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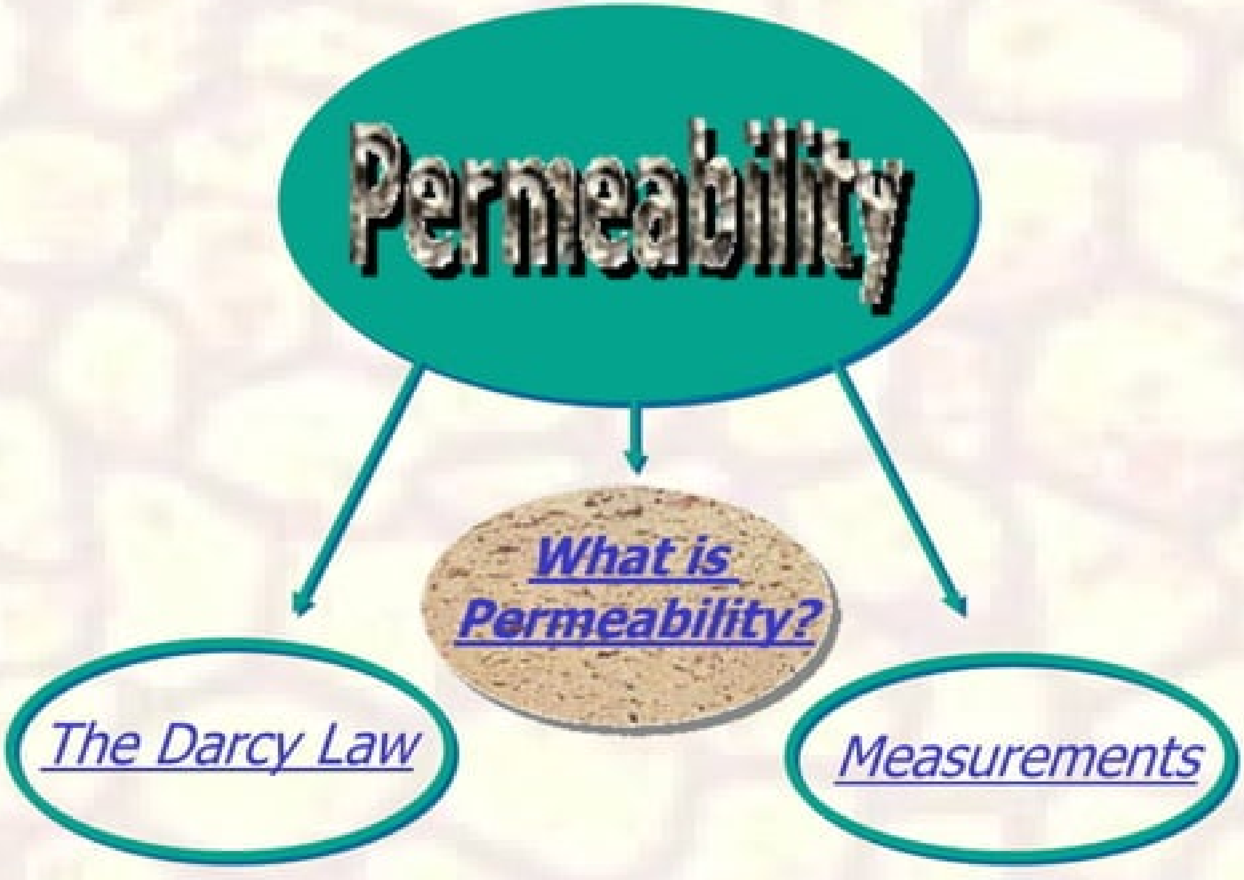
Topic overview



Next

1: *What is Permeability*

Definition:

The permeability of a rock is a measure of how easily a fluids may flow through the pore channels in a rock. It depends on the size, shape, tortuosity and number of the pore channels in the porous medium.

What is the difference between permeability and porosity ?

For more information about permeability follow these links:
http://biosystems.okstate.edu/darcy/
http://www.spe.org/learning/demo_sm/mod1/

Absolute permeability is the permeability of the porous medium if a single fluid is flowing. Effective permeability is the permeability of a fluid if another fluid is present. Relative permeability is the effective permeability divided by the absolute permeability.

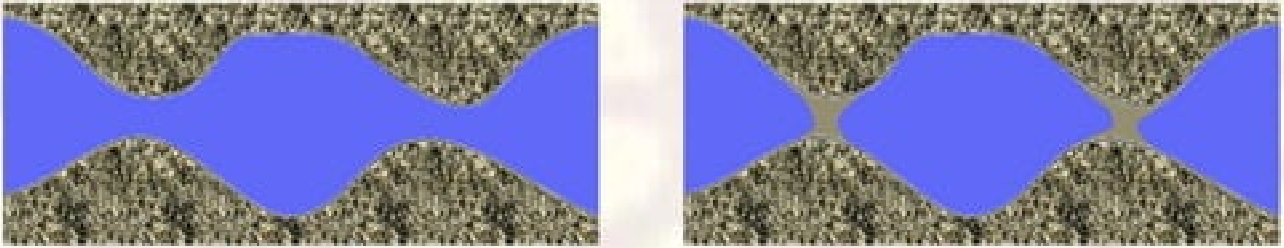
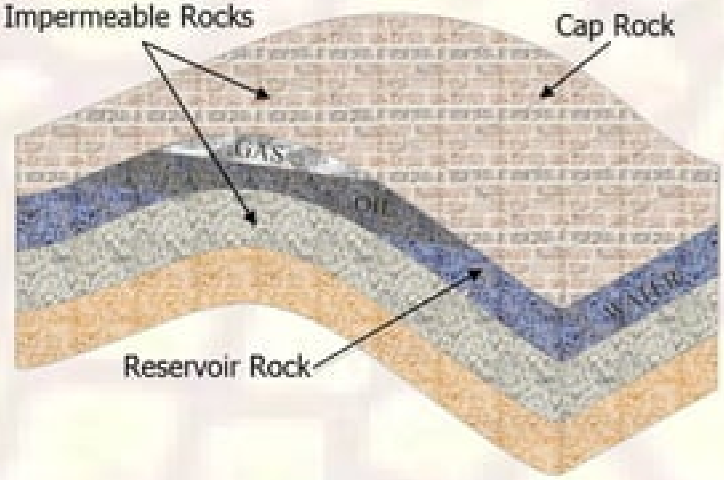


Illustration of pore and pore channels in a rock.

