POROSITY

PERMEABILITY

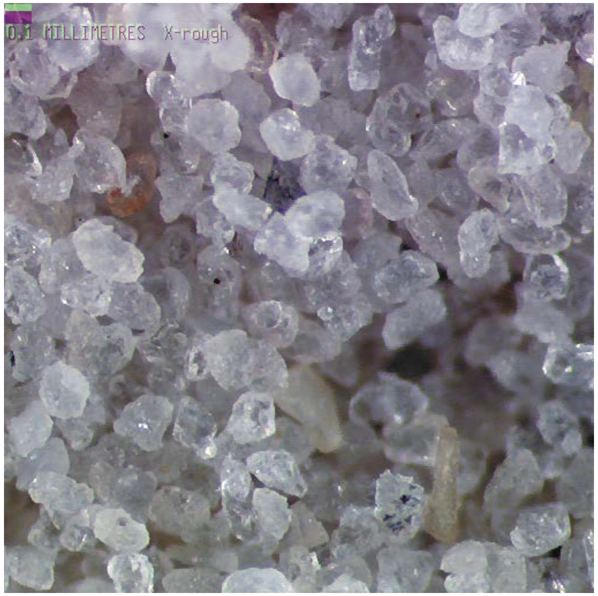
CONDUCTIVITY

Definition of Porosity

$$\phi = \frac{V_b - V_{ma}}{V_b} \cdots or,$$

$$\phi = \frac{V_p}{V_b} \cdots or,$$

$$\phi = \frac{V_p}{V_{ma} + V_p}$$



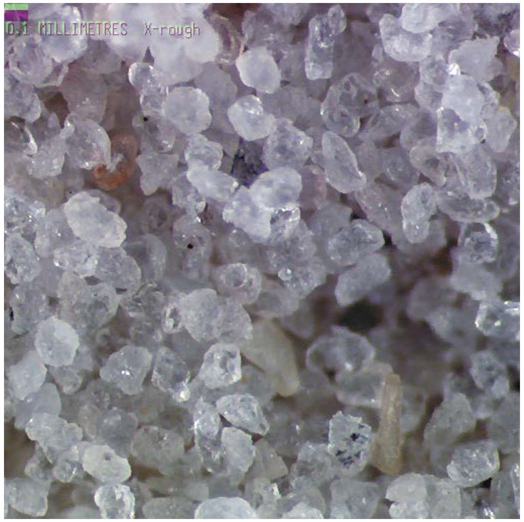
φ : porosity

V_p : pore volume

V_b : bulk volume,

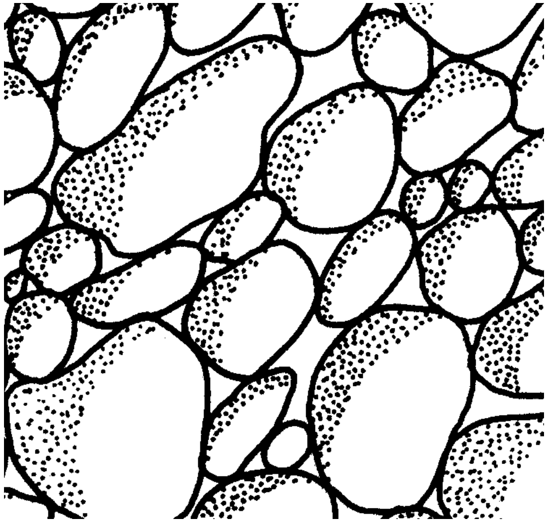
V_{ma} : matrix volume

Definition of porosity



Parameters derived from the grain texture

K	one phase permeability	[mD]
D_{dom}	dominant grain diameter	[micron]
C	sorting constant	
ϕ	porosity	[ratio]
m	cementation factor	
d_{70}	diameter of pore throat at 70 % wetting phase saturation	[micron]
d_{pore}	diameter of capillary	[micron]
P_c	capillary pressure	[psia]



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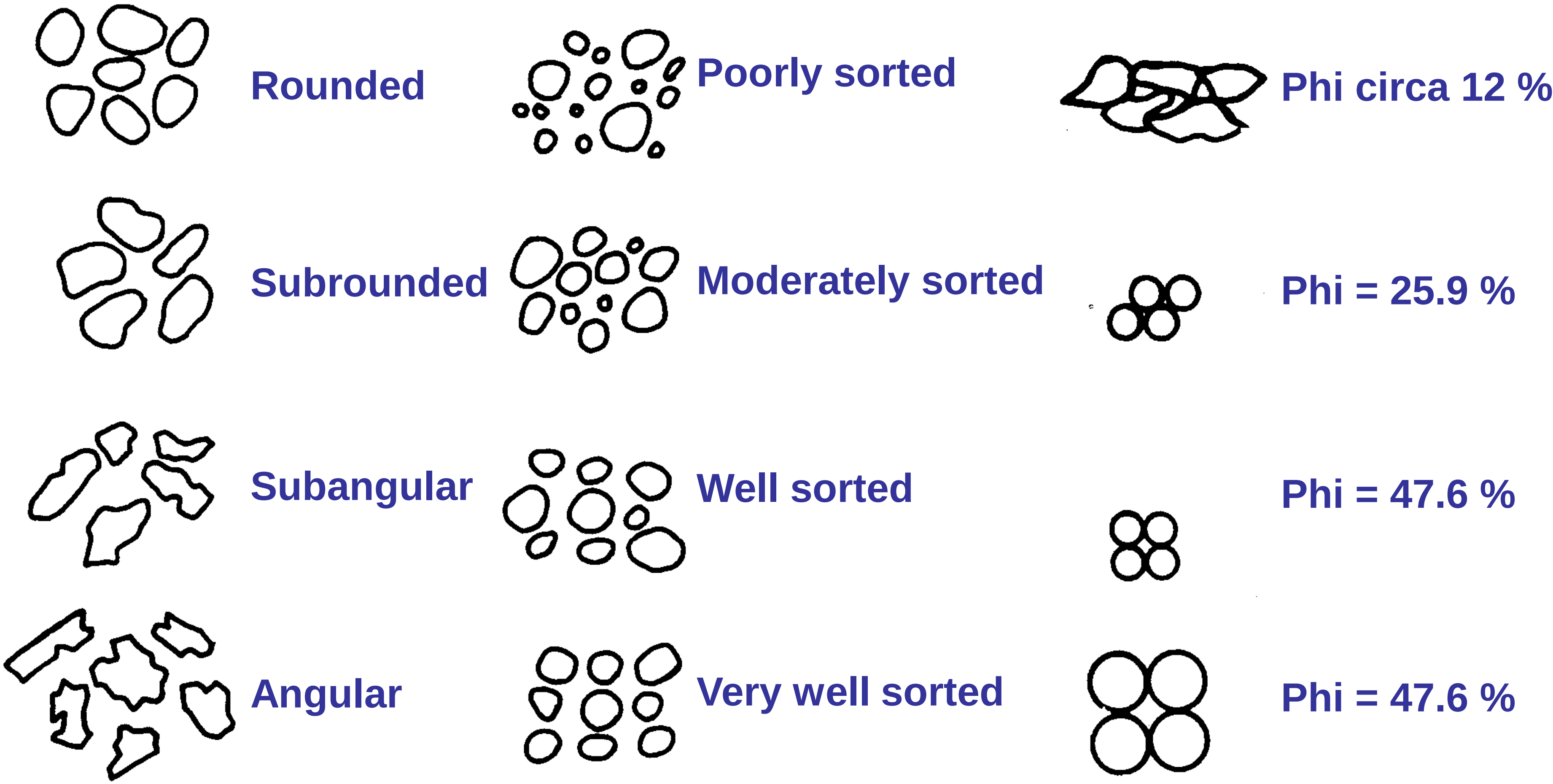
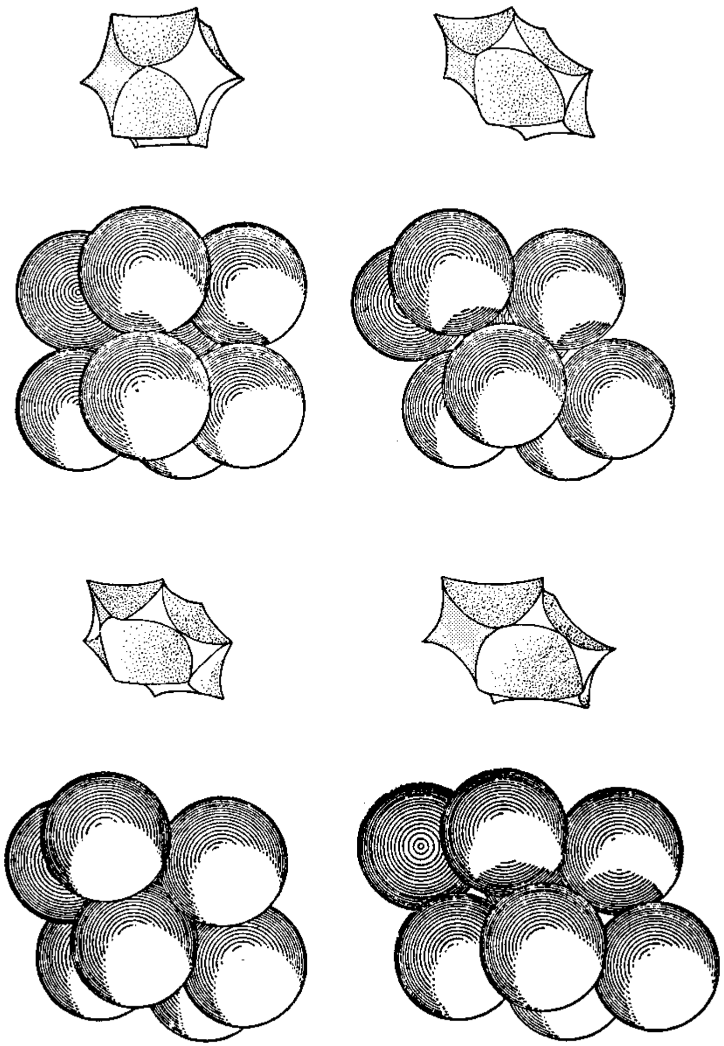
Definition of porosity

