

**Parameters That Influence Seismic Velocity**

**Conceptual Overview of Rock  
and Fluid Factors that Impact  
Seismic Velocity and Impedance**

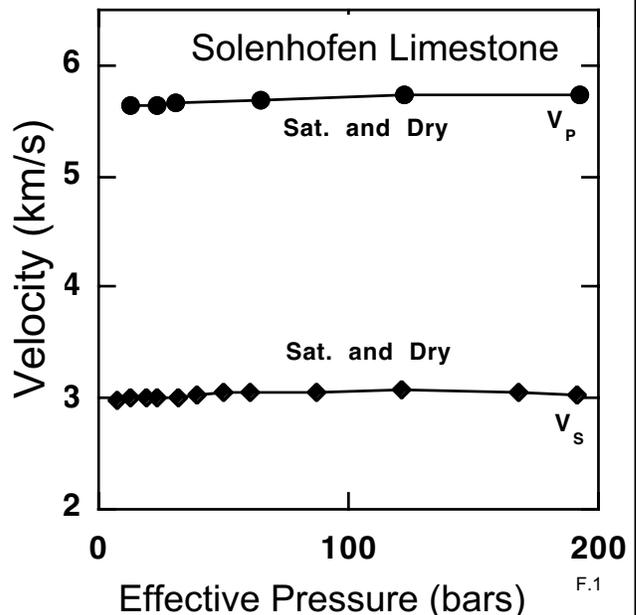
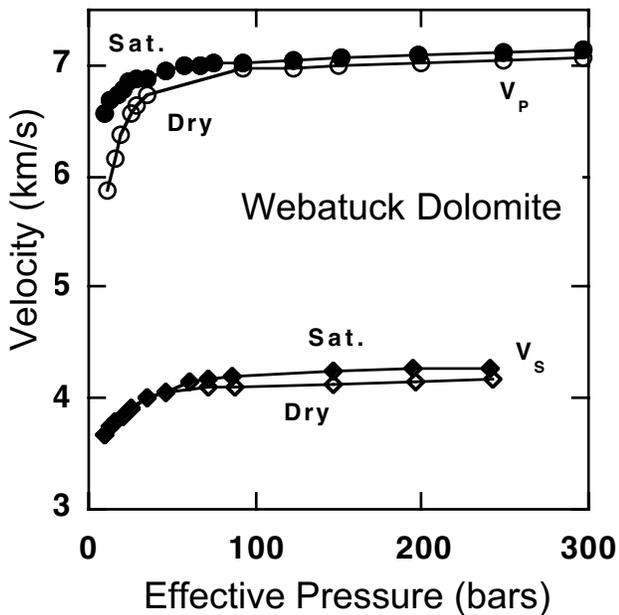
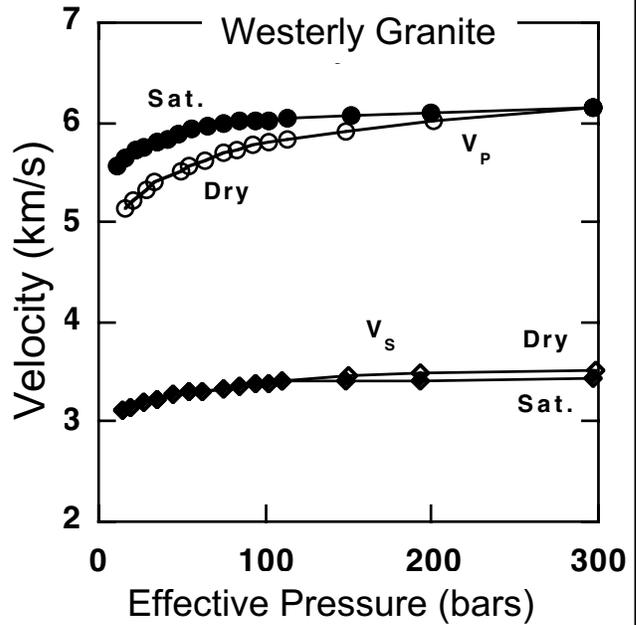
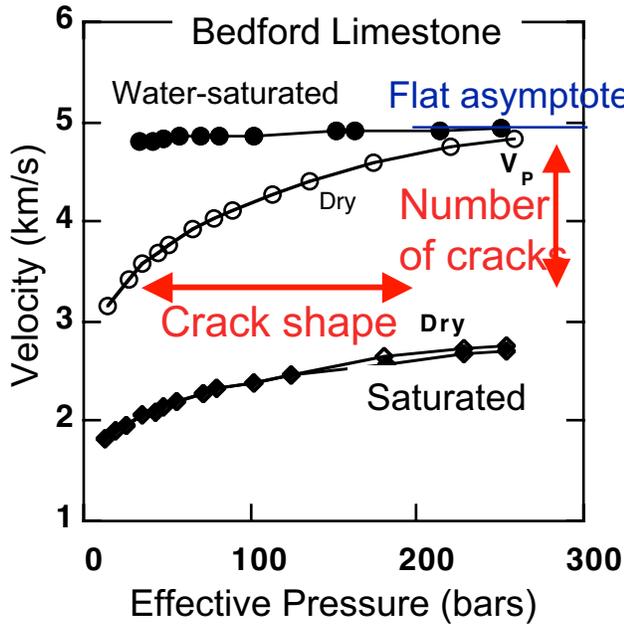
## Parameters That Influence Seismic Velocity

Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm <sup>3</sup> )	Density of constituent crystal (g/cm <sup>3</sup> )
Scree, vegetal soil	300-700	100-300	1.7-2.4	-
Dry sands	400-1200	100-500	1.5-1.7	2.65 quartz
Wet sands	1500-2000	400-600	1.9-2.1	2.65 quartz
Saturated shales and clays	1100-2500	200-800	2.0-2.4	-
Marls	2000-3000	750-1500	2.1-2.6	-
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4	-
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4	2.65 quartz
Limestones	3500-6000	2000-3300	2.4-2.7	2.71 calcite
Chalk	2300-2600	1100-1300	1.8-3.1	2.71 calcite
Salt	4500-5500	2500-3100	2.1-2.3	2.1 halite
Anhydrite	4000-5500	2200-3100	2.9-3.0	-
Dolomite	3500-6500	1900-3600	2.5-2.9	(Ca, Mg) CO <sub>3</sub> 2.8-2.9
Granite	4500-6000	2500-3300	2.5-2.7	-
Basalt	5000-6000	2800-3400	2.7-3.1	-
Gneiss	4400-5200	2700-3200	2.5-2.7	-
Coal	2200-2700	1000-1400	1.3-1.8	-
Water	1450-1500	-	1.0	-
Ice	3400-3800	1700-1900	0.9	-
Oil	1200-1250	-	0.6-0.9	-

Typical rock velocities, from Bourbie, Coussy, and Zinszner, *Acoustics of Porous Media*, Gulf Publishing.

## Parameters That Influence Seismic Velocity

### The Saturation and Pressure Dependence of P- and S-wave Velocities.



$$P_{\text{effective}} = P_{\text{confining}} - P_{\text{pore}}$$

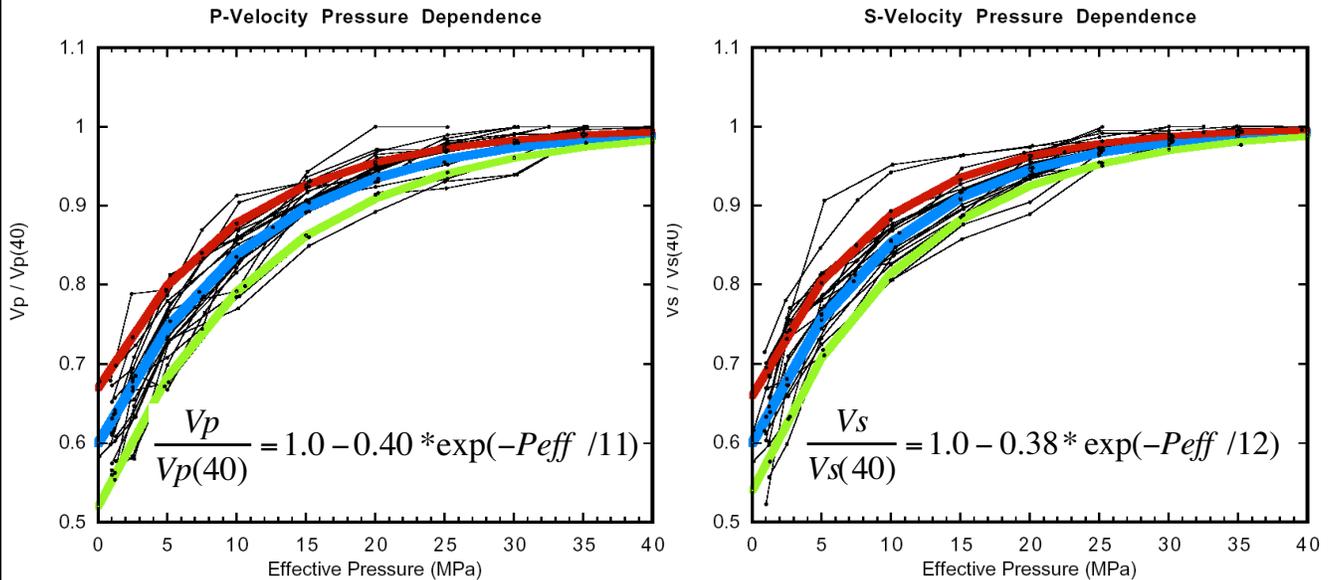
## Parameters That Influence Seismic Velocity

### Fundamental Observations of Rock Physics

- Velocities almost always increase with effective pressure. For reservoir rocks they often tend toward a flat, high pressure asymptote.
- To first order, only the difference between confining pressure and pore pressure matters, not the absolute levels of each -- "effective pressure law."
- The pressure dependence results from the closing of cracks, flaws, and grain boundaries, which elastically stiffens the rock mineral frame.
- The only way to know the pressure dependence of velocities for a particular rock is to measure it.
- Make ultrasonic measurements on dry cores; fluid-related dispersion will mask pressure effects.
- The amount of velocity change with pressure is a measure of the number of cracks; the pressure range needed to reach the high pressure asymptote is a measure of crack shape (e.g. aspect ratio).
- Velocities tend to be sensitive to the pore fluid content. Usually the P-wave velocity is most sensitive and the S-wave velocity is less sensitive.
- Saturation dependence tends to be larger for soft (low velocity) rocks.

## Parameters That Influence Seismic Velocity

# Pressure-Dependence of Velocities



**Remember: Calibrate to Dry Cores!**

F29

It is customary to determine the pressure dependence of velocities from core measurements. A convenient way to quantify the dependence is to normalize the velocities for each sample by the high pressure value as shown here. This causes the curves to cluster at the high pressure point. Then we fit an average trend through the cloud, as shown. The velocity change between any two effective pressures P1 and P2 can be conveniently written as:

$$\frac{V(P2)}{V(P1)} = \frac{1.0 - 0.38 \exp(-P2 / 12)}{1.0 - 0.38 \exp(-P1 / 12)}$$

Vp and Vs often have a different pressure behavior, so determine separate functions for them.

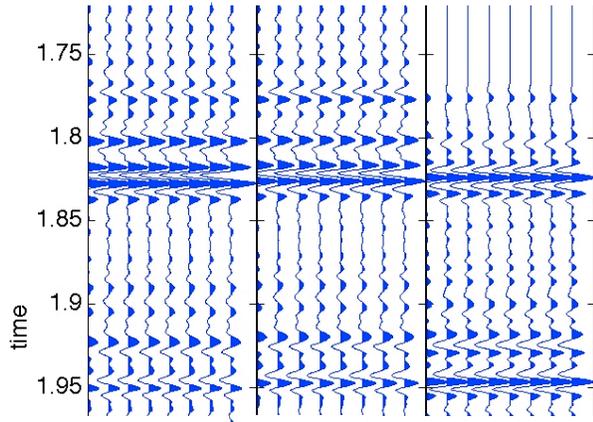
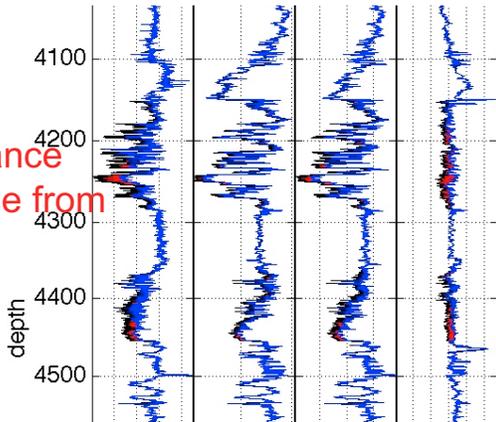
Remember to recalibrate this equation to your own cores!

# Parameters That Influence Seismic Velocity

## 4D Example: Deep, Stiff, Gas Sand

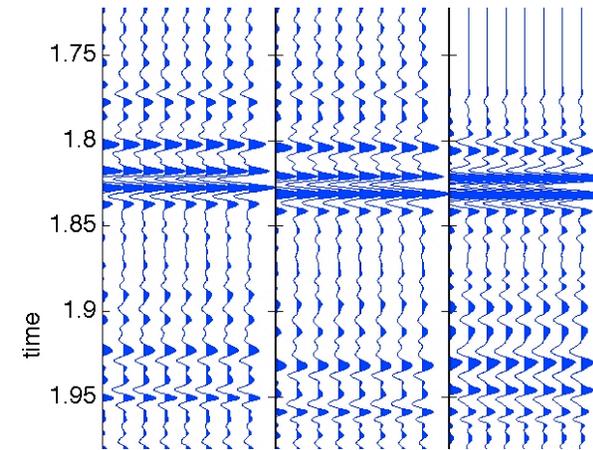
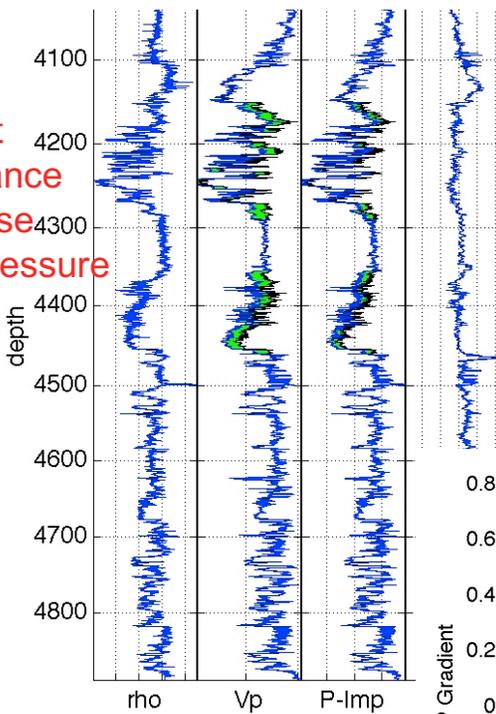
Replace Gas with Water      Gas    Water    Difference

Small impedance increase from fluids

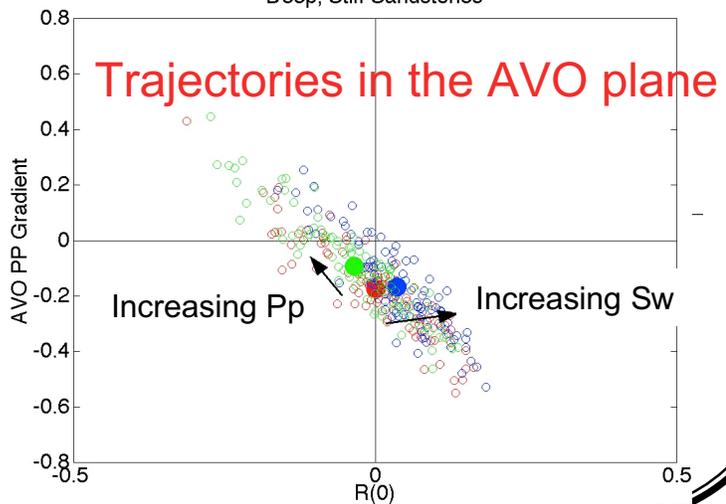


Increase Pp by 100 bars      Before    After    Difference

Modest impedance decrease from pressure



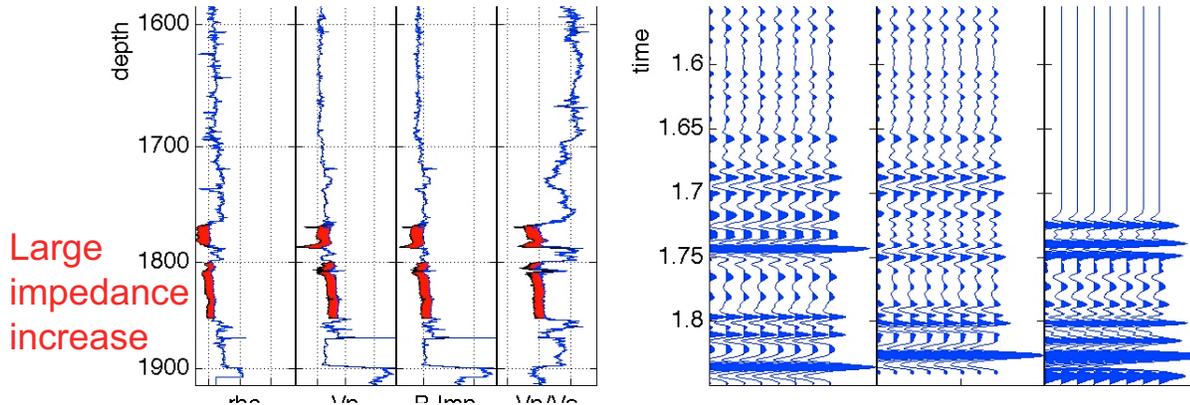
Deep, Stiff Sandstones



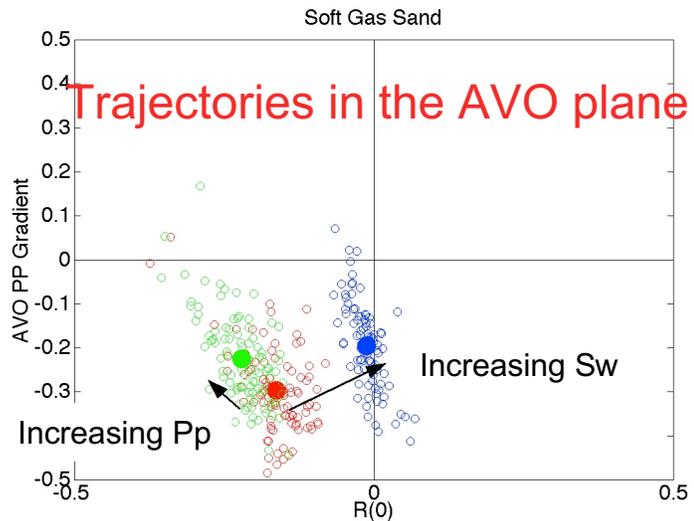
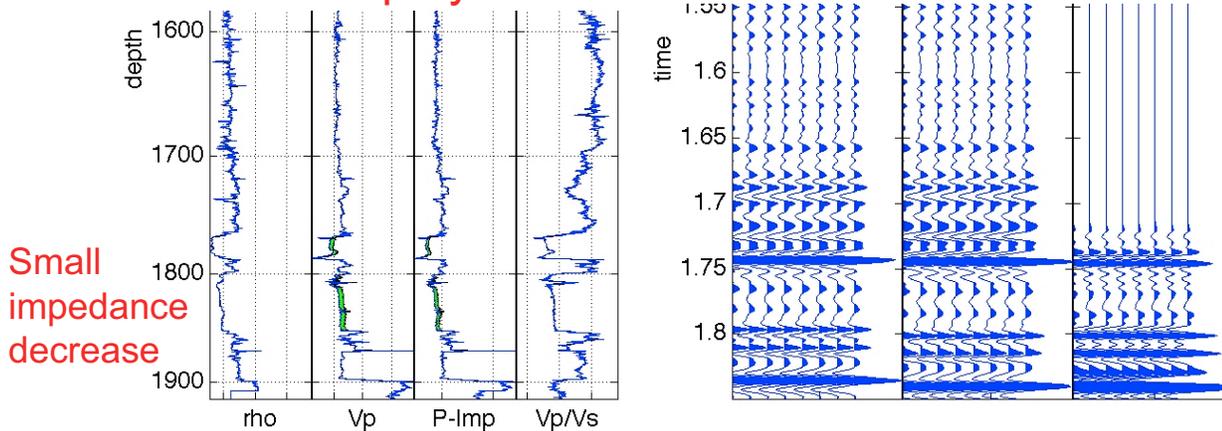
## Parameters That Influence Seismic Velocity

