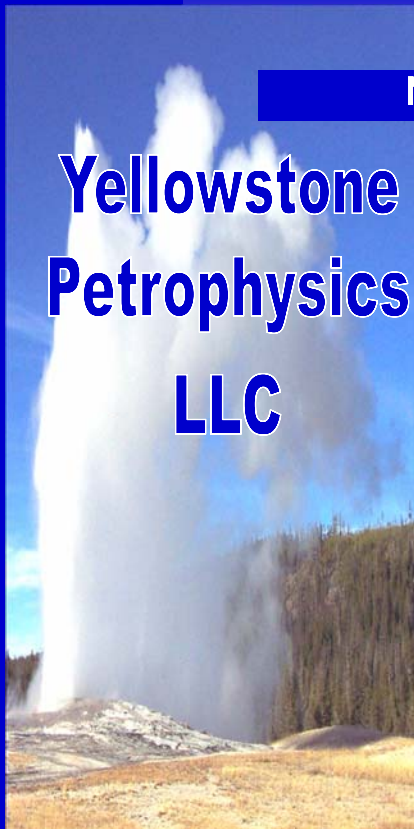
New Concepts in Petrophysics



Pore Systems and Permeability

June 23

2013 SPWLA Short Course

Facilitator:
David C. Herrick, PhD
Yellowstone Petrophysics LLC
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Dave Herrick has more or less retired and is now consulting through Yellowstone Petrophysics LLC. Dave is a petrophysicist with over 30 years experience in the petroleum industry. He was trained in chemistry and geochemistry at Indiana University (B.S.) and Penn State (Ph.D.). He has conducted research, training and technical service for Conoco, Amoco, Mobil and Baker Hughes in the areas of geochemistry, petrology and petrophysics. Dave has many publications as well as having given numerous presentations and schools on petrophysics, resistivity interpretation, and the impact of pore geometry on permeability and conductivity.

Understanding Permeability

We will:

- **Consider only the simplest case: laminar, Darcy or potential flow, no inertial effects or turbulence.**
- **Consider porous materials (like rocks) that contain a single wetting non-compressible Newtonian fluid (like H_2O).**
- **Use ideas about the flow of electricity in porous materials developed earlier (pore-geometric theory).**
- **Apply these ideas to understand the pore-geometric parameters that control permeability and fluid-flow.**

Pore Geometric Factor

$C_0 \propto$ conductivity of water in rock

$C_0 \propto$ amount of water in rock

$C_0 = f$ (geometry of water in rock)

- Archie divided out the effect of C_w on C_0:

  $C_0/C_w = 1/F = f$ or, $C_0 = fC_w$

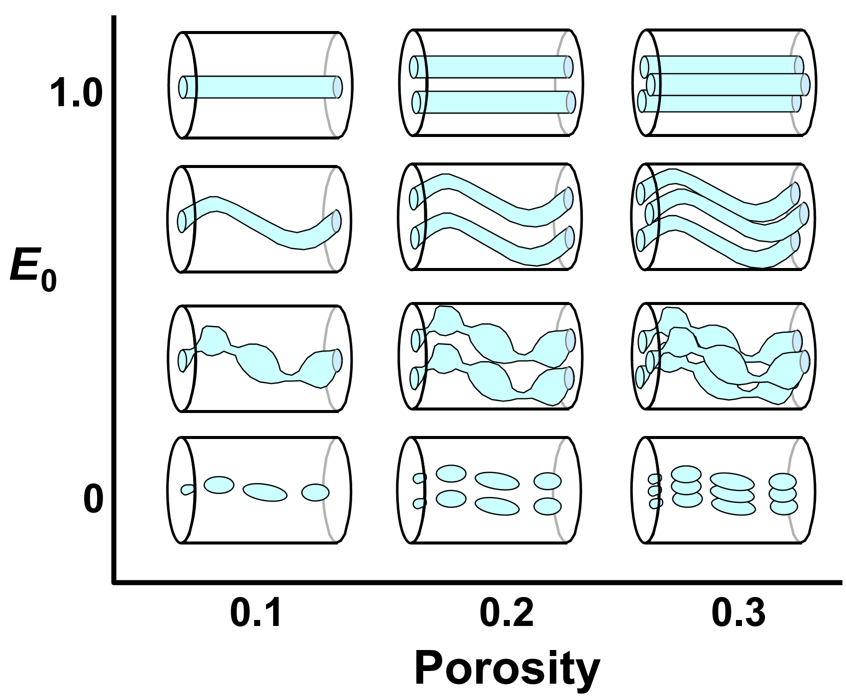
- Dividing by ϕ removes the ϕ dependence.

  $$\frac{C_0}{C_w\,\phi} = E_0$$ (E_0 is the pore-geometric factor)

  or, $C_0 = C_w\,\phi\,E_0$

- $f = E_0\phi$ (f is not uniquely determined by $E_0\phi$)

Pore Geometric Factor



Laplace's Equation

Potential is linear function of position: $\Phi = cx$

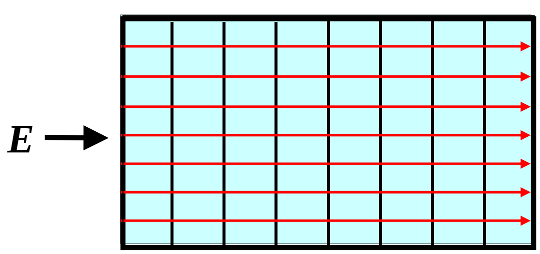
First derivative is: $\dfrac{d\Phi}{dx} = c$

Second derivative is: $\dfrac{d^2\Phi}{dx^2} = 0$ or, $\nabla^2\Phi = 0$

Meaning:

- The potential varies smoothly from point to point.
- There are no current sources or sinks.
  All current that flows into a point flows out.
- Current flows along and parallel to the interface between conductive and non-conductive components of a porous medium. Equi-potential surfaces are perpendicular to the interface.

Numerical Modeling of Electric Currents



Conductivity = C_w

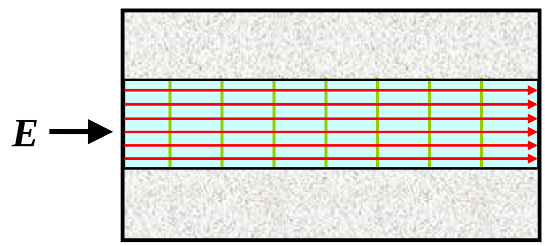
Equi-potential surfaces
(potential contours)

Current streamlines

Uniform current density

(current density = current / m^2)

Numerical Modeling of Electric Currents

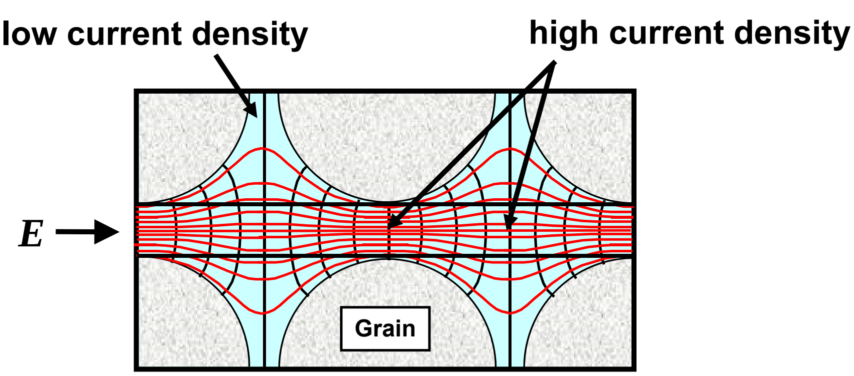


Conductivity = $C_w\phi$

Uniform current density

Maximum current for a given ϕ

Numerical Modeling of Electric Currents

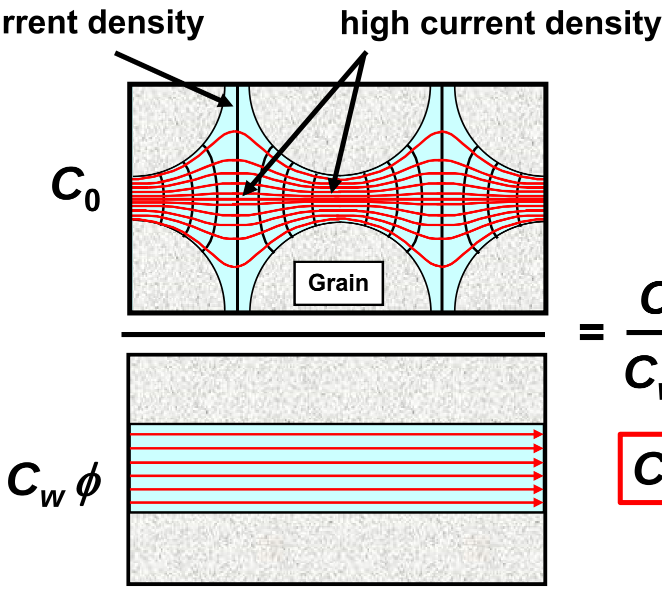


Non-uniform current density

<u>Average current density:</u>

single parameter describing the electrical effect of the pore *geometry* of a porous material.

Pore Geometric Factor

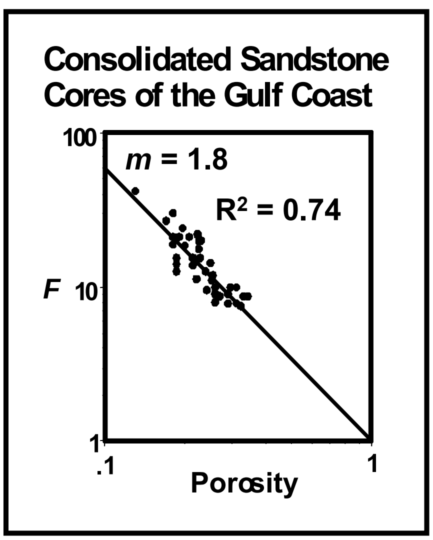


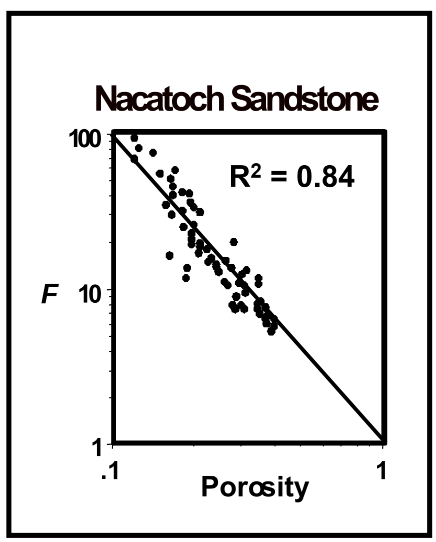
$$= \frac{C_0}{C_w\,\phi} = E_0$$

$$\boxed{C_0 = C_w E_0 \phi}$$

$$\boxed{E_0 = \frac{\text{average current density in rock}}{\text{average current density in equivalent tube}}}$$

