Bandung Train The Trainers 16th -28th May 2016

Porosity, Permeability

Train The Trainers workshop , WP 1.04 WP leader Peter Fokker TNO

Auke Barnhoorn, Fiorenza Deon, Nenny Saptadji

Cooperating companies and Universities

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Porosity Permeability Module

- **1 hour** lecture material containing a basic introduction into porosity/permeability targeted to MSc student community.

- No prior knowledge is required.

- Material contain powerpoint lecture (~1 x 1 hr) + one in-class exercises (15 minutes at the end).

- At the end of the module students will have a better understanding of the basics of porosity/permeability an appreciation of its importance for subsurface engineering for geothermal and petroleum reservoirs.

Today: Rock Properties

- Porosity
- Permeability
- Porosity-Permeability relationships

Pore space (interstitial space)

Ratio of [...] pore space and total volume [of ...] = porosity.

Pores vary in dimension:

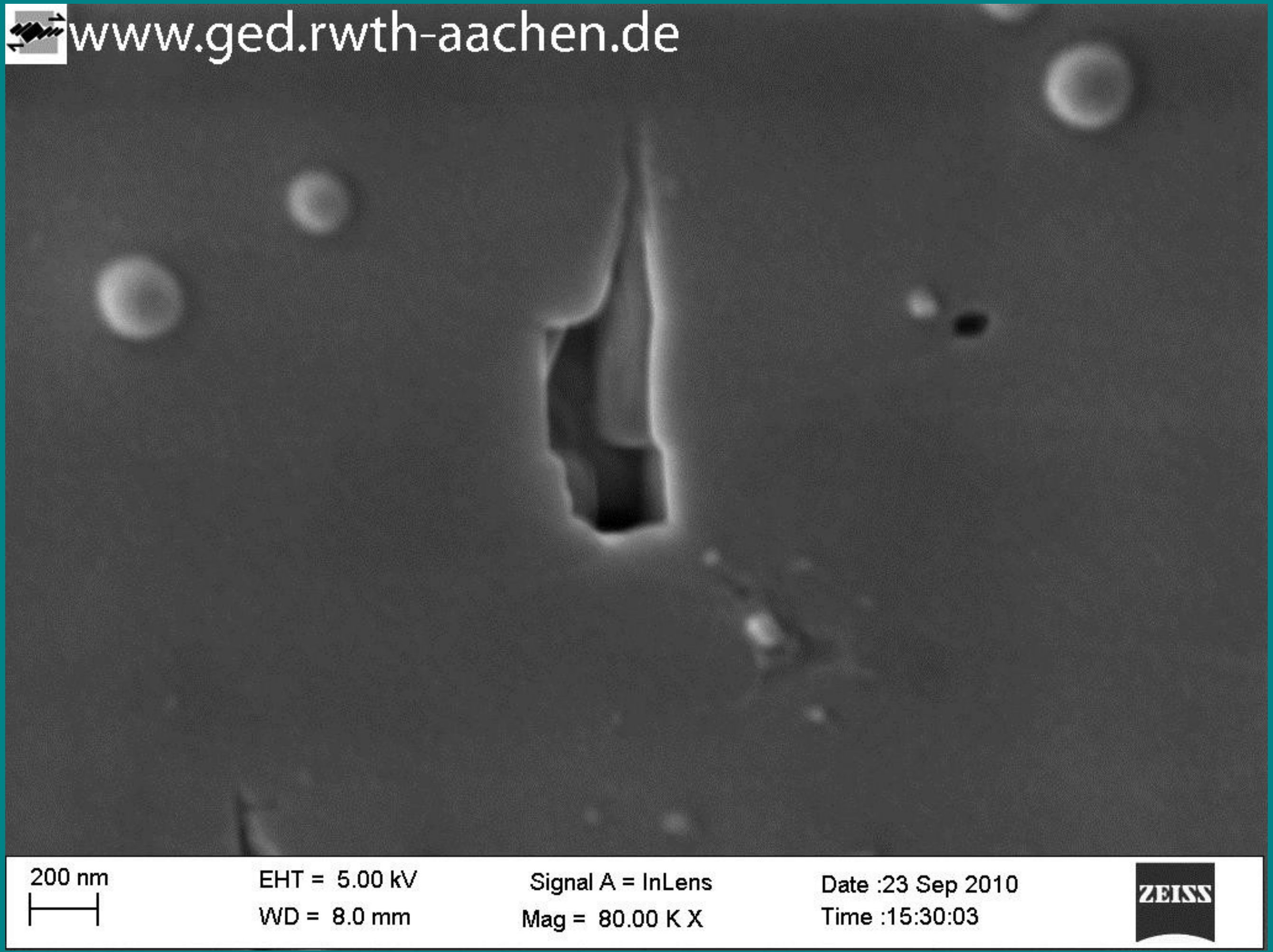
- enormous karsts in limestone caverns (100 m’s)
- minuscule subcapillary openings where water is kept by adhesive forces (nanometers).

Limestone Caves

Caves of Han (Belgium)

http://www.allesovervakanties.nl/de-grotten-van-han/

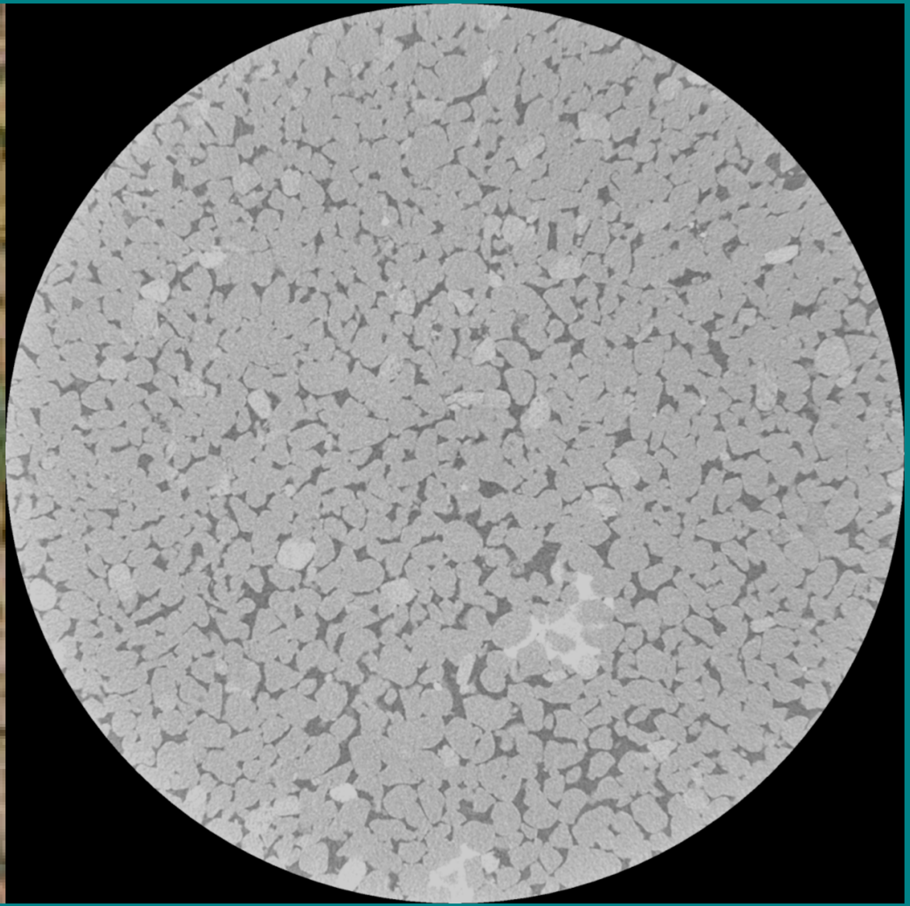
Nanometer-sized pores



http://info.drillinginfo.com/shale-gas-oil-geology/

Isolated pores in shales

Porosity Sandstone



10’s – 100’s micrometer sized pores

Example of bimodal pores: oolitic limestone

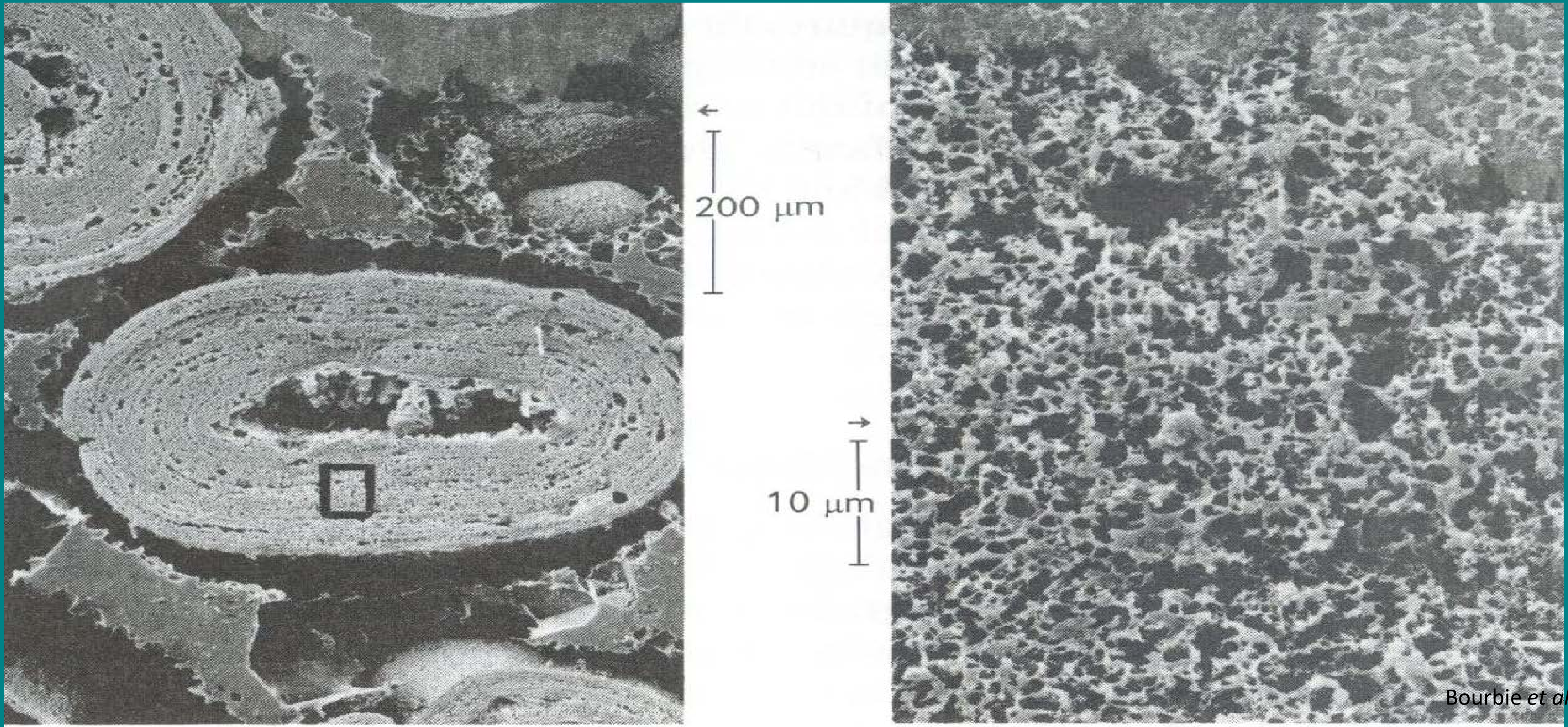


Photo 1 — Oolitic limestone.

Detail of photo 1.

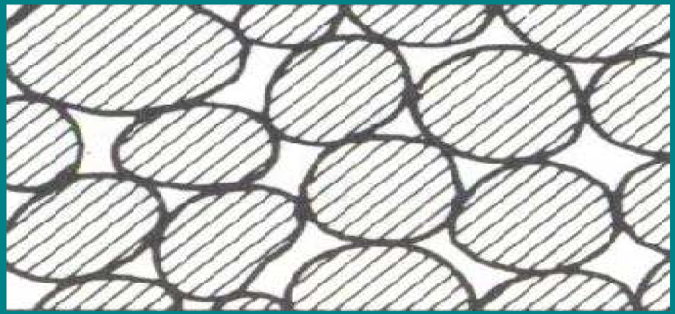
Bourbie *et al* , 1987

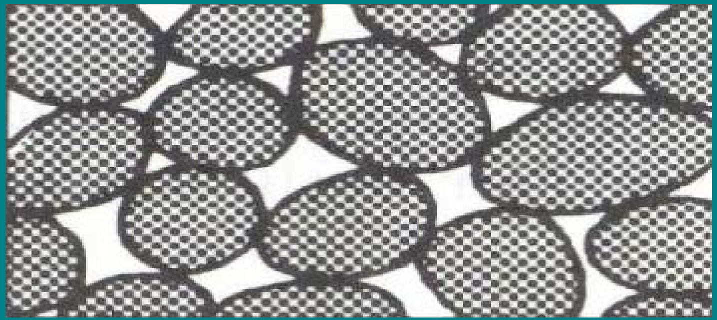
Examples of primary pore space

Two categories:

- The original interstitial space during geological formation (sedimentary and magmatic rocks).
    - Well-sorted deposition, high porosity
    - Poorly sorted deposition, low porosity
    - Well-sorted deposition of porous pebbles, very high porosity.

