Advanced Petrophysics: Porosity, Part 1 of 3

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PGE381L Outline

- Introduction to petrophysics, geology, and formation data
- **Porosity**
- Fluid saturations
- Permeability
- Quantification of heterogeneity, spatial data analysis, and geostatistics
- Interfacial phenomena and wettability
- Capillary pressure
- Relative permeability
- Dispersion in porous media
- Introduction to petrophysics of unconventional reservoirs

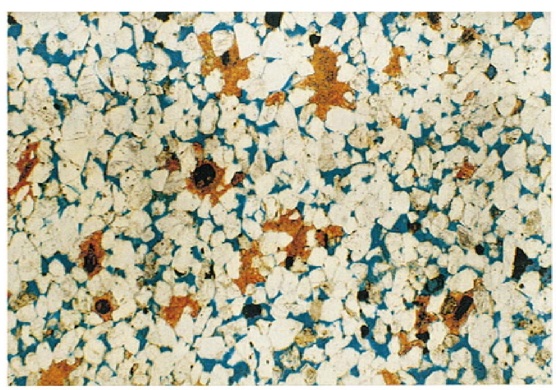
What do we Learn in this Lecture?

- What is porosity?
- What are the different types of porosity?
- Factors affecting porosity
- How to estimate porosity in the laboratory?
- How to estimate porosity in-situ condition?
- How does presence of clay minerals affect porosity assessment?
- Laboratory vs. in-situ estimates of porosity

What is Porosity?

$$\phi = \frac{V_p}{V_b} = \frac{V_p}{V_p + V_g}$$

V_p: Void space or pore volume
V_b: Bulk volume
V_g: Grain volume

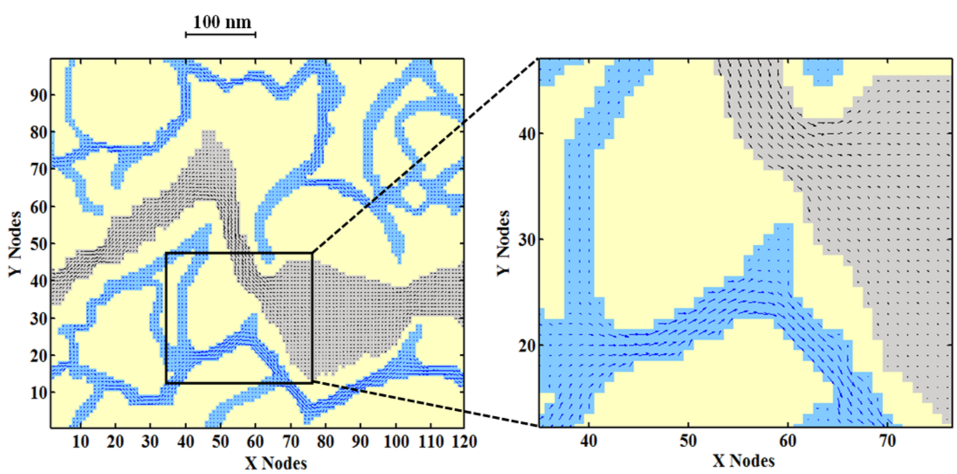


Source: Montgomery and Morison, 1999

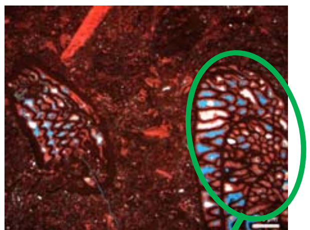
Different Types of Porosity

- Primary porosity
- Secondary porosity
- Effective porosity
- Interconnected porosity
- Total porosity
- Isolated porosity
- Vugular porosity
- Intercrystalline porosity
- Intraparticle porosity
- Interparticle porosity
- ….

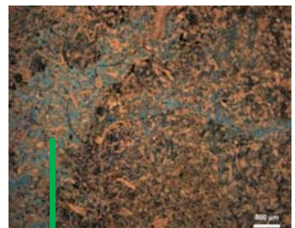
Effective, Interconnected, and Total Porosity



Intraparticle vs. Intrparticle pores



Source: Saneifar et al., 2015, AAPG Bulletin
(Heidari's research group)

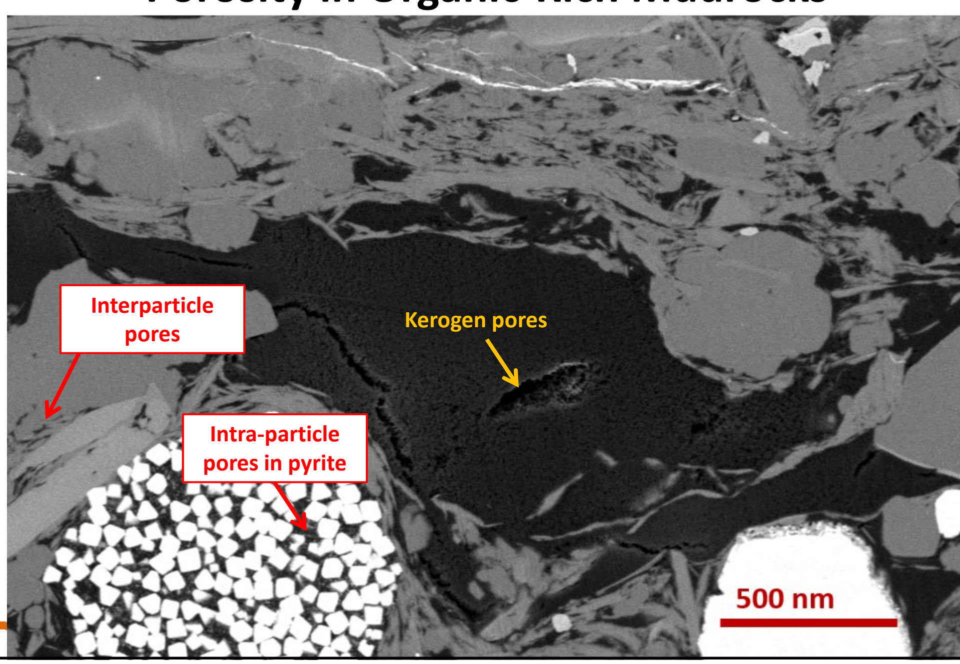


Intraparticle pores:

Isolated intrafossil pores

Interparticle pores:
Interconnected pores between grains

Porosity in Organic-Rich Mudrocks

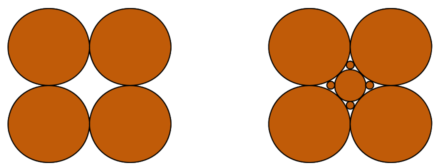


Parameters Affecting Porosity

- **Packing**

- Which one has a higher porosity value?
- What is the maximum possible porosity in a spherical grain pack?
- Does Grain size affect porosity of these packs?

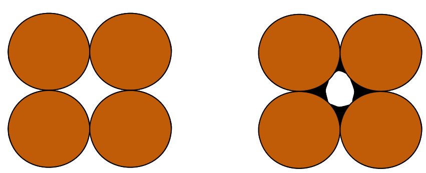
- **Sorting**



Which one has a higher porosity value?

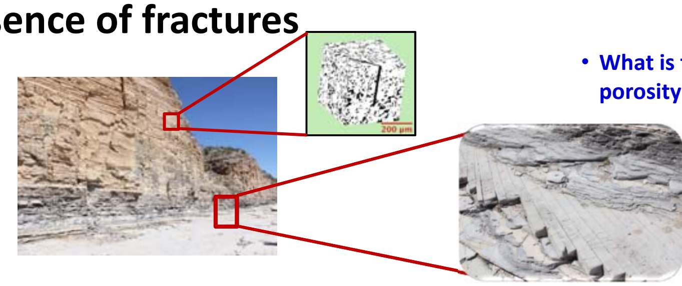
Parameters Affecting Porosity

- **Cementation**



Which one has a higher porosity value?

