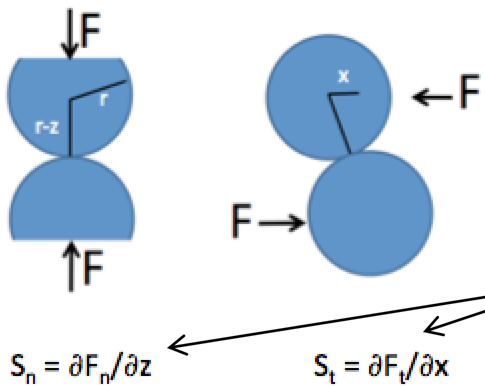
Critical porosity

Critical porosity is the highest porosity a rock can have without falling apart (the grains losing contact with each other). In a well-sorted sandstone it is about 40%. In uncompacted pure clays it can be up to 90% and it is 60-70% for many shales.

Coordination number

The coordination number is the average number of grain contacts per grain. For a random, dense pack of identical spheres it is about 9, and it increases as sorting deteriorates or as angularity increases.

Hertz–Mindlin Model



Consider 2 identical spherical grains pressed together.
Then apply a force (normal or tangential).
Can find the contact stiffnesses in each case.

Effective moduli of a random packing of spheres are

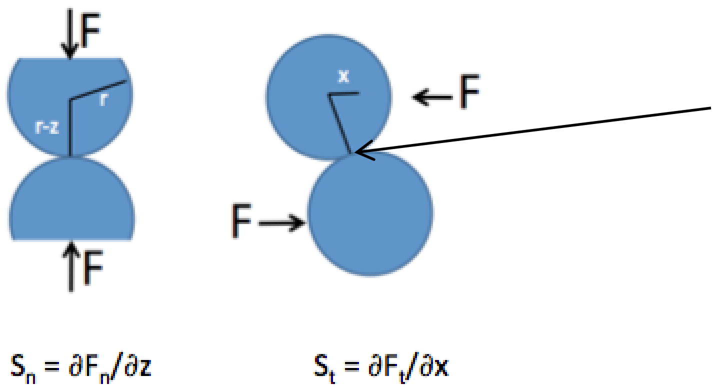
$$K_{eff} = \frac{C(1-\varphi)}{12\pi r} S_n \qquad \mu_{eff} = \frac{C(1-\varphi)}{20\pi r}\left(S_n + \frac{3}{2} S_\tau\right)$$

r is the grain radius, C is the coordination number, φ is porosity.

$$S_n = \frac{4\mu a}{1-\nu} \qquad S_\tau = \frac{8\mu a}{2-\nu} \qquad \text{(Mindlin)}$$

μ and ν are the shear modulus and Poisson's ratio of the grains, and a is the surface area of the grain contact.

Hertz–Mindlin Model



Contact area is

$$a = r\sqrt[3]{\frac{3\pi(1-\nu)}{2C(1-\varphi)\mu}P} \qquad \text{(Hertz)}$$

where P is the effective pressure.

Put all the equations together, and you get

$$K_{eff} = \sqrt[3]{\frac{C^2(1-\varphi)^2\mu^2}{18\pi^2(1-\nu)^2}P} \qquad \mu_{eff} = \frac{5-4\nu}{5(2-\nu)}\sqrt[3]{\frac{C^2(1-\varphi)^2\mu^2}{2\pi^2(1-\nu)^2}P}$$

They depend on:
i) the elastic properties of the grains (μ,ν),
ii) the effective pressure (P),
iii) the grain geometry (coordination number, C).

