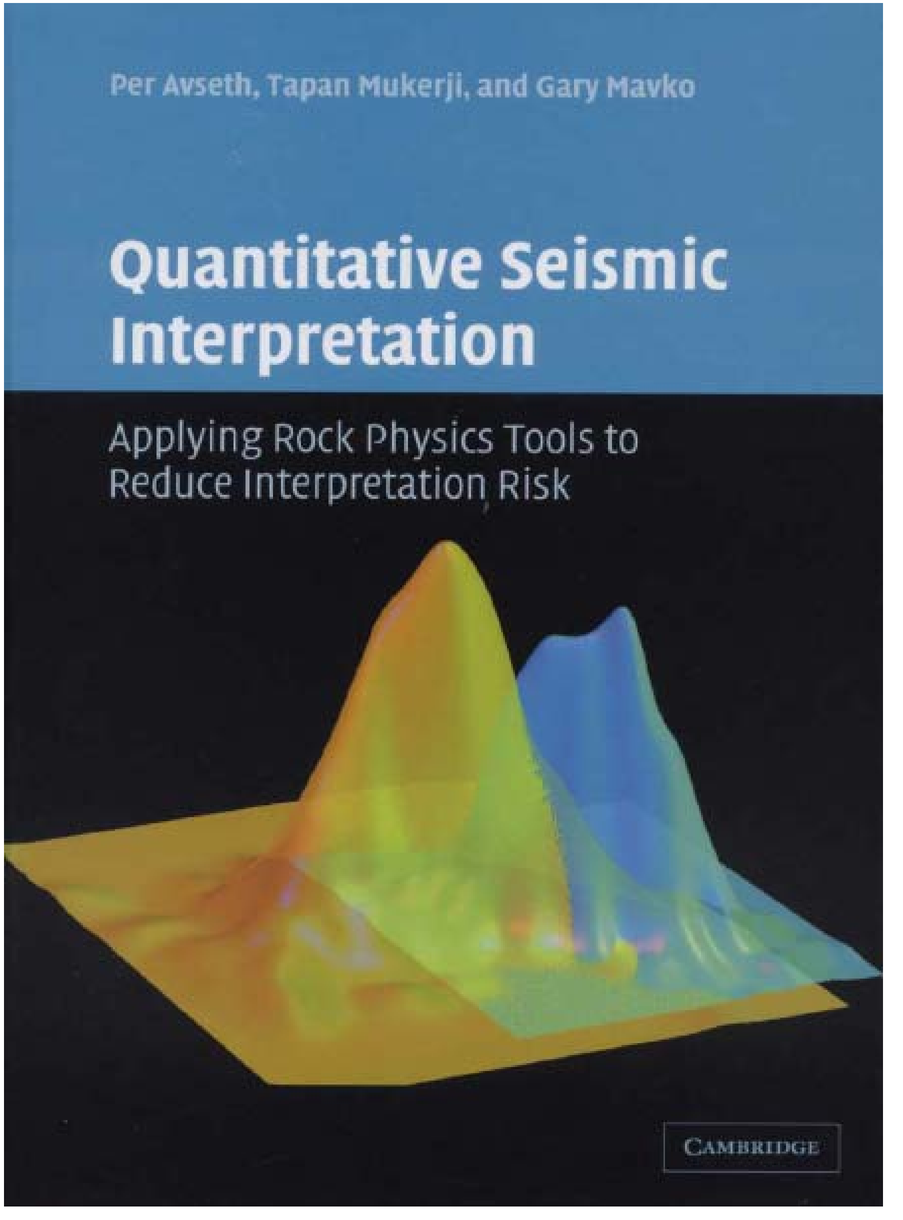
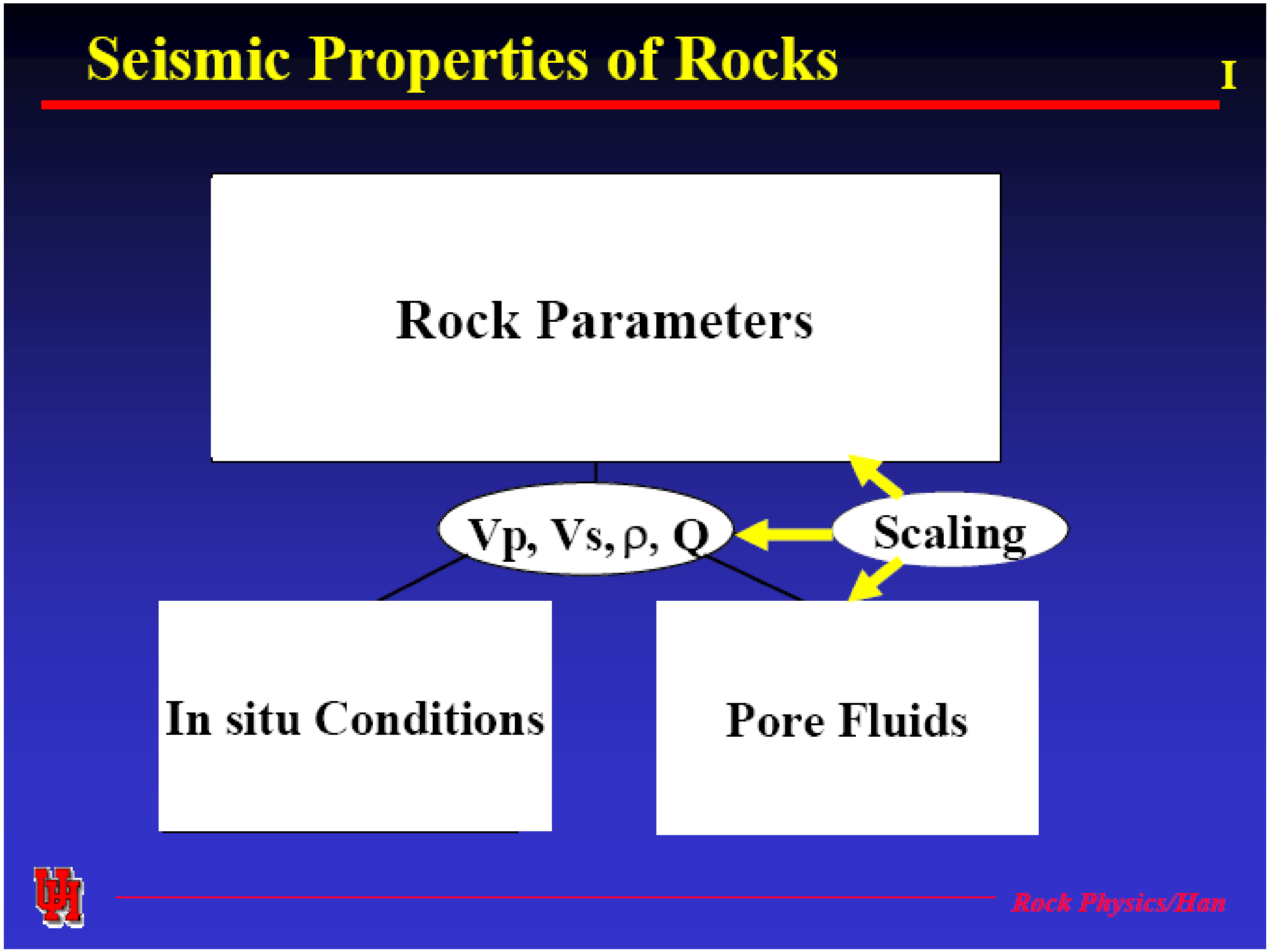
Ch.1.4 - 1.7