These two figures have the same porosity (same pore space).

In the figure to the right the pore channels are closed and the permeability is zero.

Impermeable rock (cap rock) traps hydrocarbons in the reservoir. Cap rock may be porous, but the pore channels must be "closed" to stop fluids from escaping.



Absolute and Effective Permeability

Absolute permeability

- absolute permeability is constant for a particular medium and independent of the fluid type.
- a single fluid or phase is present in the medium.
- In principle, the absolute permeability only depends on the *geometry* of the pore-channel system.

Effective permeability

- more than one fluid is present.
- each fluid will mutually reduce the pore channels open to flow for the other fluid, and the effective permeability may be much lower than absolute permeability.

Relative Permeability

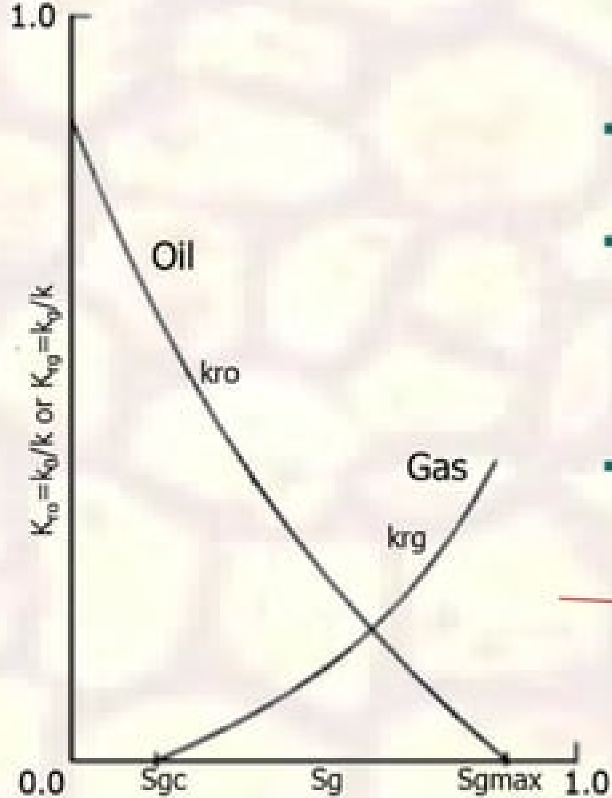


Fig.: Gas-oil relative permeability

Relative permeability

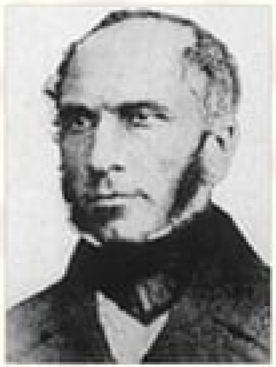
- is the ratio of effective permeability of a particular fluid to its absolute permeability.
- if a single fluid is present in a rock, its relative permeability is 1,0.
- is a dimensionless ratio devised to adapt Darcy's law to multiphase flow conditions.

- The relative permeability of a fluid is a function of its saturation.

The figure shows the relative permeability to oil and gas as functions of gas saturation for a process where the wetting phase, oil, is decreased, i.e. a drainage process.
Gas starts to flow when Sg>Sgc, the critical gas saturation. Oil flow stops at Sg=Sgmax=1-Sorg. Here Sorg is the residual oil saturation caused by gas displacement.

2: *The Darcy Law*

Henry Darcy (or D'Arcy?) (1803-1858), Hydraulic Engineer.



The "discoverer" of Darcy's Law, 1856.

His law is a foundation stone for several fields of study including ground-water hydrology, soil physics, and petroleum engineering.

biosystems.okstat.edu/darcy/Summary.htm

If you follow this link you can read a summary of Darcy's experiments.

The Darcy Law

Henry Darcy, 1856: $q = kA\dfrac{h}{\Delta l}$

q – fluid flow rate, cm^3/s
k – permeability, D
h – difference in manometer levels
A – cross-sectional area, cm^2
Δl – length of the filter, cm

Pore channels in a rock are irregular "pipes".

Idealised model:

$A = \pi(\tfrac{1}{2}d)^2$

Here are the expression for horizontal flow or the generalised form of Darcy Law.

Unit Conversions (go to "units" via index)

Horizontal Flow

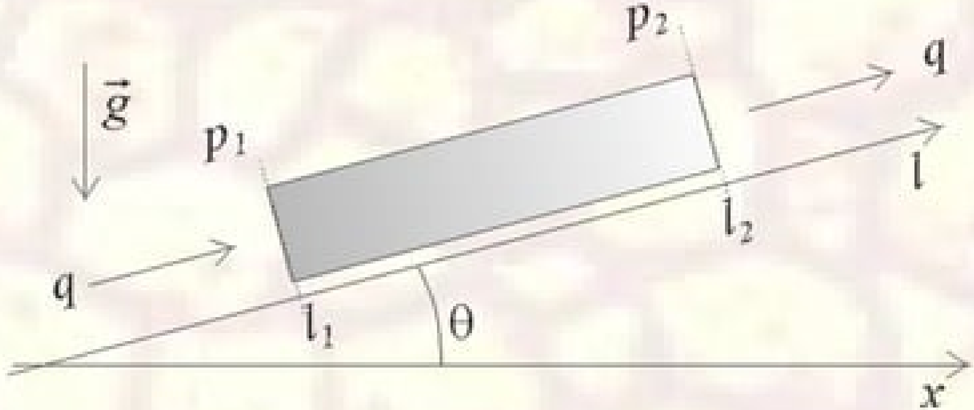
$$u_x = \frac{q}{A} = -\frac{k}{\mu}\left(\frac{dp}{dx}\right)$$

u – Darcy velocity, cm/s
q – fluid flow rate, cm^3/s
A – cross-sectional area, cm^2
k – permeability, D
μ - viscosity, cp
dp – pressure differential, atm
dx – length of core, cm

Generalised Form

$$u = \frac{q}{A} = -\frac{k}{\mu}\left(\frac{dp}{dl} + \frac{\rho g}{1{,}013310^{6}}\frac{dz}{dl}\right)$$

u – Darcy velocity, cm/s
q – fluid flow rate, cm^3/s
A – cross-sectional area, cm^2
k – permeability, D
μ - viscosity, cp
ρ - density, cp
g – gravity, cm/s^2
dp/dl – pressure gradient, atm/cm
dz – elevation, cm



The purpose of the gravitational term is to cancel out the pressure gradient for a column of fluid in equilibrium. Then, the fluid velocity will be zero, as it should be in equilibrium.