### 4D Example: Deepwater, Soft, Gas Sand

Replace Gas with Water      Gas      Water Difference

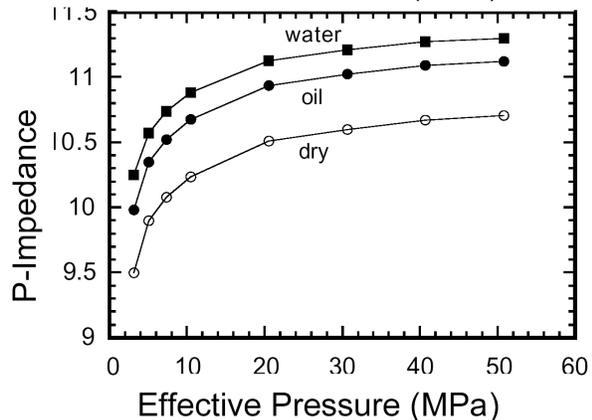
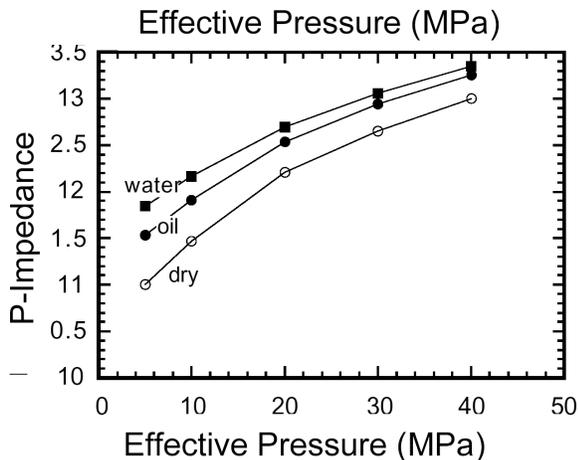
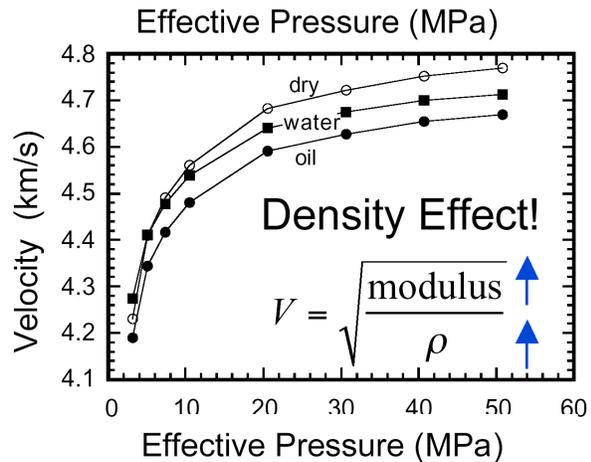
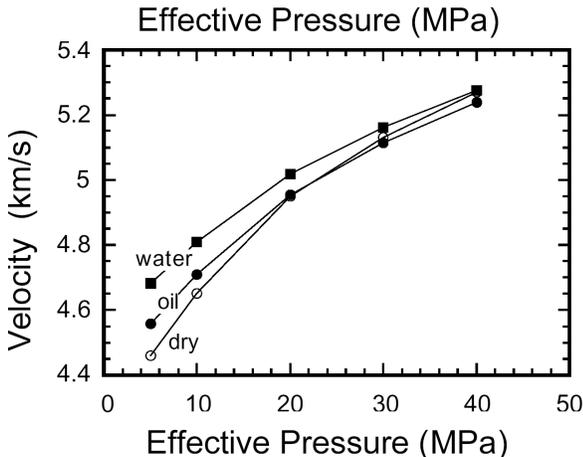
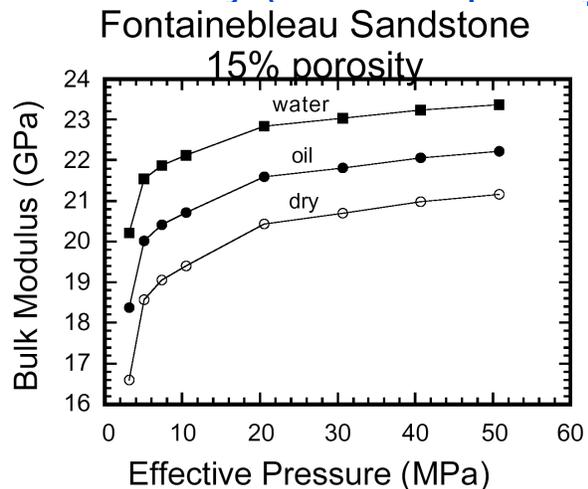
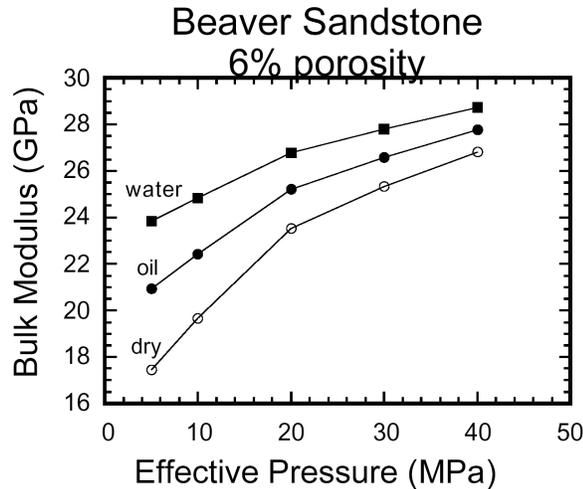


Increase Pp by 100 bars      Before      After      Difference



## Parameters That Influence Seismic Velocity

### Effects of Pore Fluid on P-wave Velocity (Low Frequency)



Density does not lead to ambiguity when Impedance is measured.

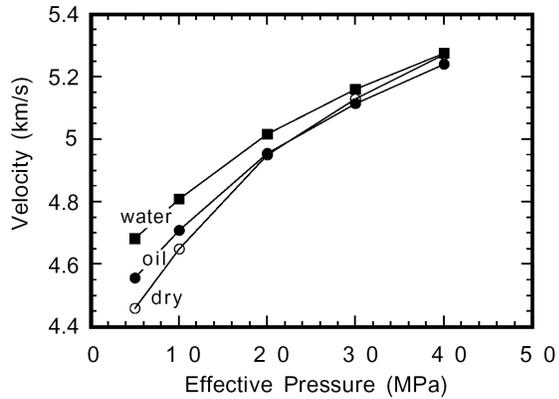
$$\text{Imp} = \rho V = \sqrt{\rho \times \text{modulus}}$$

Calculations made from dry velocities, using Gassmann relation,  $K_{\text{min}} = 36 \text{ GPa}$ ,  $K_{\text{water}} = 2.2$ ,  $K_{\text{oil}} = 1$ .

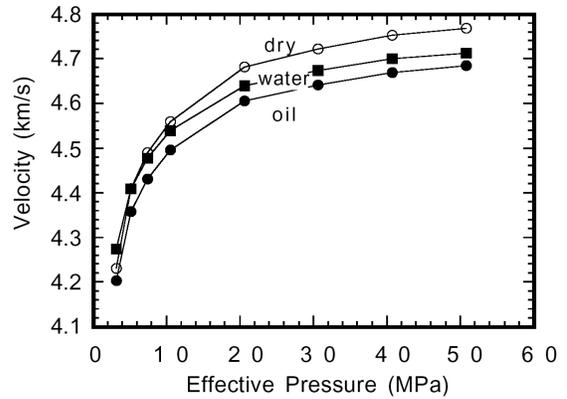
# Parameters That Influence Seismic Velocity

## Effects of Pore Fluid on P-wave Velocity (Low Frequency)

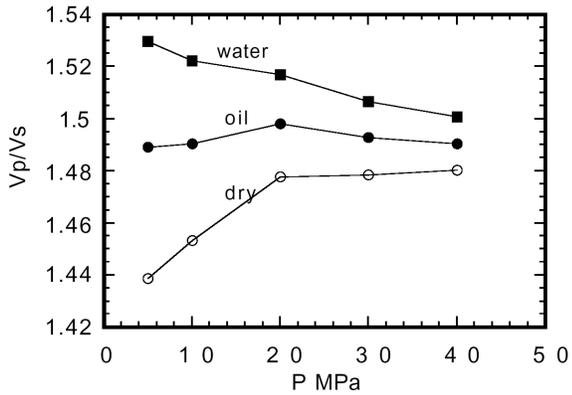
**Beaver Sandstone**  
6% porosity  
Beaver Vp



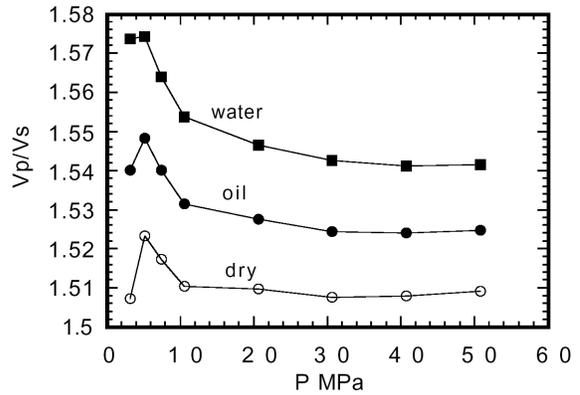
**Fontainebleau Sandstone**  
15% porosity  
Fontainebleau Vp



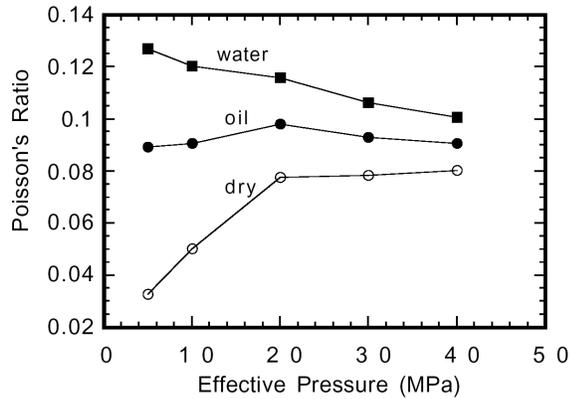
**Beaver Vp/Vs**



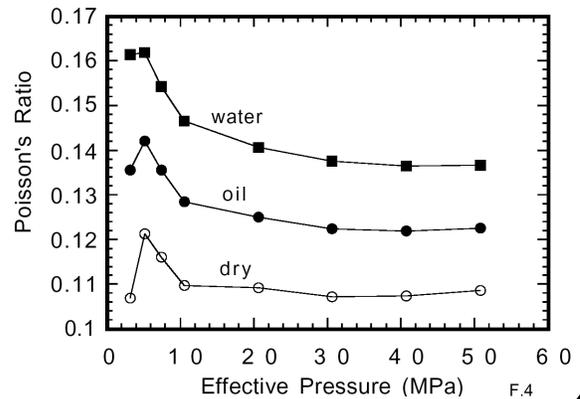
**Fontainebleau Vp/Vs**



**Beaver Poisson's Ratio**



**Fontainebleau Poisson's Ratio**



## Parameters That Influence Seismic Velocity

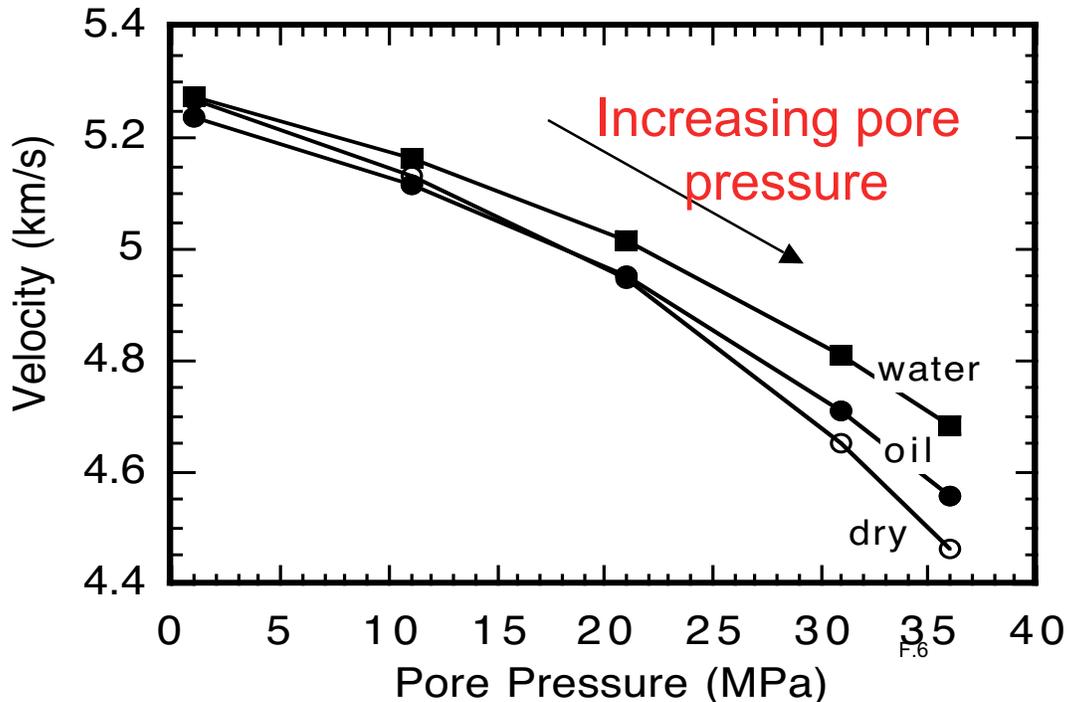
### Velocities depend on fluid modulus and density

- When going from a dry to water saturated rock, sometimes the P-velocity increases; sometimes it decreases.
- The rock elastic bulk modulus almost always stiffens with a stiffer (less compressible) pore fluid.
- The stiffening effect of fluid on rock modulus is largest for a soft (low velocity) rock.
- The bulk density also increases when going from a dry to water-saturated rock.
- Because velocity depends on the ratio of elastic modulus to density, the modulus and density effects “fight” each other; sometimes the velocity goes up; sometimes down.
- Measures of modulus ( $M = \rho V^2$ ), impedance ( $\text{Imp} = \rho V = \sqrt{\rho \text{ modulus}}$ ), and  $V_P / V_S$  don't have the density effect “ambiguity.”
- **Be careful of ultrasonic data!** At high frequencies, the elastic-stiffening effect is exaggerated for both bulk and shear moduli; so we don't often see the density effect in the lab and the velocities will be contaminated by fluid-related dispersion.

## Parameters That Influence Seismic Velocity

### Effect of Pore Pressure

Beaver Sandstone  
6% porosity



Effect of pore pressure on velocity, calculated assuming effective pressure law is valid, and assuming a fixed confining pressure of 40MPa (low frequency calculations using Gassmann relation).

