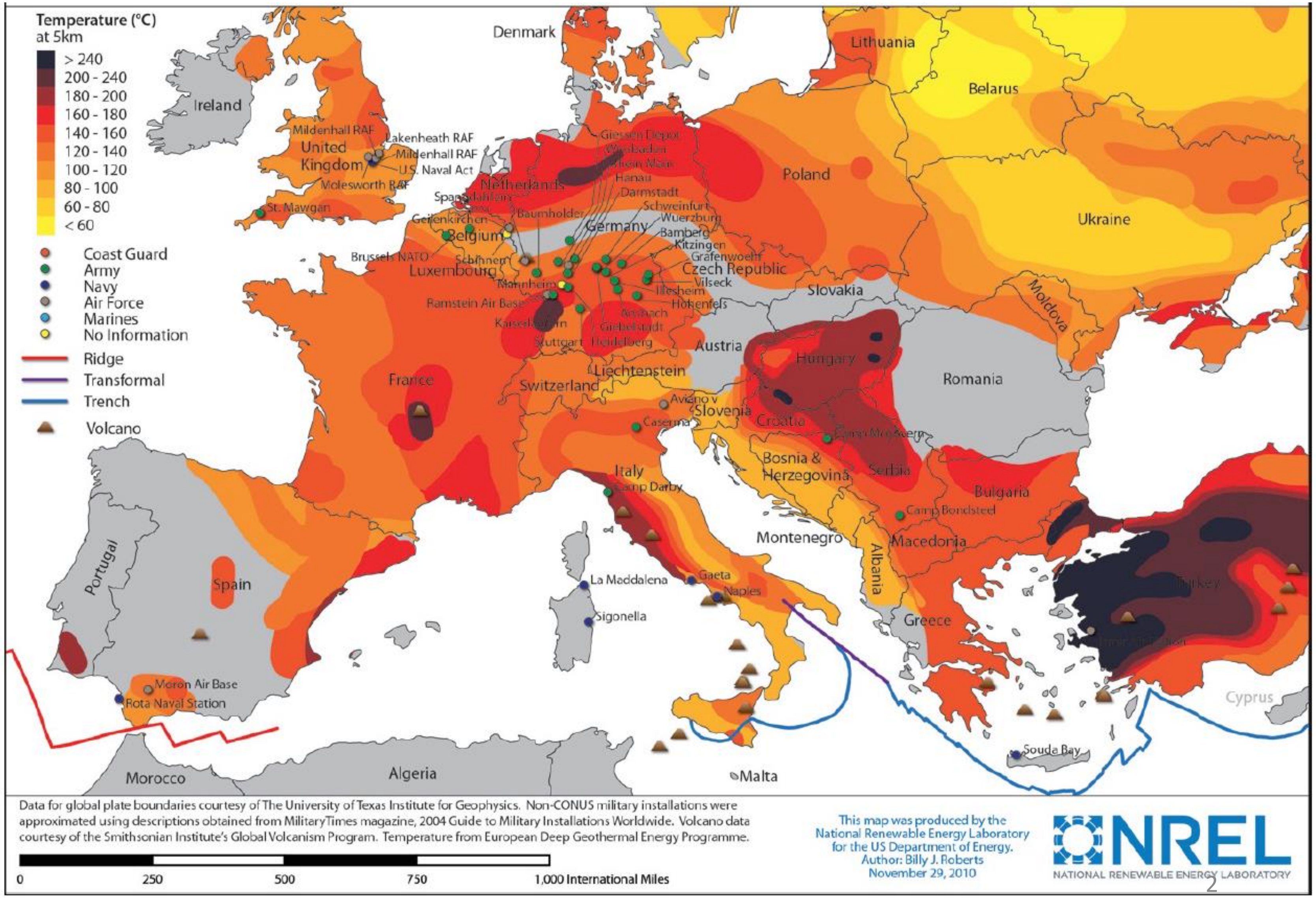
Geothermal Resource Development

Hydrology of geothermal systems

What is geothermal energy?

Large portions of Europe have subsurface temperatures in excess of 100°C

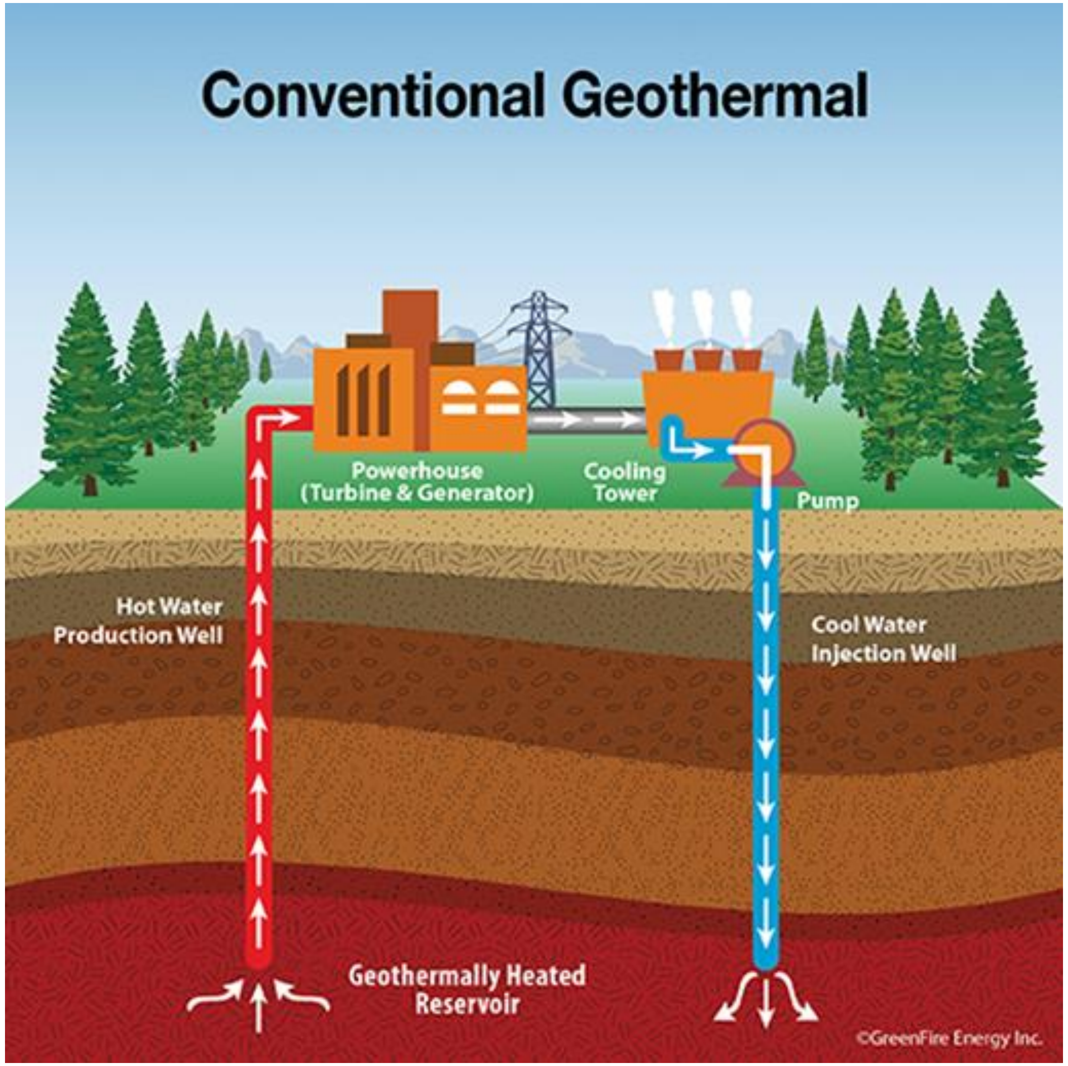
How can we extract that heat?



Extracting geothermal energy

Primary resource:
Heat

Resource vector:
Water



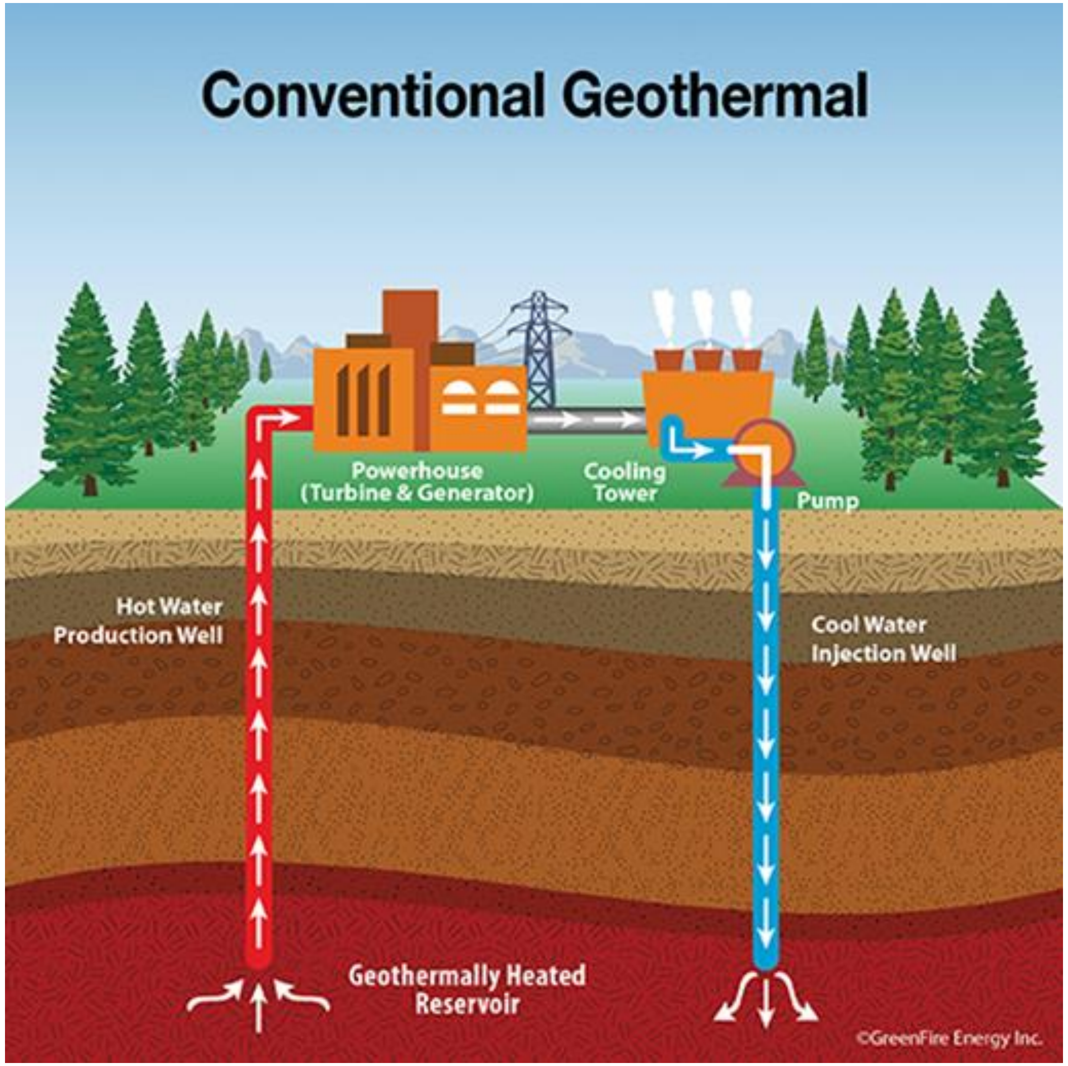
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Extracting geothermal energy

Primary resource:
Heat

Resource vector:
Water

How do we get from the injection well to the production well?