Grain Types and Grain Framework Variation



Definition of porosity

Pore Types due to Grain Framework Variation

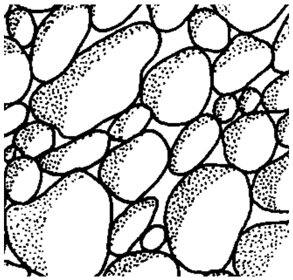


Pore shape

Grain packing

Pore shape

?



Grain packing

Definition of porosity

Porosity as a function of grain size uniformity

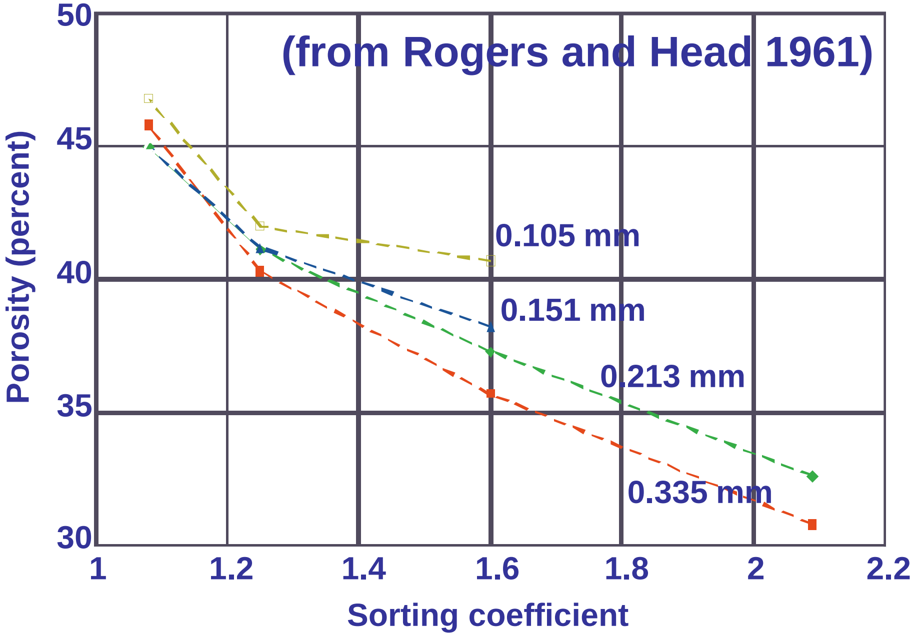
$$S_0 = \sqrt{\frac{S_{25}}{S_{75}}}$$

S_{25} Grain size at 25% cumulative weight percent.

S_{75} Grain size at 75% cumulative weight percent.

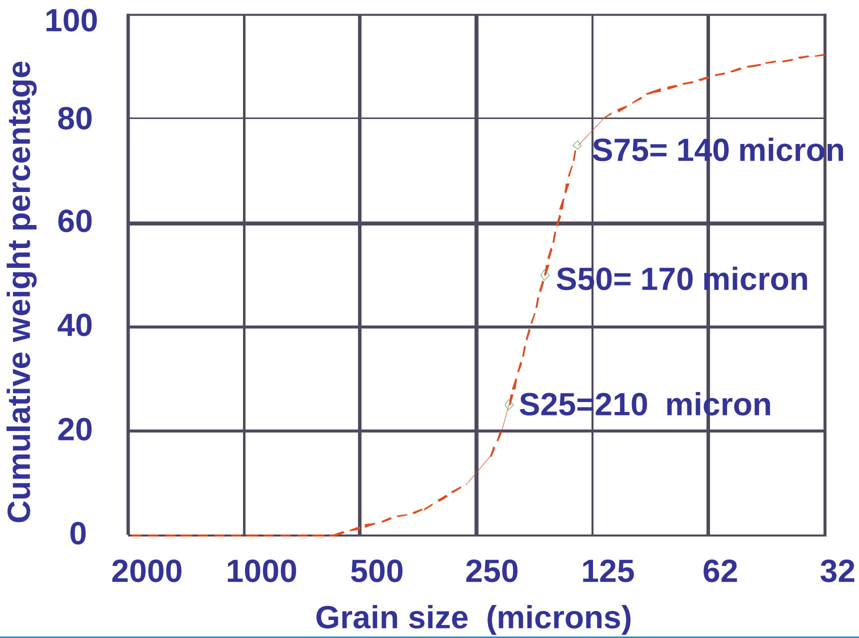
Relationship between porosity and sorting

Of sands with various median sizes.