Next

3: *Measurements*

The absolute permeability of a rock sample can be determined in the laboratory by using an inert gas that fills the sample's pores completely and shows little or no chemical interaction with the rock's mineral grains.

Click on this banner if you want to study a laboratory exercise.

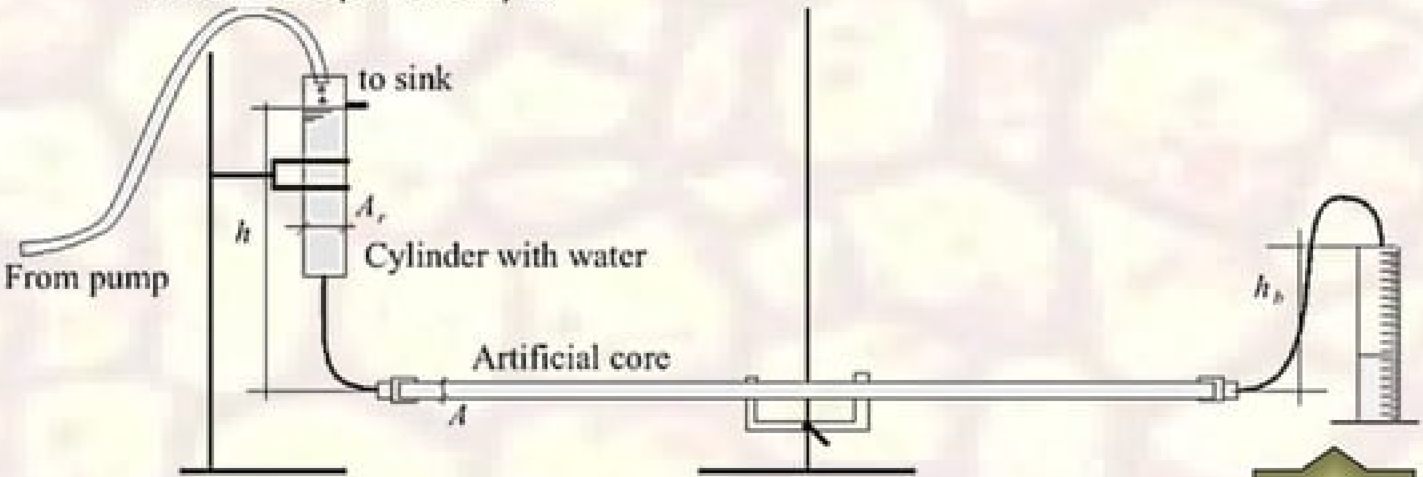
Link to examines in Reservoir Techniques: http://www.ux.his.no/~s-skj/ResTek1-v01/EksOpg/

Problem

In the figure, the height of the water level, $h(t)$, in the cylinder starts at h_0 at time $t=0$, and is recorded as a function of time as the water discharges through the artificial core sample. Show that the relationship between h and t is given by

$$\ln\frac{h_0 - h_b}{h - h_b} = \frac{k}{\mu}\frac{A}{A_r}\frac{\rho g t}{\Delta l}\frac{1}{1.01323\cdot 10^6}$$

where Δl is the length of the core. The expression is in Darcy units with the density ρ in g/cm³, and 1 atmosphere is 101325 Pascal. How can this expression be used to measure the permeability k?



Solution

Solution

We have the following two expressions for the rate q,

$$q = \frac{k}{\mu} A \frac{\rho g(h(t) - h_b)}{\Delta l \cdot 1.01325 \cdot 10^6},$$

for the rate through the core with water level difference $(h(t)-h_b)$ between inlet and outlet end, and

$$q = -\frac{\Delta h}{\Delta t} A_r,$$

for the discharge of the water in the cylinder. These two expressions for q are set equal. The result is a first order differential equation for h as a function of t. One has to use that $\int dh/h = \ln h$. Applying the initial condition that $h = h_0$ when $t = 0$, we find the expression given.

In SI-units ($\rho g h$) is in (kg/m^3 · m/s^2 · m) which is kg/(m s^2) which again is N/m^2 or Pa. If we use ($\rho g h$) in g/(cm s^2) we get a factor 10 in difference, i.e., ($\rho g h$) in the given units is equal to 1013250 atmospheres.

By plotting the left-hand-side of the equation against time t, the permeability may be calculated from the slope of the resulting straight line.

Those are all properties that are independent of the granular material.

There are also controls on permeability that are exerted by the granular material and are accounted for in the term (k) for permeability:

k is proportional to all sediment properties that influence the flow of fluid through any granular material (note that the dimensions of k are cm^2).

Two major factors:

1. The diameter of the pathways through which the fluid moves.

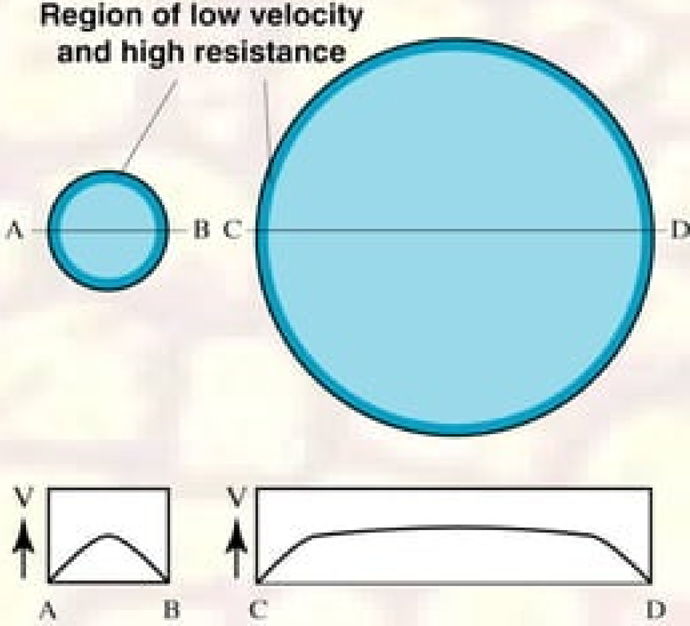
2. The tortuosity of the pathways (how complex they are).