Archie's (1942) Data



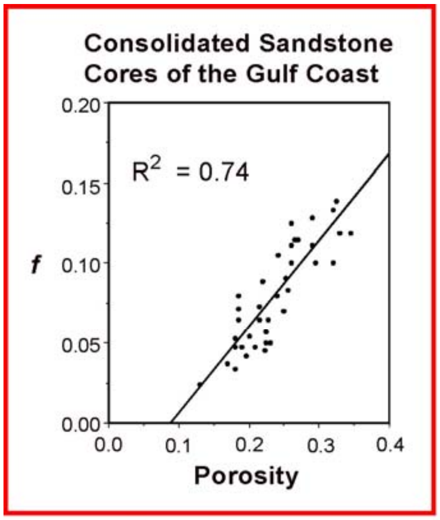


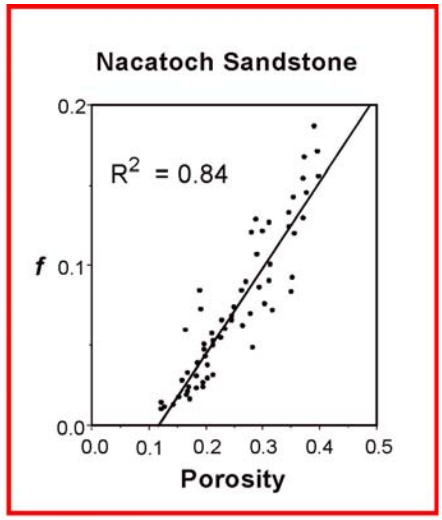
<u>assumptions!</u>:
1) straight line
2) extrapolates to (F =1, ϕ =1)

