Rock physics

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2 . Seismic properties

“Slide from Gary Mavko, and Zappone”

Contents :

1. **Introduction**

Why do we measure seismic properties of rocks in the lab?

- To give a geological interpretation of geophysical sections (e.g. seismic profiling).

- As an example, in seismic profiling, reflections are caused by contrasts in acoustic impedance (Z = V*den). In laboratory it is possible to measure seismic velocities, density and also test separately how intrinsic (fabric, texture) and extrinsic parameters (P, T, pore P) affect seismic properties, under controlled conditions (i.e. varying one parameter and keeping the other constants).

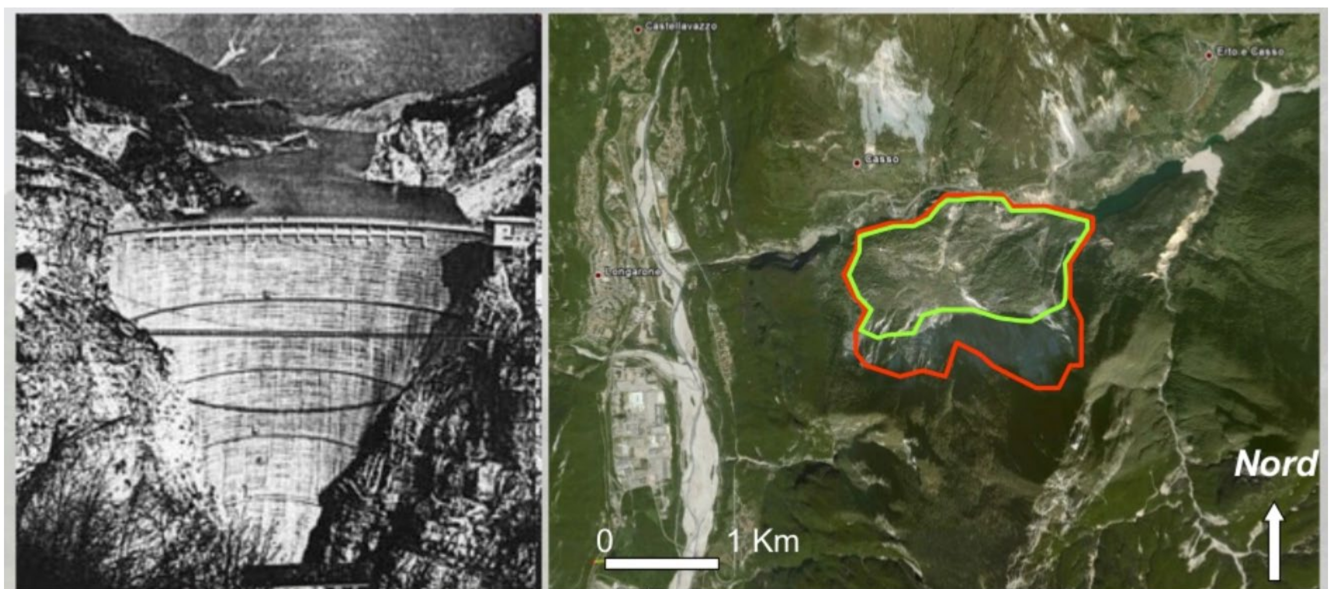
- The goal is to obtain semi-empirical laws to predict seismic properties or to extrapolate them to geological conditions.

1. **Introduction**

- **Example: Vajont dam and Monte Toc landslide**

Landslide- 9 octobre 1963

2000 dead peoples



Lorenzo Petronio et al., 2013

1. **Introduction**

➢ **Example: Vajont dam and Monte Toc landslide**

- Vajont river in the dolomites near Venice.
- Water reservoir ➔ supplying the power plant of Soverzene located at about 10 km south of Longarone.
- Operation by SADE, 1957
- Dam of 262 meters high.
- 400,000 m3 of rock were dug to anchor the dam
- 360,000 m3 of concrete were necessary for its construction.
- 168 715 000 m3 of water

1. **Introduction**

History

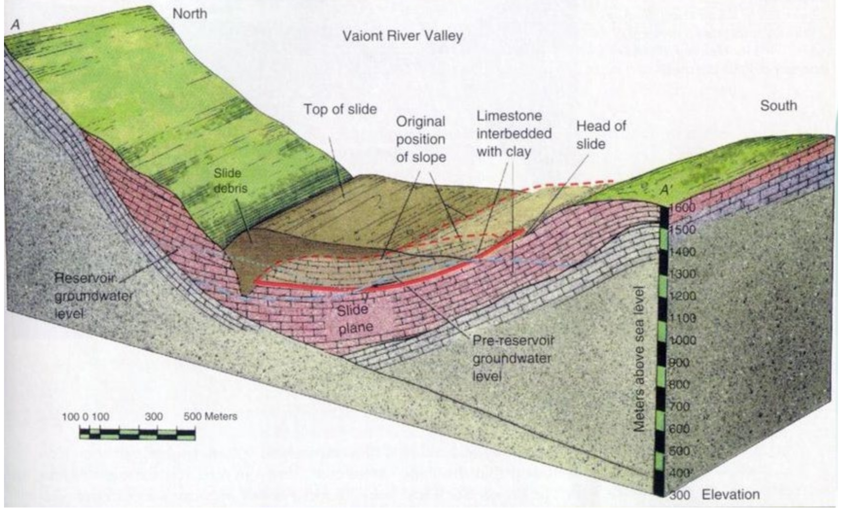
- **Example: Vajont dam and Monte Toc landslide**

- February - November 1960: the water level in the reservoir rose from 580 m to 650 m
- September - November 1960: displacement of about 3.5 cm per day ➔ lowered the reservoir to 600 m.
- 4-11-1960: rockslide ➔700 000 m3 slid into the lake in about ten minutes
- In 1962 the reservoir rose to 700 m.
- In 1963, it oscillated slowly between 700 and 650 and returned to 713, never reaching the crest of the dam (at 722.5).

Geology

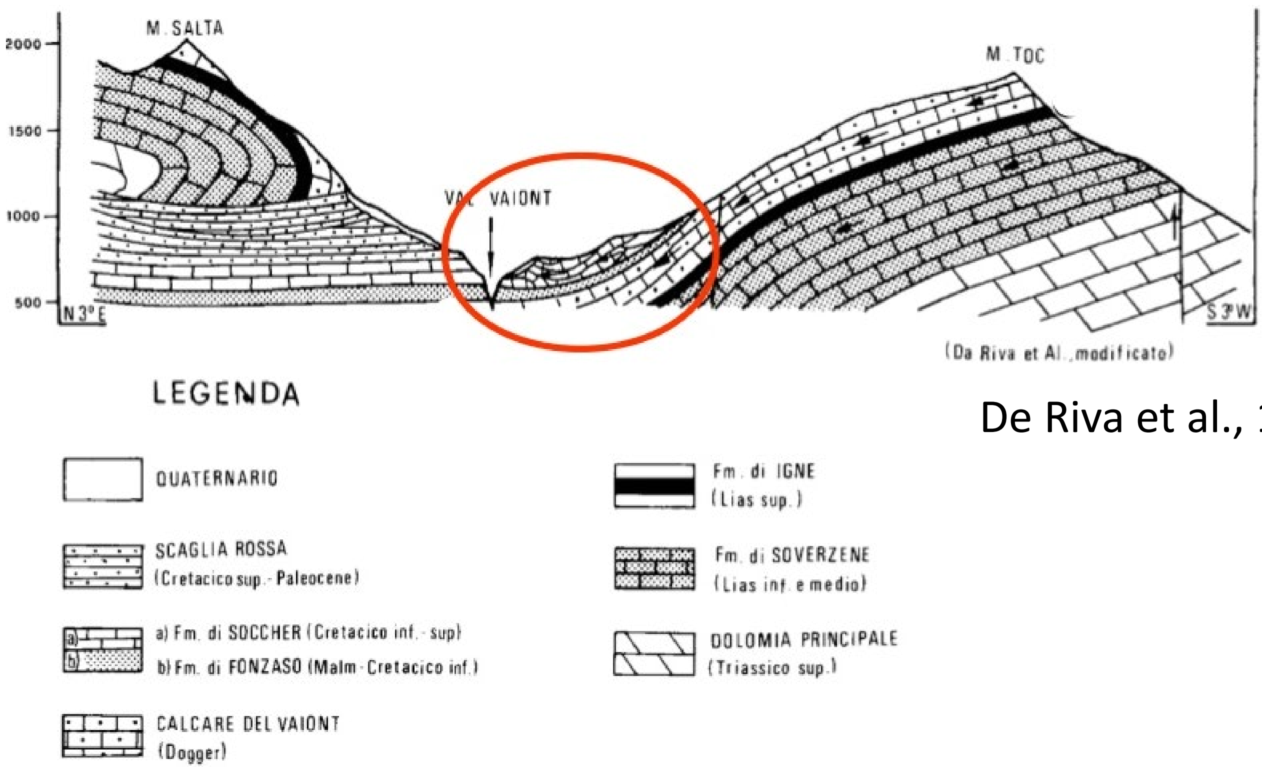
➢ **Example: Vajont dam and Monte Toc landslide**

- Frequent landslides, slip of more than cm/day
- Engineers have ignored the local geology and geophysical measurements!



Geology

- **Example: Vajont dam and Monte Toc landslide**



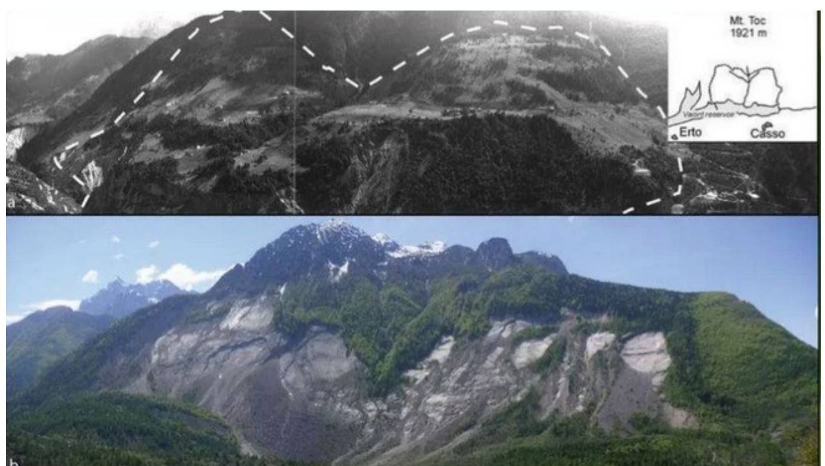
De Riva et al., 1990

1. **Introduction**

landslide

➢ **Example: Vajont dam and Monte Toc landslide**

- October 9th 1963: Landslide of 260 000 000 m3
- Filled the reservoir in 45 seconds
- 3 km long landslide on the side of the TOC mountain



1. **Introduction**

Tsunami

➢ **Example: Vajont dam and Monte Toc landslide**

- Mega-tsunami of 46 m high
- Villages of Langarone, Pirago, Rivalta, Villanova and Fae are destroyed
- about 2000 people died

1. **Introduction**

Dam has survived

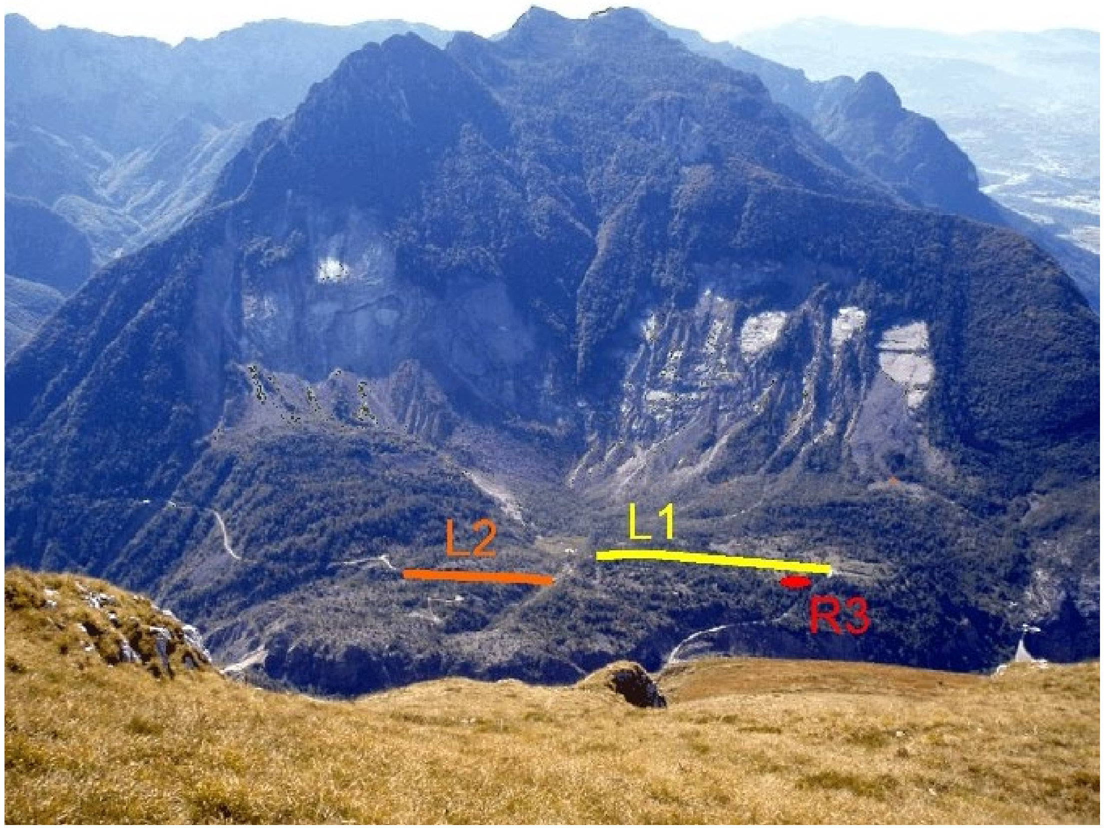
- **Example: Vajont dam and Monte Toc landslide**

But ... the engineers and creators of the project have been condemned

487 = Ce sont Les enfants de moins de 15 ans qui sont morts non pas par négligence mais par faute.