Seismic-Rock physics seminar, UH
by Jadranka Milovac
2/13/2009




Seismic Properties of Rocks
I
Rock Parameters
Vp, Vs, ρ, Q
Scaling
In situ Conditions
Pore Fluids
Rock Physics/Han

Outline

- Ch.1.4 Pressure effect on velocity
- Ch.1.5 The special role of shear wave information
- Ch.1.6 “What ifs?”: fluid and lithology substitution
- Ch.1.7 Rock physics models

- Ch.1.4 Pressure effect on velocity

  (4 ways that pressure changes influence seismic signatures)
  - Reversible elastic effects in the rock frame
  - Permanent porosity loss from compaction, crushing and diagenesis
  - Retardation of diagenesis from overpressure
  - Pore fluids changes caused by pore pressure
  - Results regarding pore pressure

Reversible elastic effects in the rock frame

- Seismic velocities almost always increase with effective pressure
- Pore space tends to elastically soften the rock by weakening the structure of mineral material
- Poorly consolidated sediments- compaction occur, velocity vs Peff behavior inelastic and irreversible with large hysteresis

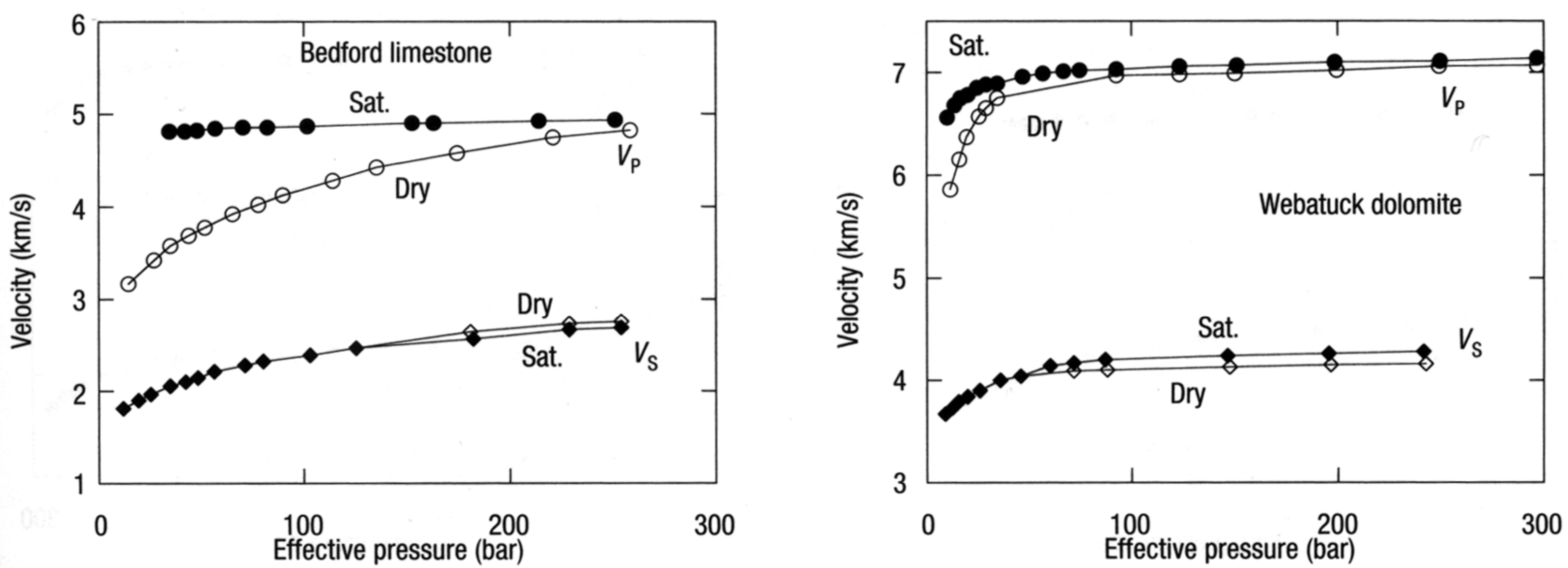
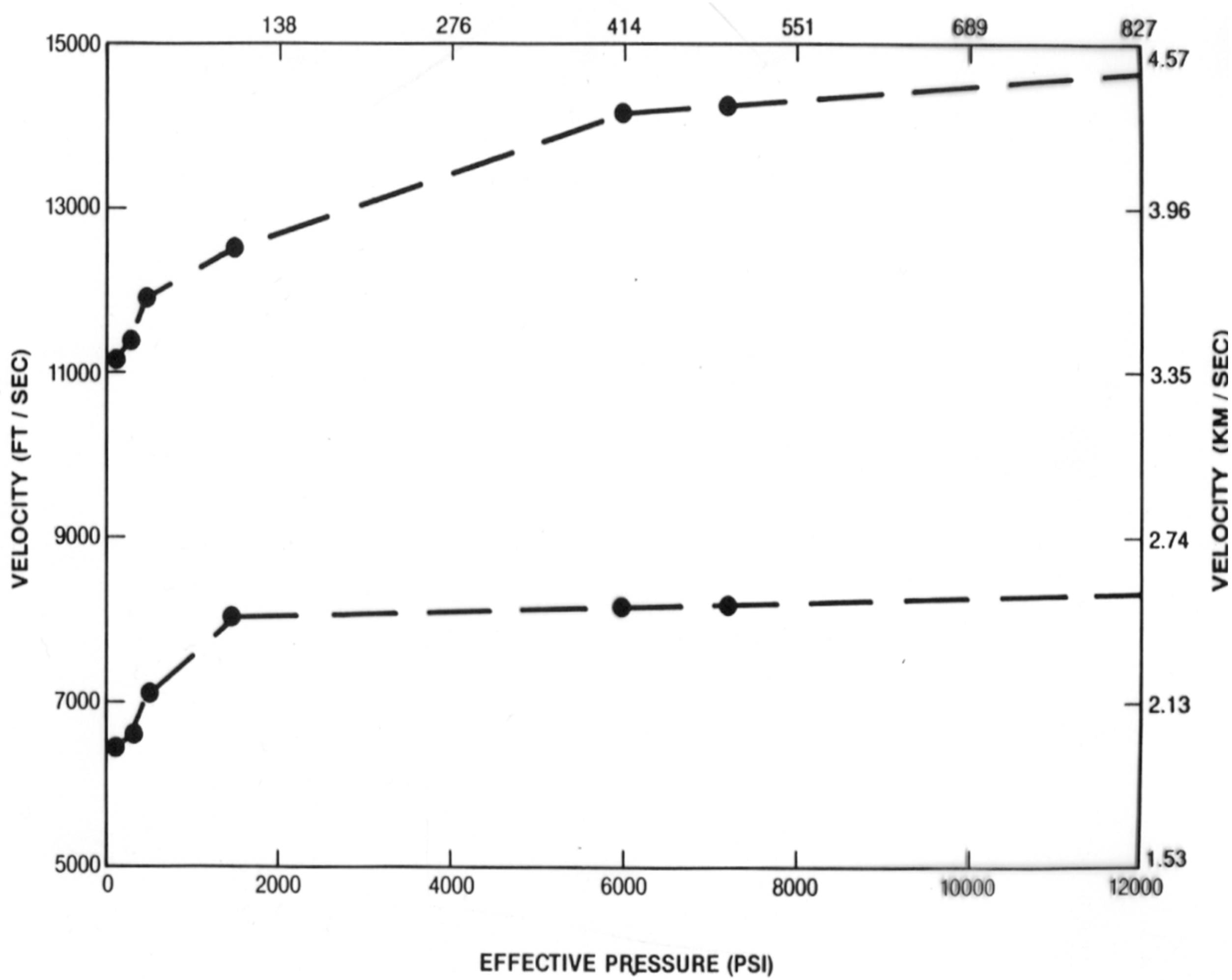