Grain size distribution with

Trask So=1.22



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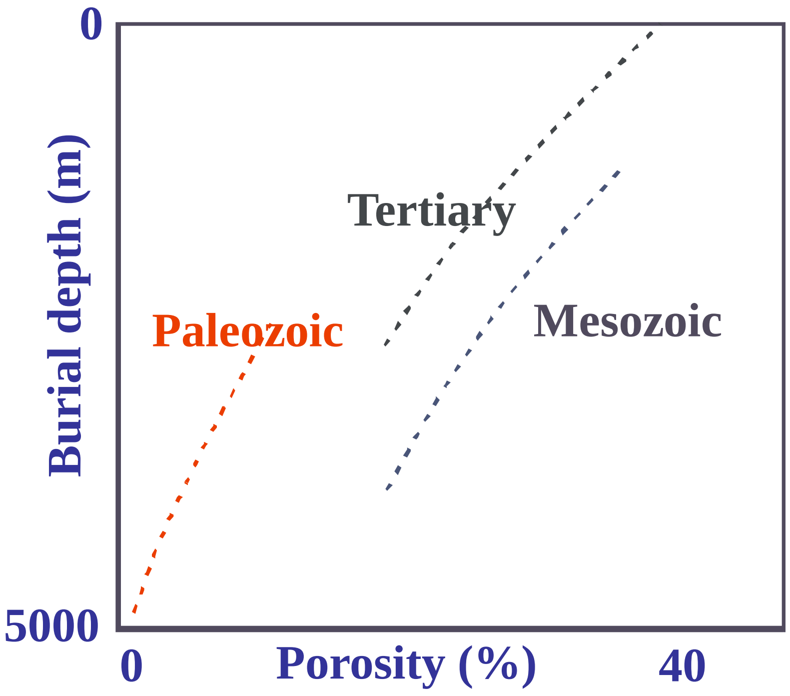
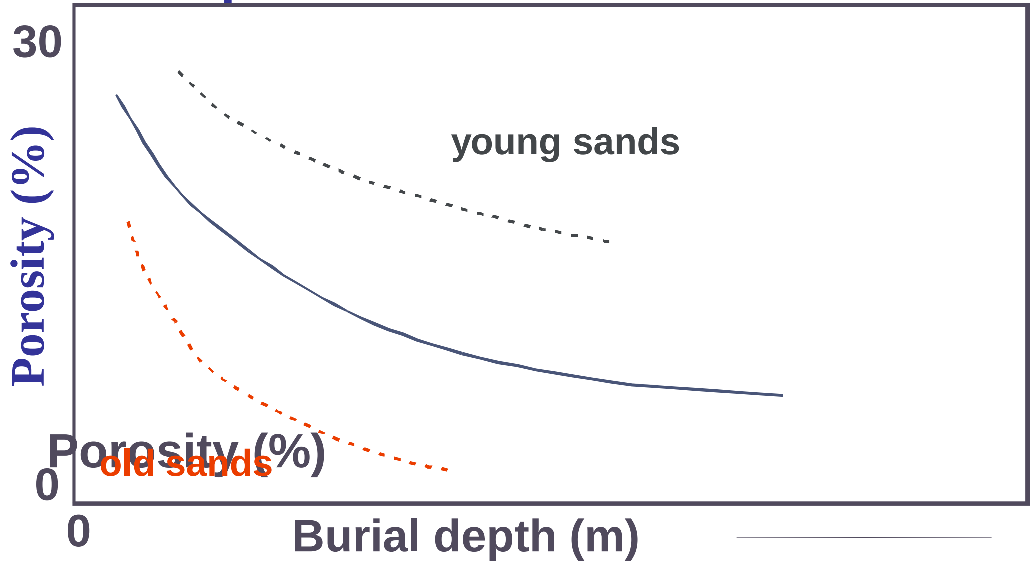
Definition of porosity

POROSITY VALUES AND SPATIAL CHARACTERISTICS

Pore space reduction during and after deposition



Porosity reduction as a function of depth.



Porosity reduction with depth of different generations of porous rock

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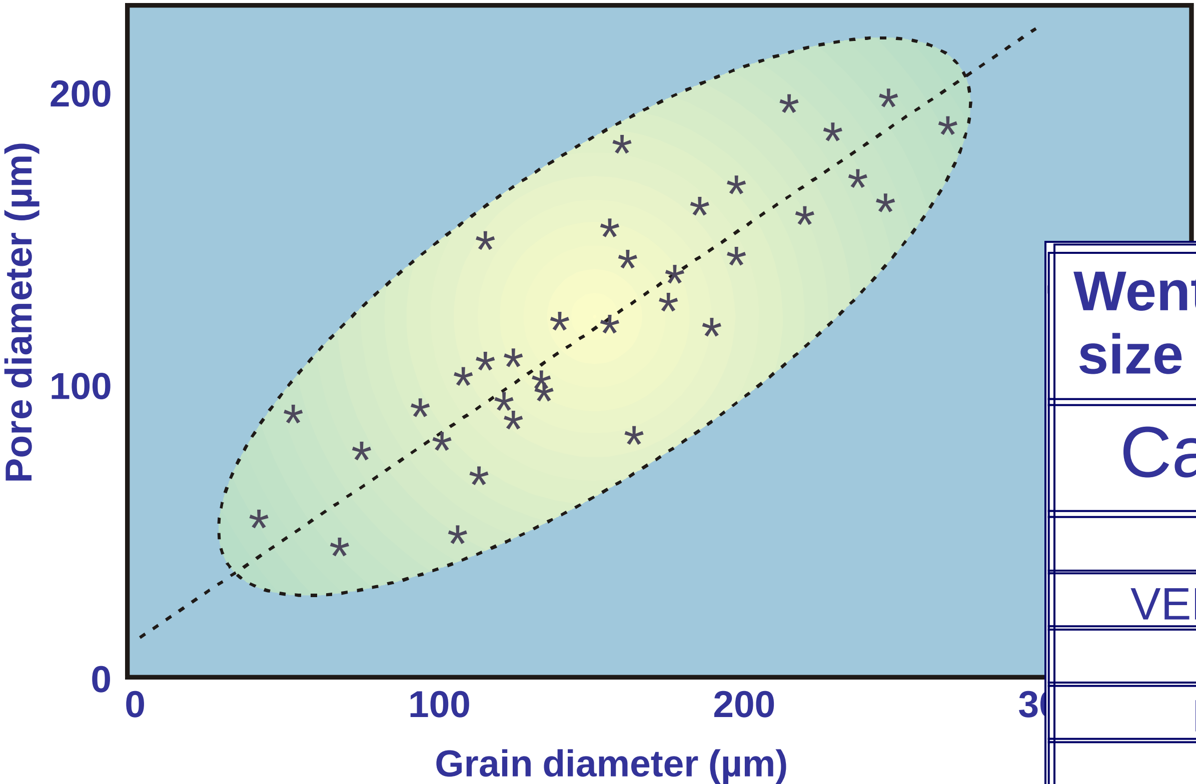
Definition of porosity

Grainsize - pore size relation



Wentworth system for grain size analysis of siliciclastics	
Category	Median grain size in µm
GRAVEL	2000
VERY COARSE	1000
COARSE	500
MEDIUM	250
FINE	125
VERY FINE	62
COARSE SILT	16
FINE SILT	8

POROSITY VALUES AND SPATIAL CHARACTERISTICS

Consolidation and cementation

average porosities of several porous rock types	
unconsolidated sands	35 - 45 %
more consolidated sandstone	20 - 35 %
tight/well cemented sandstone	10 - 20 %
limestone (e.g. Middle East)	5 - 20 %
dolomite (e.g. Middle East)	5 - 20 %
chalk (e.g. North Sea)	5 - 20 %