Bear and Verruijt, 1987

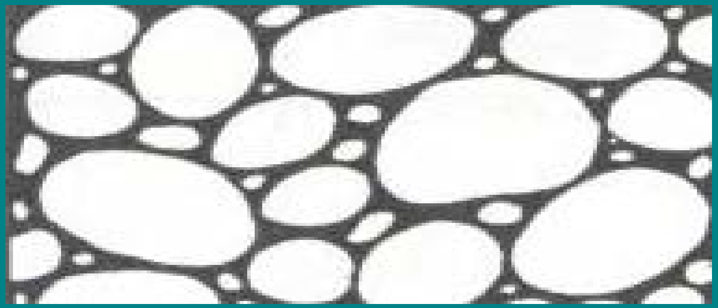


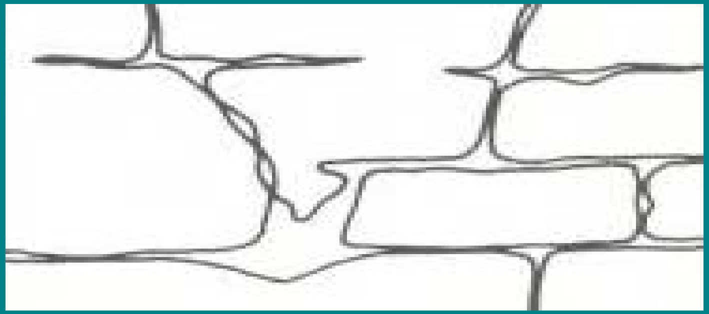


Examples of secondary pore space

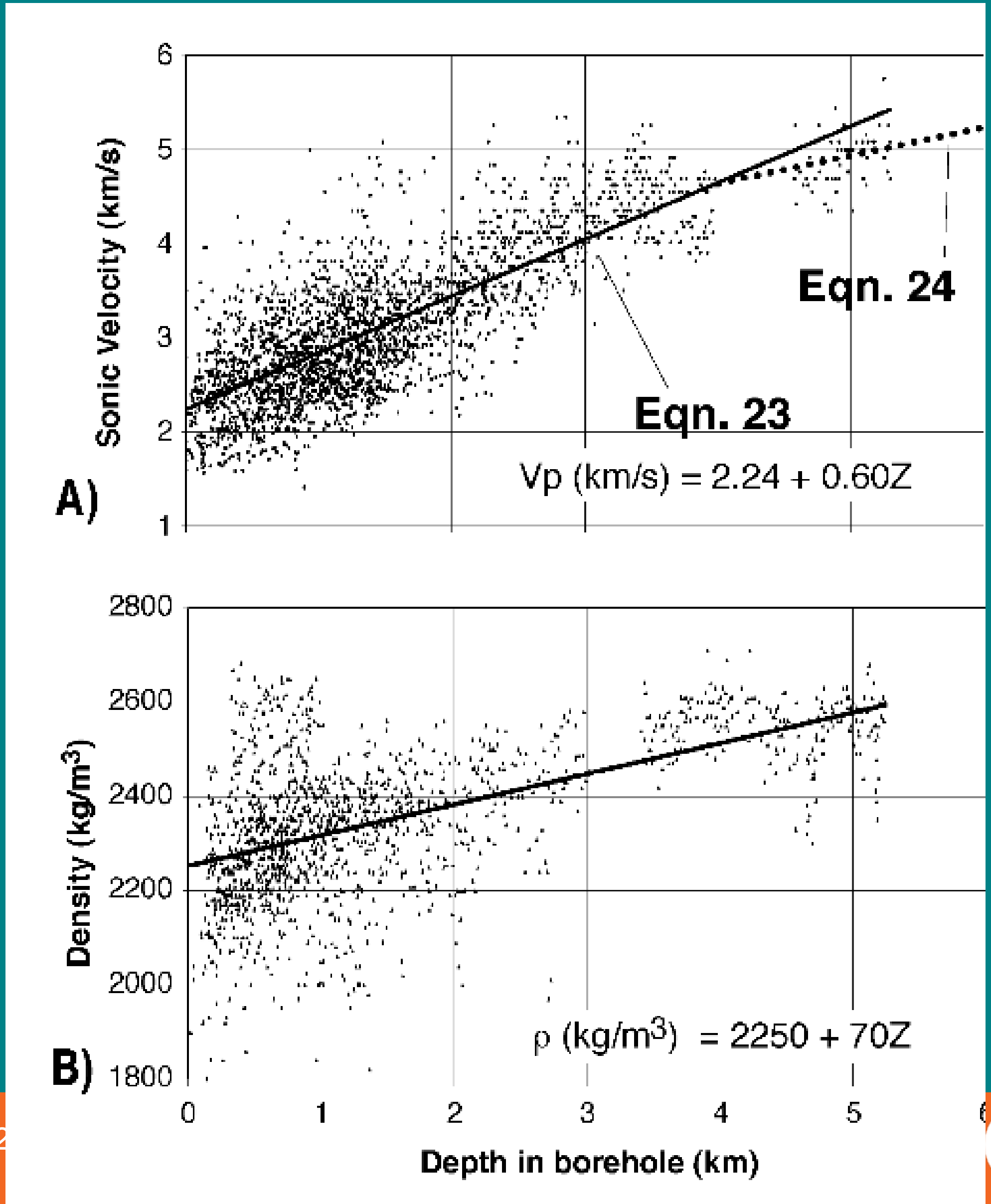
- Secondary interstitial space in the form of fissures, joints and solution passages, developed after the rock was formed.
  - Well-sorted rock with interstitial mineral growth, low porosity.
  - Rock rendered porous by solution.
  - Rock rendered porous by fracturing.
  - Rock changed by hydrothermal alteration