Figure 1.14 Seismic P- and S-wave velocities vs. *effective pressure* in two carbonates.

Fig.1.14 Pp=fixed, Pconf=increase (Avseth et al., 2005)

Velocity vs Peff: The slope of the curves

- Depends which part of the curve we are looking at
    - Low Peff, large sensitivity to pressure
    - High Peff, smaller sensitivity to Peff



(Dr.Castagna's notes)

Permanent porosity loss from compaction, crushing and diagenesis

- Porosity reduction
  - Peff large enough,
  - and held long enough
- Mechanical compaction
- Chemical compaction

2.6 Rock physics depth trends

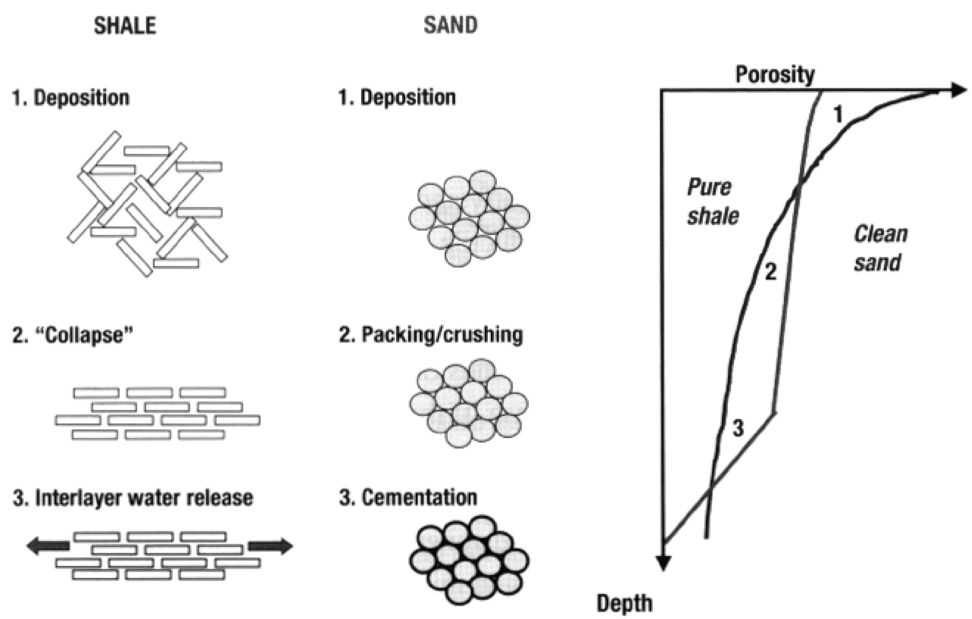
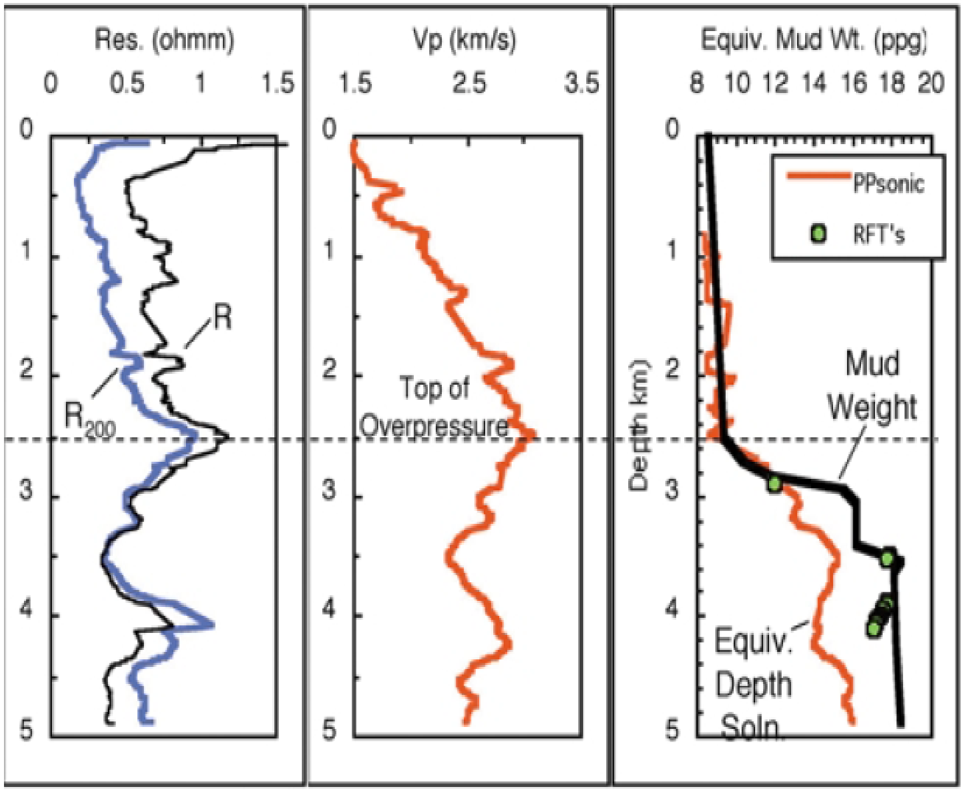


Figure 2.36 Schematic illustration of porosity–depth trends for sands and shales. Both the sand and shale trends can vary significantly because of composition, texture, pore fluids, temperature and pressure gradients. Hence, no attempt is made to assign absolute scales. However, there are a few rules of thumb. (1) The depositional porosity of shales is normally higher than that of sands. (2) The porosity gradient with depth is steeper for shales than for sands during mechanical compaction (i.e., at shallow depths). (3) The porosity gradient with depth will be steeper for sands than for shales during chemical compaction (i.e., quartz cementation of sands normally occurs at greater burial depth, beyond 2–3 km).