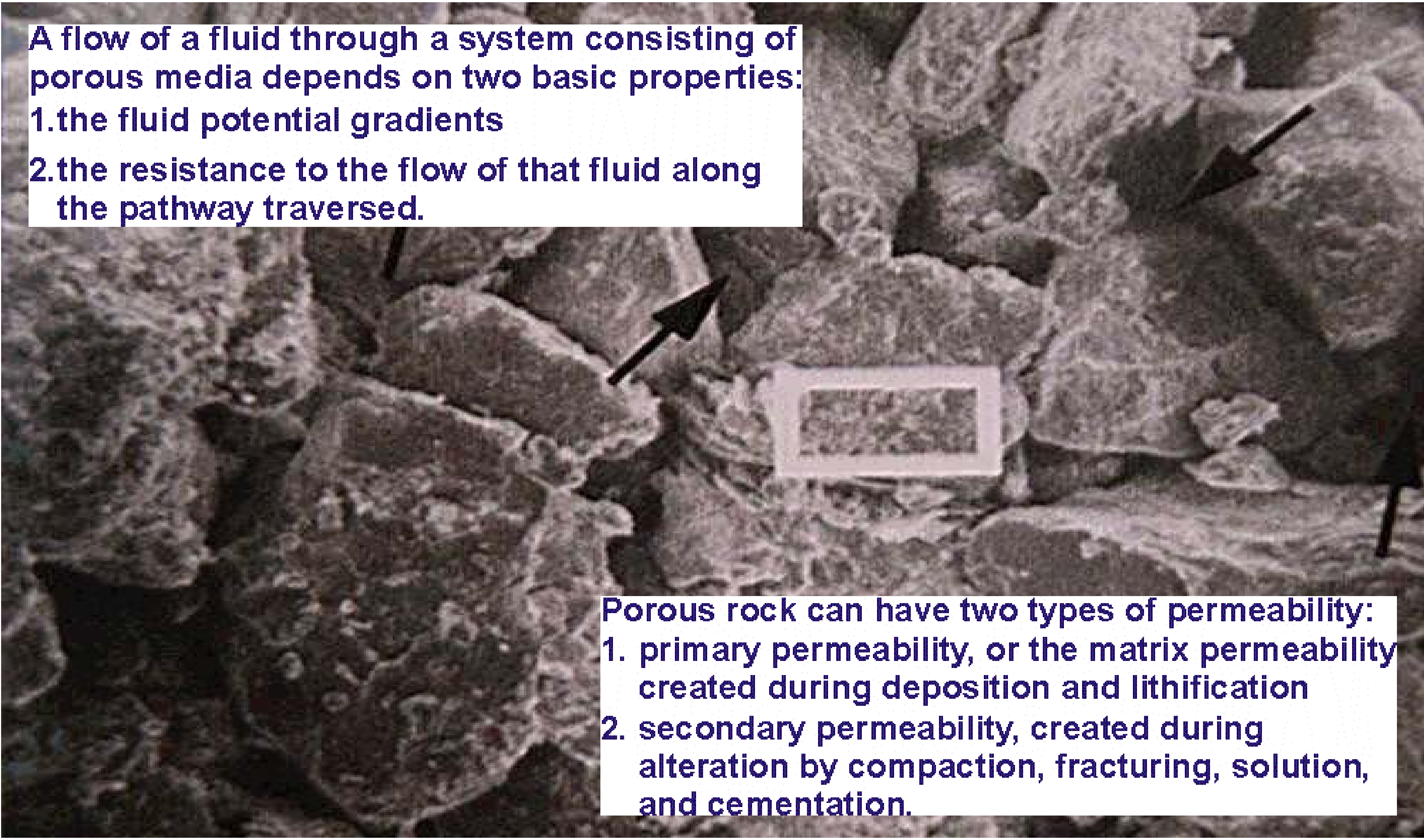
Definition of porosity

Porosity types: Inter- and Intra-granular porosity

Polarization microscopy

Thin section of Felser sandstone: //-nicols, X-nicols and the fluorescing surface showing weathering (left), mineral content (middle) and pore space distribution (right).

Definition of Permeability



A flow of a fluid through a system consisting of porous media depends on two basic properties:

1. the fluid potential gradients
2. the resistance to the flow of that fluid along the pathway traversed.

Porous rock can have two types of permeability:

1. primary permeability, or the matrix permeability created during deposition and lithification
2. secondary permeability, created during alteration by compaction, fracturing, solution, and cementation.

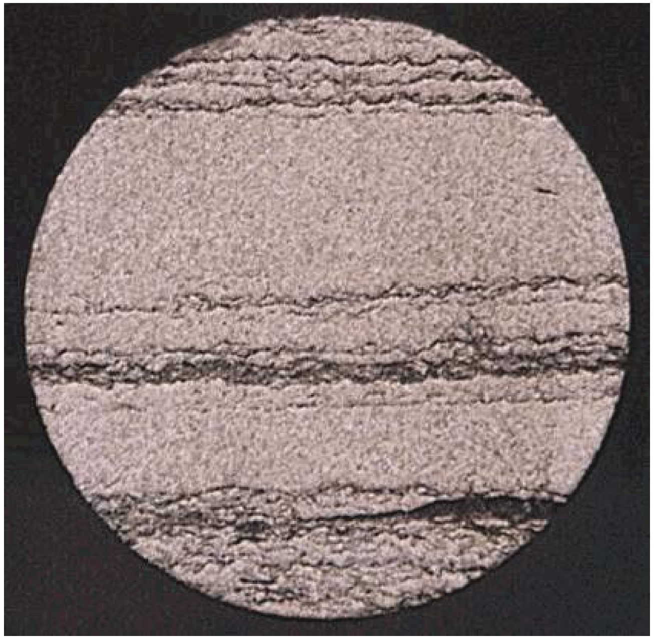
Definition of Permeability

Permeability can be derived from:

- **Lab experiments: Poiseuille, Darcy – Dijon.**

- **Texture analyses: Porosity and grain size distribution.**
  - **Spatial relation: Carman-Kozeny.**
  - **Empirical relation: van Baaren.**

- **Lab measurements transferred to logs.**

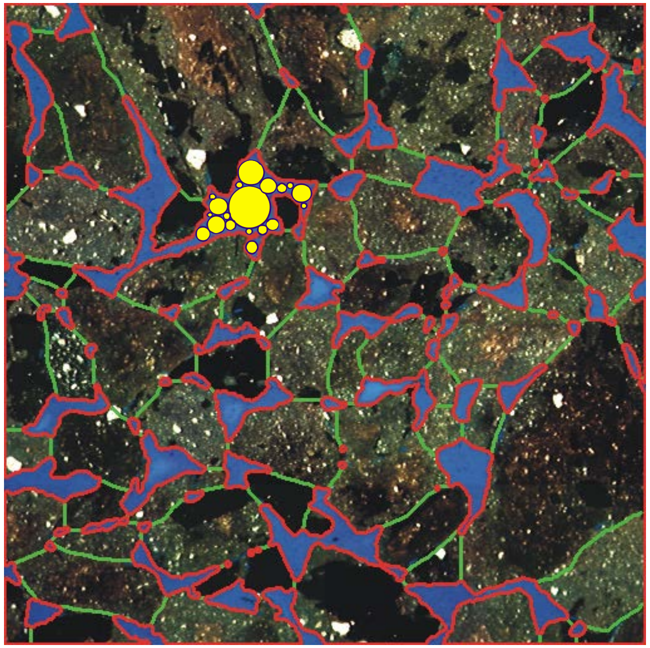


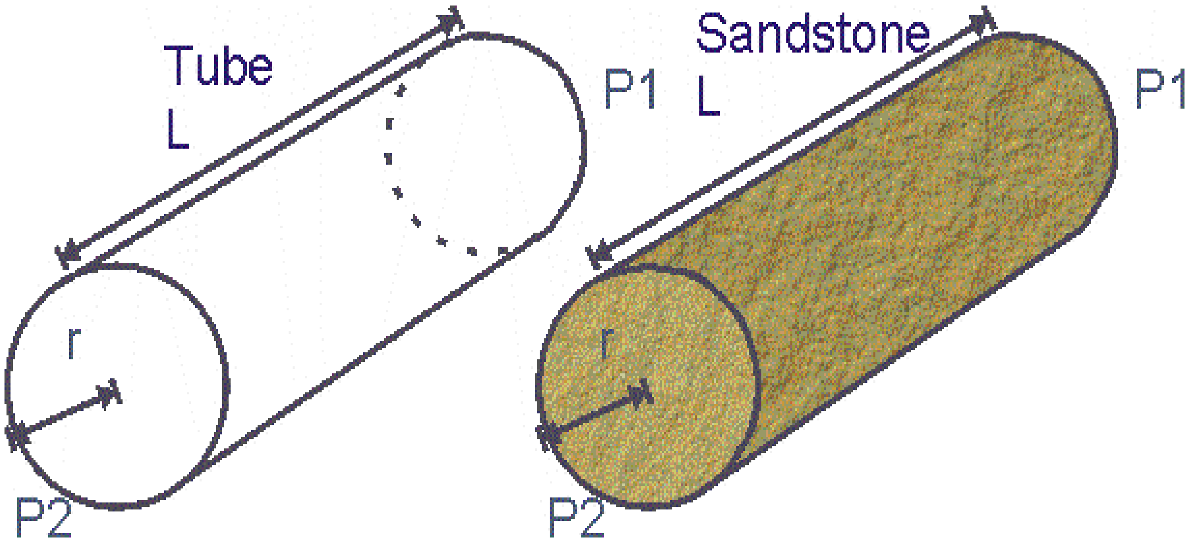
Definition of Permeability Poiseuille, Darcy – Dijon

FLOW THROUGH A TUBE (Poiseuille)

$$Q = \frac{\pi \cdot r^4 \cdot \Delta p}{8 \cdot \mu \cdot L}$$

Q : volumetric velocity in cm^3/s;
r : radius tube in cm;
ΔP : pressure difference in $dyne/cm^2$;
μ : dynamic viscosity in poise (gram/sec.cm);
L : length tube in cm.