$$\log F = -m \log \phi$$

$$\boxed{F = \phi^{-m}}$$

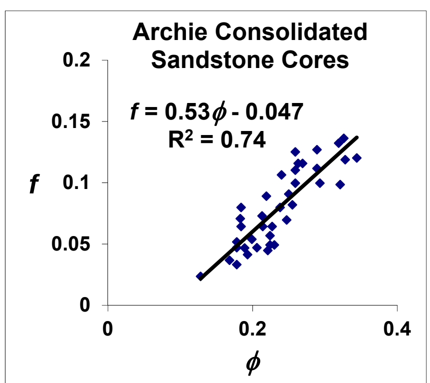
Archie's 1942 Data

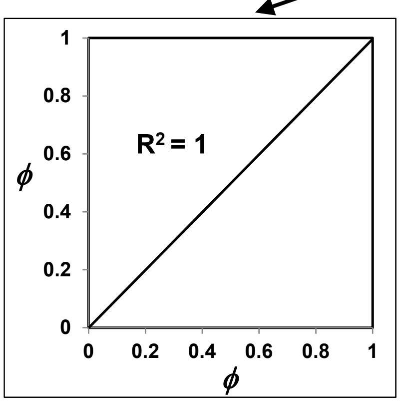


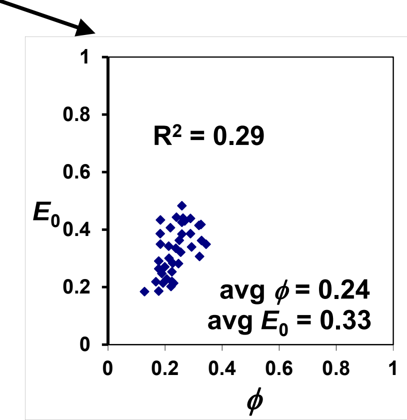


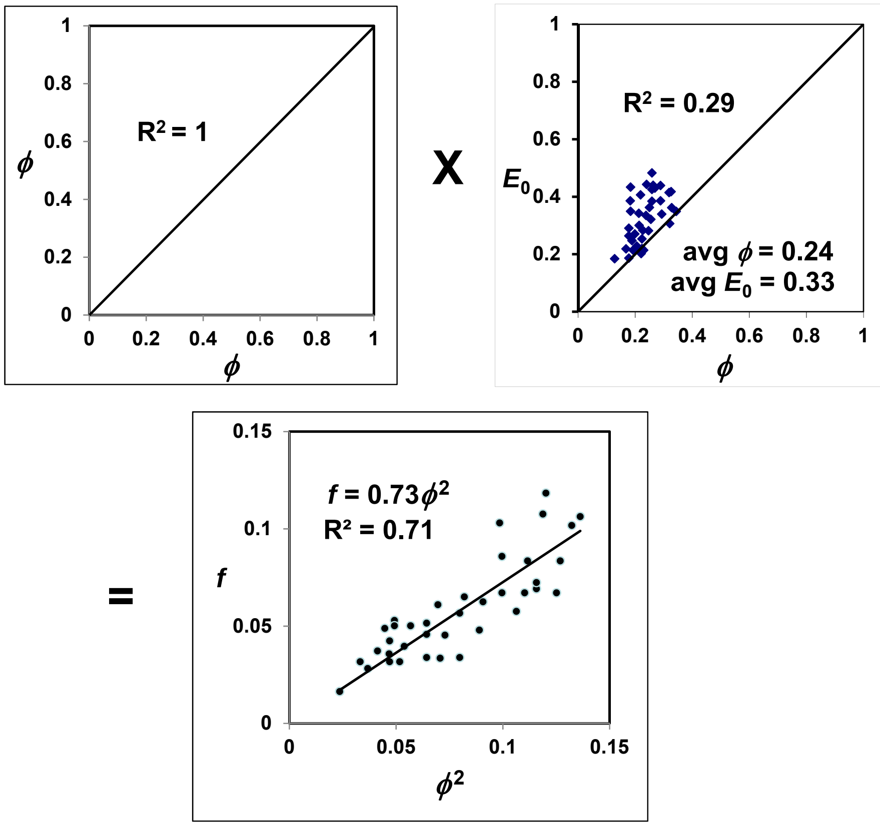
Remember: $f = E_0\, \phi$

$$\boxed{f = E_0\, \phi}$$

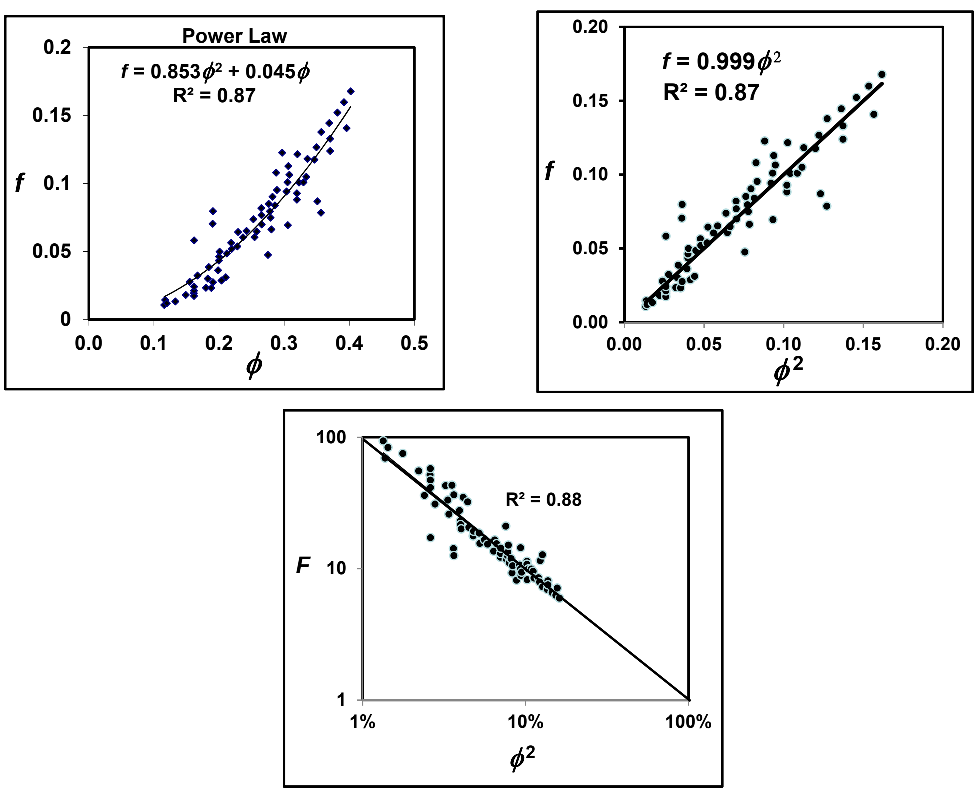




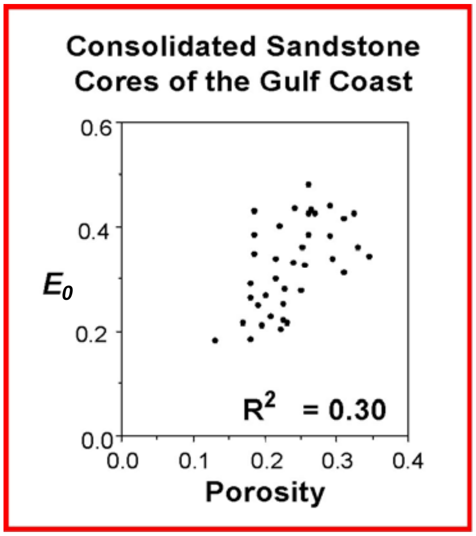


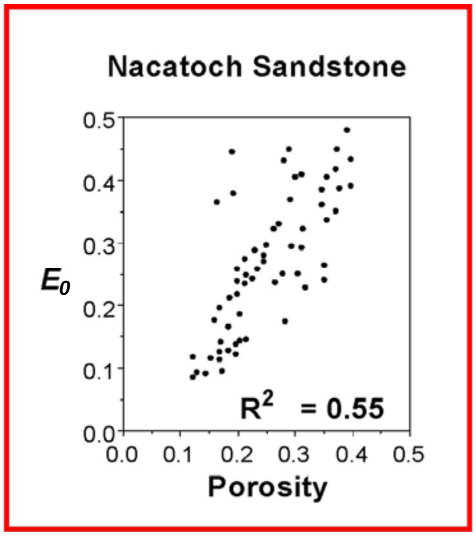


Archie Nacatoch Data Curve Fitting



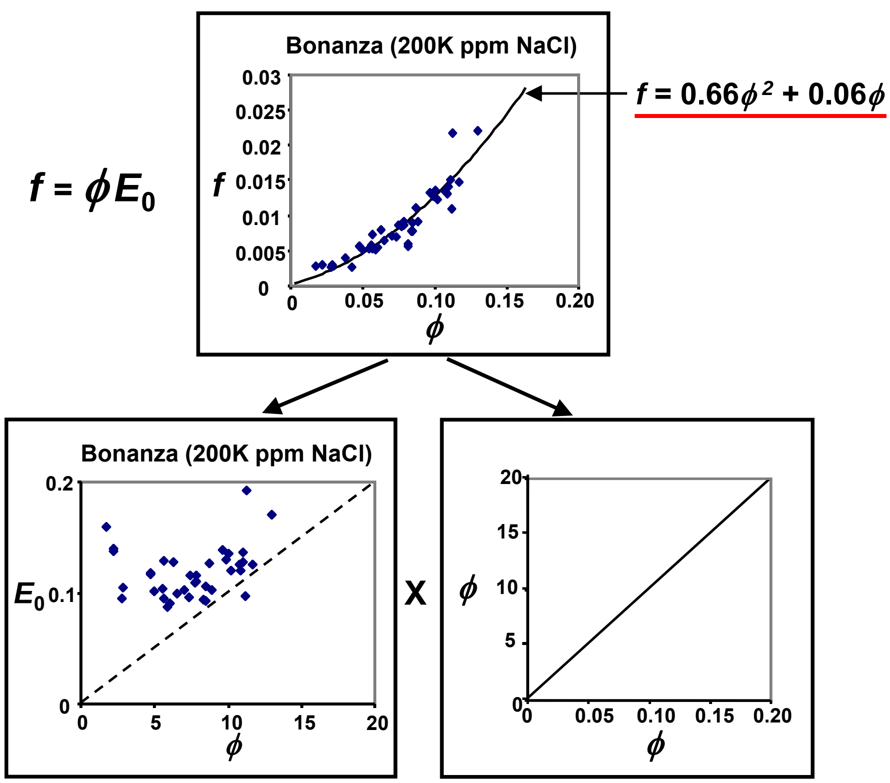
Archie's 1942 Data





Mesaverde Example

$f = \phi E_0$



Byrnes & Cluff, 2009

Wood's metal pore casts

saturation = 22%   saturation = 73%

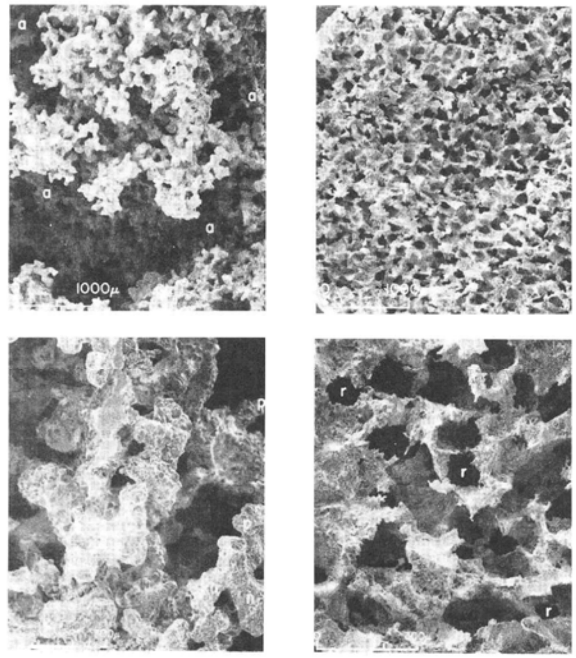
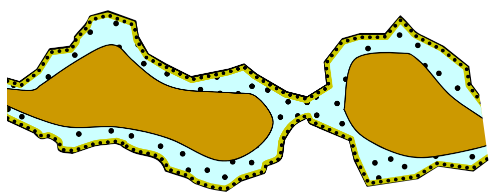


Figure 5.17 Cast of pore space in Berea sandstone. Woods metal has been introduced into the pores at two saturations (22% on left, 73% on right). Lower photographs show magnified detail of the upper ones. (Swanson, 1979 Copyright 1979, SPE–AIME)

Effect of Water Geometry

$E \rightarrow$



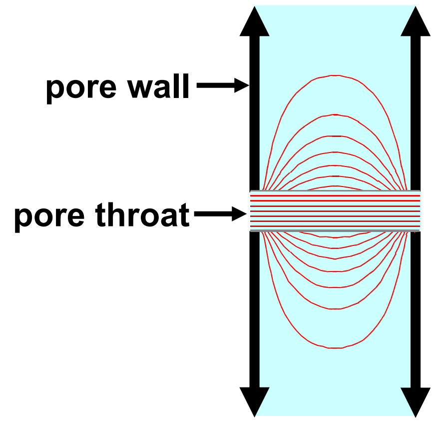
1. $S_w = 1$: C_0 reflects the smallest constriction(s)
   - 'pore throats'

2. $S_w < 1$: C_t reflects the smallest constriction(s)
   - 'pore throats'
   - between HC and grain surfaces

3. $S_w \leq 1$: C_t also includes
   - conduction in micro-pores
   - conduction by cation exchange on clay surfaces

Effect of Pore Bodies

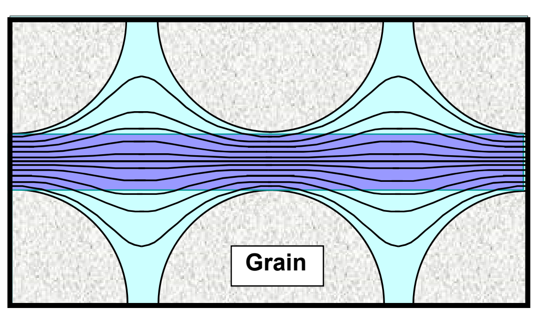
Infinitely-Wide Pore



$$d = \frac{C_p}{C_{th}} = \frac{\text{conductance of largest pore}}{\text{conductance of smallest pore}}$$

$$\boxed{d = 3}$$

Pore Body Effect



Effect of Pore Bodies:

$$d = \frac{\text{c (pore system)}}{\text{c (throat-tube)}} = 1.5$$

Definition of Tortuosity (τ) [Google]

1. a tortuous and twisted shape or position
2. twistedness or crookedness.
3. a property of curve being tortuous (twisted; having many turns).
4. a twisting or crooked part, passage, or thing
5. the state of being tortuous; twisted form or course; crookedness.
6. something winding or twisted
7. a twist, turn, or coil
8. tortuosity is a dimensionless parameter that accounts for the fact that the flow path is in general not straight.

9 The most simple mathematic method to estimate tortuosity is arc-chord ratio: ratio of the length of the curve (*L*) to the distance between the ends of it (*C*):

$\tau = \frac{L}{C}$ Arc-chord ratio equals 1 for a straight line and is infinite for a circle.

Definition of Tortuosity (τ) [Google]

10. Tortuosity is defined as the ratio of the effective average path in the porous medium to the shortest distance measured along the direction of the pore. Tortuosity is a dimensionless factor always greater than one, which expresses the degree of complexity of the sinuous pore path.

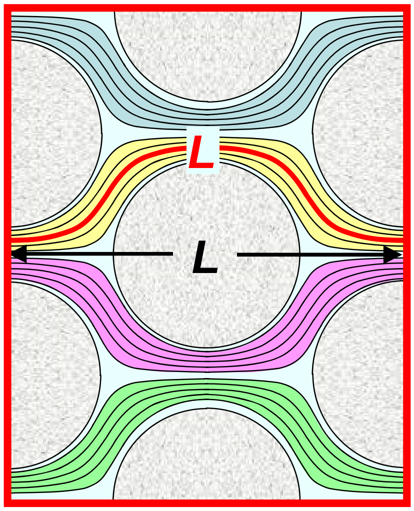
11. Geometric tortuosity is often defined as the ratio of the shortest path of interconnected points in pore fluid space to the straight line distance between those points.

12. Tortuosity may be defined as the ratio of the average length of the flow paths to the distance traveled in the direction of flow.

13. Tortuosity is the ratio of the length of the actual path to the length of the apparent path.

The definitive work on tortuosity: Clennell, B., 1997, Tortuosity: a guide through the maze, *Developments in Petrophysics*, Geol. Soc. Spec. Pub No. 122, pub. by The Geological Society, London, pp. 299-344.

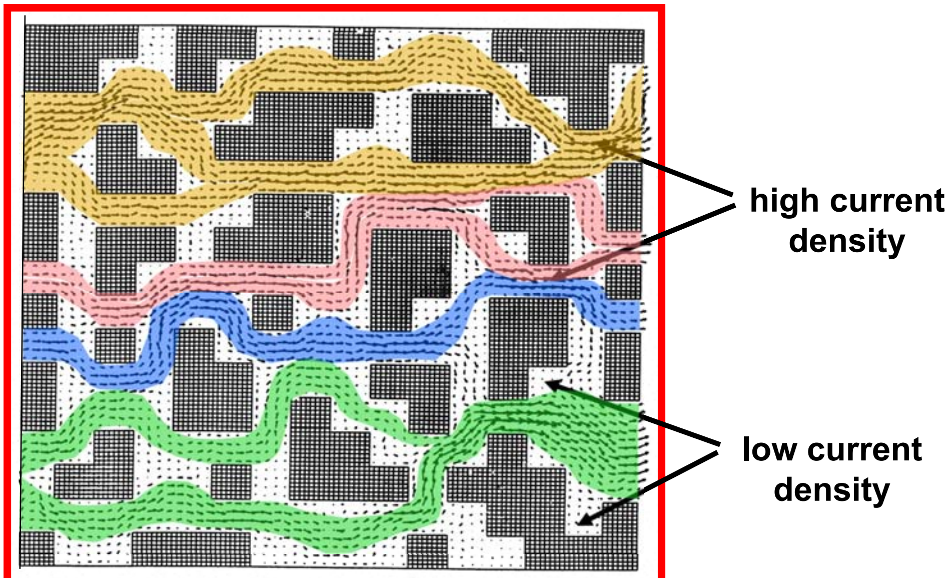
Tortuosity (τ)



$$\tau = \frac{L}{L}$$

$$\tau = \sim\pi/2 \ (\sim 1.5)$$

Stream tubes



"....The majority of the flow follows just a few winding paths, while many areas are relatively stagnant...." (Rothman, 1988)

Geometric Controls on Conductivity

1. Effect of Connectivity: none

Stream tubes are continuous, cannot cross or intersect.

2. Effect of pore bodies

$$d = \frac{c_{pore}}{c_{th\text{-}tube}} = \frac{\text{conductance of pore}}{\text{conductance of throat tube}}$$

d = ~ 1.5 (range = 1 - 3)

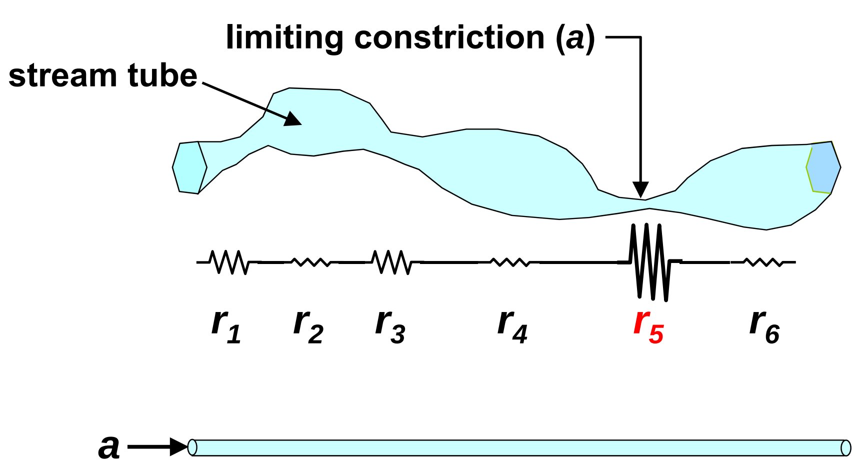
3. Inter-pore tortuosity

τ = 1 - 2 (equi-dimensional grains)

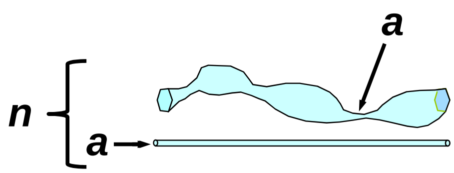
4. Conductance between pores

$$\boxed{c = c_{th\text{-}tube}\,\frac{d}{\tau}}$$

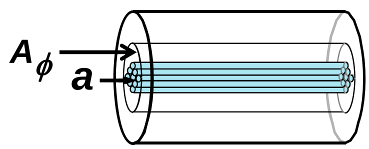
Geometric Controls on Conductivity

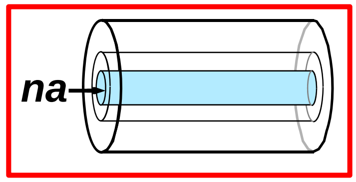


Geometric Controls on Conductivity



Conductivity model:





na = total cross-sectional area of the limiting constrictions of all stream tubes.

$$E_0 \cong \frac{na}{A_\phi} = \frac{\phi_{ee}}{\phi}$$

" A new scientific truth does not triumph by convincing its opponents, but rather because its opponents die, and a new generation grows up that is familiar with it."

