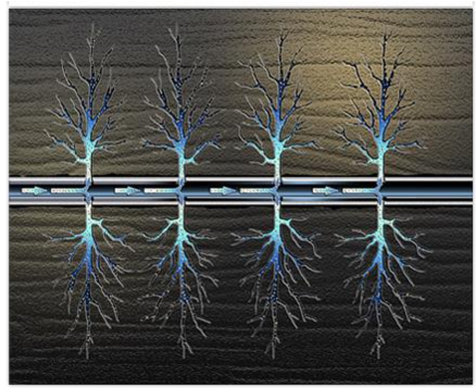
AESB3341 Petrophysics
Acoustics and Rock Mechanics

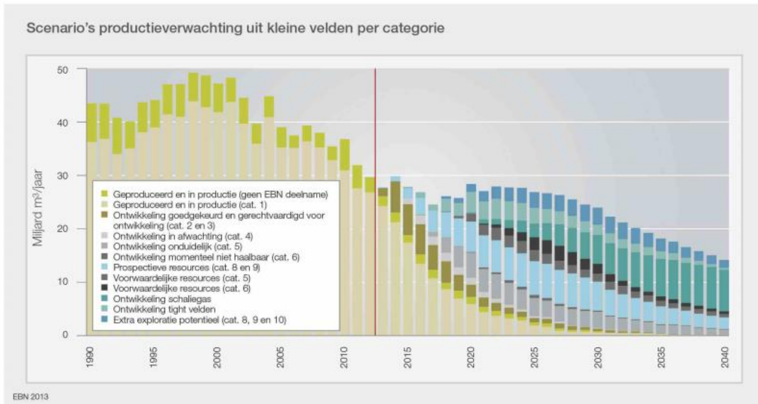
13-02-2015



Course schedule

- **Today Lectures in Rock Mechanics and Acoustics**
- **Next week: practical rock mechanics, acoustics, elasticity**

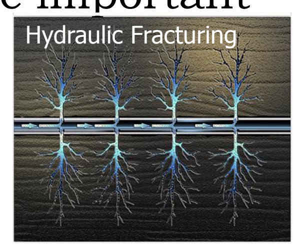
Introduction

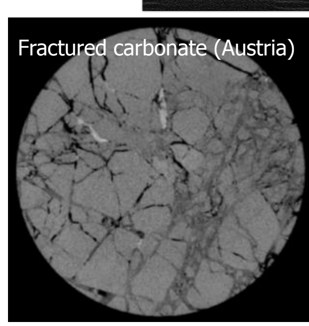


Not just in NL, but worldwide…

Fractured reservoirs more important

- Unconventional and tight gas reservoirs
- Fractured carbonates
- Deep geothermal energy





Societal relevance of rock mechanics

Induced seismicity

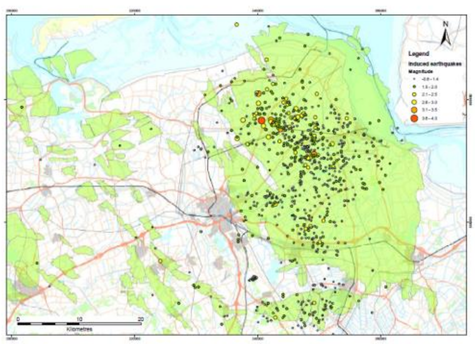


Figure 2.8 Epicenters of the registered earthquakes by the KNMI (till July 2013)


NRC HANDELSBLAD

Het China van Mao: Dood aan het volk! Boeken

Hamas staat alleen na coup in Egypte Buitenland 13

Wat ging er mis bij Marlies Dekkers Economie 21

Weg vrij voor proefboring naar schaliegas

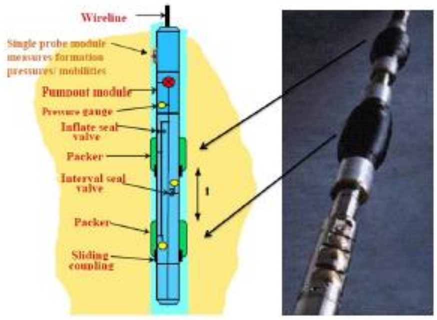
Rusland: experts naar plek van gifgas

Public acceptance of fracking

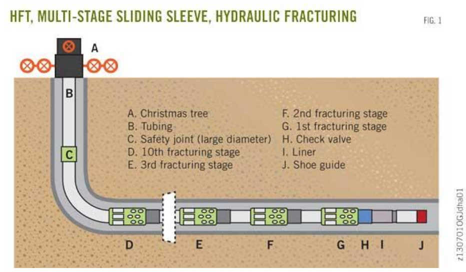
Subsurface information

- Acoustic logging:
  - link of log to seismics
  - determination of elastics constants – to be used for geomechanics
- Mechanical tests in reservoir
  - hydraulic fracturing
  - mini-fracture test

Wireline Mini-Fracture Tool



Hydraulic fracturing



Subsurface information

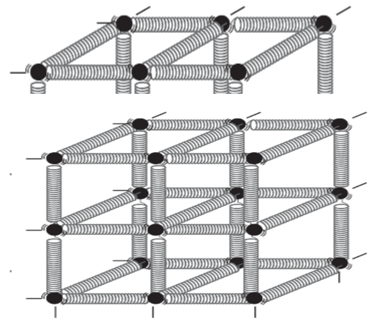
- Acoustic logging:
  - link of log to seismics
  - determination of elastics constants – to be used for geomechanics
- Mechanical tests in reservoir
  - hydraulic fracturing
  - mini-fracture test

- Today:
  - Elasticity
  - Acoustics for determination of elastic parameters
  - Rock mechanical test for determination of elastic parameters

Elastic behaviour

- Definition elasticity
  - In physics, **elasticity** is a physical property of materials which return to their original shape after the stress that caused their deformation is no longer applied.

http://en.wikipedia.org/wiki/Elasticity_%28physics%29



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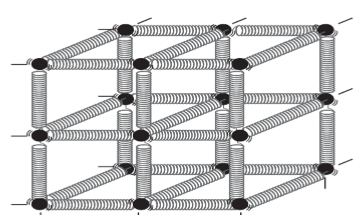

Elastisch gedrag

- Definition elasticity
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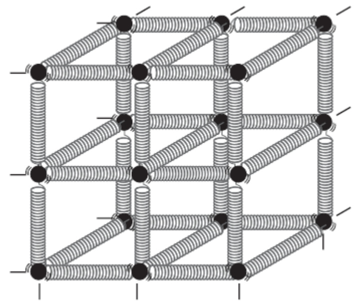
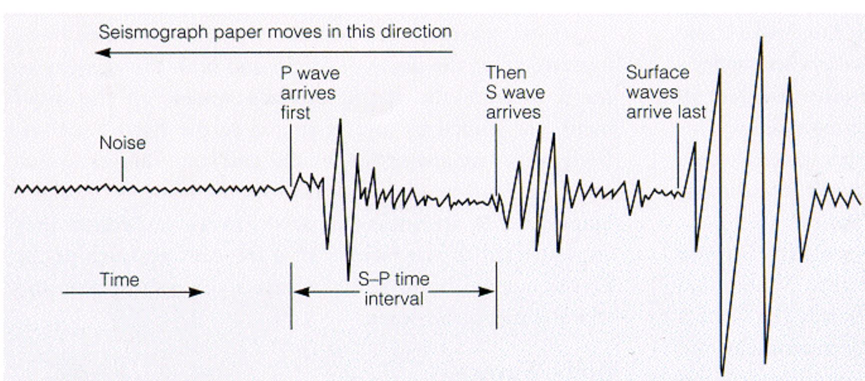
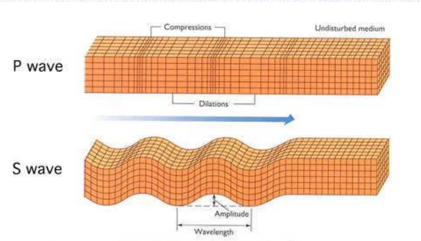