- **Presence of fractures**



- What is the contribution of fracture porosity on total porosity?

Characteristics of Sphere Packing

Packing type		Solid phase structure	Pore structure (3)	Porosity (%)	Number of contact points per sphere	Void type	Radius of maximum inscribable sphere (1)	Radius of maximum sphere passing through narrowest pore channels	Fraction of porosity contained in the maximum inscribable sphere (%)
Regular packings	Simple cubic		 Cubic void	47.6	6		0.732	0.414 curvilinear-square pore access	43
Regular packings	Simple hexagonal		 Simple rhombus void	39.6	8	2 trigonal	0.528	0.414 and 0.155 curvilinear-triangular pore access	45
Regular packings	Compact hexagonal or tetrahedral	 Separated view	 Tetrahedral void	25.9	12	2 tetrahedral + 1 octahedral	0.225 0.414	0.155	27
Dense random packing of hard spheres (2)				about 36	around 9 on average	at least five main types Bernal's canonical holes	most frequent radius 0.29		

The unit of length is the radius of the sphere.
(1) From Guillot (1982). (2) From Cargill (1984). (3) From Graton and Fraser 1935.

Source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.

How Does Secondary Pore Volume Develop in Carbonates?

- **Dominant mechanisms for development of secondary porosity in carbonates:**
  - **Solution**

    $CO_2 + H_2O = H_2CO_3$

    $H_2CO_3 + CaCO_3 = Ca(HCO_3)_2$ ⟶ **Calcium bicarbonate** ⟶ **Soluble**

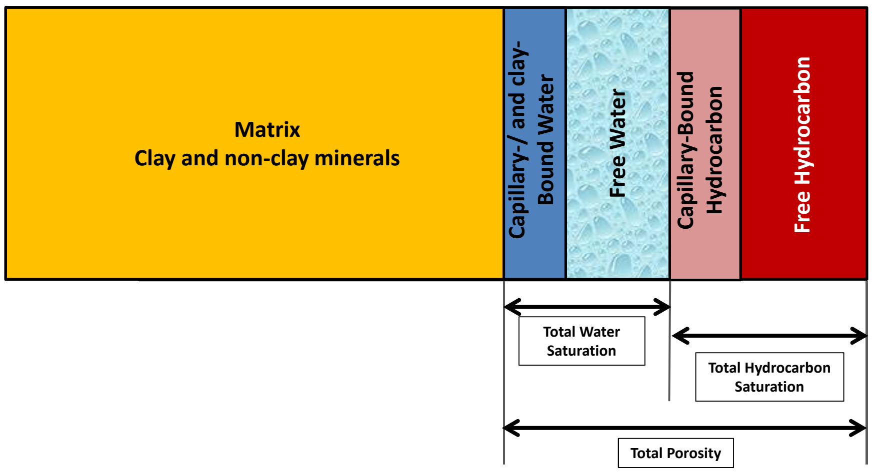
  - **Differential Dissolution**
  - **Chemical Replacement/Recrystallization**

    ➔ **Example: Dolomitization**

    $$2CaCO_3 + MgCl_2 = CaMg\,(CO_3)_2 + CaCl_2$$

  - **Fracturing**

Petrophysical Rock Model



How to Estimate Porosity

Porosity is not measured!

Porosity is estimated!

- **How to Estimate porosity?**
  - Laboratory-based porosity assessment:
    - Routine Core Analysis
    - Imaging Techniques
  - In-situ Assessment of porosity using well logs

Advanced Petrophysics: Porosity, Part 2 of 3

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What do we Learn in this Lecture?

- What is porosity?
- What are the different types of porosity?
- Factors affecting porosity
- **How to estimate porosity in the laboratory?**
- How to estimate porosity in-situ condition?
- How does presence of clay minerals affect porosity assessment?
- Laboratory vs. in-situ estimates of porosity

Porosity Assessment: Routine Core Analysis

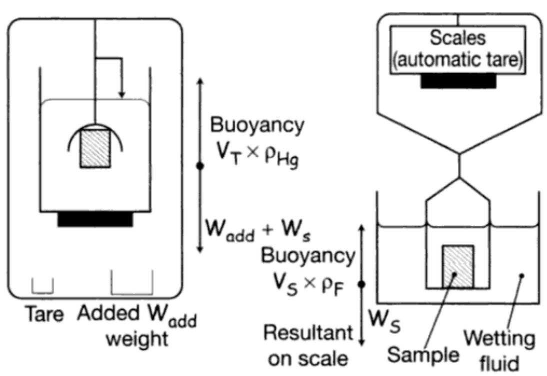
- **What information do we need to estimate porosity?**
  - **Bulk volume of the rock**
    - **Displacement of fluids that cannot easily penetrate the pores**
    - **Use Archimedes principle!**
  - **Volume of grains**
    - **Fluid displacement**
    - **Gas expansion using Boyle's law porosimeter**
  - **Volume of pores**
    - **Fluid saturation**
    - **Mercury injection**

$$\phi = \frac{V_p}{V_b} = \frac{V_p}{V_p + V_g} = \frac{V_b - V_g}{V_b}$$

What if the sample contains non-connected pore network?
What other methods might be used?

Bulk Volume of the Rock

Displacement of fluids that cannot easily penetrate the pores | **Use of Archimedes principle**



$V_T = (W_{add} + W_s)/\rho_{Hg}$ and $V_S = (W_s - W_i)/\rho_F$

where W_s and W_i represent the weights of the dry and immersed sample, respectively

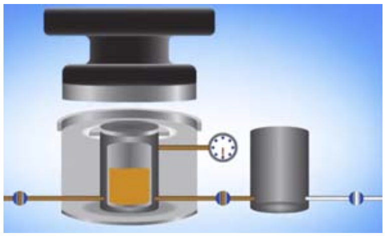
Source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.

Example

Volume and Weight Measurement

- Gas Displacement Pycnometry
  - One of the most reliable techniques for obtaining true, absolute, skeletal, and apparent volume and density
  - Gasses used: helium or nitrogen

Please watch the video!
Please take notes!



Source: www.Micromeritics.com

Boyle's Law Porosimeter

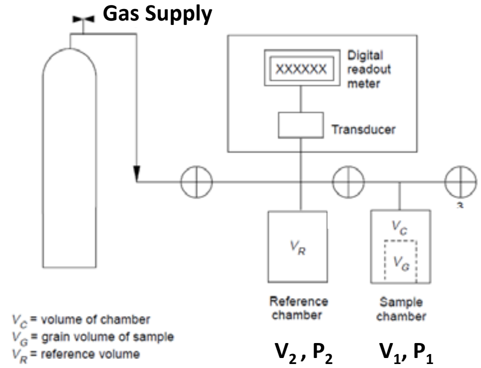
$$PV = \text{Constant at constant Temperature}$$

$$(V_1 - V_s)P_1 = (V_1 - V_s + V_2)P_2$$

$$V_s = V_1 - V_2\left(\frac{P_2}{P_1 - P_2}\right)$$

Common gases to use: air, nitrogen, or helium

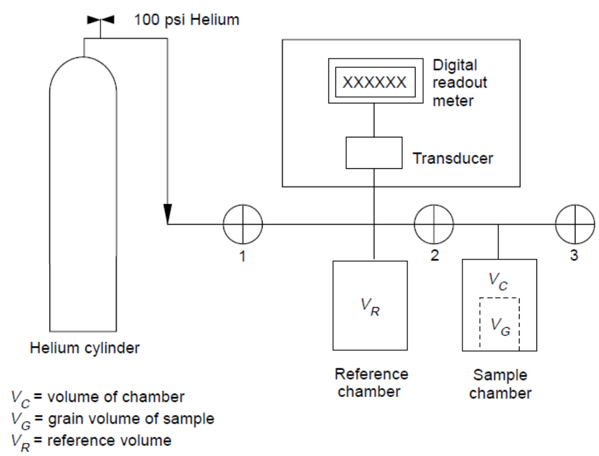
How would you calibrate such a system?