1. The diameter of the pathways.

Along the walls of the pathway the velocity is zero (a no slip boundary) and increases away from the boundaries, reaching a maximum towards the middle to the pathway.

Narrow pathway: the region where the velocity is low is a relatively large proportion of the total cross-sectional area and average velocity is low.

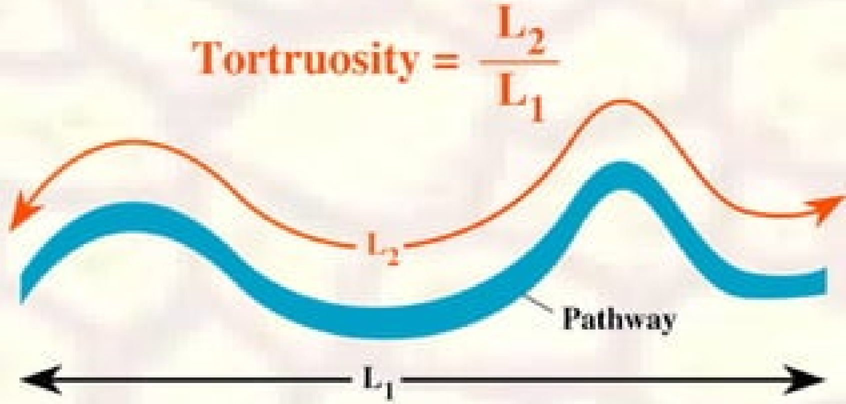
Large pathway: the region where the velocity is low is proportionally small and the average velocity is greater.

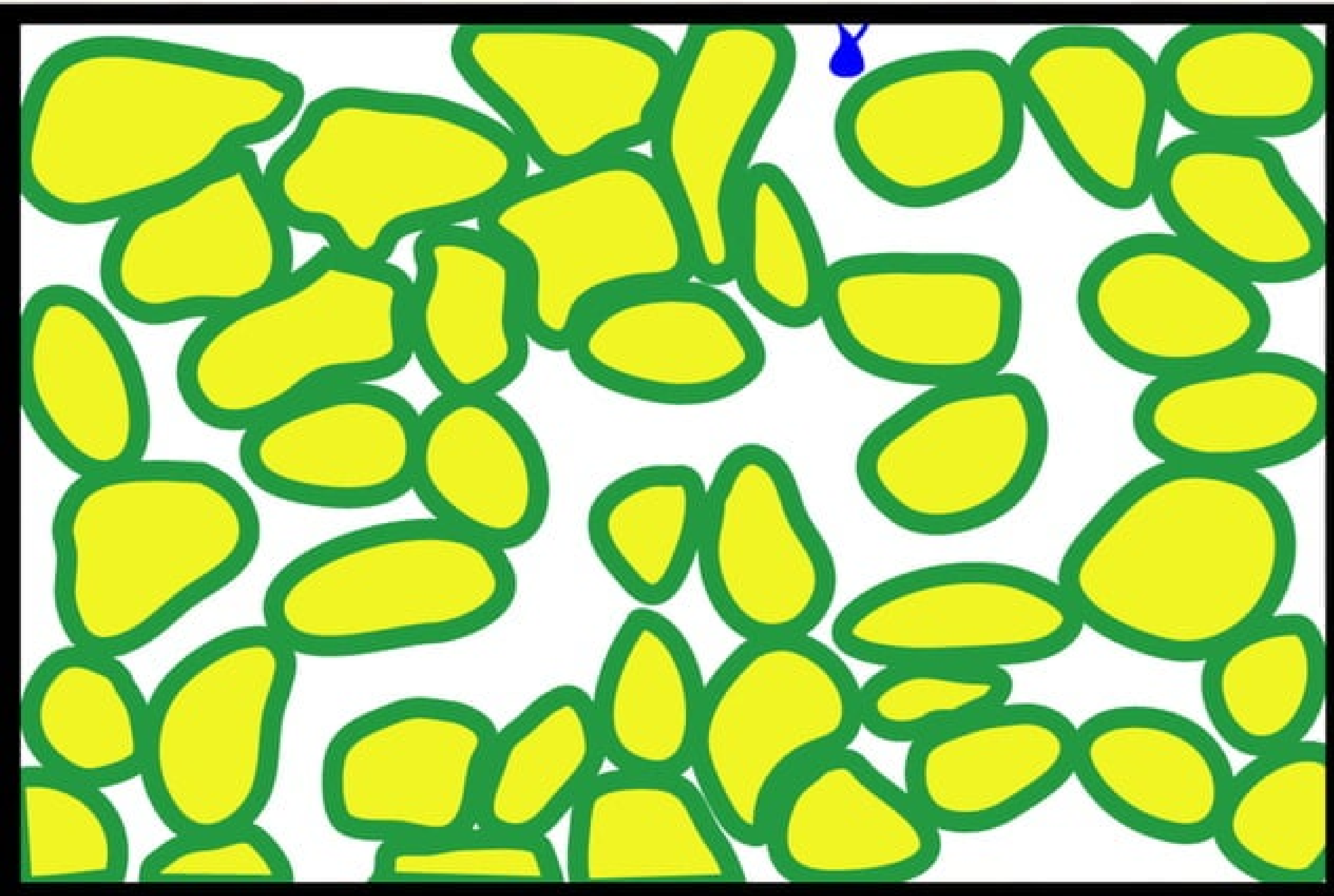


It's easier to push fluid through a large Pathway than a small one.

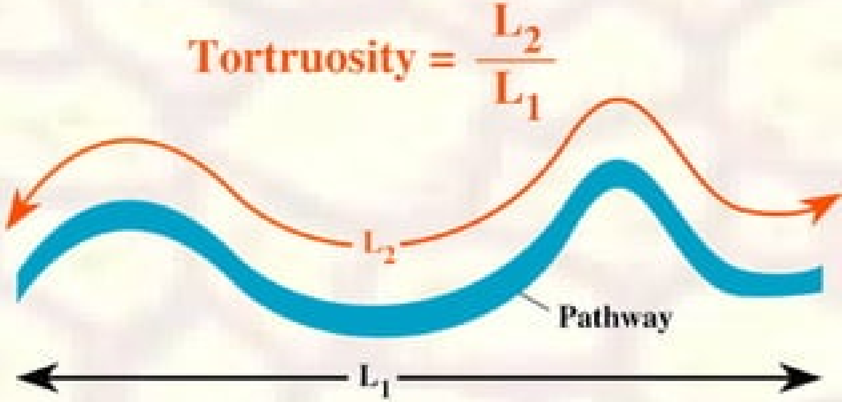
2. The tortuosity of the pathways.