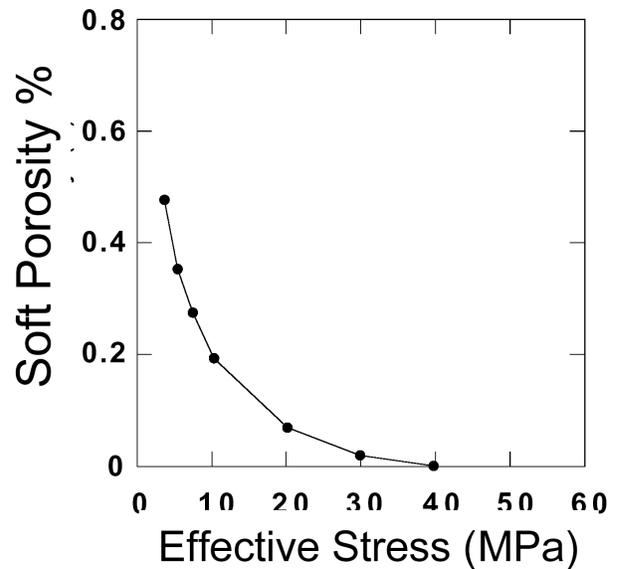
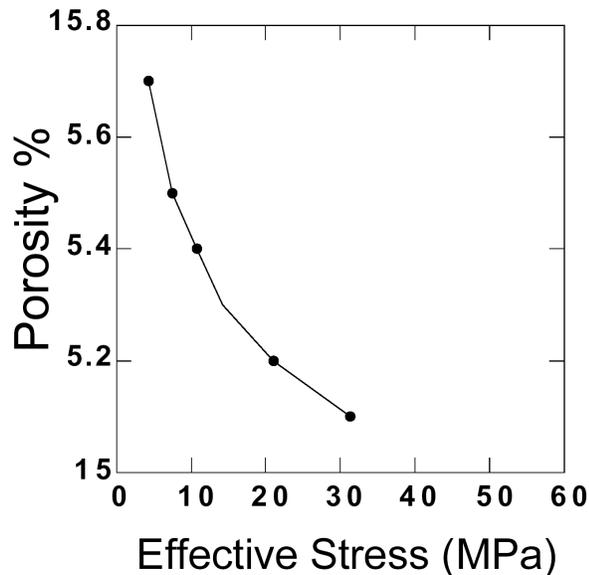
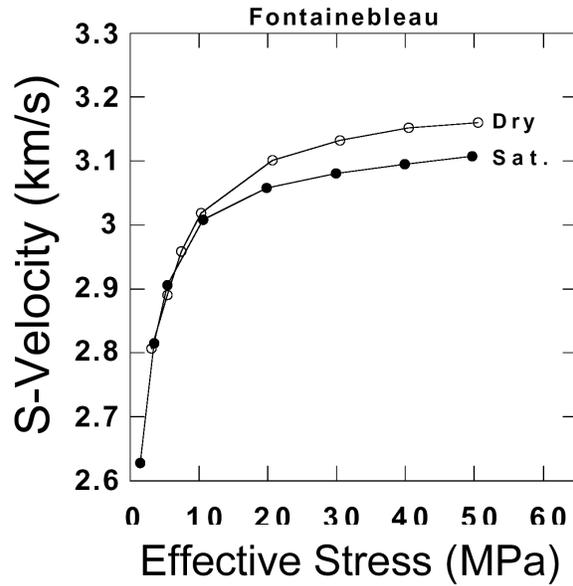
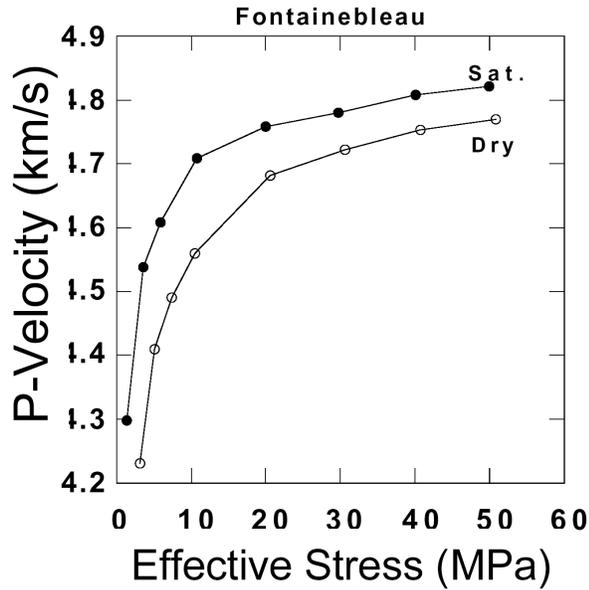
## Parameters That Influence Seismic Velocity

### Ways that Pore Pressure Impacts Velocities

- Increasing pore pressure softens the elastic mineral frame by opening cracks and flaws, tending to lower velocities.
- Increasing pore pressure tends to make the pore fluid or gas less compressible, tending to increase velocities.
- Changing pore pressure can change the saturation as gas goes in and out of solution. Velocities can be sensitive to saturation.
- High pore pressure persisting over long periods of time can inhibit diagenesis and preserve porosity, tending to keep velocities low.

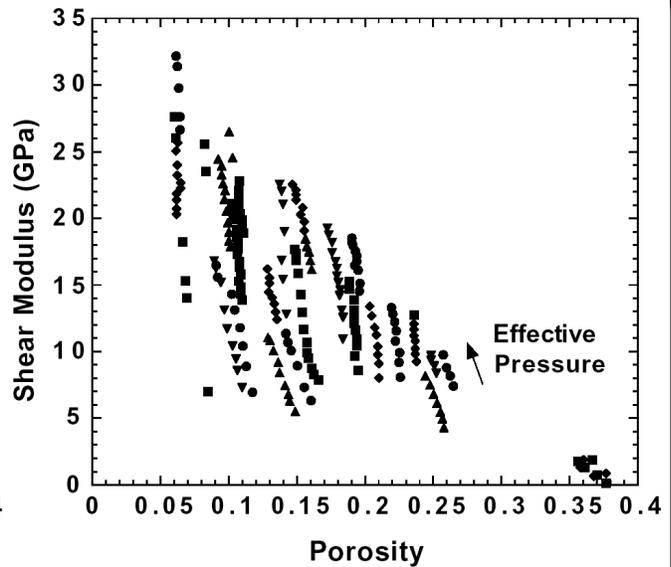
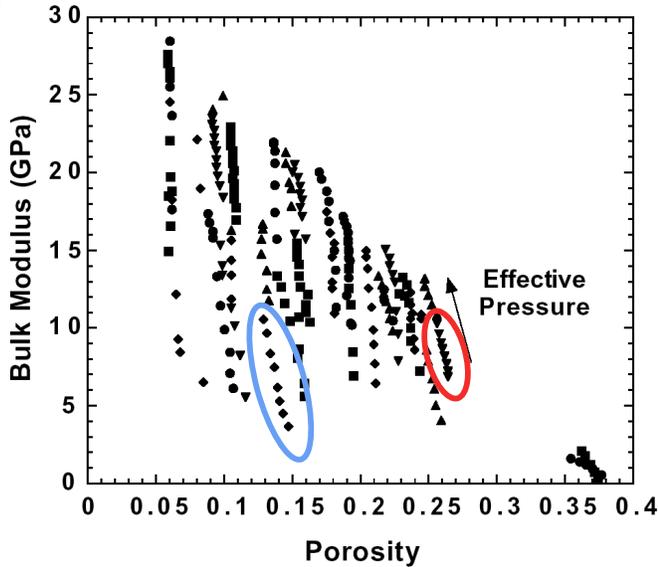
## Parameters That Influence Seismic Velocity

### Pressure Dependence of Velocities

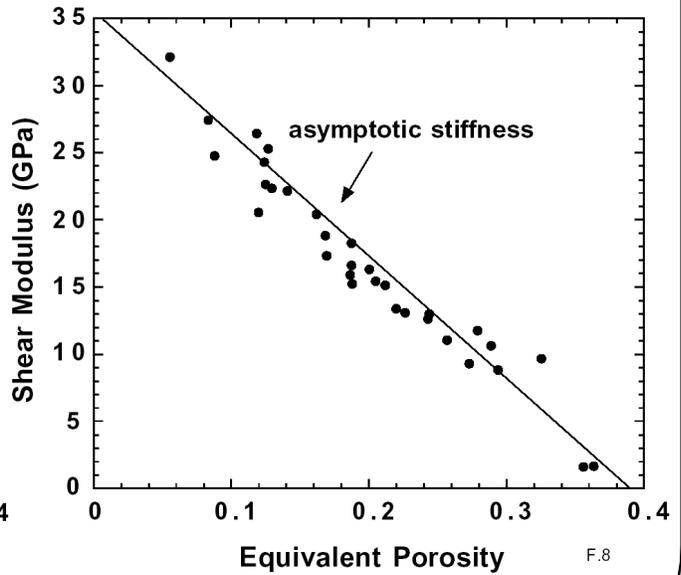
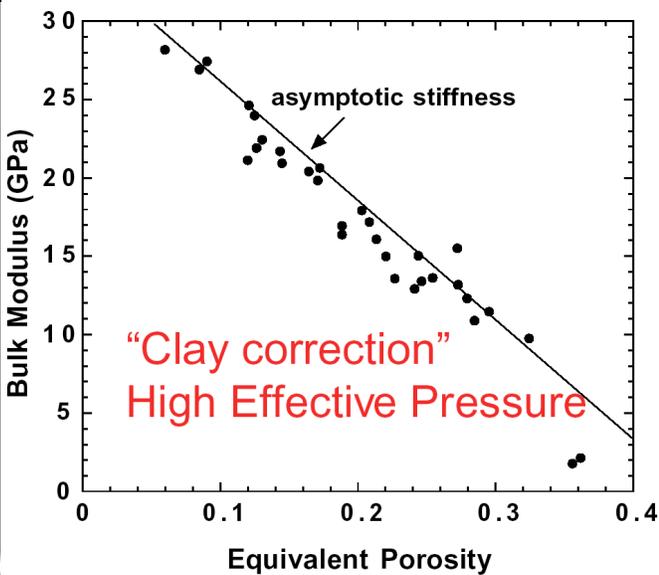


Ultrasonic velocities and porosity in Fontainebleau sandstone (Han, 1986). Note the large change in velocity with a very small fractional change in porosity. This is another indicator that pressure opens and closes very thin cracks and flaws.

## Parameters That Influence Seismic Velocity



Dry shaly sandstone data from Han (1986). Each vertical “streak” plotted with the same symbol is a single rock at different pressures. Note the large change in modulus with little change in porosity -- another illustration that cracks and flaws have a large change on velocity, even though they contribute very little to porosity.

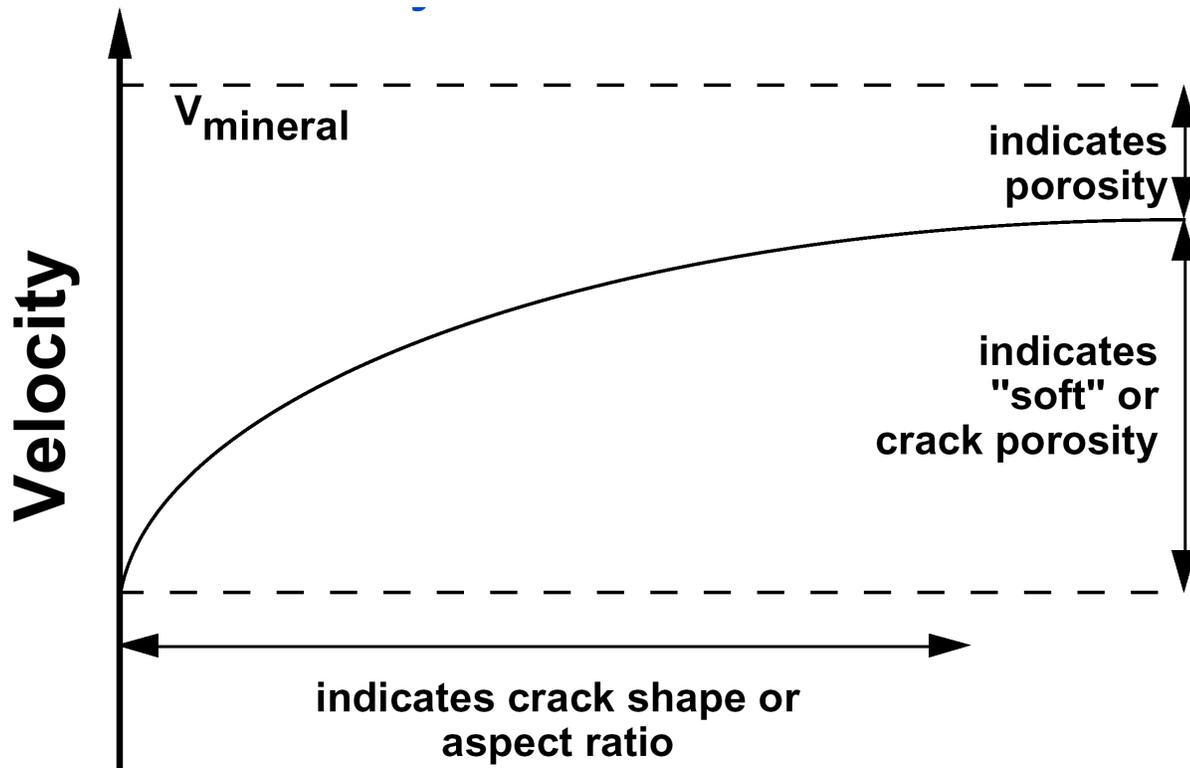


Only the values at high pressure and with Han's empirical clay correction applied.

F.8

## Parameters That Influence Seismic Velocity

### The Information in a Rock's Velocity-Pressure Curve



1. High pressure limiting velocity is a function of porosity
2. The amount of velocity change with pressure indicates the amount of soft, crack-like pore space
3. The range of the greatest pressure sensitivity indicates the shape or aspect ratios of the crack-like pore space

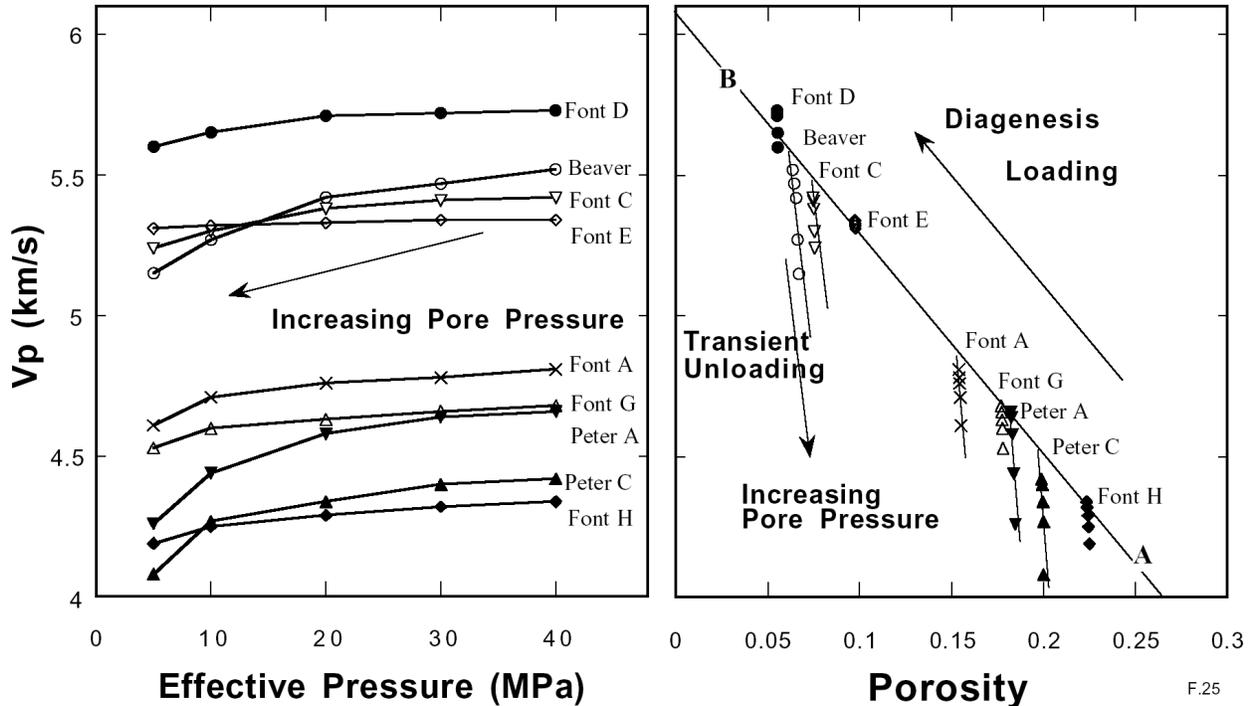
## Parameters That Influence Seismic Velocity

### Soft, Crack-Like Porosity

1. Includes micro and macrofractures and compliant grain boundaries.
2. Soft Porosity:
  - Decreases both P and S-wave velocities
  - Increases velocity dispersion and attenuation
  - Creates pressure dependence of V and Q
  - Creates stress-induced anisotropy of V and Q
  - Enhances sensitivity to fluid changes (sensitivity to hydrocarbon indicators)
3. High confining pressure (depth) and cementation, tend to decrease the soft porosity, and therefore decreases these effects.
4. High pore pressure tends to increase the soft porosity and therefore increases these effects.

## Parameters That Influence Seismic Velocity

# Seismic Velocity and Overpressure



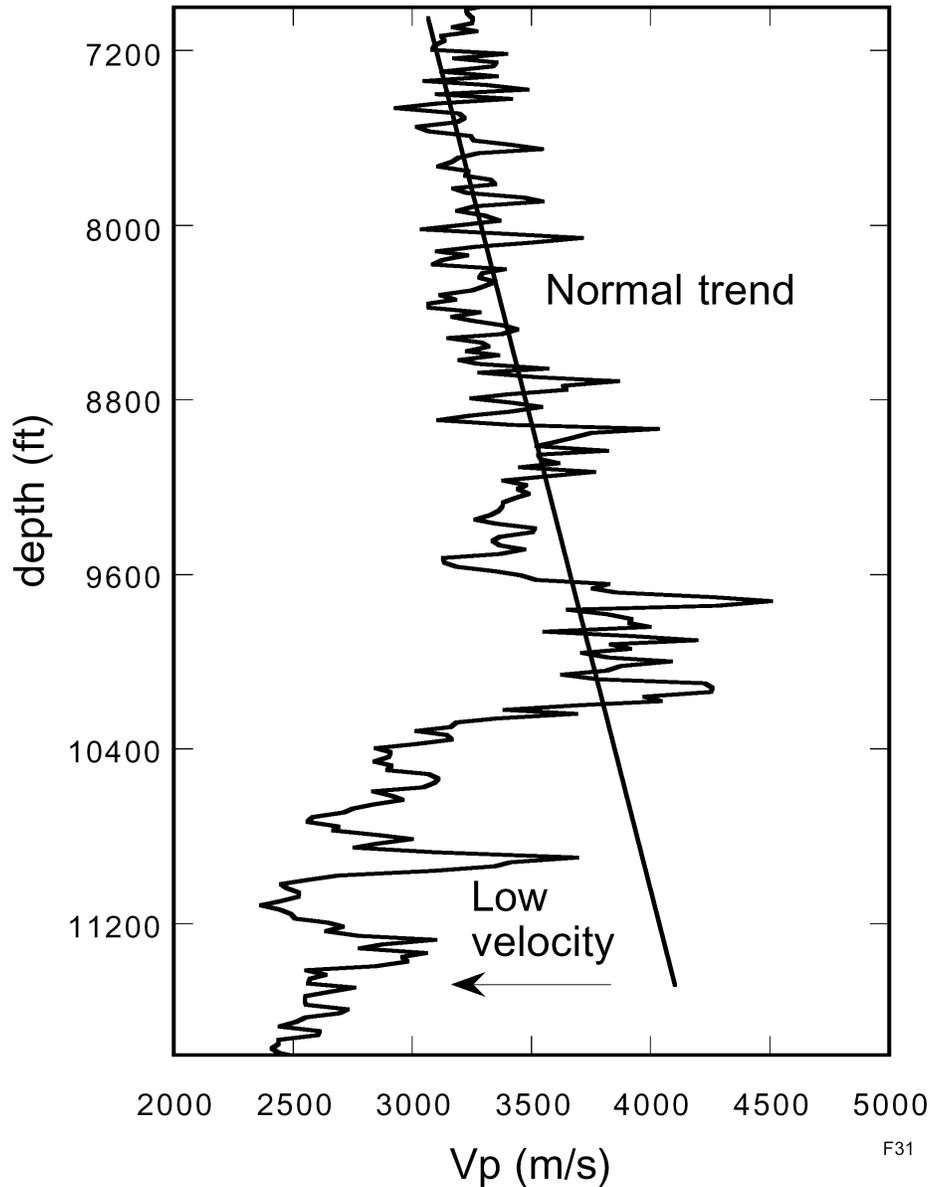
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Curves on the left show the typical increase of velocity with effective pressure. For each sample the velocity change is associated with the opening and closing of cracks and flaws. These are typical when rapid changes in effective pressure occur, such as during production.