Bear and Verruijt, 1987





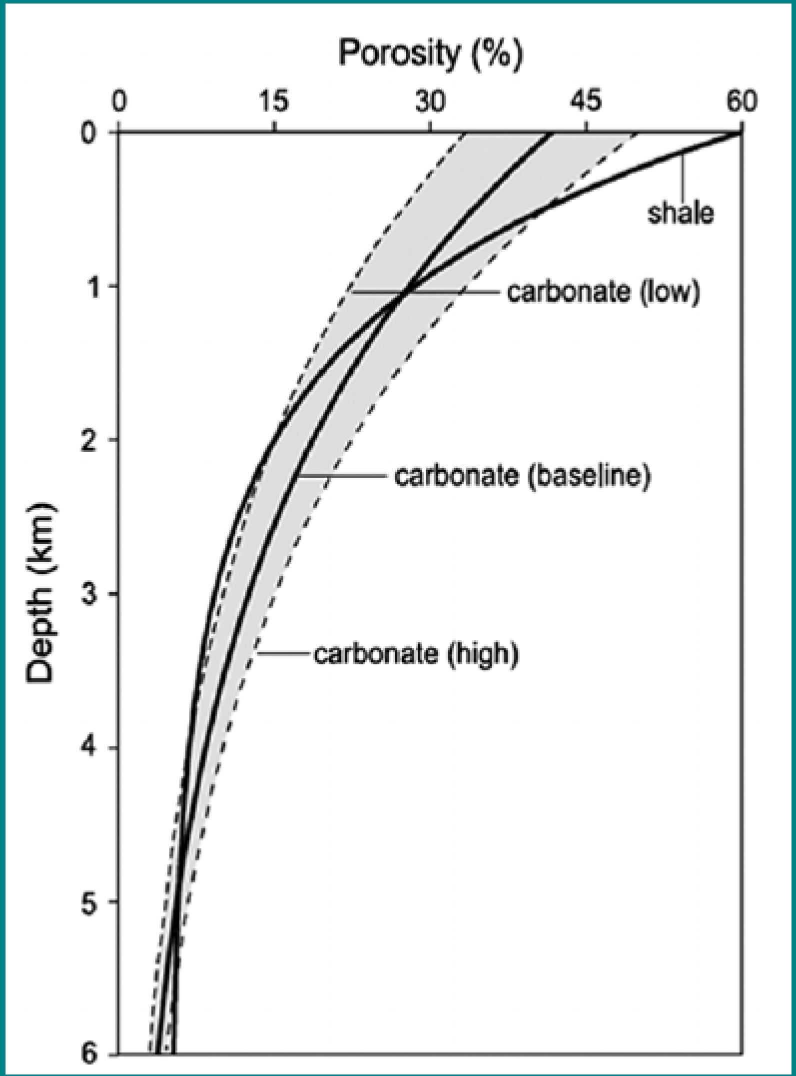
Porosity characteristics in rocks

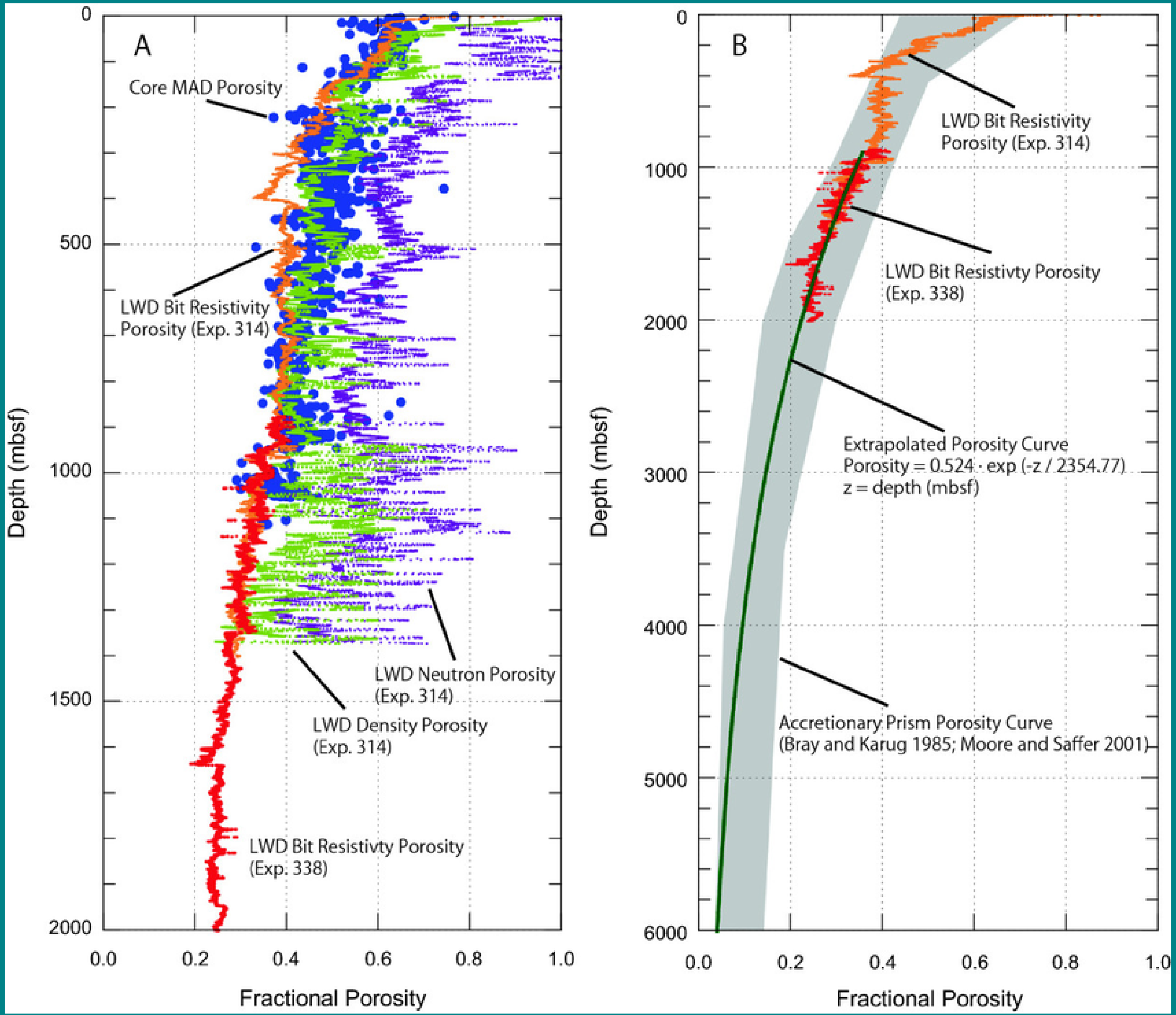


Velocity and Density increase with depth in the Earth,

because of a porosity reduction + mineralogy change

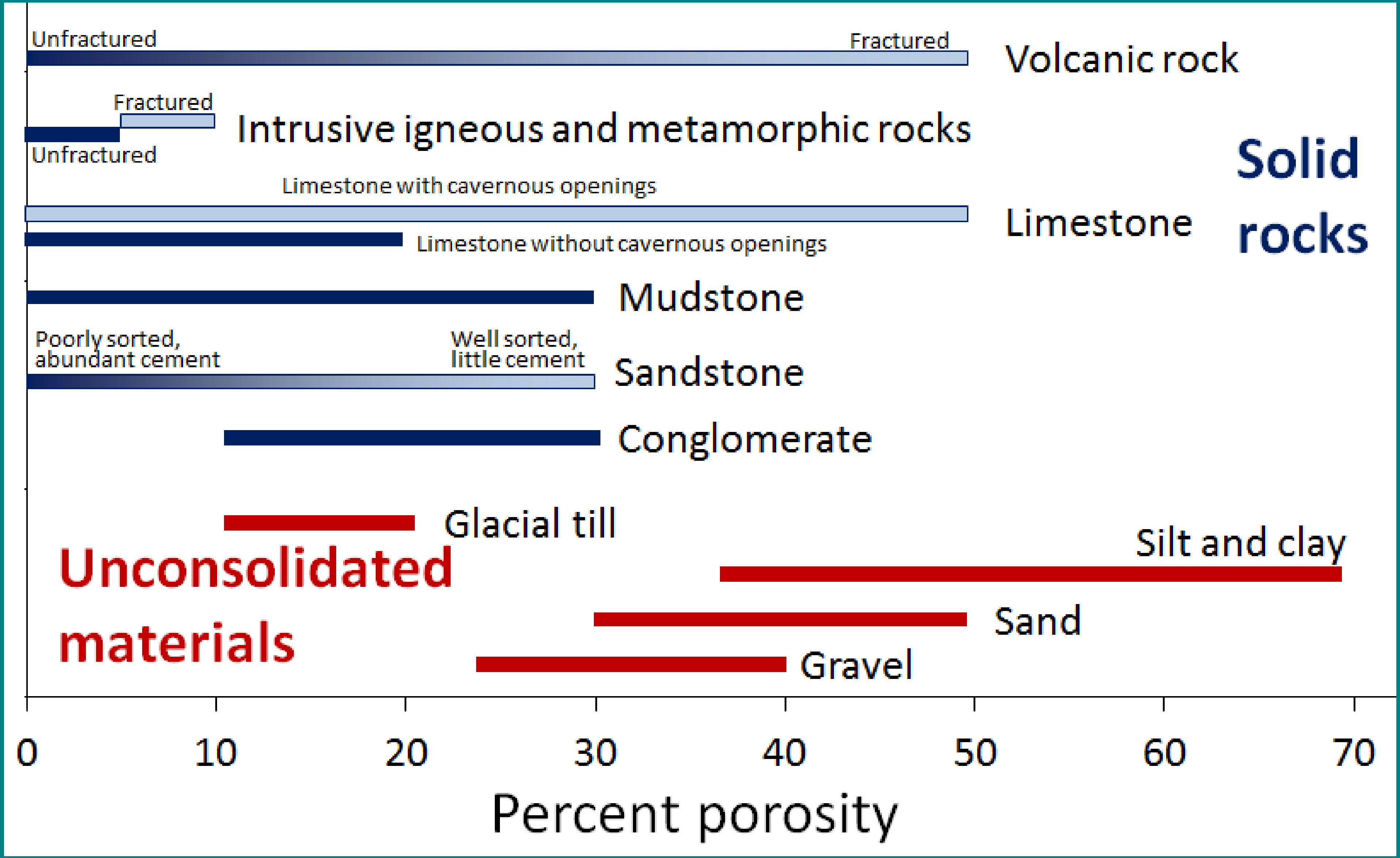
Brocher (2005) Compressional and Shear-Wave Velocity versus Depth Relations for Common Rock Types in Northern California





Pal et al., 2014

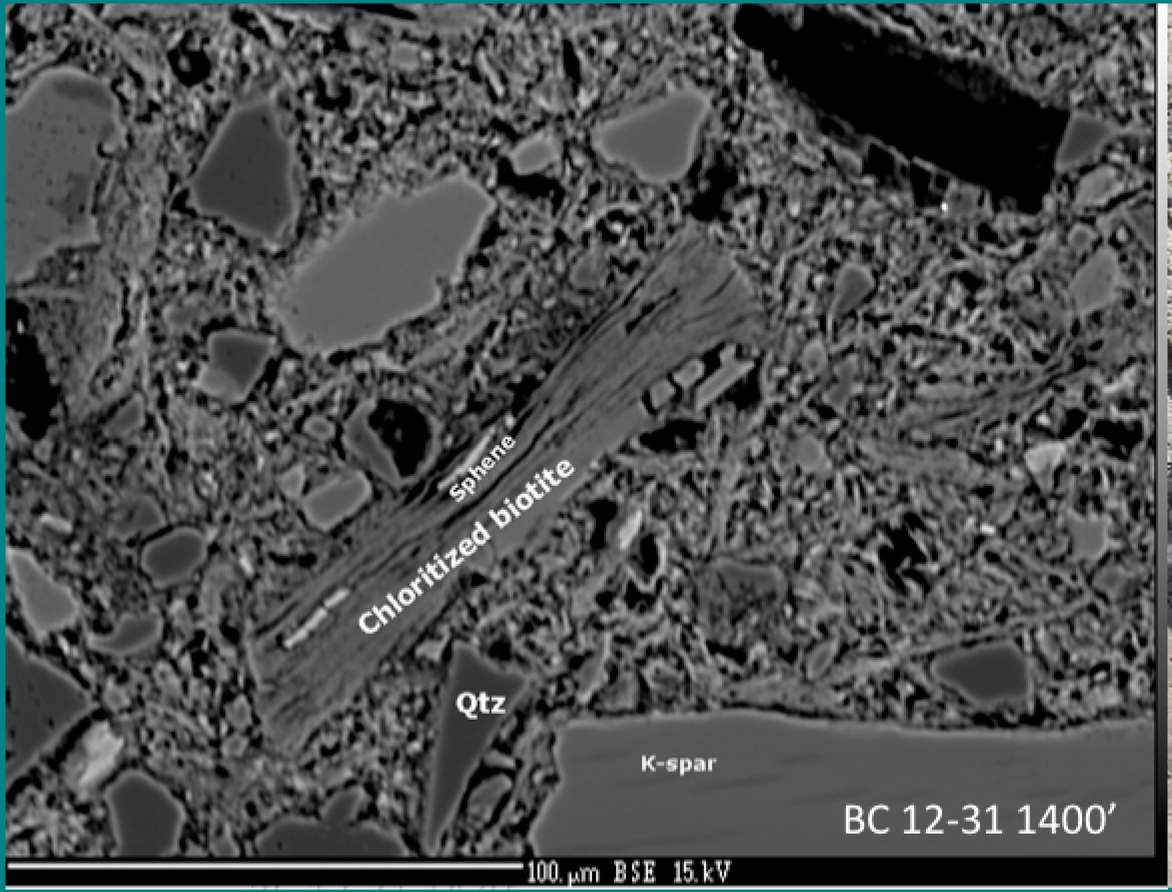
Sugihara et al., 2014



https://opentextbc.ca/geology/chapter/14-1-groundwater-and-aquifers/

Porosity in tuff vs gaseous lava

Small pores (μm sized)



Large pores (cm sized)

http://classic.geology.ucdavis.edu/classes/geothermalresources_F2010/alteration/index.html

Porosity in basalt vs gaseous lava

No pores / only fracture porosity

Large pores (cm sized)

http://classic.geology.ucdavis.edu/classes/geothermalresources_F2010/alteration/indexhtml

Fracture porosity

Basalts close to Bandung

Musamdam, Oman

Porosity generally small (fluid storage space small, need to come from far)

Stratovolcano

http://volcano.oregonstate.edu/stratovolcanoes

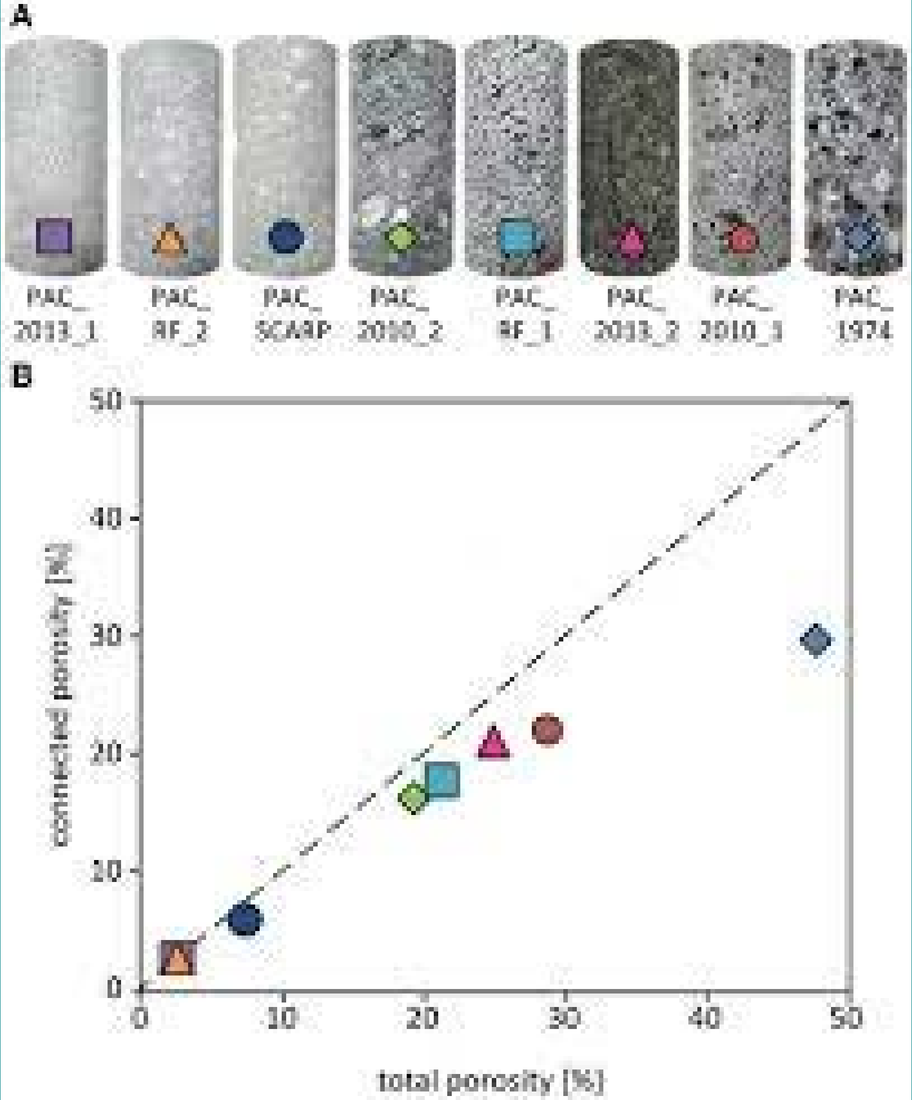
- Very complexly chaotically/layered
- Lava
- Tuff
- Basalt
- Fractured or not

- All with different porosity, pore sizes

Connected porosity vs. total porosity

Unconnected/isolated pores can occur in:

- Limestones
- Shales
- Fractured rocks
- Volcanic rocks



Schaefer et al., 2015

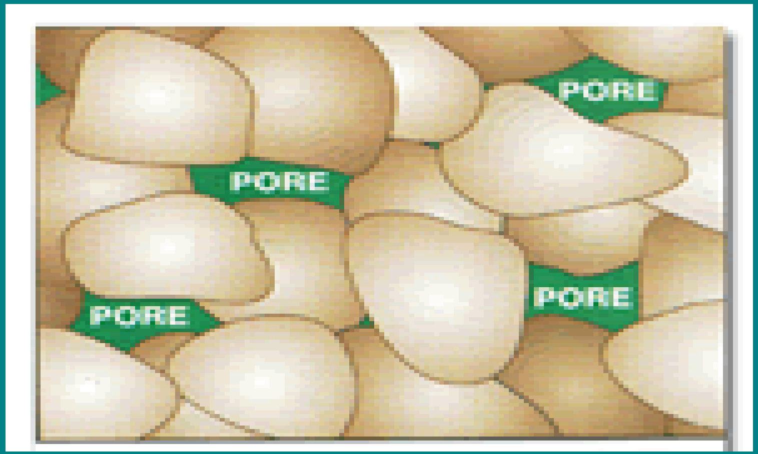
Pore space (interstitial space)

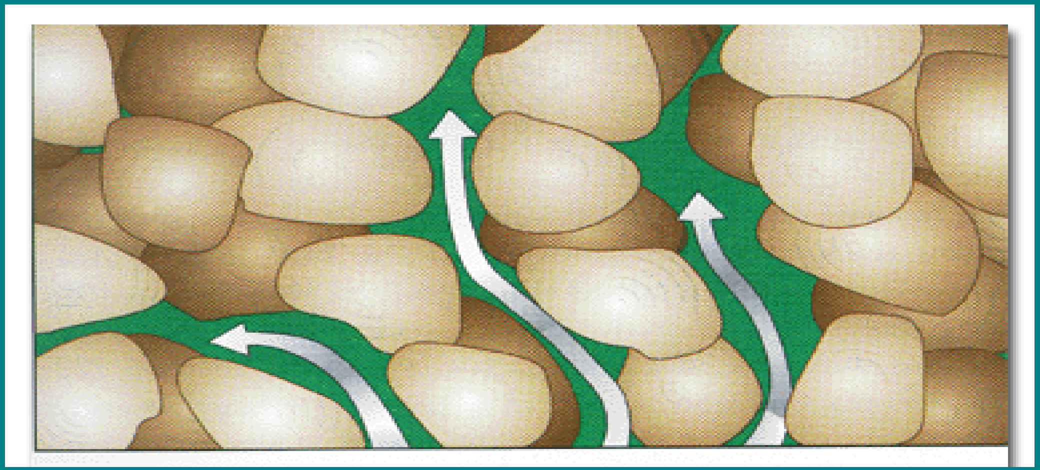
Ratio of [...] pore space and total volume [of ...] = porosity.

Flow only exists through the pores that are mutually connected by channels.

Permeability

Permeability is the ability of a rock to allow flow and is of fundamental importance in porous media.