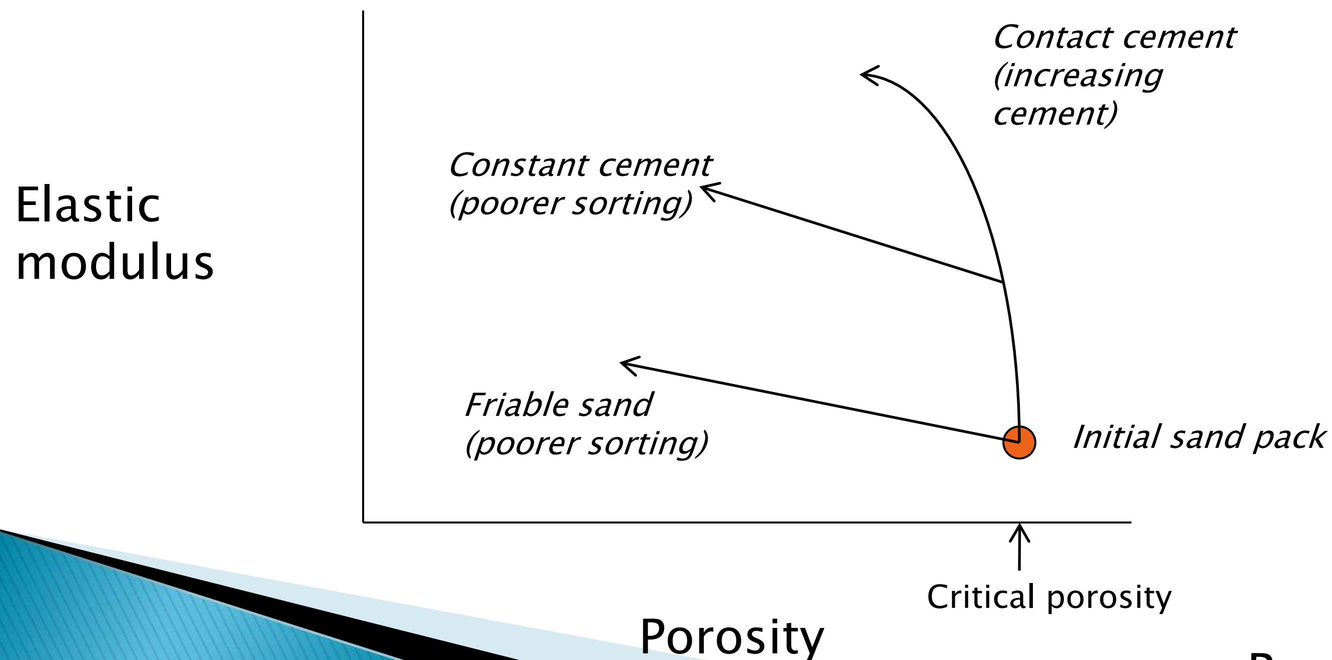
These are dry moduli. Use Gassmann to put fluids into the rocks.

Clean Sand Models

Friable sand: Unconsolidated sand. Can model changes in sorting. Uses Hertz-Mindlin and Hashin-Shtrikman.

Contact cement: High porosity sands with small amount of cement at grain contacts.

Constant cement: Sands of variable sorting have the same amount of contact cement. May be a constant depth model, so useful to model variations within a reservoir.



Per Avseth again!

Sandy Shale Models

Constant clay: Uses the friable sand model with clay mineral properties for the grains, as shales are normally not cemented. Assumes sand or silt grains are suspended in the clay, so a soft (Reuss average) rock results.

Dvorkin-Gutierrez: Reduce clay porosity by adding dispersed silt grains, and use Hashin-Shtrikman lower bound.

Yin-Marion: Uses Reuss average to disperse silt grains into the shale.

These models are all isotropic. In fact, shales are almost always anisotropic.

Shaly Sand Models

Constant clay: Assume that clay particles occupy the space between sand grains and no cement.

Dvorkin-Gutierrez: Models increasing clay content using Hashin-Shtrikman lower bound.

Yin-Marion: Models increasing clay content using Gassmann to put clay minerals into pore space.

Laminated sand-shale sequences: Models vertical velocity with lower bound (Reuss) average.