Max Planck

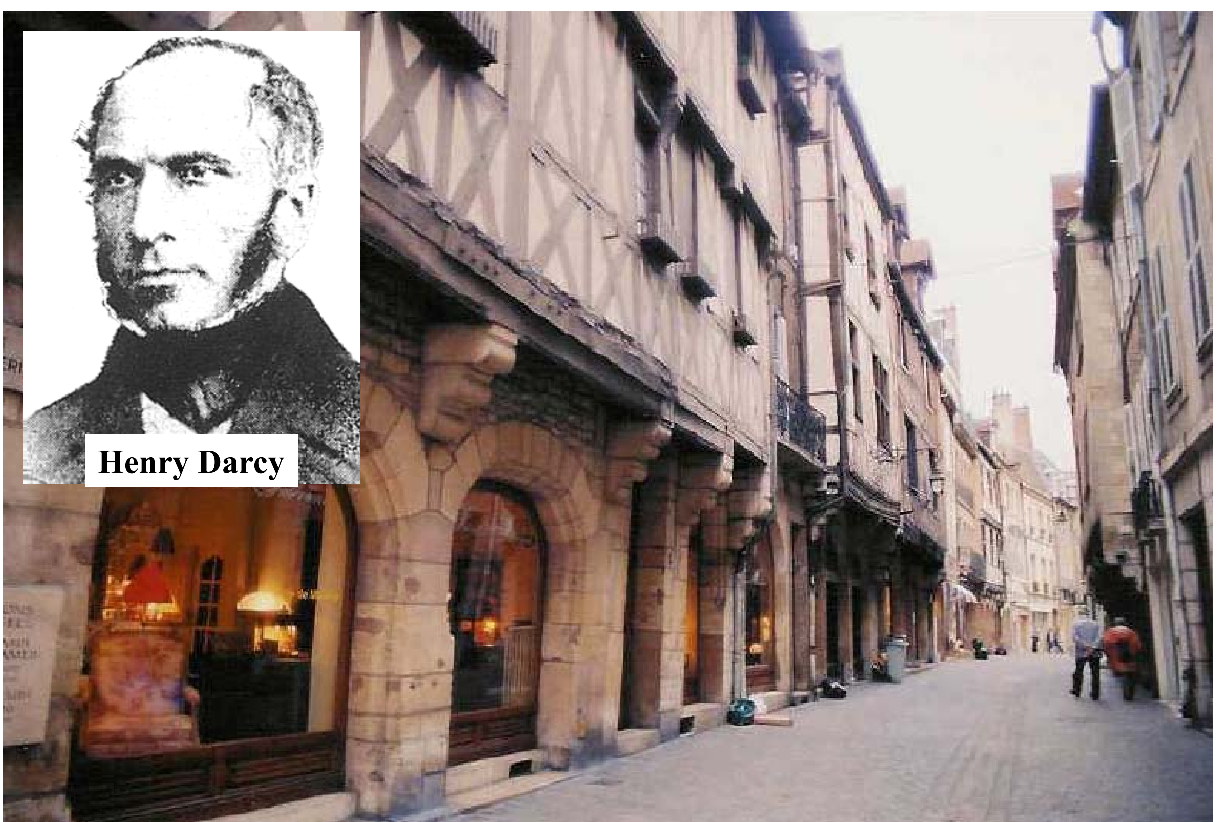
"Progress is made with every funeral"

Robert Frank

“The perpetual obstacle to human advancement is custom.”
- John Stuart Mill (1806-1873)

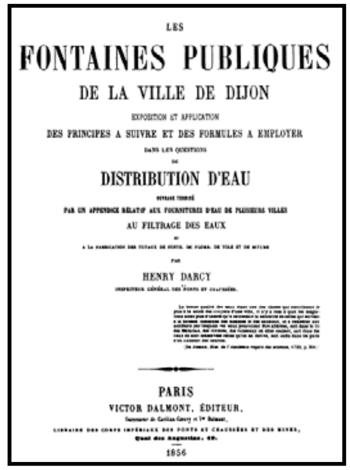
“Every man prefers belief to the exercise of judgment.”
- Seneca (4 B.C.-65 A.D.)

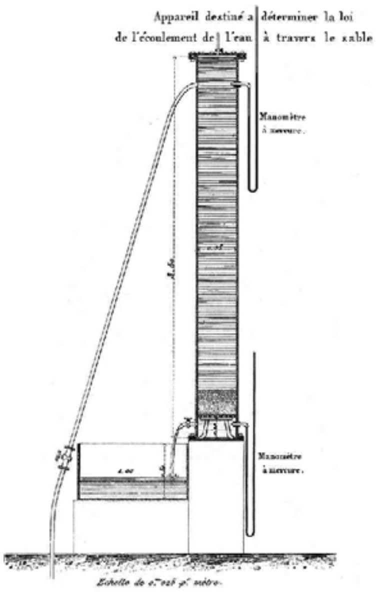
“Where we all think alike, no one thinks very much.”
- Walter Lippmann

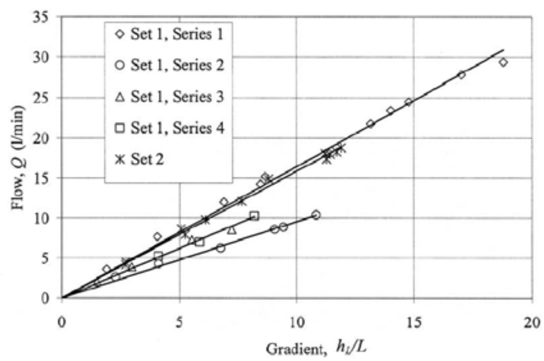


The city of Dijon 1850's

Henry Darcy, 1856


LES
FONTAINES PUBLIQUES
DE LA VILLE DE DIJON
EXPOSITION ET APPLICATION
DES PRINCIPES A SUIVRE ET DES FORMULES A EMPLOYER
DANS LES QUESTIONS
DE
DISTRIBUTION D'EAU
OUVRAGE TERMINÉ
PAR UN APPENDICE RELATIF AUX FOURNITURES D'EAU DE PLUSIEURS VILLES
AU FILTRAGE DES EAUX
PAR
HENRY DARCY
PARIS
VICTOR DALMONT, ÉDITEUR,
1856





Permeability

Darcy: 1850's - experiments on sand-packs

$$Q \propto \Delta P \frac{A}{L}$$

$$Q = K \left(\Delta P \frac{A}{L}\right)$$

$$K = \frac{k}{\mu}$$ **(Nutting, 1930)**

$$\boxed{Q = k \, \Delta P \frac{1}{\mu} \frac{A}{L}}$$ ***k* = 'permeability'**

Permeability

Permeability -

- **is *a proportionality constant* in a flow equation.**
- **has no specific physical meaning.**
- **reflects rock properties (ϕ, pore geometry) in an unspecified way.**

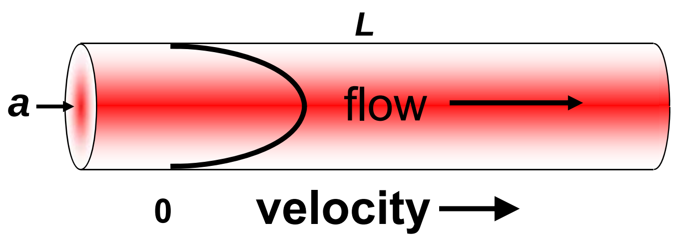
potential gradient
fluid
external geometric properties

$$Q = k\left(\Delta P \, \frac{1}{\mu} \, \frac{A}{L}\right)$$

internal rock properties
(i.e. ϕ, pore geometry)

Laminar Flow in a Tube

Hagen-Poiseuille Equation:
Exact solution of Navier-Stokes Eqn. for straight cylindrical tube.



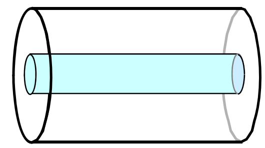
$$Q_{tube} = \frac{a}{8\pi} \, \frac{\Delta P}{\mu} \, \frac{a}{L}$$

$k_{tube} = a/\,8\pi$

- **zero flow velocity at the tube surface.**
- **viscous interaction between fluid molecules.**

Hydraulic Efficiency

$$Q_r = k\,\frac{\Delta P}{\mu}\,\frac{A}{L}$$



$$Q_t = \frac{\phi A}{8\pi}\,\frac{\Delta P}{\mu}\,\frac{\phi A}{L}$$

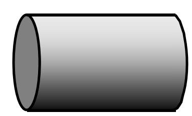
Hydraulic Efficiency (*H*)

$$H = \frac{Q_r}{Q_t} = \frac{k\,\frac{\Delta P}{\mu}\,\frac{A}{L}}{\frac{\phi A}{8\pi}\,\frac{\Delta P}{\mu}\,\frac{\phi A}{L}}$$

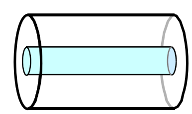
$$\boxed{H = \frac{Q_r}{Q_t} = \frac{k}{\phi^2 A/8\pi}}$$

Hydraulic Efficiency

$$\boxed{H = \frac{Q_r}{Q_t} = \frac{k}{\phi^2 A/8\pi}}$$



k



$\phi^2 A/\,8\pi$

Example

$\phi = 30\%$
$k = 1$ D
$A = 9$ cm^2

$$\boxed{H = 3 \times 10^{-7}}$$

The pore space in this 1D rock is <u>30 MILLION</u> times <u>less</u> conductive than the same amount of pore space in a tubular configuration!