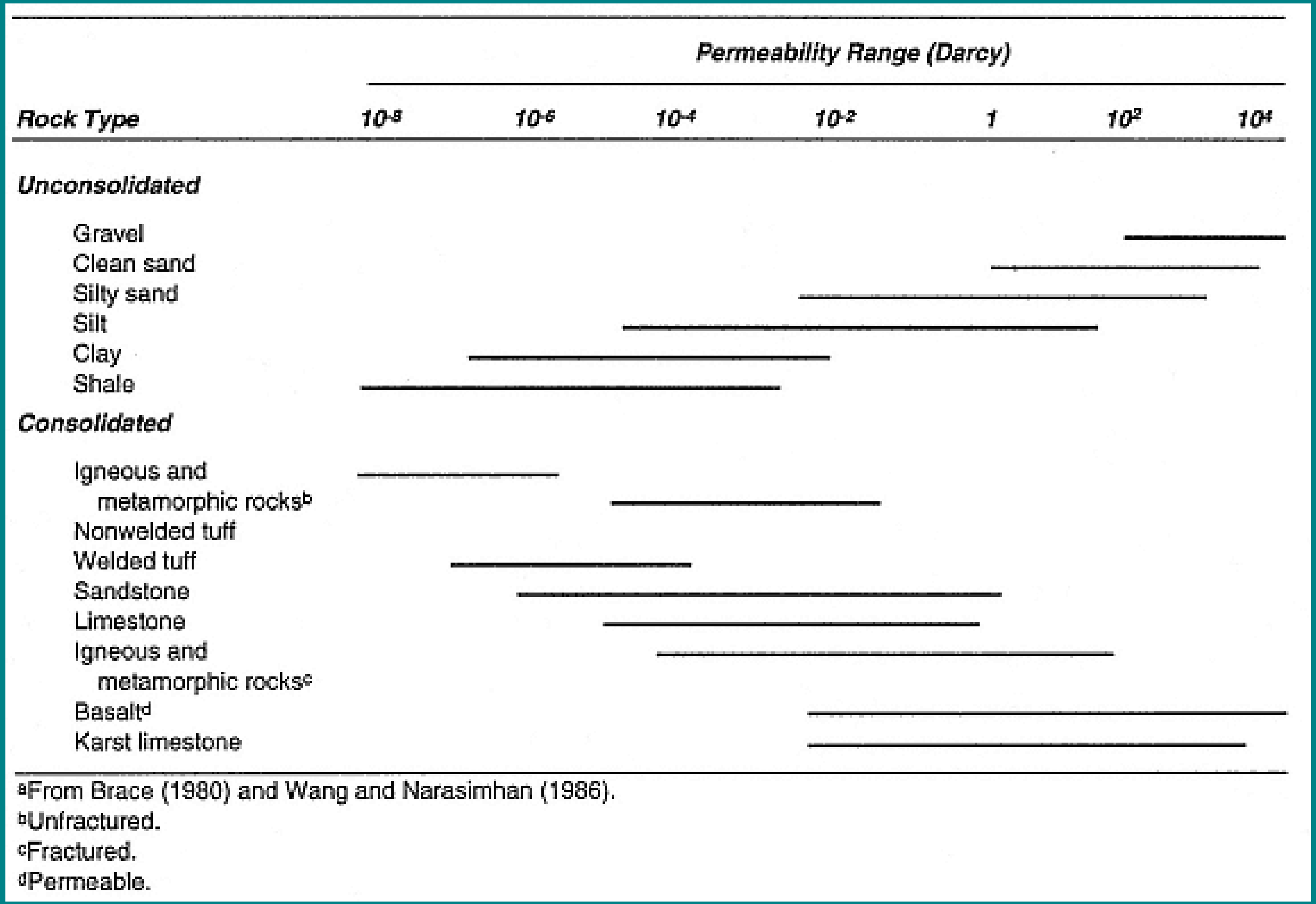
The interconnected pore space gives the rock permeability.

Permeability = flow

- Permeability controls the production potential, the production curve and the infrastructure design

- Permeability of the reservoir
- Permeability of the near wellbore area

Permeability of geothermal rocks



Connectivity of porosity primary control in unfractured rocks

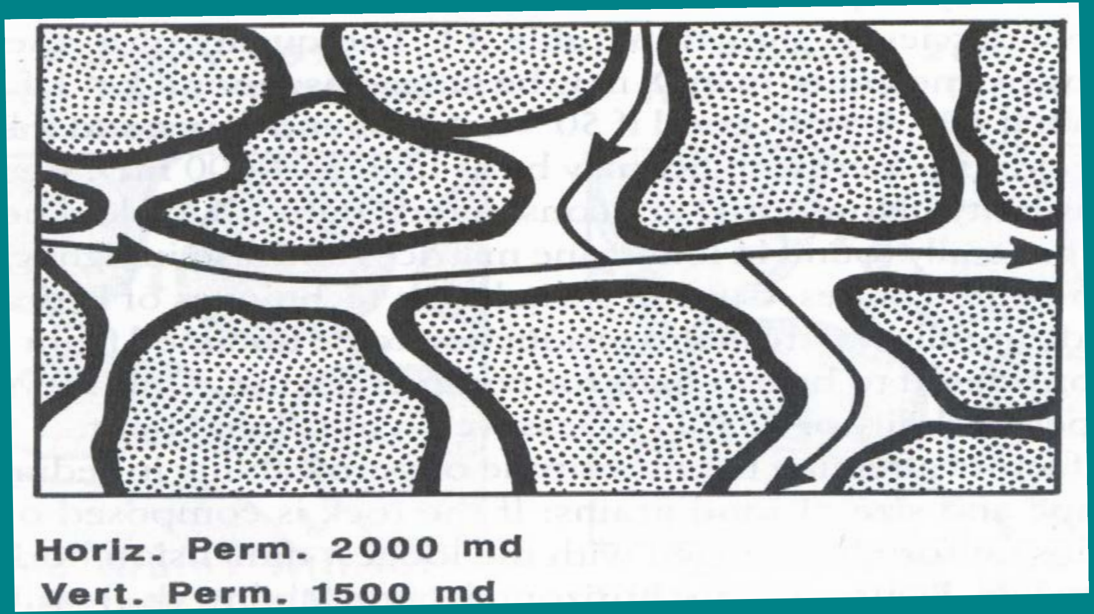
Connectivity of fractures primary control in fractured aquifers

http://publishing.cdlib.org/ucpressebooks/view?docId=ft6v19p151&chunk.id=d0e16837&toc.id=&brand=ucpress

Primary permeability

As with porosity the classification of permeability is in:

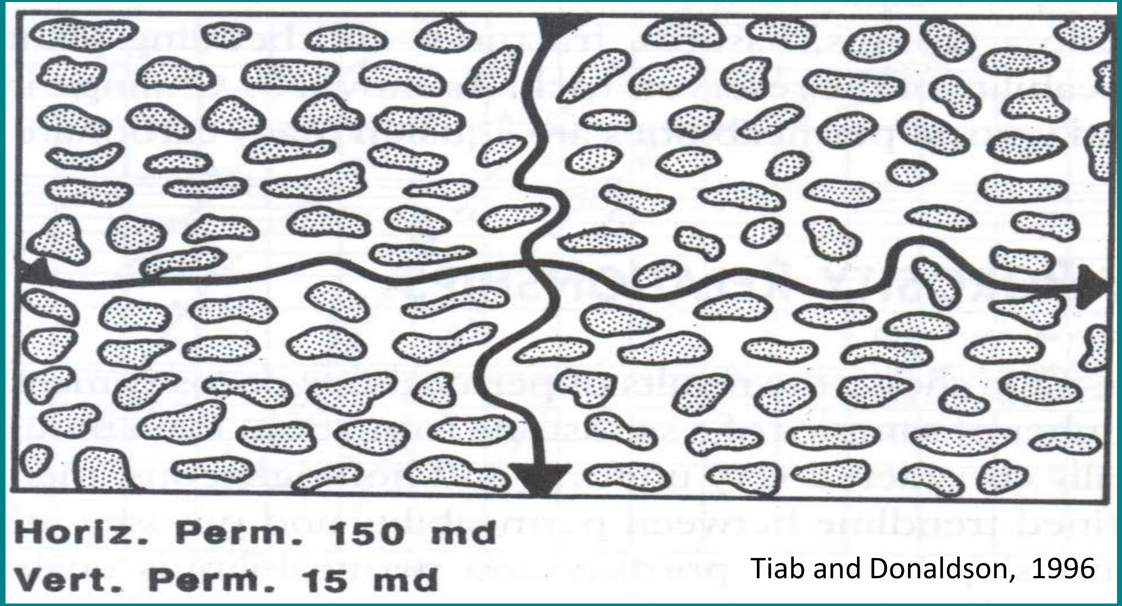
- primary (or matrix) permeability exists during deposition and consolidation
  - large, round, well-sorted grains have high permeability in all directions.



Tiab and Donaldson, 1996

Primary permeability

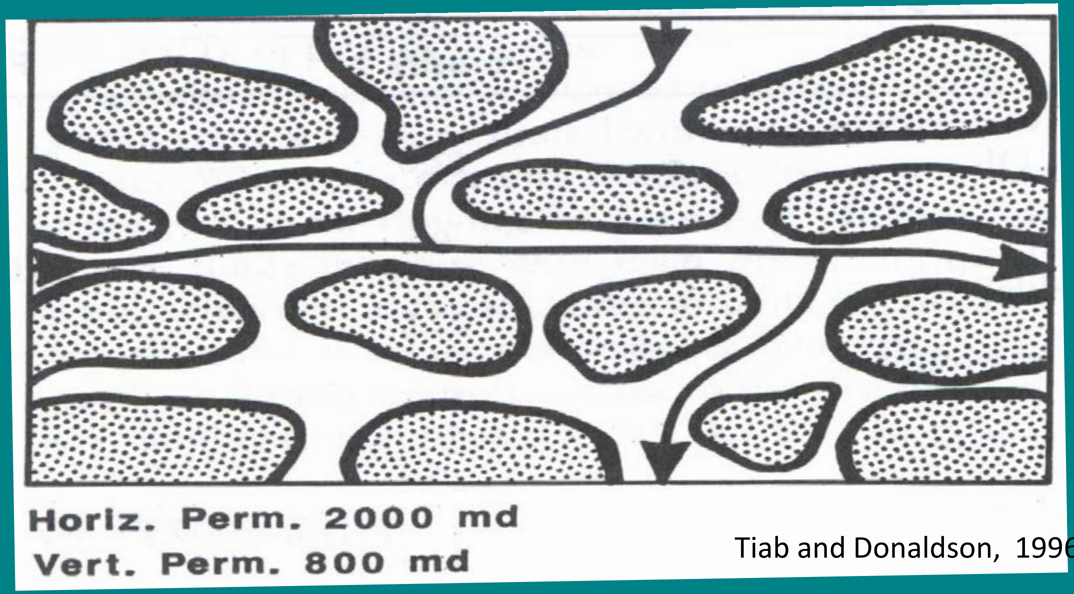
- small, irregularly shaped, and poorly sorted grains have low permeability.



Tiab and Donaldson, 1996

Permeability anisotropy in porous media

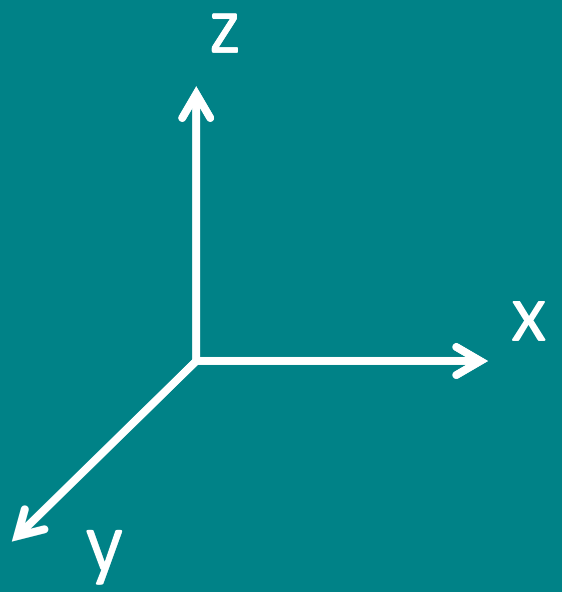
- large flat grains (e.g. shales) have directional permeability (anisotropy), which influences the flow significantly. The ratio horizontal/vertical permeability can be > 10.



Tiab and Donaldson, 1996

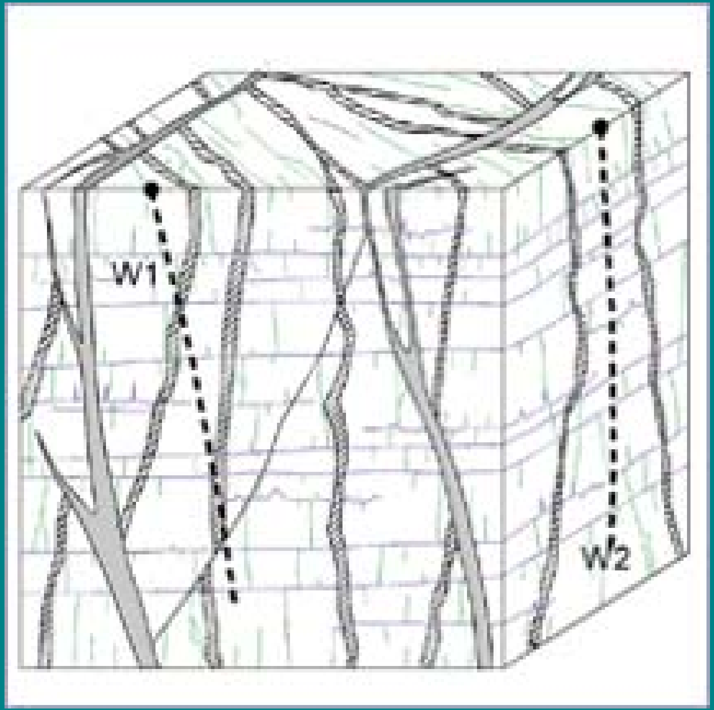
What is anisotropy?

- Isotropy $V_x = V_y = V_z$
- Anisotropy $V_x \neq V_y \neq V_z$



Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies identical properties in all directions.