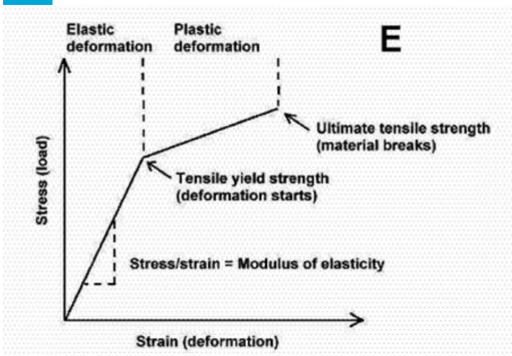
Seismic waves



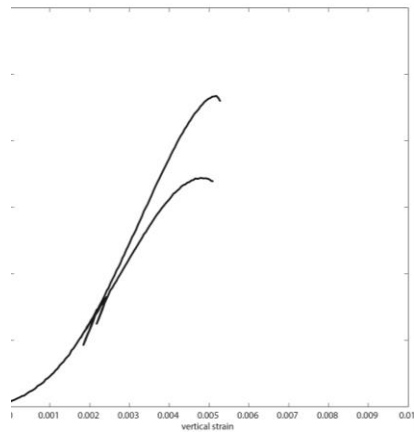
http://www.tjhsst.edu/~jlafever/wanimate/Wave_Properties2.html



Elasticity



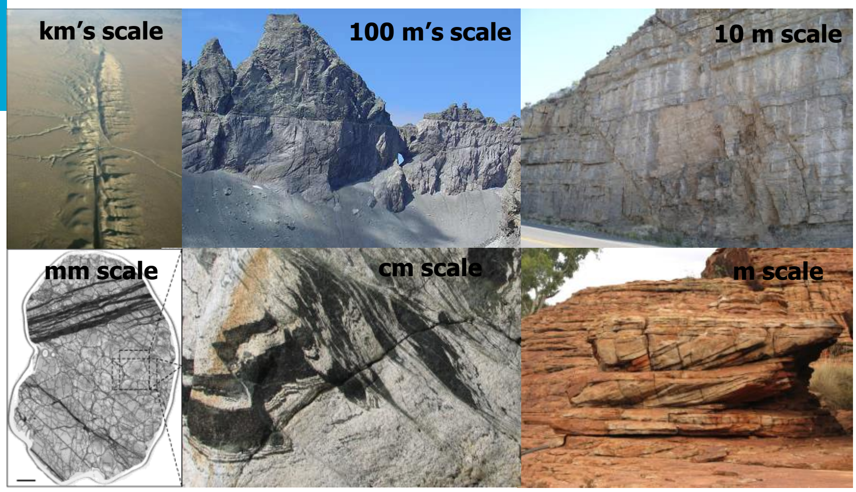
sandstone



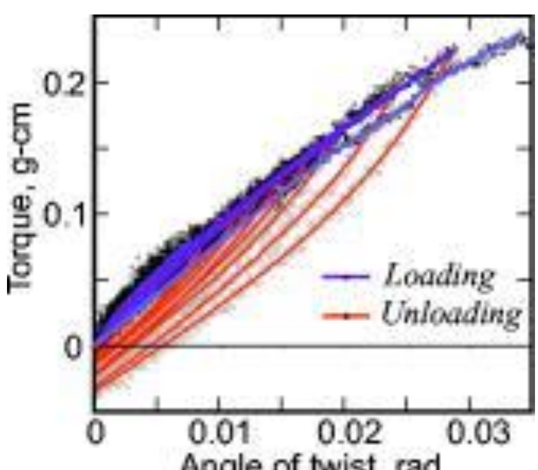
Inelastic behaviour

Transition to inelasticity
Above a certain stress known as the elastic limit or the yield strength of an elastic material, the relationship between stress and strain becomes non-linear. Beyond this limit, the solid may deform irreversibly, exhibiting plasticity.

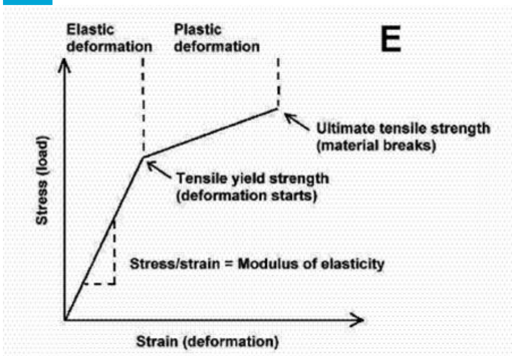
Fractures on Earth



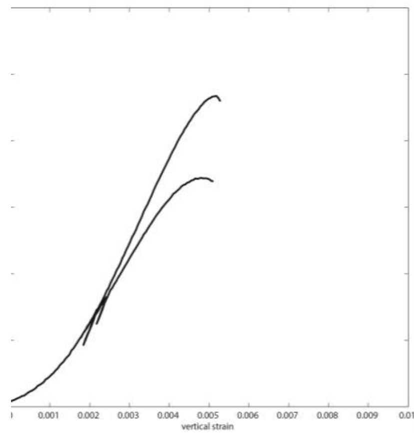
Inelastic behaviour



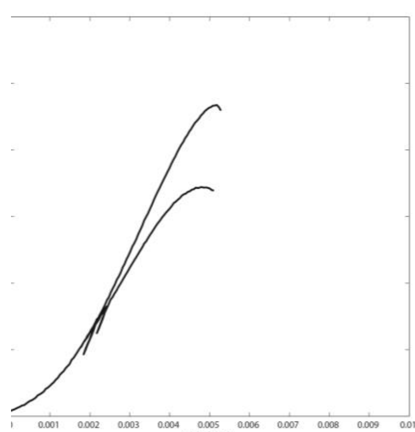
Elasticity



sandstone



Sandstone



Elastic Moduli

- **Elastic moduli describe the elastic behaviour of a rock**
  - **Rock type dependent**
  - **Can vary with change in conditions (P,T)**

  - Used to predict & quantify elastic mechanical behaviour of rocks
    - Experiments
    - Geomechanical numerical modelling
    - Reservoir simulations
    - Etc.

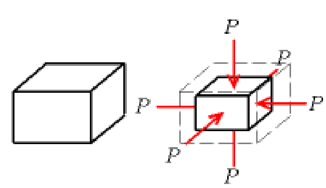
- Wave propagation in seismics/geophysics can almost always be described by elasticity.

Bulk modulus

The elastic mechanical behavior of a material can completely be described by the bulk and shear modulus.

- The bulk modulus K_b [Pa] (also compression modulus) gives the resistance against deformation due to uniform compression and is defined by the hydrostatic pressure increase Δp that is necessary for a relative volume decrease $\Delta V/V$:

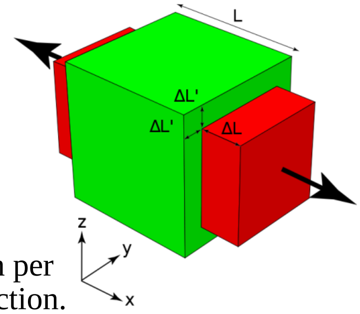
$$K_b = -V \frac{\partial p}{\partial V}$$



in which V is the initial volume that changes ΔV due to Δp.