Rock Physics Diagnostics

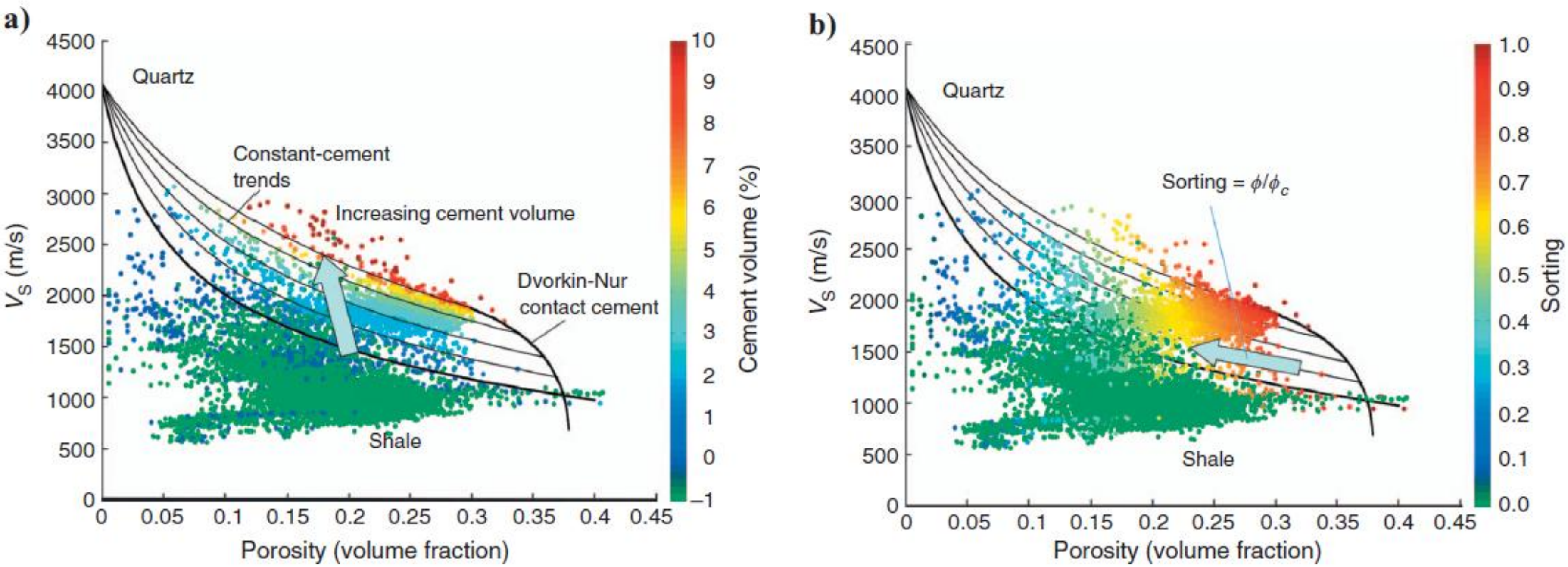


Figure 10. Shear-wave velocity-log data versus total porosity and superimposed diagnostic rock-physics models. Using the models, we can quantify (a) the cement volume and (b) the degree of sorting. Green data points are shale data with high GR values and for practical reasons are given the value −1 in cement volume and zero in sorting.

Avseth et al, 2010. Rock physics diagnostics of depositional texture, diagenetic alterations, and reservoir heterogeneity in high-porosity siliciclastic sediments and rocks – A review of selected models and suggested workflows. Geophysics, 75, A31-A47.

Rock Physics Diagnostics

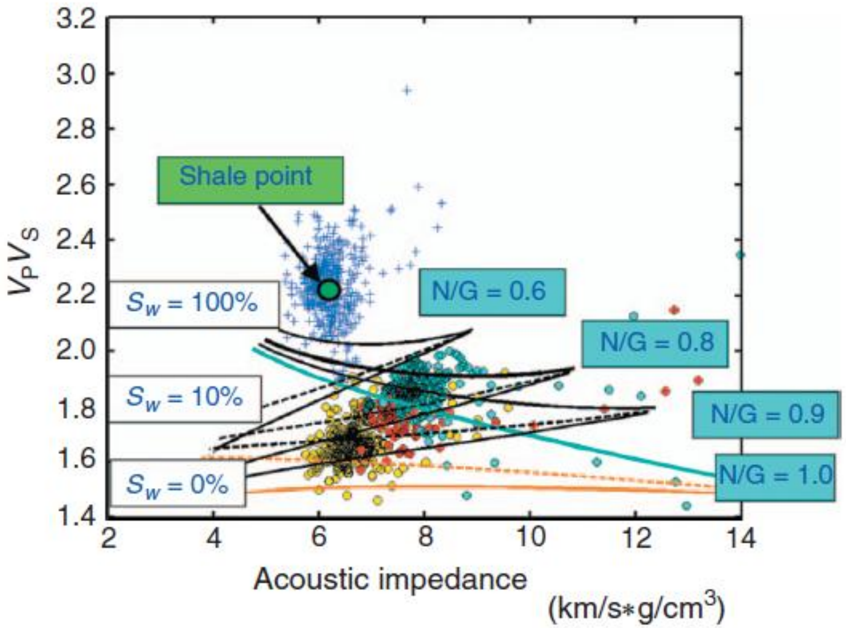
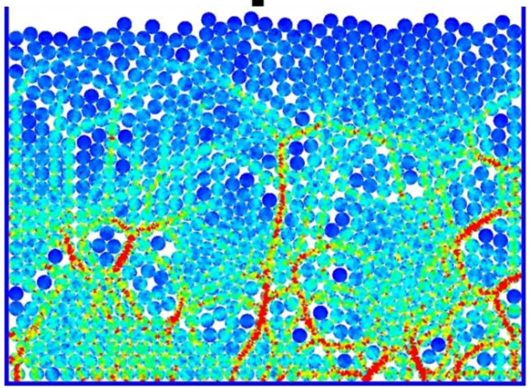