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Definition of Permeability Poiseuille, Darcy – Dijon

FLOW THROUGH A SAND BED (Darcy)

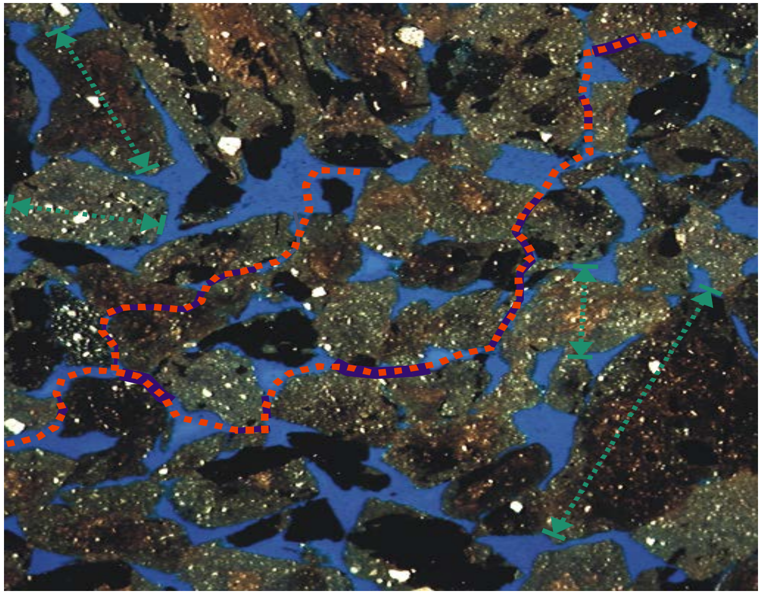
$$Q = \frac{-k(h2 - h1)}{l}$$

Q	: volumetric fluid velocity in $L^3.t^{-1}$
l	: thickness of the sand L.
h_2, h_1	: the elevation above a reference level of water in manometers terminated above and below a vertical column of sand and L
k	: a proportionality factor also in $L^3.t^{-1}$, which contains the properties of the fluid and the porous medium.

FLOW THROUGH A CORE (Darcy - Dijon, 1856)

$$Q = \frac{k \cdot A \cdot \Delta P}{\eta \cdot L}$$

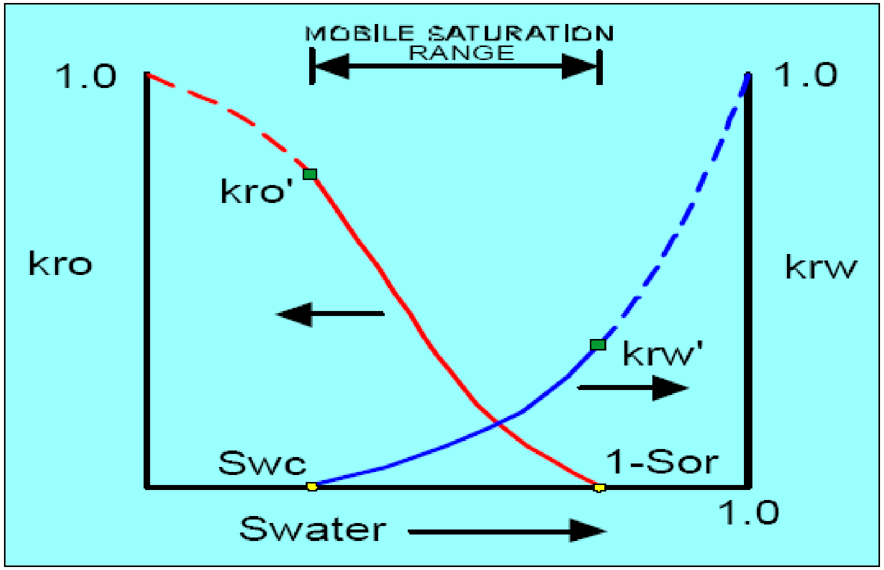
Q	: volumetric fluid velocity in $cm^3.s^{-1}$
A	: surface area perpendicular to flow direction in cm^2
ΔP	: pressure difference in atm.
η	: dynamic viscosity of the fluid in cpoise (kg/sec.cm)
L	: length in cm
k	: permeability in Darcy (1 D=$0.986 \cdot 10^{-8}$ cm^2)



Definition of Permeability Poiseuille, Darcy – Dijon

$$Relative\ Permeability = \frac{Effective\ Permeability}{Absolute\ Permeability}$$

$$kr_o(Sw) = \frac{k(Sw)}{k(Sw=1)}$$



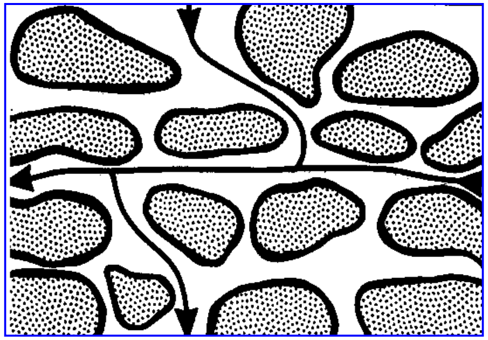
Example: One phase or liquid permeability is 100 mD.

Kro(Swc)=70 md/ 100 mD=0.7

Frequently measured with increasing water saturation - Imbibition oil - water relative permeability

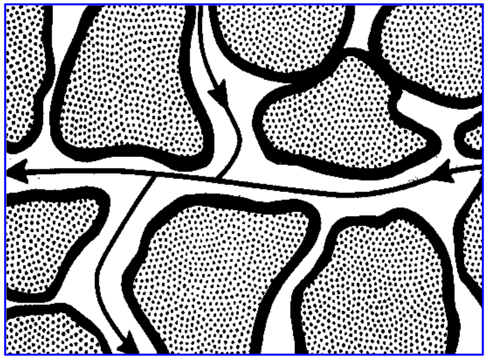
Definition of Permeability

Relations to texture properties: Shape and size of sand grains



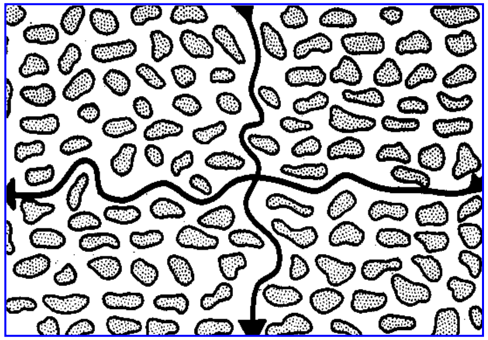
Grains elongated,large, flat and regularly arranged:

- **horizontal permeability high,**
- **vertical permeability medium-to-large**



Grains large and uniformly: rounded:

- **permeability high in all directions**



Grains small, irregular shaped:

- **permeability quickly reduces to very low values**

Definition of Permeability: Spatial relation: Carman-Kozeny

Texture analyses: Porosity and grain size distribution.