Young's modulus

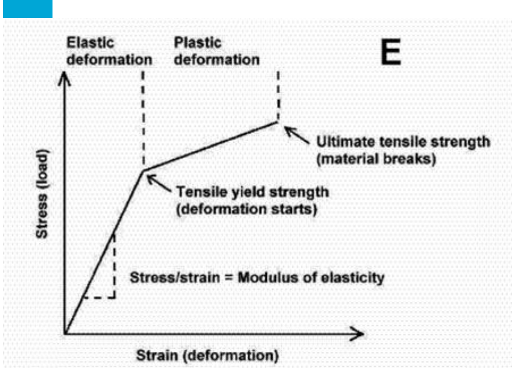
Young's modulus E [Pa] is a measure of the stiffness of the material and is given by the ratio of uniaxial stress σ_{xx} [Pa] and uniaxial strain ε_{xx} [-].



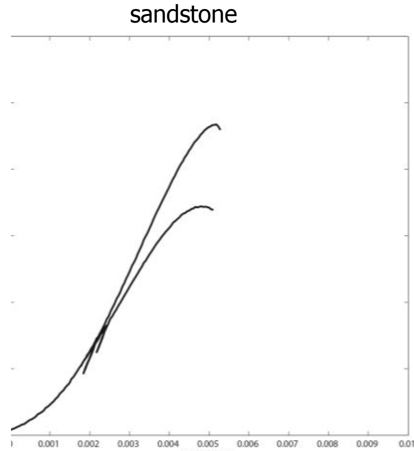
with $$E = \frac{\sigma_{xx}}{\varepsilon_{xx}} = \frac{9K_b\mu}{3K_b + \mu}$$

- $\sigma_{xx} = F/A$ is the force F in the x-direction per area A with the normal in the x-direction.
- $\varepsilon_{xx} = \Delta L/L$ is the relative change in length (tension or compression) in the x-direction due to a force in the x-direction.

Elasticity



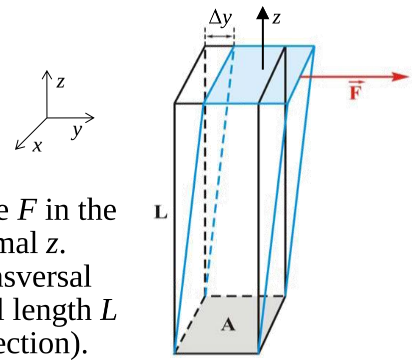
sandstone



Shear modulus

- The shear modulus μ (or G) [Pa] gives the resistance against deformation due to shearing and is defined by the shear strain ε_{ij} as a result of a shearing stress σ_{ij}. For example:

in which $\mu = \dfrac{\sigma_{zy}}{2\varepsilon_{zy}}$

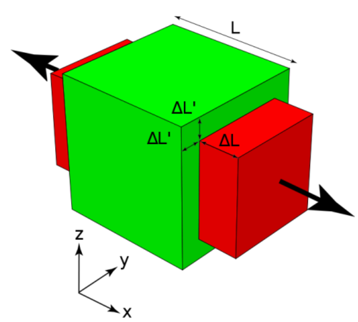


- the shear stress $\sigma_{zy} = F/A$ is the force F in the y-direction per area A with normal z.
- the shear strain $\varepsilon_{zy} = \Delta y/L$ is the transversal displacement Δy over the initial length L perpendicular to A (in the z-direction).

Poisson's ratio

Poisson's ratio v [-] describes the strain in the transversal direction (e.g. y and z), which originates from tension (stretching) or compression in the axial direction (e.g. x).

with $$v = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}} = \frac{3K_b - 2\mu}{2(3K_b + \mu)}$$



- $\varepsilon_{xx} = \Delta L/L$ is the uniaxial strain.
- $\varepsilon_{yy} = \Delta L'/L'$ is the transversal (or lateral) strain.

Elastic relationships in isotropic materials

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

Mavko, 2003

Determine Poisson's ratio using van Kb and μ

$$\nu = \frac{3K_b - 2\mu}{2(3K_b + \mu)}$$

Determine Young's modulus using Kb and μ

$$E = \frac{9K_b\mu}{3K_b + \mu}$$

Message: if you have 2 elastic constants, you can calculate all 4!!

Elastic relationships in isotropic materials

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

Mavko, 2003

Examples of earth's materials

Mineral	Density	Young's Modulus	Bulk Modulus	Shear Modulus	Vp	Vs	Poisson's Ratio
Quartz	2.6500	95.756	36.600	45.000	6.0376	4.1208	0.063953
Calcite	2.7100	84.293	76.800	32.000	6.6395	3.4363	0.31707
Dolomite	2.8700	116.57	94.900	45.000	7.3465	3.9597	0.29527
Clay (kaolinite)	1.5800	3.2034	1.5000	1.4000	1.4597	0.94132	0.14407
Muscovite	2.7900	100.84	61.500	41.100	6.4563	3.8381	0.22673
Feldspar (Albite)	2.6300	69.010	75.600	25.600	6.4594	3.1199	0.34786
Halite	2.1600	37.242	24.800	14.900	4.5474	2.6264	0.24972
Anhydrite	2.9800	74.431	56.100	29.100	5.6432	3.1249	0.27888
Pyrite	4.9300	305.85	147.40	132.50	8.1076	5.1842	0.15417
Siderite	3.9600	134.51	123.70	51.000	6.9576	3.5887	0.31876
gas	0.00065000	0.0000	0.00013000	0.0000	0.44721	0.0000	0.50000
water	1.0000	0.0000	2.2500	0.0000	1.5000	0.0000	0.50000
oil	0.80000	0.0000	1.0200	0.0000	1.1292	0.0000	0.50000

Mavko, 2003

Table J-2

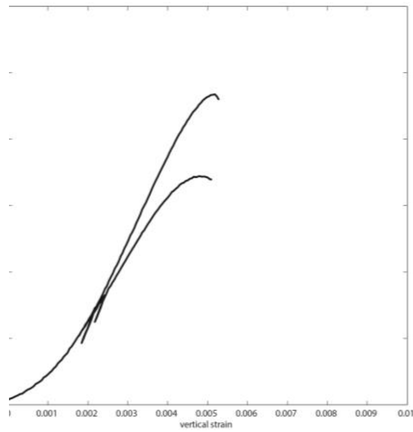
Acoustic parameters of certain minerals, rocks and fluids (from Ellis *et al.*, 1988).