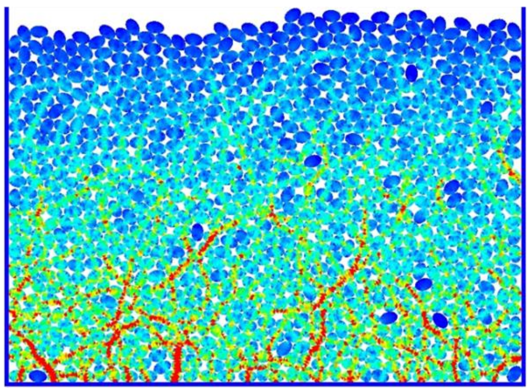
Figure 19. Rock-physics template of acoustic impedance versus V_P/V_S, including models for varying net-to-gross (N/G) and gas saturation $(1 - S_w)$ created by the five-step procedure. The colored model lines represent the clean-sand models without shale interbedding (i.e., N/G = 1.0). The cyan line represents clean sands with 100% water saturation S_w. Porosity is 40% at the left end point and decreases to the right toward the mineral point (which is outside the range of the plot). The dashed orange line is the corresponding 10% water saturation and 90% gas saturation, whereas the solid orange line represents 100% gas. These three sandstone lines "rotate" upward toward the selected shale point when N/G decreases, indicated by black lines. For well-log data, the brine sands (cyan) and oil sands (red) fall between N/G = 1 and 0.8. Most of the gas sands (yellow) seem to fall on similar porosities, with N/G varying between 1 and 0.6.

Avseth et al, 2010. Rock physics diagnostics of depositional texture, diagenetic alterations, and reservoir heterogeneity in high-porosity siliciclastic sediments and rocks – A review of selected models and suggested workflows. Geophysics, 75, A31-A47.