Source: API Recommended Practice 40

Helium Porosimetry

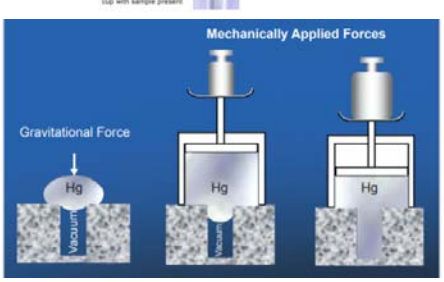
Why do we use Helium?



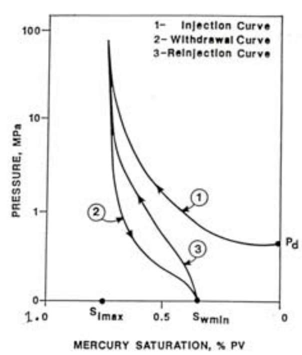
Please see API Recommended Practice 40

Example

Mercury Injection Porosimetry or Purcell (1949) Method



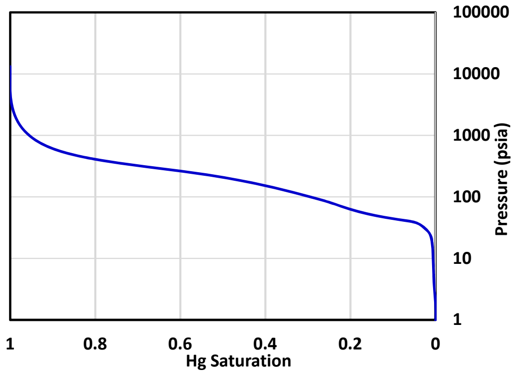
Source: www.Micromeritics.com

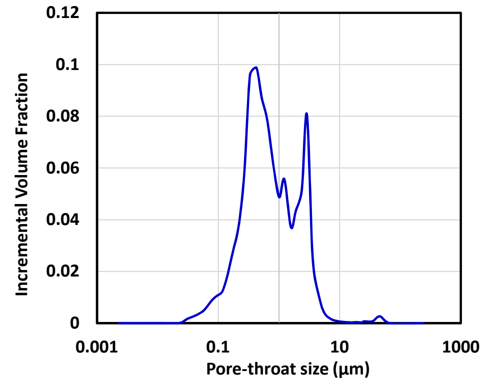


- How would you estimate volume of the sample?
- How would you estimate porosity?
- How would you estimate pore-throat-size distribution?

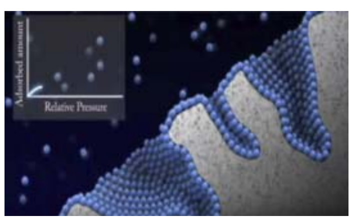
Note: More details on the measurement concept, interpretation, and limitations will be provided in the "Capillary Pressure Lecture"

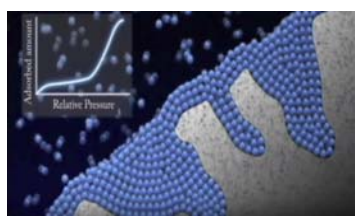
Example: Mercury Injection Porosimetry





Nitrogen Adsorption Porosimetry



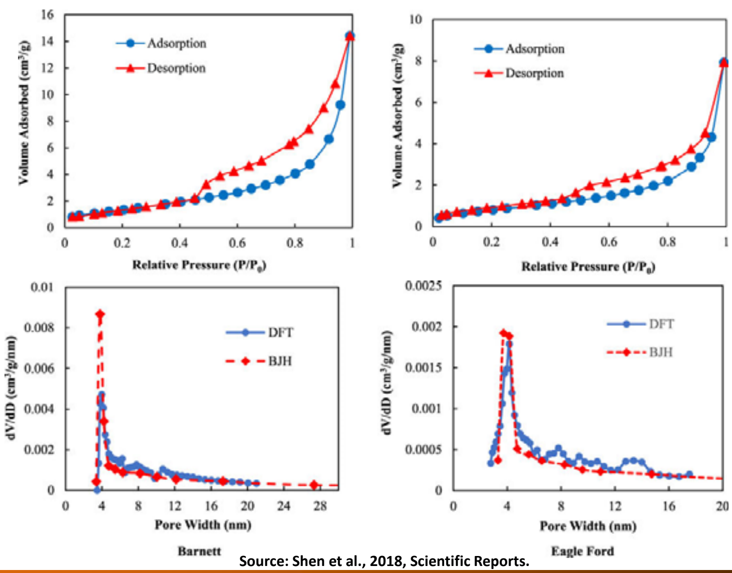


Courtesy of Quantachrome Instruments

Please watch the video!
Please take notes!

Pore size: 3 to 300 nm

Example

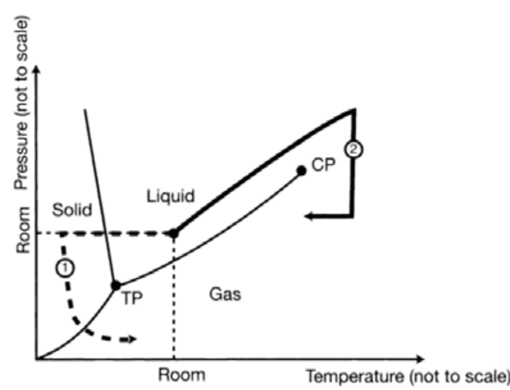


Source: Shen et al., 2018, Scientific Reports.

How do we Clean and Dry the Samples?

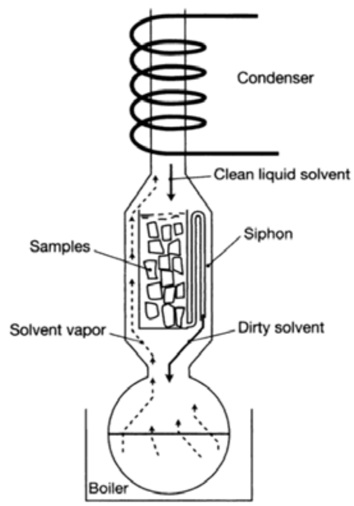
- Drying in ventilated oven (85C to 105C)
  - Be careful about the clay content of your samples!
- Advanced drying methods:
  - Lyophilisation
  - Bypassing the critical point

	Advantages	Disadvantages	Use
Lyophilisation	Speed	Very small samples (less than a few mm^3)	– Mainly SEM observation – Mercury injection
Bypassing the Critical Point	Samples of normal size	Relatively slow: Miscible exchanges and intermediate solvents	All petrophysical measurements



Source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.

Cleaning the Samples: Soxhlet Extractor



Source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.