	ρ g/cm^3	K GPa	μ GPa	Δt_c µs/ft	Δt_s µs/ft	$\Delta t_c/\Delta t_s$	Poisson's ratio
Mineral							
Quartz	2.65	36.6	45.0	50.5	74.0	1.48	0.35
Calcite	2.71	76.8	32.0	45.9	88.7	1.93	0.32
Aragonite	2.92	44.8	38.8	53.0	83.6	1.57	0.16
Dolomite	2.87	94.9	45.0	41.5	77.0	1.86	0.30
Anhydrite	2.98	56.1	29.1	54.0	97.5	1.81	0.28
Halite	2.16	24.8	14.9	67.0	116.0	1.73	0.25
Muscovite	2.79	61.5	41.1	47.2	79.4	1.68	0.23
Biotite	3.05	59.7	42.3	49.4	81.8	1.83	0.21
Pyrite	4.93	147.4	48.7	36.2	56.0	1.55	0.15
Hematite	5.24	100.2	95.2	46.3	71.5	1.54	0.14
Siderite	3.96	124.0	51.0	43.8	84.9	1.94	0.32
Rutile	4.26	217.1	108.1	33.1	60.5	1.83	0.29
Barite	4.51	54.5	23.8	69.7	132.7	1.90	0.31
Albite	2.63	75.6	25.67	47.2	97.7	2.06	0.35
Hornblende	3.20	95.3	44.8	44.0	81.5	1.86	
Steel				50.8			
Casing				57.1			
Iron				53.0			
Sulphur	2.02			122.0			
Aluminum				48.7			
Lead				141.1			
Concrete				~95.0			
Neoprene				192.5			
	ρ_{ma}	K_{ma}	μ_{ma}	Δt_{cma}	Δt_{sma}	$\Delta t_c/\Delta t_s$	
Rocks							
Sandstone	2.65	37.5	31.8	55.5	88.0	1.59	
Limestone	2.71	70.1	31.1	47.5	88.5	1.86	
Dolostone	2.87	82.9	43.5	~43.5	78.5	1.80	
Anhydrite	2.98	67.1	32.7	50.0	92.0	1.84	
Granite	2.56-2.68			46.8-53.5			
Basalt	2.7-2.9			57.5			
Gypsum	2.35			52.5			
Polyhalite	2.79			57.5			
Trona	2.08			65.0			
Halite	2.04			66.7			
Carnalite	1.57			83.3			
Sylvite	1.86			74.0			
Langbeinite	2.82			52.0			
Anthracite	1.47			90-120			
Limonite	3.55	60.1	31.3	56.9	102.6	1.80	0.28
Lignite	1.19			160.0			
Bitume	1.24			90-150			
Fluids							
Pure water	1.00	2.2		205.5			
Salty water	1.10	3.2-3.8		165-180			
Ice				87.1			
Mud	1.2	2.5-2.8		200-210			
Oil	~0.88			238			
Kerosene				214.5			
Methane	0.25			626			

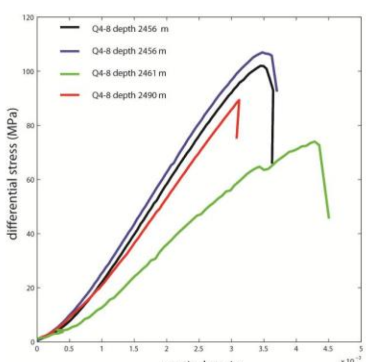
Elastic moduli

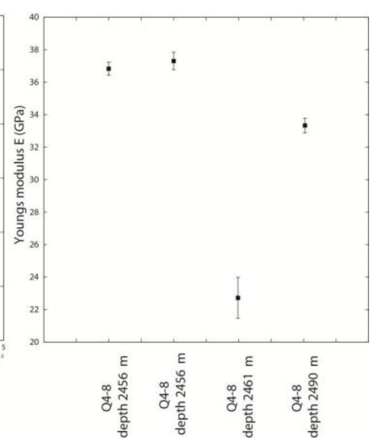
- If you know 2 elastic moduli (for isotropic materials) you can calculate all other moduli
- And thus fully describe the elastic behaviour of the material

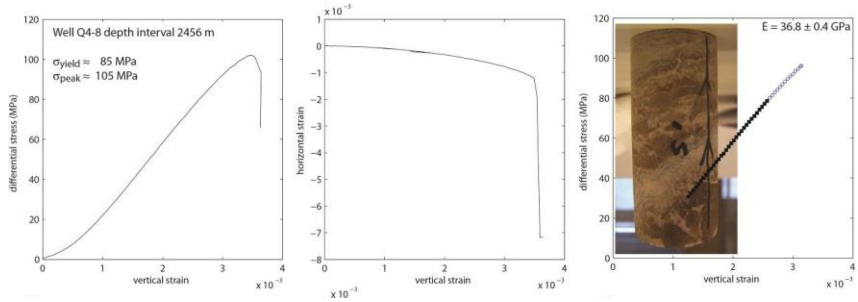
Rock Mechanics



Shaley sandstone







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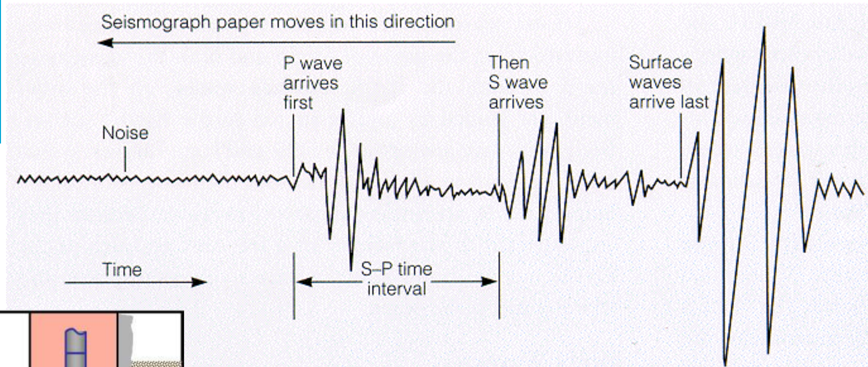
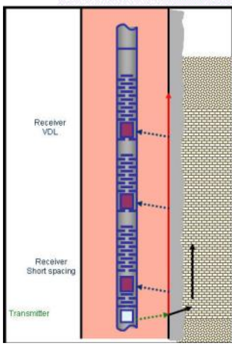
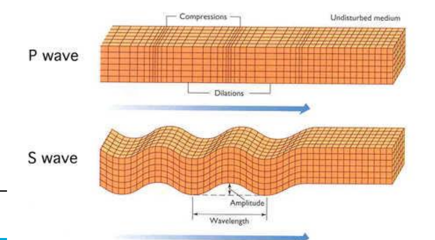
$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}} = \frac{3K_b - 2\mu}{2(3K_b + \mu)}$$

Acoustics logging

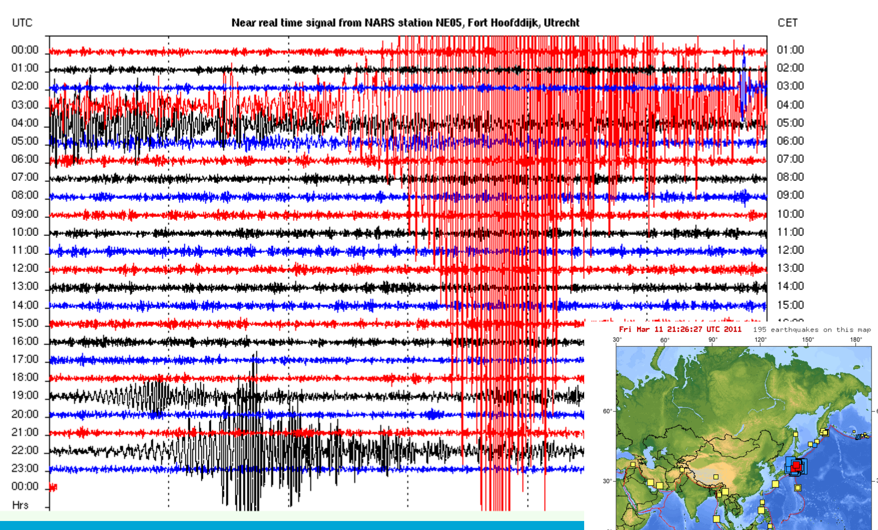
Seismic waves



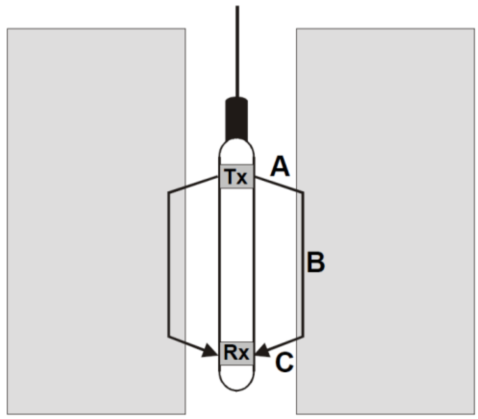




Seismogram of M 7.2 Earthquake, Japan, 9th of March 2011 registered in Utrecht (the Netherlands)