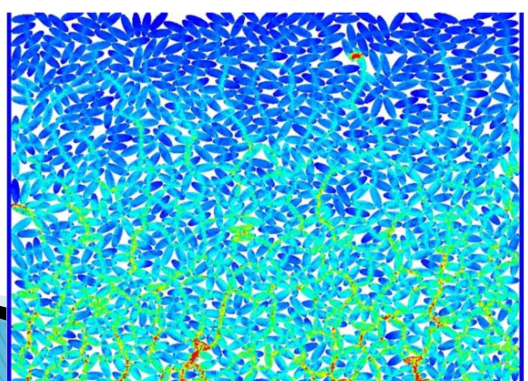
Elastic responses



α = 1, friction > 0



α = 1.8, friction >0



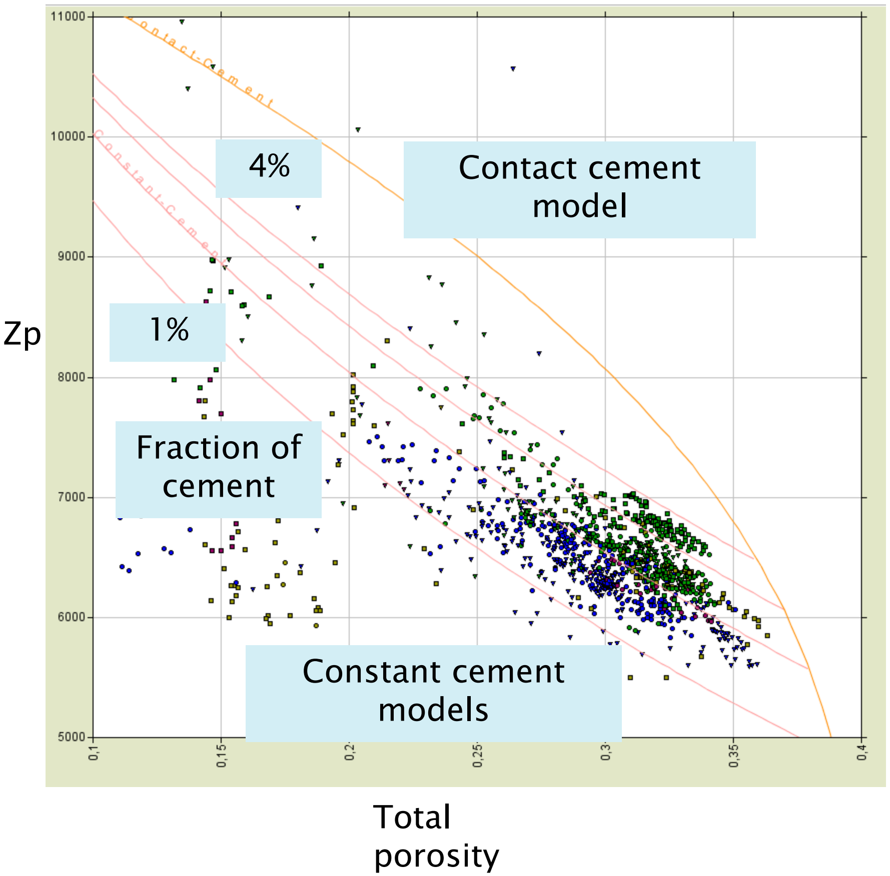
α = 3, frictionless >0

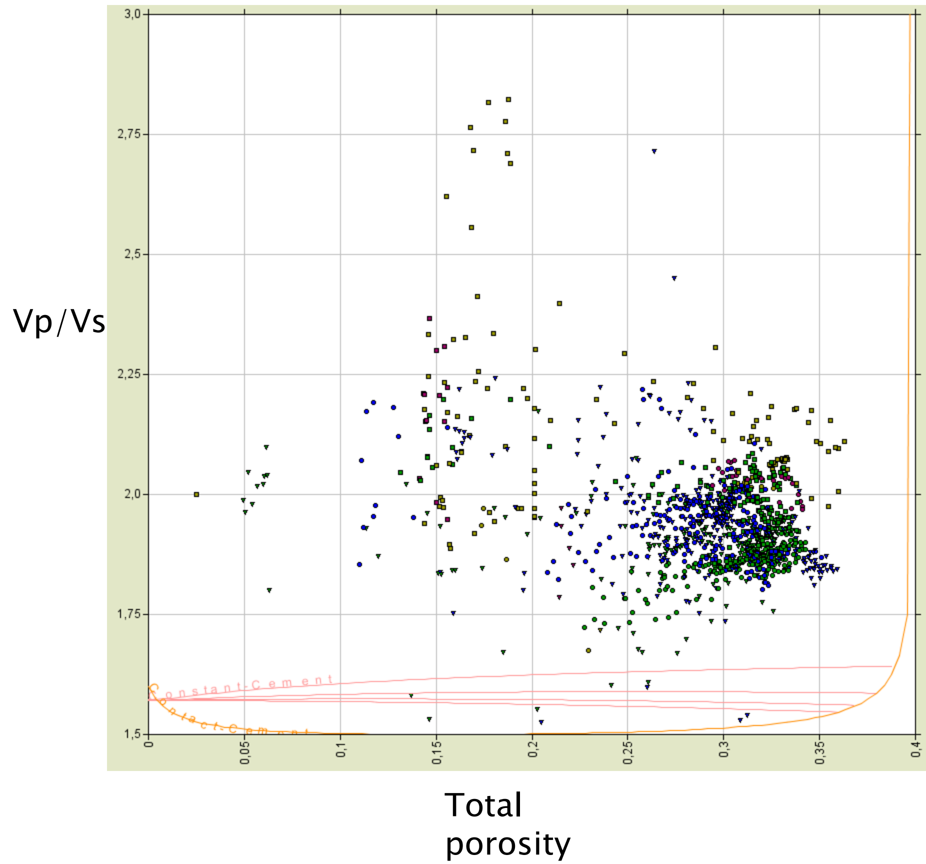
Numerical experiment:
Local stresses generated while depositing ellipsoidal grains of different aspect ratios. Gravity is the external force.

A passing seismic wave also acts as an external force. How uniform are the stresses?