From tubes to a general relation

Poiseuille

$$k = \frac{n \cdot \pi \cdot r^4}{8 A_c}$$

A_c : capillary tube surface

$$\varphi = \frac{V_p}{V_b} = \frac{n \cdot \pi \cdot r^2}{A_c}$$

porosity of tube system

$$k = \frac{r^2 \varphi}{8}$$

k for capillary tubes

$$S_{Vgr} = S_{Vp} \cdot \frac{\varphi}{1-\varphi}$$

S_{Vgr} the total area in the pore space per unit of grain volume

S_{Vp} the internal surface area per unit pore volume

Kozeny for tubes

$$k = \left(\frac{1}{2 s_{Vgr}^2} \right) \cdot \frac{\varphi^3}{(1-\varphi)^2}$$

$$\tau = \left(\frac{L_a}{L} \right)^2$$

Tortuosity

La path length

L minimum length

Kozeny for grains

$$k = \left(\frac{1}{2\tau \cdot s_{Vgr}^2} \right) \cdot \frac{\varphi^3}{(1-\varphi)^2}$$

2τ generally 5

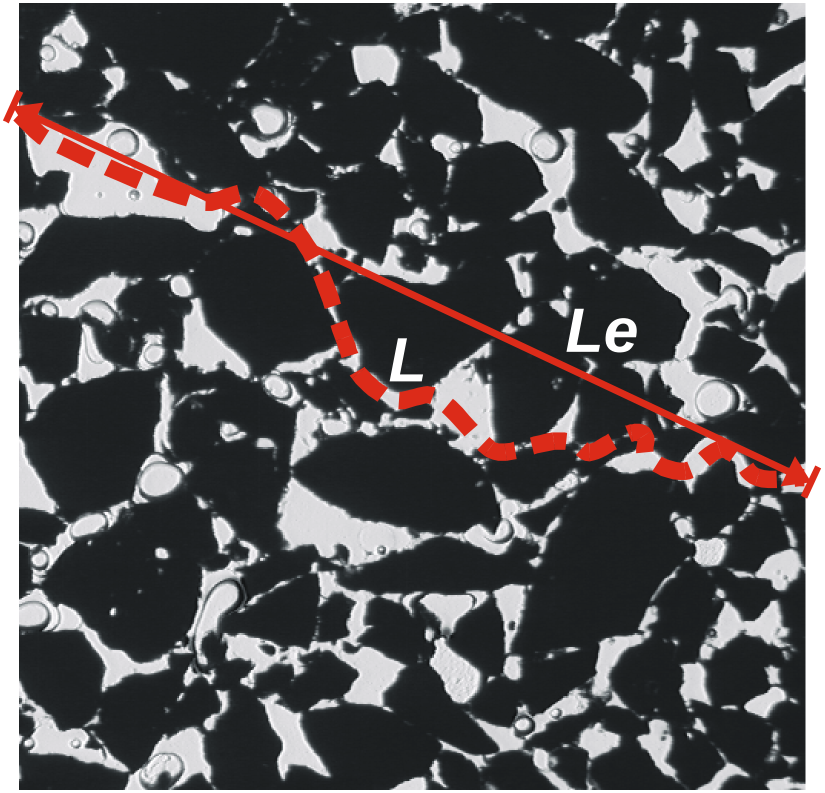
Definition of Permeability: Spatial relation: Carman-Kozeny

Permeability transition from 3D to 2D

$$\tau = \left(\frac{L_a}{L}\right)^2$$

Tortuosity
La path length
L minimum length

2τ **generally 5**



$$k_{ck} = \frac{\phi^3}{k_0\left(\frac{L_e}{L}\right)^2 (1-\phi)^2 S_{Vgr}^2} \rightarrow k_{ck} = \frac{\phi^3}{5(1-\phi)^2 S_{Vgr}^2}$$

From 3D-volumetric to 2D-area using pore perimeter (P) and pore area (Ap) and subtituting S_{Vp} for S_{Vgr} gives:

$$k_{ck} = \frac{\phi}{5\left(\frac{4}{\pi}\frac{P}{A_p}\right)^2}$$

Shape factor

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Definition of Permeability

Comparison formation factors, grain-size, lithology, and permeability

Lithology	F	grainsize	Permeability k
			Darcy
		mm	
gravel with sand	7.5	3.00	large
coarse sand with gravel	6	0.70	200
coarse sand	5	0.20	50
medium sand	4	0.05	25
fine sand	3.5	0.01	10

Definition of Permeability - Empirical relation: van Baaren for K_{LIQUID}.

van Baaren relation (1979)

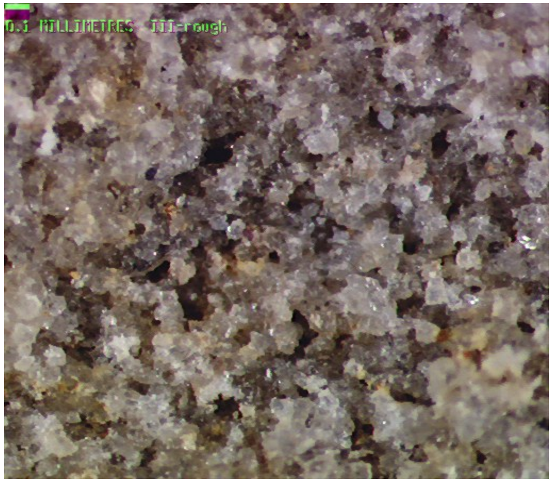
$$k = 10 . D_{dom}^{2} \cdot C^{-3.64} \cdot \varphi^{m+3.64}$$

- k : one-phase permeability (mD)
- D_{dom} : dominant grainsize (micron) from cutting inspection with a microscope.
- C : a constant derived from the sorting observed with a microscope
- ϕ : porosity, fraction of bulk volume. Derived from well log evaluation.
- m : cementation factor. Estimated by scratching of rock samples

D_{dom}, C, rom cuttings, cores and sidewall samples, m guesed or from samples

Relation of cementation factor (m) and sand consolidation

Consolidation	Cementation factor	
	atmospheric	in-situ [3]
unconsolidated sand	1.4	1.6
unconsolidated to friable sand	1.5	1.7
friable sandstone	1.6	1.8
hard to friable sandstone	1.7	1.9
hard sandstone	1.8	2.0
very hard sandstone	2.0	2.2



Relation of sorting, C, to the spread in dominant grain size D_{dom}.

Sorting	C	$D_{dom.max}/D_{dom.min}$
extremely well to very well sorted	0.70	2.5
very well to well sorted	0.77	
well sorted	0.84	3.5
well to moderately sorted	0.87	
moderately sorted	0.91	8
moderately to poorly sorted	0.95	
poorly sorted	1.00	

Definition of Permeability Lab measurements transferred to logs.

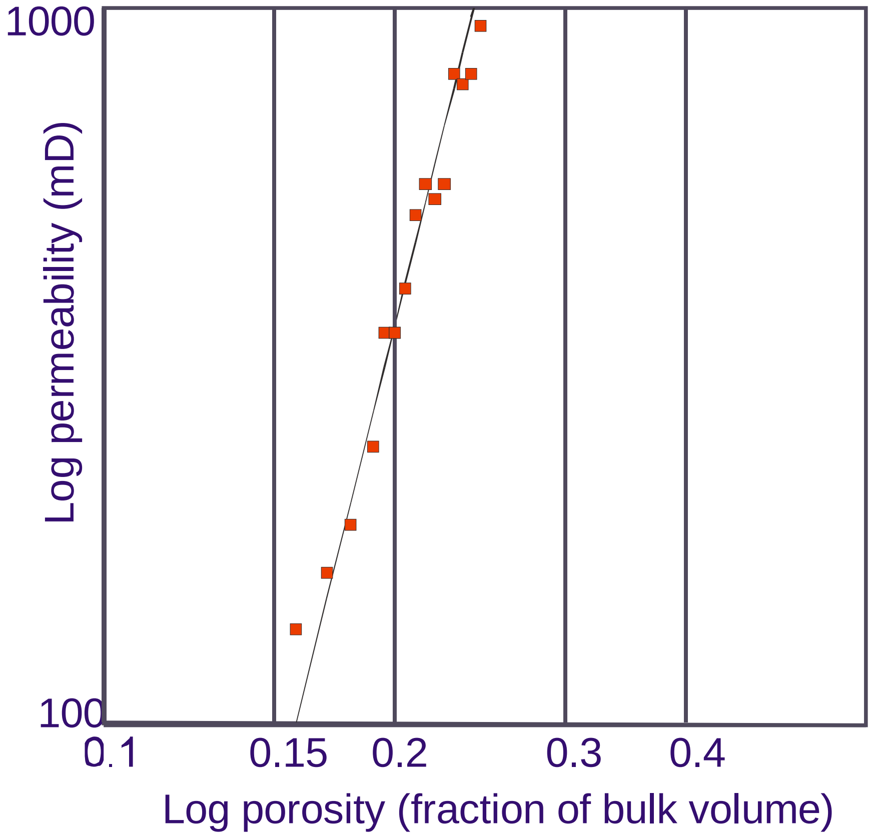
Empirical permeability relations

Permeability from logs

Depending on the environment of deposition core permeabilities can often be correlated with the core porosities