Parameters Affecting Laboratory Measurements

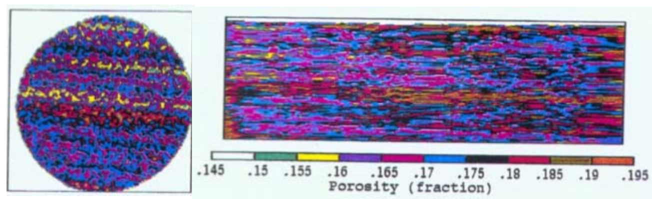
- Core recovery techniques (including coring fluid)
- Sample preservation technique
- Sample size and shape (crushed? sieved to what size?)
- Sample drying conditions:
  - ✓As received, dried (at what temperature and how long?), or at equilibrium conditions (what temperature and how long?).
- Standard temperature and pressure used for reporting measured gas volumes
- Total sorbed (including free porosity) gas vs. adsorbed gas
- Cell calibration technique
- Temperature measurement and control of cell
- Sample density reported (bulk or grain; wet or dry)
- Was equilibrium reached at each adsorption level, or was test step terminated at selected adsorption time?
- Sample volume tested
- Sample evacuated prior to testing
- Gas used in adsorption measurement
- Gas used in "free gas volume" porosity measurement

Please see API Recommended Practice 40

Porosity Assessment using Imaging Methods

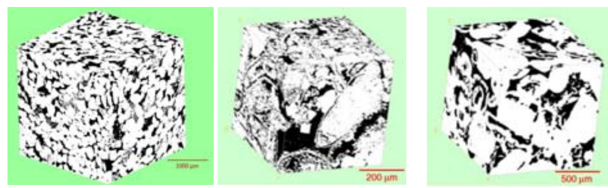
- **CT-scan imaging**
  - **Resolution: ~100-200 μm, 1-2 mm**
    (depends on the equipment and the sample size)

$$\phi = \frac{\psi_{wet} - \psi_{dry}}{\psi_{brine} - \psi_{air}}$$



Porosity image of a Berea sandstone from CT imaging. L = 60.2 cm, d = 5.1 cm (source: Peters and Afzal, 1992)

- **Micro-CT-scan imaging**
  - **Resolution: ~1 μm**
    (depends on the equipment and the sample size)



What challenges would you expect to face?

Advanced Petrophysics: Porosity, Part 3 of 3

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What do we Learn in this Lecture?

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- **How does presence of clay minerals affect porosity assessment?**
- **Laboratory vs. in-situ estimates of porosity**

Porosity Assessment Using in-situ Density Measurements

Which one has the highest density?

Porosity Assessment Using Density Measurements

Derivation:

Porosity Assessment Using Density Measurements

$$\rho_b = \phi_T \rho_f + (1 - \phi_T)\rho_m$$

ϕ_T: Total porosity

$$\rho_f = S_w \rho_w + S_o \rho_o + S_g \rho_g$$

$$S_w + S_o + S_g = 1$$

$$\phi_T = \frac{\rho_b - \rho_m}{\rho_f - \rho_m}$$

ρ_b: Bulk density/Rock density

ρ_m: Matrix/grain density

ρ_f: Fluid density

$$\rho_m = C_1 \rho_1 + C_2 \rho_2 + \ldots + C_n \rho_n$$

C_i: Solid volumetric concentration of matrix components

ρ_i: density of matrix components

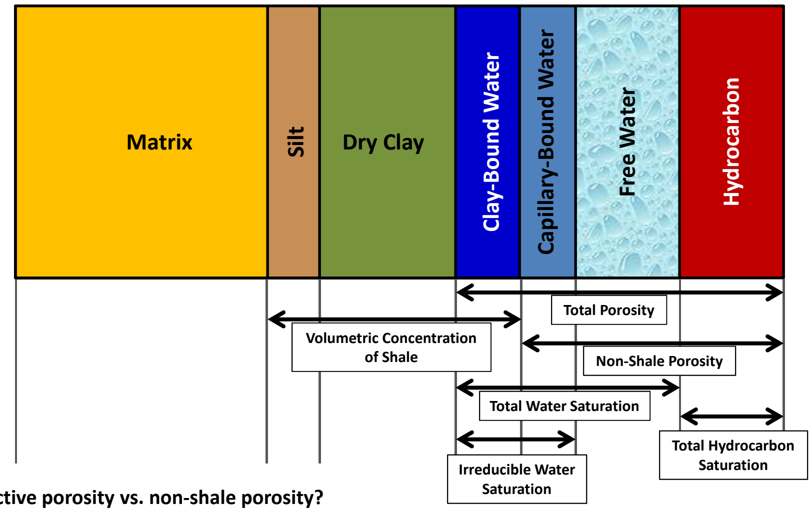
Porosity Assessment Using Neutron Porosity and Density Measurements

Please take notes!

Example

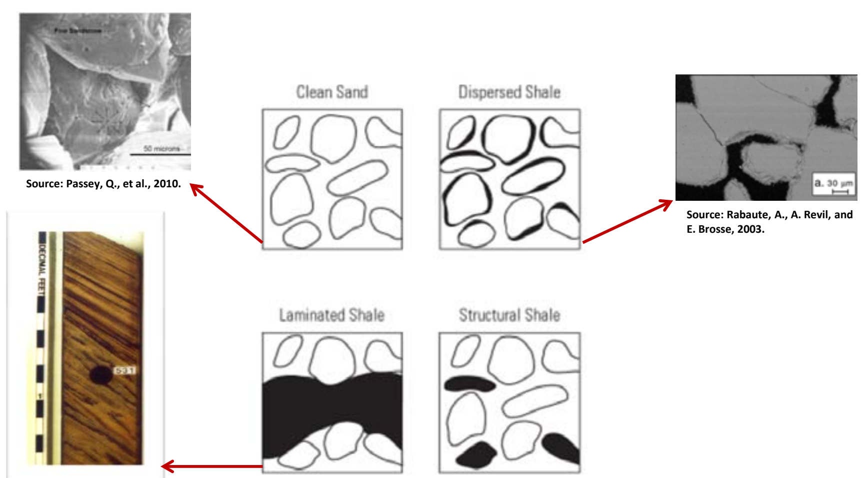
- **Estimate porosity in the examples distributed in the class.**

Petrophysical Rock Model: Shaly-Sand Formations



Effective porosity vs. non-shale porosity?

Porosity in Shaly Sand Formations



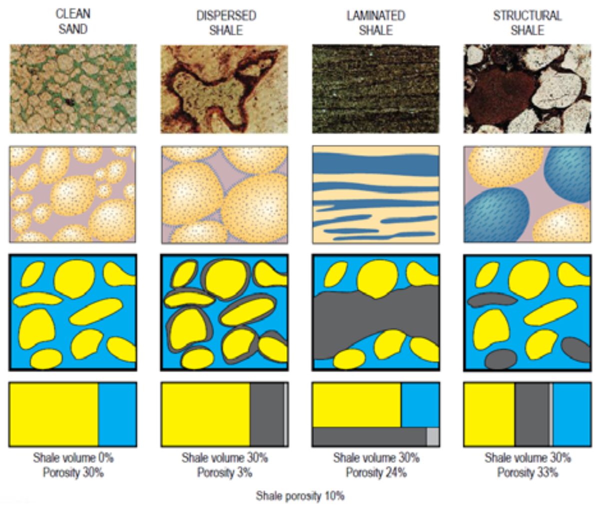
Source: Passey, Q., et al., 2010.

Source: Rabaute, A., A. Revil, and E. Brosse, 2003.

Classification of shale by distribution. From Poupon et al.