http://amcg.ese.ic.ac.uk/index.php?title=Solids_Modelling

Rock physics crossplots for sands

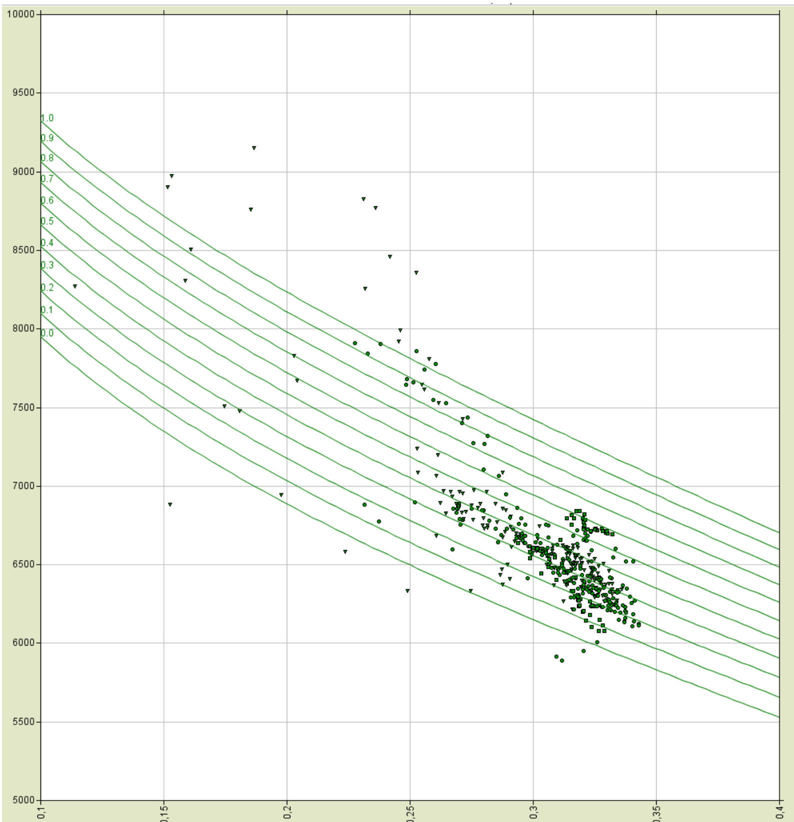


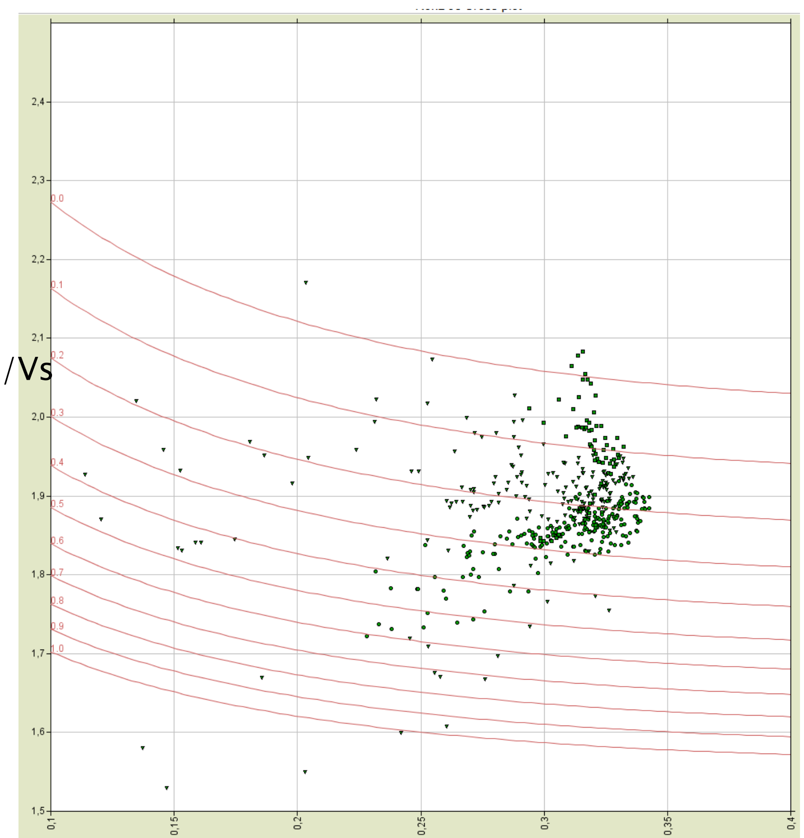


Zp against porosity plots show that one explanation for the trends could be that blue sand is less cemented than green sand.

However the same models completely fail to predict Vp/Vs correctly. Hertz-Mindlin seems to predict both bulk and shear moduli incorrectly, but errors compensate so Vp and Zp are ok, whereas Vs is not.

Rock physics crossplots for the sand





The curves are the formulae due to Bachrach and Avseth (Geophysics 2008). This is an uncemented sand model and thus is not entirely appropriate for this sand. However it gives more consistent predictions than the models tried earlier.

Each curve in the set corresponds to a different degree of shear slippage at grain contacts.

Comparison of the green and blue units suggests that, according to this model, the blue unit is better sorted and less angular than the green. However care should be taken with such an interpretation since cementation is not accounted for.

Porosity Changes

What is causing porosity change?

- Clay in pore space
- Change in sorting
- Change in compaction
- Change in cementation

General workflow:

- Use Gassmann to get dry rock properties from original porosity rock.
- Fit a suitable rock physics model to dry rock properties.
- Calculate new properties at different porosity with rock physics model.
- Use Gassmann to resaturate.