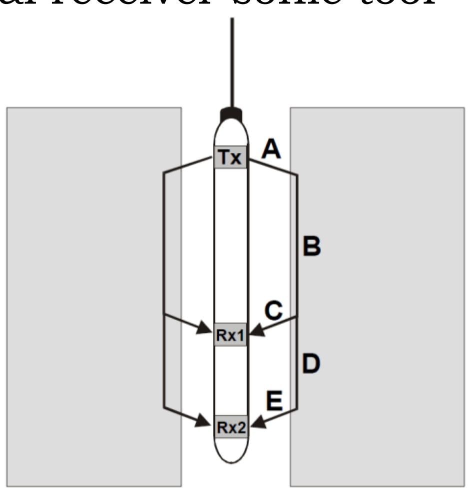


Sonic Tools: 1st generation



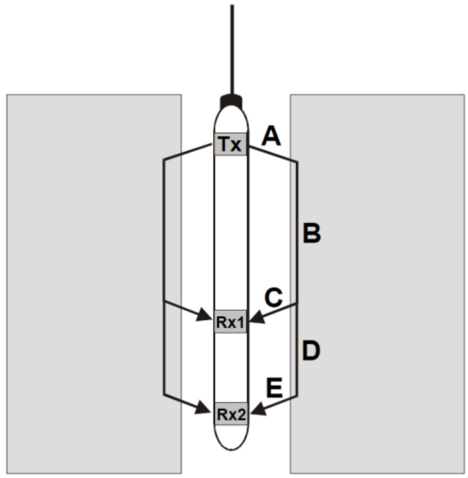
Travel time always too long…, WHY?

Sonic Tools: 1st generation dual receiver sonic tool



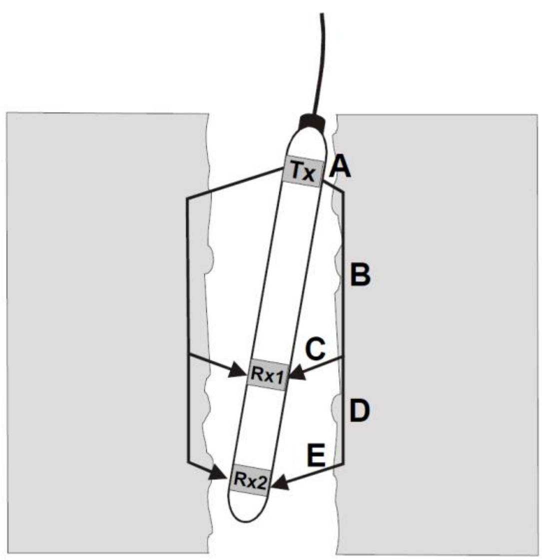
Travel time determined correctly…, WHY?

Sonic Tools: 1st generation dual receiver sonic tool



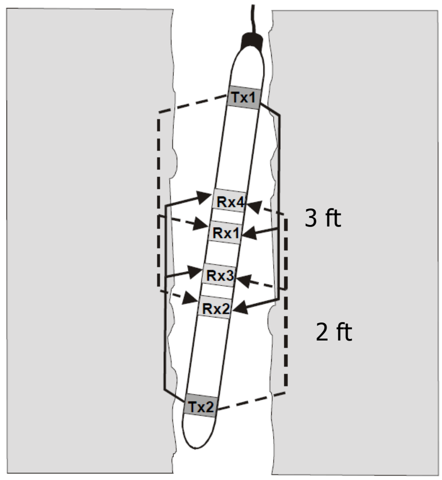
A+B+D+E –(A+B+C) = D+E-C
If C = E, so Trx2-Trx1 = D

In tilted configuration



C ≠ E

Borehole Compensated Sonic (BHC) Tool



Two pairs of receiver signals are averaged e.g. Tx1-Rx1 and Tx2-Rx3

Logging Speed / Resolution

A typical pulse for the BHC is 100 µs to 200 µs, with a gap of about 50 ms, giving about 20 pulses per second. There are four individual Tx-Rx readings needed per measurement, so 5 measurements can be made per second. At a typical logging speed of 1500 m/h (5000 ft/h), gives one reading per 8 cm (3 inches) of borehole. Several versions of the BHC are available with different Tx-Rx distances (3 ft. and 5 ft. being typical), and the Rx-Rx distance between pairs of receivers is usually 2 ft.

Depth of Investigation

This is complex and will not be covered in great detail here. In theory, the refracted wave travels along the borehole wall, and hence the depth of penetration is small (2.5 to 25 cm). It is independent of Tx-Rx spacing, but depends upon the wavelength of the elastic wave, with larger wavelengths giving larger penetrations. As wavelength $\lambda = V/f$ (i.e., velocity divided by frequency), for any given tool frequency, the higher the velocity the formation has, the larger the wavelength and the deeper the penetration.

Common Industry Names

Tool	Mnemonic	Company
Compensated sonic sonde	CSS	BPB
Long spaced compensated sonic	LCS	
Borehole compensated sonde	BCS	Halliburton
Long spaced sonic	LSS	
Borehole compensated sonic	BHC	Schlumberger
Long spaced sonic	LSS	
Array sonic (standard mode)	DTCO	
Borehole compensated acoustilog	AC	Western Atlas
Long-spaced BHC acoustilog	ACL	

Tool Codes

- See Serro 2008 Well Logging Handbook Chapter 3 – book downloadable from TU Delft Library

Schlumberger

Tool code	Tool description
Surface equipment	
CSU	Cyber Service Unit
MAXIS 500	Multitask Acquisition & Imaging System
MAXIS Express	Multitask Acquisition & Imaging System
Resistivity - induction tools	
ACEN	Array Induction Toc
ADEPT	Adaptable Electron
AIT	Array Induction Ima
ALAT	Azimuthal Lateroloˌ
ARC5	Array Resistivity Cc
ARI	Azimuthal Resistivi
CDR	LWD Compensatec
CHFR	Cased-Hole Forma
CHFR-Plus	Cased-Hole Forma
DIL	Dual Induction Log
DIT	Dual Induction Tool
DLL	Dual Laterolog
EPT	Electromagnetic Pr
ES	Electrical Survey Ti
HALS	High Resolution Azimuthal Laterolog
HRLA	High Resolution Laterolog Array
IL	Induction Log
IRT	Induction Resistivity Tool