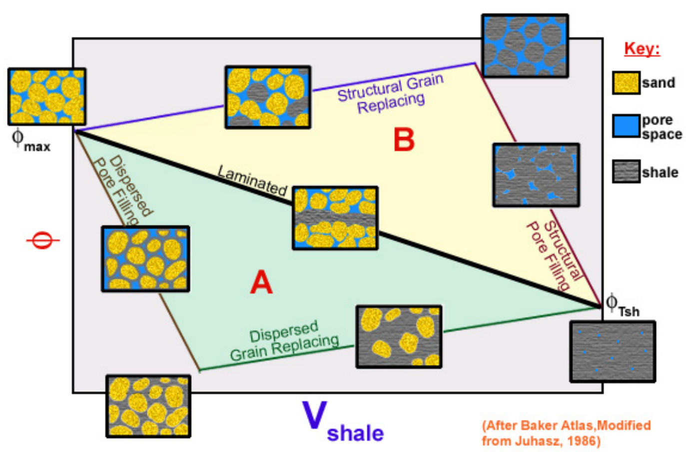
Source: Ellis, D. V. and Singer, J. M., 1987.

Shale Types

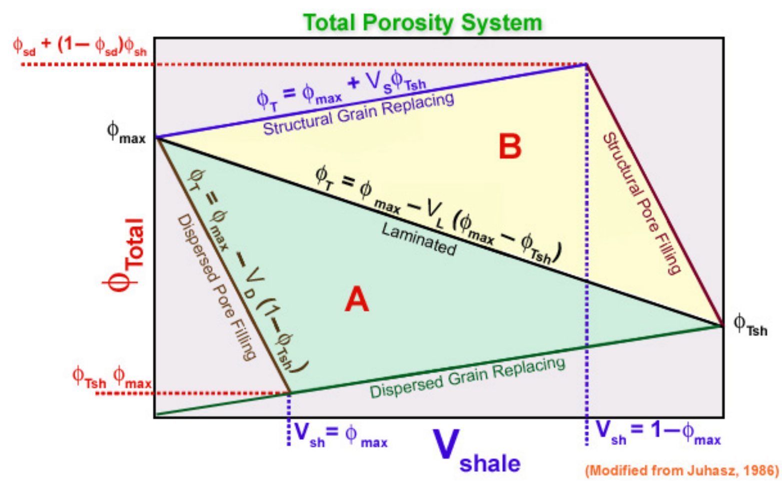


Source: Photomicrographs from Scholle, 1979
Courtesy of Schlumberger, Tom Neville

Thomas-Stieber Diagram



Thomas-Stieber Diagram



Laminated Shaly-Sand Formations

Laminated shale

$$\rho_b = (1 - C_{sh})\rho_s + C_{sh}\rho_{sh}$$

$$\phi_s = \frac{\rho_s - \rho_m}{\rho_f - \rho_m}$$

Derivation:

Laminated Shaly-Sand Formations

Density porosity and neutron porosity correction for the effect of shale:

$$\phi_{D,m}^{sh} = \frac{\phi_{D,m} - C_{sh}\left(\phi_{D,m}\right)_{sh}}{1 - C_{sh}}$$

$$\phi_{N,m}^{sh} = \frac{\phi_{N,m} - C_{sh}\left(\phi_{N,m}\right)_{sh}}{1 - C_{sh}}$$

Derivation:

Non-Shale Porosity

What is next?

Oil $$\phi_s = \frac{\phi_D^{sh} + \phi_N^{sh}}{2}$$

Gas $$\phi_s = \sqrt{\frac{\left(\phi_D^{sh}\right)^2 + \left(\phi_N^{sh}\right)^2}{2}}$$

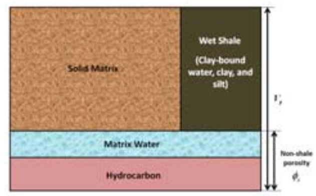
$$\phi_t = \left(1 - C_{sh}\right)\phi_s + C_{sh}\phi_{sh}$$

What about assessment of S_w?

Dispersed Shaly-Sand Formations

$$\rho_b = \phi_s \rho_f + \left(1 - \phi_s - C_{sh}\right)\rho_m + C_{sh}\rho_{sh}$$

Dispersed shale



Derivation:

Total Porosity vs. Non-Shale Porosity

Density porosity and neutron porosity correction for the effect of shale:

$$\phi_{D,m}^{sh} = \phi_{D,m} - C_{sh}\left(\phi_{D,m}\right)_{sh}$$

$$\phi_{N,m}^{sh} = \phi_{N,m} - C_{sh}\left(\phi_{N,m}\right)_{sh}$$

Derivation:

Non-Shale Porosity

What is next?

Oil

$$\phi_s = \frac{\phi_D^{sh} + \phi_N^{sh}}{2}$$

Gas

$$\phi_s = \sqrt{\frac{\left(\phi_D^{sh}\right)^2 + \left(\phi_N^{sh}\right)^2}{2}}$$

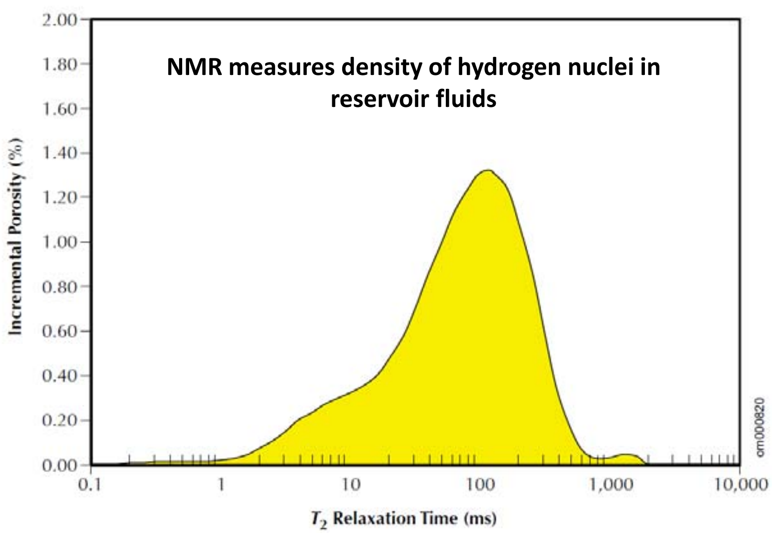
$$\phi_t = \phi_s + C_{sh}\phi_{sh}$$

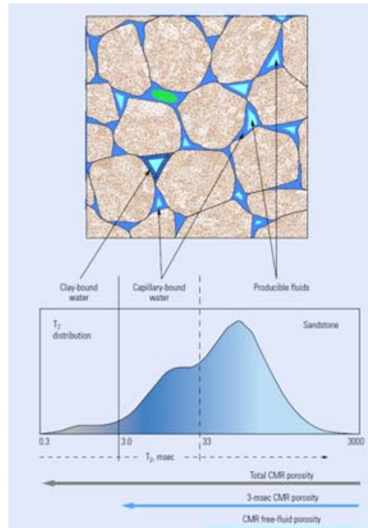
What about assessment of S_w?

Examples

- **Estimate total porosity and non-shale/sand porosity in the examples distributed in the class.**

Porosity Assessment Using NMR Measurements



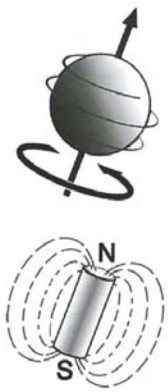


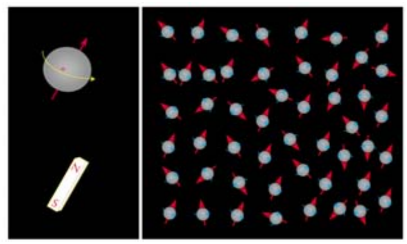
Source: Schlumberger Oilfield Review, 2000

Benchtop NMR Equipment

NMR Physics

Most of nuclei have both magnetic moment and angular momentum





The magnetic axis is aligned with the spin axis

Source: Coates et al., 1999. Courtesy of Halliburton.