Tortuosity is a measure of how much a pathway deviates from a straight line.

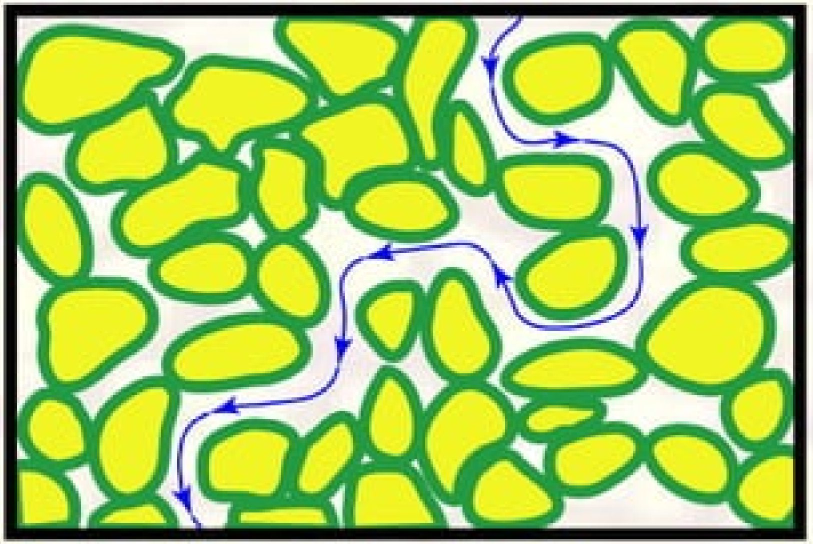




2. The tortuosity of the pathways.



Tortuosity is a measure of how much a pathway deviates from a straight line.



The path that fluid takes through a granular material is governed by how individual pore spaces are connected.

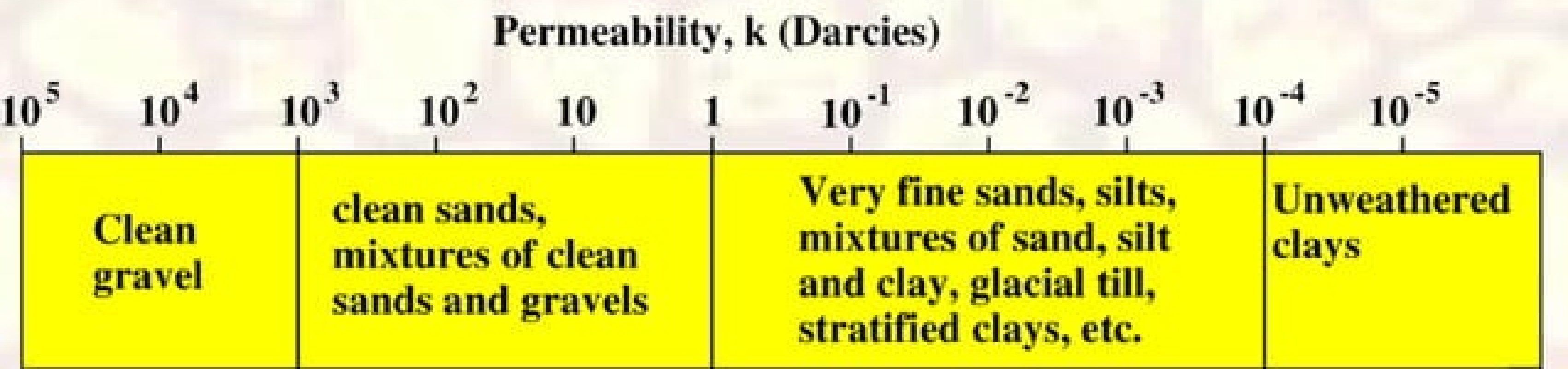
The greater the tortuosity the lower the permeability because viscous resistance is cumulative along the length of the pathway.

Pathway diameter and tortuosity are controlled by the properties of the sediment and determine the sediment's permeability.

The units of permeability are *Darcies (d):*

1 darcy is the permeability that allows a fluid with 1 centipoise viscosity to flow at a rate of 1 cm/s under a pressure gradient of 1 atm/cm.

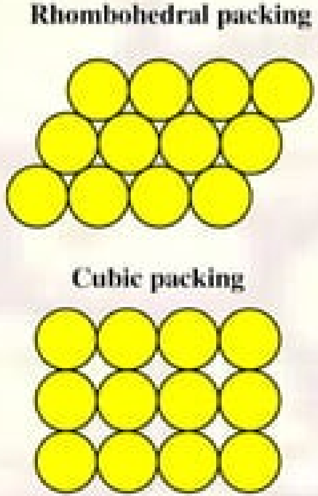
Permeability is often very small and expressed in *millidarcies* ($\frac{1}{1000}d$)



a) Sediment controls on permeability

i) Packing density

Tightly packed sediment has smaller pathways than loosely packed sediment (all other factors being equal).



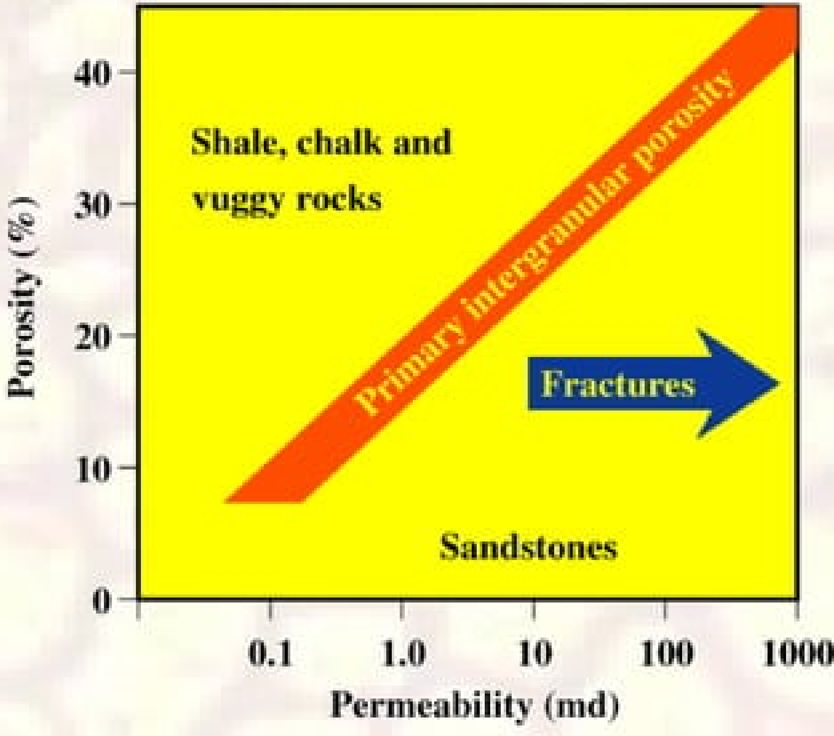
Smaller pathways reduce porosity and the size of the pathways so the more tightly packed the sediment the lower the permeability.

ii) Porosity

In general, permeability increases with primary porosity.