➔ Geophysical monitoring

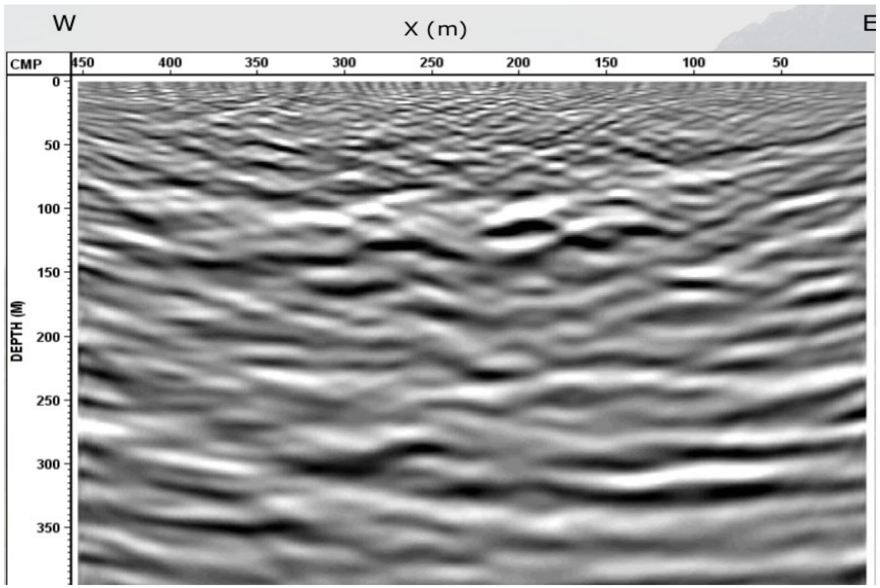
Seismic survey

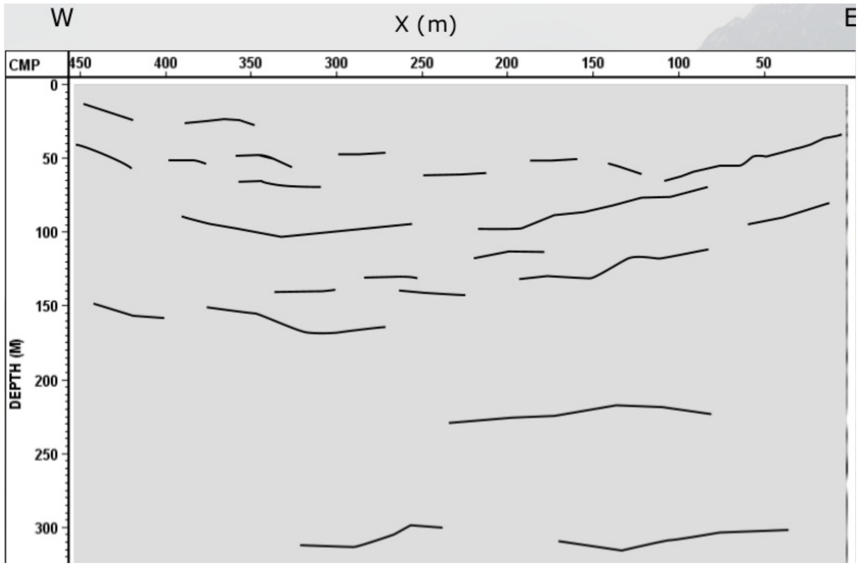


- Seismic reflexion
- Seismic refraction

Lorenzo Petronio et al., 2013

Common shot gathers: L1 data



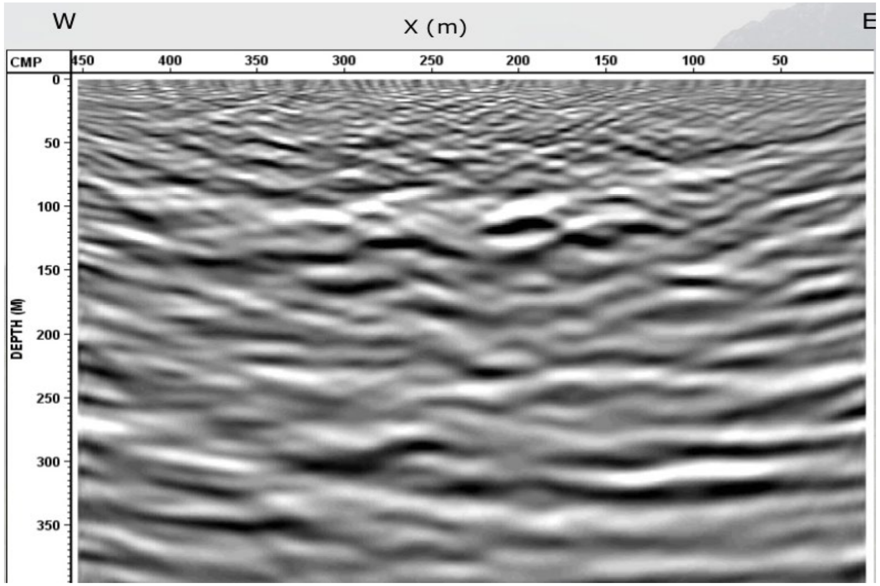


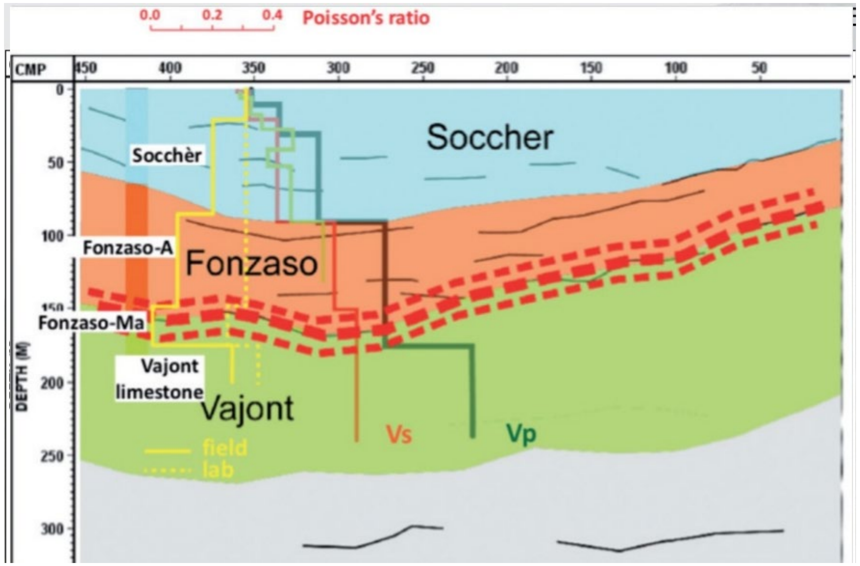
Lorenzo Petronio et al., 2013

How can interpret this data?➔ lab measurement

1. **Introduction**

Common shot gathers: L1 data





Lorenzo Petronio et al., 2013

How can interpret this data?➔ **lab measurement**

2. **What is a seismic wave ?**

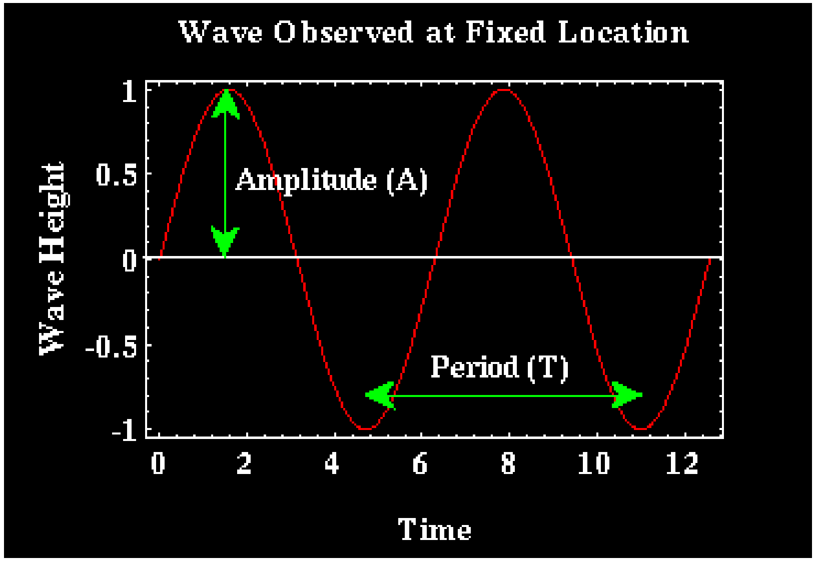
- Waves

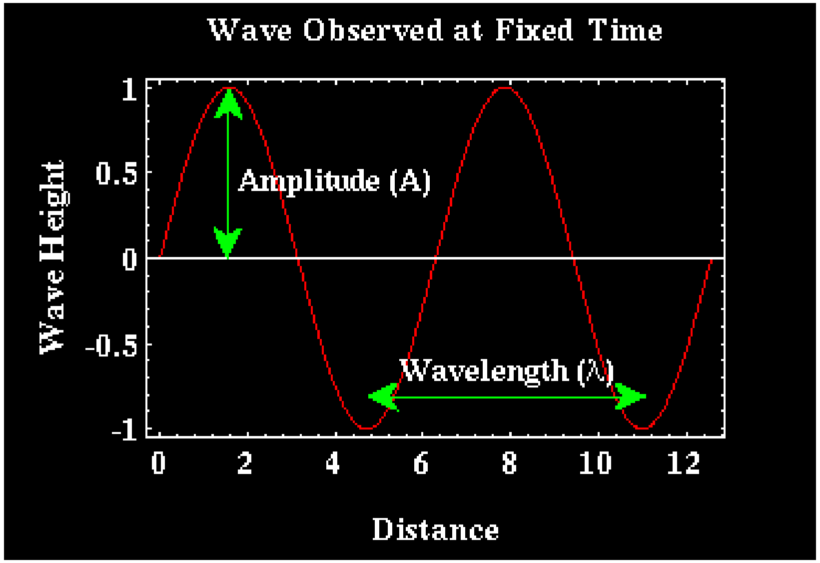
Turquey EQ, 2023, Mo 7.7

A wave of energy ('elastic wave ') that is generated by an earthquake or other earth vibration and that travels within the earth or along its surface

2. What is a seismic wave ?

- Waves





$f(t) = A \sin(\omega t - \phi)$

Speed V [m/s]

Wave length $\lambda = V T = V / f$ [m]

Time t [s]

Phase ϕ [rad]

Amplitude A [ ]

Period T [s]

Frequency f [Hz]

Pulsation $\omega = 2 \pi f = 2 \pi / T$ [rad/s]

2. What is a seismic wave ?

➢ Seismic waves

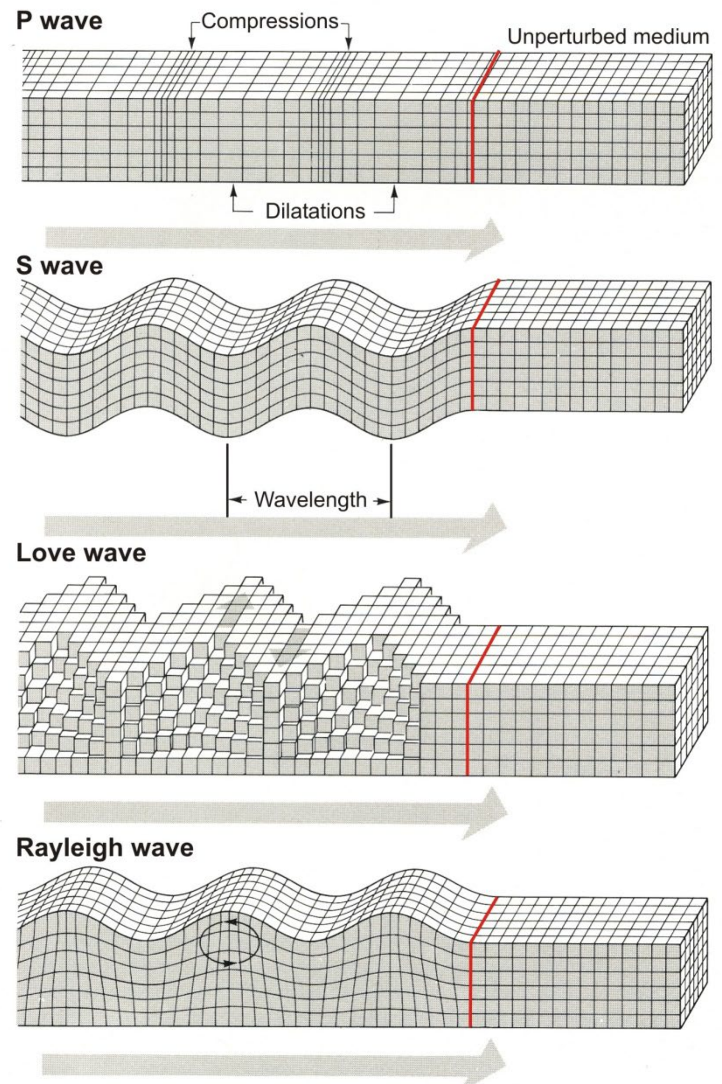
$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

$$\upsilon = \frac{3K - 2\mu}{2(3K + \mu)} = \frac{1}{2}\frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2}$$

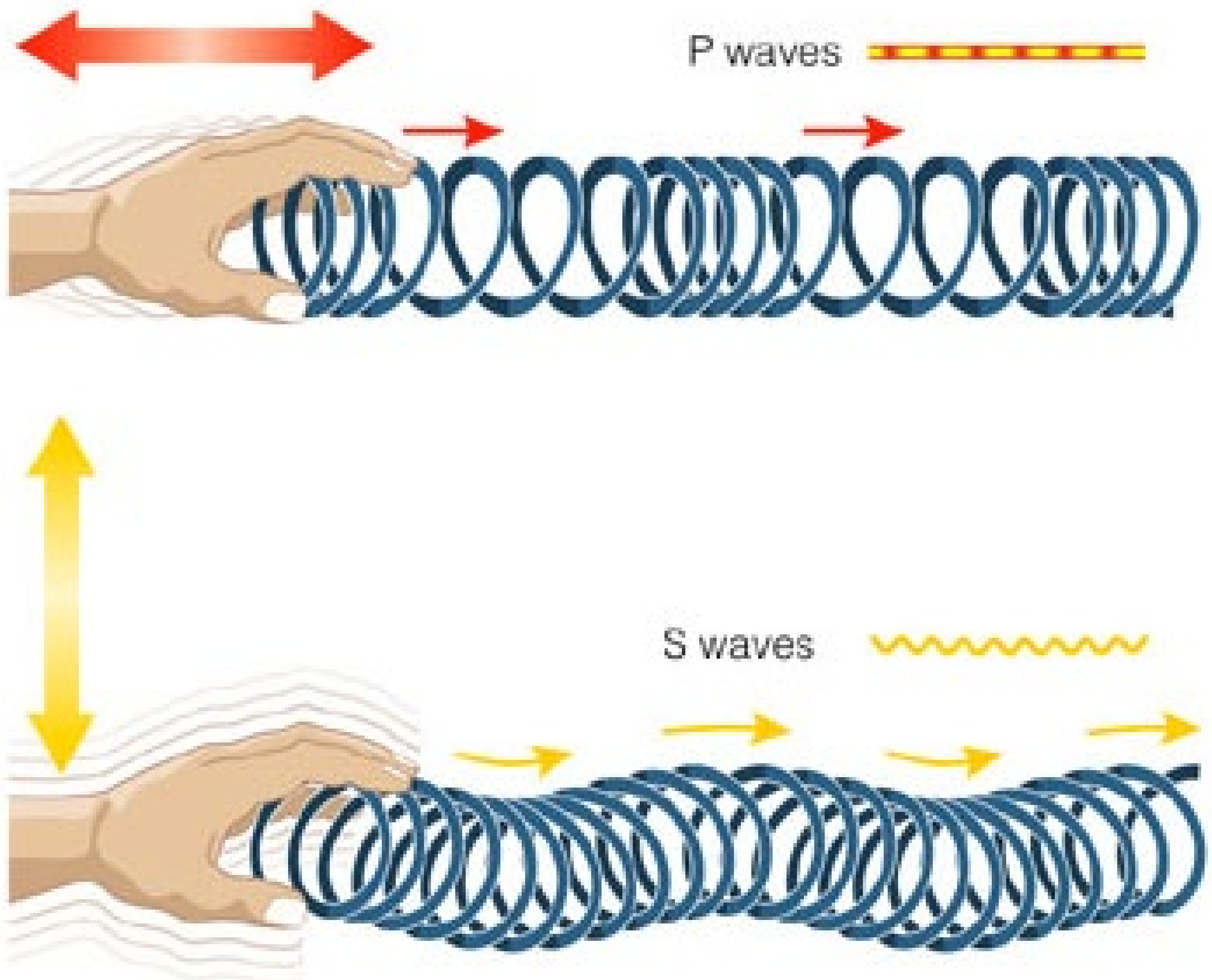
K bulk modulus, μ shear modulus

- $Vs < Vp$
- $Vs = 0$ if $\mu = 0$ (fluids)