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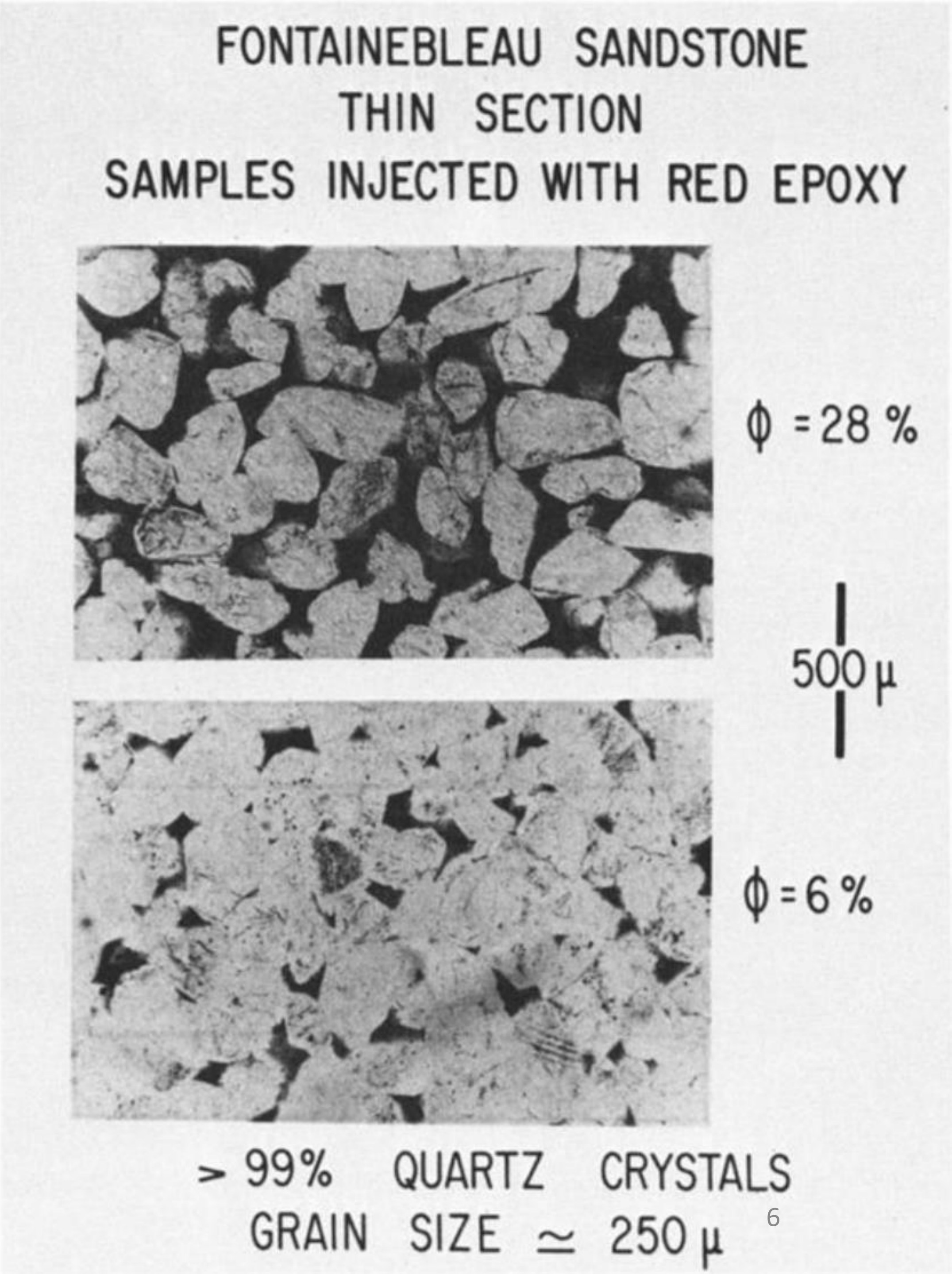
Topics covered today...

1. Matrix porosity and permeability
2. Fracture porosity and permeability
3. Effect of depth
4. Hydrological properties of real geothermal systems

Porosity recap:

- Fraction of pore space in a material
- Scalar
- Different types of porosity are important for different physical properties:
  - total porosity ↔ uniaxial compressive strength
  - **connected porosity ↔ permeability**

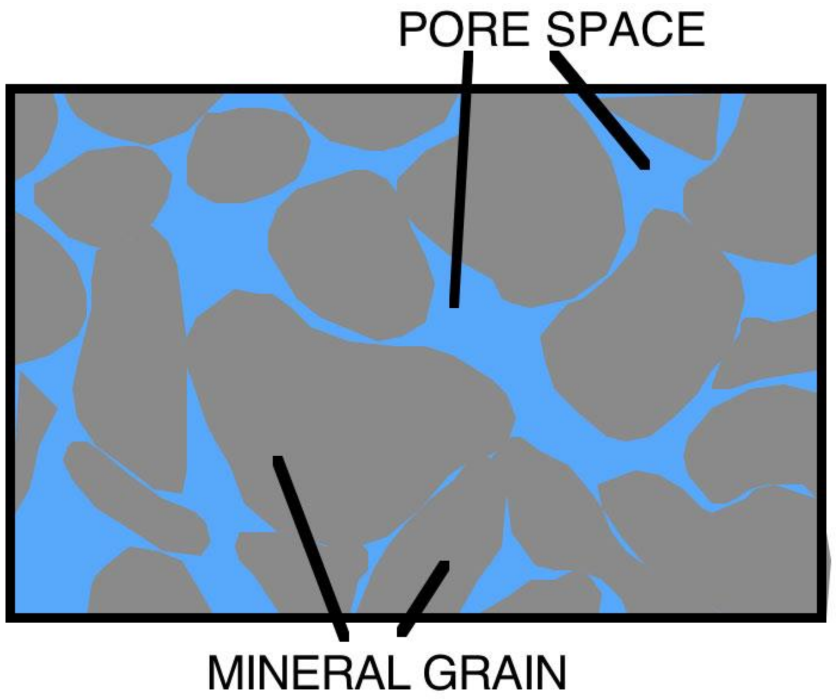


Bourbié and Zinszner, 1985

Porosity

Porosity $\boldsymbol{\phi}$ is defined as the ratio of pore volume to total volume.

$$\boldsymbol{\phi = \frac{V_p}{V_t} = \frac{V_t - V_s}{V_t}}$$



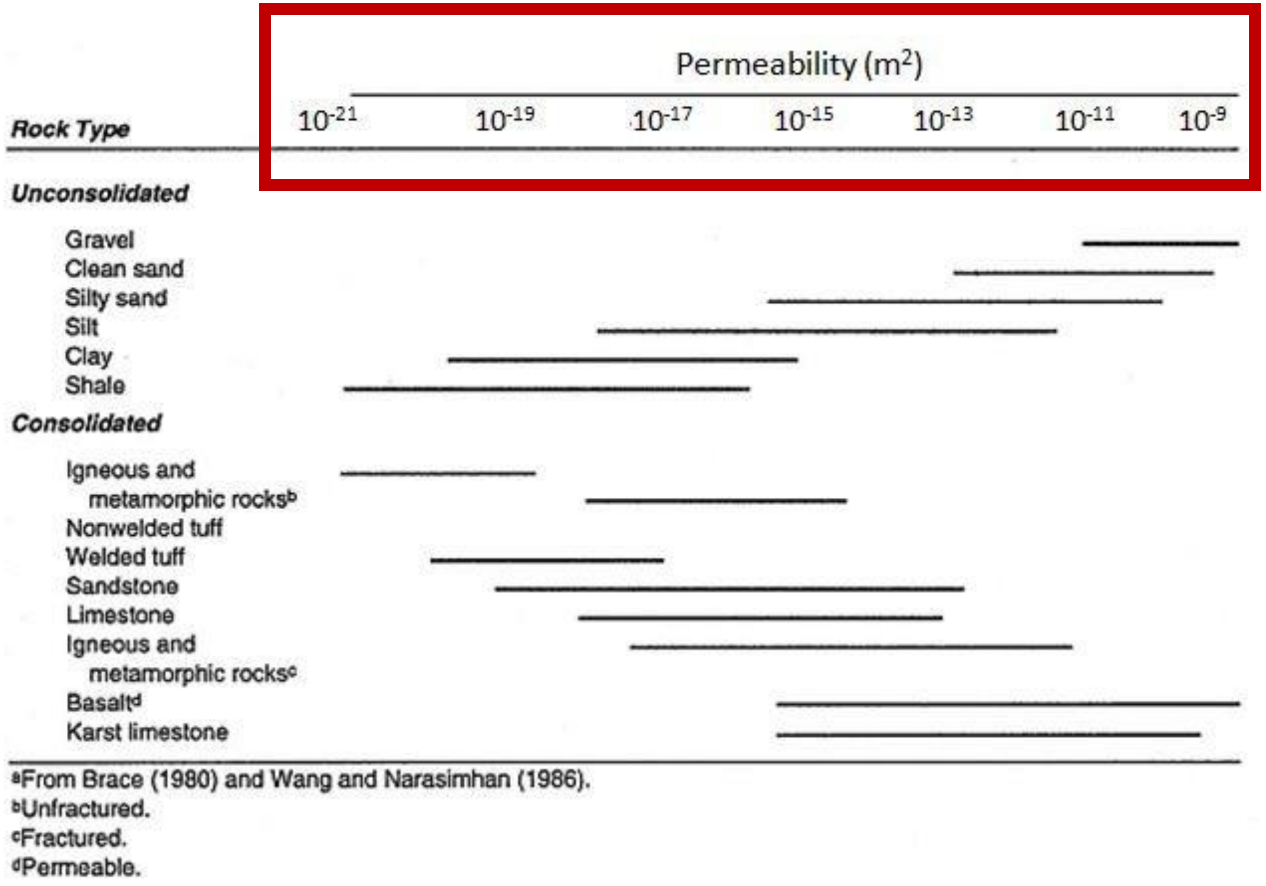
$\boldsymbol{V_p}$ → pore volume

$\boldsymbol{V_s}$ $(or\ V_m)$ → solid (matrix) volume

$\boldsymbol{V_t}$ $(or\ V_b)$ → total (bulk) volume

Permeability recap:

- Property that describes the ease with which fluid can travel through a material
- Material constant
- Varies over several orders of magnitude
- Permeability is controlled by the **connectivity**, **geometry**, and **tortuosity** of the pore space.
- Critical parameter for geosciences problems, especially in the lithosphere