Curves on the right show the same data projected on the velocity- porosity plane. Younger, high porosity sediments tend to fall on the lower right. Diagenesis and cementation tend to move samples to the upper left (lower porosity, higher velocity). One effect of over- pressure is to inhibit diagenesis, preserving porosity and slowing progress from lower right to upper left. This is called “loading” type overpressure. Rapid, late stage development of overpressure can open cracks and grain boundaries, resembling the curves on the left. This is sometimes called “transient” or “unloading” overpressure. In both cases, high pressure leads to lower velocities, but along different trends.

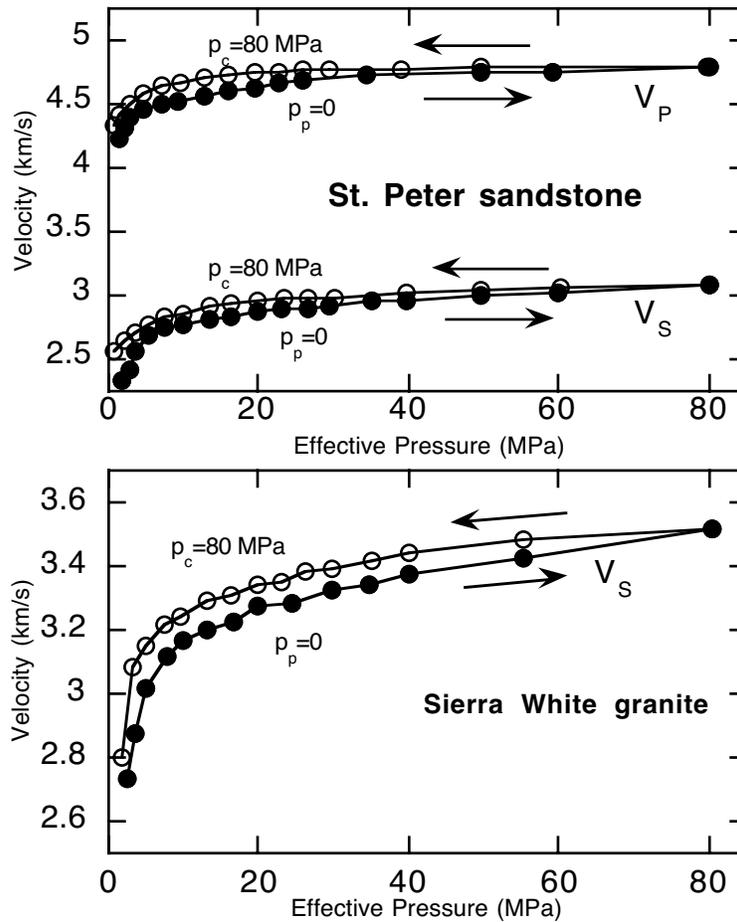
## Parameters That Influence Seismic Velocity

### Seismic Velocity and Overpressure



A typical approach to overpressure analysis is to look for low velocity deviations from normal depth trends. Caution: when overpressure is “late stage,” estimates of pressure can be too low.

## Parameters That Influence Seismic Velocity



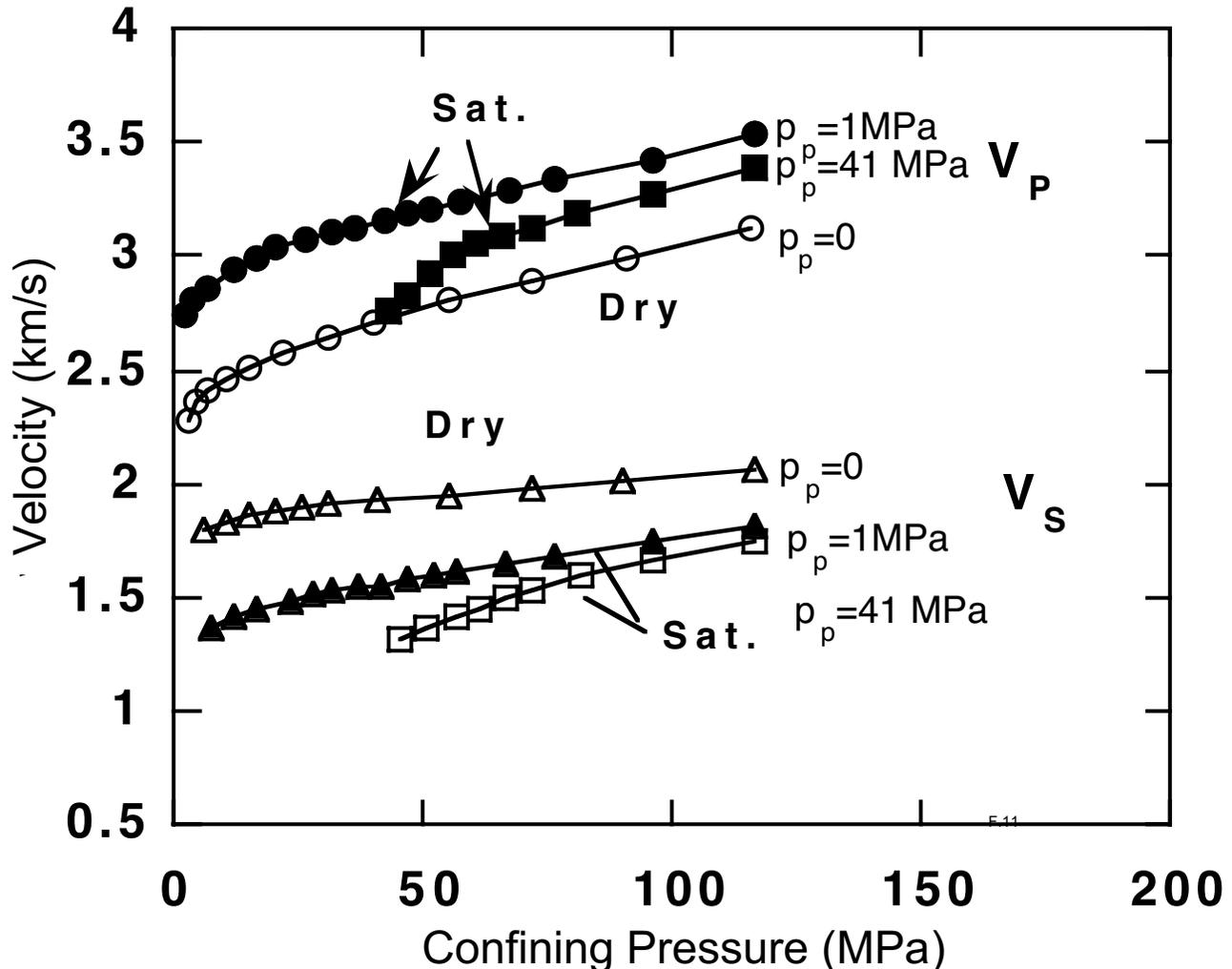
F.9

Experiments that illustrate the effective pressure law. In the first part of the experiment, effective pressure is increased by increasing confining pressure from 0 to 80 MPa, while keeping pore pressure zero (solid dots). Then, effective pressure is decreased by keeping confining pressure fixed at 80 MPa, but pumping up the pore pressure from 0 to nearly 80 MPa (open circles). (Jones, 1983.)

The curves trace approximately (but not exactly) the same trend. There is some hysteresis, probably associated with frictional adjustment of crack faces and grain boundaries. For most purposes, the hysteresis is small compared to more serious difficulties measuring velocities, so we assume that the effective pressure law can be applied. This is a tremendous convenience, since most laboratory measurements are made with pore pressure equal 0.

## Parameters That Influence Seismic Velocity

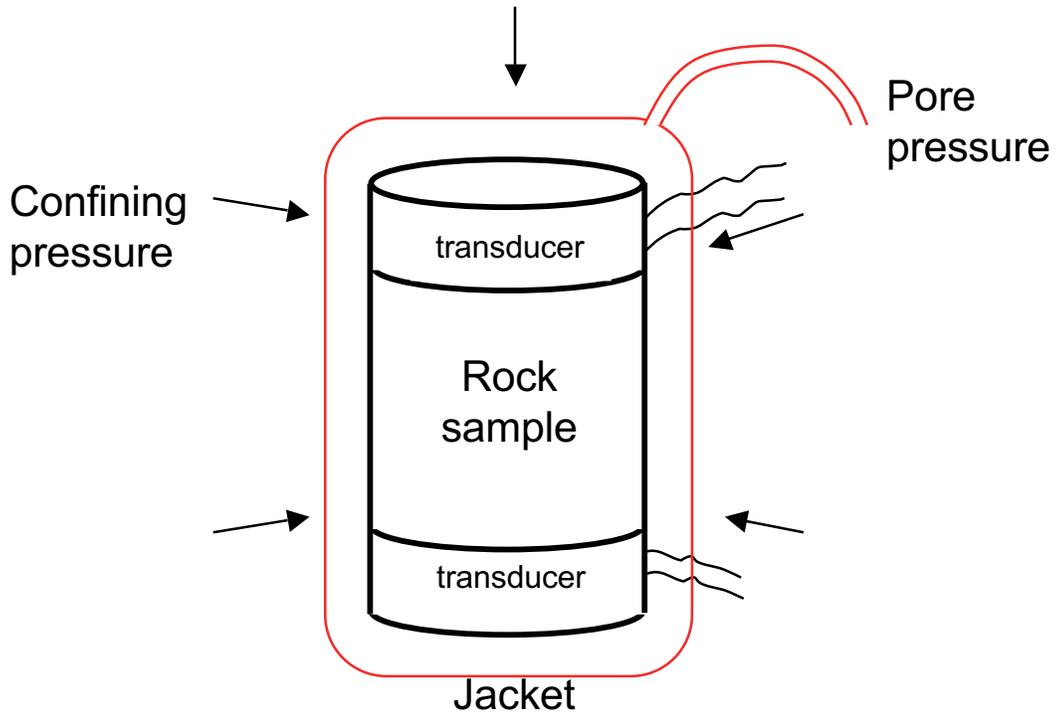
Pierre shale (ultrasonic), from Tosaya, 1982.



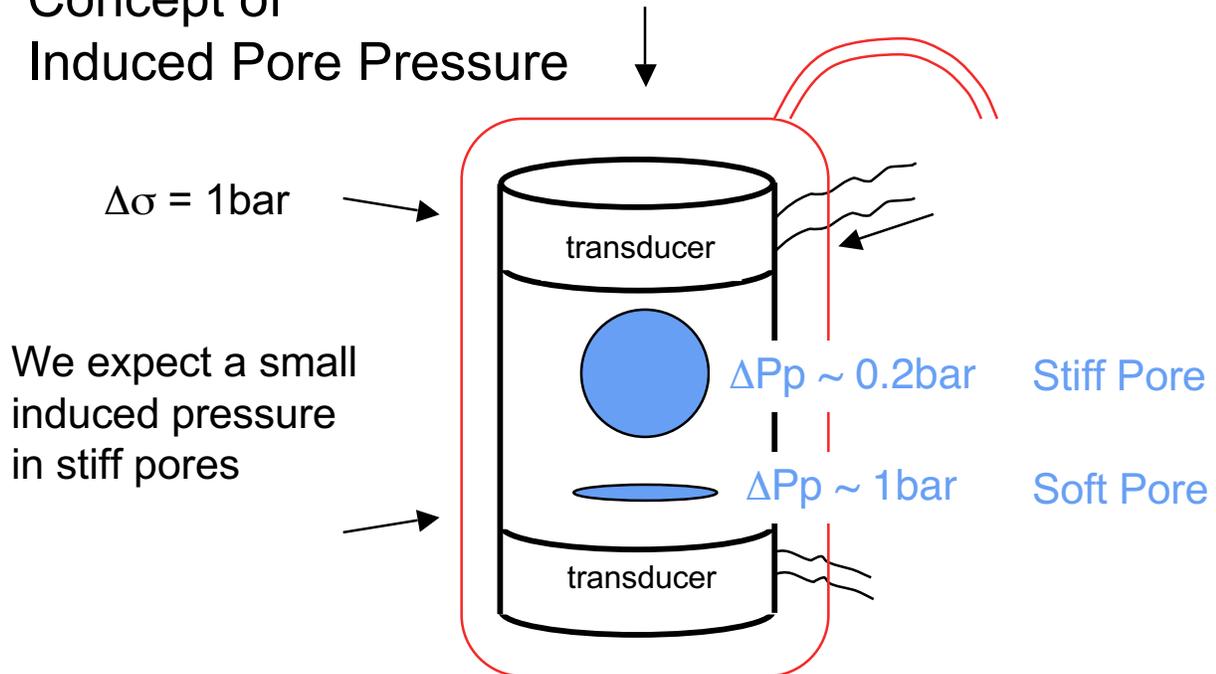
For shales, we also often see an increase of velocity with effective pressure. The rapid increase of velocity at low pressures is somewhat elastic, analogous to the closing of cracks and grain boundaries that we expect in sandstones.

The high pressure asymptotic behavior shows a continued increase in velocity rather than a flat limit. This is probably due to permanent plastic deformation of the shale.

# Parameters That Influence Seismic Velocity

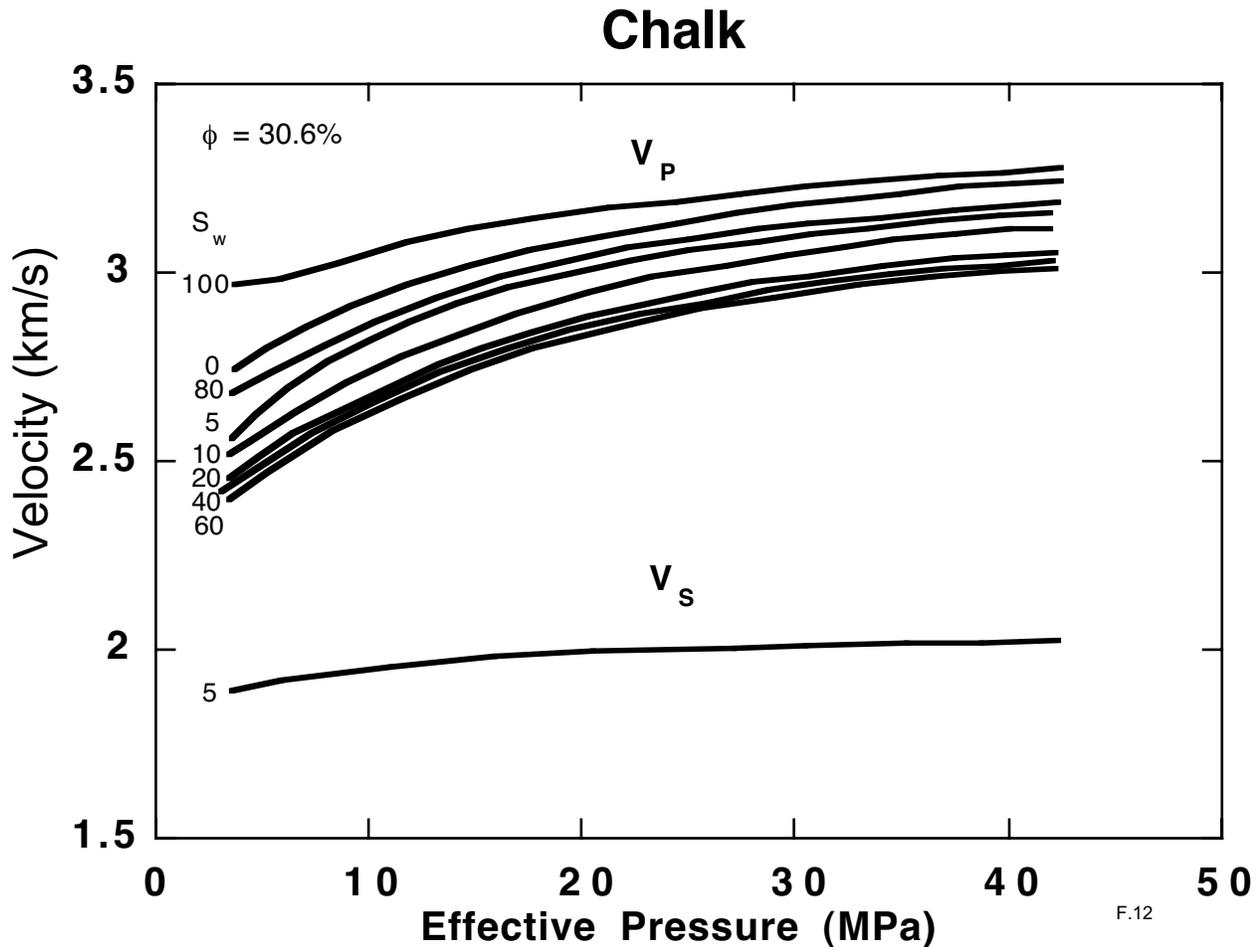


## Concept of Induced Pore Pressure



## Parameters That Influence Seismic Velocity

Chalk (ultrasonic), from Gregory, 1976, replotted from Bourbie, Coussy, and Zinszner, 1987, Gulf Publishing Co.