$$k = 10^{\left(C_1 + C_2 \cdot \log(\varphi)\right)}$$

$$k = 10^{\left(C_1 + C_2 \cdot \varphi\right)}$$



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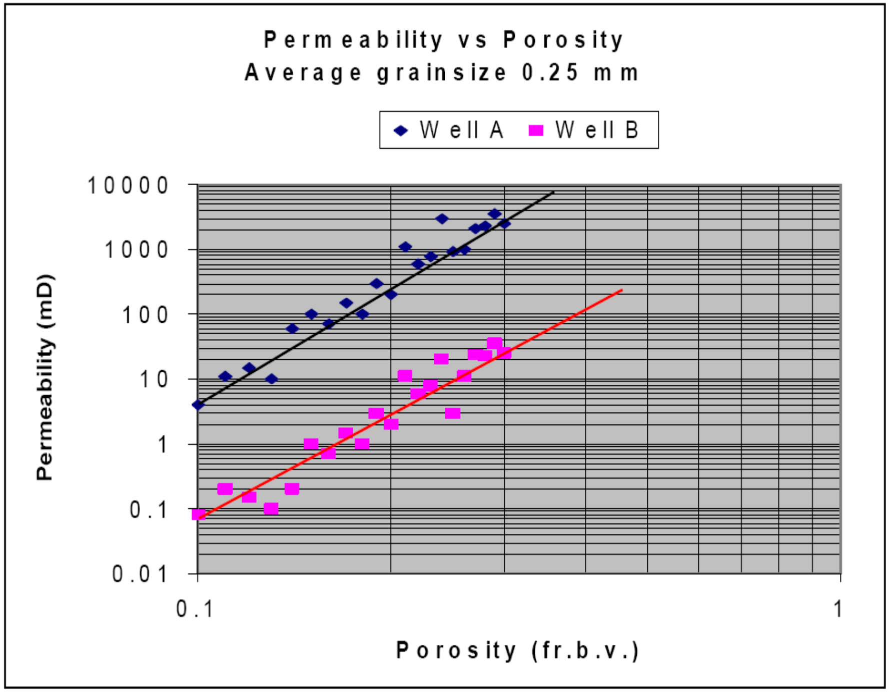
Definition of Permeability Lab measurements transferred to logs.

Example.

Sandstone properties in well A and well B:

- Average grainsize 0.25 mm
- Well sorted (C=0.84)
- Friable sandstone, m=1.8



K in well B about factor 100 lower than K in well A. Caused by illitisation in the pore throats.

Definition of Permeability from logs: Overview (1)

1. $K = F(\phi)$ **Plugs & logs** $K = 10^{C_1 + C_2 \log(\phi)}$

2. $K = F(f, Swirr)$ **Lab tests** $K = \left[\frac{100\ \phi^2\ (1 - Swirr)}{Swirr} \right]^2$

3. $K = F(f, grainsize)$ $K = 10 D_{dom}^2 C^{-3.6} \phi^{m+3.6}$

- cuttings description **Texture analysis**
  - clay indicators from logs density-neutron, GR, SP etc.

4. K = F(acoustic parameters)
   - compressional velocity (ϕ)
   - amplitudes (Lebreton, 1978)
   - stonely wave attenuation (Staal, Robinson, 1977)

NOT DISCUSSED IN THIS COURSE !

Definition of Permeability from logs: Overview (2)

5. Mudcake development: No K, no mudcake
6. Spontaneous potential: No K, no SP deflection
7. RFT pre-tests
8. DST, production tests kh (mD.m) from build-up
9. Nuclear Magnetic Resonance Log
10. Leverett J
11. Multi-variate analysis

Reservoir permeability

ITEM 5 - 11 ARE NOT DISCUSSED IN THIS COURSE !

EXERCISES POROSITY & PERMEABILITY

In Scheveningen a new giant sea aquarium is placed on a foot of Bentheimer sandstone. This porous sandstone is used to trap water during leakage. Unfortunately the aquarium burst and lost much water in de sandstone. The centre part is fully saturated with water and the question is: will the floor of the Scheveningen pier give away or not?

We like to know: what is the porosity of the sandstone?

CORE DATA:

- Dry core weight: 423 gram,
- Density of the water: 1.05 $g.cm^{-3}$
- Saturated weight of the sandstone: 461 gram.
- The sample dimensions are: 110 mm length and 38 mm diameter.

BABYLON EXERCISE

In Babylon American, Chinese, German, Dutch and African reservoir and hydrological engineers have to cooperate in the water and energy supply for the building of a big tower.

Both absolute units and hybrid units are used to define permeability. In the end a conversion table is made to compare values.

Fill the table with cgs-units (centimeter, gram, seconds), SI-units (m,kg,s), Darcy units, oilfield units and hydrological units.

PorPerm Excercises

			Absolute units			Hybrid units	
Parameter	**Symbol**	**Dimension**	**SI**	**cgs**	**hydrology**	**Darcy**	**oilfield**
Length	l	L	m	cm			ft
Mass	m	M	kg	g			lb
Time	t	T					hr
Velocity	v	L/T					ft/sec
Rate	Q	L^3/T					stb/d (liquid) Mscf/d (gas)
Pressure	P	$(ML/T^2)/L^2$	N/m^2	dyne/cm 2		atm	psia
Density	❒	M/L^3					lb/cu.ft
Viscosity	♒	M/LT				cp	cp
Permeability	k	L^2				Darcy	mD ($10^{-15}m^2$)

PorPerm Excercises

In Turkey a new small oil reservoir was detected in a slowly dipping and fractured layer. The part that reached the surface contained an aquifer filled with water from the mountains. Both the governement and the oil company wanted to know the reservoir permeabilities.

The government uses the conventional system (D) and the reservoir engineers use the units from the American oil industry (mD). Calculate both values with different units.

DATA:

Lab values:

- Cylindrical core: Length 100 mm, diameter 40 mm.
- Fluid viscosity: 2.5 cp
- Flow rate: 0.021 l/min
- Pressure drop: 3.4 atm

Permeability calculations with spatial information

Good old Kozeny had problem with some ideas about grain surfaces. He did have a uniform sandstone with a permeability of 480 mD and a porosity of 17 %.

He likes to know:

- The average pore throat radius
- The surface specific areas of the pores SVp and grains SVgr.

He assumed that the flow channels were tubes. Use the equations 4.15 and 4.16 of the TA3500 lecture notes to solve this problem (See Blackboard).

PorPerm Excercises

Upscaling or averaging permeabilities

Construct the total or average permeability of the combined layers in the three given situations.

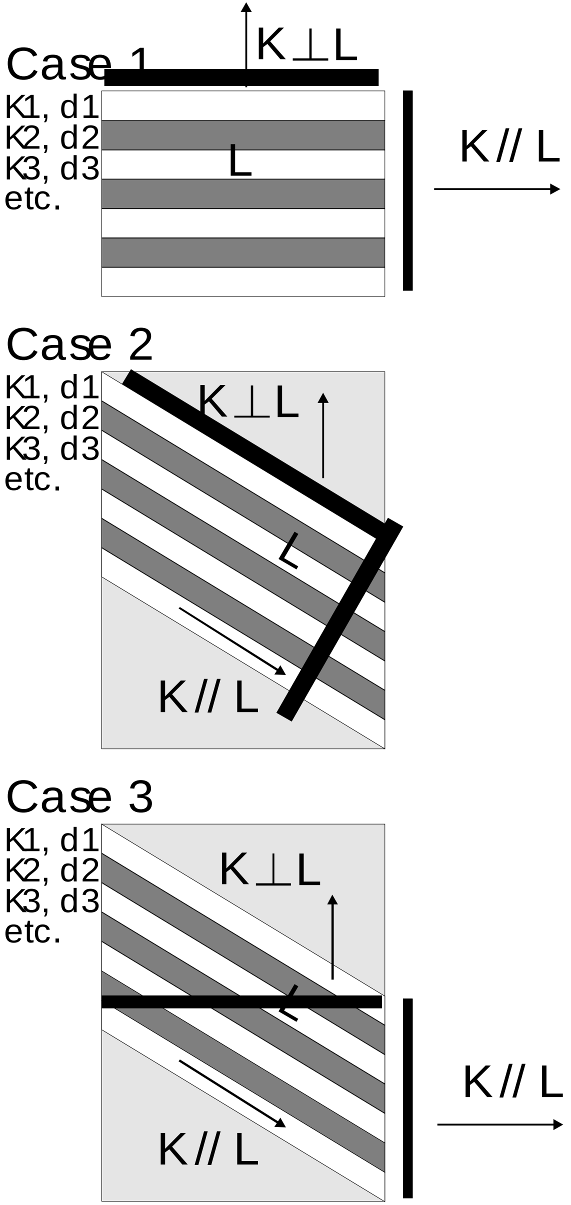
Help: Compare the electrical resistivity of a body with the fluid resistivity when zones in a body do have different permeabilities or resistivities:

$$R_{tot} = R_1 + R_2 + \ldots + R_n$$

Parallel

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

Series



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PorPerm Excercises

Solutions

SCHEVENINGEN STORY.