Rock masses


A. Kushnir


https://www.isleofmullcottages.com/blog/top-5-locations-for-columnar-basalt/


https://stock.adobe.com/fr/search?k=metamorphic+rocks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https://www.nps.gov/moru/learn/nature/geologicactivity.htm


https://www.worldatlas.com/articles/how-are-sedimentary-rocks-formed.html


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Components of rock masses

https://hardscape.co.uk/granite-facts-geology/

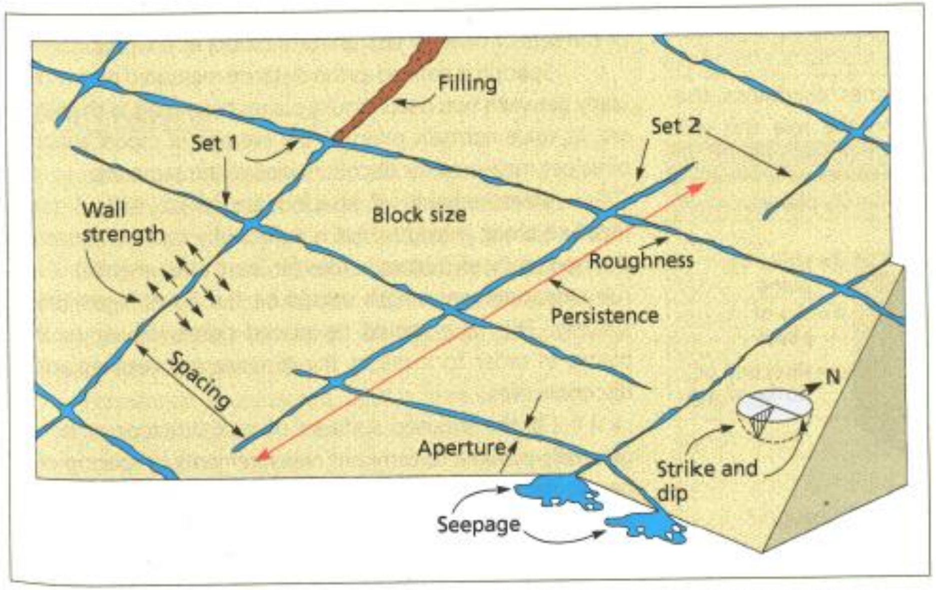


Figure 6.4 Diagram of the geometric properties of discontinuities (Hudson, 1989).

Matrix porosity and permeability

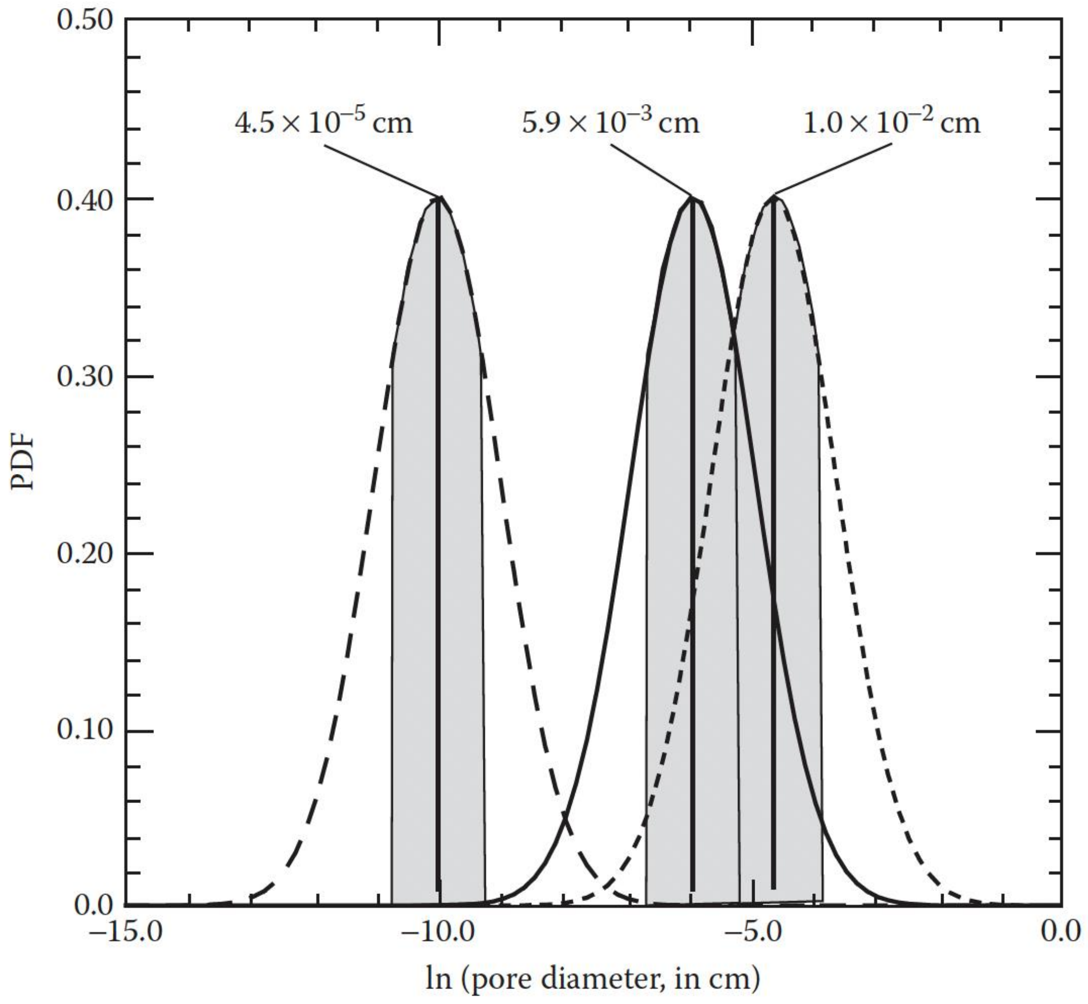
Matrix porosity

Pore sizes in rocks and sediments are extremely variable.

Pore size distribution of rocks can be approximated by a log-normal probability density function (PDF)

PDFs are mathematical simplifications that we apply to geometrically complex systems

- they can provide quantitative approximations for modelling the behaviour of natural systems, including fluid flow.

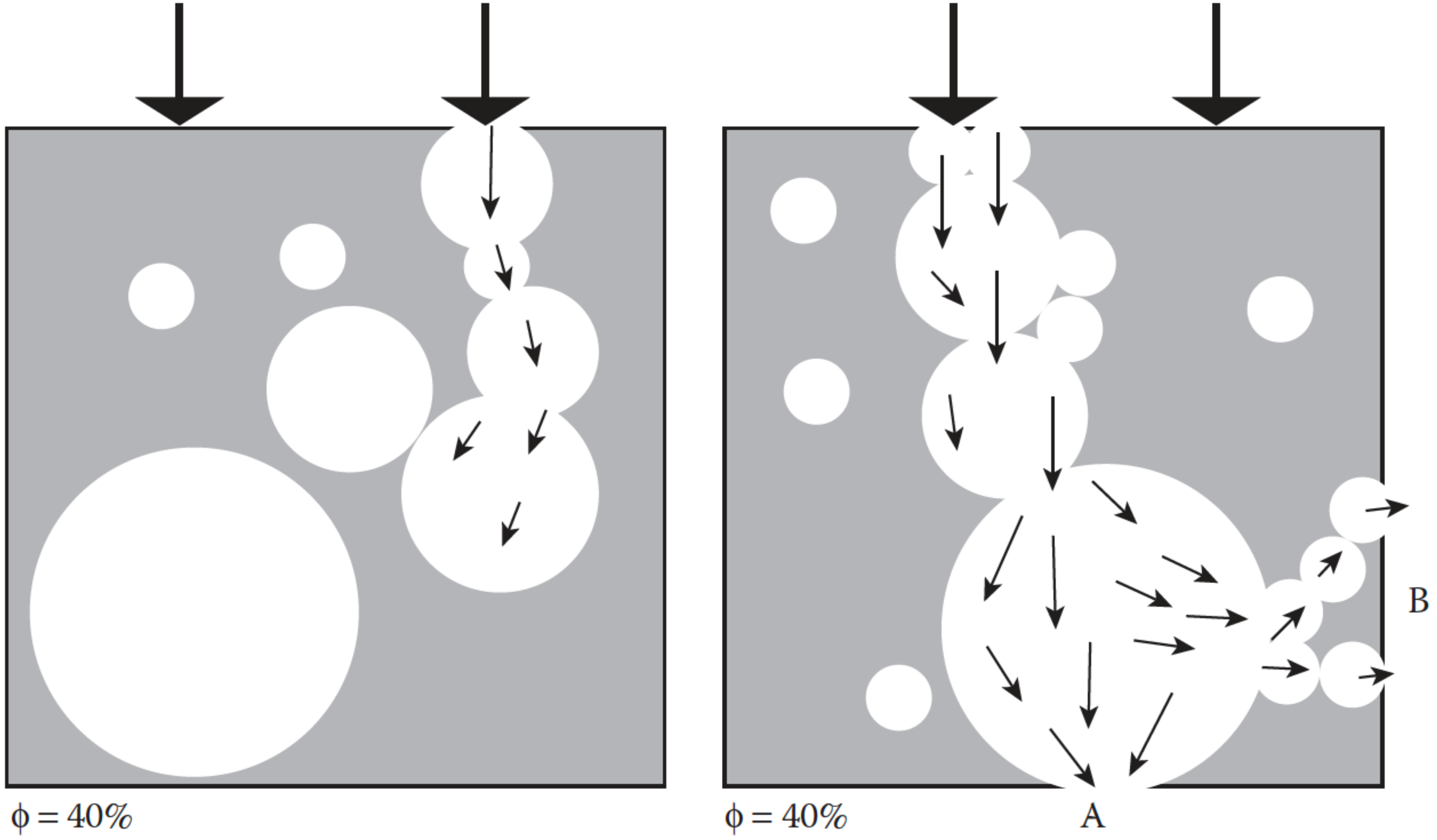


Source: Glassley, W. E., *Geothermal Energy*

Pore connectivity

Fluids need connected pore spaces through which to flow.