2. **<u>What is a seismic wave ?</u>**

- <u>P and S waves</u>



2. **What is a seismic wave ?**

➢ Moduli from velocities

- ρ **density**
- K **bulk modulus = 1/compressibility**
- μ **shear modulus**
- λ **Lamé's coefficient**
- E **Young's modulus**
- ν **Poisson's ratio**
- **M = P-wave modulus = K + (4/3)** μ

$$\mu = \rho V_s^2$$

$$K = \rho\left(V_P^2 - \frac{4}{3}V_s^2\right)$$

$$\mathrm{M} = \rho V_P^2$$

2. **<u>What is a seismic wave ?</u>**

- <u>Velocity vs density</u>

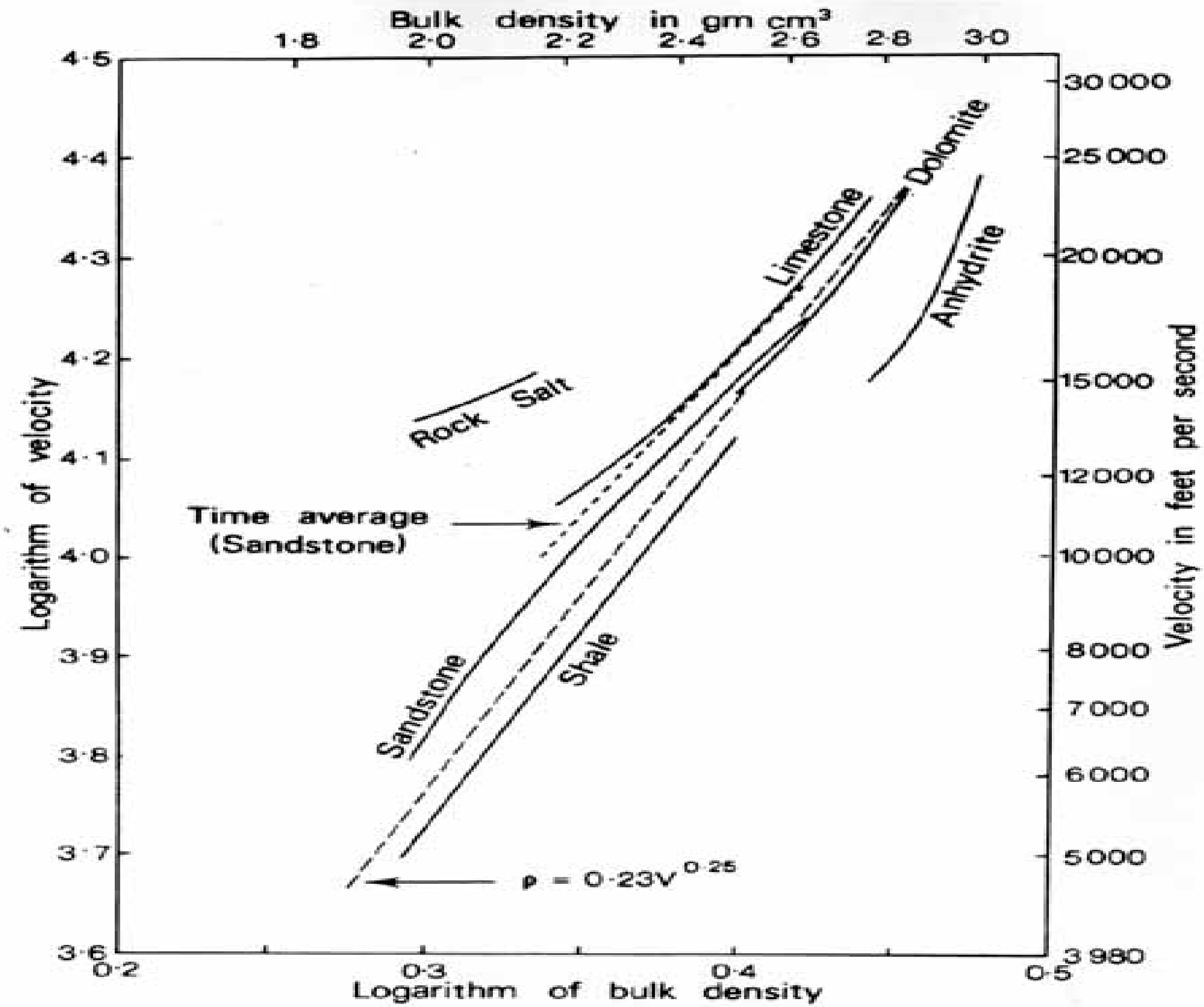


Figure 2/7 Velocity–density relationships in rocks of different lithology (after Gardner *et al*., 1974).

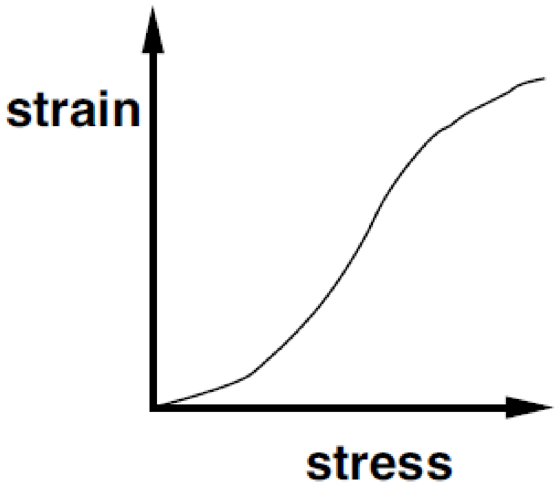
3. Elasticity

➢ Elastic, linear medium

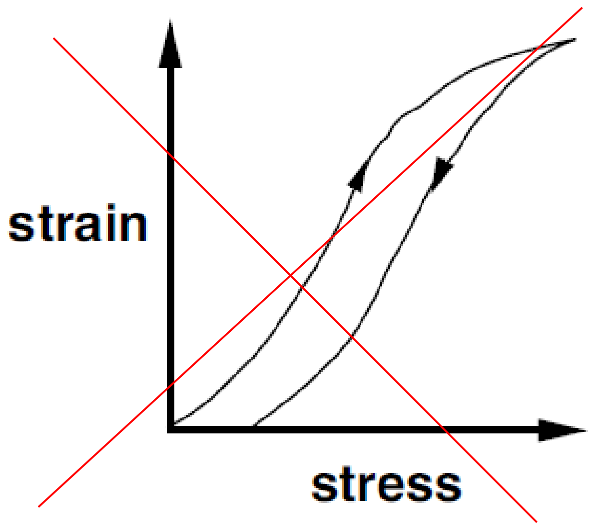
An elastic material is one where the stress is a unique function of the strain and vice versa. An elastic solid has the following properties:

- The displacements and strains are independent of the history of loading
- When we remove the applied loads, the body returns to a unique relaxed state.

Elastic



Inelastic



3. **Elasticity**

- Hooke's law (linear relationship)

$\sigma = c\,\varepsilon$ and $\varepsilon = s\,\sigma$

where c = stiffness coefficients (dimensions of stress)

s = compliance coefficients (dimensions of 1/stress)

σ = stress tensor (second order symmetric tensor)

ε = deformation tensor (second order symmetric tensor)

$$\sigma_{ij} = c_{ijkl}\,\varepsilon_{kl} \quad \text{or} \quad \varepsilon_{ij} = s_{ijkl}\,\sigma_{kl}$$

i,j,k,l can have the values 1,2 or 3 (so 3 x 3 x 3 x 3 = 3^4 = 81 coefficients).

But due to the symmetry of the deformation and stress tensors the 81 coefficients are not independent.

In addition thermodynamic considerations of the crystal energy also reduce the number of independent coefficients.

In Voigt notation we can write the C_{ijkl} tensor as 6 by 6 symmetric tensor C_{ij} with **21** independent values for a triclinic crystal.

3. **Elasticity**

- Hooke's law (linear relationship)

81 elastic constants 9 x 9

$$
\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \\ \sigma_{32} \\ \sigma_{13} \\ \sigma_{21} \end{bmatrix} = \begin{bmatrix}
c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} & c_{14} & c_{15} & c_{16} \\
c_{12} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} & c_{24} & c_{25} & c_{26} \\
c_{13} & c_{23} & c_{33} & c_{34} & c_{35} & c_{36} & c_{34} & c_{35} & c_{36} \\
c_{14} & c_{24} & c_{34} & c_{44} & c_{45} & c_{46} & c_{44} & c_{45} & c_{46} \\
c_{15} & c_{25} & c_{35} & c_{45} & c_{55} & c_{56} & c_{45} & c_{55} & c_{56} \\
c_{16} & c_{26} & c_{36} & c_{46} & c_{56} & c_{66} & c_{46} & c_{56} & c_{66} \\
c_{14} & c_{24} & c_{34} & c_{44} & c_{45} & c_{46} & c_{44} & c_{45} & c_{46} \\
c_{15} & c_{25} & c_{35} & c_{45} & c_{55} & c_{56} & c_{45} & c_{55} & c_{56} \\
c_{16} & c_{26} & c_{36} & c_{46} & c_{56} & c_{66} & c_{46} & c_{56} & c_{66}
\end{bmatrix} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \epsilon_{23} \\ \epsilon_{31} \\ \epsilon_{12} \\ \epsilon_{32} \\ \epsilon_{13} \\ \epsilon_{21} \end{bmatrix}
$$

3. **Elasticity**

- <u>21 independant elastic constants 6 x 6 symmetric tensor</u>

- Stress and strain tensor are symmetric
- 6 values of stress and strain
- The strains $\partial\varepsilon_{ij}$ and $\partial\varepsilon_{kl}$ are interchangable

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{12} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{13} & c_{23} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{14} & c_{24} & c_{34} & c_{44} & c_{45} & c_{46} \\ c_{15} & c_{25} & c_{35} & c_{45} & c_{55} & c_{56} \\ c_{16} & c_{26} & c_{36} & c_{46} & c_{56} & c_{66} \end{bmatrix} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix}$$

3. **Elasticity**

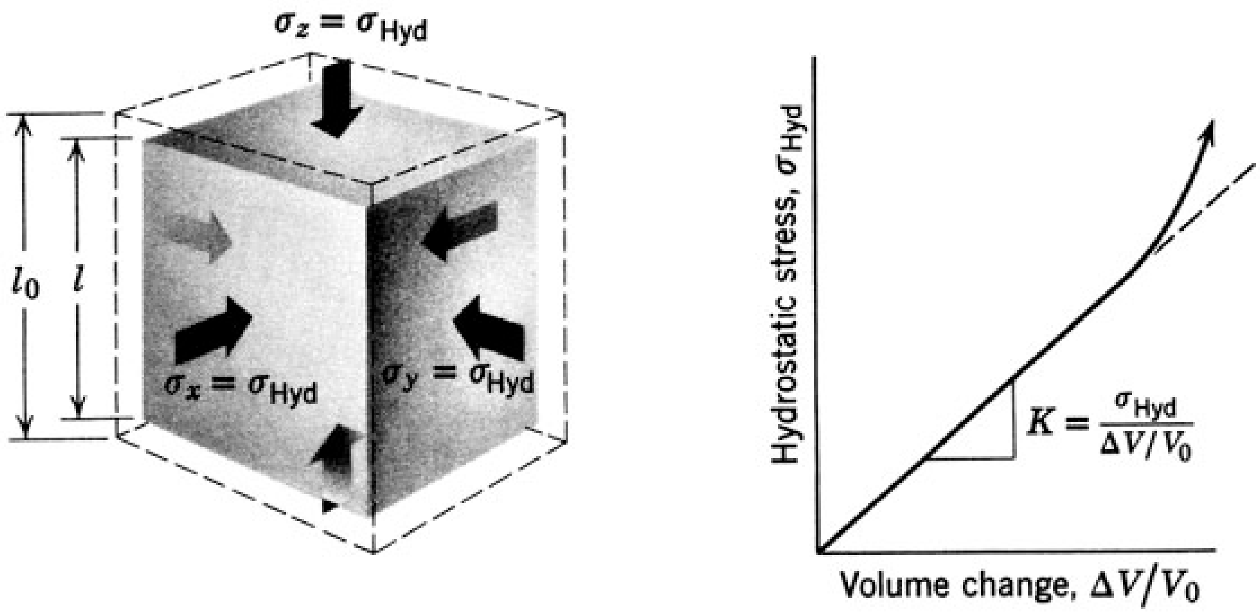
➢ Elastic moduli – stress/strain

- Young's modulus $E = \frac{\sigma_z}{\varepsilon_z}$ (uniaxial compression)
- Shear modulus $\mu = \frac{\tau}{\gamma}$ (simple shear) =G
- Bulk modulus $K = \frac{P}{\Delta V / V_0}$ (volume deformation: dilatation; hydrostatic compression)

3. **Elasticity**

- Bulk modulus (K)

Unit= Pa : $m^1L^{-1}T^{-2}$

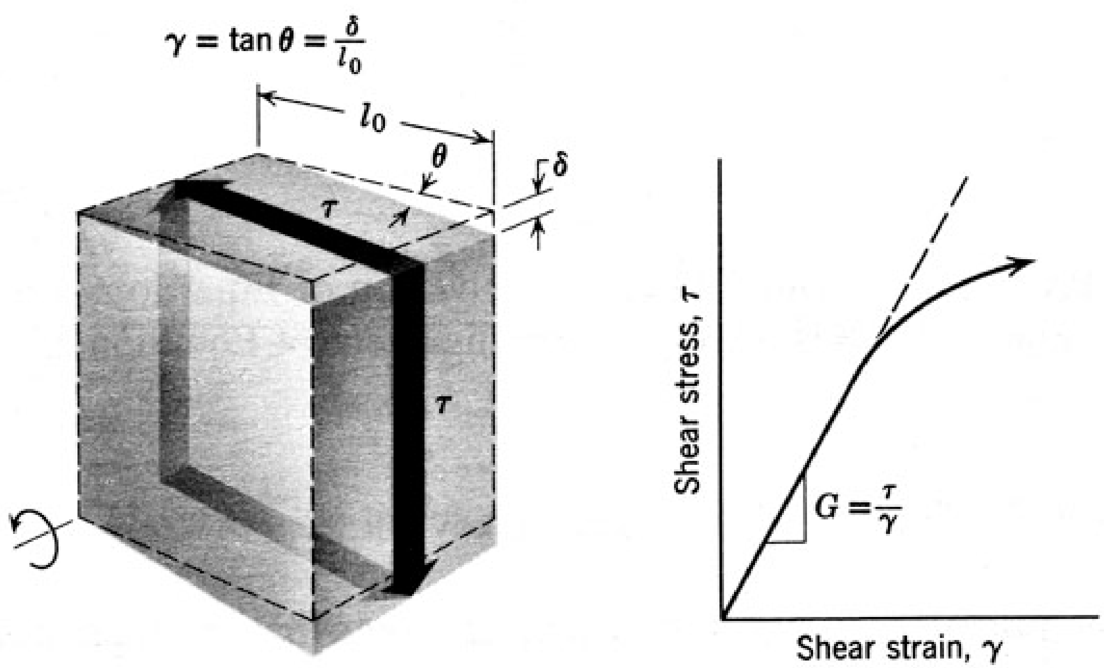


Hydrostatic stress versus volume change. Dashed lines surrounding cube represent initial stress-free size.