(Avseth et al., 2005)

Retardation of diagenesis from overpressure

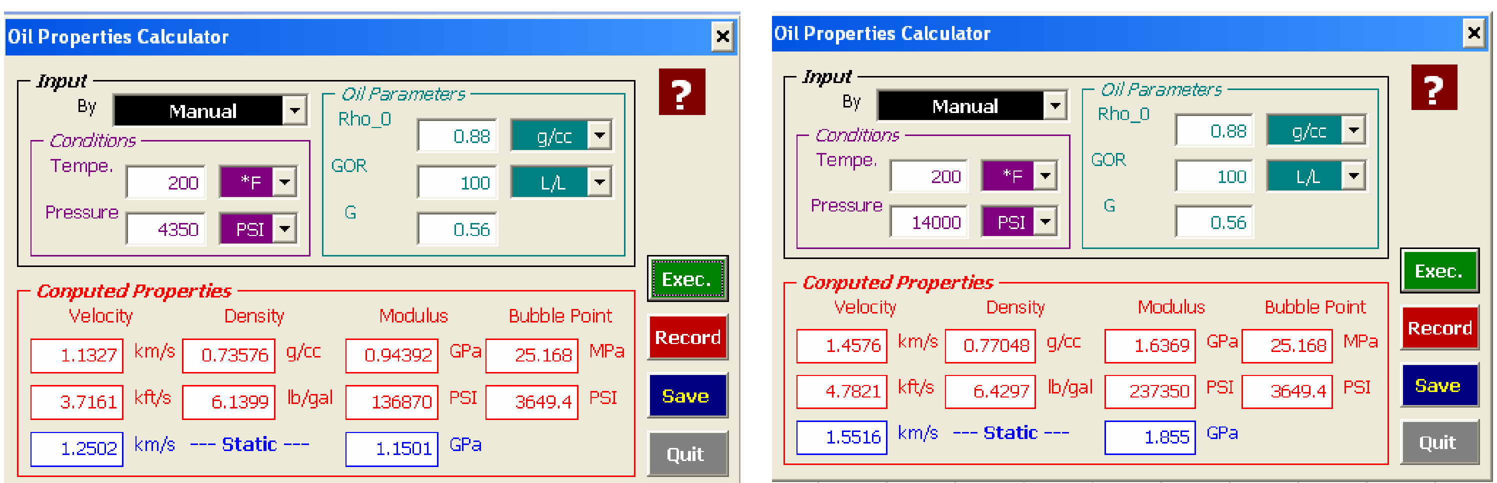
- Overpressure=Pore pressure higher than the normal
- Overpressure helps to maintain porosity and keep the velocity low
- Might be misleading



(Bowers, 2002)

Pore fluids changes caused by pore pressure

- Seismic velocities can depend strongly on the properties of the fluid
- Pressure effect on both: Density, and Bulk modulus
- Pressure effect is larger for gase, less for oil, and smallest for water
- Reservoir condition fluid properties: Batzle and Wang (1992)
- Different software: FLAG, geoPVT, etc.