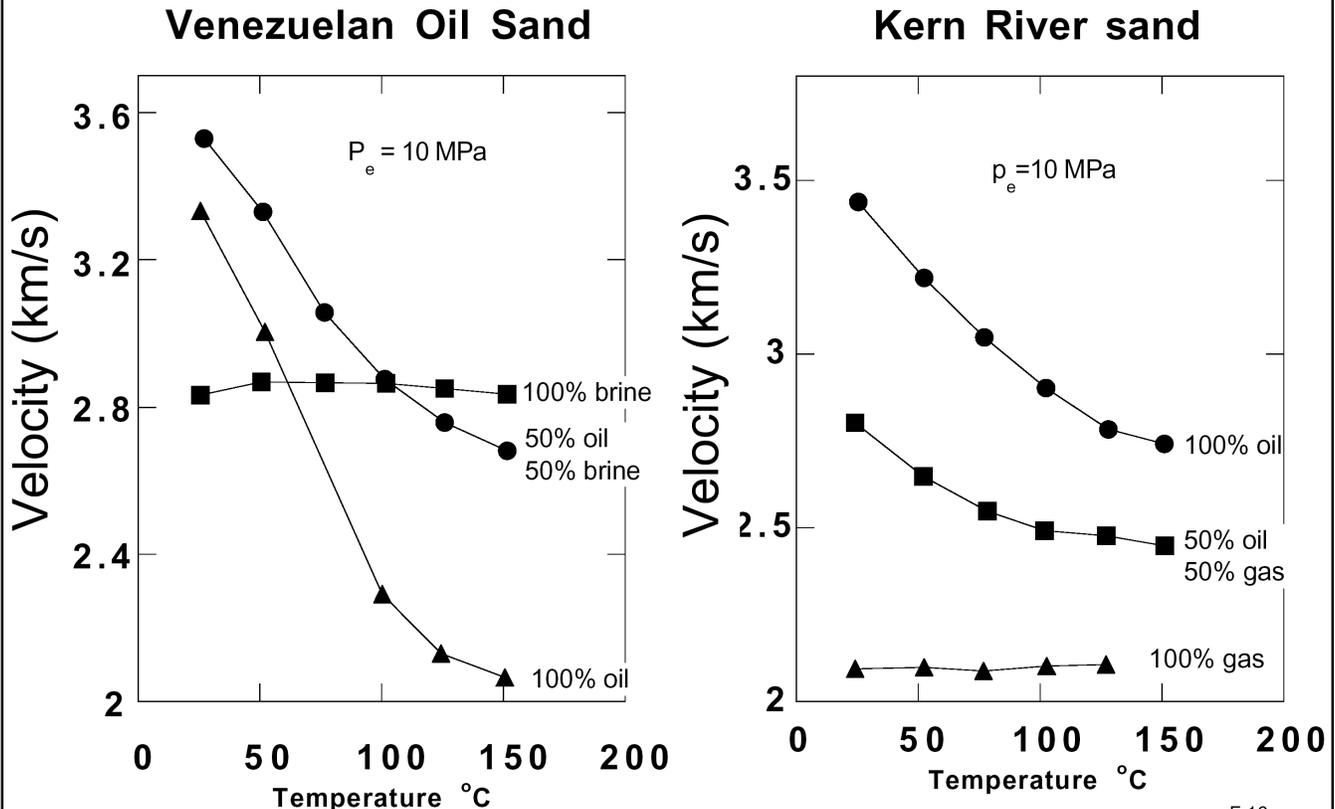


For chalks, we also see an increase of velocity with effective pressure. The rapid increase of velocity at low pressures is somewhat elastic and reversible.

The high pressure asymptotic behavior shows a continued increase in velocity rather than a flat limit. This is probably due to permanent crushing of the fragile pore space.

## Parameters That Influence Seismic Velocity

Influence of temperature on oil saturated samples, from Tosaya, et al. (1985).

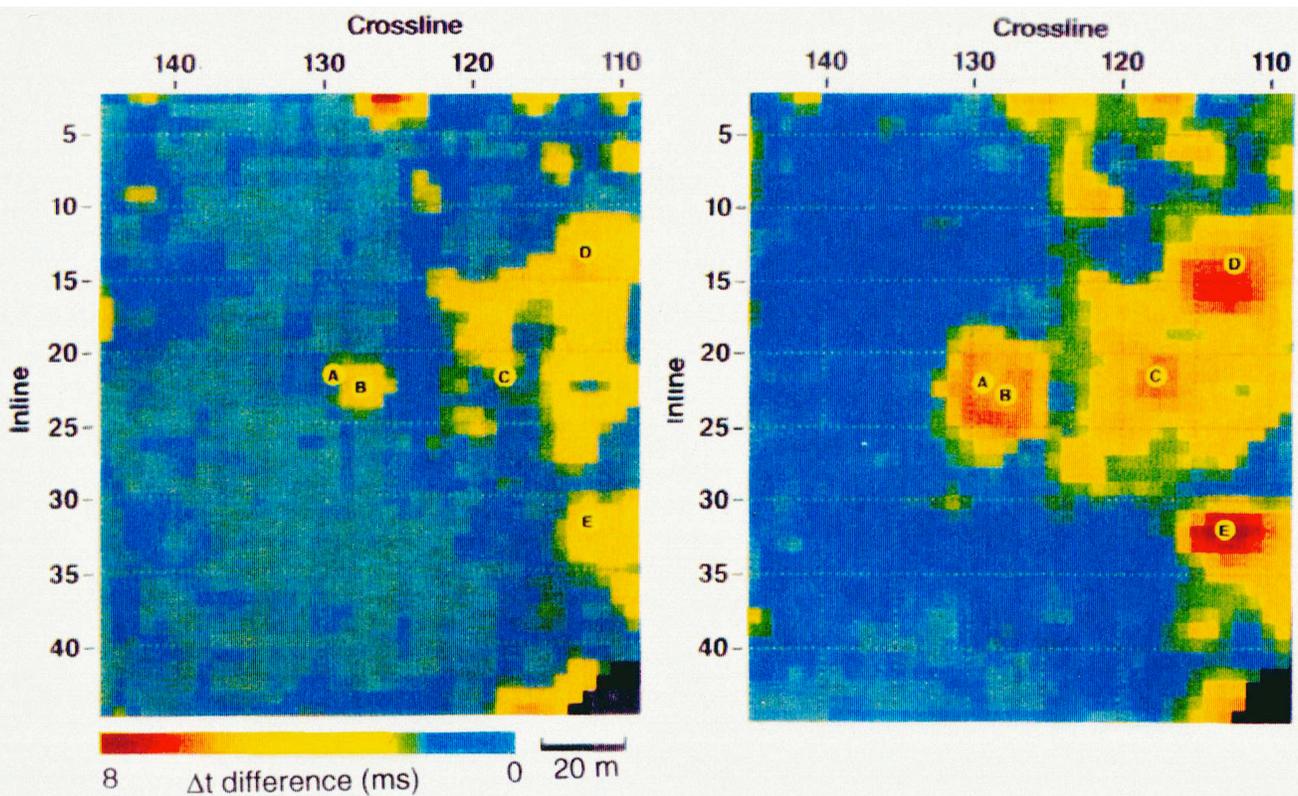


We observe experimentally that velocities are most sensitive to temperature when the rocks contain liquid hydrocarbons (oil). We believe that this results from an increase of the oil compressibility and a decrease of the oil viscosity as the temperature goes up.

In field situations other factors can occur. For example, gas might come out of solution as the temperature goes up.

## Parameters That Influence Seismic Velocity

### An Early, Successful 4D Field Study Thermal Signature of Steam Flood



F30

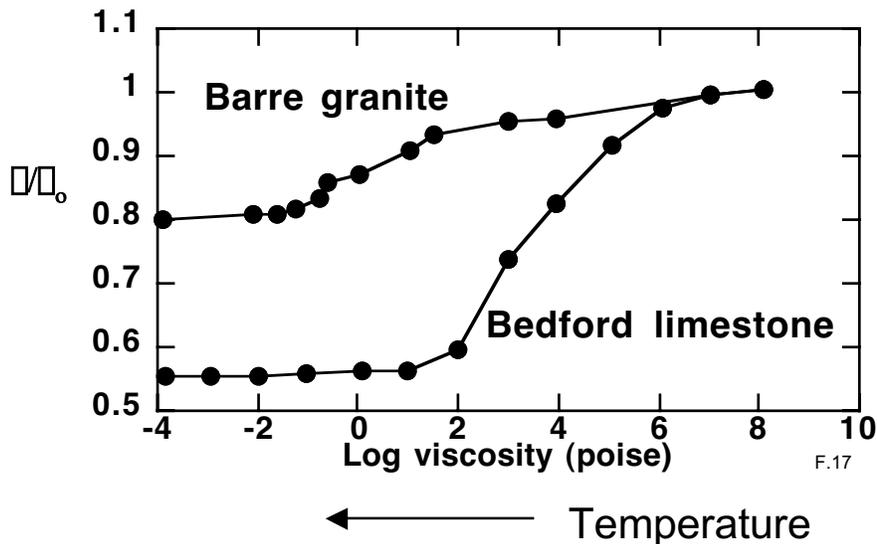
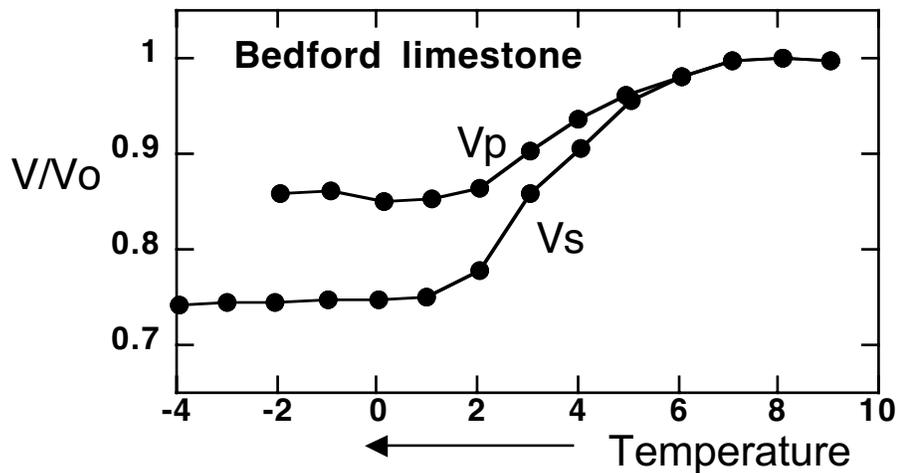
Traveltime increase in steamed interval after a few months of steam injection.

After a few more months, the anomaly spreads.

From DeBuyl, 1989

## Parameters That Influence Seismic Velocity

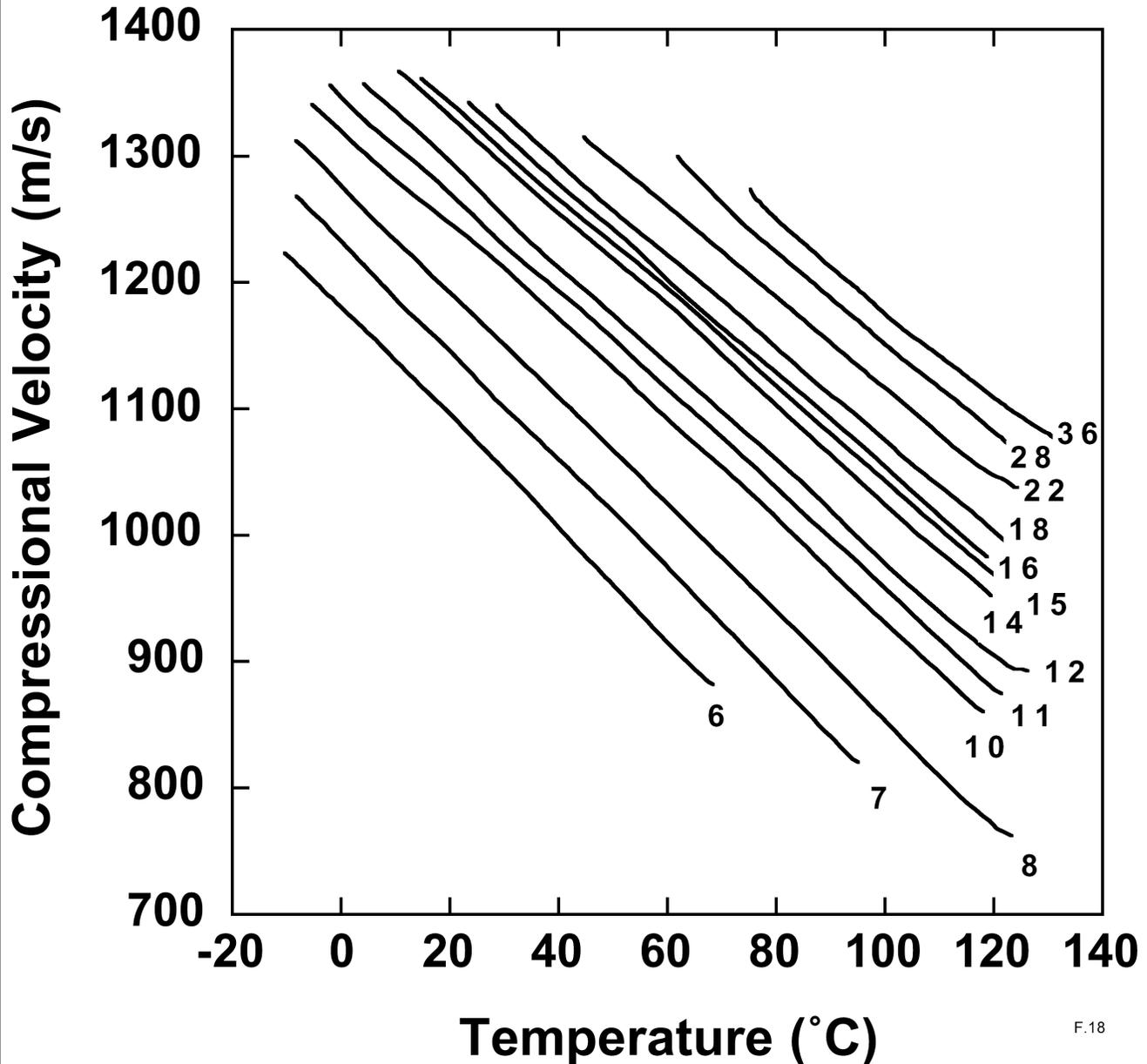
Velocity vs. viscosity in glycerol saturated samples, from Nur (1980).



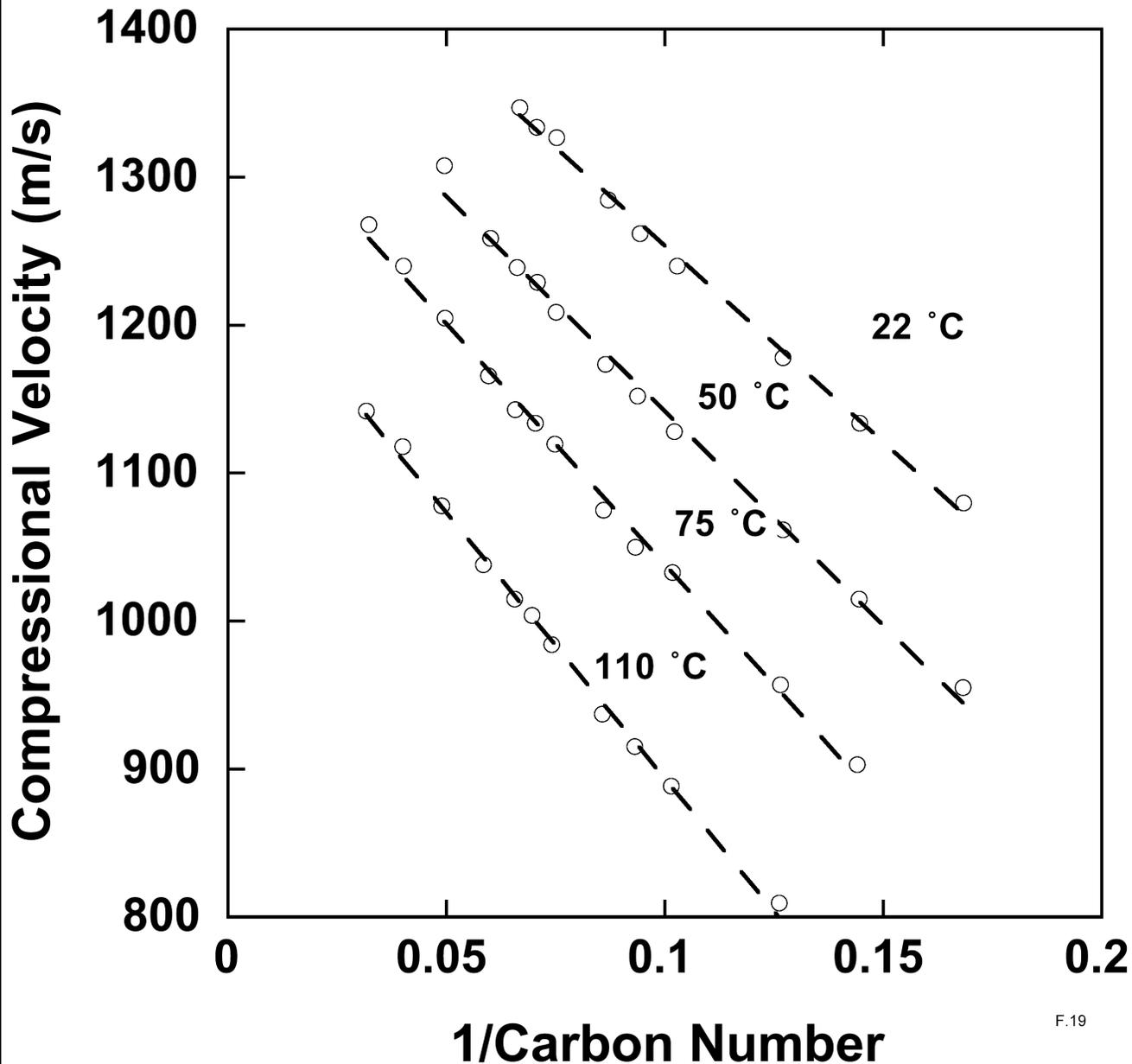
In this experiment the pore fluid is glycerol, whose viscosity is extremely sensitive to temperature. The data show a classical viscoelastic behavior with lower velocity at low viscosity and higher velocity at higher viscosity. Viscosity is one of several pore fluid properties that are sensitive to temperature.