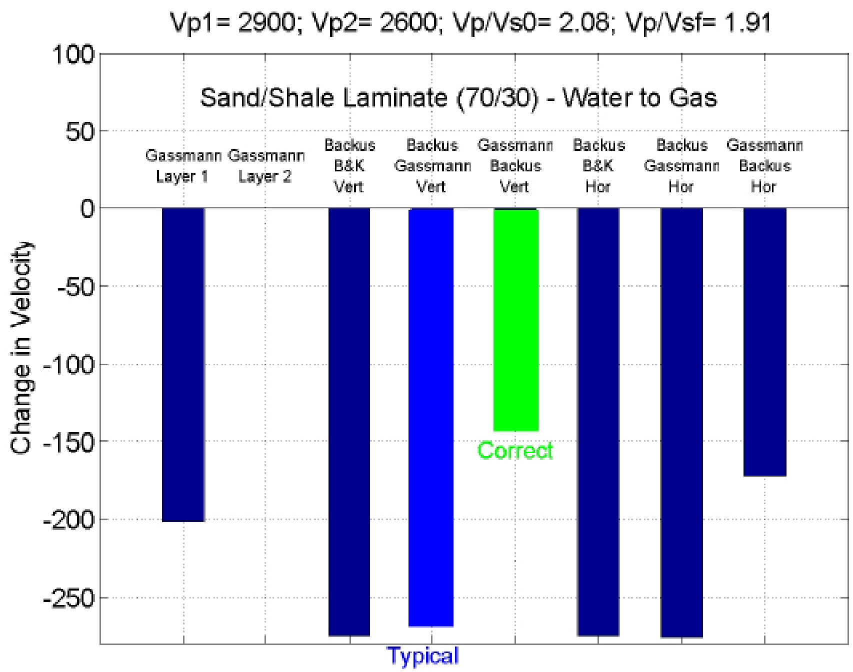
Fluid Substitution in Laminated Sands

Correct workflow is

- Calculate dry sand properties (Gassmann)
- Put new fluid into sand (Gassmann)
- Upscale (Backus averaging)

Wrong, but common workflow is

- Upscale (Backus averaging)
- Calculate dry effective medium properties (Gassmann)
- Put in new fluid (Gassmann)

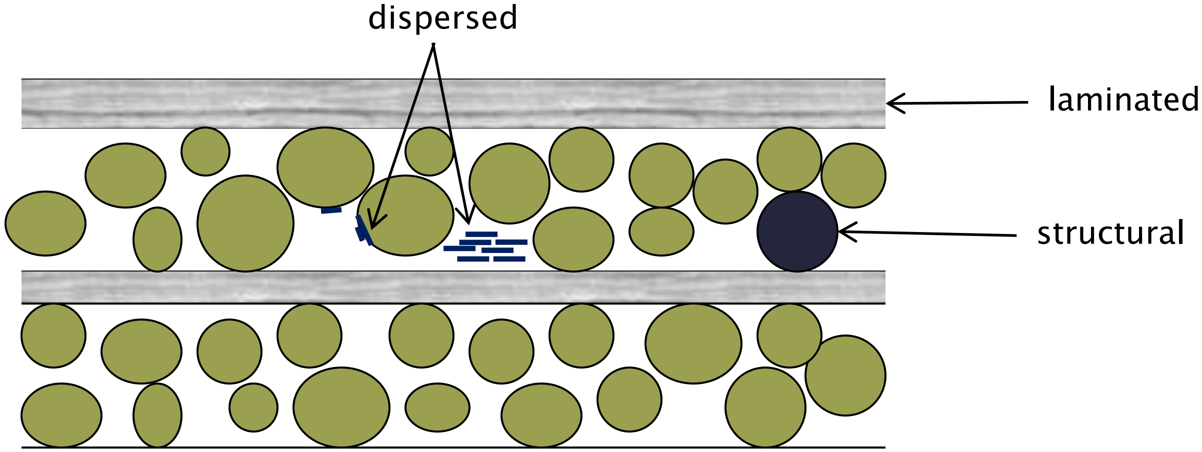


Anisotropy also changes with fluid!

Mavko et al, SRB Annual Report, 2006.

Changing clay content …

Where is the clay?
Structural clay – replace sand grains with clumps of clay
Dispersed clay – clay goes into pore space
Laminated clay – thin layers of sand and clay



Porosity: clay has nano-pores which should not be included in fluid subs

Laminated clay doesn’t contribute to effective porosity
Structural clay leaves the sand porosity unchanged
Dispersed clay reduces the effective sand porosity

Backus averaging

Replace many thin elastic layers by one thicker layer with the same elastic response as the stack of thin ones.

If the thin layers are isotropic, the equivalent thick layer will be VTI.
If the thin layers are VTI, the thick layer will also be VTI.