(remember: 1 Darcy = 9.9×10^{-9} cm^2)

Equivalence of Electrical and Fluid Flow

Resistivity

$$R_0 = \rho \frac{A}{L}$$

Archie's Eqn.

$$R_0 = F\, R_w$$

Ohm's Law

$$V = I\, \rho$$

Flow through a rock:

Ohm's Law: $I = f \;\Delta V \;\frac{1}{R_w}\; \frac{A}{L}$

$$\updownarrow \quad \updownarrow \quad \updownarrow \quad \updownarrow \quad \updownarrow$$

Darcy's Law: $Q = k \;\Delta P \;\frac{1}{\mu}\; \frac{A}{L}$

flow rate = pore geometry & volume, potential difference, flow impedance, system size

f = 'electrical permeability'

Flux in a Potential Field

A flux is ***linearly proportional*** to the potential gradient.

$$Q_f = -K\, \nabla P$$ Darcy's law (hydraulic conductivity)

$$J = -\sigma\, \nabla V$$ Ohm's law (electrical conductivity)

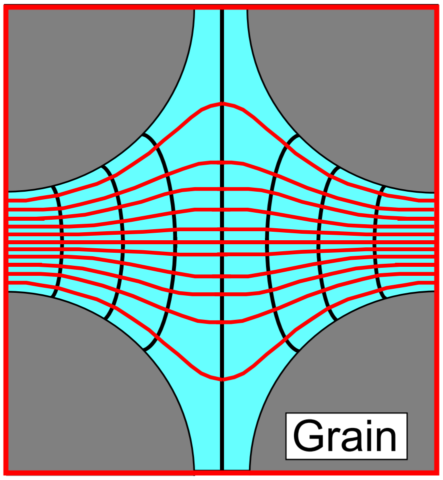
$$Q_d = -D\, \nabla C$$ Fick's law (diffusion)

$$Q_h = -\kappa\, \nabla T$$ Fourier's law (heat conduction)

$$\varepsilon = s\, \nabla \sigma$$ Hooke's law (elasticity)

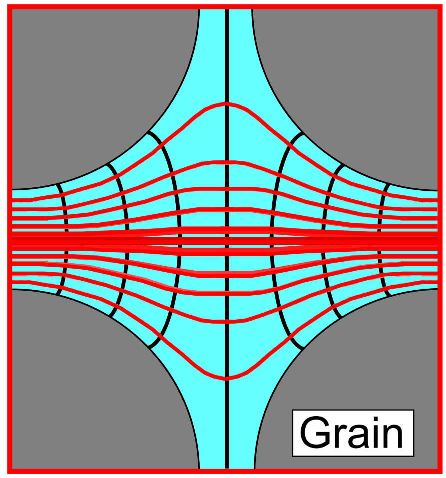
Effect of Surfaces

Electric Current Flow



$'k' = f$

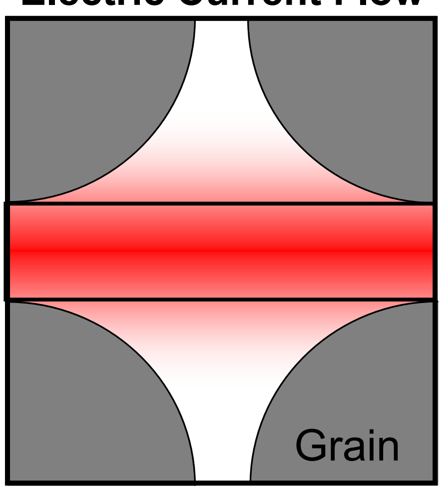
Laminar Fluid Flow



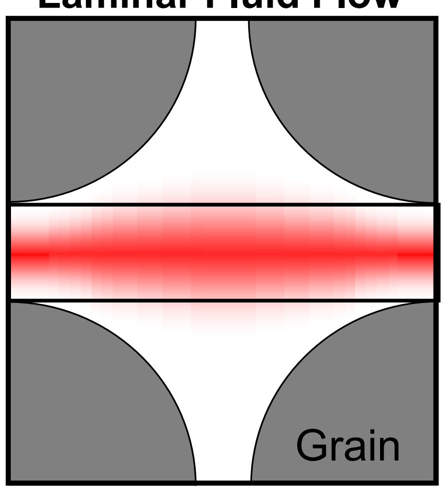
$k = f\ S$

Effect of Grain Surfaces

Electric Current Flow



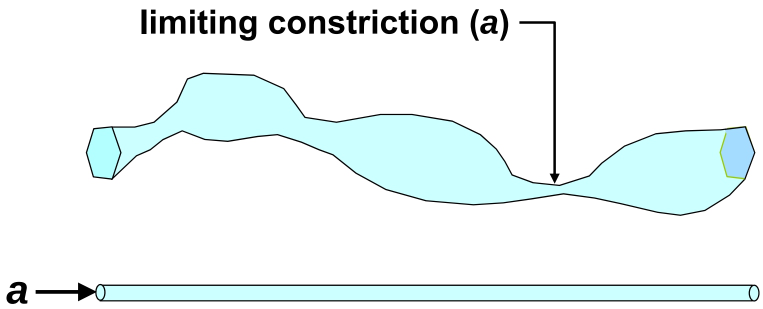
Laminar Fluid Flow



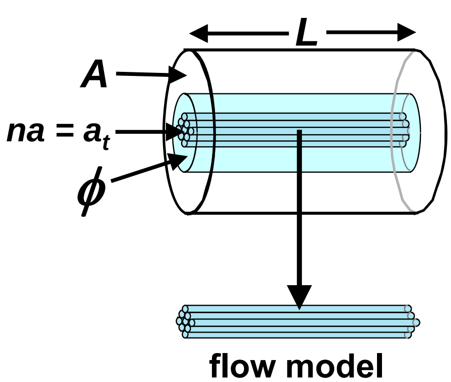
Tubes defined by pore throats are a good model for the flow of electric currents.

Tubes defined by pore throats are an *even better* model for the flow of fluids.

Stream-Tubes



Flow Model



$$Q = \frac{a}{8\pi}\,\frac{\Delta P}{\mu}\,\frac{na_t}{L}\left[\frac{A}{A}\right]$$

$$Q = \left[\frac{a_t}{A}\,\frac{a}{8\pi}\right]\frac{\Delta P}{\mu}\,\frac{A}{L}$$

$$\boxed{k = E_0\phi\,\frac{a}{8\pi}}$$

$$S = \frac{a}{8\pi}$$

$$\boxed{k = E_0 \phi \frac{a}{8\pi}}$$

What is the relative importance of the factors that control permeability?

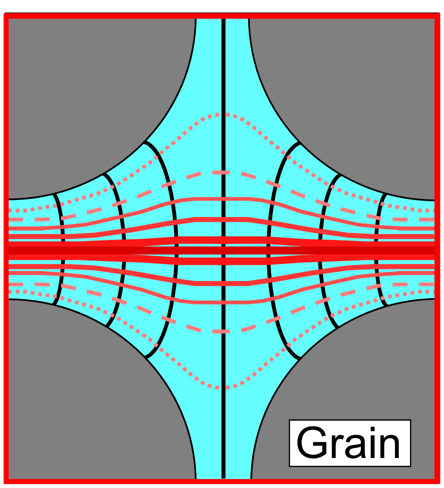
What does this imply about your ability to determine permeability from logs?

Pore Geometry ⟶ Permeability

Pore geometry ⟶ eqi-potential surfaces

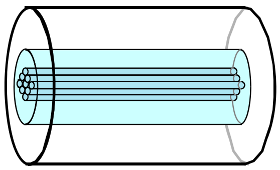
⟶ electric current density distribution

+ surface effect in pore throats ⟶ permeability



$$k = \frac{C_0\, a}{C_w\, 8\pi}$$

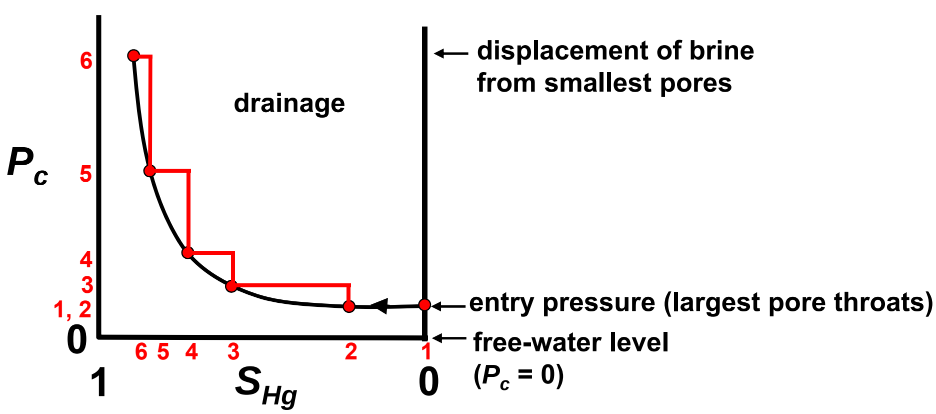
Validation of the Flow Model



$$k = f\ \frac{a}{8\pi}$$

$$\boxed{a = 8\pi\ k/f}$$

Hg Injection Capillary Pressure



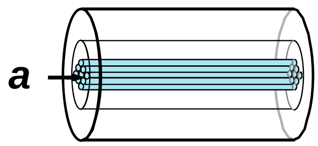
for Hg and P_c (psi), r (µm)

$$r_i = \frac{107}{P_{c\text{-}i}}$$

then: $$\boxed{\bar{r} = \frac{\sum_{i=2}^{i=n}[r_i\,(S_{Hg(i)} - S_{Hg(i-1)})]}{\sum_{i=1}^{i=n}(S_{Hg(i)})}}$$

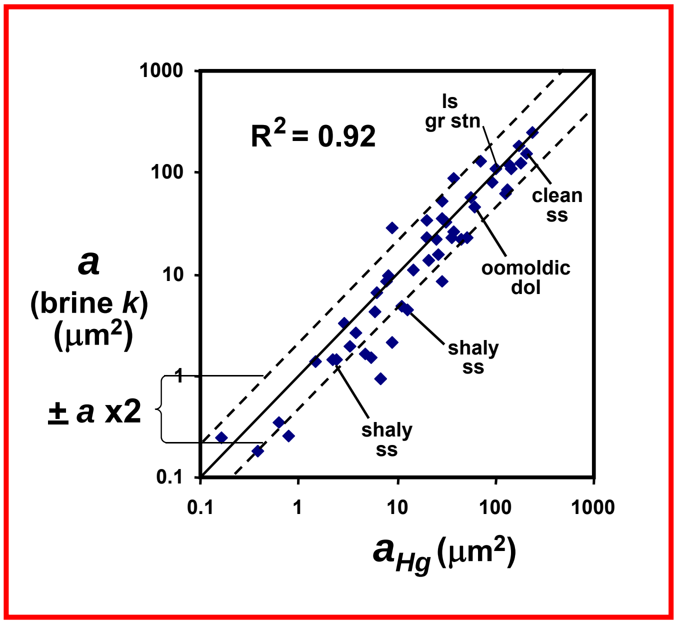
n = no. of pressure steps

Validation of the Flow Model



$$a_{(\mu m^2)} = 0.025 \frac{k_{md}}{f}$$

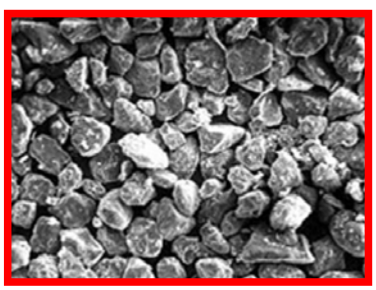
(0.025 => 8π, units)

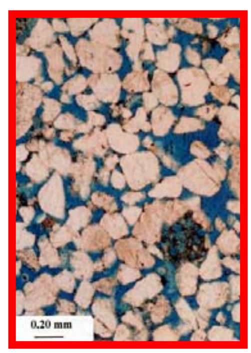


52 clean & shaly sandstone & carbonate samples from the Shell Rock Catalog.