Other factors:
- Tortuosity
- Pore throat size
- Fluid viscosity

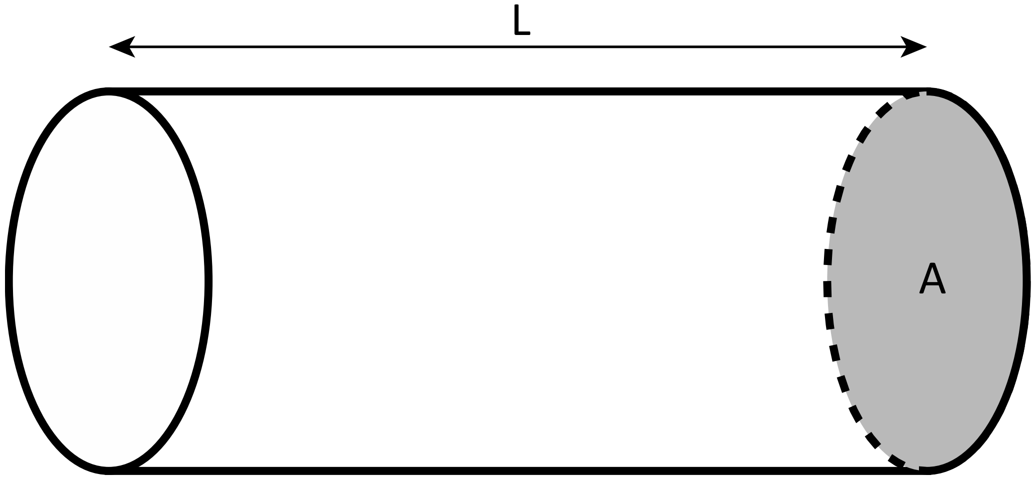


Source: Glassley, W. E., *Geothermal Energy*

Darcy’s Law

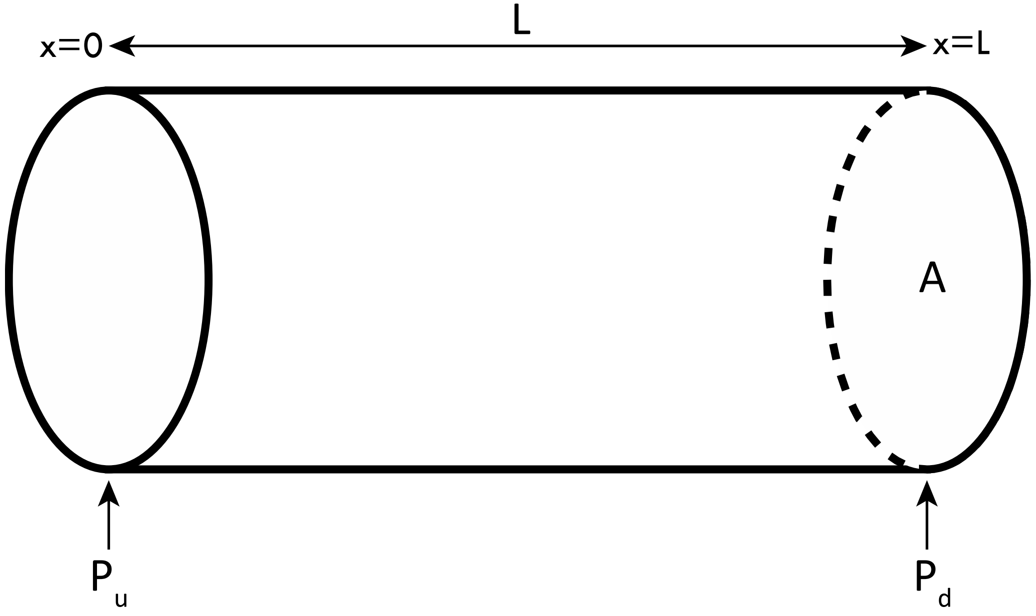
Consider a cylinder of permeable material.

Darcy's Law



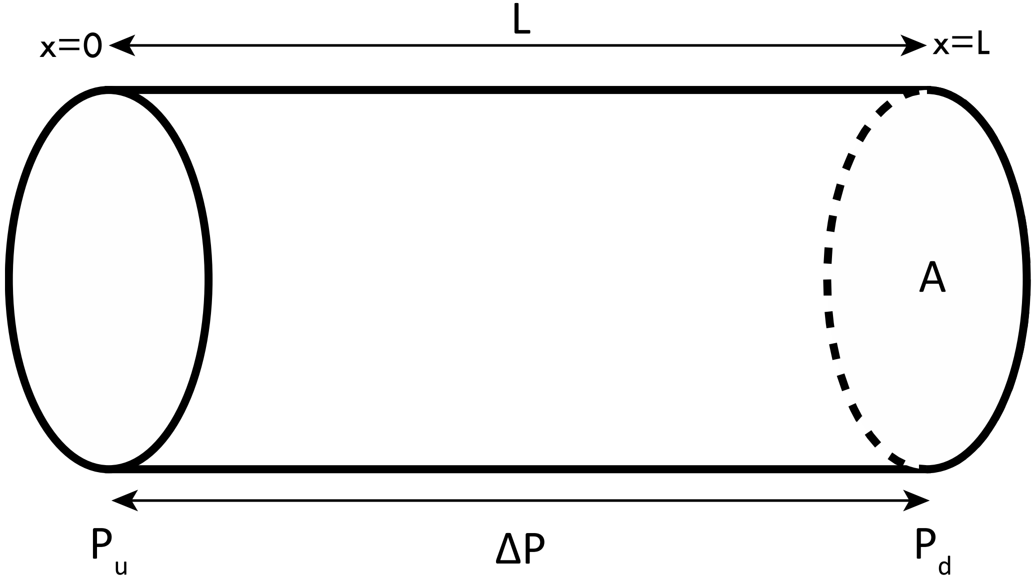
L – length of the sample
A – cross-sectional area of the sample

Darcy's Law



L – length of the sample
A – cross-sectional area of the sample
P_u – pore fluid pressure at the inlet of the sample
P_d – pore fluid pressure at the outlet of the sample

Darcy’s Law



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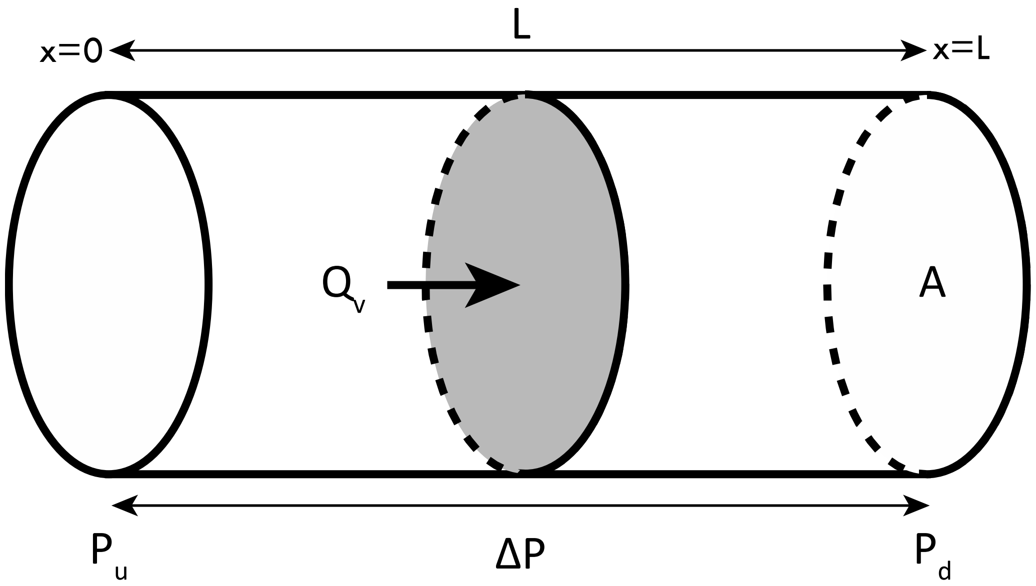
$\Delta P = P_u - P_d$

Darcy's Law



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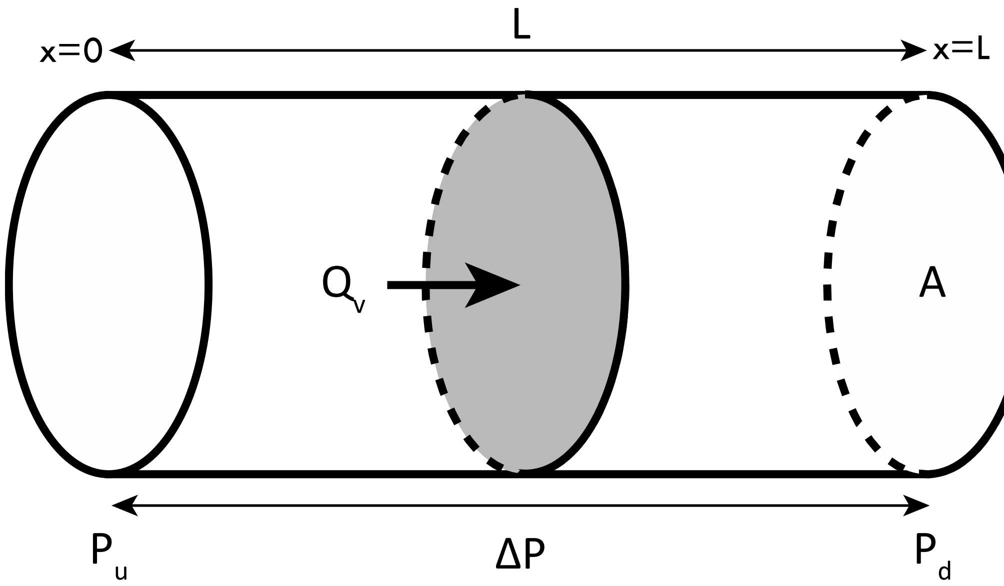
Darcy's Law:

$$Q_v = \frac{-kA}{\mu}\frac{dP}{dx}$$

Q_v is the volumetric flow rate
μ is the viscosity of the pore fluid

k is the permeability of the material and does not depend on the fluid

Darcy's Law



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Darcy's Law:

$$Q_v = \frac{-kA}{\mu}\frac{dP}{dx} \xrightarrow{\text{Integrated over the sample length}} Q_v = \frac{-kA(P_d - P_u)}{\mu L}$$

Q_v is the volumetric flow rate
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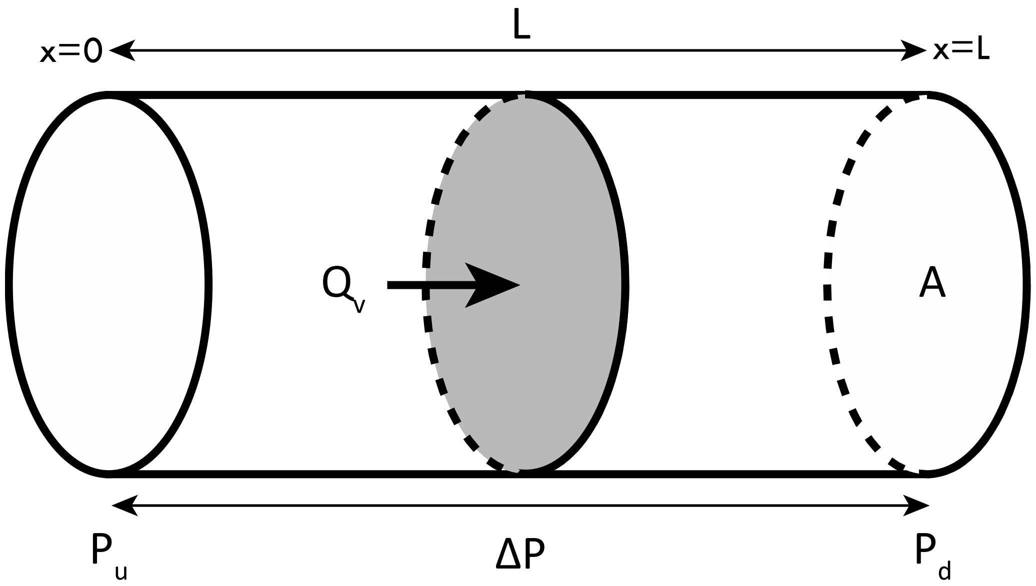
Darcy's Law



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Five conditions must be met for this equation to be valid:

- **Laminar flow**
- **No fluid accumulation**
- **Single-phase fluid flow**
- **The porous media is not reactive with the flowing fluid**
- **The fluid is incompressible**

Darcy's Law

Pressure gradient

$$q = \frac{Q}{A} = -\frac{k}{\mu} \times \frac{\Delta(P - \rho g z)}{\Delta L}$$

Where:

q – flux (m^3/m^2.s = m/s)

Q – volumetric flow rate (m^3/s)

A – area (m^2)

P – pressure (MPa)

k – permeability (m^2)