The larger and more abundant the pore spaces the greater the permeability.

Pore spaces must be well connected to enhance permeability.

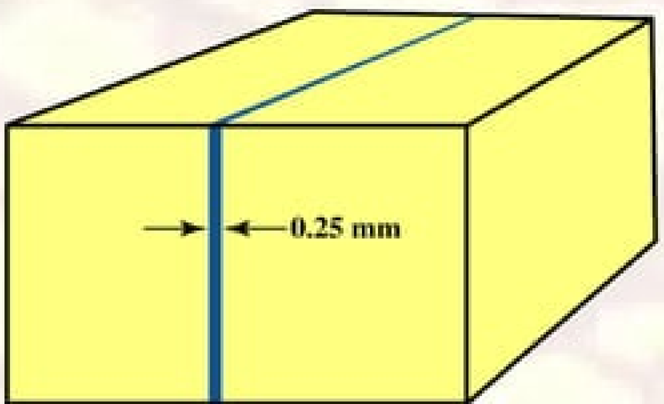


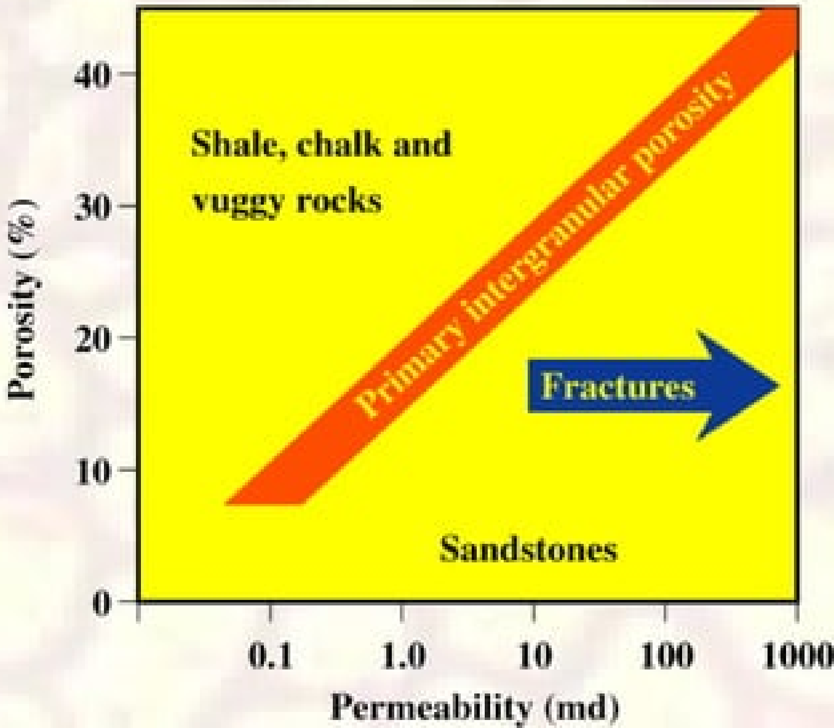
Shale, chalk and *vuggy* rocks (rocks with large solution holes) may have very high porosity but the pores are not well linked.

The discontinuous pathways result in low permeability.

Fractures can greatly enhance permeability but do not increase porosity significantly.

A 0.25 mm fracture will pass fluid at the rate that would be passed by13.5 metres of rock with 100 md permeability.





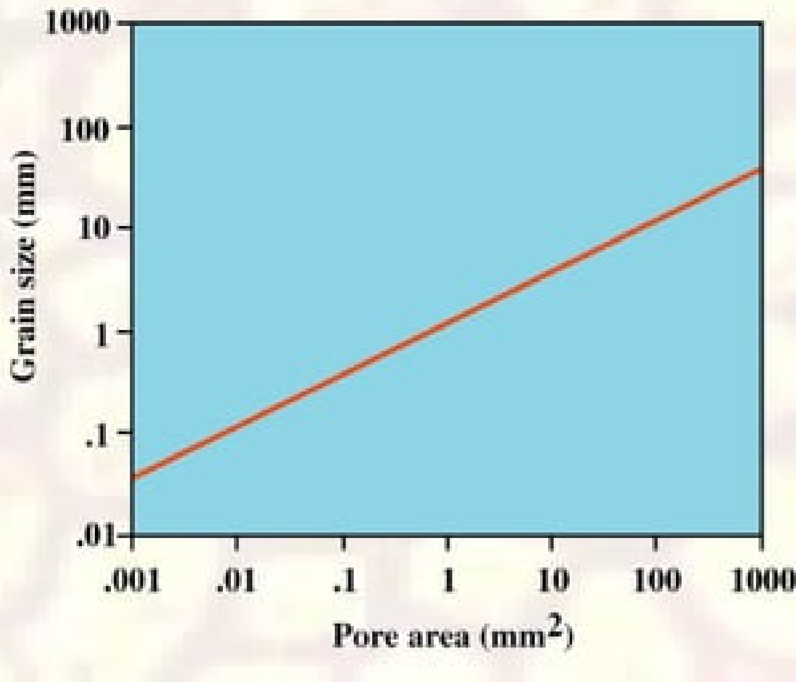
iii) Grain Size

Unlike porosity, permeability increases with grain size.

The larger the grain size the larger the pore area.

For spherical grains in cubic packing:

$$\text{Pore area} = 0.74d^2$$

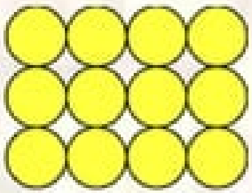


A ten-fold increase in grain size yields a hundred-fold increase in permeability.