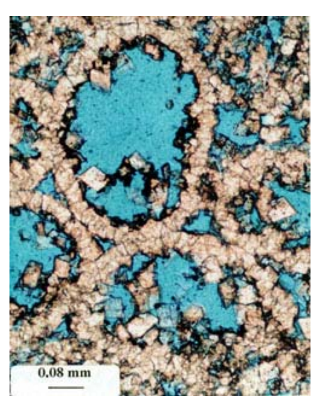
Examples from the Shell Rock Catalog

clean, well-sorted sandstone





oomoldic dolomite



Impact of pore geometry on Permeability

The agreement between the average limiting stream-tube constriction size calculated from *k,* and *f,* and limiting pore-throat size from capillary pressure measurements shows that:

- **Limiting constriction (pore-throat) size *is* the only pore-geometric parameter of importance.**
- **The effects of tortuosity, connectivity, pore-bodies, etc. *are* minimal.**
- ***Pore systems conduct (electricity and fluids) as if they were a bundle of tubes whose size is determined by the sizes of the limiting constrictions.***

Kozeny-Type Permeability Models

The Kozeny Equation (1927)

Assumption:

Flow is through tubes with constant but arbitrary cross-section.

The volume of the tube bundle is equal to that of the pore volume.

$$\boxed{k = \frac{c_k\,\phi^3}{(A_s/V_t)^2}}$$

Where:

c_k = a constant = f (cross-sectional shape of the tubes)

A_s = surface area of the pores (grains)

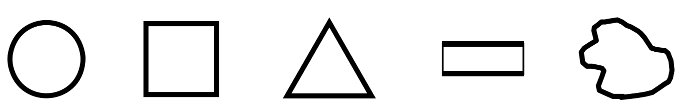
V_t = volume of the sample

Kozeney Constant (c_k)

$$\boxed{k = \frac{c_k\,\phi^3}{(A_s/V_t)^2}}$$

C_k = Kozeny shape constant

Assumption: flow is through tubes with constant, but arbitrary cross-section.



C_k = .5 .56 .6 .7 .6 ± .1

Kozeny Equations: Relationships

Kozeny-type permeability models attempt to account for the effects of pore geometry.

Kozeny

$$\boxed{k = \frac{c_k\,\phi^3}{(A_s/V_t)^2}}$$

Carman - Kozeny

$$\boxed{k = \frac{c_k\,\phi^3}{(A_s/V_g)^2(1-\phi)^2}}$$

Modified Carman - Kozeny

$$\boxed{k = \frac{c_k\,\phi^x}{\tau^2\,(A_s/V_g)^2\,(1-\phi)^2}}$$

The Kozeny Equation (Panda & Lake)

$$\boxed{k = \frac{\left[\overline{D}_p^2\phi^3\left(\gamma C_{D_p}^3 + 3C_{D_p}^2 + 1\right)^2\right]}{\left\{2\tau_e(1-\phi)^2\left[6\left(1+C_{D_p}^2\right)(1-\phi_0)/(1-\phi) + \left(a_{vb}P_b + a_{vl}P_l + a_{vf}P_f\right)\overline{D}_p\left(\gamma C_{D_p}^3 + 3C_{D_p}^2 + 1\right)\right]^2\right\}}}$$

Kozeny Equations: Relationships

- Flow is through the pore system
- A_s/V_p is the relevant factor

$$V_p = \phi V_t$$

$$V_g = (1-\phi) V_t$$

$$V_p = \frac{\phi}{(1-\phi)} V_g$$

$$\boxed{k = \frac{c_k \phi^3}{(A_s/V_t)^2}} = \boxed{\frac{c_k \phi^3}{(A_s/V_g)^2 (1-\phi)^2}} = \boxed{\frac{c_k \phi}{(A_s/V_p)^2}}$$

Kozeny   Carman - Kozeny

The Kozeny Equation

$$k = \frac{c_k \phi}{\tau^2 (A_s/V_p)^2} \quad \text{Kozeny}$$

$$k = E_0 \phi \frac{a}{8\pi} \quad \text{(the 'real' relationship)}$$

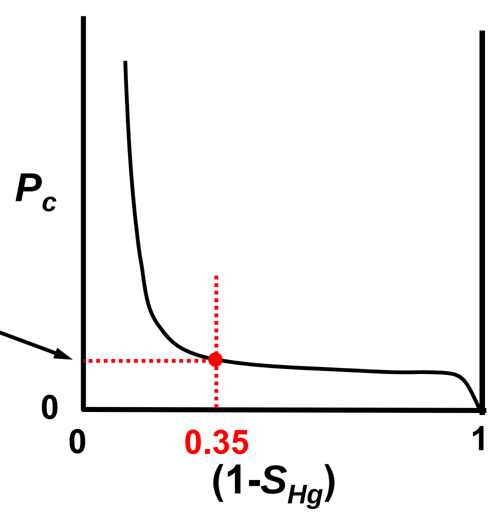
$(V_p/A_s)^2$ may correlate with $\left(E_0 \frac{a}{8\pi}\right)$

- a correlation is not guaranteed.
- any correlation will be rock-type dependent.

other capillary pressure – permeability relationships

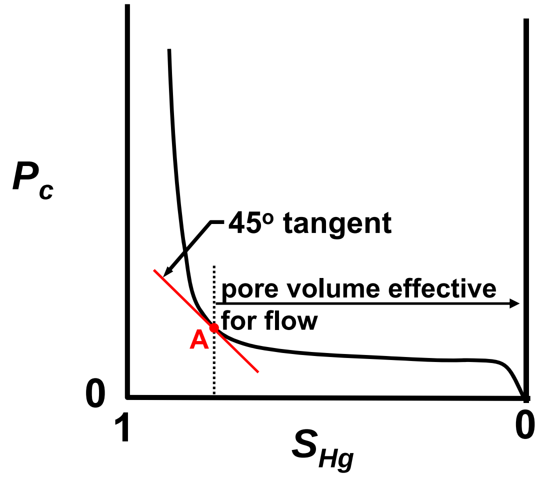
Winland (Kolodzie,1980)

$$r_{35} = \frac{107}{P_{c\text{-}35}}$$



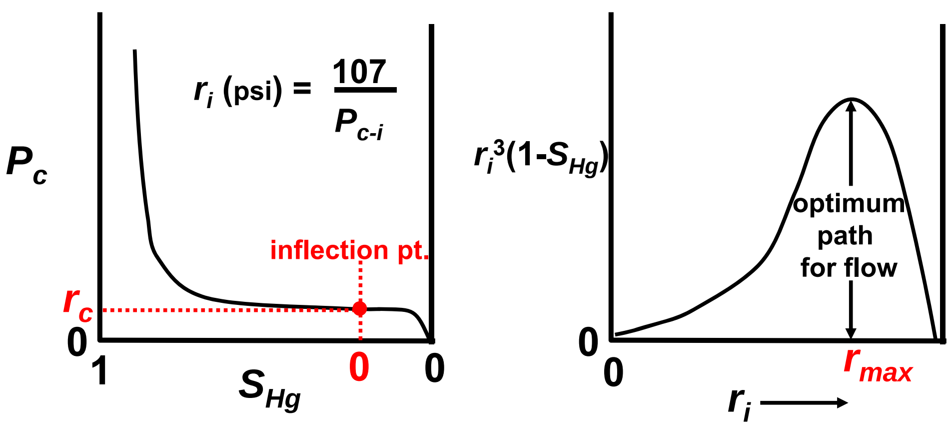
$$\boxed{\log r_{35} = a \log k + b \log \phi + c}$$

Swanson (1981)



power-law correlation with parameters a & b: $k_w = a\left[\dfrac{S_{Hg}}{P_c}\right]^b$

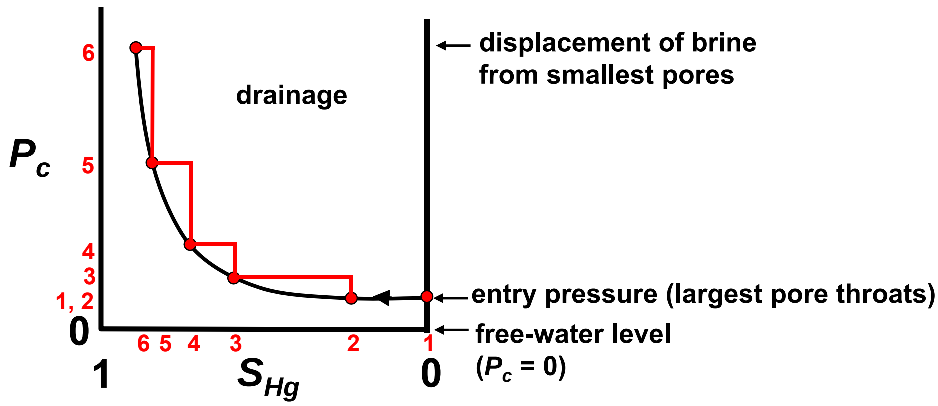
Katz & Thompson (1987)



$$k = (1/89)\,(r_{max}^3/r_c)\,\phi\,S_{max}$$

$$k = (1/226)\,r_c^2\,(C_0/C_w)$$

Hg Injection Capillary Pressure



for Hg and P_c (psi), r (μm)

$$r_i = \frac{107}{P_{c-i}}$$

then:

$$\boxed{\bar{r} = \frac{\sum_{i=2}^{i=n}[r_i(S_{Hg(i)} - S_{Hg(i-1)})]}{\sum_{i=1}^{i=n}(S_{Hg(i)})}}$$