Permeability anisotropy in fractured media

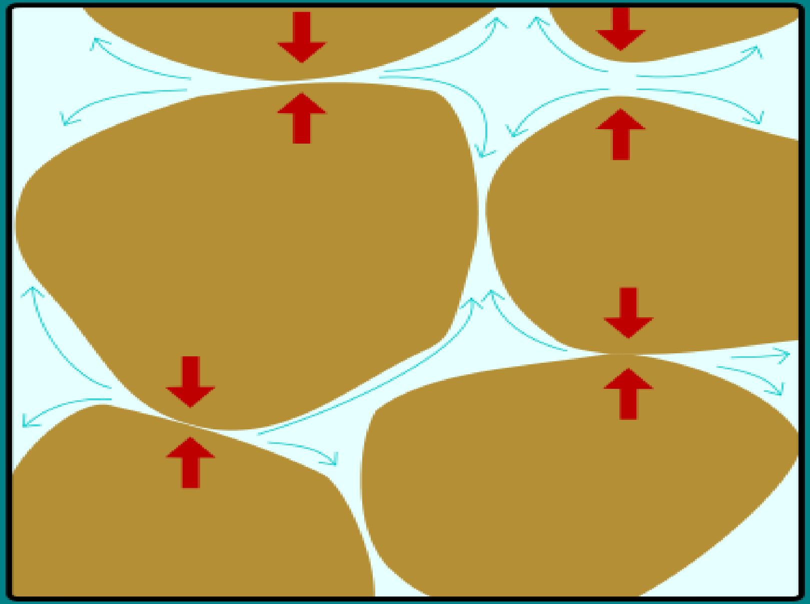


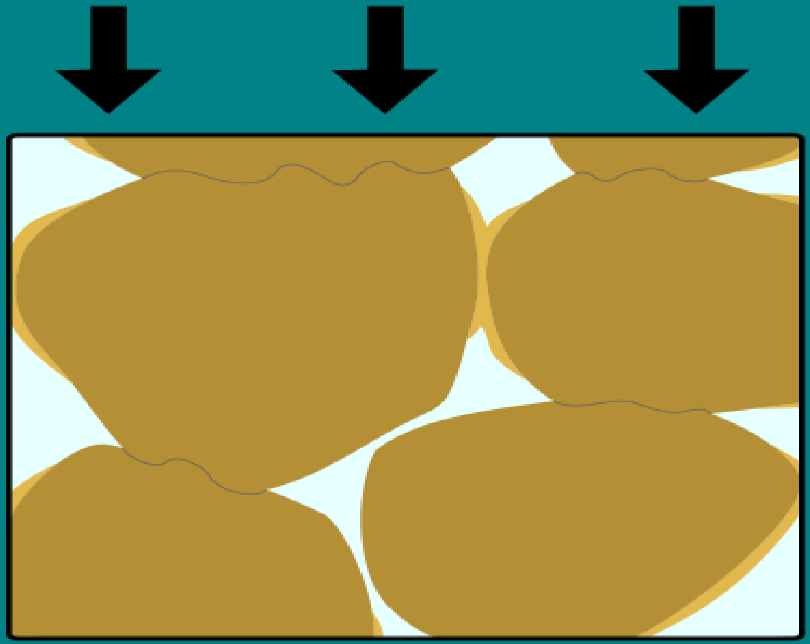
Fractures are often in specific orientations/directions, so usually large anisotropy

http://www.geoscience.co.uk/services/fractured-reservoir-characterisation.html

Secondary permeability

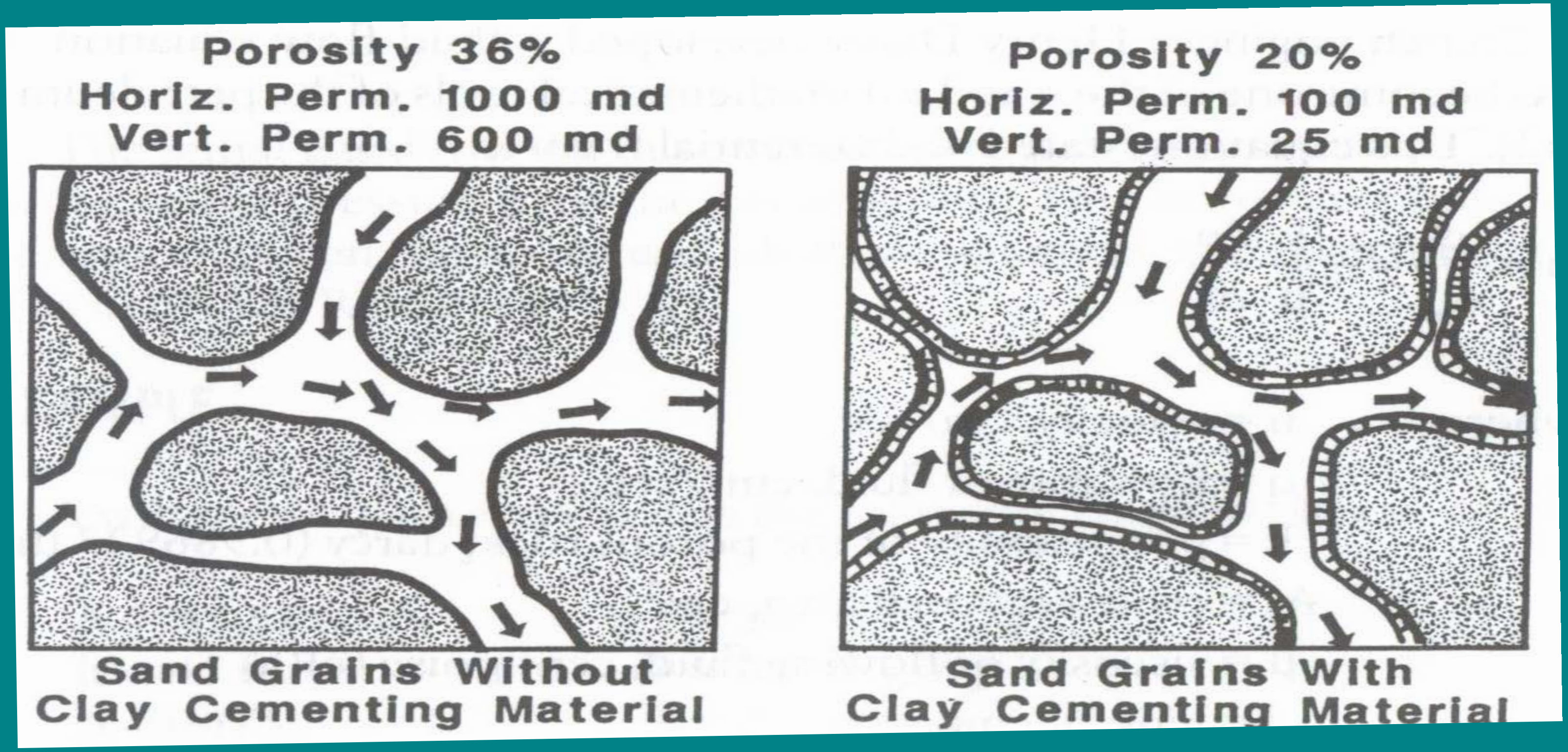
- secondary (or induced) permeability originates from later
    - compaction (lower permeability)





Secondary permeability

- cementation (lower permeability)



Tiab and Donaldson, 1996

Secondary permeability

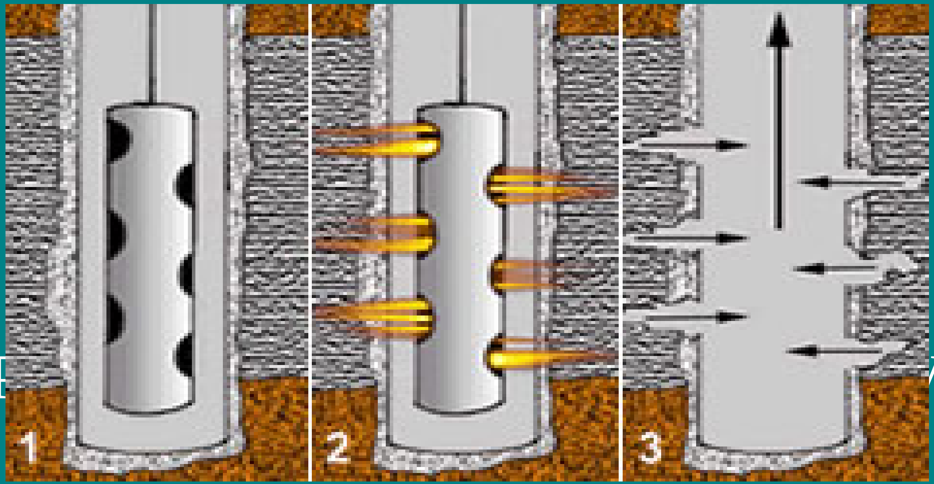
- mechanical fracturing (higher permeability)

Secondary permeability

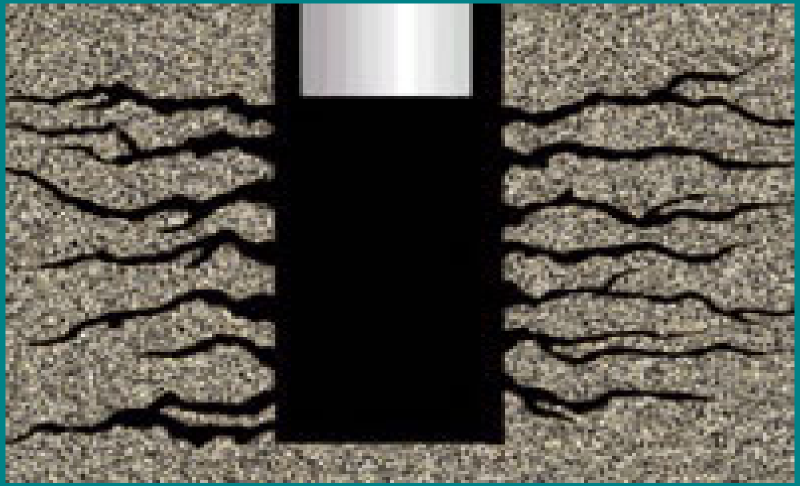
- chemical solution (higher permeability)

Hydraulic fracturing and acidizing

Current stimulation techniques of hydraulic fracturing and acidizing allow petroleum production in rocks which were regarded being ‘too tight’ 30 years ago.



F Verzuring



Fracture porosity/permeability

Basalts close to Bandung

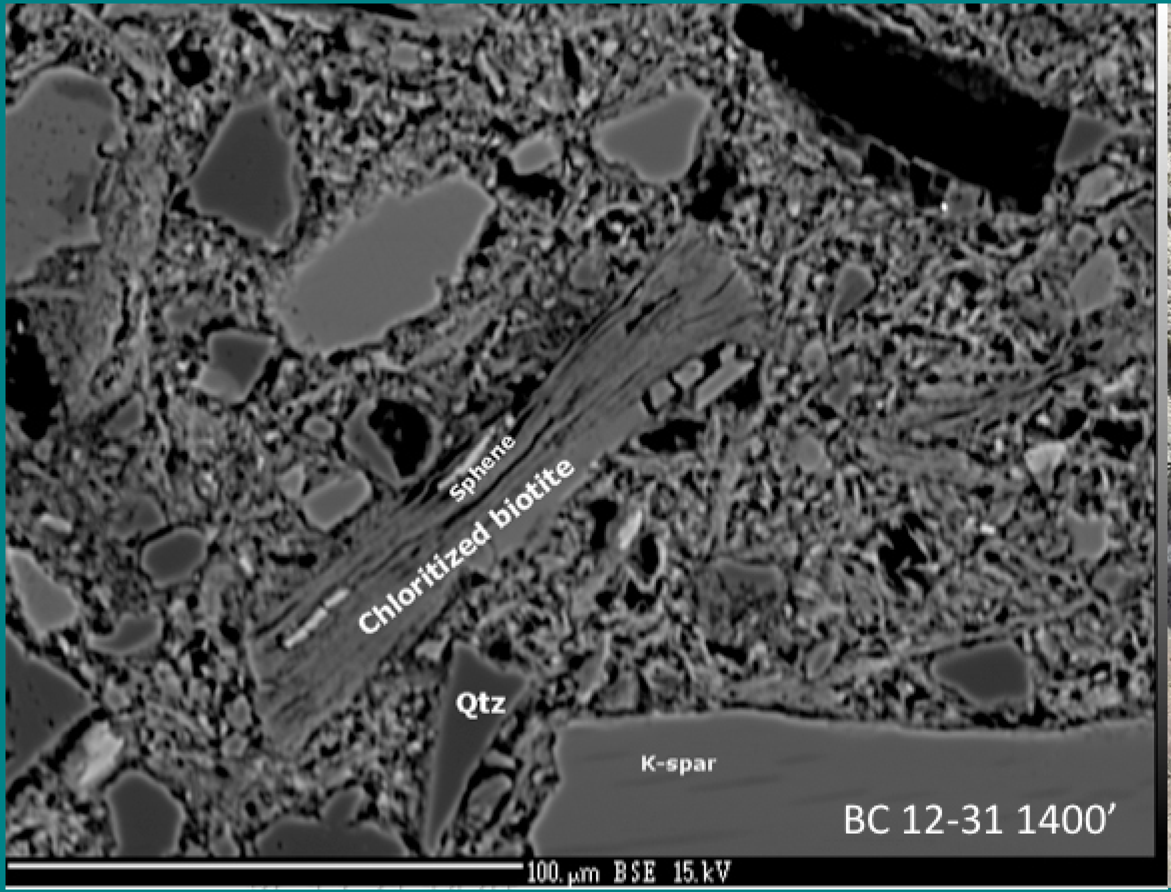
Musamdam, Oman

Porosity generally small (fluid storage space small)

Permeability generally large (but fluid travels quickly)

Permeability in tuff vs gaseous lava

Tuff: Permeability present but low



No or very low permeability because pores are unconnected

http://classic.geology.ucdavis.edu/classes/geothermalresources_F2010/alteration/index.html