NMR Physics

- **NMR measurements can be run on any nucleus that has an odd number of protons or neutrons or both**

$$\Rightarrow \; {}^{1}H \;,\quad {}^{13}C \;,\quad {}^{23}Na$$

We only discuss proton (hydrogen) NMR (MR, MRI) $\xrightarrow{\text{Why?}}$ **Abundant in earth (W, HC)**
Large magnetic moment

$\downarrow$

Strong and measurable signal

How Does an NMR Tool Work?

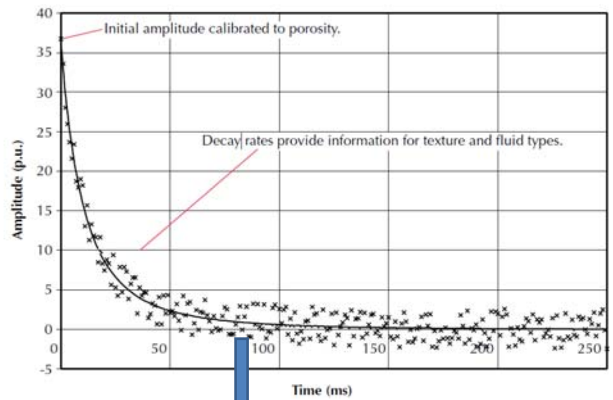
- Protons randomly oriented in the formation
- Tool generates magnetic field
- Protons get aligned to the applied magnetic field
- An oscillating magnetic field is applied
- Protons will be tipped from their new equilibrium position
- Removal of magnetic field
- Protons will be back to their original direction

NMR tool measures the amplitude of the generated SPIN-ECHO trains over time

The Decay of Spin-Echo Train

- What parameters affect spin-echo trains?
  - HI (Hydrogen Index)
    - Measure of the density of hydrogen atoms in the fluid
  - T_1 (Longitudinal relaxation time)
    - How fast the tipped protons in the fluid relax longitudinally (relative to the axis of the static magnetic field)
  - T_2 (Transverse relaxation time)
    - How fast the tipped protons in the fluid relax transversely (relative to the axis of the static magnetic field)
  - D (Diffusivity)
    - Measure of the extent to which molecules move at random in the fluid

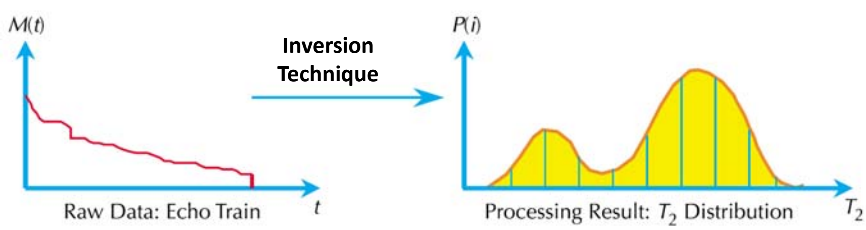
The Decay of Spin-Echo Train

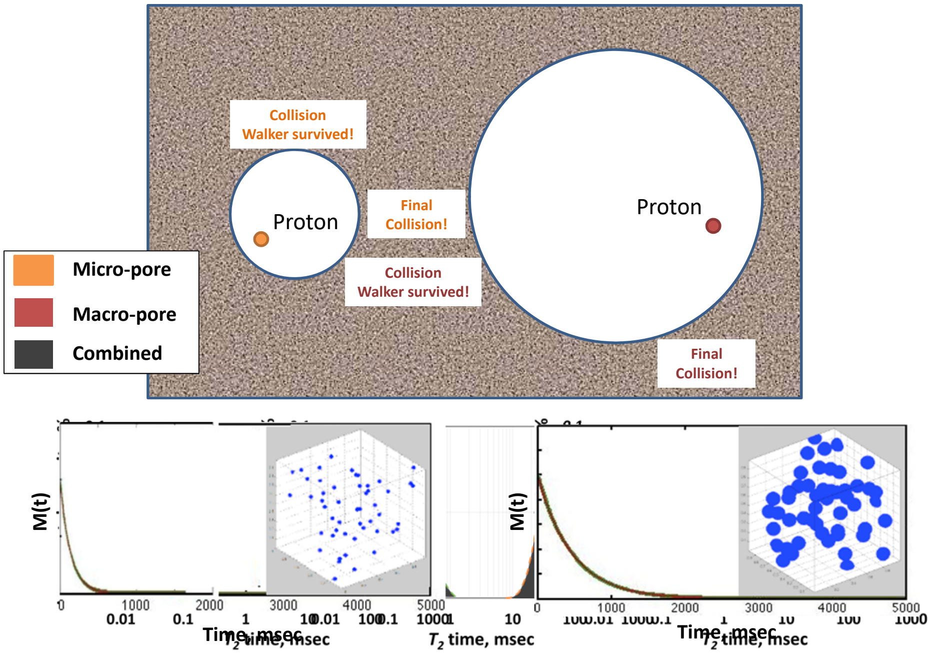


A function of the amount and distribution of hydrogen present in fluids

Source: Coates et al., 1999. Courtesy of Halliburton.

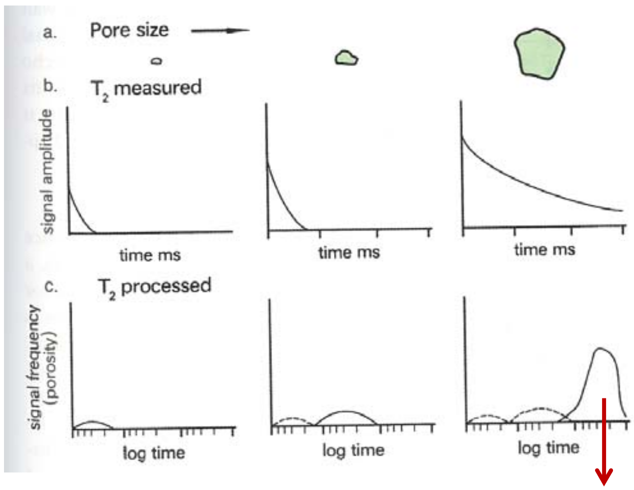
T_2 Distribution

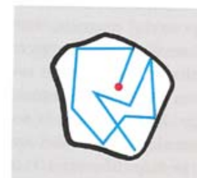




T_2 Distribution

Pore Size and T_2-Distribution



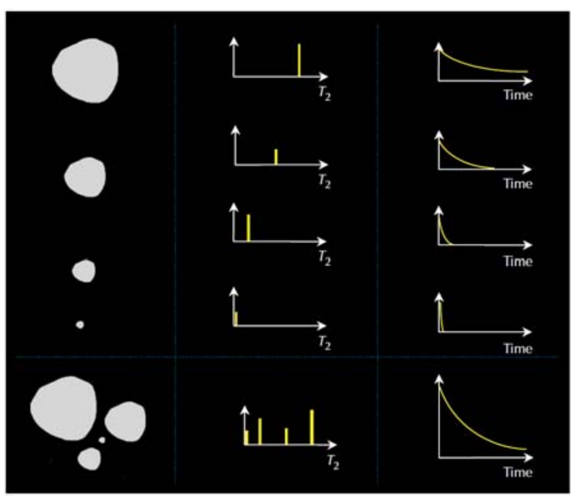


Area underneath the curve = CMR porosity

Source: Rider, M. and Kennedy, M., 2011, The Geological Interpretation of Well Logs