3. **Elasticity**

- Shear modulus or modulus of rigidity (G, μ)

Unit= Pa : $m^1L^{-1}T^{-2}$

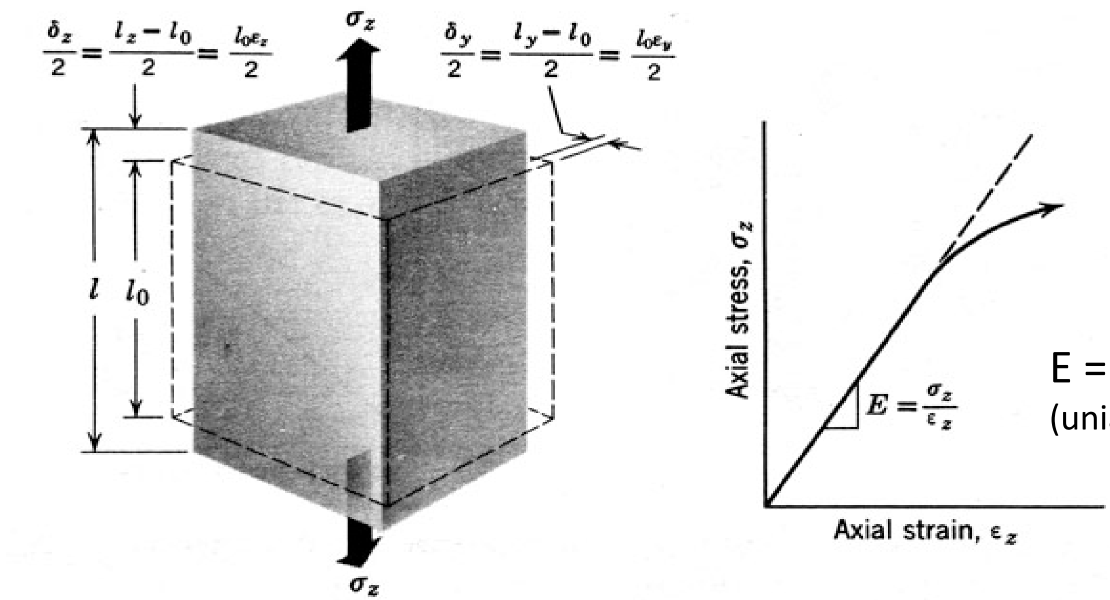


Geometry of shear stress–shear strain relationship. Dashed lines represent initial stress-free shape: a cube of edge length l_0. (A rigid body rotation, as indicated, would also occur.) Shear strain $\gamma = \delta/l_0 = \tan\theta$.

3. **Elasticity**

➢ Young's modulus or Elastic modulus

Unit= Pa : $m^1L^{-1}T^{-2}$



$E = \sigma_z/\varepsilon_z$
(uniaxial compression)

Uniaxial tensile (or compressive) stress. Poisson's ratio, ν, is the ratio of transverse to axial strain. Dashed lines represent initial stress-free shape: a cube of edge length l_0.

Poisson's ratio, ν, another elastic constant, is the ratio of transverse to axial strain

$$\nu = \frac{-\varepsilon_y}{\varepsilon_z}$$

3. **Elasticity**

Lambda et mu= Lame constant

Relationships Among Elastic Constants in an Isotropic Material

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

3. **Elasticity**

➢ Seismic waves

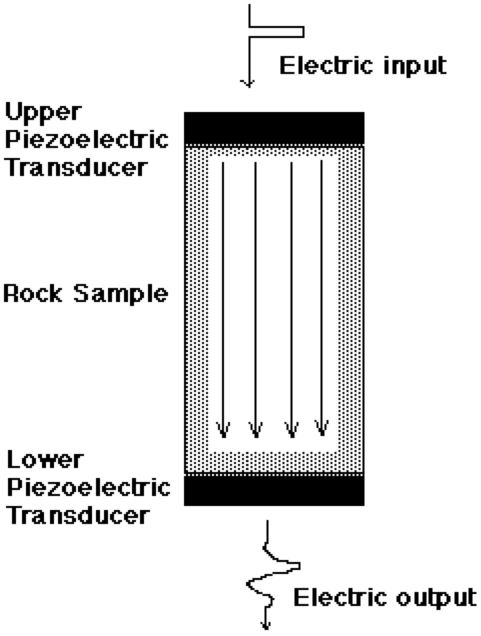
Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm^3)	Density of constituent crystal (g/cm^3)
Scree, vegetal soil	300-700	100-300	1.7-2.4	-
Dry sands	400-1200	100-500	1.5-1.7	2.65 quartz
Wet sands	1500-2000	400-600	1.9-2.1	2.65 quartz
Saturated shales and clays	1100-2500	200-800	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_3 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	-

1. Introduction
2. What is a seismic wave?
3. Elasticity
4. Experimental methods
5. Parameters that influence seismic waves.
6. Seismic attenuation

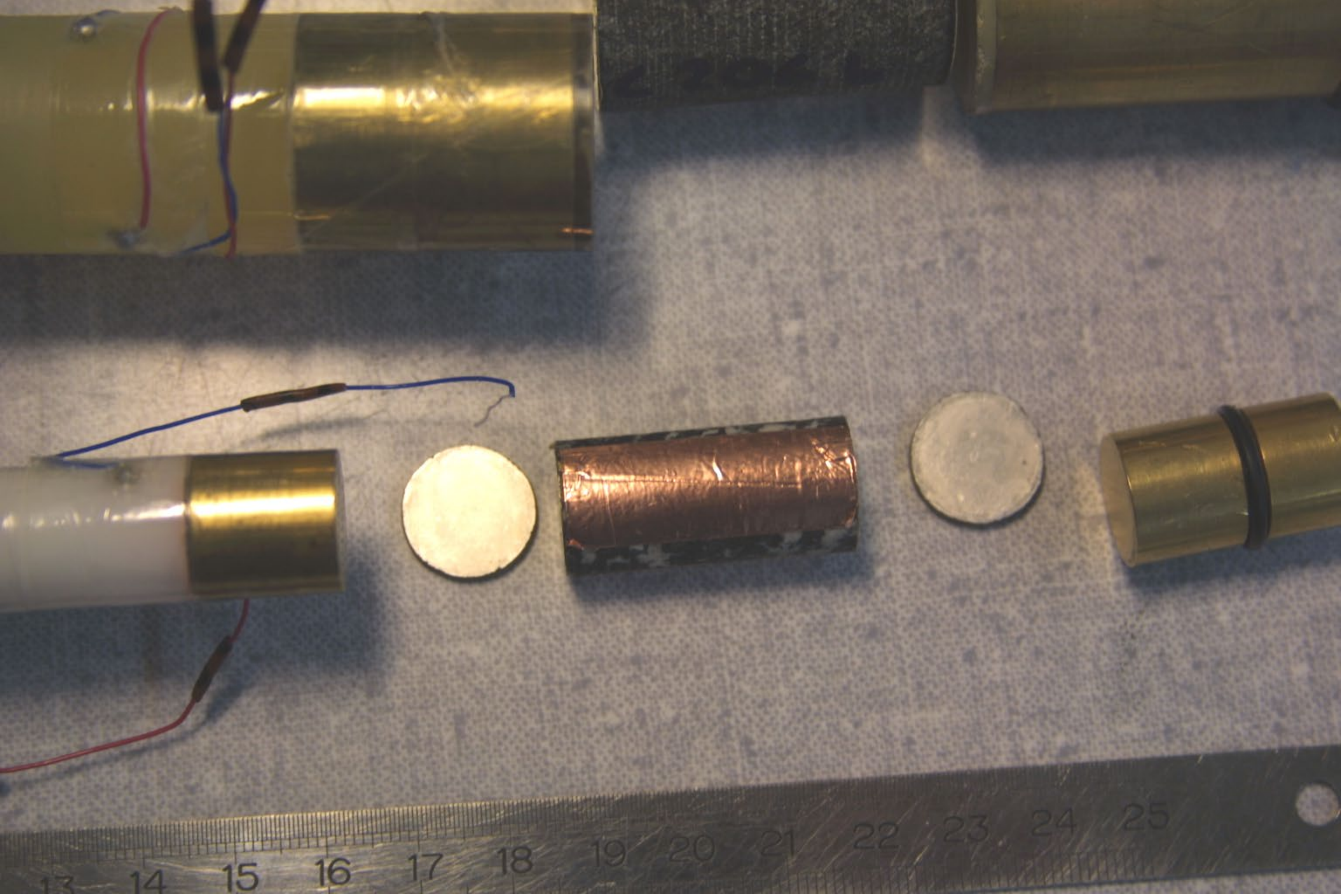
4. **Experimental approach**

➢ Experimental approach: Pulse Transmission

- Simplest technique. An electric pulse is converted into a seismic wave through a piezoelectric transducer and is sent to the specimen. On the other side of the specimen, another piezoelectric transducer convert the seismic wave into an electric signal, which is displayed on an oscilloscope.



- Limitations:
- The wavelength should be bigger than grainsize and not too bigger than the sample
- Vp and Vs measurement only
- Requires calibration for buffer rods.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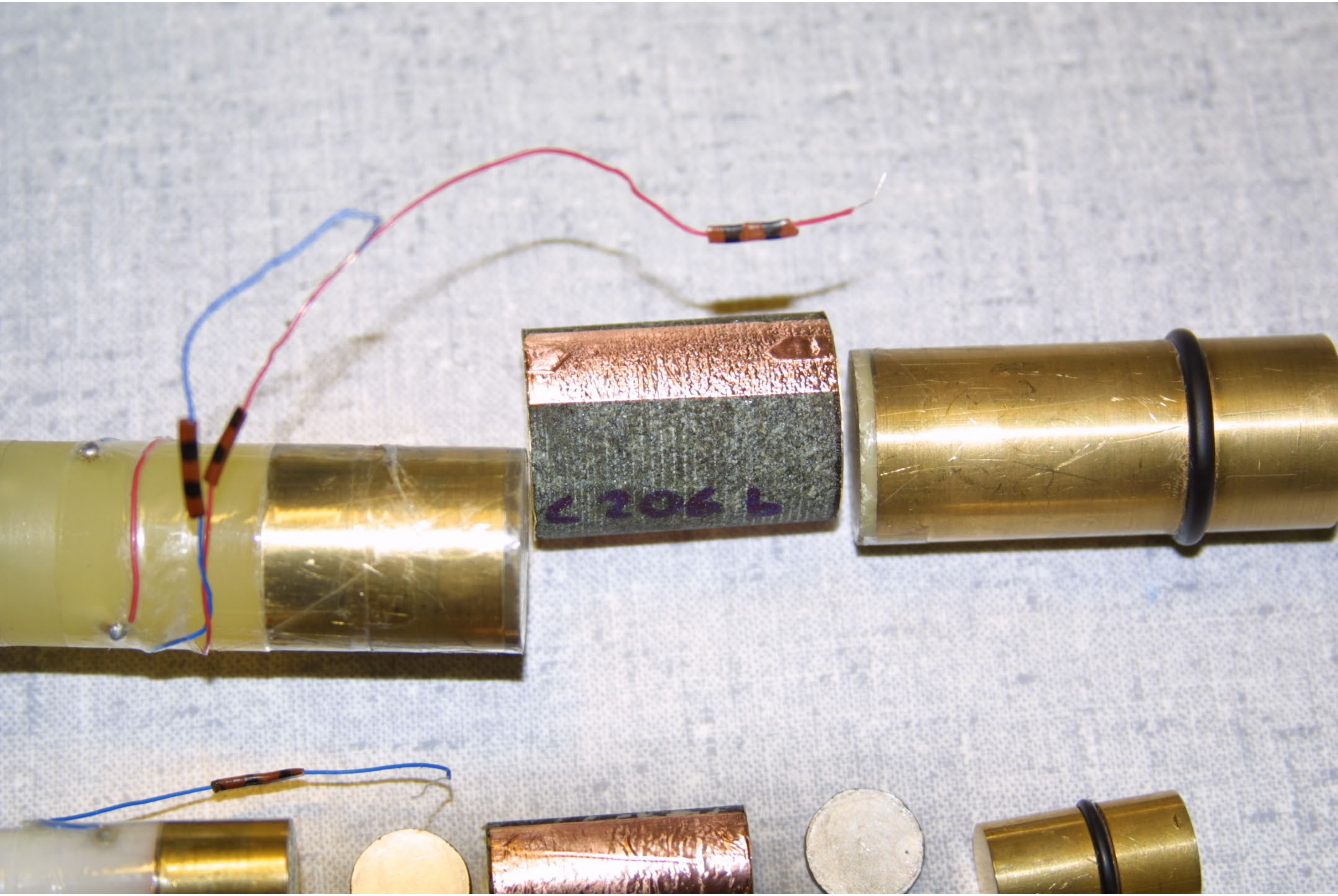
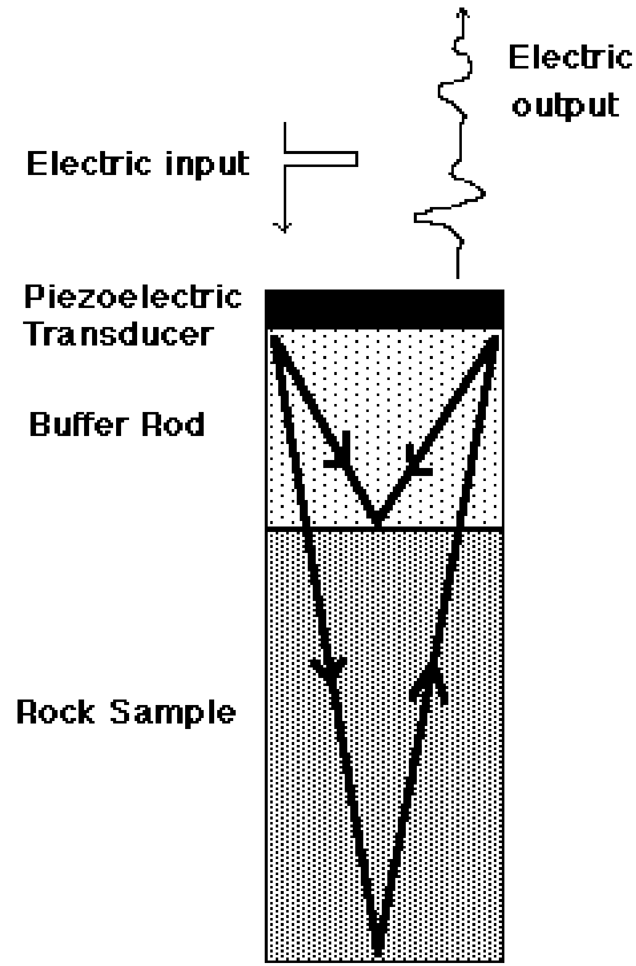


4. **Experimental approach**

➢ Experimental approach: Pulse-echo

- it is possible to measure attenuation and use smaller specimens.
- No calibration required for thermal gradient in the buffer rod

- Limitations:
- Must be a good contrast in the acoustic impedance between the rock and the buffer rod
- Much lower signal due to loss of energy for multiple reflections
- More difficult sample preparation
- Possibility of overlapping signals (therefore more difficult interpretation)



4. **Experimental approach**

➢ Experimental approach : resonant ultrasound spectroscopy

This is a new technique where a specimen is suspended on piezoelectric transducers that vibrate. All the resonant mode are found while changing the frequency. These are converted into elastic constants with algorithms.