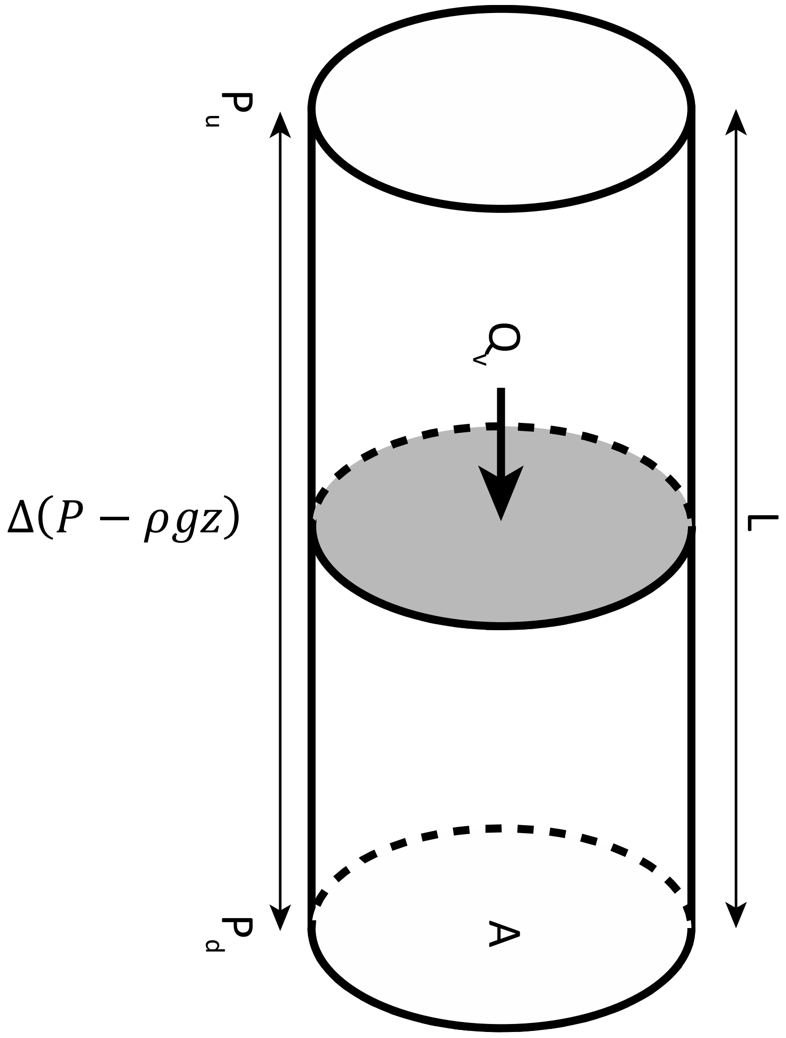
ΔL – length of the flow regime over the pressure gradient (m)

ρ – fluid density (kg/m^3)

g – acceleration due to gravity (m^2/s)

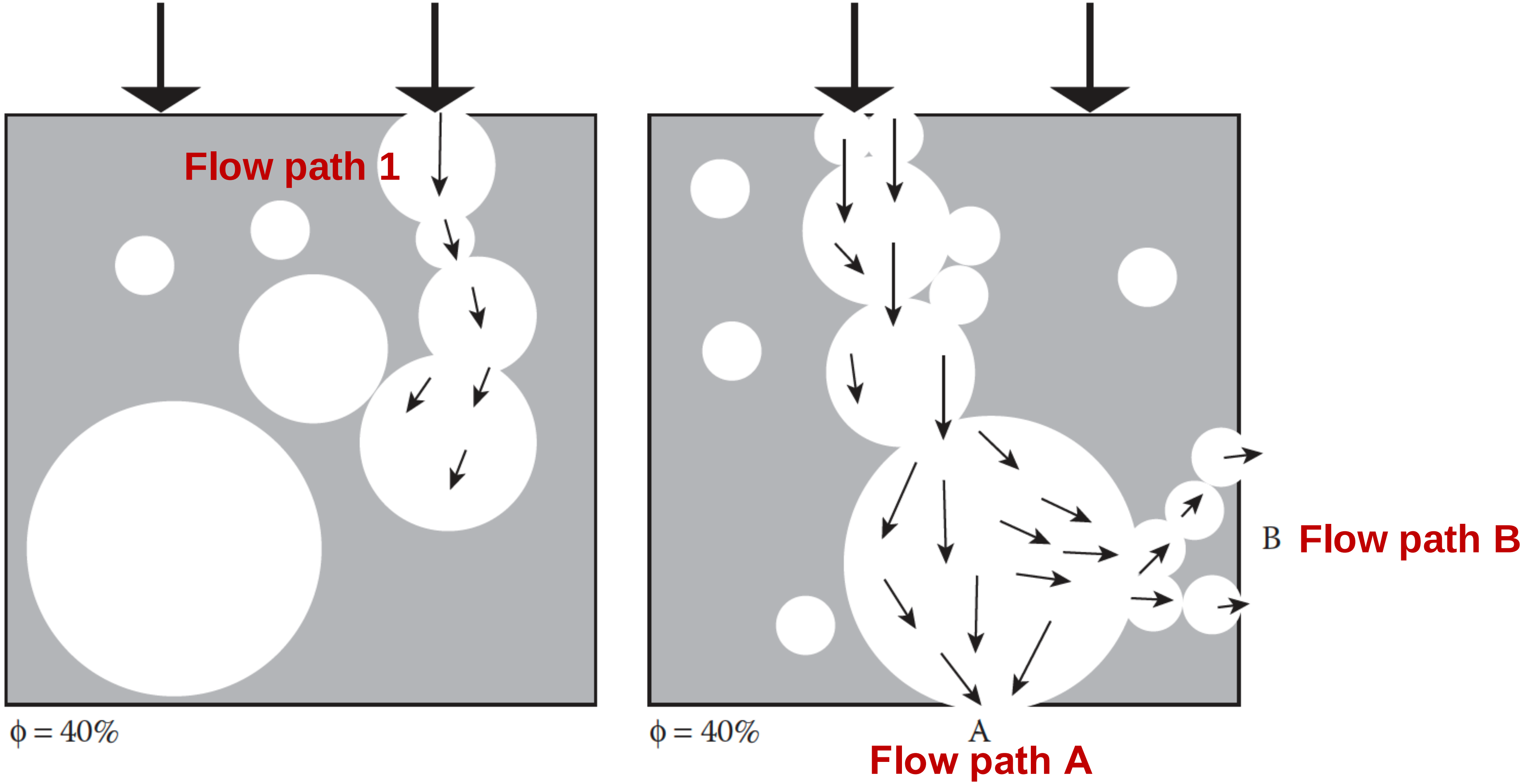
z – vertical distance of the system (m)

μ – dynamic viscosity (kg/m.s)



Permeability

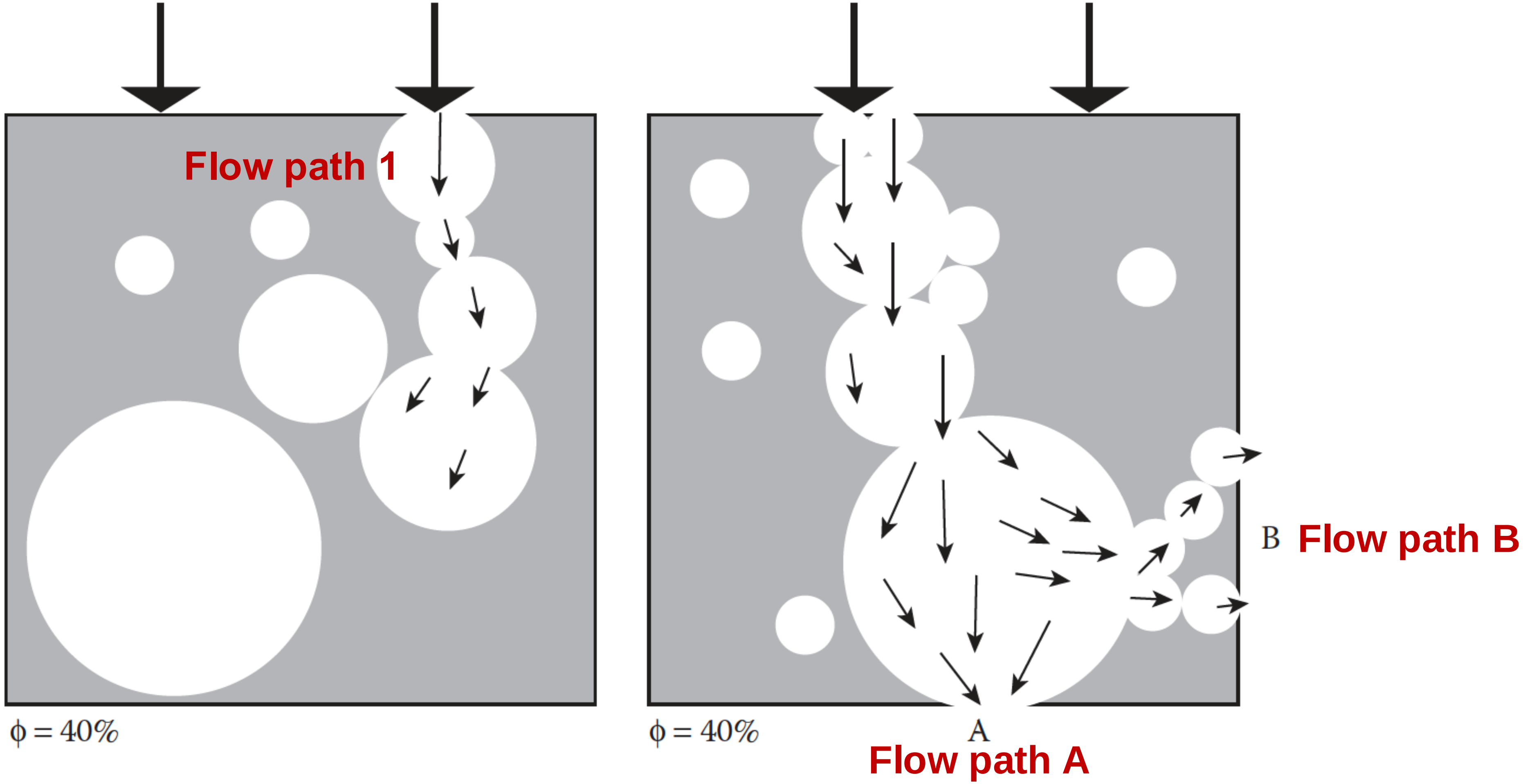
Which flow path is most permeable?



Source: Glassley, W. E., *Geothermal Energy*

Permeability

$k_1 = 0\ m^2 < k_B < k_A$



Source: Glassley, W. E., *Geothermal Energy*

Permeability

- Permeability k has dimensions of area, or m^2 in SI units.

- But the traditional unit is the Darcy:

$$\mathbf{1\ \mathit{Darcy} \cong 10^{-12}\ \mathit{m}^2}$$

(In a water saturated rock with permeability of 1 Darcy, a pressure gradient of 1 bar/cm gives a flow velocity of 1 cm/sec.)