Multi-Exponential Decay

$$M(t) = \sum M_i(0)\, e^{-\frac{t}{T_{2i}}}$$



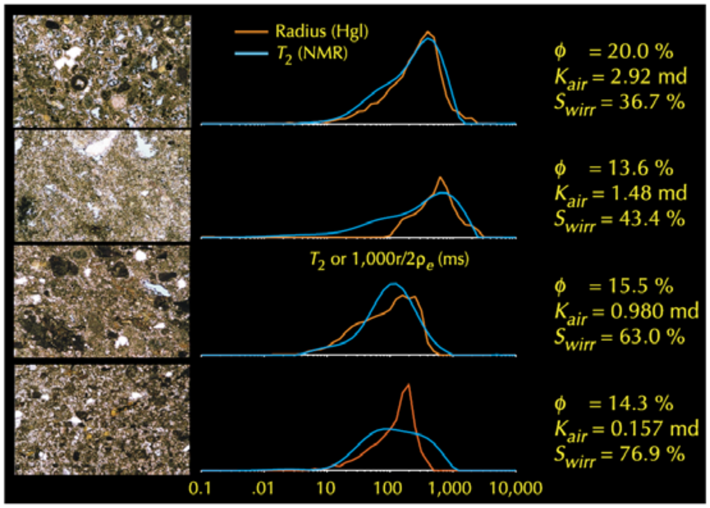
$M(t)$ = measured magnetization at time t

$M_i(0)$ = initial magnetization from the i^{th} component of relaxation

T_{2i} = decay constant of the i^{th} component of transverse relaxation

Source: Coates et al., 1999. Courtesy of Halliburton.

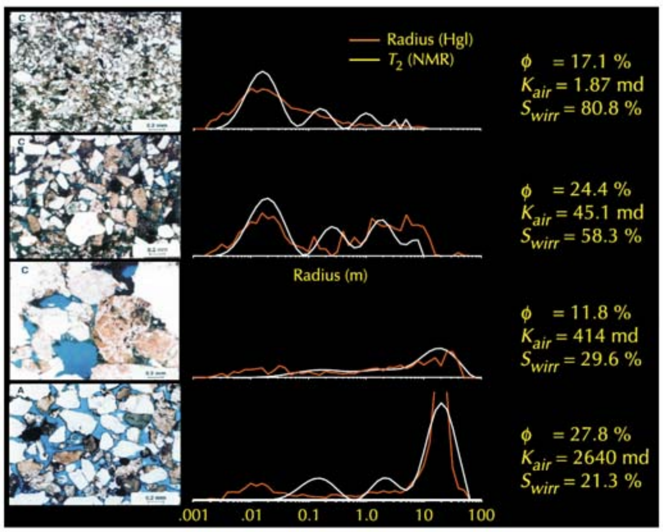
Pore Size Distribution



Carbonate Samples

Source: Coates et al., 1999. Courtesy of Halliburton.

Pore Size Distribution



Sandstone Samples

Source: Coates et al., 1999. Courtesy of Halliburton.

How to Calculate Porosity and Pore-size Distribution?

$$\frac{1}{T_2} = \frac{1}{T_{2Bulk}} + \boxed{\frac{1}{T_{2Surface}}} + \frac{1}{T_{2Diffusion}} = \frac{1}{T_{2B}} + \boxed{\rho_2 (\frac{S}{V})_{pore}} + \frac{D(\gamma \cdot G \cdot TE)^2}{12}$$

Surface Relaxivity

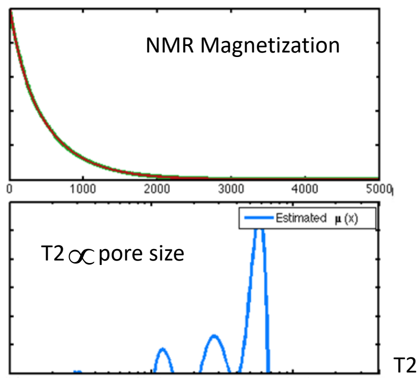
Surface/Volume ratio

Diffusion Coefficient

Gyromagnetic Ratio

Field Gradient

Inter-Echo Spacing



$T_2 \propto$ pore size:

- Assumption 1:

Short TE, brine saturated

- Assumption 2:

All pores have similar geometry!

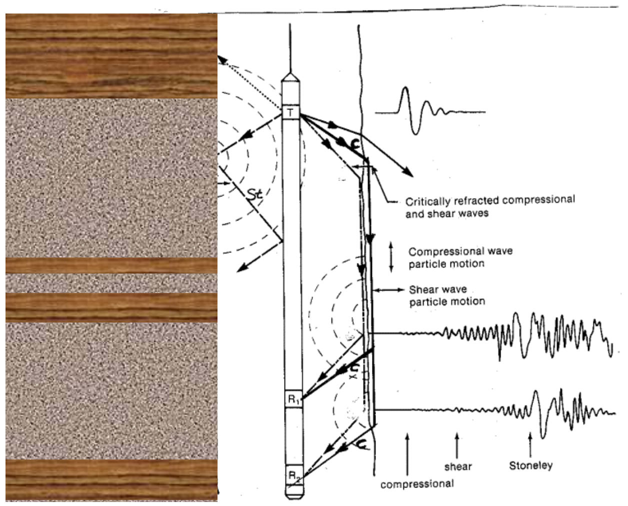
$$\frac{1}{T_{2Surface}} \propto (\frac{S}{V})_{pore} \propto (\frac{1}{R})_{pore}$$

Example

- **What is the dominant pore size in the example distributed in the class?**

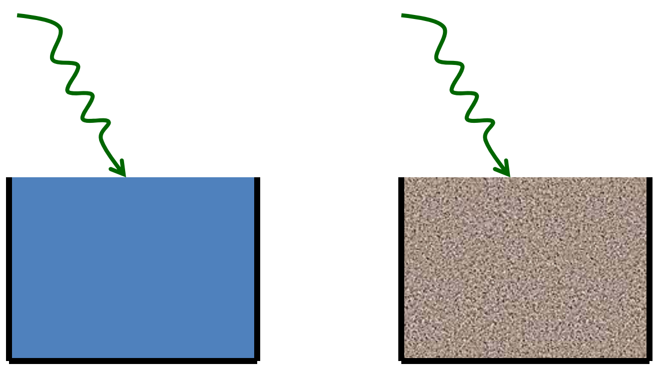
- **How would you estimate porosity of this sample?**

Acoustic Measurements



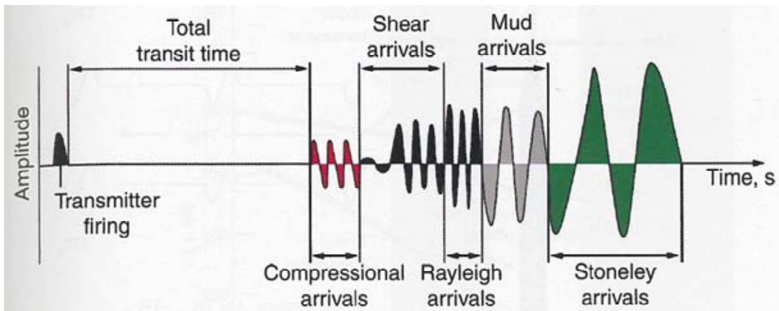
Travel Time for Acoustic Waves

Which one travels faster?