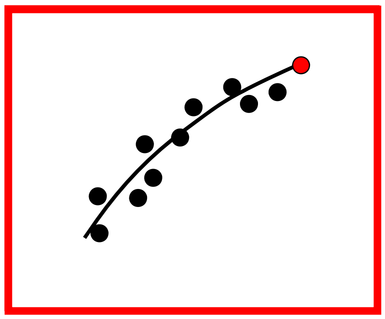
n = no. of pressure steps

Interpretation of Permeability – Porosity Cross-Plots

Interpretation of ϕ-k plots

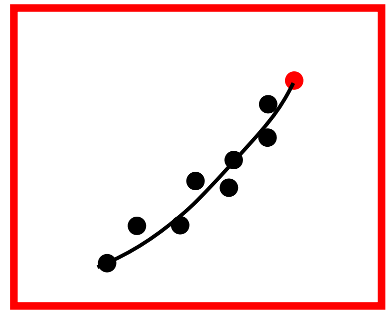
Diagenesis:

log k



ϕ

f



ϕ

a <u>quadratic</u> for
Archie sands
'shaly' sands

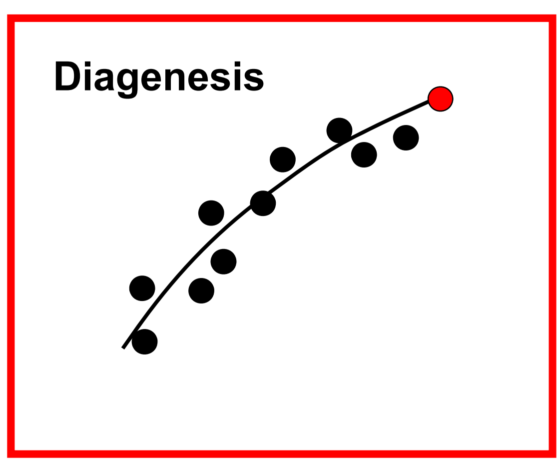
Permeability Prediction:

$$k = E_0 \phi \frac{a}{8\pi}$$

$$\frac{k}{\phi} = E_0 \frac{a}{8\pi}$$

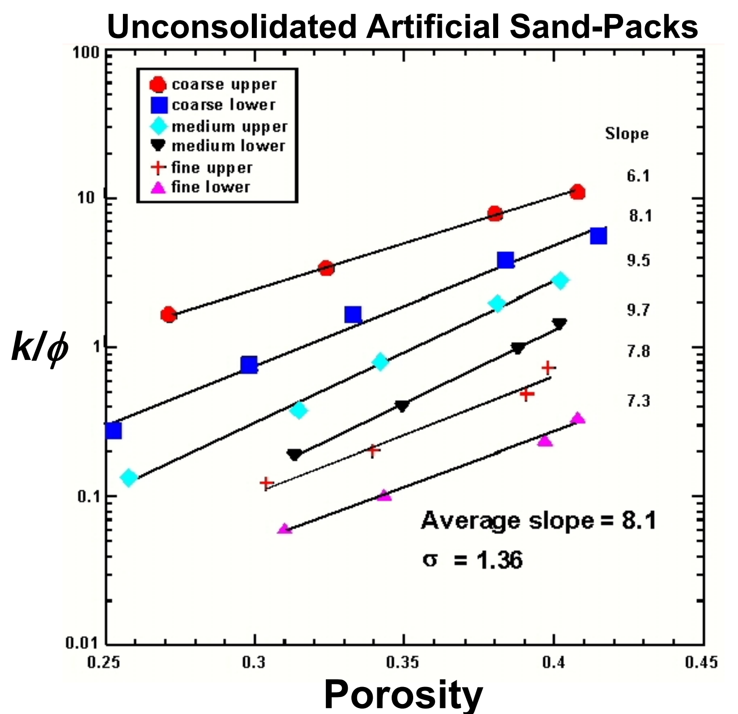
$\log \frac{k}{\phi}$

(pore throats)



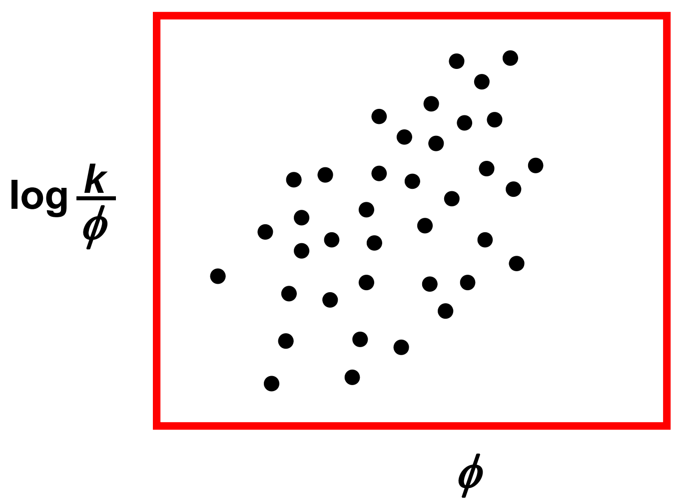
ϕ (pore volume)

Beard & Weyl (1973): Effect of Sorting



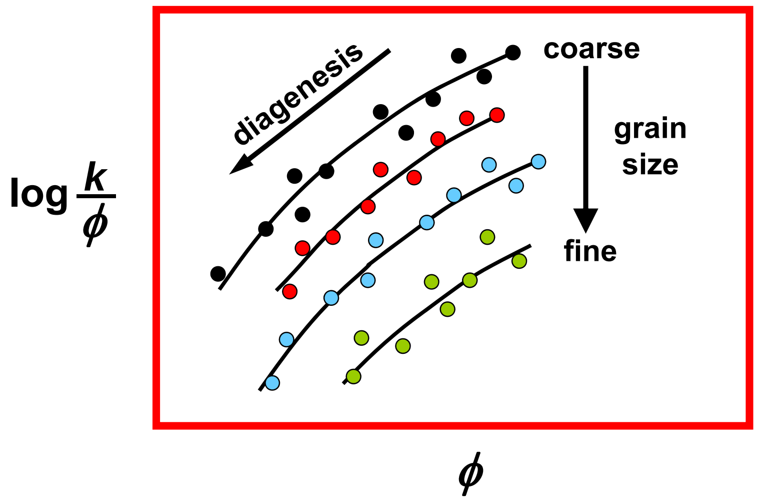
(data have been edited)

Diagenesis



no correlation → more than one 'rock type'

Diagenesis



Permeability Prediction From Geologic Models

$$k = \phi\, E_0 \frac{a}{8\pi}$$

$\boxed{k \; \alpha \; \phi}$

E_0 The geologic processes that decrease ϕ also generally decrease the total cross-sectional area of limiting constrictions (pore throats), e.g. quartz cementation.

$\boxed{k \; \alpha \; \phi^2}$

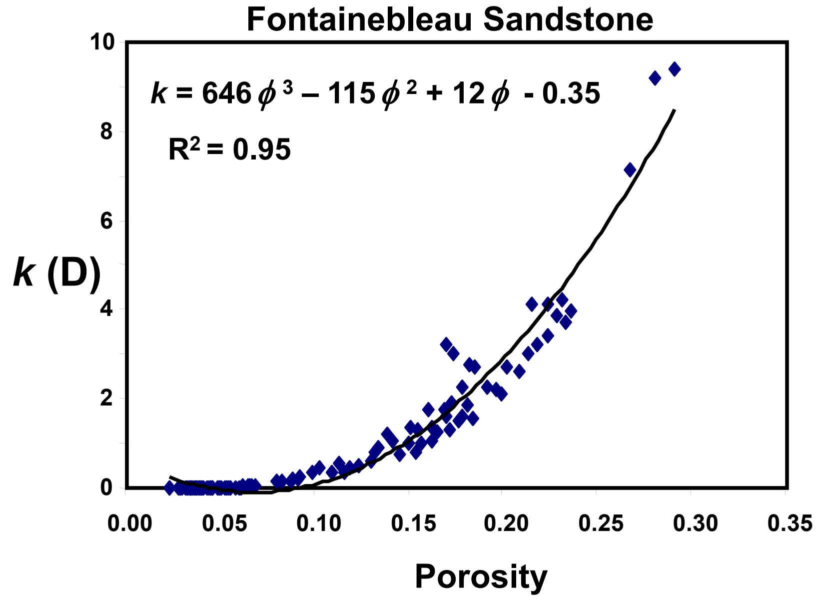
$\frac{a}{8\pi}$ The same geologic processes that vary ϕ and E_0 also vary the average cross-sectional area of the limiting constrictions.

$\boxed{k \; \alpha \; \phi^3}$

Permeability Prediction From Geologic Models

Data of Bourbie & Zinszner (1985) in Bryant, Cade & Mellor (1993)

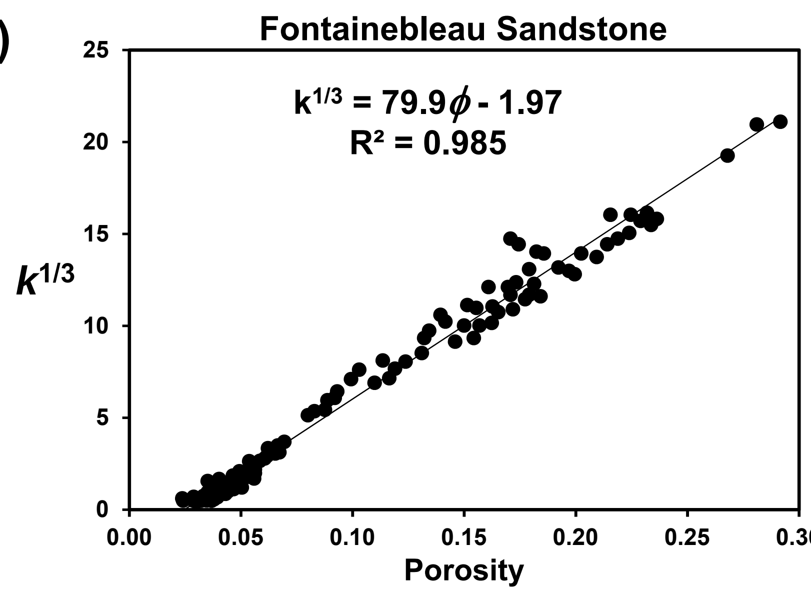
$k = f(\phi^3)$



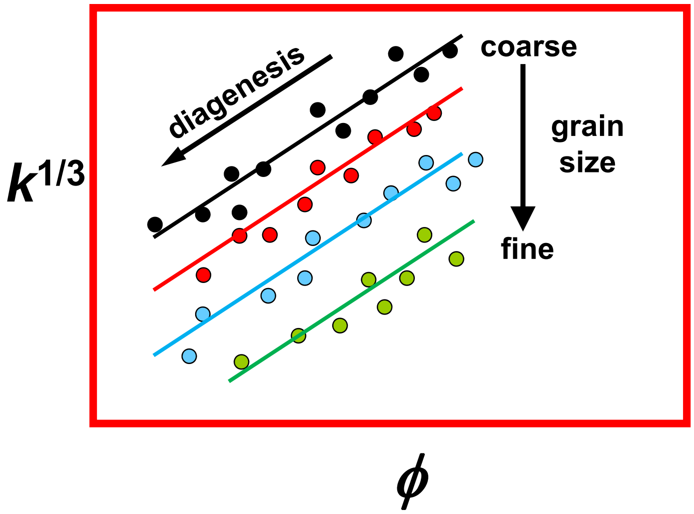
Permeability Prediction From Geologic Models

Data of Bourbie & Zinszner (1985) in Bryant, Cade & Mellor (1993)

$k^{1/3} = f(\phi)$



$k - \phi$ Plots



Summary

1. All measurement details must be known before a statement about permeability can be interpreted.
2. Permeability (k) has no intrinsic physical meaning. It is only a proportionality constant in the Darcy flow equation.
3. By default, k must reflect all internal properties of a rock that affect fluid flow (but not explicitly).
4. Ohm's Law and Darcy's Law have the same form and the same solution: $k \sim f$, ($k \sim E_0\phi$).
5. $k = E_0\phi\, a/8\pi$ is dominated by the average cross-sectional area of the limiting constrictions (a) by orders of magnitude.