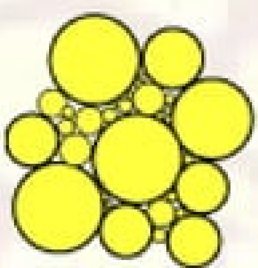
iv) Sorting

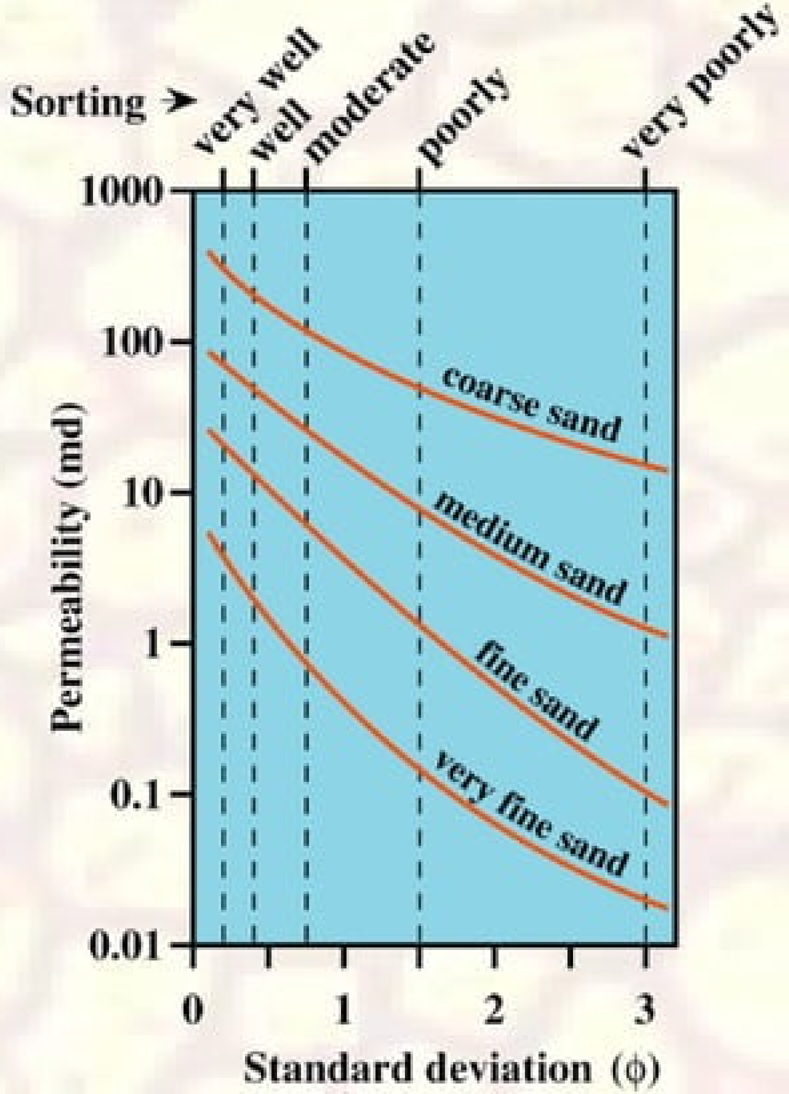
The better sorted a sediment is the greater its permeability.

In very well sorted sands the pore spaces are open.



In poorly sorted sands fine grains occupy the pore spaces between coarser grains.





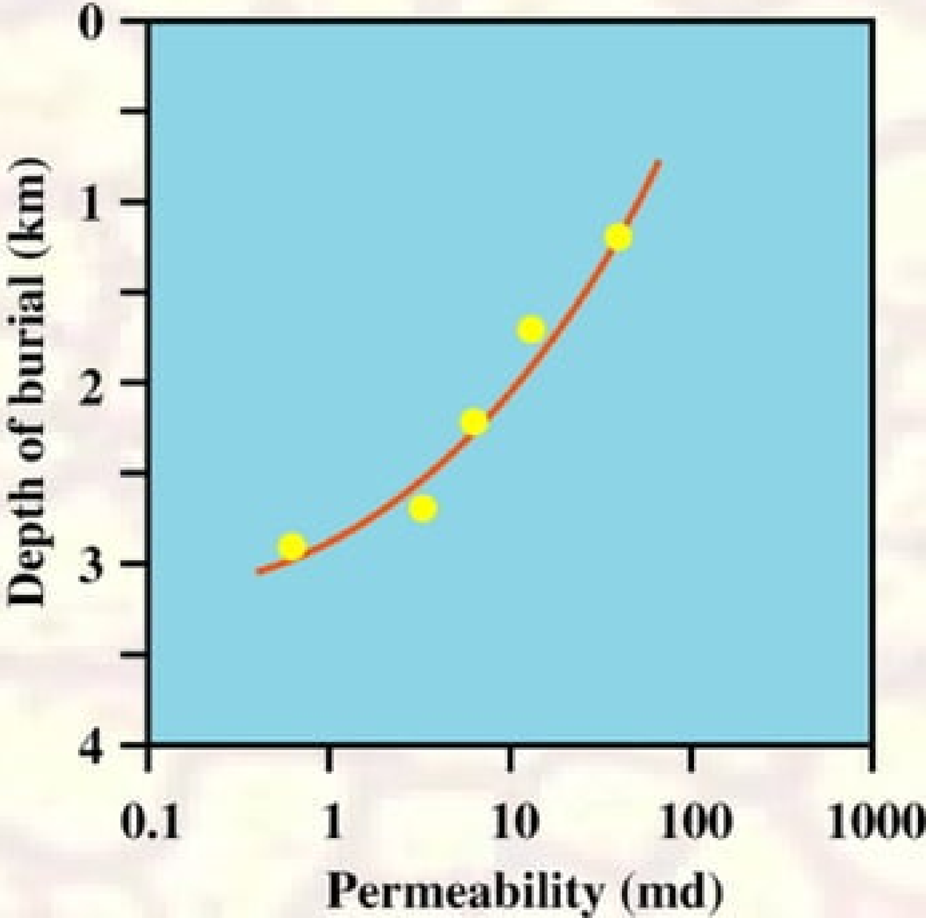
v) Post-burial processes

Like porosity, permeability is changed following burial of a sediment.

In this example permeability is reduced by two orders of magnitude with 3 km of burial.