Acoustic tools

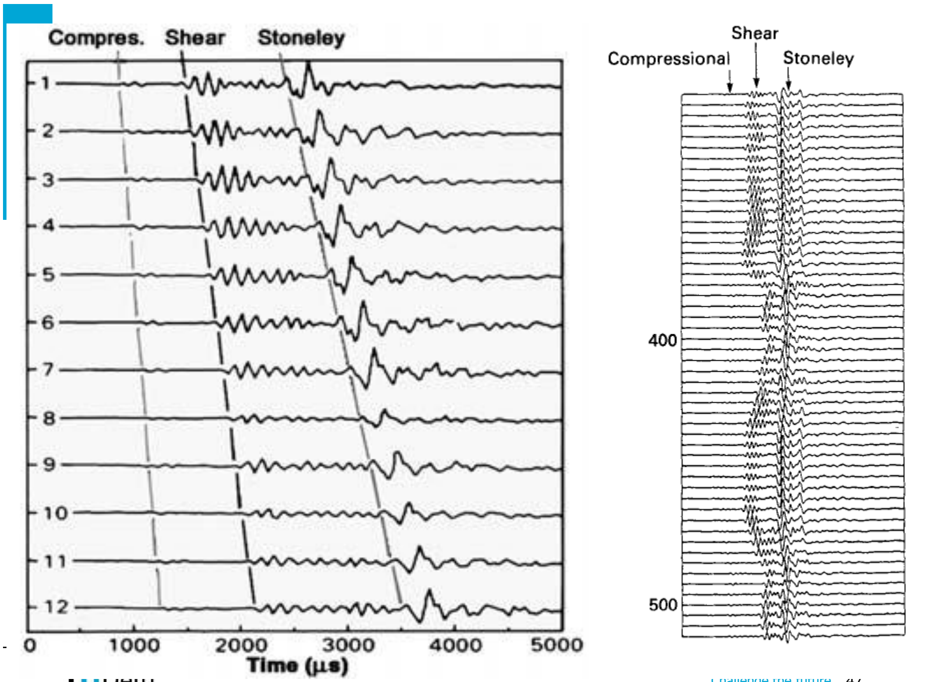
Array-Sonic	
DSI	Dipole Shear Sonic Imager
DSST	Dipole Shear Sonic Tool
ISONIC	LWD Sonic tool
LSS	Long-Spaced Sonic
SDT	Sonic Digital Tool
SL	Sonic Log
SLT	Sonic Logging Tool
Sonic Scanner	Radial and Axial Acoustic Scanning measurements
sonicVISION	LWD sonic tool

Slowness

In practice the sonic log data is not presented as a travel time, because different tools have different Tx-Rx spacings, so there would be an ambiguity. Nor is the data presented as a velocity. The data is presented as a *slowness* or the travel time per foot traveled through the formation, which is called delta t (Δt or ΔT), and is usually measured in μs/ft. Hence we can write a conversion equation between velocity and slowness:

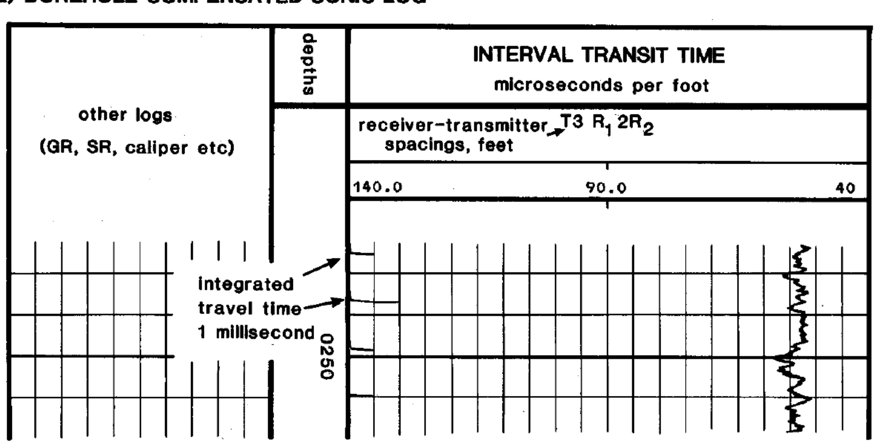
$$\Delta t = \frac{10^6}{V}$$

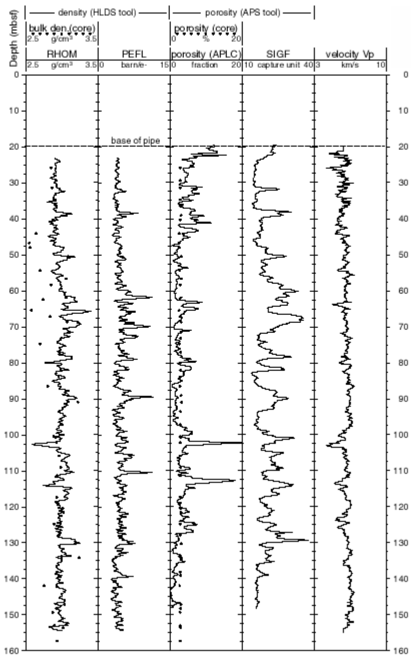
where the slowness, Δt is in microseconds per foot, and the velocity, V is in feet per second.



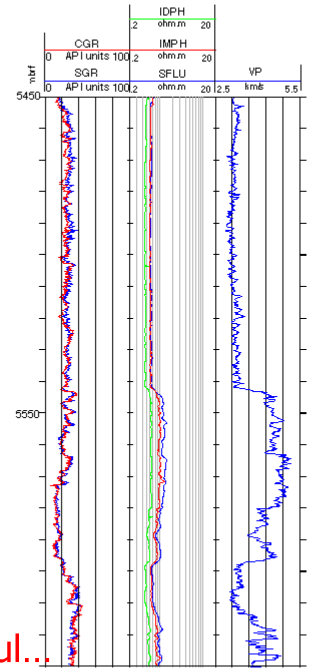
Examples of sonic logs

(a) BOREHOLE COMPENSATED SONIC LOG

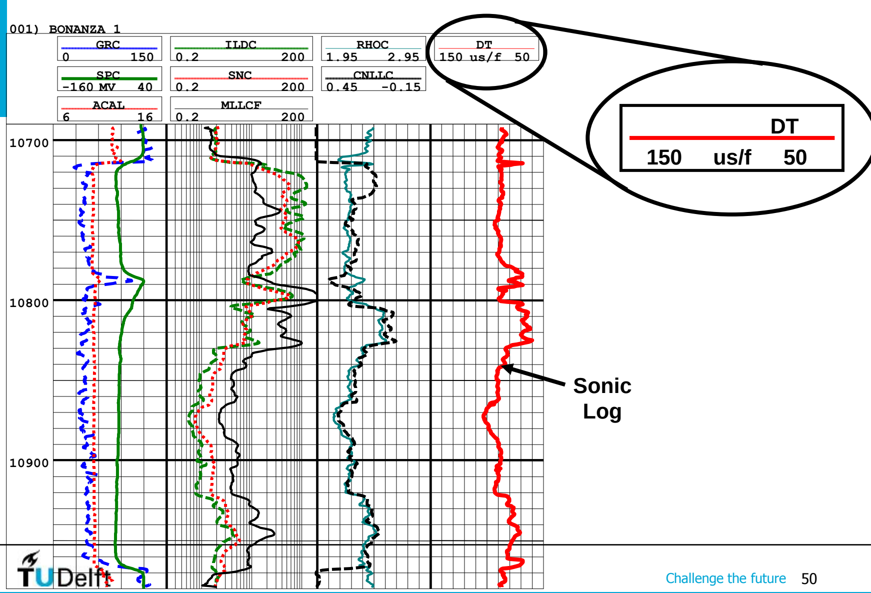




be careful…



SONIC LOG



COMMON LITHOLOGY MATRIX TRAVEL TIMES USED

Lithology	Typical Matrix Travel Time, Δt_{ma}, µsec/ft
Sandstone	55.5
Limestone	47.5
Dolomite	43.5
Anydridte	50.0
Salt	66.7