- Limitations:

The rock specimen must be suspended, therefore it is not convenient to run under confining pressure because it is very difficult to place a jacket.

4. **Experimental approach**

➢ Shape of specimens: a comparison

- Cylinder: the most used shape. Seismic properties can be measured in one direction only. Easy to assembly and cheap.

- Cube: more difficult to prepare and almost impossible to achieve true hydrostatic pressure. Three mutually perpendicular directions can be measured simultaneously. It is very difficult to place a jacket. Therefore pore pressure can be applied only occasionally.

- Sphere: difficult to prepare and needs also a very large pressure vessel. Allows measurements on infinite directions on the same sample.

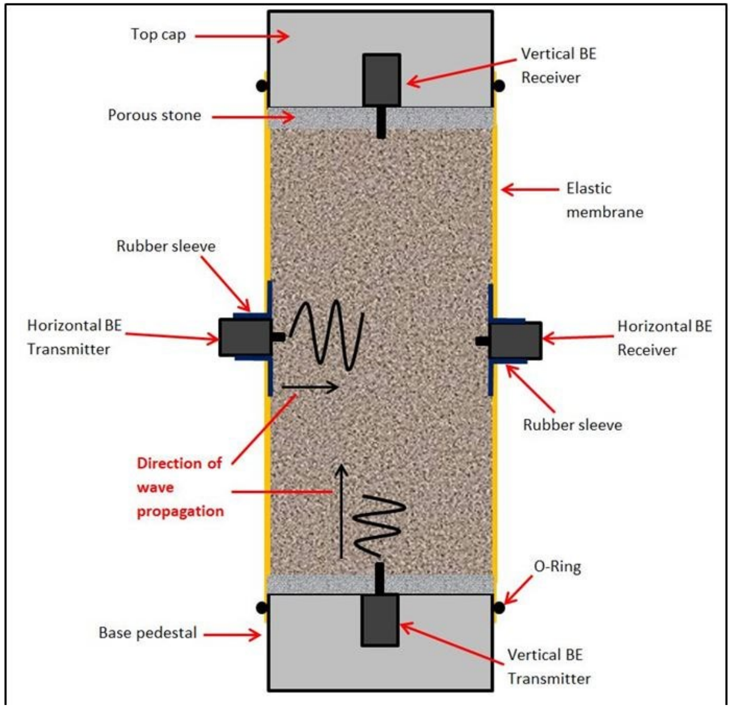
4. **Experimental approach**

➢ High-pressure and high-temperature testing machines for seismic property measurements on rocks

- Solid Medium: up to 20 GPa and 2000 K. Confining pressure is never truly hydrostatic. Very small specimens.

- Fluid medium, externally heated (Heard type): up to 0.3 GPa and 1100 K. Very long and stable hot zone. Large specimens.

- Gas medium, internally heated (Paterson Rig): up to 0.6 GPa and 1600 K. Best solution.



1. Introduction
2. What is a seismic wave?
3. Elasticity
4. Experimental methods
5. Parameters that influence seismic waves.
6. Seismic attenuation

5. **Parameters that influence Seismic waves**

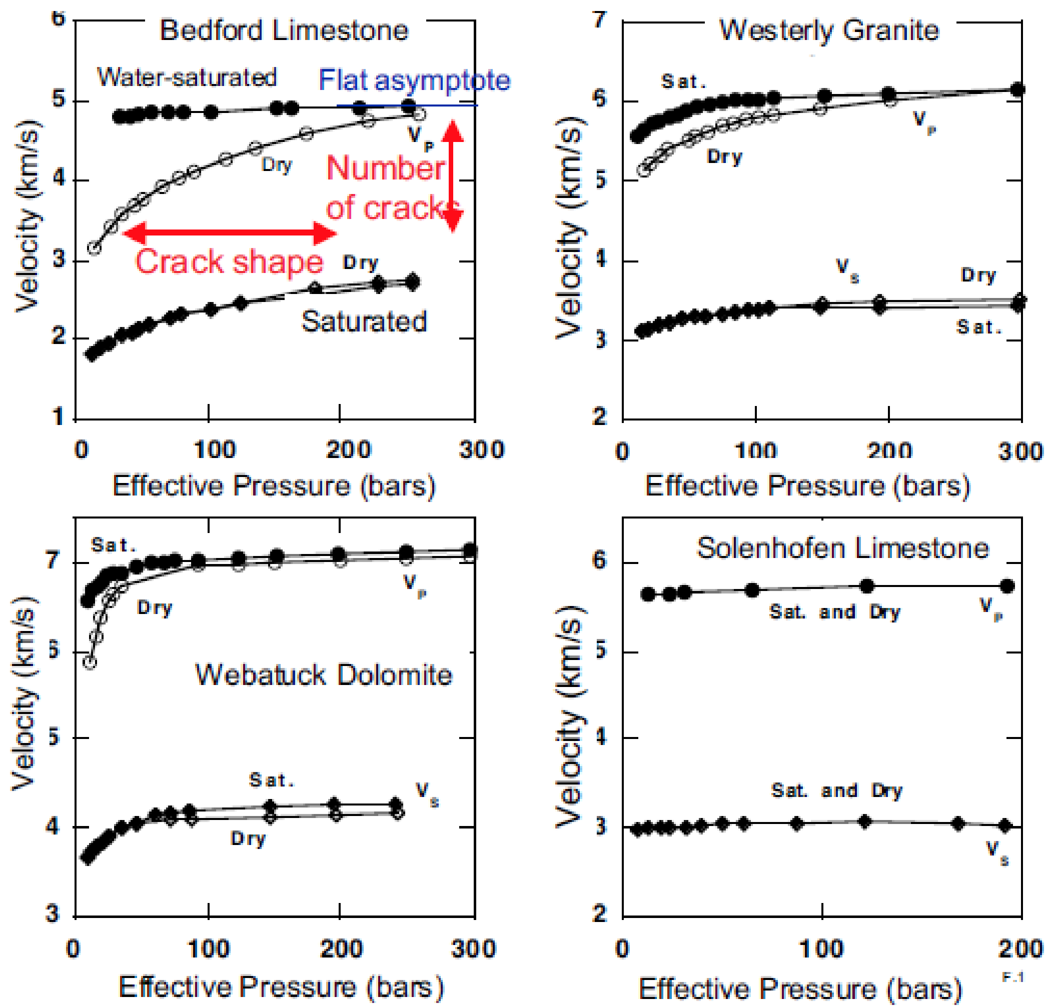
- Parameters that influence Seismic velocity
  (elastic properties + density)

Rocks elastic properties depend from:

- Elastic properties of solid matrix
- Elastic properties of fluid
- Geometry:
  - orientation of crystals (crystallographic and shape)
  - and of pore space (shape, connectivity).
- Effective pressure (= confining – pore pressure)
- Temperature

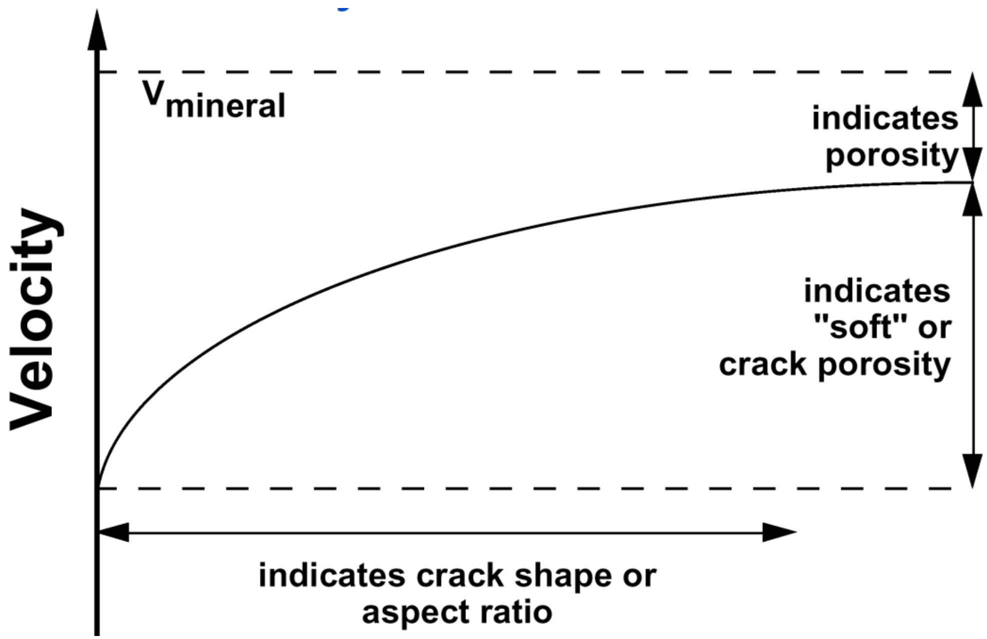
5. **Parameters that influence Seismic waves**

➢ Pressure-Dependence of Velocities and effect of saturation

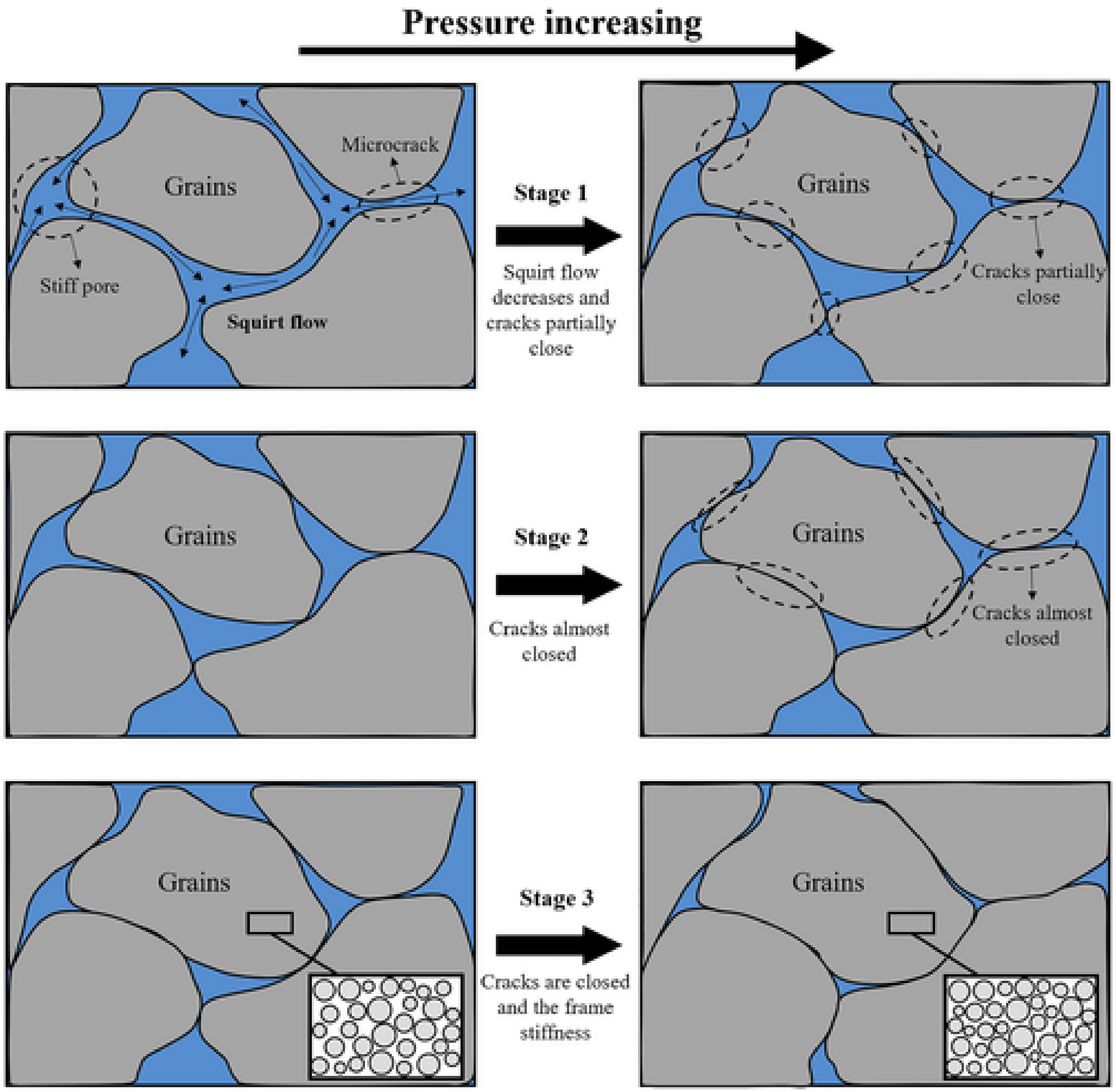


5. **Parameters that influence Seismic waves**

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



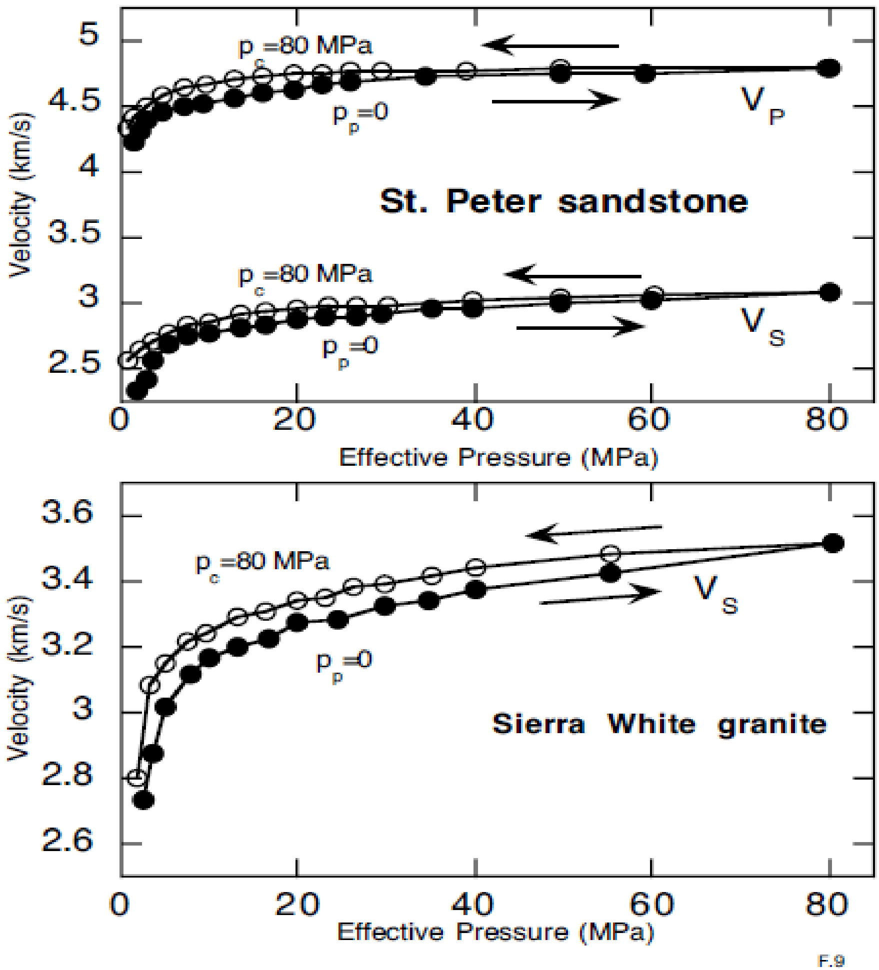
1. High pressure limiting velocity is a function of porosity
2. The amount of velocity change with pressure indicates the amount of soft, crack-like pore space
3. The range of the greatest pressure sensitivity indicates the shape or aspect ratios of the crack like pore space