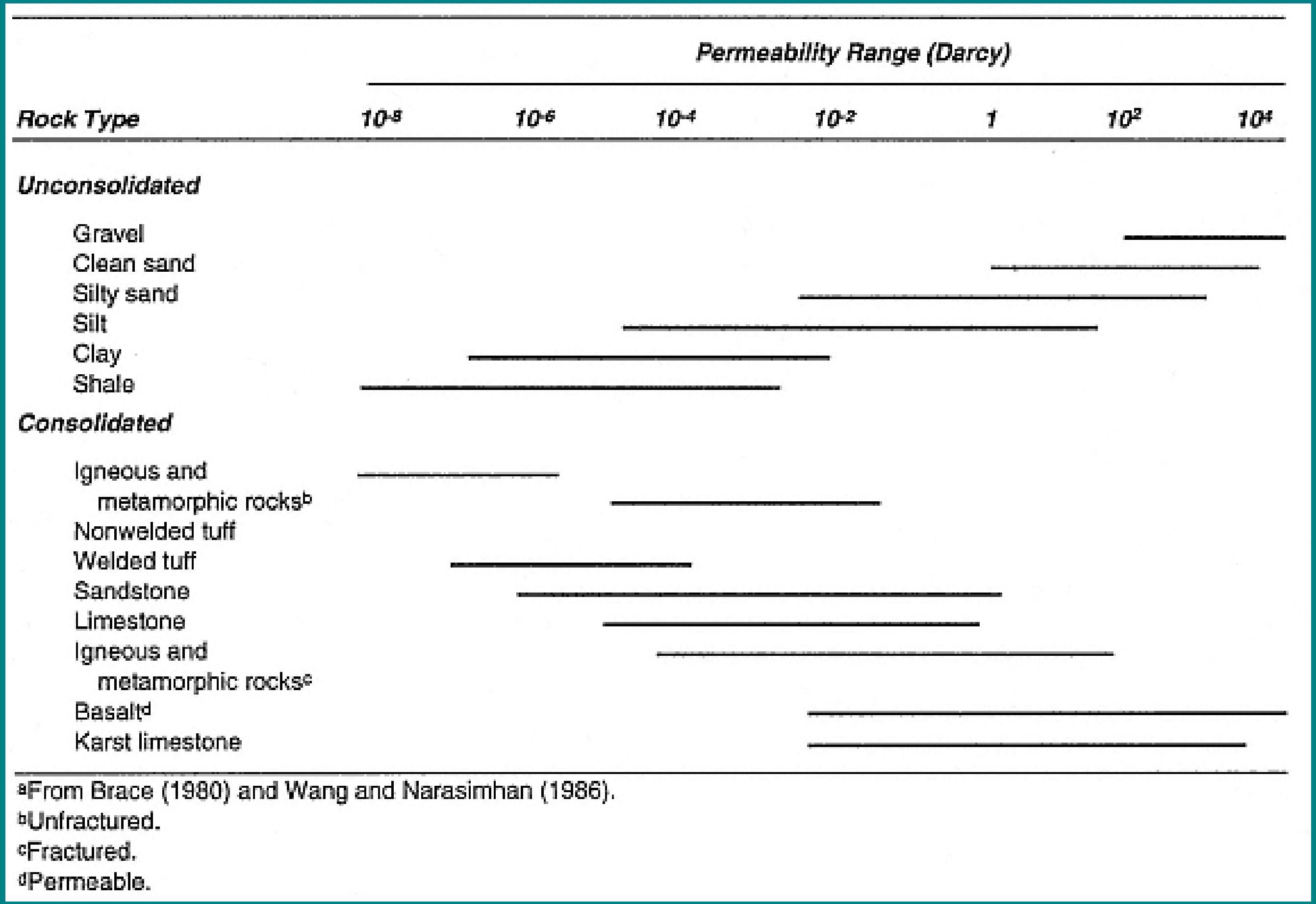
Porosity in basalt vs gaseous lava

Permeability absent except for in fractures

Large pores (cm sized)

http://classic.geology.ucdavis.edu/classes/geothermalresources_F2010/alteration/indexhtml

Permeability of geothermal rocks



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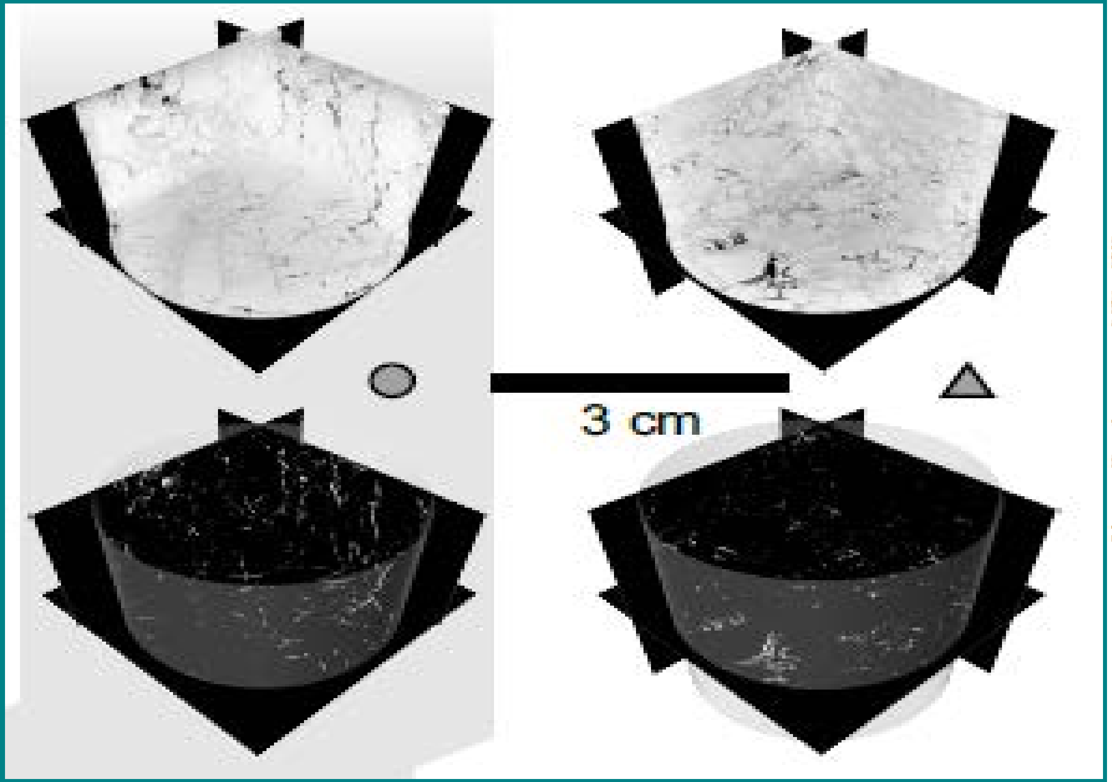
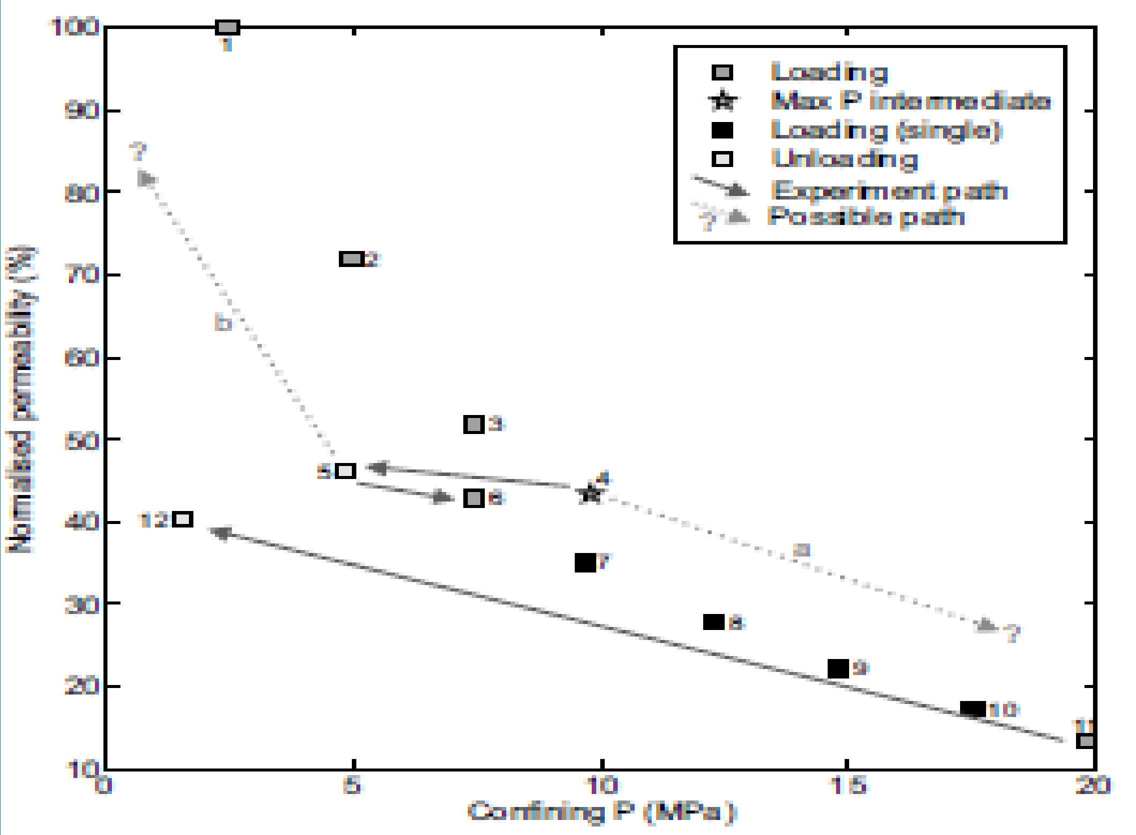
http://publishing.cdlib.org/ucpressebooks/view?docId=ft6v19p151&chunk.id=d0e16837&toc.id=&brand=ucpress

Permeability measurements of fractured dolomite

Voorn et al., 2015



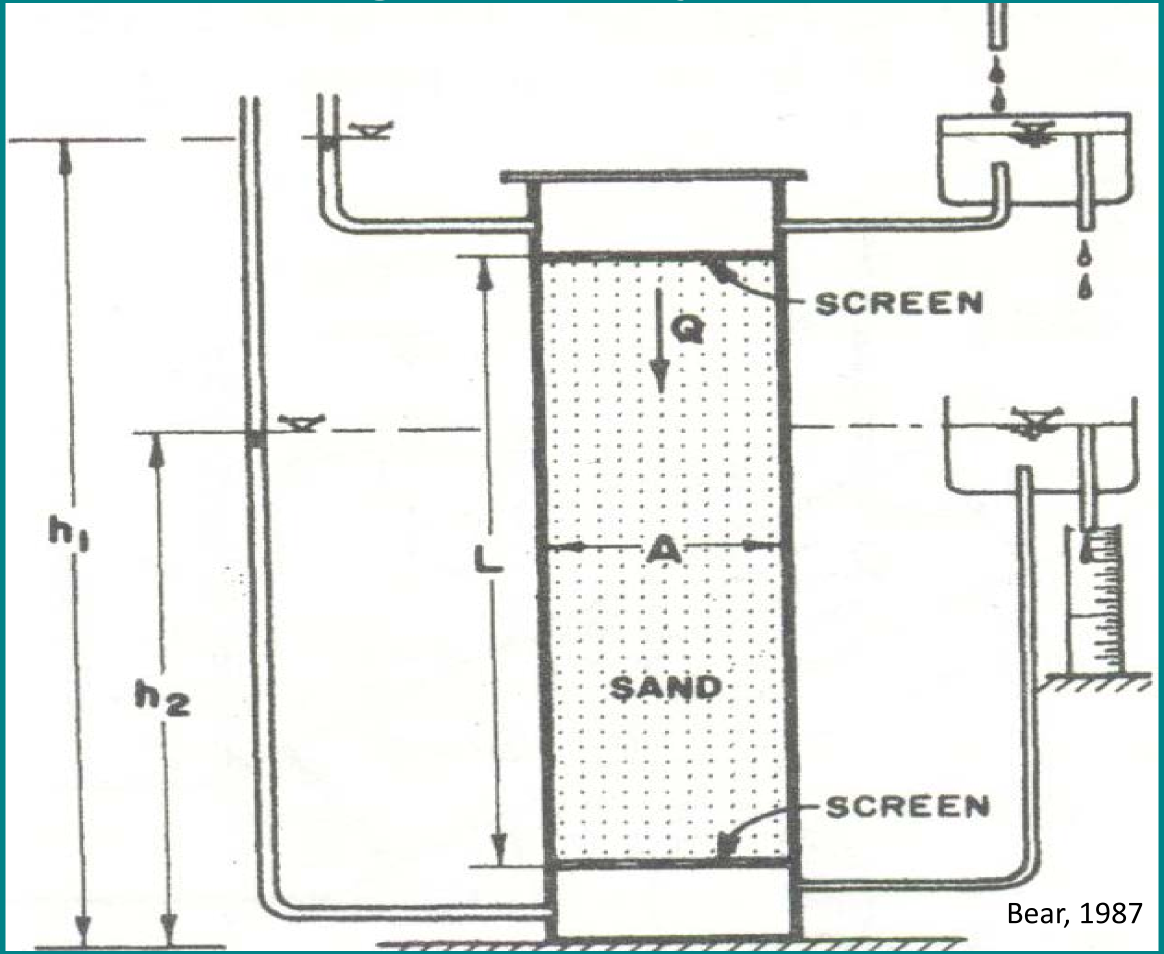


Permeability measurements at high pressure conditions

$$\kappa = ?$$

Darcy’s experiment (1856)

Henry Darcy investigated the vertical flow of water through a filter layer of homogeneous sand.