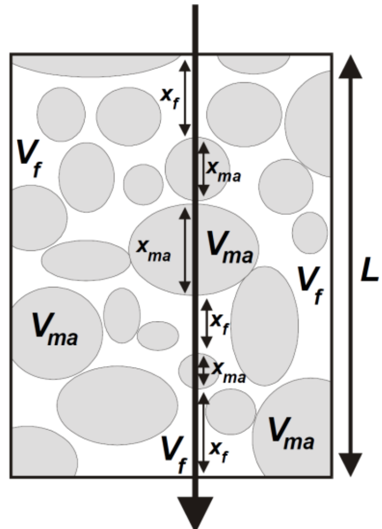
Wave speeds rocks

Material	Δt (µs/ft.)	V (ft./s)	V (m/s)
Compact sandstone	55.6 – 51.3	18000 – 19500	5490 – 5950
Limestone	47.6 – 43.5	21000 – 23000	6400 – 7010
Dolomite	43.5 – 38.5	23000 – 26000	7010 – 7920
Anhydrite	50.0	20000	6096
Halite	66.7	15000	4572
Shale	170 – 60	5880 – 16660	1790 – 5805
Bituminous coal	140 – 100	7140 – 10000	2180 – 3050
Lignite	180 – 140	5560 – 7140	1690 – 2180
Casing	57.1	17500	5334
Water: 200,000 ppm, 15 psi	180.5	5540	1690
Water: 150,000 ppm, 15 psi	186.0	5380	1640
Water: 100,000 ppm, 15 psi	192.3	5200	1580
Oil	238	4200	1280
Methane, 15 psi	626	1600	490

Sonic log - porosity

Wyllie Time Average Equation

$$\frac{1}{V} = \frac{\phi}{V_p} + \frac{(1-\phi)}{V_{ma}}$$



Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, **21**, no. 1, 41-70.

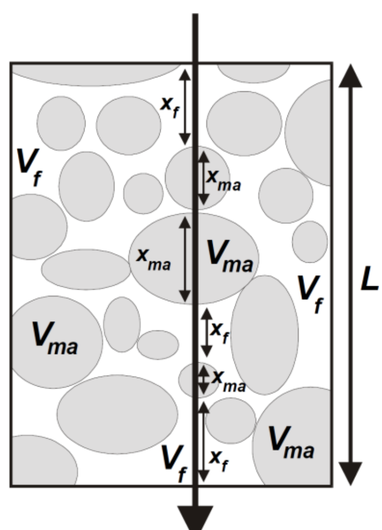
Sonic log - porosity

Wyllie Time Average Equation

$$\frac{1}{V} = \frac{\phi}{V_p} + \frac{(1-\phi)}{V_{ma}}$$

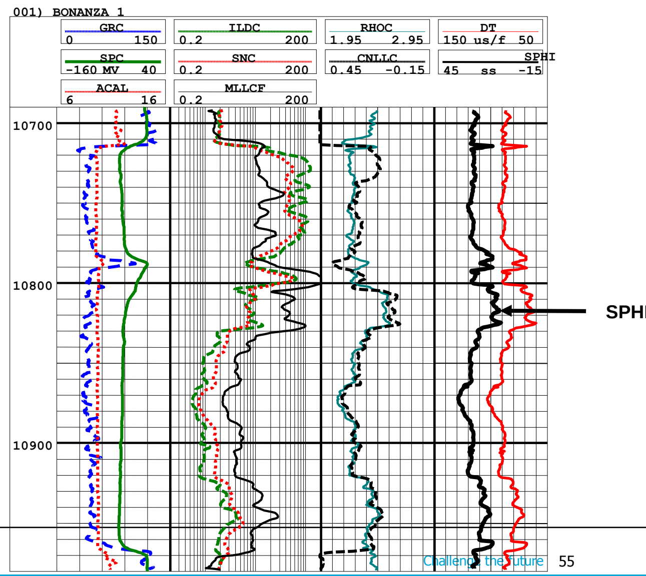
$$\Delta t = \phi\, \Delta t_p + (1-\phi)\Delta t_{ma}$$

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_p - \Delta t_{ma}}$$



Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, **21**, no. 1, 41-70.

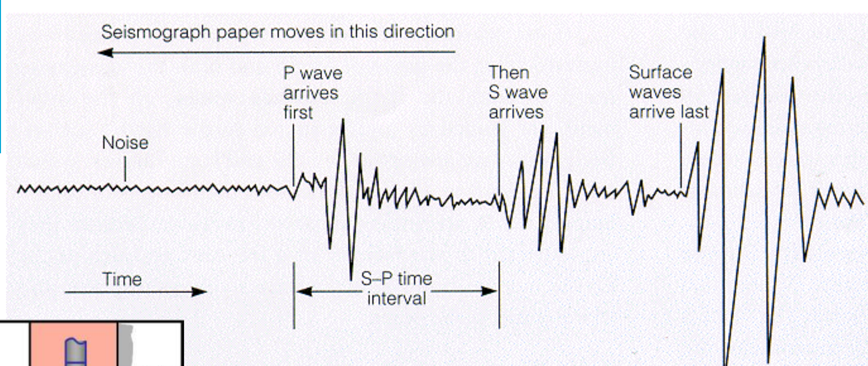
EXAMPLE SOLUTION SONIC LOG

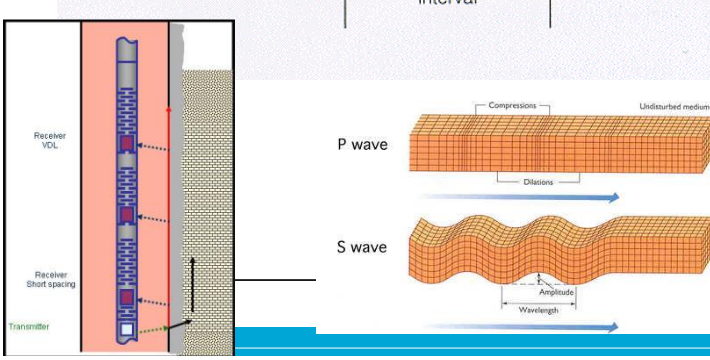


Assume a matrix travel time, Δt_m = 51.6 μsec/ft.

In addition, assume the formation is saturated with water having a Δt_f = 189.0 μsec/ft.

Seismic waves



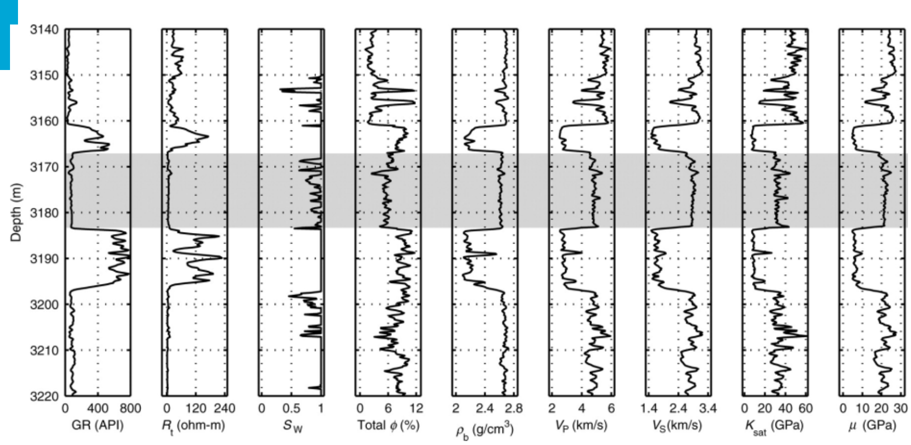


Few recordings of Vp and Vs simultaneously in boreholes

Table J-4
Logging While Drilling (LWD) acoustic sondes proposed by the main service companies.