Ba&Carcione, 2022

5. **Parameters that influence Seismic waves**

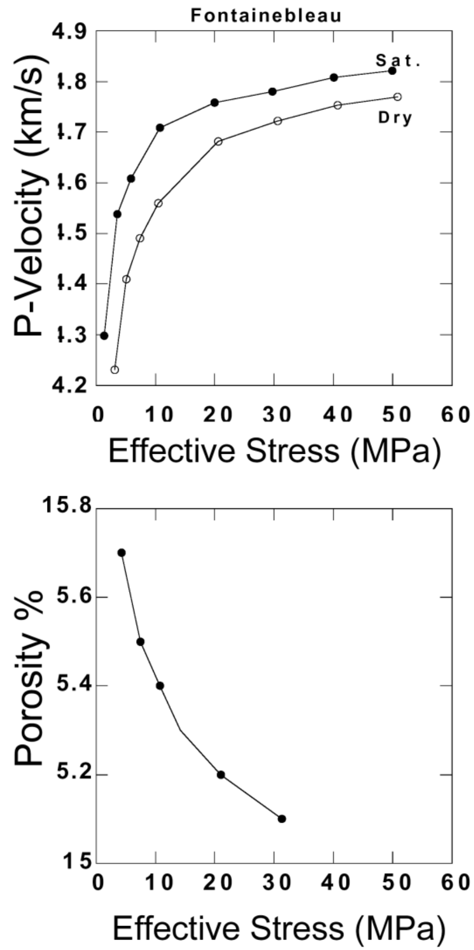
- Effective pressure-Dependence of Velocities



Jones, 1983.

5. **<u>Parameters that influence Seismic waves</u>**

➢ <u>Effective pressure-Dependence of Velocities</u>

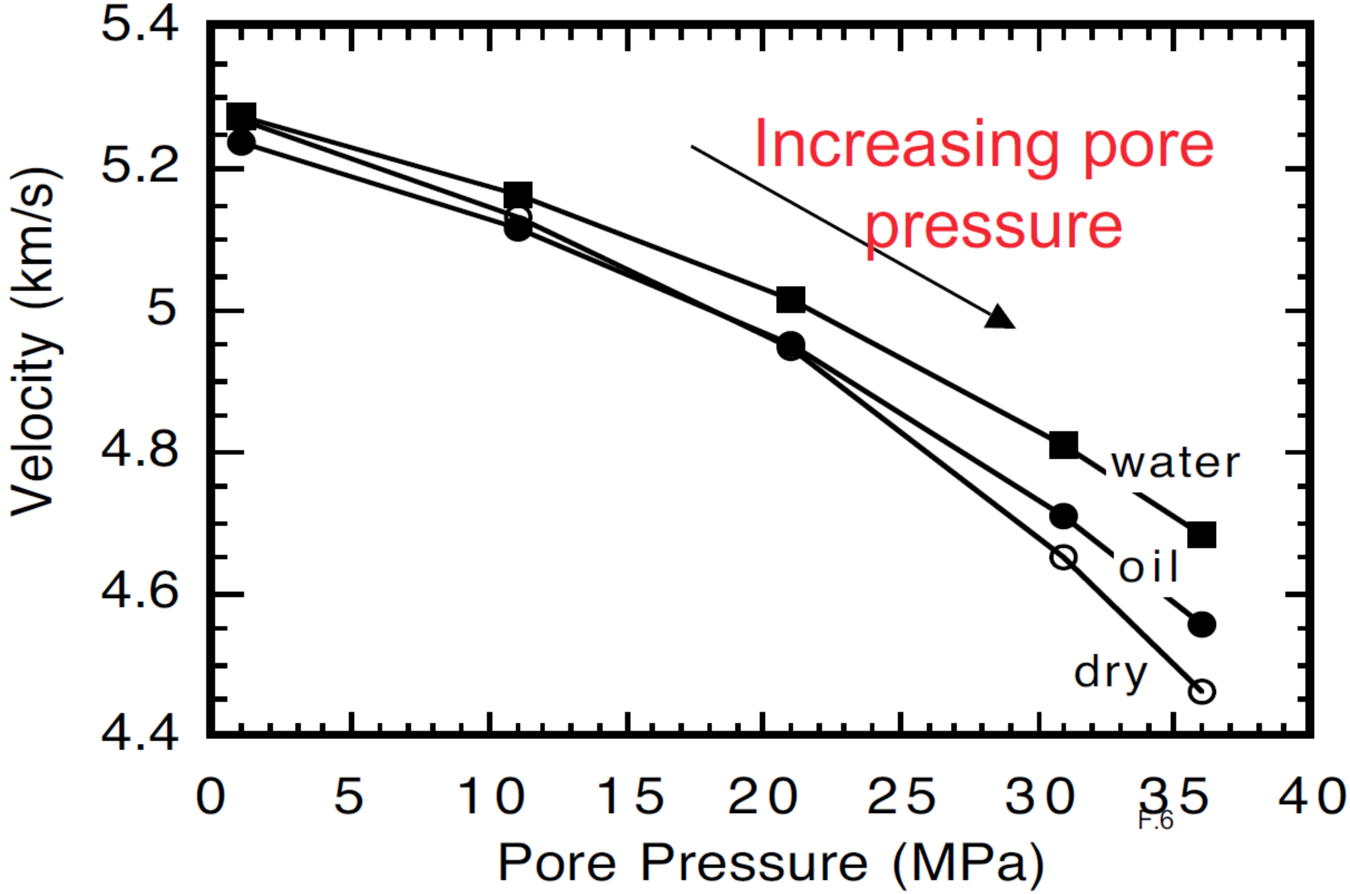


Ultrasonic velocities and porosity in Fontainebleau sandstone (Han, 1986). Note the large change in velocity with a very small fractional change in porosity. This is another indicator that pressure opens and closes very thin cracks and flaws.

5. **Parameters that influence Seismic waves**

➢ Effective pressure-Dependence of Velocities

- 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

5. **Parameters that influence Seismic waves**

- Pore pressure-Dependence of 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.

5. **Parameters that influence Seismic waves**

➢ Pressure-Dependence of Velocities

- 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.

5. **Parameters that influence Seismic waves**

- Velocity vs Porosity

$$\frac{1}{V} = \frac{\phi}{V_f} + \frac{1-\phi}{V_m}$$

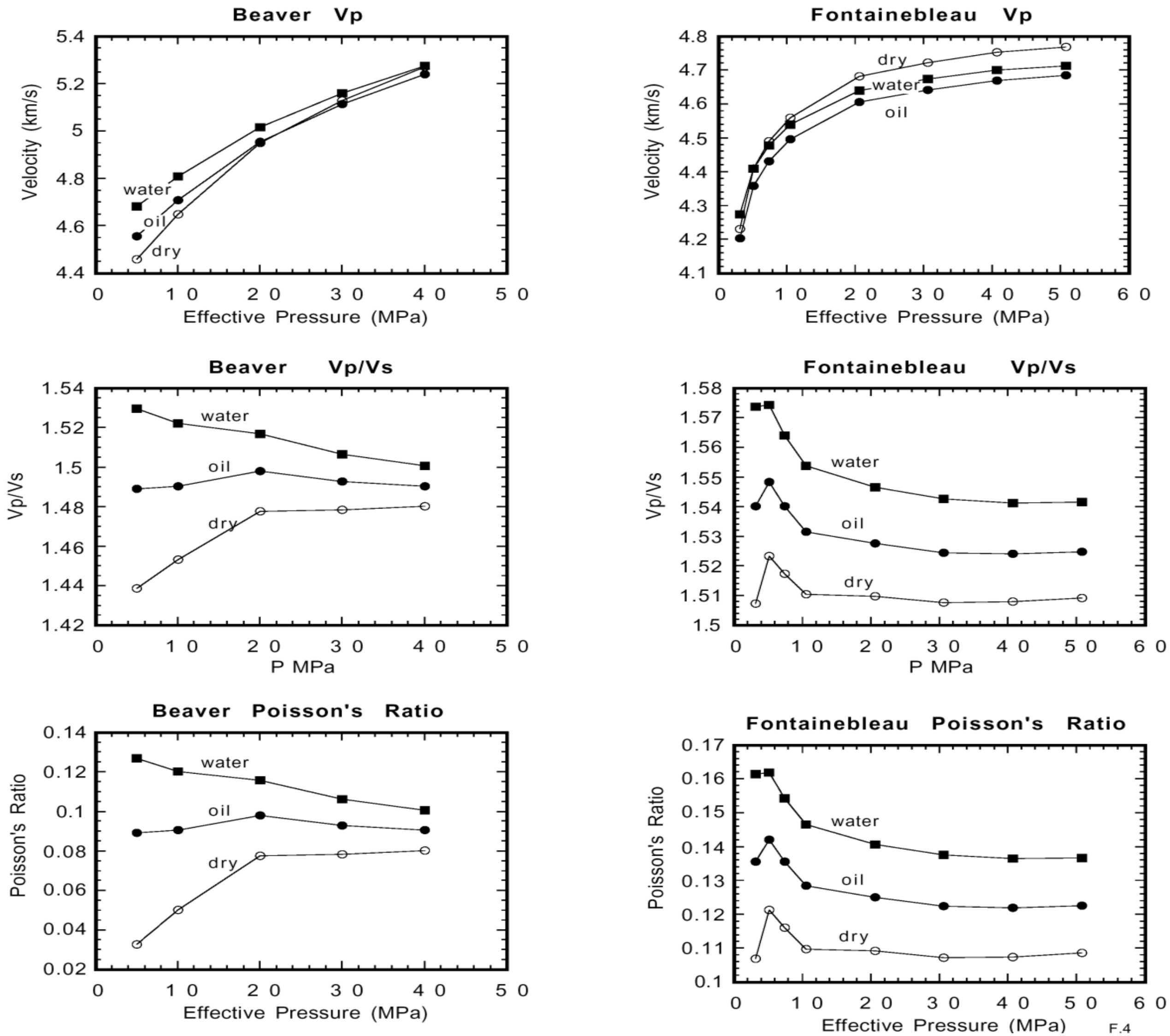
Wyllie equation

Where **ϕ** is the **porosity**,
Vf is the **velocity of the interstitial fluid**,
and **Vm** is the **velocity of the rock matrix**

(Wyllie et al. 1956).

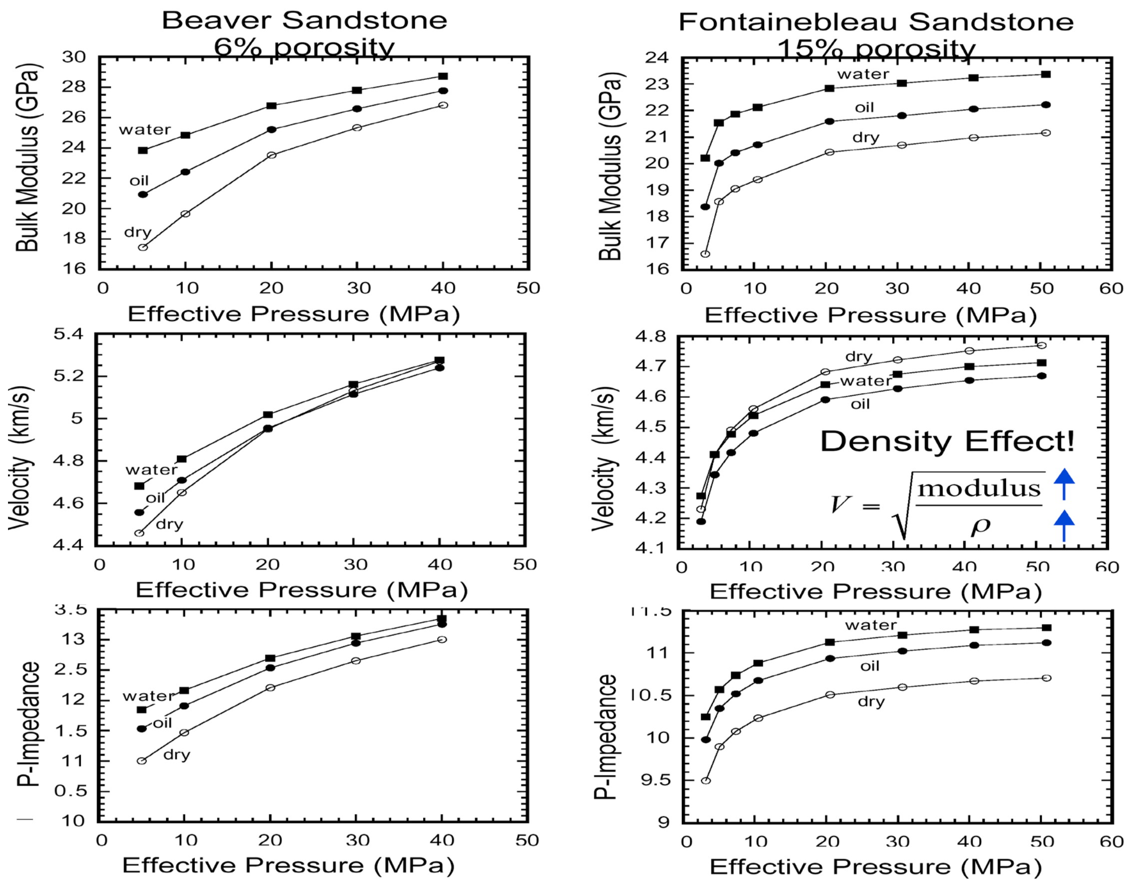
5. **Parameters that influence Seismic waves**