Transit time (Slowness), µs/ft or µs/m ← $$\Delta t = \frac{10^6}{V}$$ → Velocity, ft/s or m/s

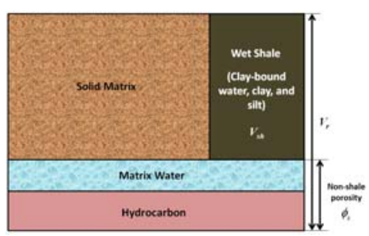
Acoustic-Wave Velocities

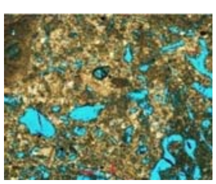


Source: Bateman, R. M., 2012, Openhole Log Analysis and Formation Evaluation

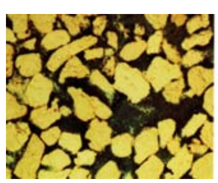
Rock Properties affecting Acoustic Waves

- **What parameters affect travel of acoustic waves in a formation?**

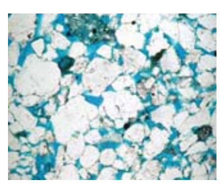




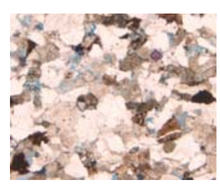
Mouldic dolomitic limestone



sandstone



sandstone



Tight-gas sand

Can we Use Acoustic Measurements for Porosity Assessment?

- **Wylie's Time-Average Equation**
  - Consolidated and compacted formations
  - Uniformly-distributed small pores
  - Isotropic, fluid-saturated rock, with homogeneous mineralogy

$$\frac{1}{V_P} = \frac{\phi}{V_{P,\,fluid}} + \frac{(1-\phi)}{V_{P,matrix}}$$

$$\Delta t = \phi\, \Delta t_f + (1-\phi)\,\Delta t_m$$

Be careful with this approximation!

Can it be considered as Inter-connected porosity?

Sonic porosity

$$\phi = \frac{\Delta t - \Delta t_m}{\Delta t_f - \Delta t_m}$$

Measured slowness

Fluid transit time

Matrix/grain transit time

Correction for compaction

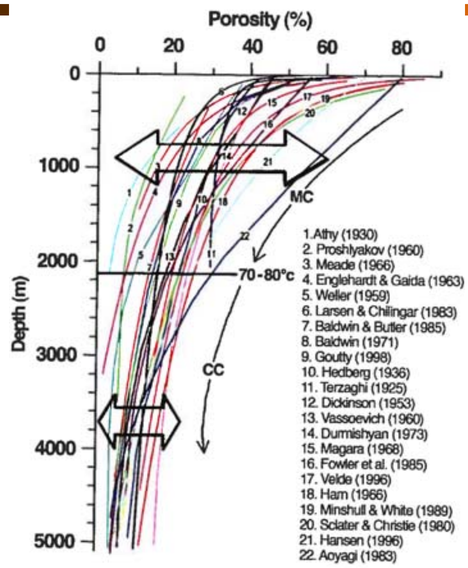
$$\phi = \frac{\Delta t - \Delta t_m}{\Delta t_f - \Delta t_m} \times \frac{1}{C_p}$$

C_p → Compaction Coefficient

$$C_p = \frac{\Delta t_{sh}(C)}{100}$$

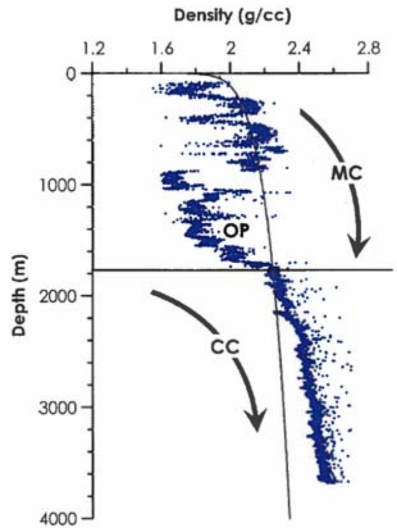
→ Shale Compaction Coefficient, from 0.8 to 1.3

Variation of Porosity with Depth



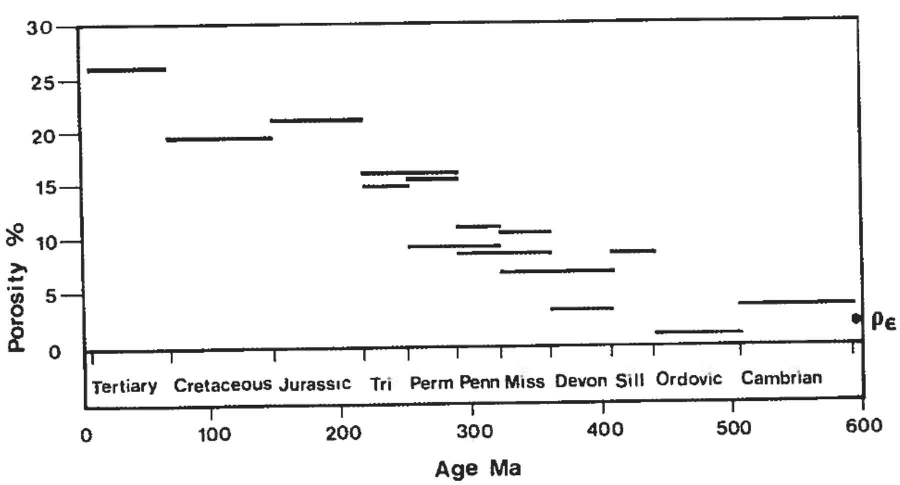
Source: Rider, M. and Kennedy, M., 2011, The Geological Interpretation of Well Logs

Shale Compaction with Depth



Source: Rider, M. and Kennedy, M., 2011, The Geological Interpretation of Well Logs

Shale Porosity vs. Geologic Age



Laboratory vs. In-situ Estimates of Porosity

- **Why do we experience differences in porosity estimates from the laboratory and in-situ measurements**
  - **The core may be altered during recovery**
  - **The core in the laboratory is no longer subjected to the overburden and lateral stresses that it was subjected to in the reservoir**
  - **Reservoir heterogeneity**
  - **Upscaling issues and the different volumes of investigation/measurements in the laboratory and in-situ condition**

Impact of Stress on Porosity, Compressibility

Pore volume compressibility

$$c_f = \frac{1}{V_p}\left(\frac{\partial V_p}{\partial P}\right)_T = \frac{1}{\phi}\left(\frac{\partial \phi}{\partial P}\right)_T$$

- **Experimental data (Newman, 1973) shows that there is no universal correlation for pore volume compressibility and porosity**
  - **➔pore volume compressibility should be measured in the laboratory.**
  - **➔Why is it important to be quantified?**

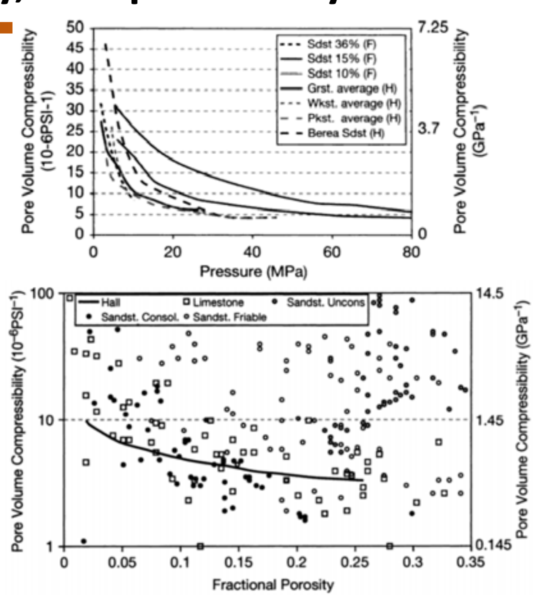


Image source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics.

Complementary References

- Peters, E. J., 2012, Advanced Petrophysics. Live Oak Book Company. Chapter 2
- Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.
- Coates, G. R., Xiao, L., Prammer, M. G., NMR Logging: Principles and Applications. Halliburton Energy Services Publication.