Kozeny-Carman Equation

$$k = \frac{[n^3/(1-n)^2]}{(5 \times S_A)^2}$$

Where:

k – permeability (m^2)

n – porosity, as a fraction

S_A – specific surface area of the pore spaces per unit volume of solid (cm^2/cm^3)

Kozeny-Carman Equation

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Where:

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$$k = c_o \times \frac{1}{T} \times \frac{[n^3/(1-n)^2]}{(S_A)^2}$$

Where:

k – permeability (m^2)

n – porosity, as a fraction

S_A – specific surface area of the pore spaces per unit volume of solid (cm^2/cm^3)

***T* – tortuosity of the flow pathway (ratio of the actual path taken between two points, L_t, and a straight path between two points, *L*, $T=L_t/L$)**

c_o – a constant characteristic of the system

Hydraulic conductivity

Measure of the ability of a rock to allow fluid flow.

The volume of fluid flowing through a specified cross-sectional area under the influence of a unit hydraulic gradient.

$$K = \frac{k}{\mu} \times \rho g$$

Units: m/s

Permeability and hydraulic conductivity are related by the characteristics of the fluid.

Hydraulic conductivity is fluid-dependent; permeability is not!

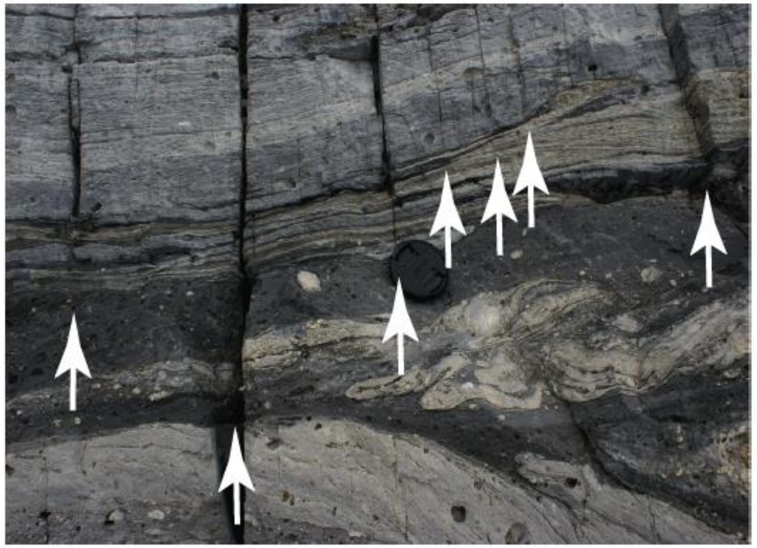
Fracture porosity and permeability

Fracture permeability

Fracture permeability depends on:

- Fracture aperture
- Fracture orientation
- Fracture length
- Fracture roughness
- Interconnectedness with other fractures

(a)



(b)

(c)

(d)

Hydraulic conductivity and permeability of a fracture

Hydraulic conductivity of a fracture:

$$K_f = \frac{\rho \times g}{\mu} \times \frac{a^2}{12}$$

a – fracture aperture *(m)*

Permeability of a fracture:

?

Fracture transmissivity

Fracture transmissivity

The discharge through a fracture at some velocity across a given unit aperture.

$$T_f = \frac{\rho \times g}{\mu} \times \frac{a^2}{12} \times a = \frac{\rho \times g \times a^3}{12 \times \mu}$$

Note: This is often referred to the cubic law because of the dependence of the transmissivity on the cube of the aperture of the fracture.

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Fluid properties ($\frac{\rho \times g}{\mu}$) — **Fracture aperture** ($\frac{a^2}{12} \times a$)

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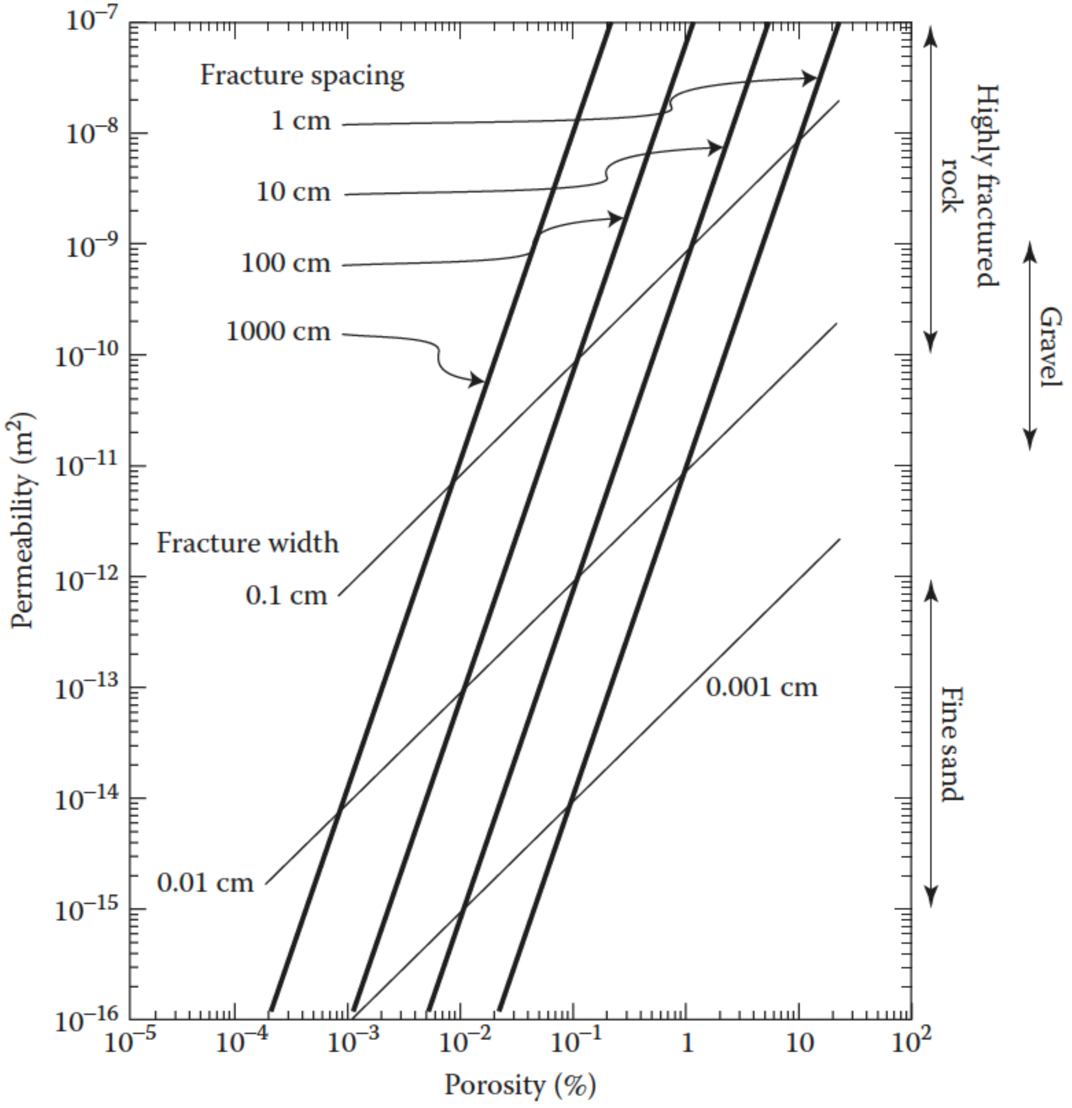
Fluid properties ← $\frac{\rho \times g}{\mu}$

Fracture aperture ← $\frac{a^2}{12} \times a$

Careful: Fracture aperture can vary widely within a fracture set and within individual fractures! Fracture surface roughness also contributes to the tortuosity of fractures and may reduce the **effective fracture aperture**.

Fracture aperture matters!



Source: Glassley, W. E., *Geothermal Energy*

For a given fracture spacing:

- Increasing fracture width by an order of magnitude increases permeability by 2 orders of magnitude

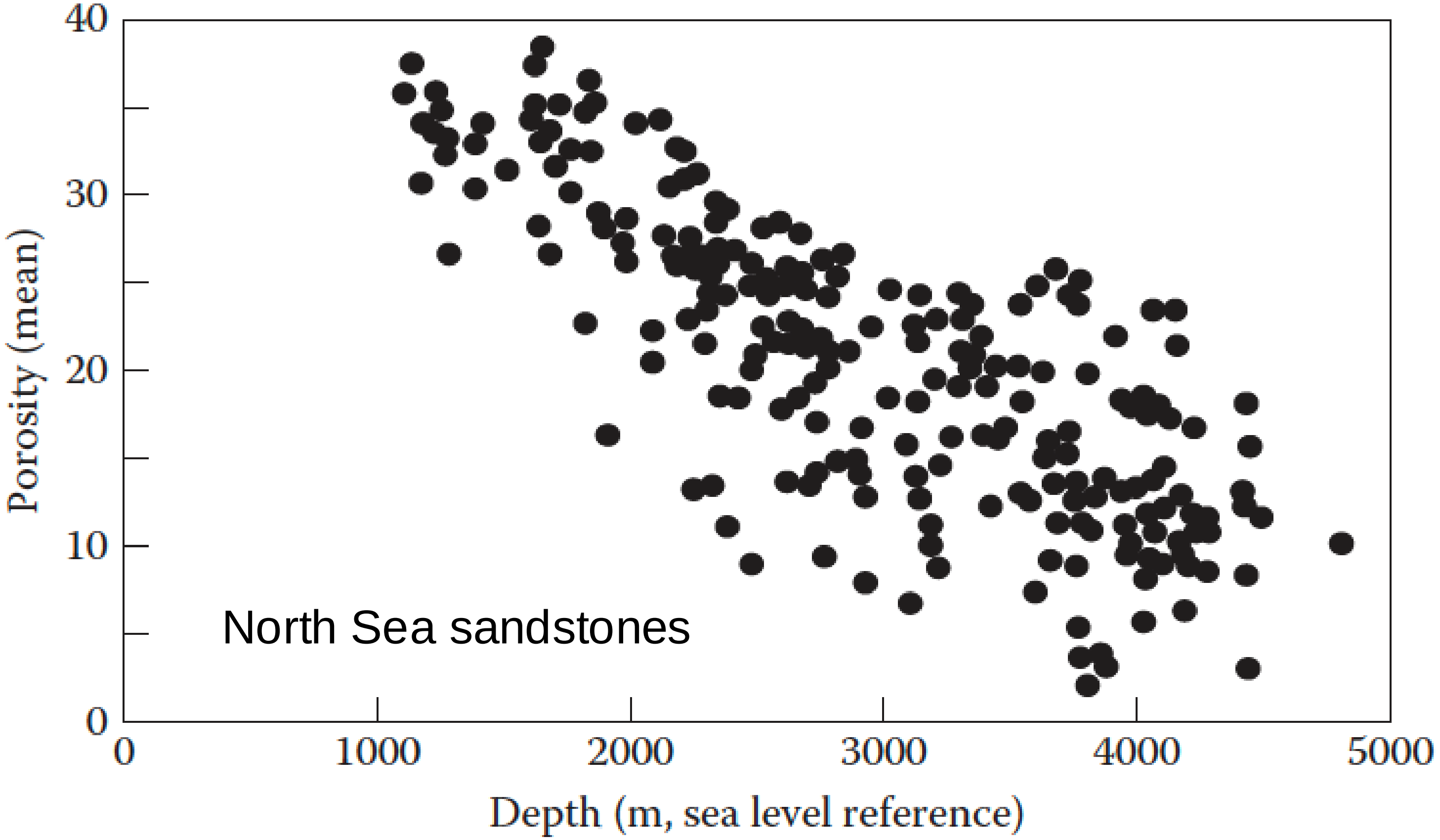
For a given fracture width:

- Increasing fracture spacing by and order of magnitude increases permeability by one order of magnitude

Permeability is sensitive to fracture aperture.