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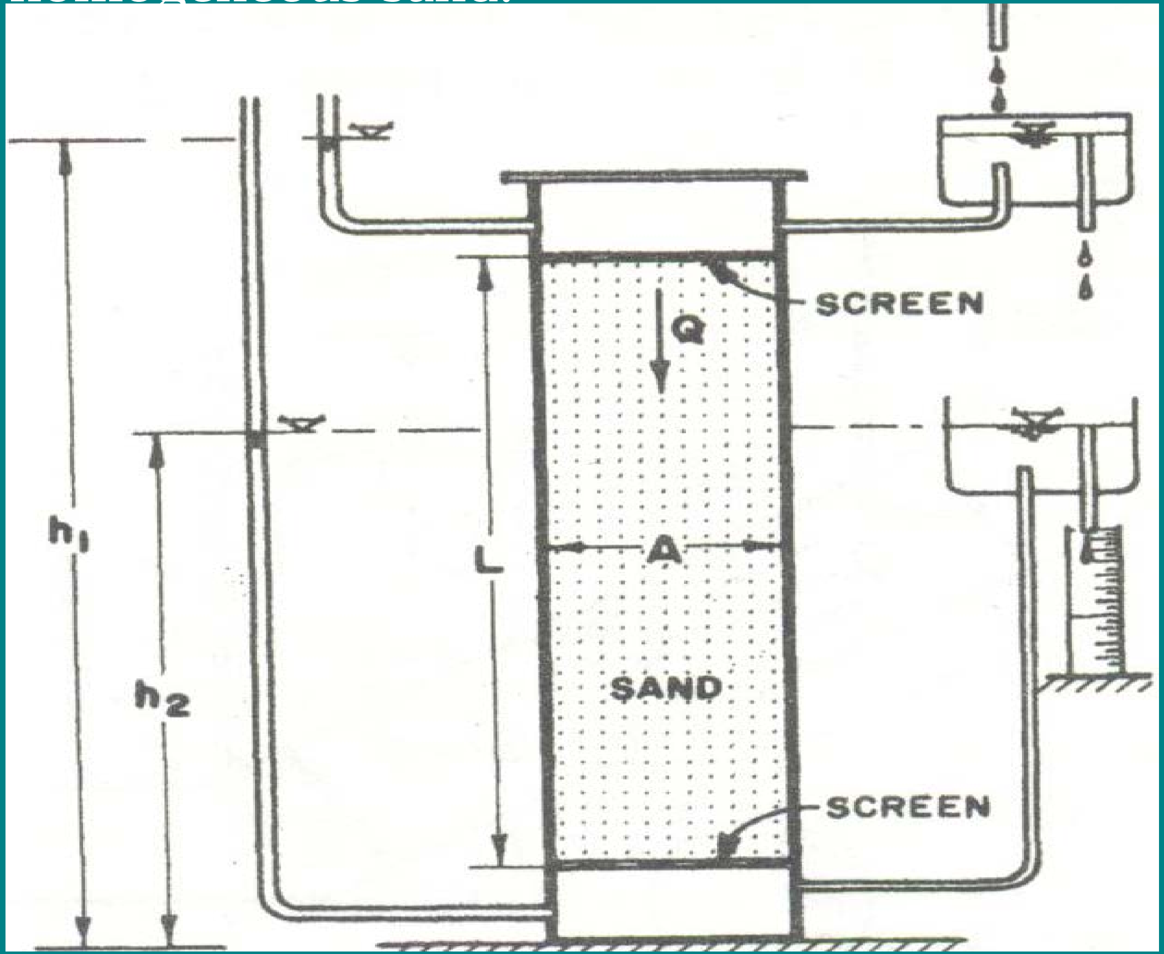
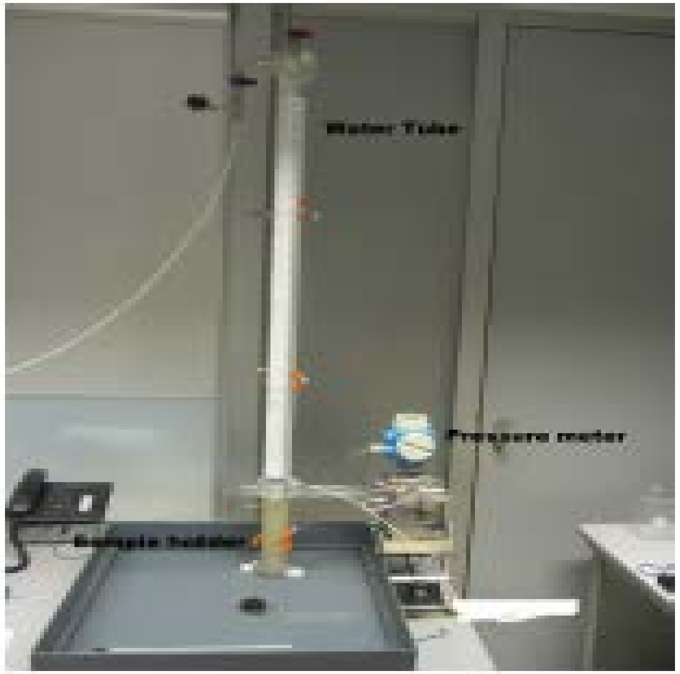
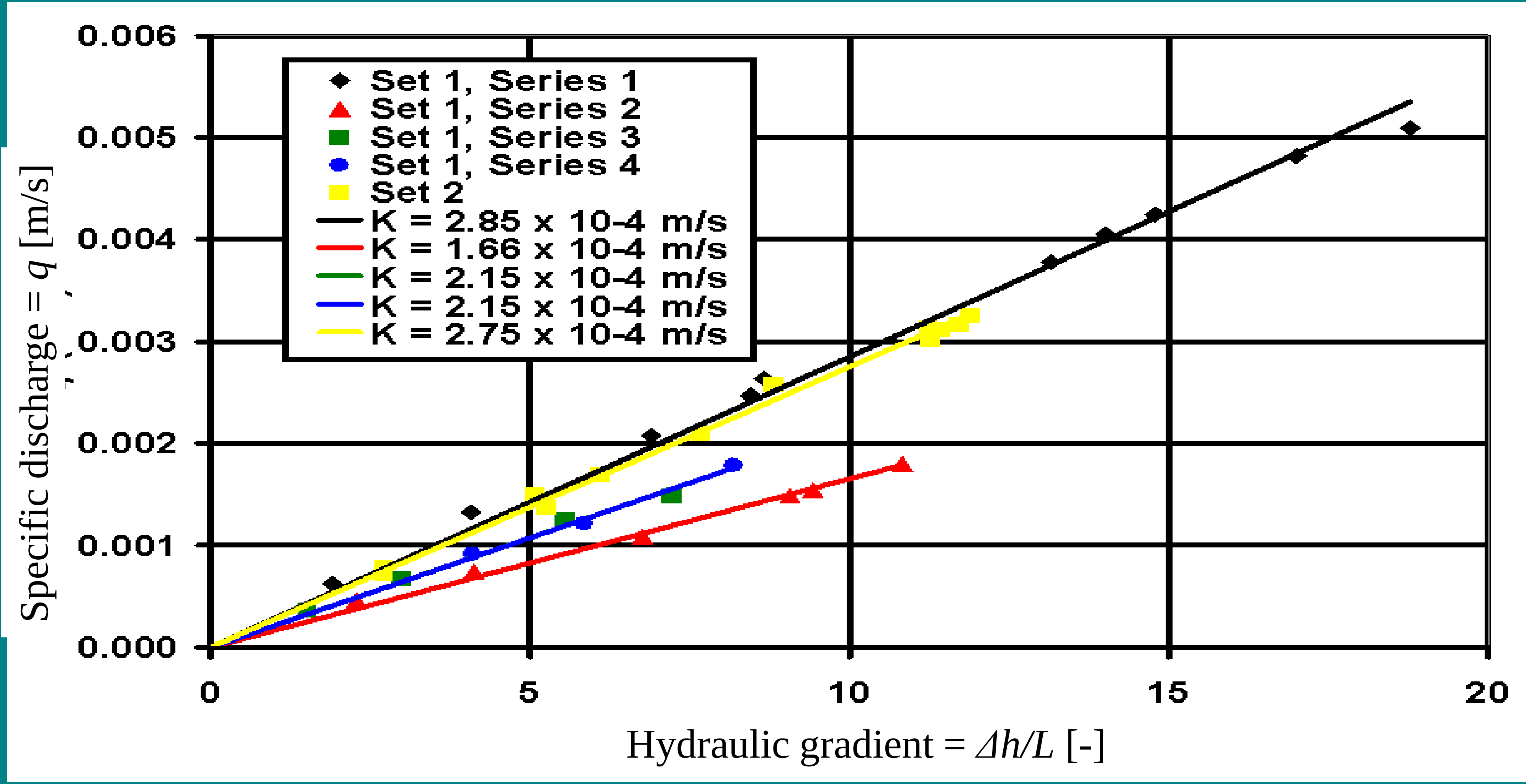


Bear, 1987



BSc thesis Caroline Vriesde (2015)

Results of Darcy’s experiment



Conclusions of Darcy's experiment

He concluded that the flow rate (volume per unit time) Q [m^3/s] is

- proportional to the cross-sectional area A [m^2],
- proportional to the piezometric head (h_1 - h_2) [m],
- inversely proportional to the length of the sand layer L [m].

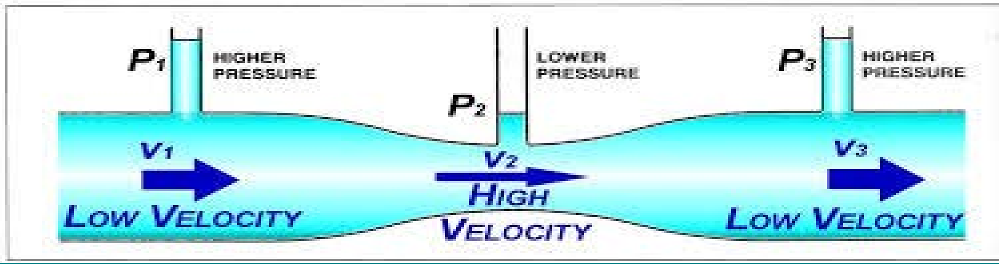
Combination of the conclusions gives:

$$Q = KA\frac{(h_1 - h_2)}{L}$$

in which K is the hydraulic conductivity or hydraulic permeability [m/s].

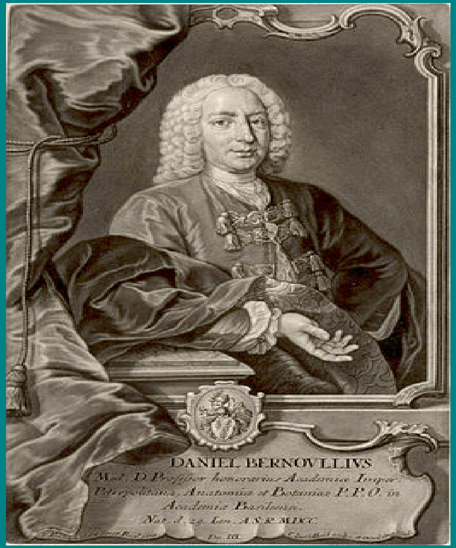
http://en.wikipedia.org/wiki/Darcy%27s_law

Bernoulli’s Law (1738)



Energy conservation in stationary flow of an incompressible fluid:

$$^{1}/_{2}\,\rho v^2 + p + \rho g h = constant$$



In which

- \- p is fluid pressure [Pa]
- \- v is fluid velocity [m/s]
- \- ρ is density of an incompressible fluid [kg/m3]
- \- g is gravity = 9.81 [m/s2]
- \- h is height [m].

http://nl.wikipedia.org/wiki/Wet_van_Bernoulli
http://mitchellscience.net/Physics/BernoulliPrinciple

Horizontal flow

If the fluid flows with a constant speed,

$$\mathrm{p} + \rho g h = constant$$

In the special case of horizontal flow, *h* is constant, so that Darcy's law becomes

$$Q = KA\frac{(p_1 - p_2)}{\rho g L}$$

in which

- $(p_1 - p_2)$ is the pressure difference over length L [Pa].
- $q = Q/A$ is the Darcy velocity ('specific discharge') [m/s].

Intrinsic permeability

To separate the fluid properties and the rock properties, we use the intrinsic permeability κ (also k_0) [m^2] with

$$K = \frac{\rho g \kappa}{\eta}$$

and

- η is the viscosity [Pa s];
- g is the gravity acceleration = 9.81 [m/s^2];
- ρ is the incompressible fluid density [kg/m^3].

1 Darcy (= 9.8697 10^{-9} cm^2) ≈ 1 µm^2 ≈ 10^{-12} m^2.

Practical unit: 1 mD ≈ 10^{-15} m^2.

Darcy’s law

In differential form with flow in the *x*-direction

$$q = -\frac{\kappa}{\eta}\frac{\partial p}{\partial x}$$

with

- $\partial p/\partial x$ is the pressure gradient in the flow direction x [Pa/m].