Company tool Name	T.	Frequency (kHz)	R.A.	T.-R. sp. (ft)	R.-R. (in.)	Measurement type	Acoust. Aper. (ft)	Accuracy (μs/ft))
Schlumberger SonicVISION		wide	4			Δt_C, Δt_S	2	1
Halliburton/ Sperry Sun Bi-modal AcousTic BAT sensor	2	6-8 & 12-15 in phase or opposite phase	2A of 7		6	Δt_C, Δt_S		
Baker-Hughes SoundTrak (Acoustic Properties eXplorer APX)	1 Q	10-18 M; 2-6 Q	4x6 A		9	Δt_C, Δt_S, Δt_{St}	45 in.	

T. : transmitter; R. : receiver; A. : array; sp. : spacing; Aper. : aperture; M. : monopole; Q. : quadrupole.



Determine elastic moduli using acoustic waves

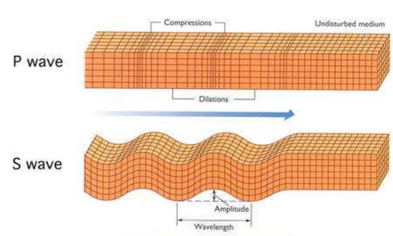
- The wave speeds (*Vp* en *Vs* [m/s]) of a pressure wave and shear wave determines together with the density of the material the bulk en shear moduli

- Thus to determine E, μ, Kb, Poisson's ratio etc you need:
  - Vp
  - Vs
  - Density.

Vp and Vs

$$\mu = v_s^2 \rho$$

$$K_b = (v_p^2 - \frac{4}{3} v_s^2)\rho$$

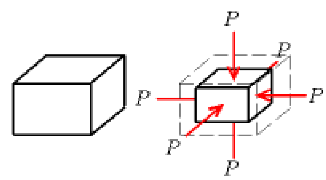


Bulk modulus

The elastic mechanical behavior of a material can completely be described by the bulk and shear modulus.

- The bulk modulus K_b [Pa] (also compression modulus) gives the resistance against deformation due to uniform compression and is defined by the hydrostatic pressure increase Δp that is necessary for a relative volume decrease $\Delta V/V$:

$$K_b = -V \frac{\partial p}{\partial V}$$

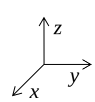


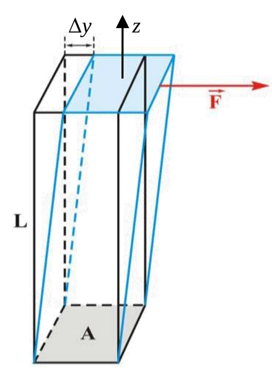
in which V is the initial volume that changes ΔV due to Δp.

Shear modulus

- The shear modulus μ (or G) [Pa] gives the resistance against deformation due to shearing and is defined by the shear strain ε_{ij} as a result of a shearing stress σ_{ij}. For example:

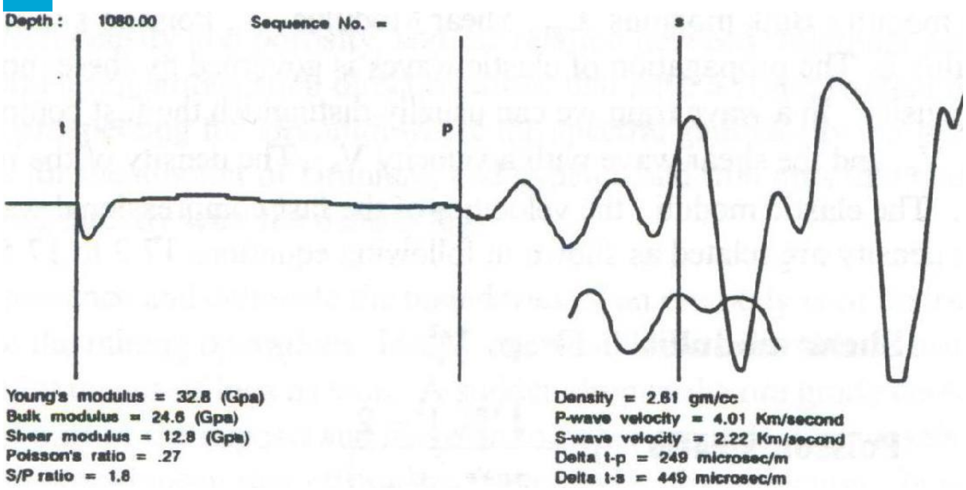
in which $\mu = \dfrac{\sigma_{zy}}{2\varepsilon_{zy}}$

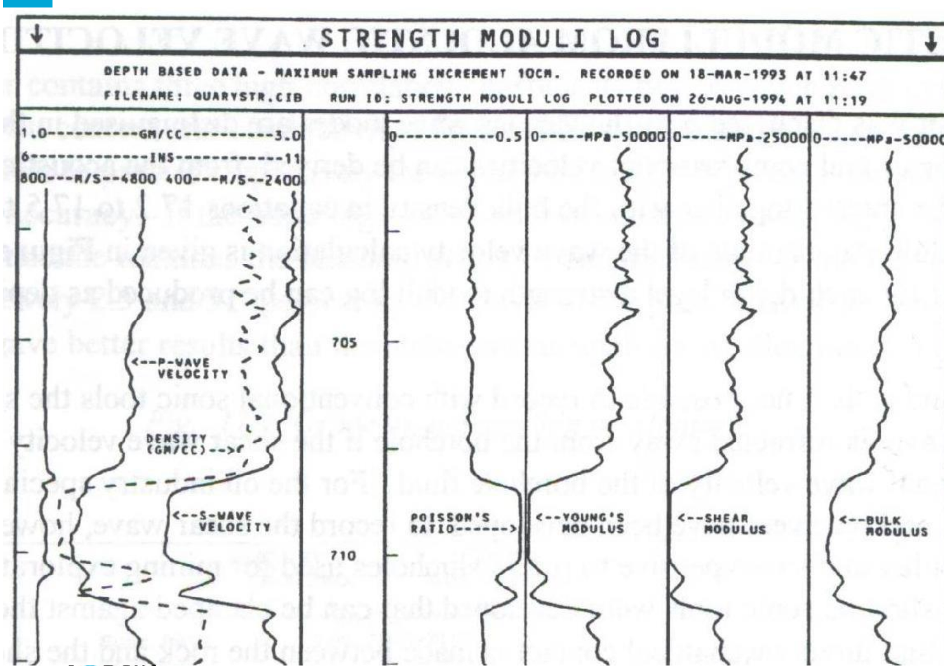




- the shear stress $\sigma_{zy} = F/A$ is the force F in the y-direction per area A with normal z.
- the shear strain $\varepsilon_{zy} = \Delta y/L$ is the transversal displacement Δy over the initial length L perpendicular to A (in the z-direction).

Example velocity and moduli





Exercise

- Sandstone ρ = 2.65 g/cm3, Vp = 5491 m/s. Vs = 3463 m/s
- Limestone ρ = 2.71 g/cm3, Vp = 6417 m/s. Vs = 3444 m/s
-
- Wat are Kb, μ, E and ν for these 2 rock types?

Moduli

- Bulk modulus $$K_b = -V\frac{\partial p}{\partial V}$$
- Shear modulus $$\mu = \frac{\sigma_{zy}}{\varepsilon_{zy}}$$

Direct from acoustic borehole data

- Poisson's ratio $$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$
- Young's modulus $$E = \frac{\sigma_{xx}}{\varepsilon_{xx}}$$

Direct from lab experimental data

Questions

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  - 015-2789682
  - room 3.01 (in Delft on: Mon, Tue, Thu & Fri)

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