FLAG. Example: Pressure effect on oil properties

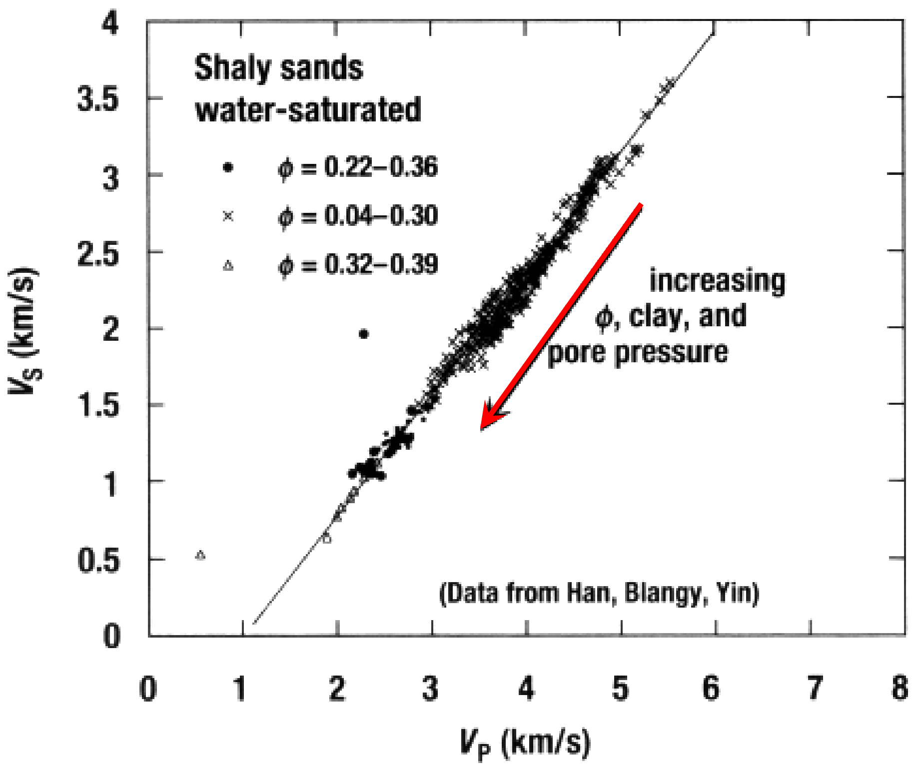
Results regarding pore pressure

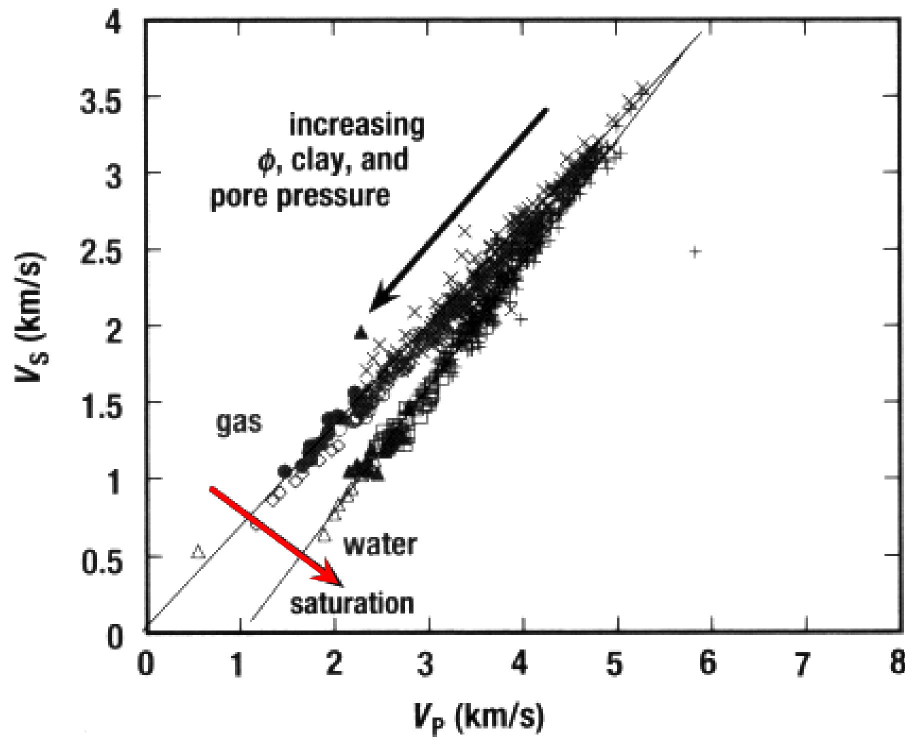
- Elastic effects are important for 4D seismic monitoring (depletion)
- The current state of the art requires calibration of pressure dependence on velocity
- Micro cracks on core data (damage of the core)
- Overpressure

- Ch.1.5 The special role of shear wave information
  - The problem of nonuniqueness of rock physics effects on Vp and Vs
  - “The Magic” of Vp combined with Vs
  - Vp-Vs relations
  - Shear-related attributes

“The Magic” of Vp combined with Vs

- Single trend: Porosity 0.4-40%, Effective pressure 5-50MPa, Clay fraction 0-50%
- Trend of saturation is perpendicular to trends of porosity, clay, pore pressure





Vp vs Vs for (left) water saturated sandstone, (right) water and gas saturated sandstone

Data from Han(1986), Blangy (1992), qnd Yin (1992)

(Avseth et al., 2005)

Vp-Vs relations

- Fluid: 100% water
- Rock: Different lithologies (monomineralic rocks)
  - Limestone
  - Dolomite
  - Sandstone
  - Shale
- Rock: multimineralic rock (Greenberg-Castagna)

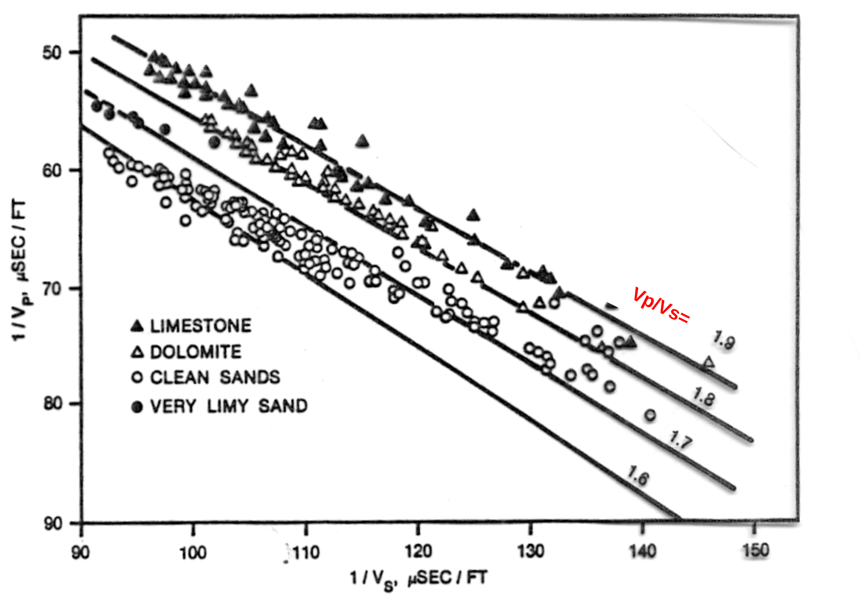


Figure 1. Laboratory measurements on limestones, dolomites, and sandstones from Pickett (1963).

(figure from Dr. Castagna's notes)

V_p - V_s Relationships

Table 1. Some reported mineral properties. Mineral velocities are averaged to represent zero-porosity isotropic aggregates.

Mineral	Density (gm/cc)	V_p (km/s)	V_s (km/s)	V_p/V_s	Reference*
Calcite	2.71	6.53	3.36	1.94	(1)
Calcite	2.71	6.26	3.24	1.92	(2)
Dolomite	2.87	7.05	4.16	1.70	(3)
Halite	2.16	4.50	2.59	1.74	(4)
Muscovite	2.79	5.78	3.33	1.74	(5)
Quartz	2.65	6.06	4.15	1.46	(2)
Quartz	2.65	6.05	4.09	1.48	(6)
Anhydrite	2.96	6.01	3.37	1.78	(7)

(Castagna, 1993)

V_p - V_s Relationships

Table 2. Some interpreted clay velocities. These data are extrapolations to 100 percent clay from mixed lithologies.