## Parameters That Influence Seismic Velocity

### Alkanes



Compressional velocities in the n-Alkanes vs. temperature. A drastic decrease of velocity with temperature! The numbers in the figure represent carbon numbers. From Wang, 1988, Ph.D. dissertation, Stanford University.

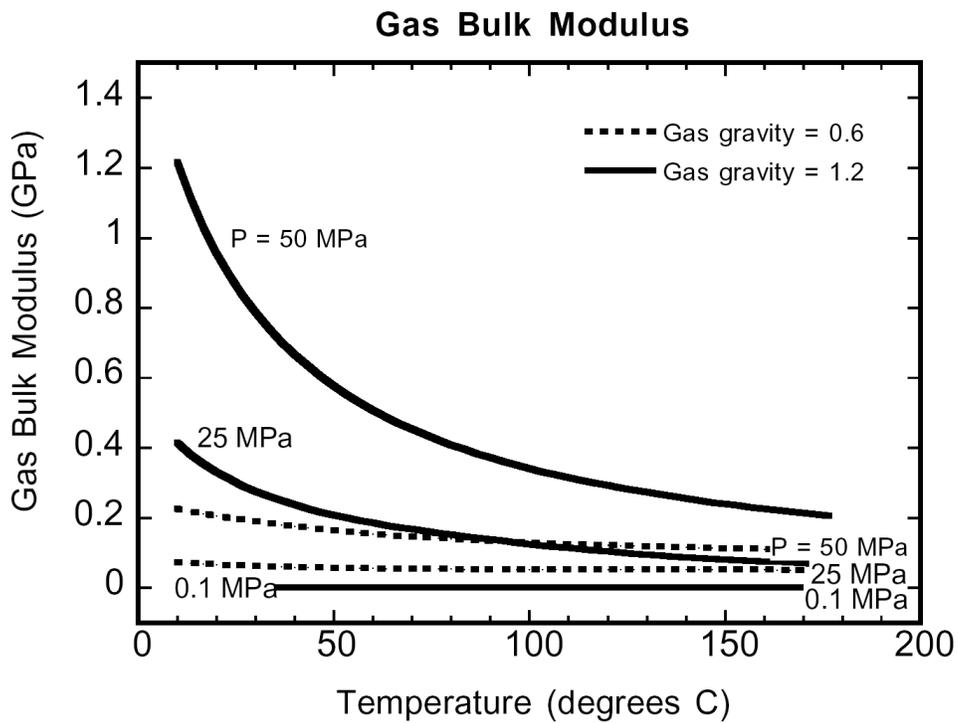
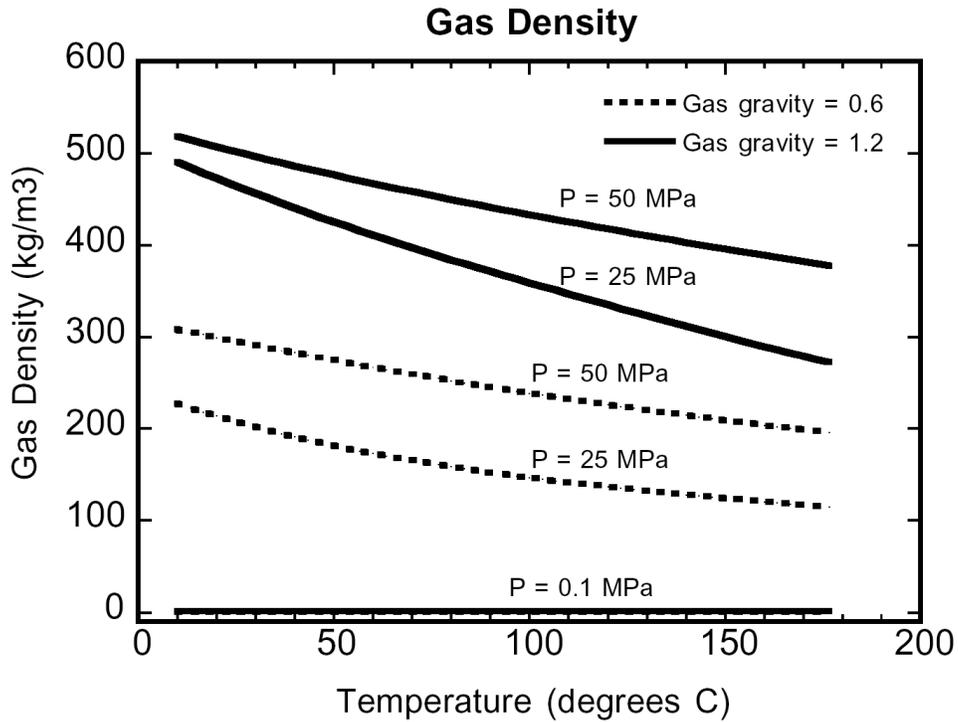
**Parameters That Influence Seismic Velocity****Alkanes**

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Compressional velocities in the n-Alkanes vs. inverse of the carbon numbers, at different temperatures. From Wang, 1988 Ph.D. dissertation, Stanford University.

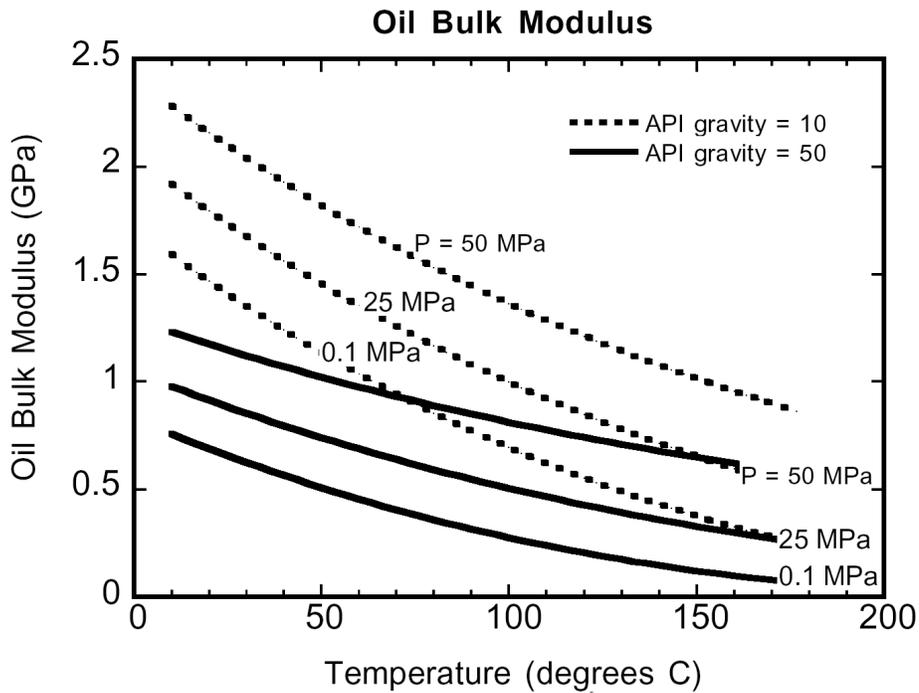
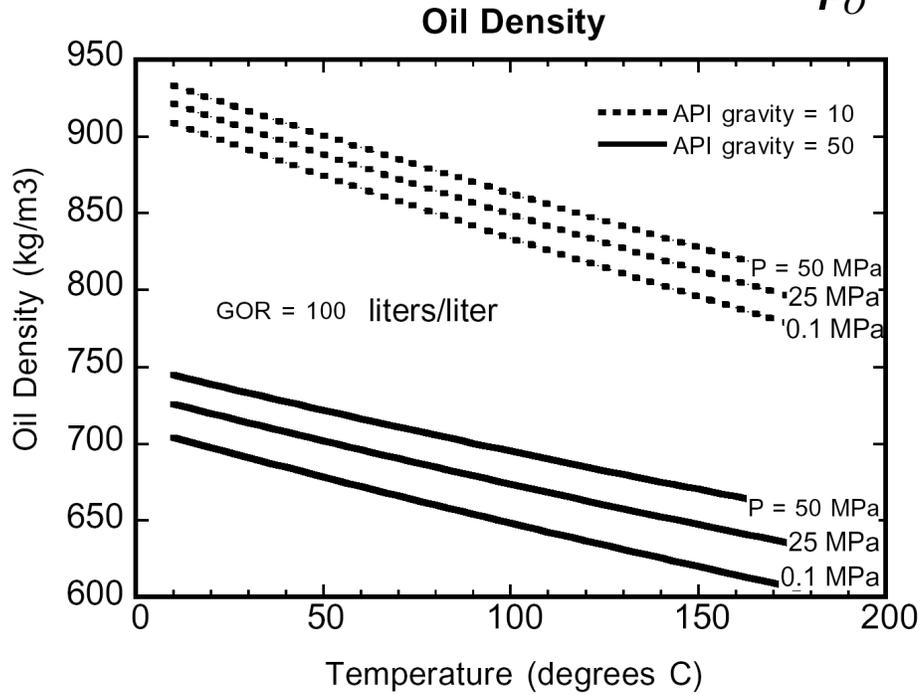
## Parameters That Influence Seismic Velocity

Batzle-Wang formulas for fluid density and bulk modulus (Geophysics, Nov. 1992).



## Parameters That Influence Seismic Velocity

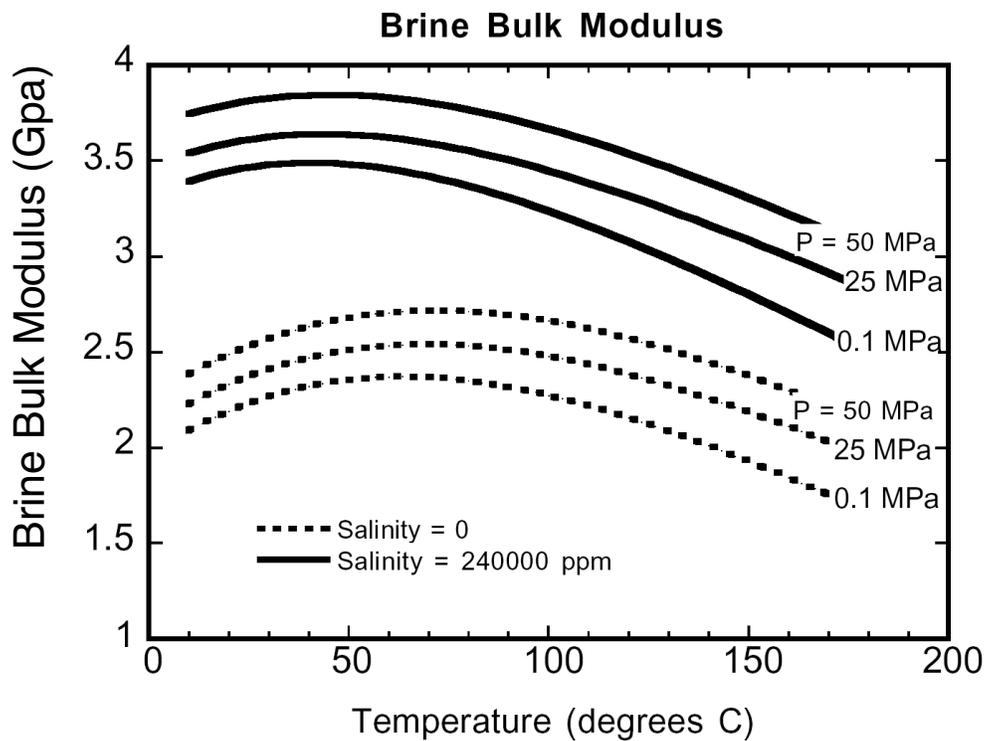
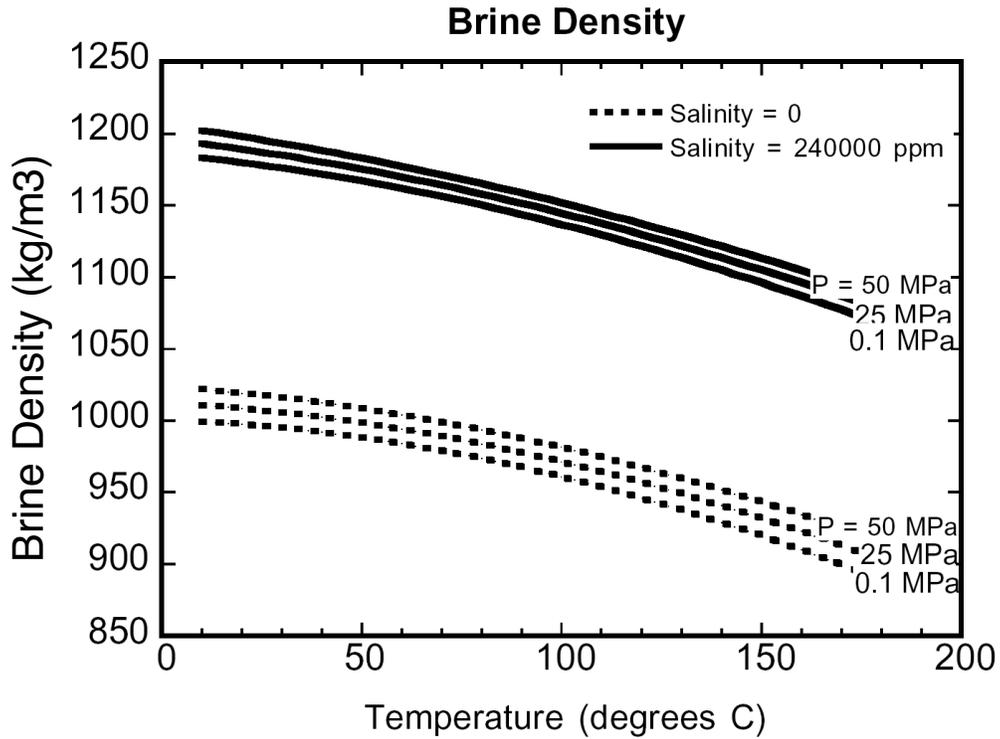
$$API = \frac{141.5}{\rho_o} - 131.5$$



$$1 \text{ l/l} = 5.615 \text{ ft}^3/\text{bbl}$$

F30

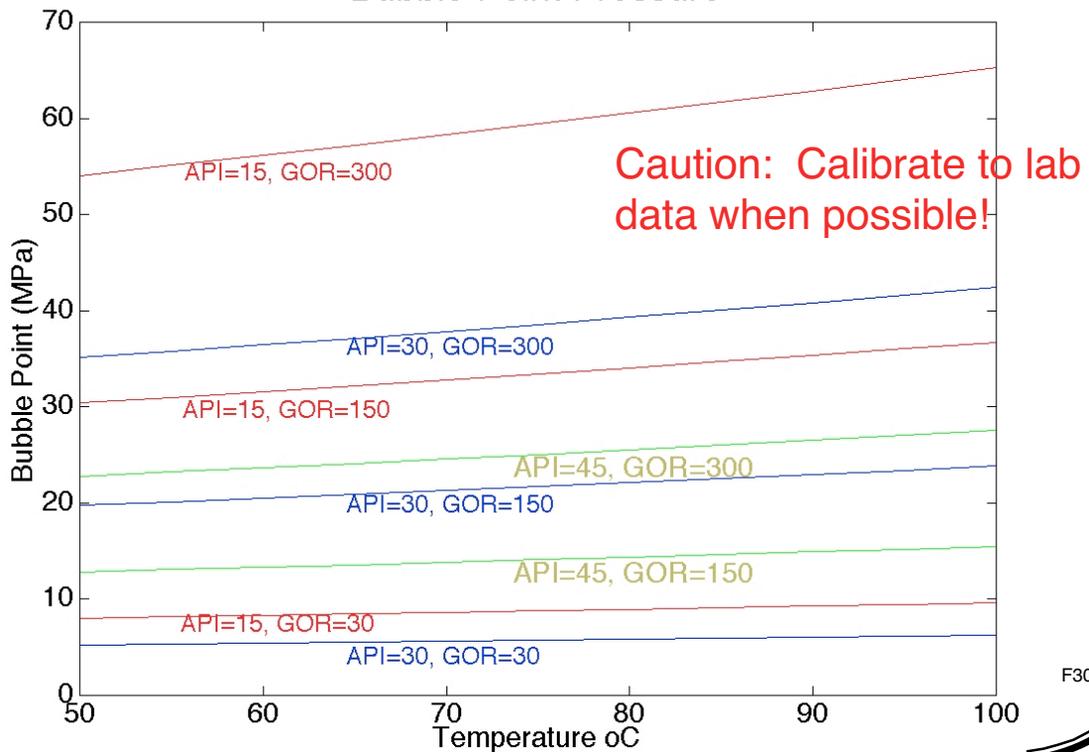
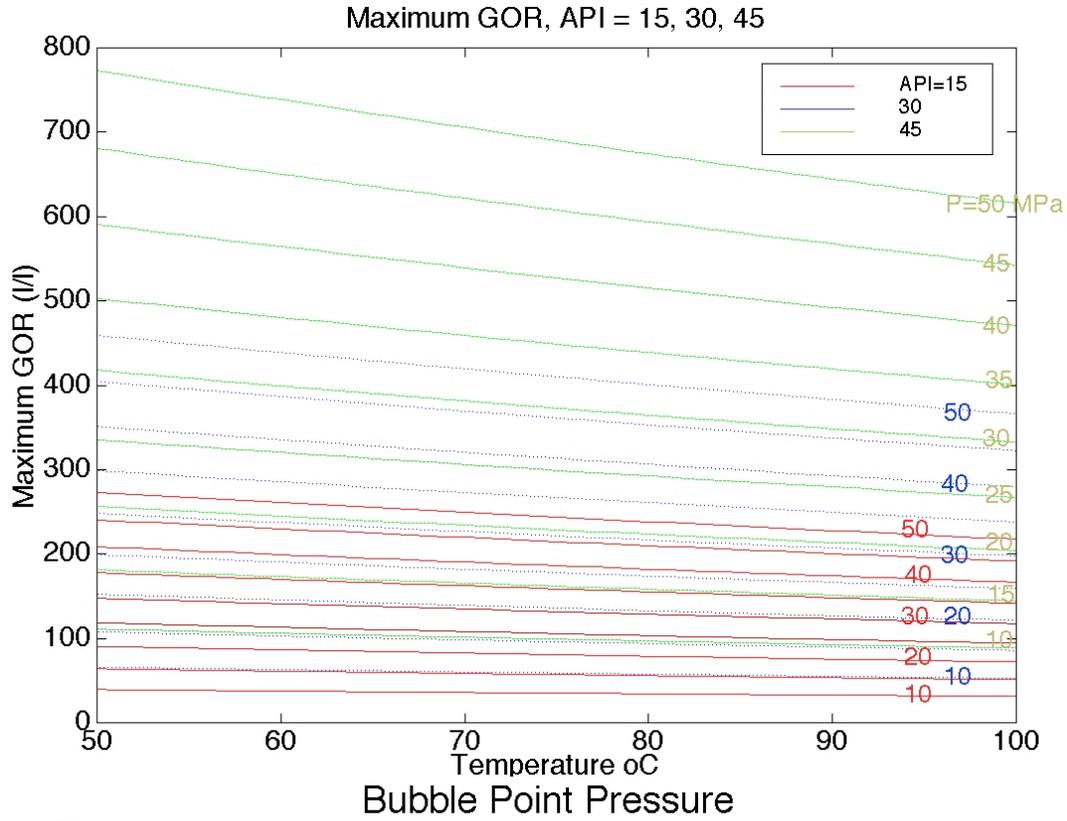
## Parameters That Influence Seismic Velocity