In general with the mobility

$$q = -\frac{\kappa}{\eta}\, grad\ p$$

The average fluid velocity v (also w) [m/s] is the speed through the effective area φA with porosity φ:

$$v = \frac{Q}{\varphi A} = \frac{q}{\varphi}$$

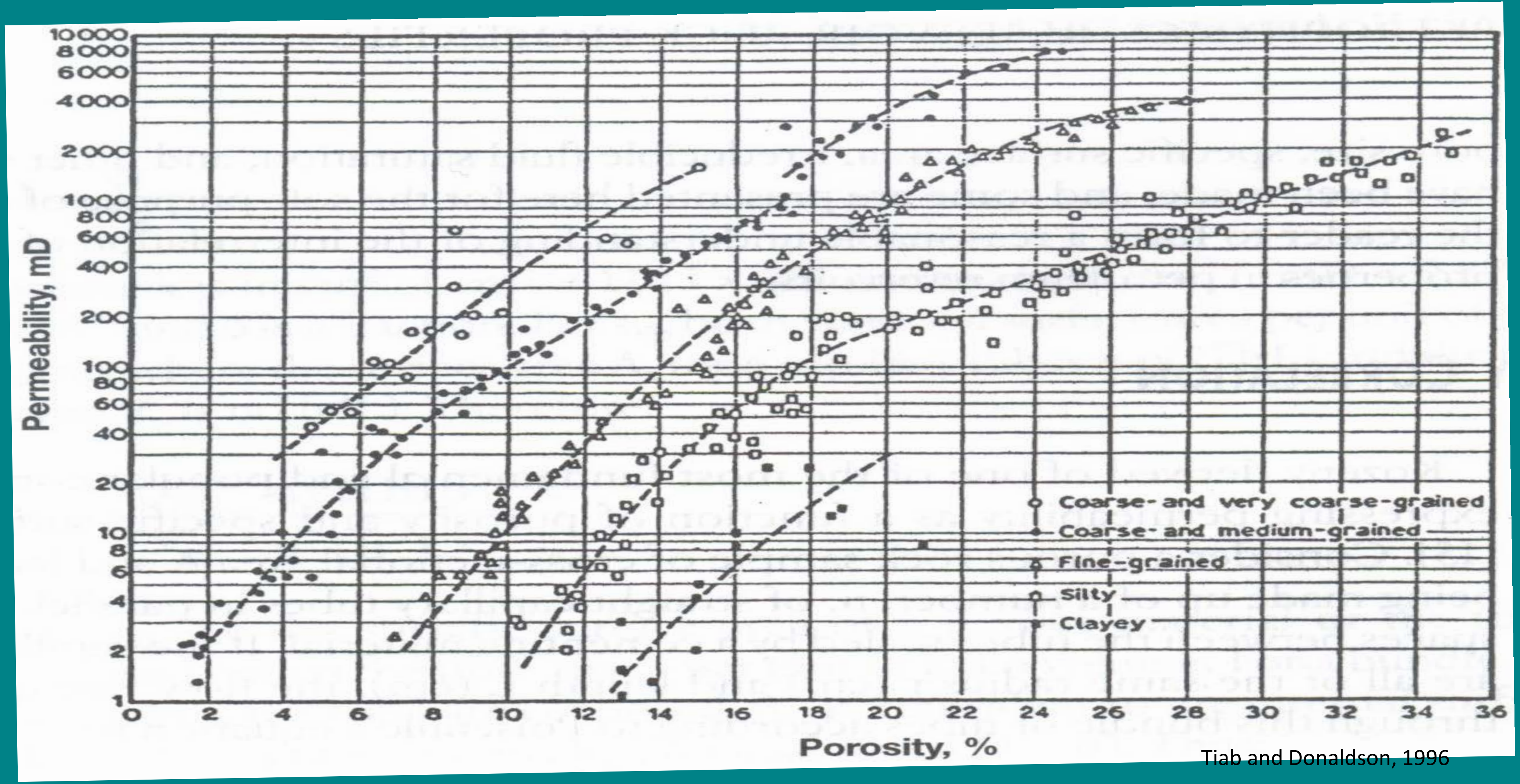
Permeability-porosity relationships

- Permeability important for flow, important for production engineers
- Very difficult to measure

- Porosity important for storage space
- Easy to measure

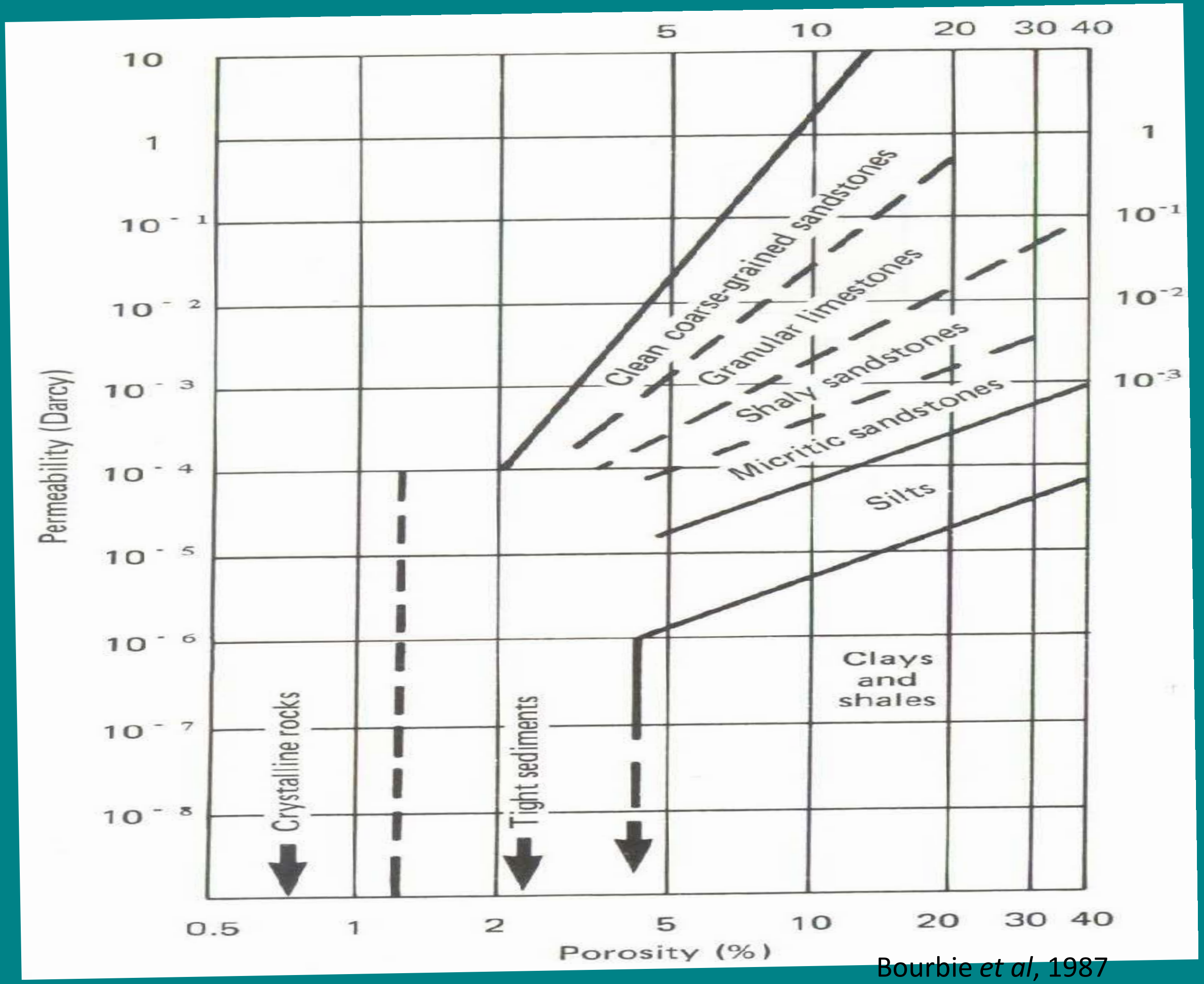
- Porosity-permeability relationships exists

Porosity-permeability relationships

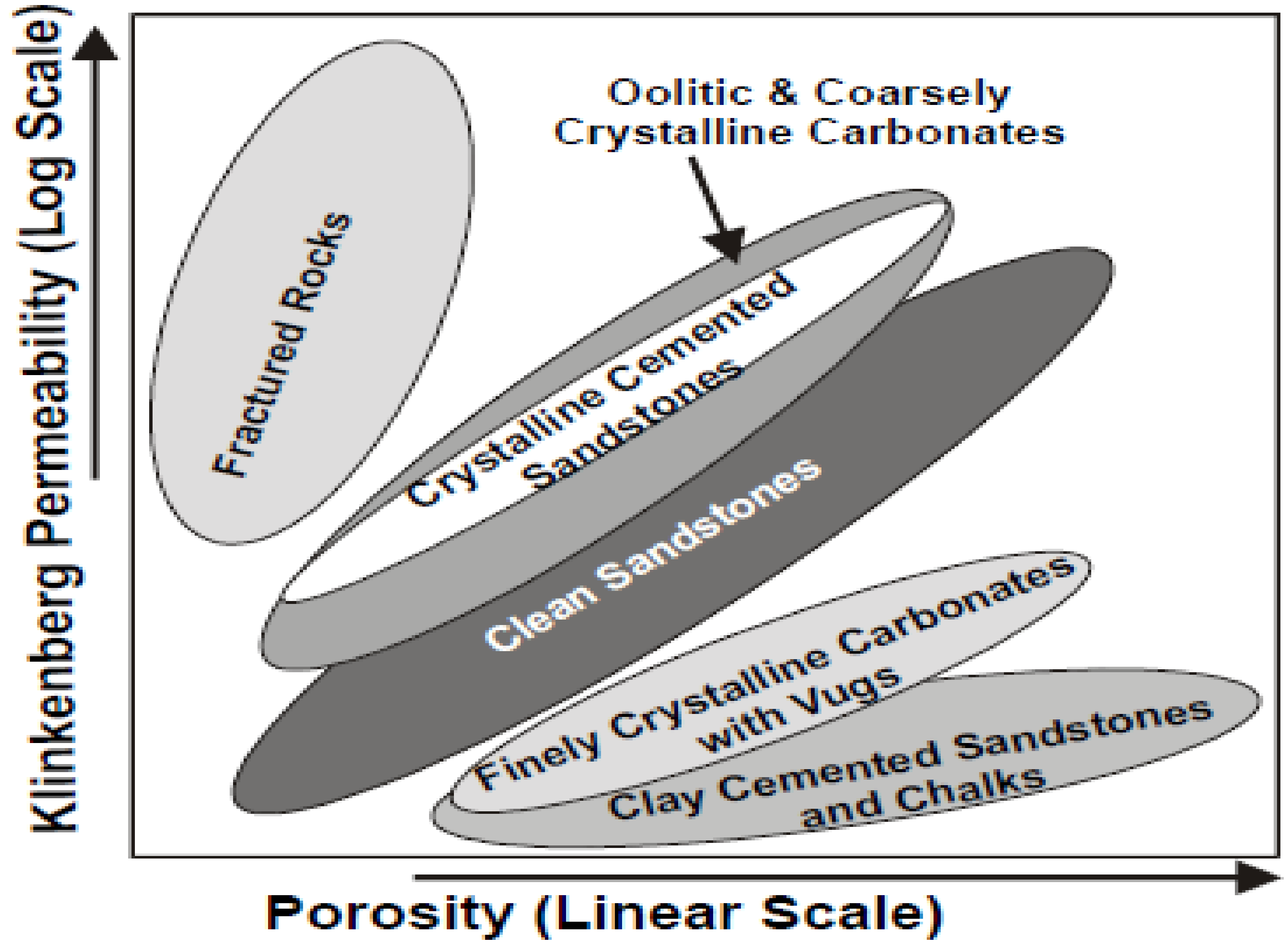


Tiab and Donaldson, 1996

Porosity-permeability variaties



Bourbie *et al*, 1987



Klinkenberg Permeability (Log Scale)
Oolitic & Coarsely
Crystalline Carbonates
Fractured Rocks
Crystalline Cemented
Sandstones
Clean Sandstones
Finely Crystalline Carbonates
with Vugs
Clay Cemented Sandstones
and Chalks
Porosity (Linear Scale)

Carman-Kozeny

Various forms of the Carman-Kozeny equation exist:

$$\kappa = \frac{B\varphi^3 d^2}{\alpha_\infty}$$

$$\kappa = \frac{B\varphi^3}{(1-\varphi)^2} d^2$$

$\varphi = porosity, d$ = grain size and α_∞ = tortuosity

Porosity-permeability relationship

Bourbie *et al*, (1987) discuss the more general form $\kappa \propto d^2\varphi^n$

in which n has been observed experimentally to vary with porosity

$n > 7$ for $\varphi < 5$ %

$n < 2$ for $\varphi > 30$ %.

The Carman-Kozeny relation value $n = 3$ appears appropriate for very clean materials (such as Fontainebleau sandstone and sintered glass).

For more general natural materials is n probably 4 or 5.

Porosity-permeability exercise – 10 min

From a well both porosity-permeability data from cored samples is available as well as a porosity log.
Open Excel file named PorosityPermeabilityExercise.xls

1. Determine porosity-permeability relation from the core data in the sheet named core data.
2. Then fill in the relation in column C and D from the sheet log data. The permeability values calculated in column D will be automatically plotted in the log to the right.
3. The geothermal field needs a minimum permeability of 10 mDarcy to be econonically viable. What section of the log would be producable and what is then the minimum porosity?
4. Now it turns out that the minimym permeability is 100 mDarcy (ten times as large). Which section is then producable and what is then the mininum porosity?

Good Book

Djebbar Tiab and Erle Donaldson, 2011

Petrophysics

Thank you!

Contact Details

Auke Barnhoorn

Department of Geoscience and Engineering

Faculty of Civil Engineering and Geosciences

Delft University of Technology

The Netherlands

More information or questions:

www.citg.tudelft.nl/aukebarnhoorn or auke.barnhoorn@tudelft.nl

@AukeBarnhoorn