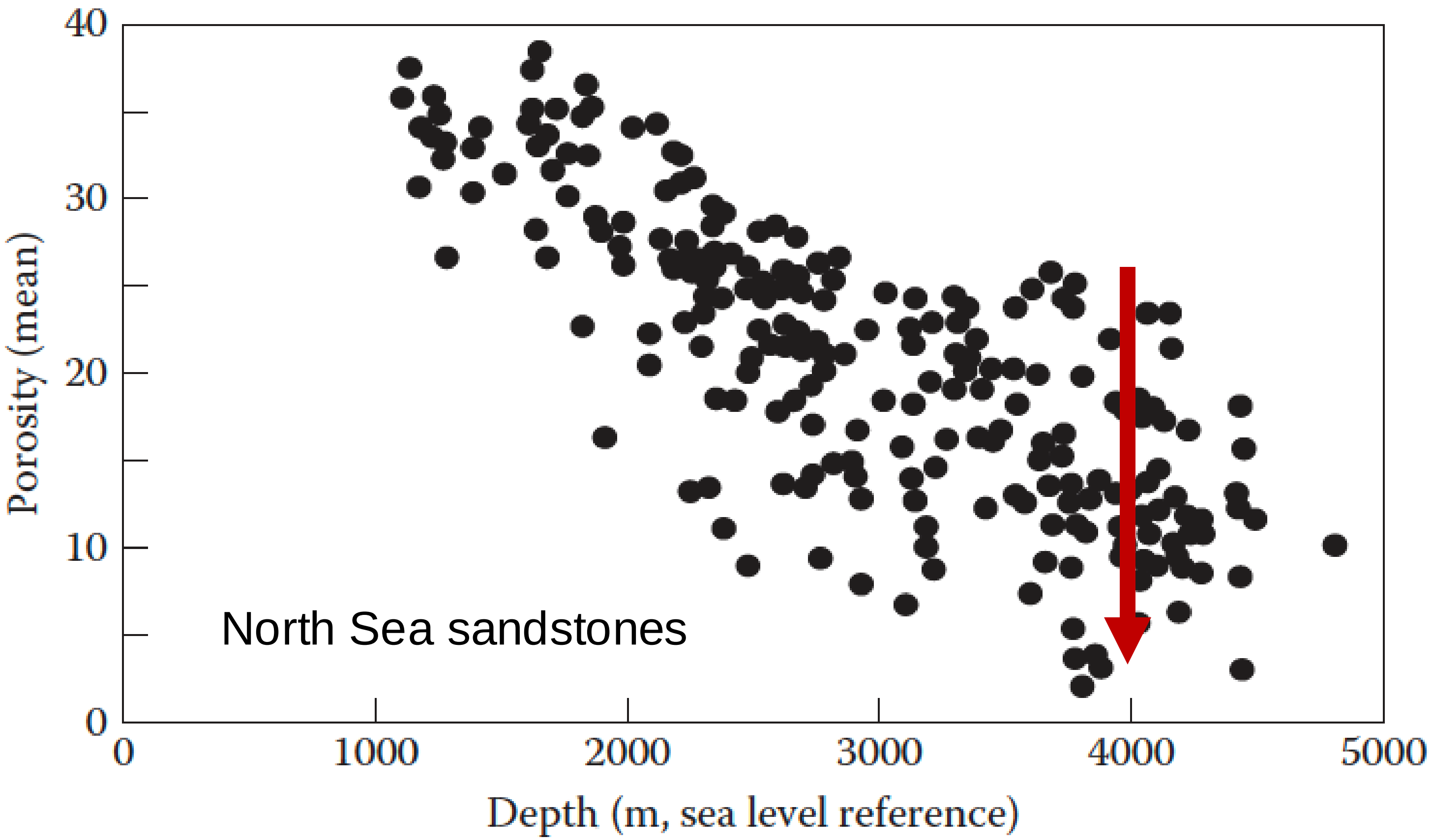
Effect of depth

Porosity and permeability with depth



Source: Glassley, W. E., *Geothermal Energy*

Porosity and permeability with depth



In general:

- porosity decreases with increasing depth, due to compaction and recrystallisation

Magnitude of decrease in porosity depends on the rock strength, when porosity reduction is compaction-controlled.

What happens to fractures with depth?

Source: Glassley, W. E., *Geothermal Energy*

Empirical relationships for permeability reduction with depth

Consider fracture aperture change with depth:

$$q = C \times a_c^3 \times \nabla P$$

Where :

q – fluid flux

C – empirical constant

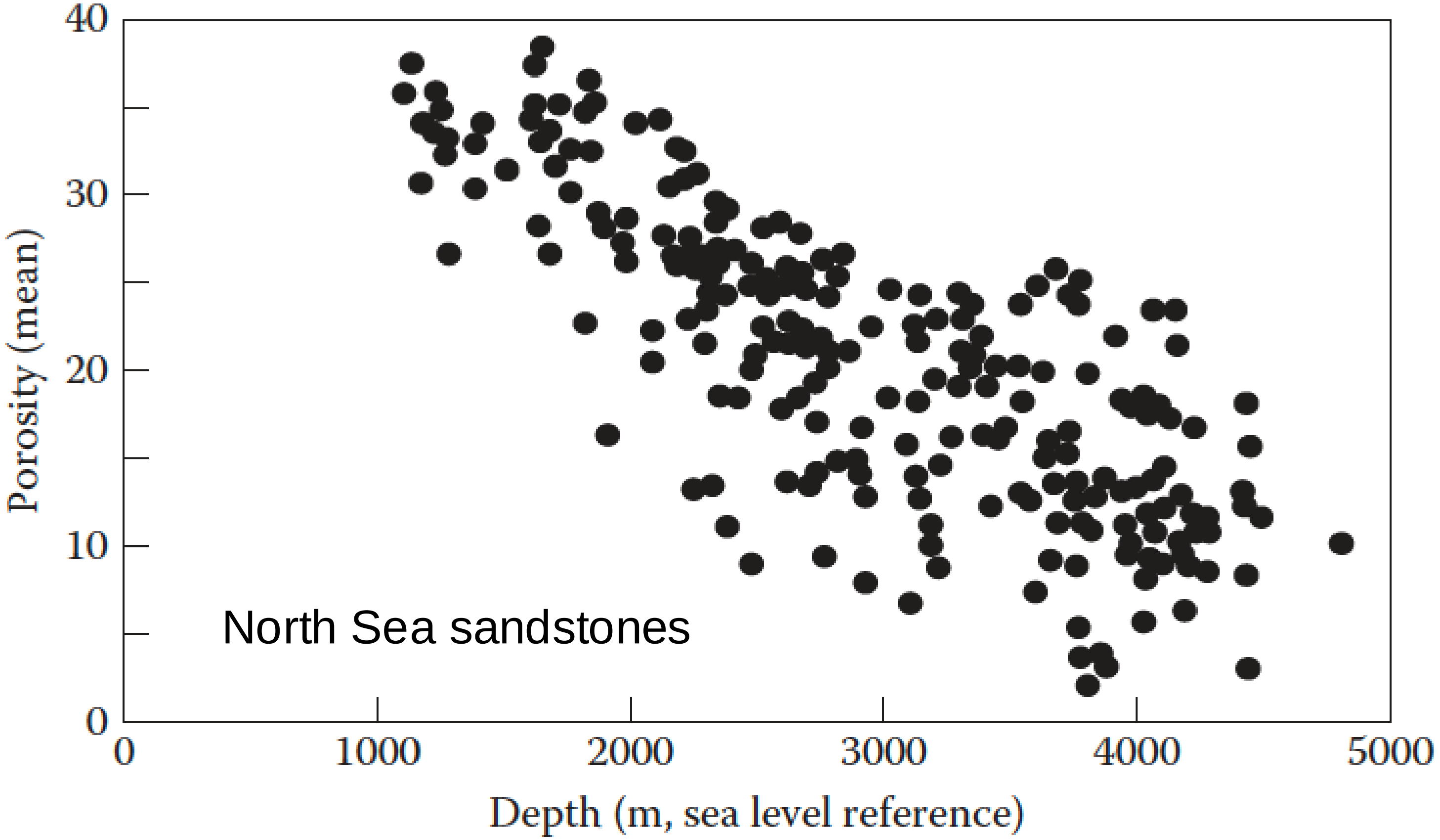
a_c – « conducting » aperture

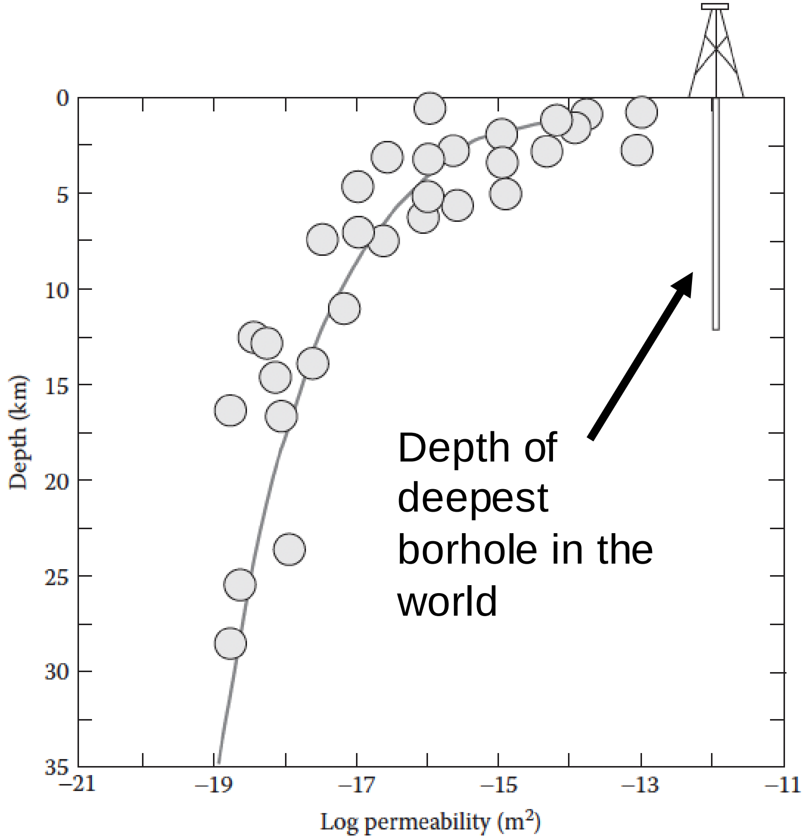
∇P – pressure change with depth

Caveats:

- Conducting aperture depends on roughness, tortuosity, etc.
- This approximation is ok at depths less than a kilometer
- **Below 1 km depth, permeability becomes hard to predict: need on-site investigations!**