Description	V_p (km/s)	V_s (km/s)	V_p/V_s	Reference*
Mixed clays	3.40	1.60	2.13	(1)
Mixed clays	3.41	1.63	2.09	(2)
Montmorillonite/ illite mixture	3.60	1.85	1.95	(3)
Illite	4.32	2.54	1.70	(4)

(Castagna, 1993)

Vp-Vs relations - Limestone

- Castagna et al. (1993)
  - **Vs=0.5832Vp-0.0777 (km/s)**
- Pickett (1963)
  - **Vs=Vp/1.9**

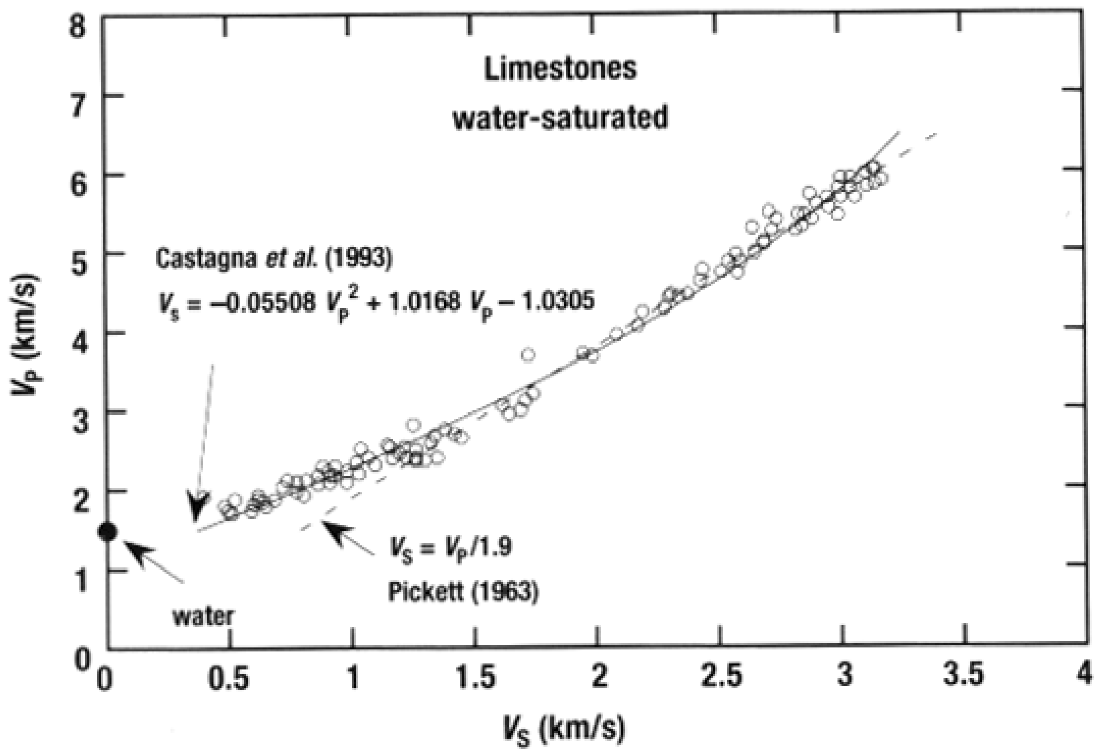


Figure 1.22 Plot of V_P vs. V_S data for water-saturated limestones with two empirical trends superimposed. Data compiled by Castagna *et al.* (1993).

(Avseth et al., 2005)

Vp-Vs relations – Dolomite

- Pickett (1963, lab data)
  - **Vs=Vp/1.8**
- Castagna et al. (1993, lab data)
  - **Vs=0.5832Vp-0.0777 (km/s)**

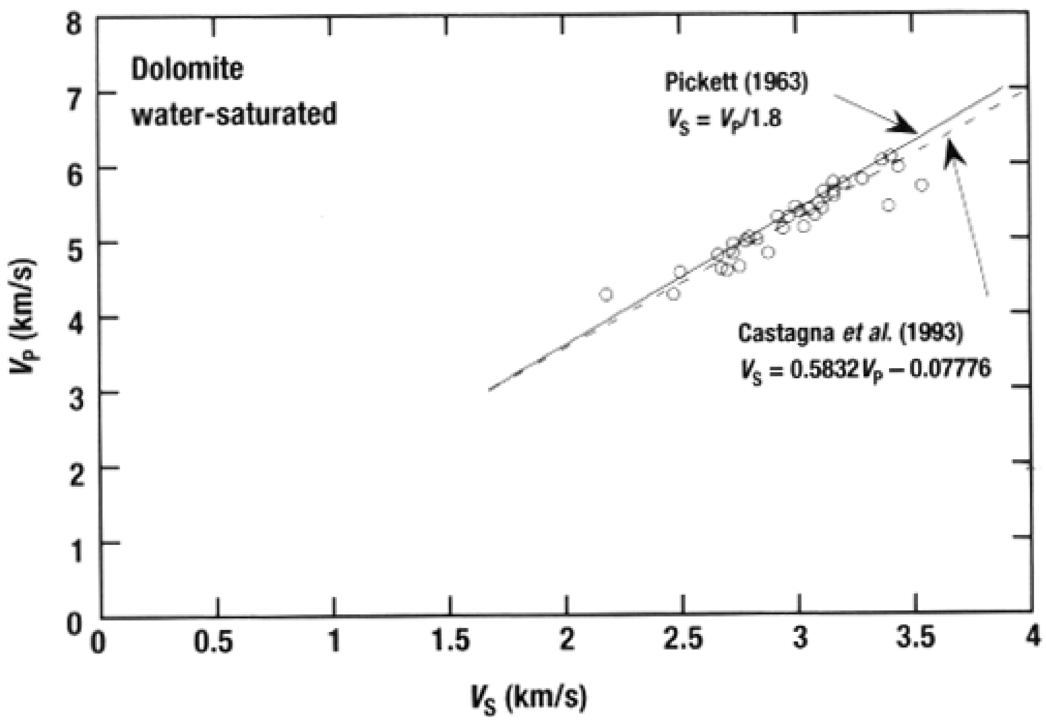


Figure 1.23 Plot of V_P vs. V_S data for water-saturated dolomites with two empirical trends superimposed. Data compiled by Castagna *et al.* (1993).

(Avseth et al., 2005)

Vp-Vs relations - Sandstone

- Castagna et al. (1993, laboratory data)
  - **Vs = 0.8042Vp - 0.8559 (km/s)**
- Han (1986, laboratory data)
  - **Vs=0.7936Vp-0.7868 (km/s)**
- Pickett (1963, laboratory data)
  - **Vs=Vp/1.6 (very clean)**
  - **Vs=Vp/1.7 (limy sand)**