- Pore fluid (type)-Dependence of Velocities



5. **Parameters that influence Seismic waves**

➢ Pore fluid (type)-Dependence of Velocities



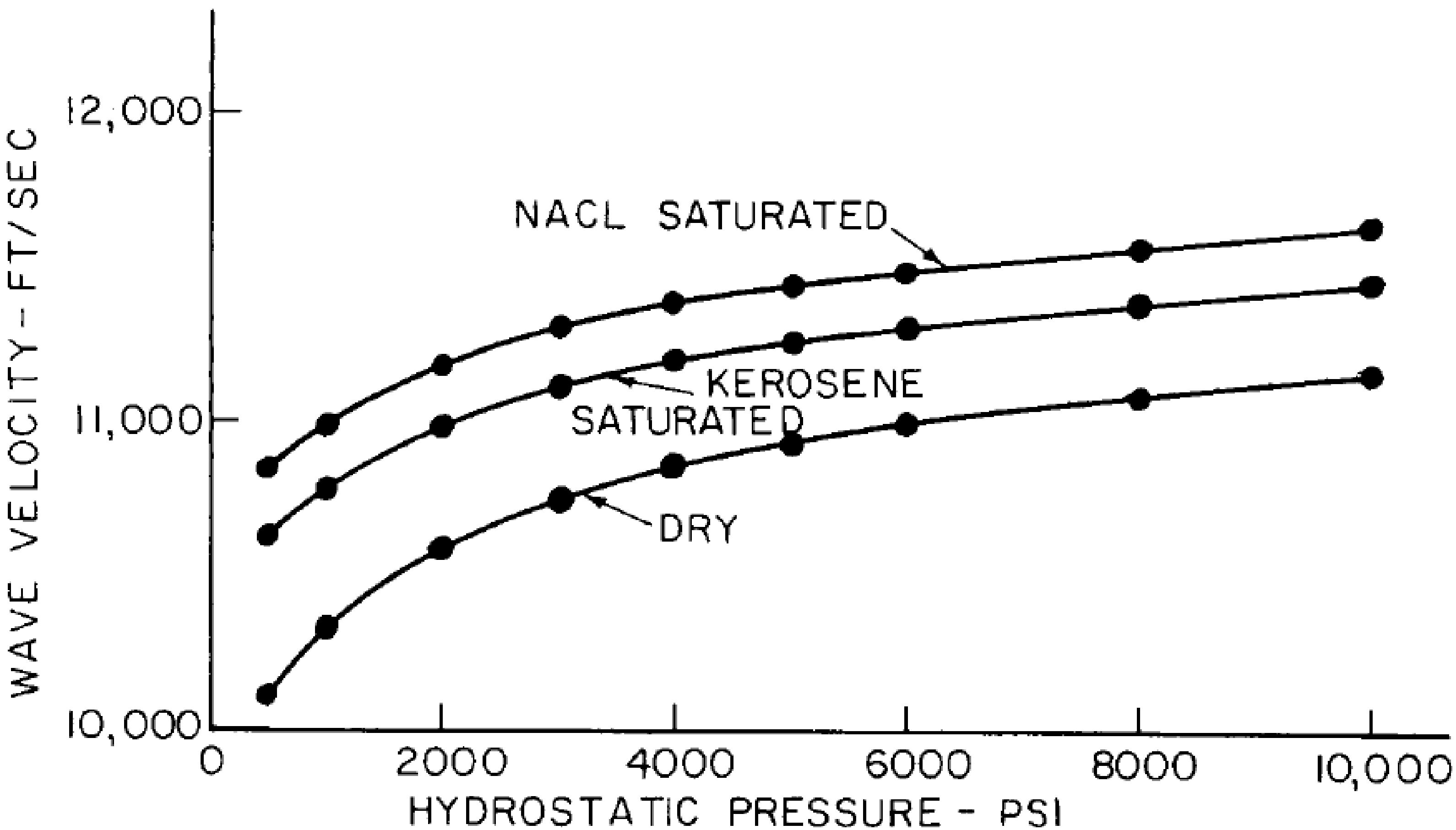
Density does not lead to ambiguity
when Impedance is measured.

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

Calculations made from dry velocities, using Gassmann relation,
Kmin = 36 GPa, Kwater = 2.2, Koil = 1.

5. **Parameters that influence Seismic waves**

➢ Pore fluid-Dependence of Velocities



King, 1966

5. **Parameters that influence Seismic waves**

- Pore fluid-Dependence of Velocities

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.

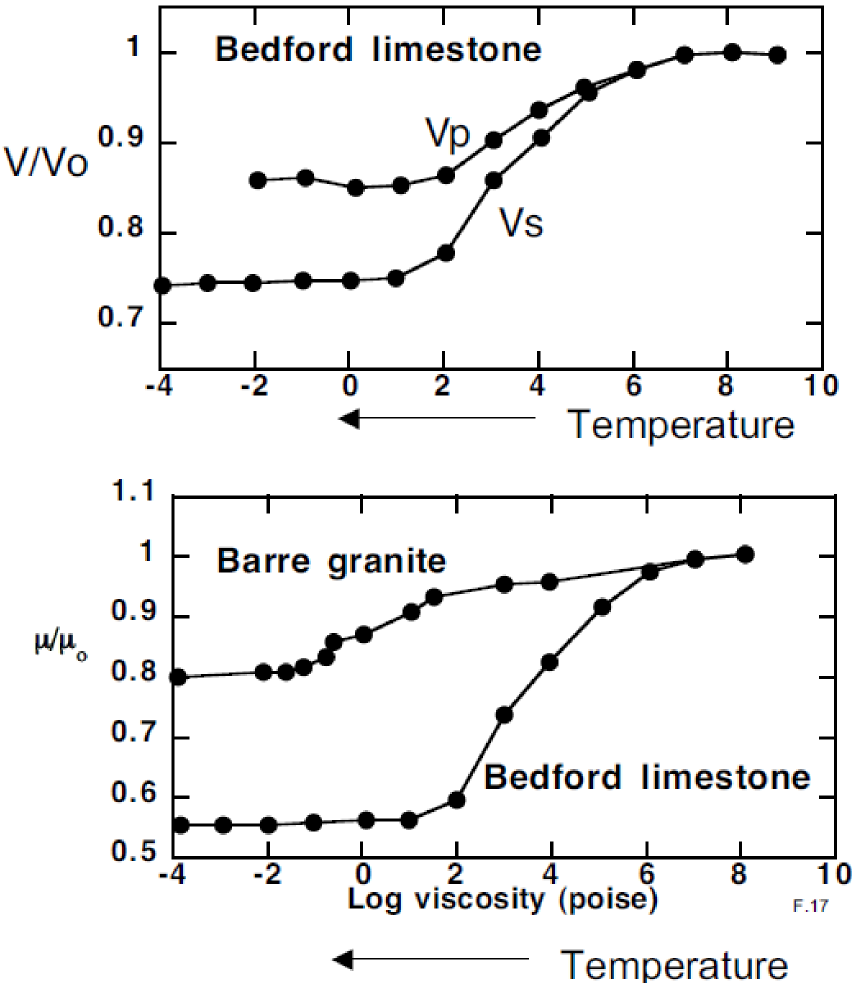
- The bulk density also increases when going from a dry to water-saturated rock.

- 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 ($\rho V=\sqrt{\rho * modulus}$), and $\frac{Vp}{Vs}$ 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.

5. **Parameters that influence Seismic waves**

- Fluid viscosity -Dependence of Velocities



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.

5. **Parameters that influence Seismic waves**

➢ Fluid properties that influence seismic velocity

- 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.
- 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.

$$K_s^{-1} = K_T^{-1} - \frac{\alpha^2 T}{\rho c_p}$$

α= thermal expension; Cp = heat capacity

5. **Parameters that influence Seismic waves**

➢ Soft, Crack-Like Porosity

1. Includes micro and macro-fractures 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

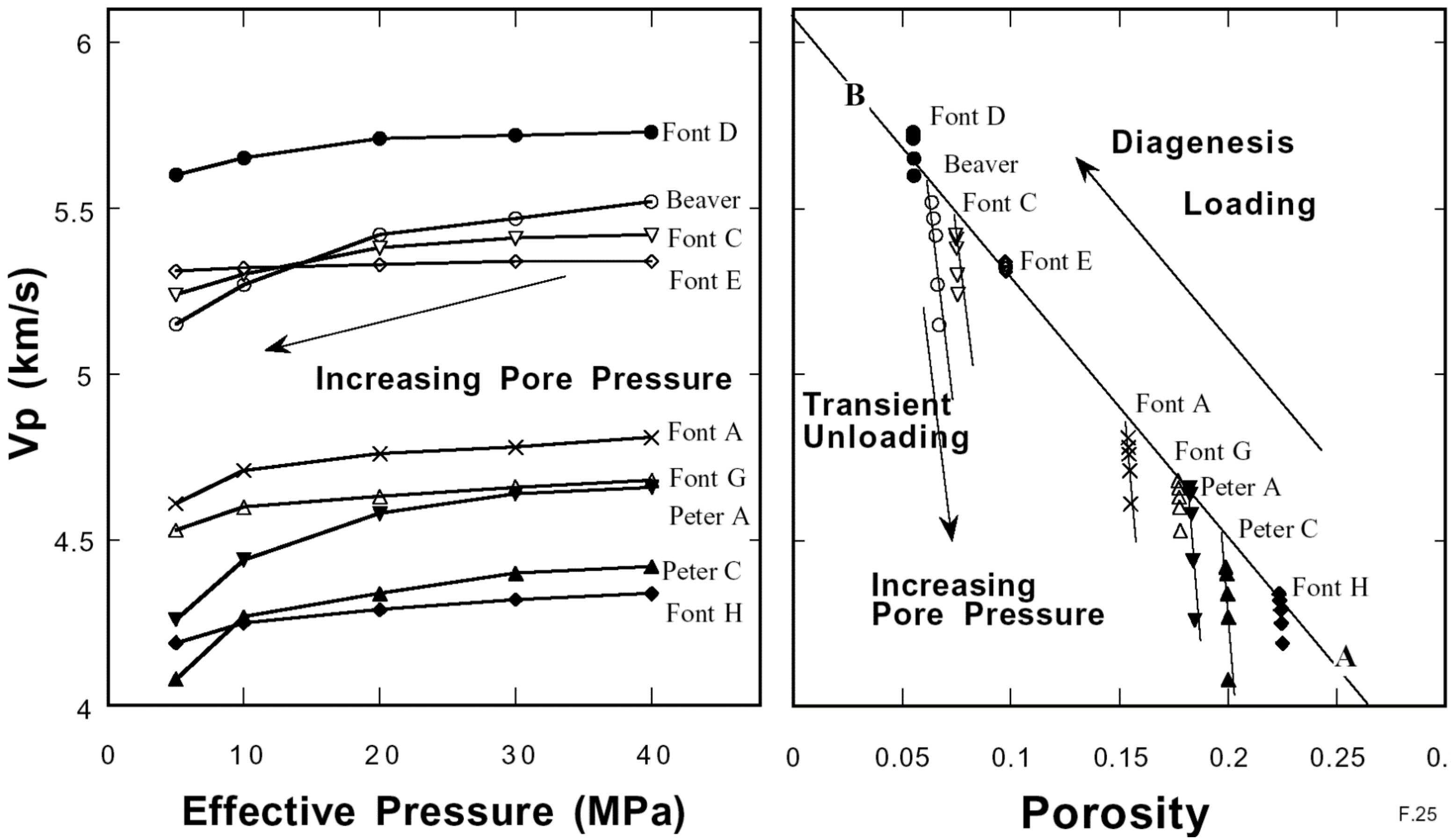
(sensitivity to hydrocarbon indicators)

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

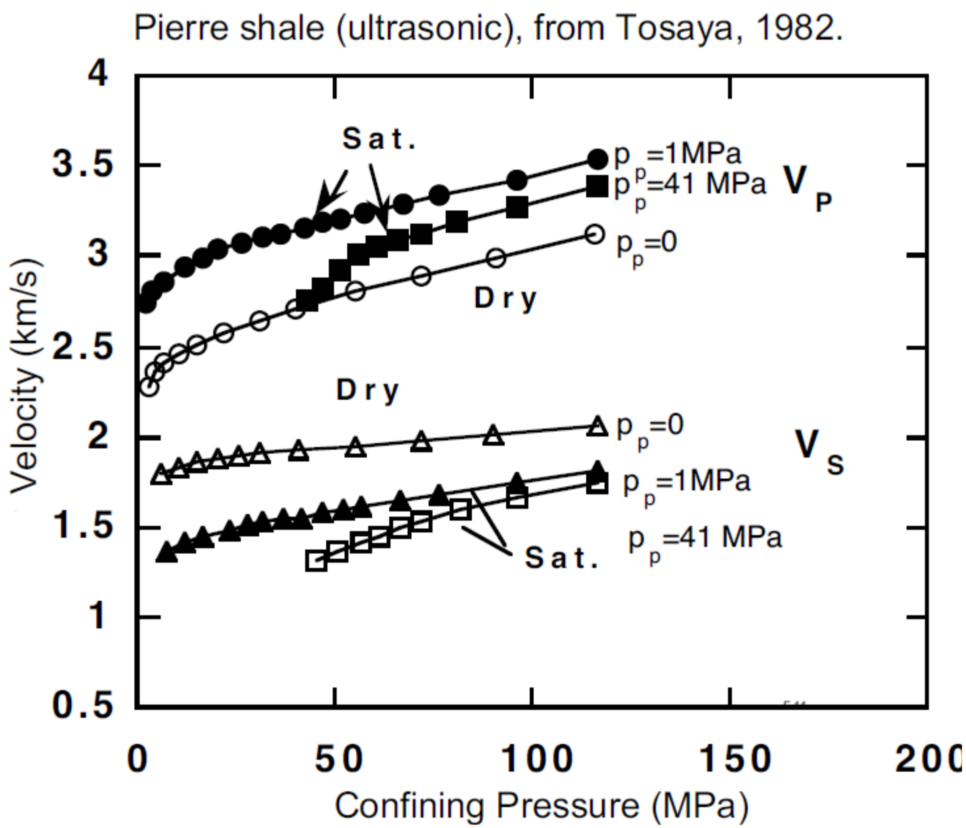
5. **Parameters that influence Seismic waves**

- Soft, Crack-Like Porosity



5. **Parameters that influence Seismic waves**

- Effective pressure-Dependence of Velocities

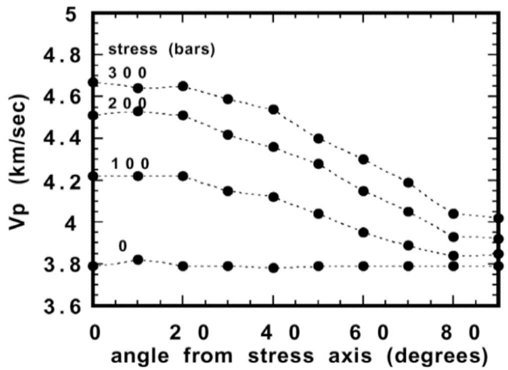


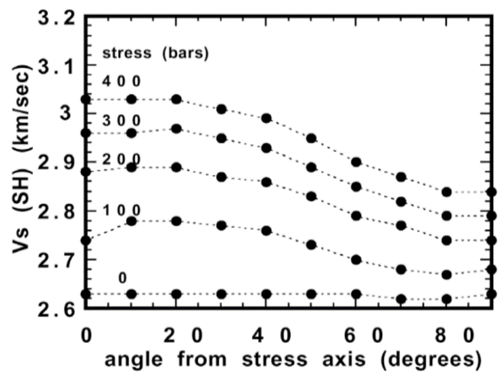
For shales, we also often see an increase of velocity with effective pressure. The rapid increase of velocity at low pressures is somewhat elastic, analogous to the closing of cracks and grain boundaries that we expect in sandstones.