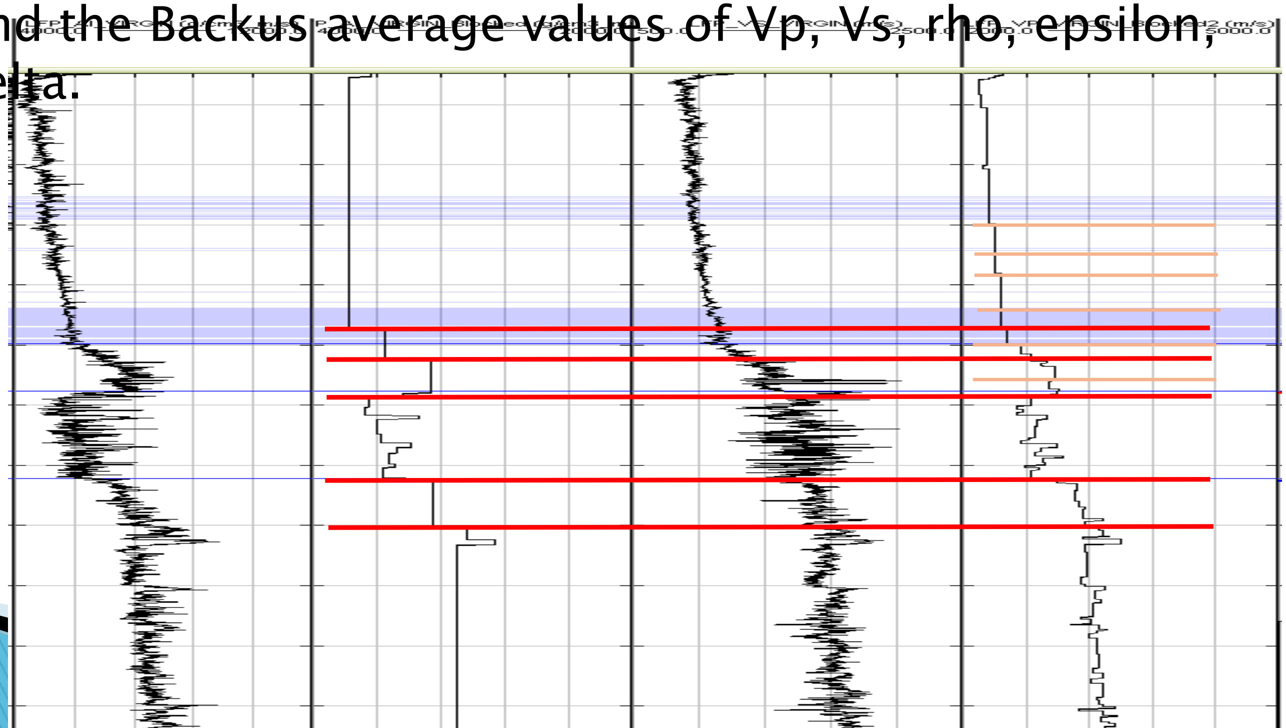
Rule of thumb:
If the thick layers are less than (minimum wavelength)/10 in thickness, a wave equation synthetic calculated using them (with anisotropic modelling) will be the same for all offsets as one from the original fine layers.
Minimum wavelength is Vs/fmax.

- Run time of wave equation modelling depends on the number of layers, so blocking makes it much faster.
- Cross plots for calibration of seismic or inversion should be made with seismic sampling, so Backus averaging can be used for this.

Backus averaging

Preferred workflow

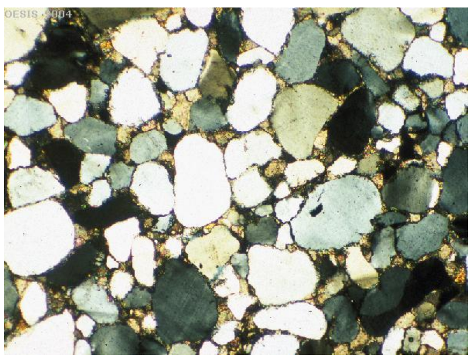
1. Identify the main seismic boundaries (anything that produces a medium to strong reflection).
2. For each interval in turn, find the minimum Vs in that interval.
3. Split the interval into sub-blocks of thickness less than Vs/(10 fmax).
4. For each sub-block, use the original unblocked logs to find the Backus average values of Vp, Vs, rho, epsilon, delta.

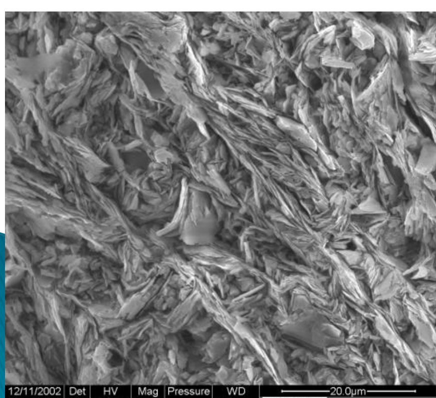


Scale problem

Properties of interest:
Lithology, porosity, saturation, net-to-gross, etc ...

Measurable quantities:
Impedances, maybe density, maybe attenuation, maybe anisotropy





The size of a seismic Fresnel volume is roughly the size of a football stadium

Challenge for the rock physicists

Find simple rock physics models without unknown parameters (aspect ratios, coordination numbers, cement fraction etc) which relate *average* porosity, net/gross, etc to *average* elastic properties for an unknown mixture of lithologies within Lerkendal stadium.

Upscaling problem