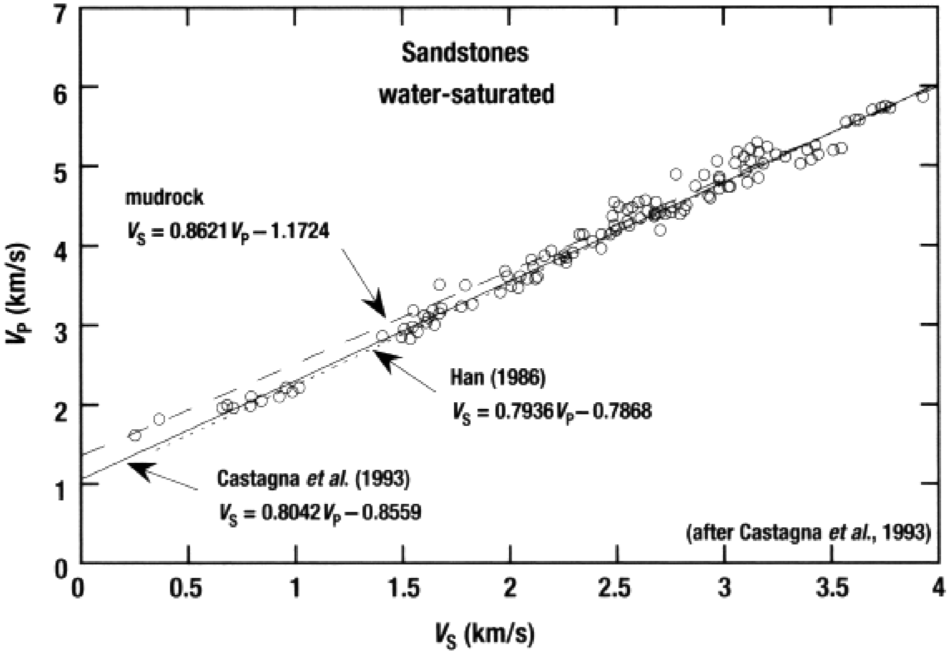


Figure 1.24 Plot of V_P vs. V_S data for water-saturated sandstones with three empirical trends superimposed. Data compiled by Castagna *et al.* (1993).

(Avseth et al., 2005)

Vp-Vs relations - Shale

- MUDROCK line, Castagna et al.(1985, in situ- log data)
  - **Vs = 0.8621*Vp – 1.1724 (km/s)**

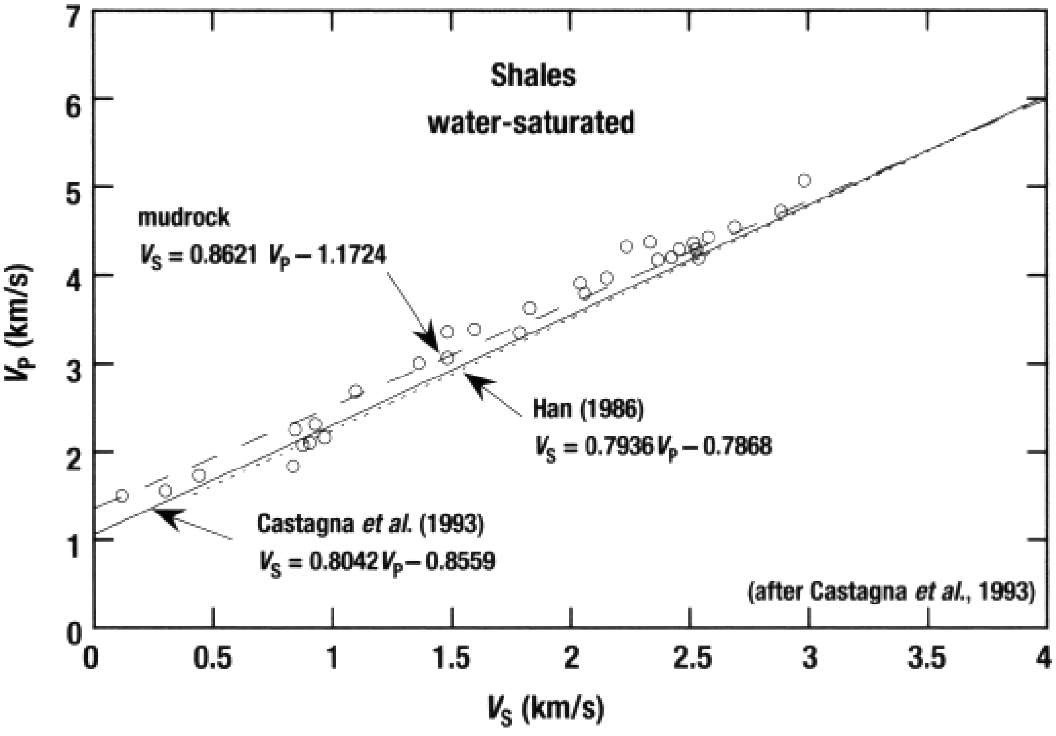


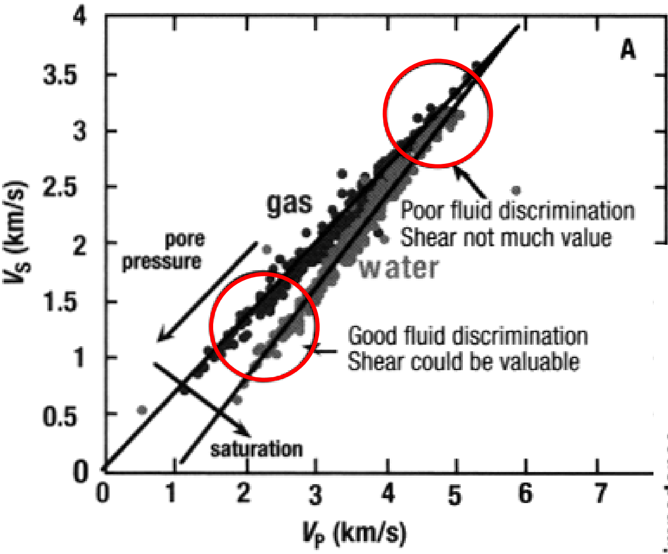
Figure 1.25 Plot of V_P vs. V_S data for water-saturated shales with three empirical trends superimposed. Data compiled by Castagna *et al.* (1993).

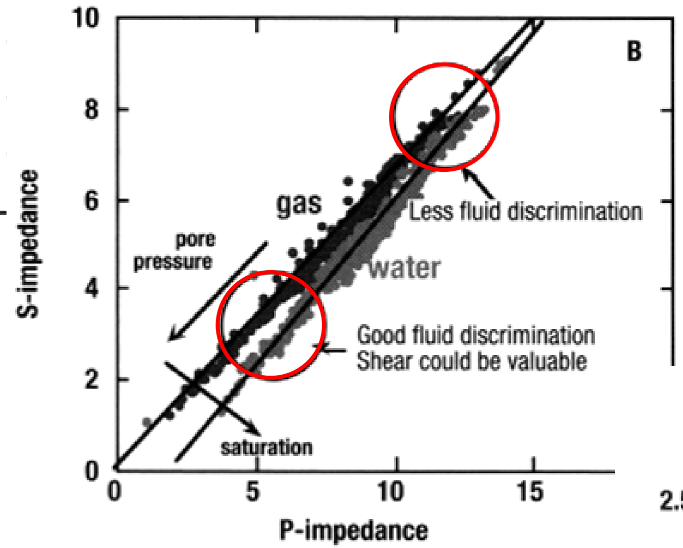
(Avseth et al., 2005)

Shear-related attributes

- Only three key seismic parameters:
  - **Vp, Vs, Density**
- Vp/Vs vs AI
- AI, EI
- A, B (intercept and gradient)
- λ, μ (Lame coefficients)
- Etc.