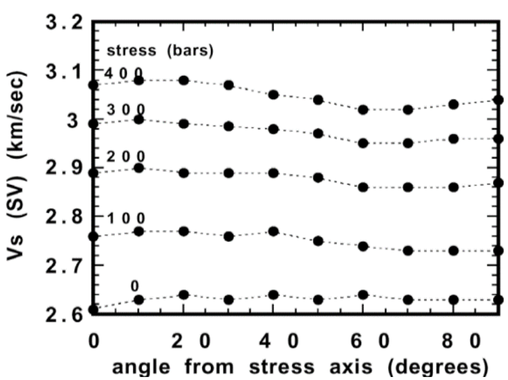
The high pressure asymptotic behavior shows a continued increase in velocity rather than a flat limit. This is probably due to permanent plastic deformation of the shale.

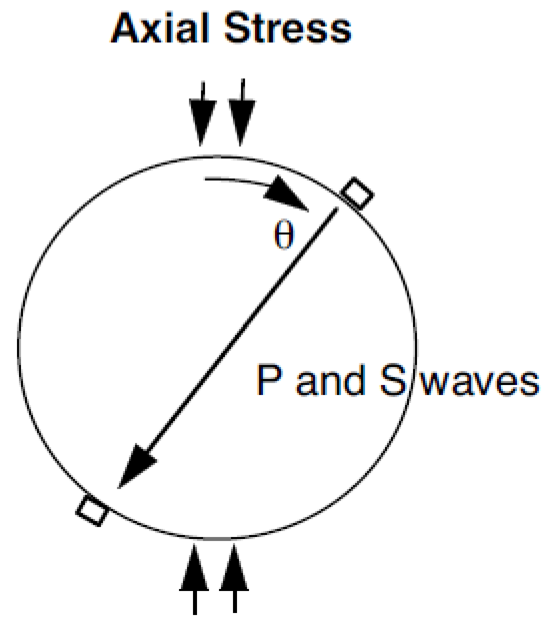
5. **Parameters that influence Seismic waves**

- Stress- induced velocity anisotropy







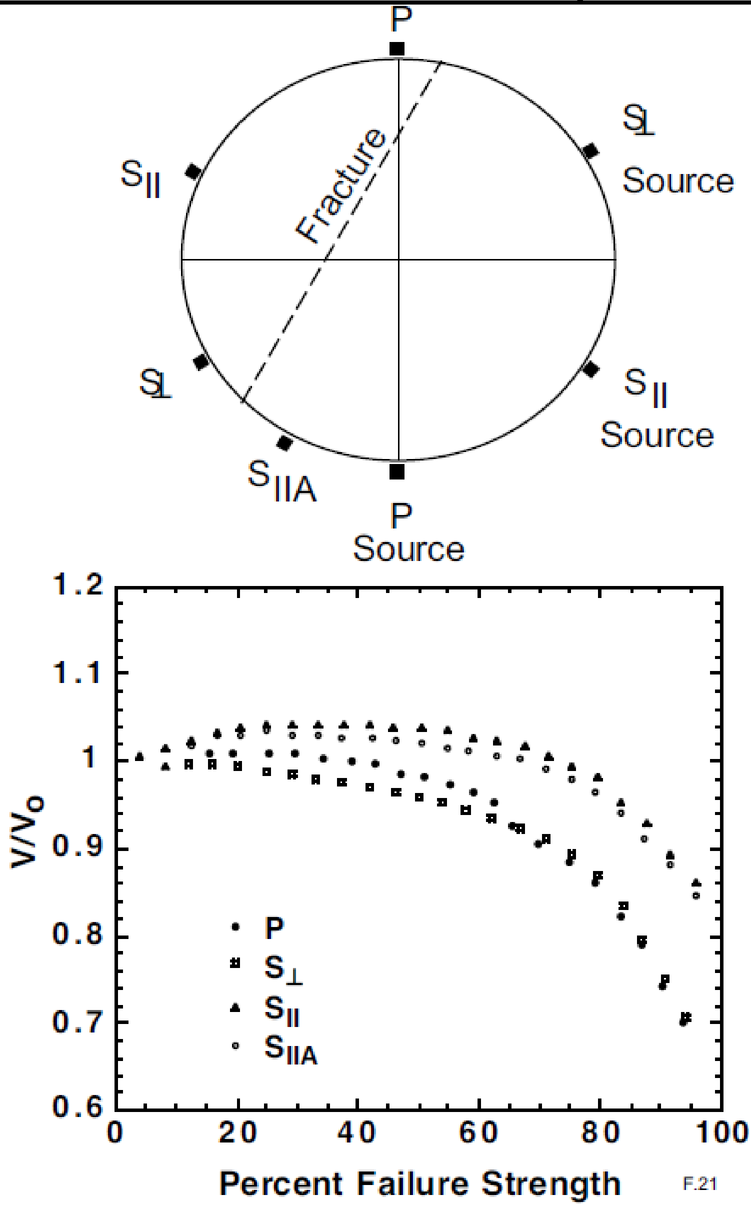


Stress-induced velocity anisotropy in Barre Granite (Nur, 1969). In this classic experiment, Nur manipulated the crack alignment by applying uniaxial stress. Initially the rock is isotropic, indicating an isotropic distribution of cracks. Cracks normal to the stress (or nearly so) closed, creating crack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

Nur, 1969

5. **Parameters that influence Seismic waves**

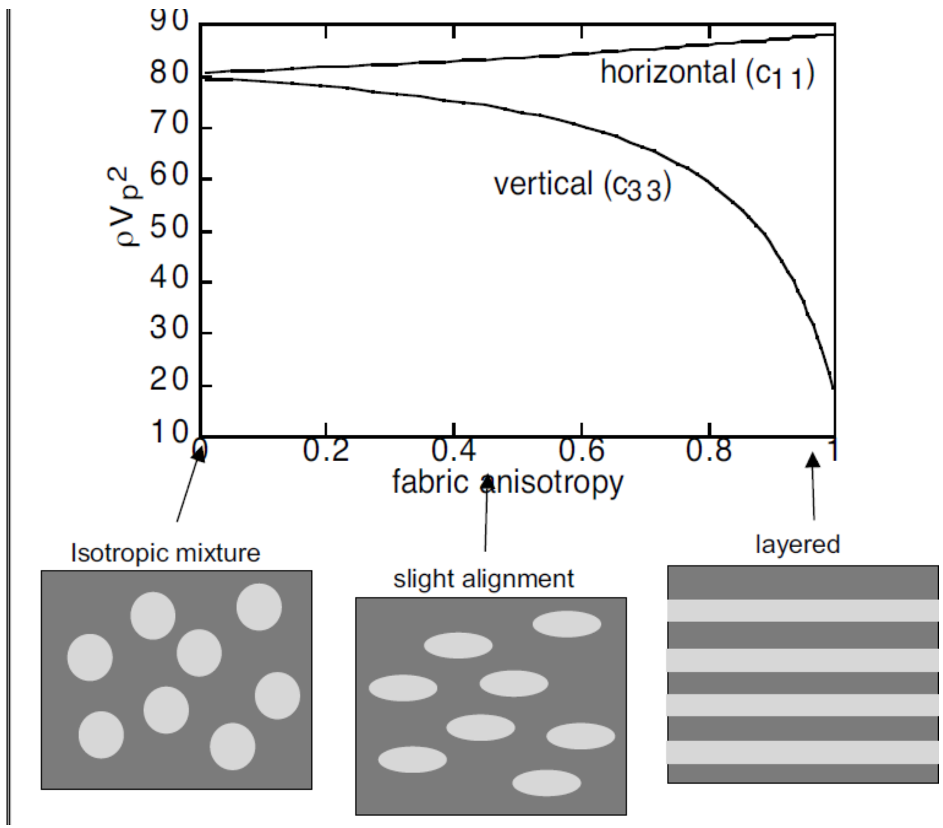
- Stress- induced velocity anisotropy



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

5. **Parameters that influence Seismic waves**

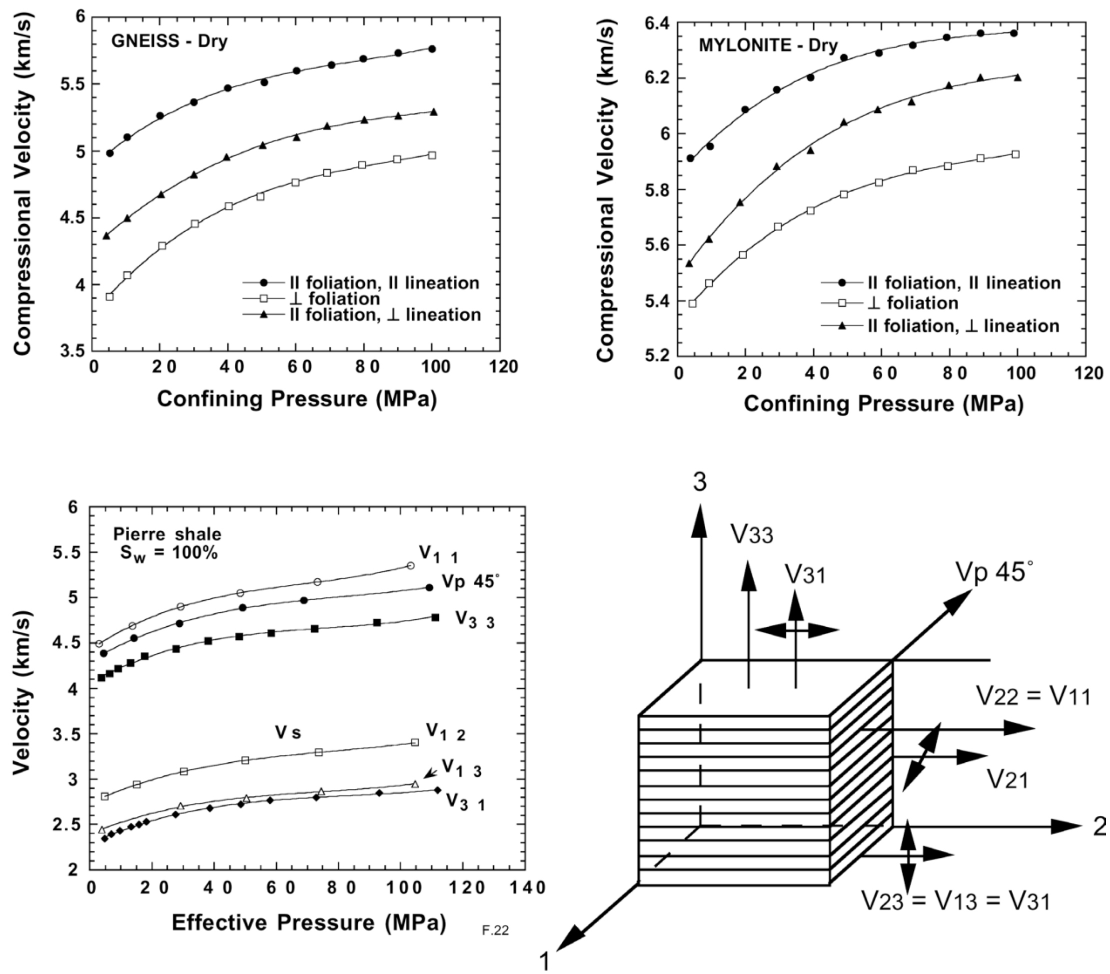
➢ Seismic Anisotropy Due to Rock Fabric



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.

5. **Parameters that influence Seismic waves**

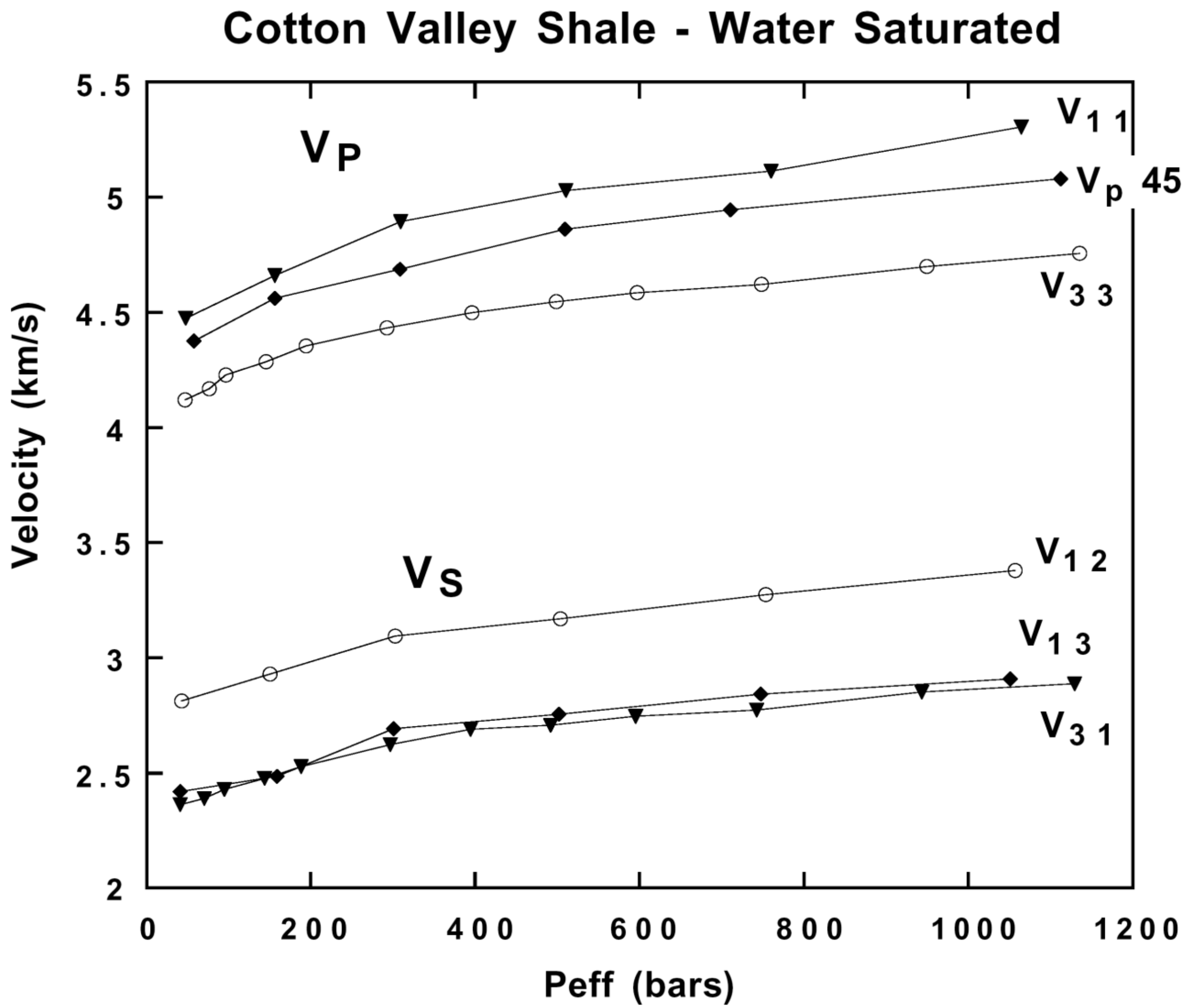
➢ Seismic Anisotropy Due to Rock Fabric



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

5. **Parameters that influence Seismic waves**

➤ Seismic Anisotropy Due to Rock Fabric



Cotton Valley shale (ultrasonic), from Tosaya, 1982