Cementation
Clay formation
Compaction
Pressure solution

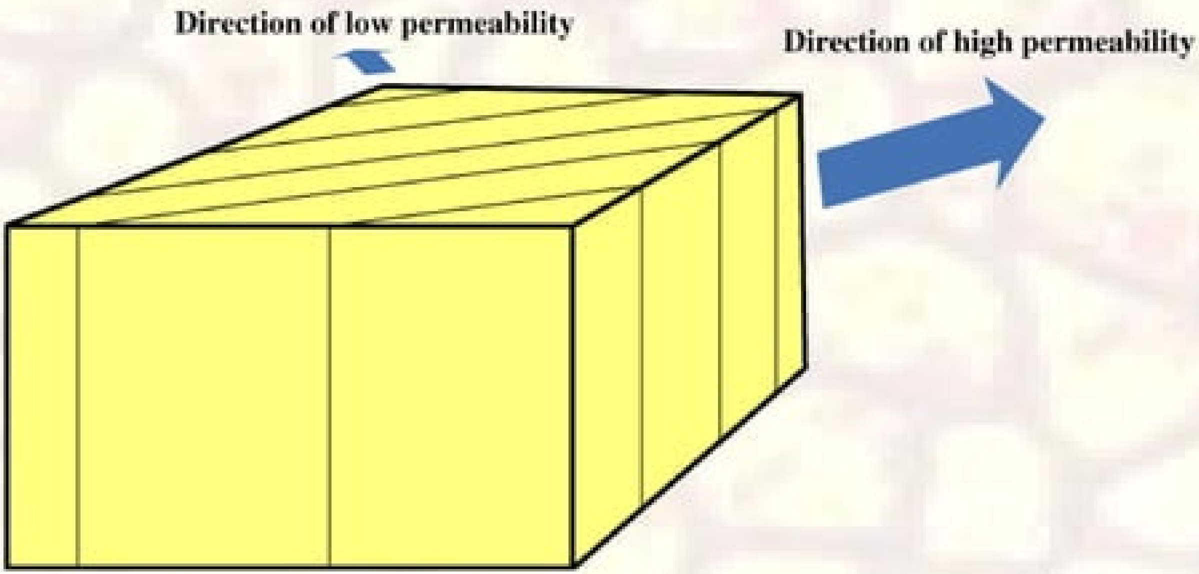
All act to reduce permeability



b) Directional permeability

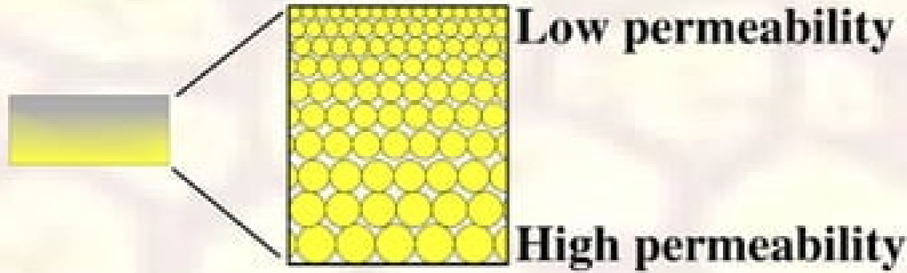
Permeability is not necessarily *isotropic* (equal in all directions)

Fractures are commonly aligned in the same direction, greatly enhancing permeability in the direction that is parallel to the fractures.

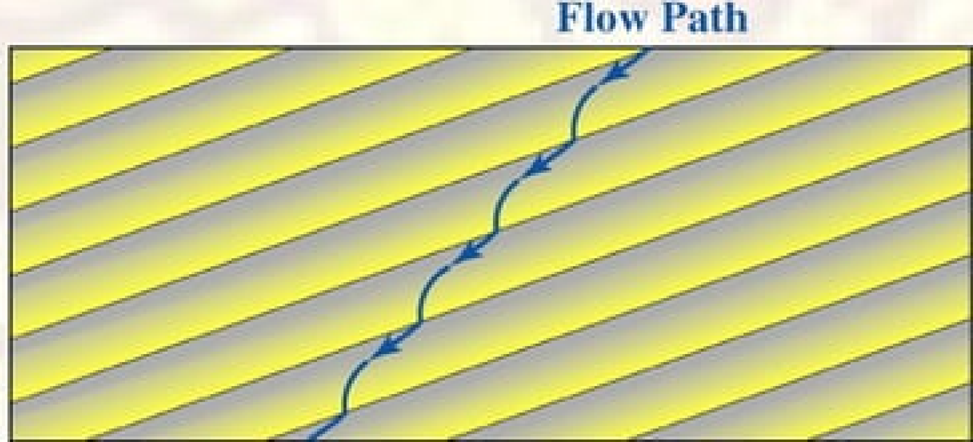


Variation in grain size and geological structure can create directional permeability.

E.g., Graded bedding: grain size becomes finer upwards in a bed.

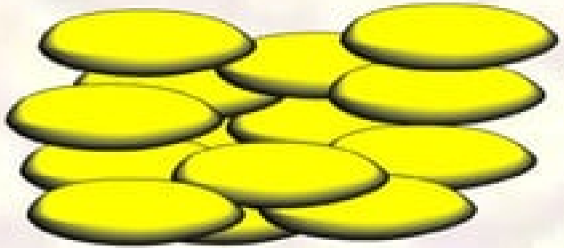


Fluid that is introduced at the surface will follow a path that is towards the direction of dip of the beds.



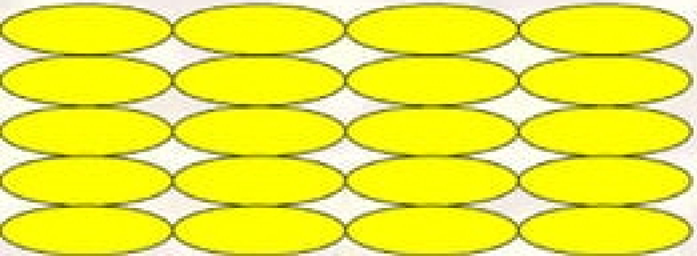
Fabric (preferred orientation of the grains in a sediment) can cause directional permeability.

E.g., A sandstone unit of prolate particles.



The direction **along** the long axes of grains will have larger pathways and therefore greater permeability than the direction that is parallel to the long axes.

View along the grain long axes.



View across the grain long axes.