F30

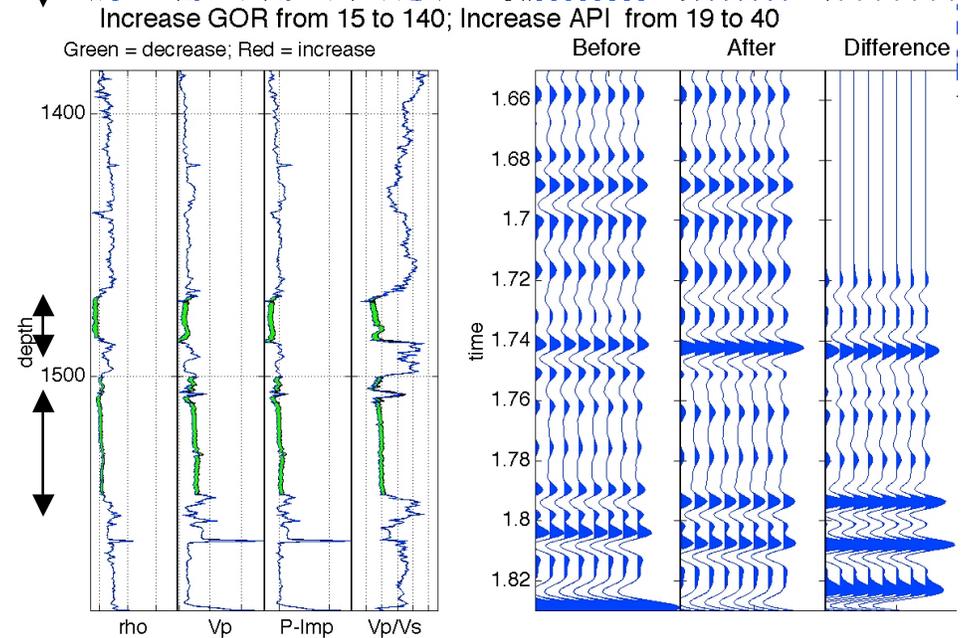
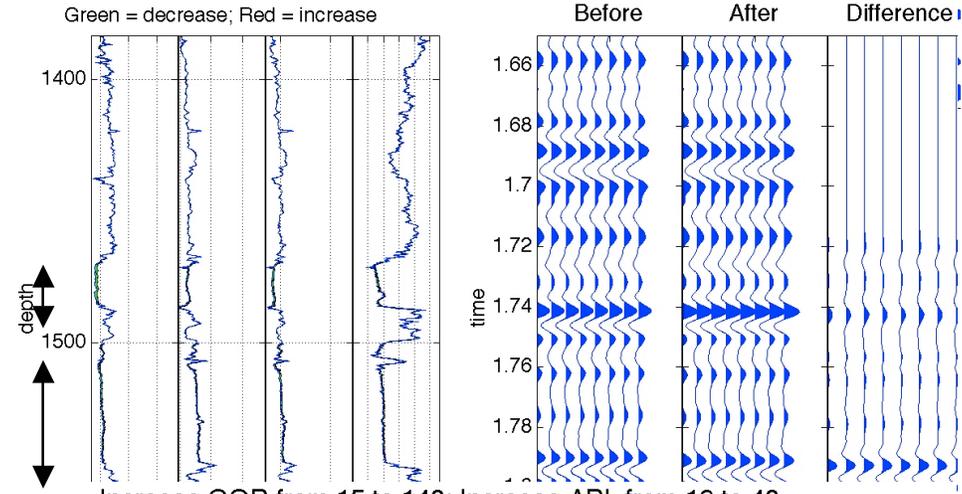
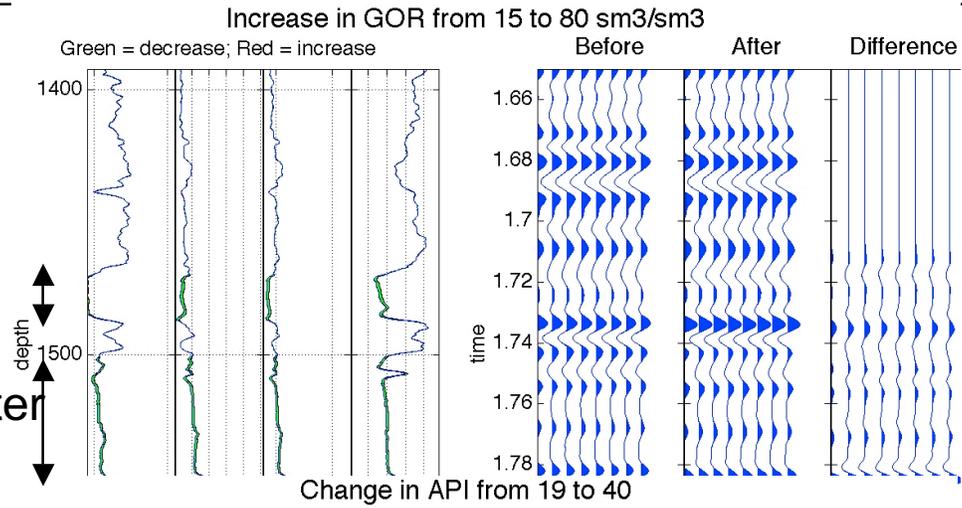
## Parameters That Influence Seismic Velocity

BubblePoint computed using Batzle, Wang Relations



# Parameters That Influence Seismic Velocity

Soft  
Deepwater  
Sands



## Parameters That Influence Seismic Velocity

### Fluid Properties

- The density and bulk modulus of most reservoir fluids increase as pore pressure increases.
- The density and bulk modulus of most reservoir fluids decrease as temperature increases.
- The Batzle-Wang formulas describe the empirical dependence of gas, oil, and brine properties on temperature, pressure, and composition.
- The Batzle-Wang bulk moduli are the adiabatic moduli, which we believe are appropriate for wave propagation.
- In contrast, standard PVT data are isothermal. Isothermal moduli can be ~20% too low for oil, and a factor of 2 too low for gas. For brine, the two don't differ much.

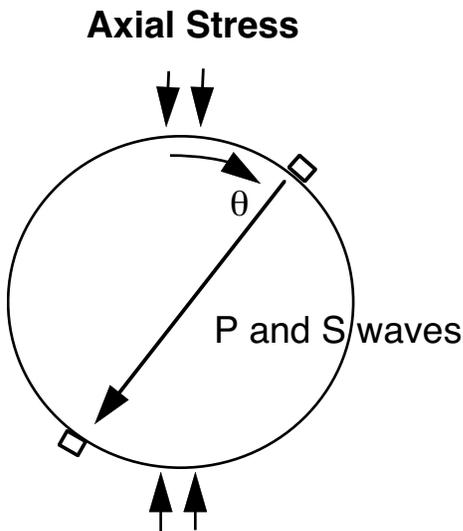
$$K_S^{-1} = K_T^{-1} - \frac{\alpha^2 T}{\rho C_p}$$

$\alpha$  = thermal expansion;  $C_p$  = heat capacity

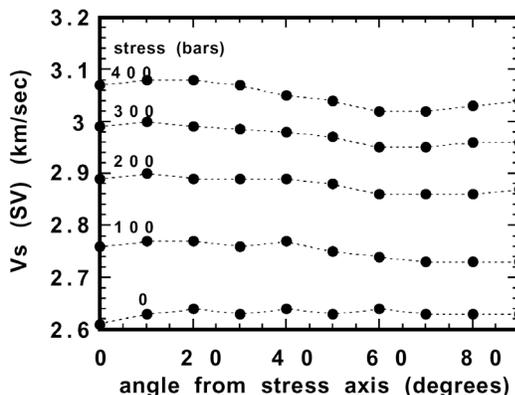
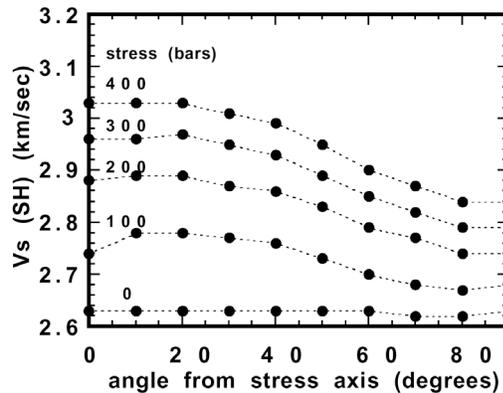
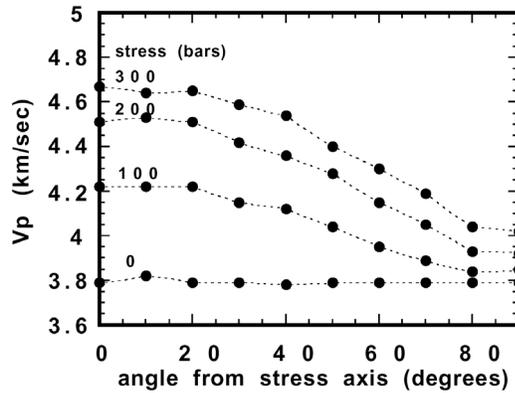
Nice paper by Virginia Clark, July '92 Geophysics.

## Parameters That Influence Seismic Velocity

### Stress-Induced Velocity Anisotropy -- the Historical Basis for Seismic Fracture Detection



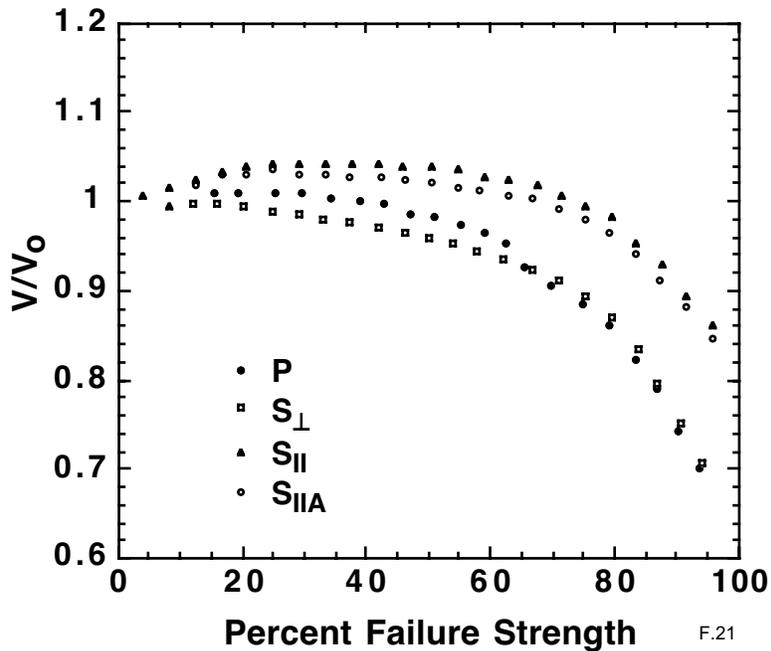
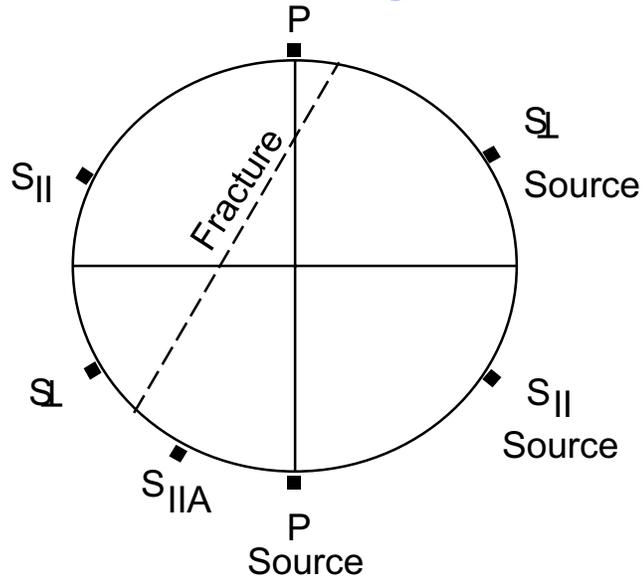
Measurement angle related to the uniaxial stress direction



Stress-induced velocity anisotropy in Barre Granite (Nur, 1969). In this classic experiment, Nur manipulated the crack alignment by applying uniaxial stress. Initially the rock is isotropic, indicating an isotropic distribution of cracks. Cracks normal to the stress (or nearly so) closed, creating crack alignment and the associated anisotropy.

**Parameters That Influence Seismic Velocity**

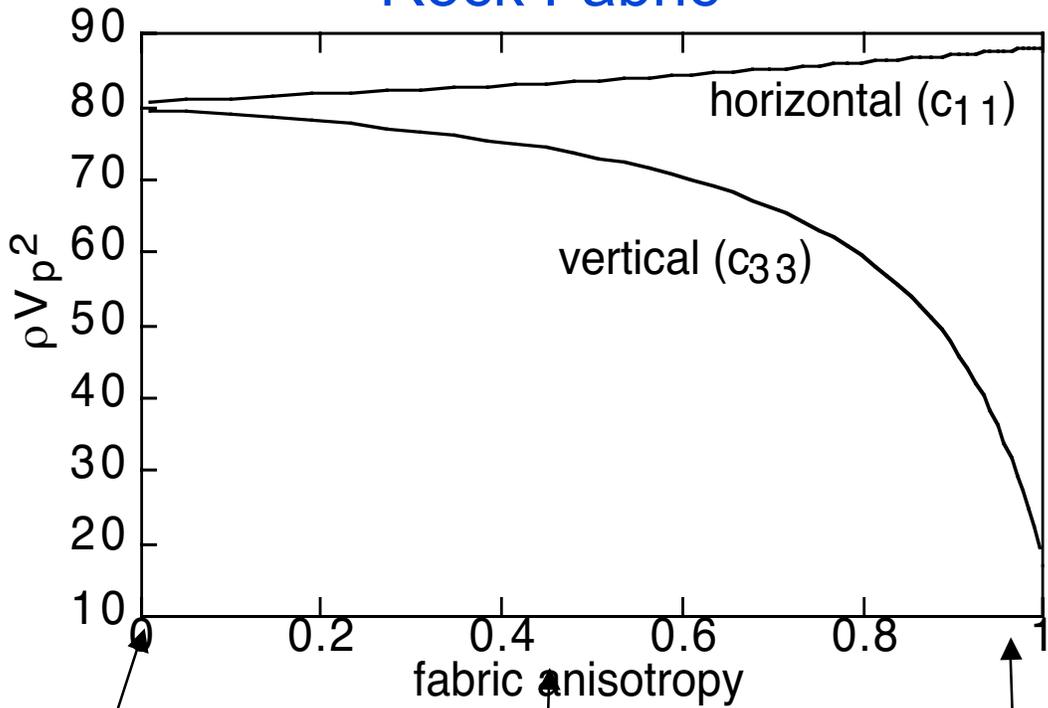
**Stress-Induced Velocity Anisotropy Due to Crack Opening Near Failure**



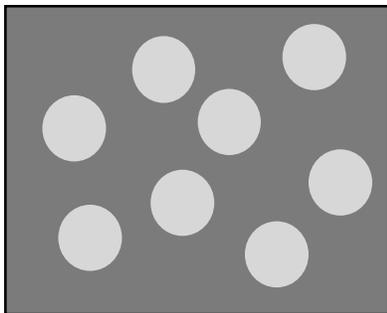
Uniaxial stress-induced velocity anisotropy in Westerly Granite (Lockner, et al. 1977).