Summary

6. A good physical model for fluid flow is a bundle of tubes with total cross-sectional area equal to that of the limiting constrictions and the cross-sectional area of each tube equal to that of the average limiting constriction. This model is verified with experimental data.

7. Plotting $k^{1/3}$ vs ϕ gives a linear relationship showing how the total and average limiting constriction size vary as diagenesis changes porosity.

8. A lack of correlation between $k^{1/3}$ and ϕ implies a mixture of two or more 'rock-types.'

9. If the $k^{1/3}$ (or k/ϕ, or log k/ϕ) and ϕ relationship is known for the diagenesis relating a suit of rock samples, then it may be possible to interpret a mixture of varying grain-size and diagenesis.

New Concepts in Petrophysics

Pore Systems and Permeability

June 23

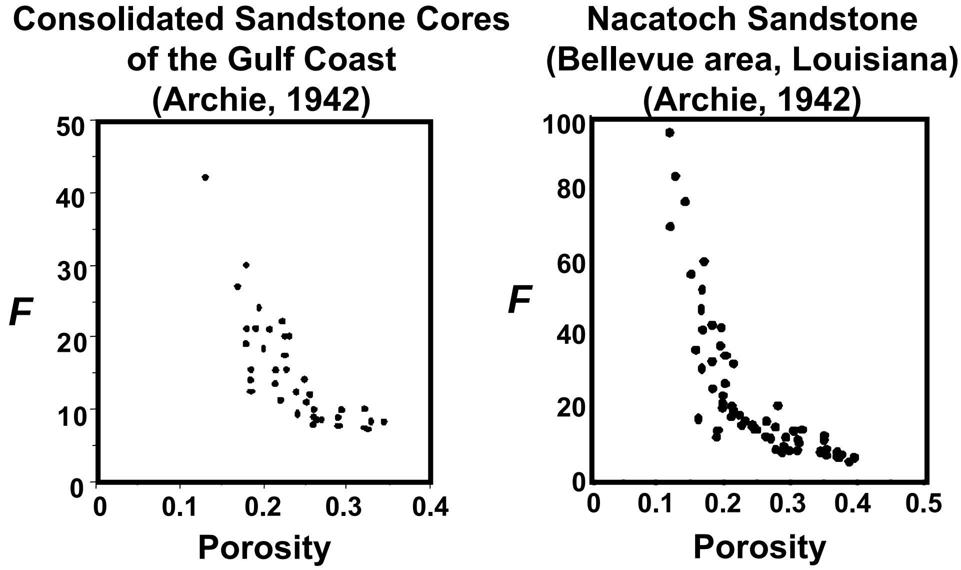
2013 SPWLA Short Course

Facilitator:
David C. Herrick, PhD
Yellowstone Petrophysics LLC
davidcherrick@gmail.com

G. E. Archie's (1942) Data

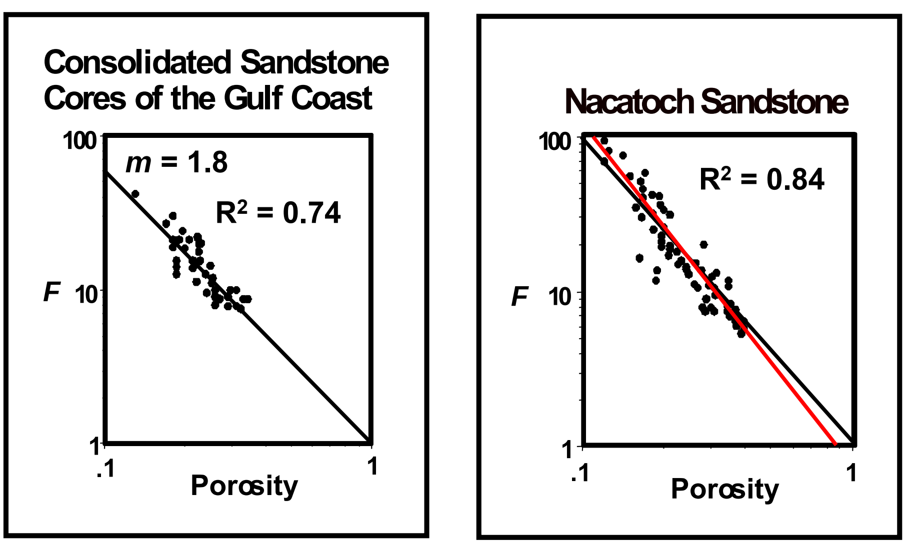
Formation Resistivity Factor: $F = R_0/R_w$

- a rock property independent of R_w



Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics, *Transactions AIME* , v. 146.

Archie's (1942) Data

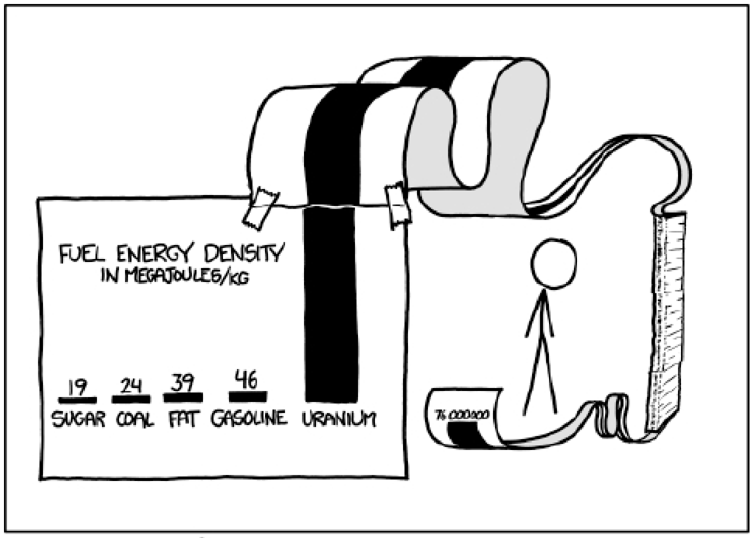


<u>assumptions!</u>:

1) straight line
2) extrapolates to (F =1, ϕ =1)

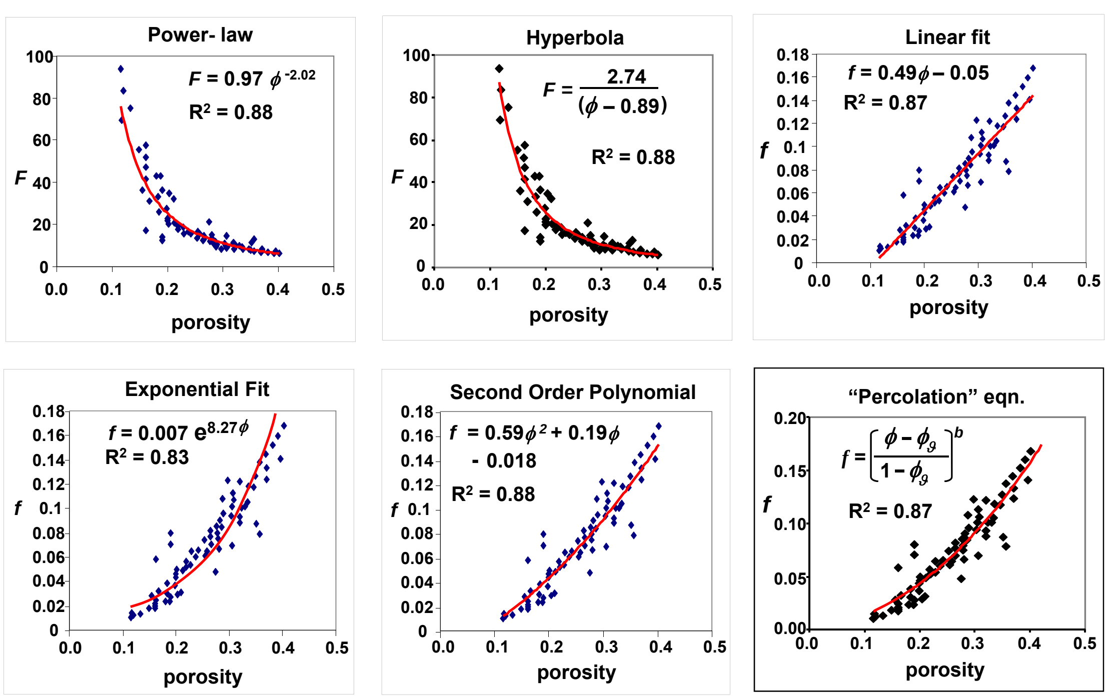
$$\log F = -m \log \phi$$

$$\boxed{F = \phi^{-m}}$$



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

Archie's 1942 Nacatoch Data



Archie's S_w Equation

Archie (1942): from the initial description (abstract?)

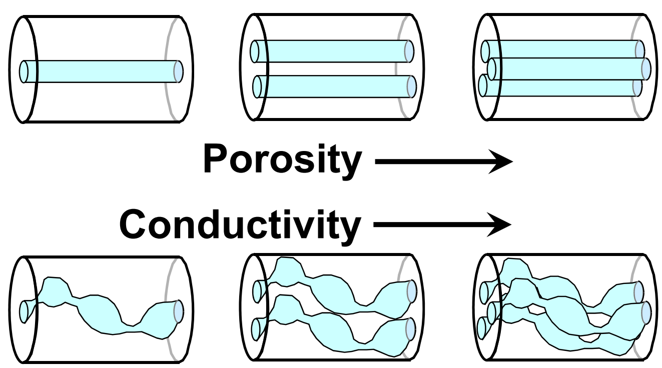
"From the available information, it is apparent that much care must be exercised in applying to more complicated cases the methods suggested. It should be remembered that the equations given are not precise and represent only approximate relationships. It is believed, however, that under favorable conditions their application falls within useful limits of accuracy."

"it appears that the formation resistivity factor F is a function of the type and character of the formation, and varies, among other properties, with the porosity and permeability of the reservoir rock; many points depart from the average line shown, which represents a reasonable relationship."

"…the indicated empirical relationship

$F = \phi^{-m}$ …"

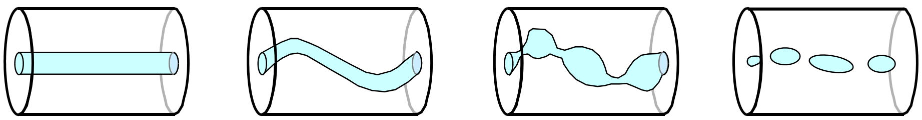
Conductivity = f (Porosity)



Conductivity $\propto$ Porosity

Conductivity = *f* (Pore Geometry)

models: identical except for geometry of pore space



max ⟵ Conductivity 0

Conductivity = *f* ??(Pore Geometry)