Shear-related attributes





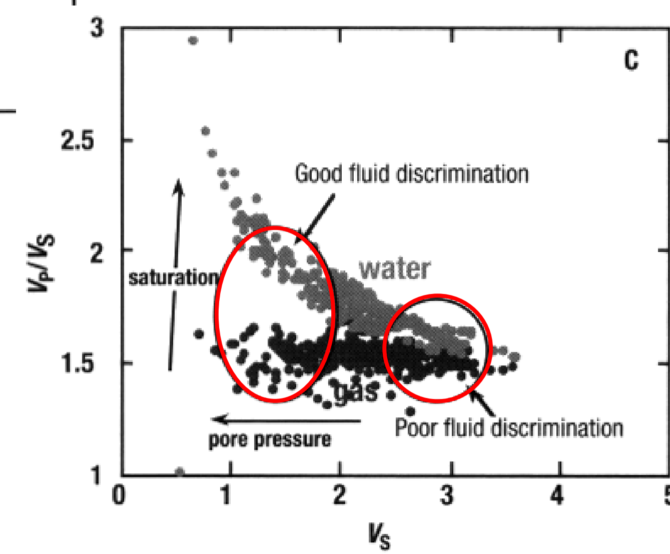


Figure 1.29 Saturation and pressure discrimination are very similar in different attribute domains. A. Plot of V_P vs. V_S sandstone data, showing the value of combining P- and S-wave data for separating lithology, pore pressure, and saturation (same as Figure 1.21). B. Same rock samples as in A, but plotted as P- and S-wave impedances. C. Same rock samples plotted as V_P/V_S vs. V_S.

(Avseth et al., 2005)

TABLE 2.1.1. Relationships among elastic constants in an isotropic material (after Birch, 1961).

K	E	λ	ν	M	μ
$\lambda + 2\mu/3$	$\mu\frac{3\lambda+2\mu}{\lambda+\mu}$	—	$\frac{\lambda}{2(\lambda+\mu)}$	$\lambda + 2\mu$	—
—	$9K\frac{K-\lambda}{3K-\lambda}$	—	$\frac{\lambda}{3K-\lambda}$	$3K - 2\lambda$	$3(K-\lambda)/2$
—	$\frac{9K\mu}{3K+\mu}$	$K - 2\mu/3$	$\frac{3K-2\mu}{2(3K+\mu)}$	$K + 4\mu/3$	—
$\frac{E\mu}{3(3\mu-E)}$	—	$\mu\frac{E-2\mu}{(3\mu-E)}$	$E/(2\mu) - 1$	$\mu\frac{4\mu-E}{3\mu-E}$	—
—	—	$3K\frac{3K-E}{9K-E}$	$\frac{3K-E}{6K}$	$3K\frac{3K+E}{9K-E}$	$\frac{3KE}{9K-E}$
$\lambda\frac{1+\nu}{3\nu}$	$\lambda\frac{(1+\nu)(1-2\nu)}{\nu}$	—	—	$\lambda\frac{1-\nu}{\nu}$	$\lambda\frac{1-2\nu}{2\nu}$
$\mu\frac{2(1+\nu)}{3(1-2\nu)}$	$2\mu(1+\nu)$	$\mu\frac{2\nu}{1-2\nu}$	—	$\mu\frac{2-2\nu}{1-2\nu}$	—
—	$3K(1-2\nu)$	$3K\frac{\nu}{1+\nu}$	—	$3K\frac{1-\nu}{1+\nu}$	$3K\frac{1-2\nu}{2+2\nu}$
$\frac{E}{3(1-2\nu)}$	—	$\frac{E\nu}{(1+\nu)(1-2\nu)}$	—	$\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$	$\frac{E}{2+2\nu}$

(RP handbook)

- Ch.1.6 “What ifs?”: fluid and lithology substitution

- Well control and extrapolation of the data
  - Laterally
  - Vertically
- “What if the fluid change?”
- “What if the lithology change?”

- Ch.1.7 Rock physics models
  - Theoretical models
    - Inclusion models
    - Contact models
    - Computational models
    - Bounds
    - Transformations
  - Empirical models
  - Heuristic models
  - Their hybrid approach

"All models are wrong….some are useful"

Theoretical models

- Inclusion models -
  - Approximate rock as an elastic solid containing cavities (cavities=pore space)
  - Vast majority of models: pore cavities are ellipsoidal (Kuster and Toksoz,1974; O'Connell and Budiansky,1974; Cheng,1978,1993; Hudson, 1980,1981,1990; etc.)
  - Berryman (1980)- both pores and grains as ellipsoidal "inclusions"
  - Mavko and Nur(1978) and Mavko(1980)- inclusion cavities non-ellipsoidal in shape
  - Shoeneberg (1983) and Pyrak-Nolte et al. (1990)- inclusions as infinite planes

- Contact models -
  - Approximate rock as collection of separate grains, whose elastic properties are determined by deformability and stiffness of their grain-to-grain contact
  - Based on Hertz-Mindlin model (Mindlin, 1949): Walton,1987; Digby,1981; Norris and Johnson, 1997; Makse et al.,1999)
  - Dvorkin and Nur (1996), added mineral cement at contact grains

Theoretical models

- Computational models -
  - Grain-pore microgeometry determined by thin-section and CT-scan image
  - Advantage: elastically quantify features in thin sections
  - Geometry represented by grids (finite elements)
- Bounds -
  - Robust and free of approximations, other than treat rock as elastic composite
  - Valuable mixing lows
  - Voigt-Reuss and Hashin-Shtrikman
- Transformations -
  - Free of geometric assumptions
  - Gassmann (1951)
  - Berryman and Milton (1991)- composite of two porous media having separate mineral and dry-frame moduli

Empirical models

- Approach:
  - Assume some function form
  - Define coefficients by calibrating a regression to the data

- Examples:
  - Han (1986)- regression for velocity-porosity-clay behavior in sandstones
    - $Vp,s=a + b*PHI + c*V_{CL}$
  - Geenberg-Castagna (1992)- relation for Vp-Vs for multimineralic rocks
  - Gardner et al.(1974): Vp-density relationship
    - RHOB=0.23*(Vp)^(0.25) (g/cc; kft/s)
  - Neural-networks
  - Etc.

Heuristic models

- "Pseudo-theoretical"- use intuitive means to argue why certain parameters should be related in certain way

- Examples:
  - Wyllie time avg eq. relating velocity and porosity
    - $1/Vp=PHI/V_{fluid}+(1-PHI)/V_{mineral}$
  - Moddified upper and lower Hashin-Shtrikman bounds to describe cementing and sorting trends

- Thank you!