**Parameters That Influence Seismic Velocity**

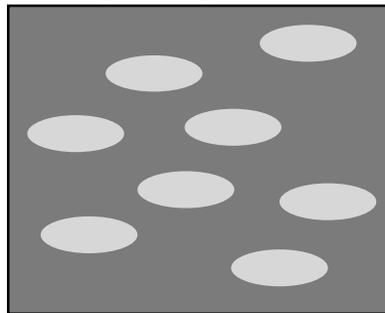
**Seismic Anisotropy Due to Rock Fabric**



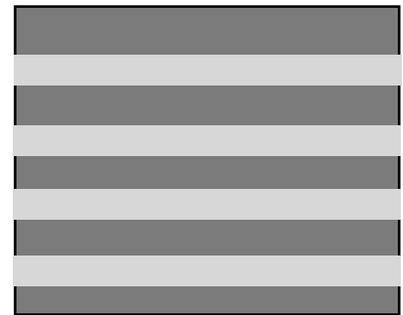
Isotropic mixture



slight alignment



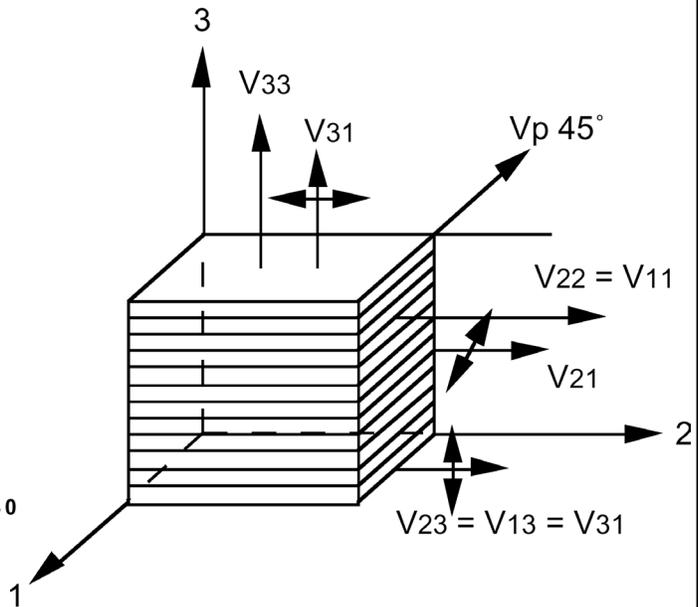
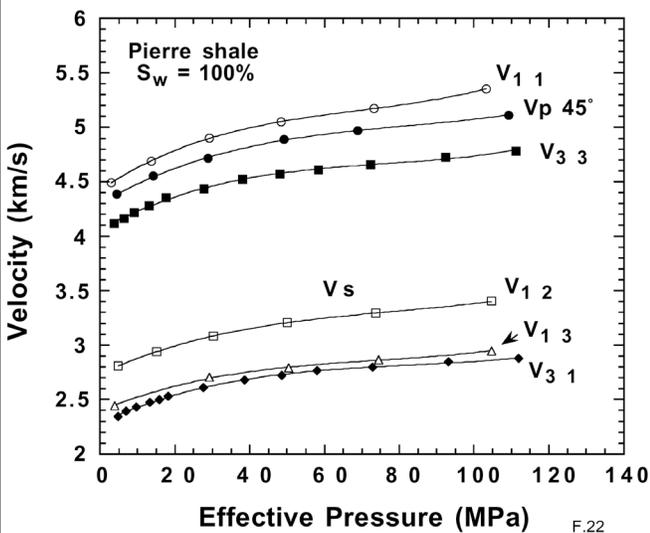
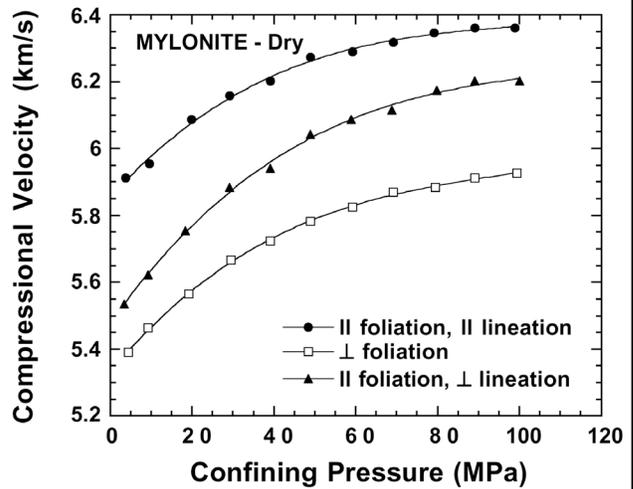
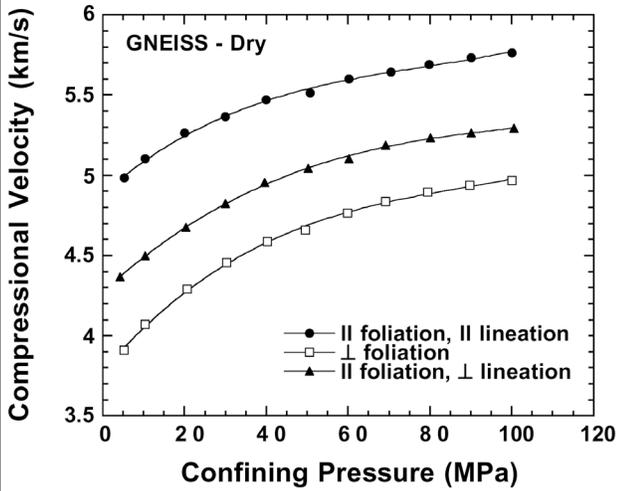
layered



Virtually any rock that has a visual layering or fabric at a scale finer than the seismic wavelength will be elastically and seismically anisotropic. Sources can include elongated and aligned grains and pores, cracks, and fine scale layering. Velocities are usually faster for propagation along the layering.

# Parameters That Influence Seismic Velocity

## Velocity Anisotropy Due to Fabric

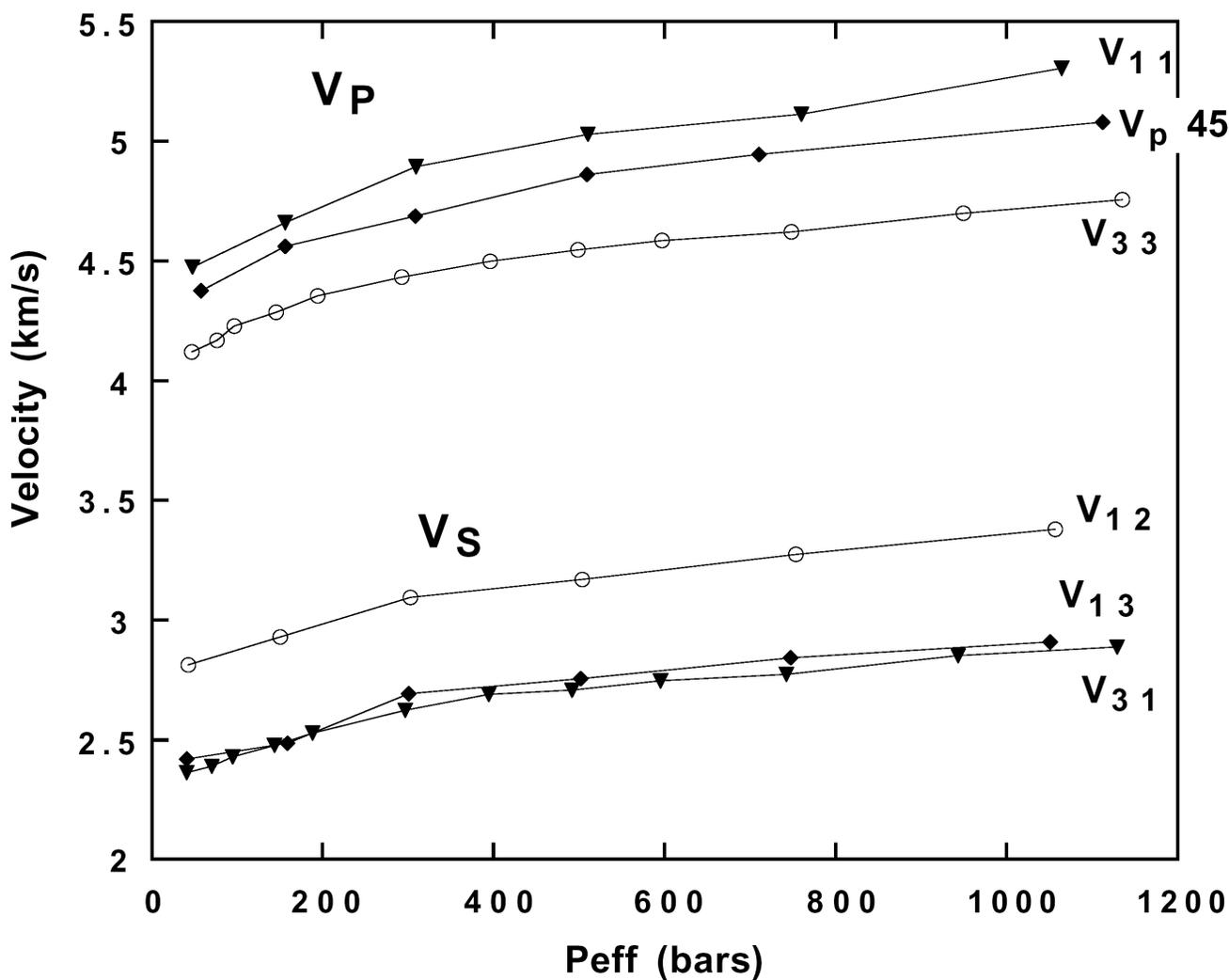


Anisotropic velocities vs. pressure. (a) and (b) Jones (1983), (c) Tosaya (1982).

**Parameters That Influence Seismic Velocity**

**Velocity Anisotropy in Shale**

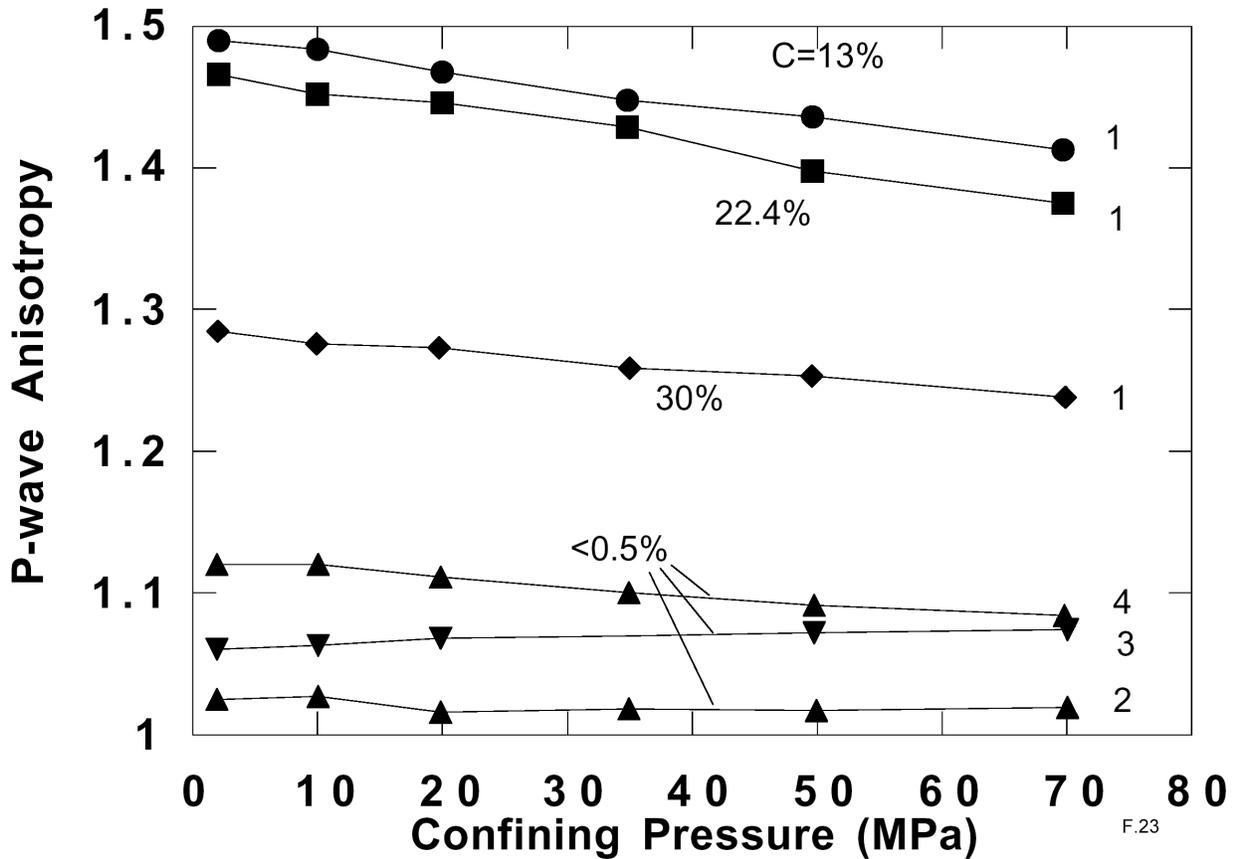
**Cotton Valley Shale - Water Saturated**



Cotton Valley shale (ultrasonic), from Tosaya, 1982.

**Parameters That Influence Seismic Velocity**

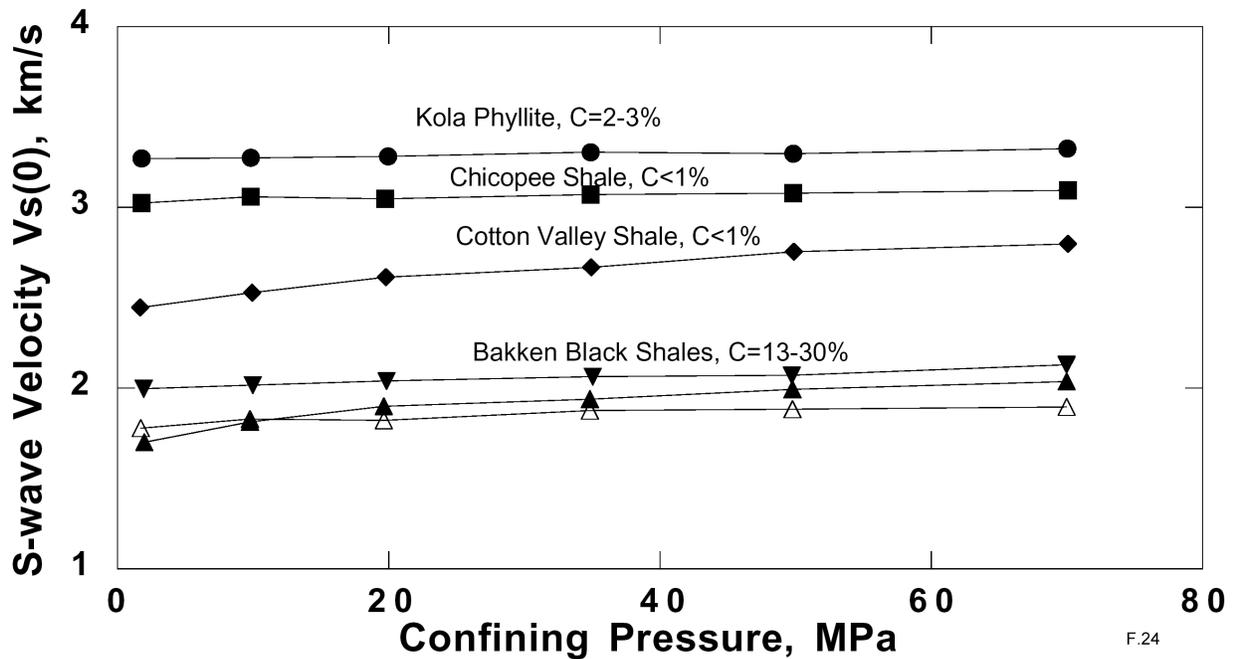
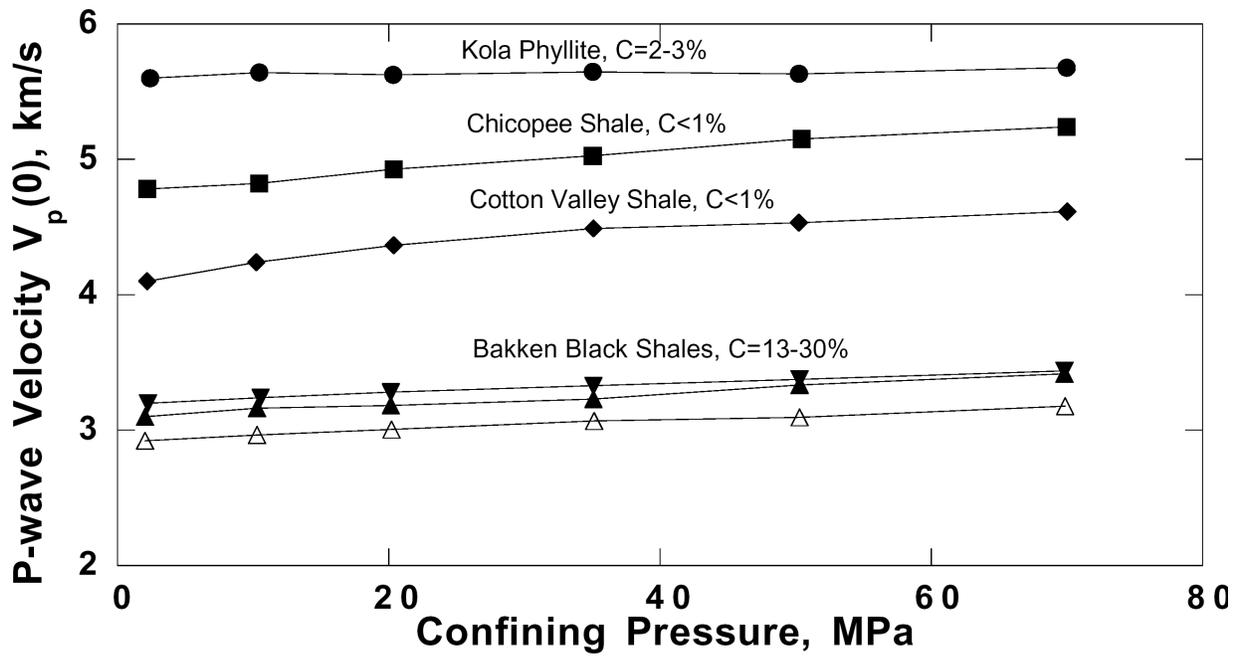
**Velocity Anisotropy Resulting From Thinly Layered Kerogen**



P-wave anisotropy in shales (from Vernik, 1990):  
 (1) Bakken black shales, (2) Bakken dolomitic siltstone,  
 (3) Bakken shaly dolomite, (4) Chicopee shale (Lo, et al,  
 1985).

Vernik found that kerogen-bearing shales can have very large anisotropy, easily 50%.

### Parameters That Influence Seismic Velocity



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Velocities in kerogen-rich Bakken shales (Vernik, 1990) and other low porosity argillaceous rocks (Lo et al., 1985; Tosaya, 1982; Vernik et al., 1987). Compiled by Vernik, 1990.