Dry core weight: 423 gram, specific gravity (ρ) of the water: 1.05 g/cc and a saturated weight of 461 gram. The sample dimensions are: 110 mm length and 38 mm diameter.

Answer:

$V_b = \pi \times (1.9)^2 \times 11.5 = 124.8\ cm^3$

The pore volume is:

$$V_p = \frac{1}{\rho}\left(W_{wet} - W_{dry}\right) = \frac{461 - 423}{1.05} = 36.2cc$$

$$\varphi = \frac{V_p}{V_b} = \frac{36.2}{124.8} = 0.29........\times 100 = 29\%$$

PorPerm Excercises

Answers Babylon excercise

			Absolute units			Hybrid units	
Parameter	Symbol	Dimension	SI	cgs	hydrology	Darcy	oilfield
Length	l	L	m	cm	m	cm	ft
Mass	m	M	kg	g	kg	g	lb
Time	t	T	s	s	s	s	hr
Velocity	v	L/T	m/s	cm/s	m/s	cm/s	ft/sec
Rate	Q	L^3/T	m^3/s	cm^3/s	m^3/s	cm^3/s	stb/d (liquid) Mscf/d (gas)
Pressure	P	$(ML/T^2)/L^2$	N/m^2	$dyne/cm^2$	m	atm	psia
Density	❒	M/L^3	kg/m^3	g/cm^3	1	g/cm^3	lb/cu.ft
Viscosity	♒	M/LT	kg/m.s	g/cm.s	1	cp	cp
Permeability	k	L^2	m^2	cm^2	m/s	Darcy	mD
1 Darcy converted to the different units			$(10^{-12} m^2)$	$(10^{-8} cm^2)$	1	1	$(10^{-15} m^2)$

PorPerm Excercises

Solutions:
Turkey questions

Use equation 4.9 to define the permeability in Darcies

$$k = \frac{0.35 \times 2.5 \times 10}{12.57 \times 3.4} = 0.204\ \text{Darcy} = 204\ \text{mD}$$

To use equation 4.9, first one has to convert all values to american units.

$$\Delta p = 3.4\ (\text{atm}) \times 14.7\ \text{psi/atm} = 50\ \text{psi}$$

$$q = \left(0.35\ \frac{\text{cm}^3}{\text{sec}}\right)\left(\frac{1}{30.48^3}\ \frac{\text{ft}^3}{\text{cm}^3}\right)\left(\frac{1}{5.615}\ \frac{\text{bbl}}{\text{ft}^3}\right)\left(24 \times 60 \times 60\ \frac{\text{sec}}{\text{D}}\right)$$
$$= 0.19\ \text{bbl/D}$$

$$L = (10\ \text{cm})\left(\frac{1}{30.48}\ \frac{\text{ft}}{\text{cm}}\right) = 0.328\ \text{ft}$$

$$A = \Pi \frac{d^2}{4} = \Pi \frac{4^2}{4} = 12.57\ \text{cm}^2 = 0.0135\ \text{ft}^2$$

The permeability of this core sample **is:**

$$k = \frac{q\mu L}{1.127 \times 10^3 A\, \Delta P} = \frac{0.19 \times 2.5 \times 0.328}{1.127 \times 10^3 \times 0.0135 \times 50} = 204\ \text{mD}$$

Because of the many unit systems employed by the industry, it is very important that petroleum engineers be able to convert units from one system to another.

PorPerm Excercises

Answers Kozeny issue

(a) Assuming the flow channels in the core sample may be represented by a bundle of capillary tubes, the pore throat radius can be estimated from Equation **4.15** First, the permeability is converted from mD to μm²:

$$k = 480 \times 9.8717 \times 10^{-4} = 0.4738\ \mu m^2$$

Substitute the value of K in μm² into Equation **4.15** and solve for r:

$$r = \sqrt{\frac{8 \times 0.47}{0.17}} = 4.72\ \mu m \text{ or } 4.72 \times 10^{-4}\ cm$$

(b) The specific surface area per unit pore volume is:

$$s_{Vp} = \frac{2}{r} = \frac{2}{4.72 \times 10^{-4}} = 4{,}237\ cm^{-1}$$

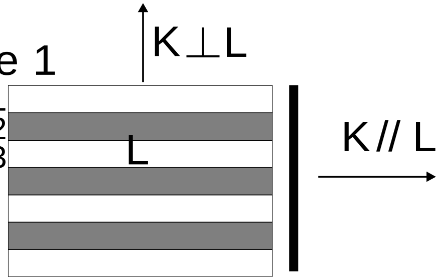
The specific surface area per unit grain volume is calculated from Equation **4.16**

$$s_{Vgr} = 4{,}237\left(\frac{0.17}{1 - 0.17}\right) = 868\ cm^{-1}$$

PorPerm Excercises: Solutions Upscaling

Case 1

K1, d1
K2, d2
K3, d3
etc.

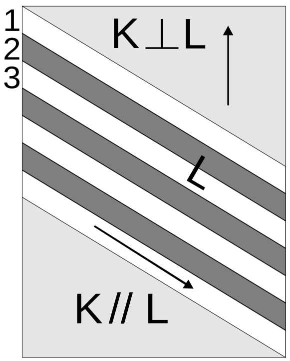


$$K_{av.hor} = K_{av.//L} = \frac{d_1 k_1 + \ldots\ldots + d_n k_n}{d_1 + \ldots\ldots + d_n}$$

$$K_{av.perp} = \frac{d_1 + \ldots\ldots + d_n}{\frac{d_1}{k_1} + \ldots\ldots + \frac{d_n}{k_n}}$$

Case 2

K1, d1
K2, d2
K3, d3
etc.

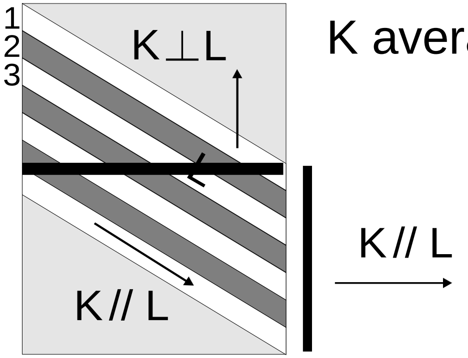


K parallel to layer: $$K_{av.//L} = \frac{d_1 k_1 + \ldots\ldots + d_n k_n}{d_1 + \ldots\ldots + d_n}$$

K perpendicular to layer: $$K_{av.perp} = \frac{d_1 + \ldots\ldots + d_n}{\frac{d_1}{k_1} + \ldots\ldots + \frac{d_n}{k_n}}$$

Case 3

K1, d1
K2, d2
K3, d3
etc.



K average vertical: $$K_{av.vert} = \frac{1}{\frac{\cos^2(90-\alpha)}{K_{av//L}} + \frac{\sin^2(90-\alpha)}{K_{av.perp}}}$$

K average horizontal: $$K_{av.hor} = \frac{1}{\frac{\cos^2(\alpha)}{K_{av//L}} + \frac{\sin^2(\alpha)}{K_{av.perp}}}$$