Porosity and permeability with depth





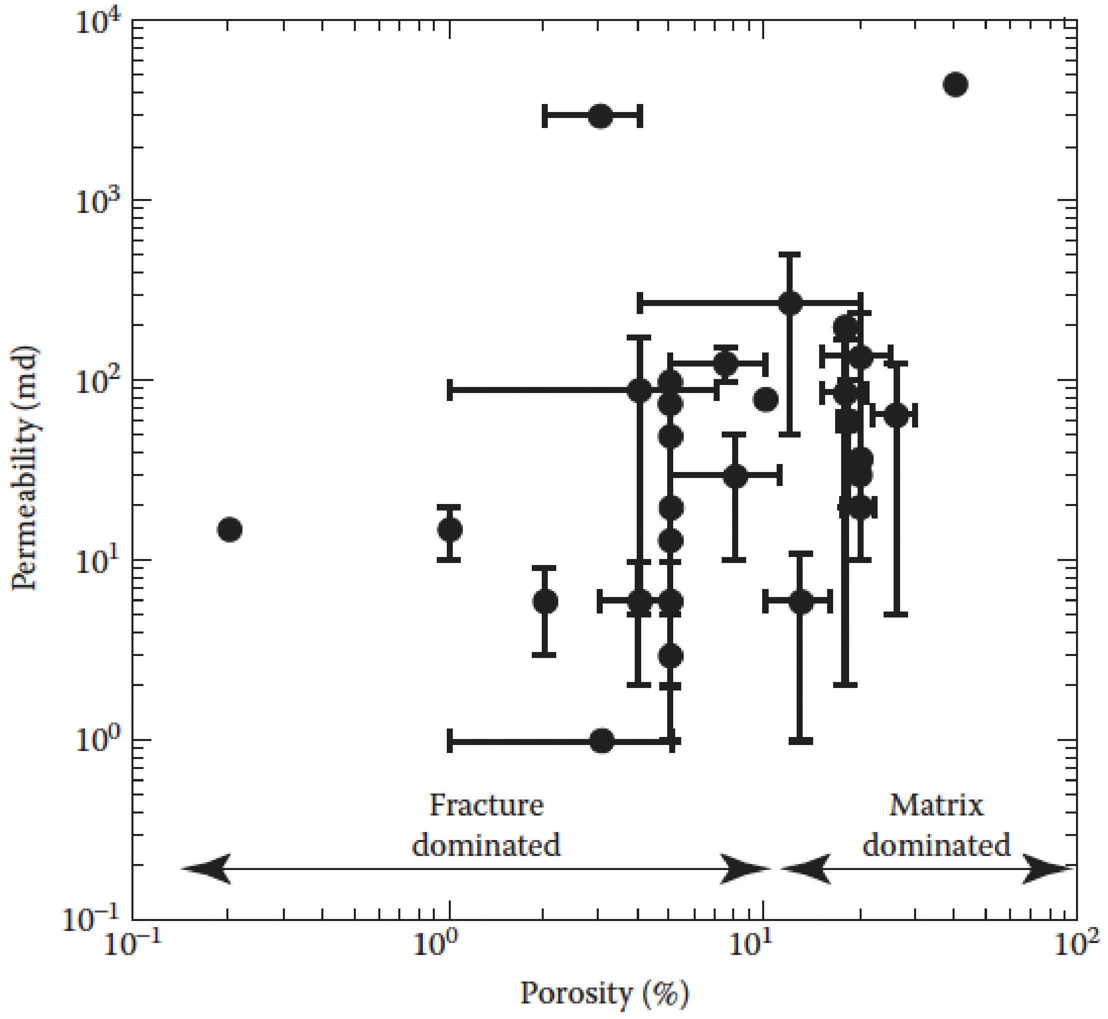
Source: Glassley, W. E., *Geothermal Energy*

Hydrological properties of real geothermal systems

Hydrological properties of real geothermal systems

Permeability-porosity ranges for various geothermal systems.

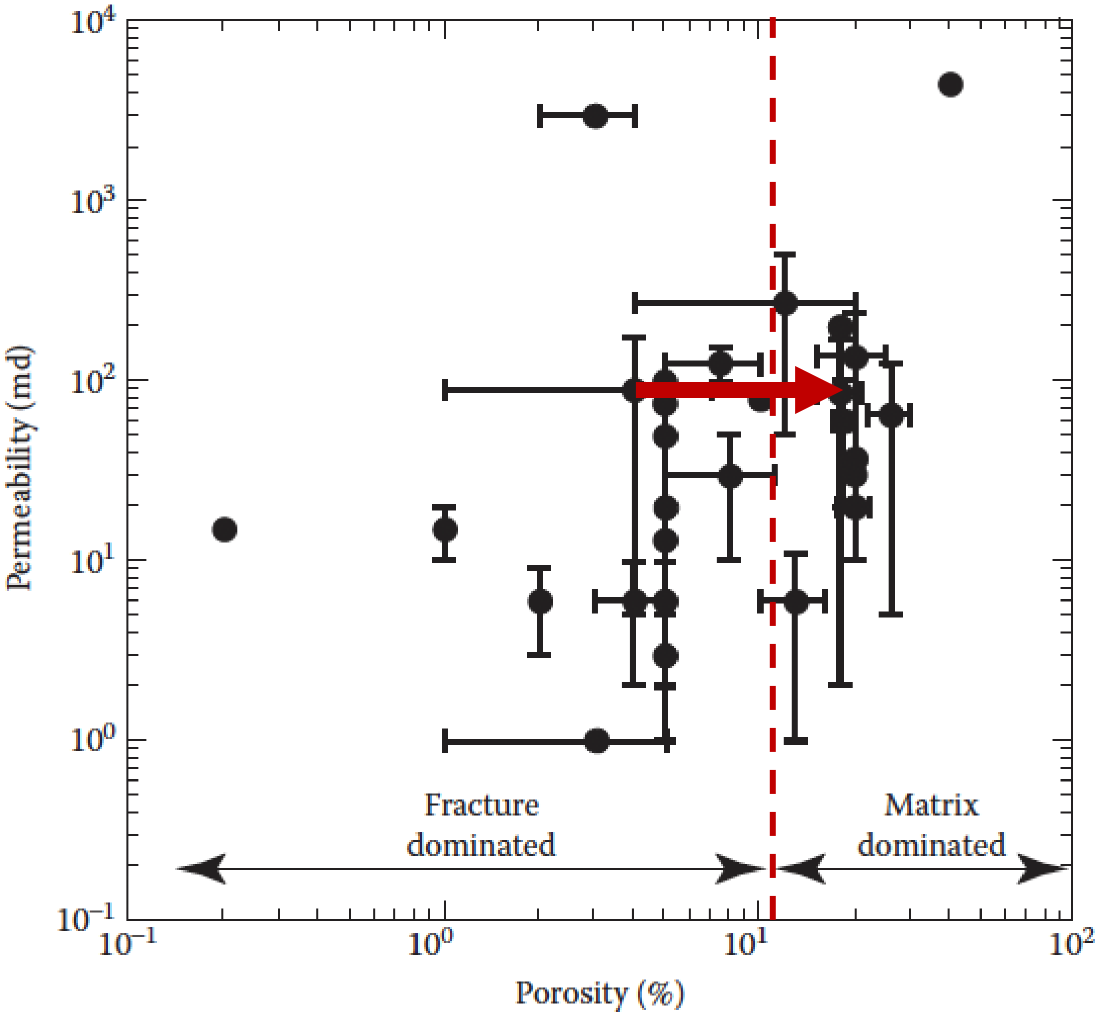
What are some conclusions that we can draw?



Source: Glassley, W. E., *Geothermal Energy*

Hydrological properties of real geothermal systems

- To achieve the same permeability, matrix-dominated geothermal systems need higher connected porosities.
  - **Practicality:** Geothermal exploration focusses on regions where there is pre-existing hydrological data; this saves resources and reduces project risk!



Source: Glassley, W. E., *Geothermal Energy*

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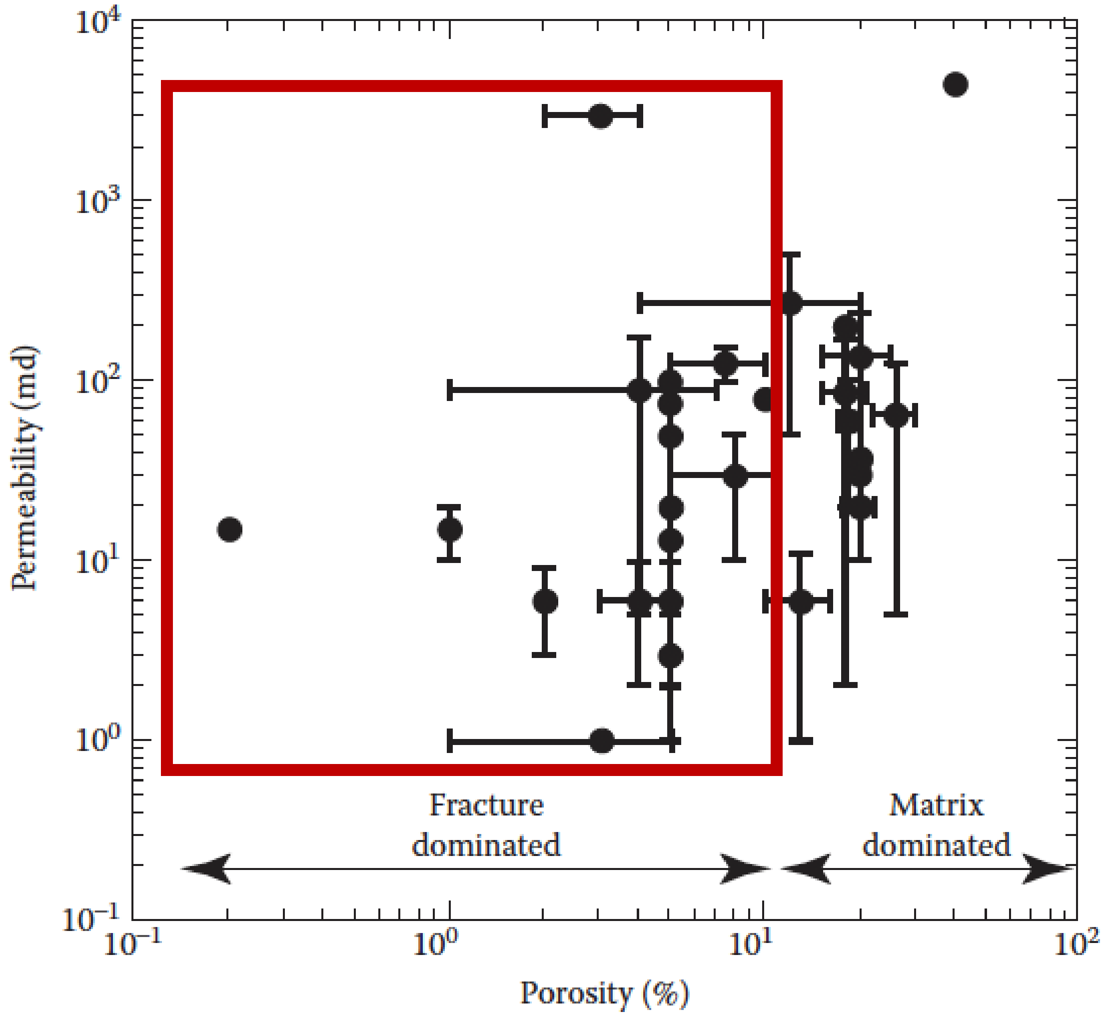
- Low fracture porosities (as low as 0.2%) can support sufficient fluid flow for power production.
  - **Practicality:** Fractures are key, but they can be hard to locate by drilling. We need high-quality, high-resolution subsurface data on fracture properties.



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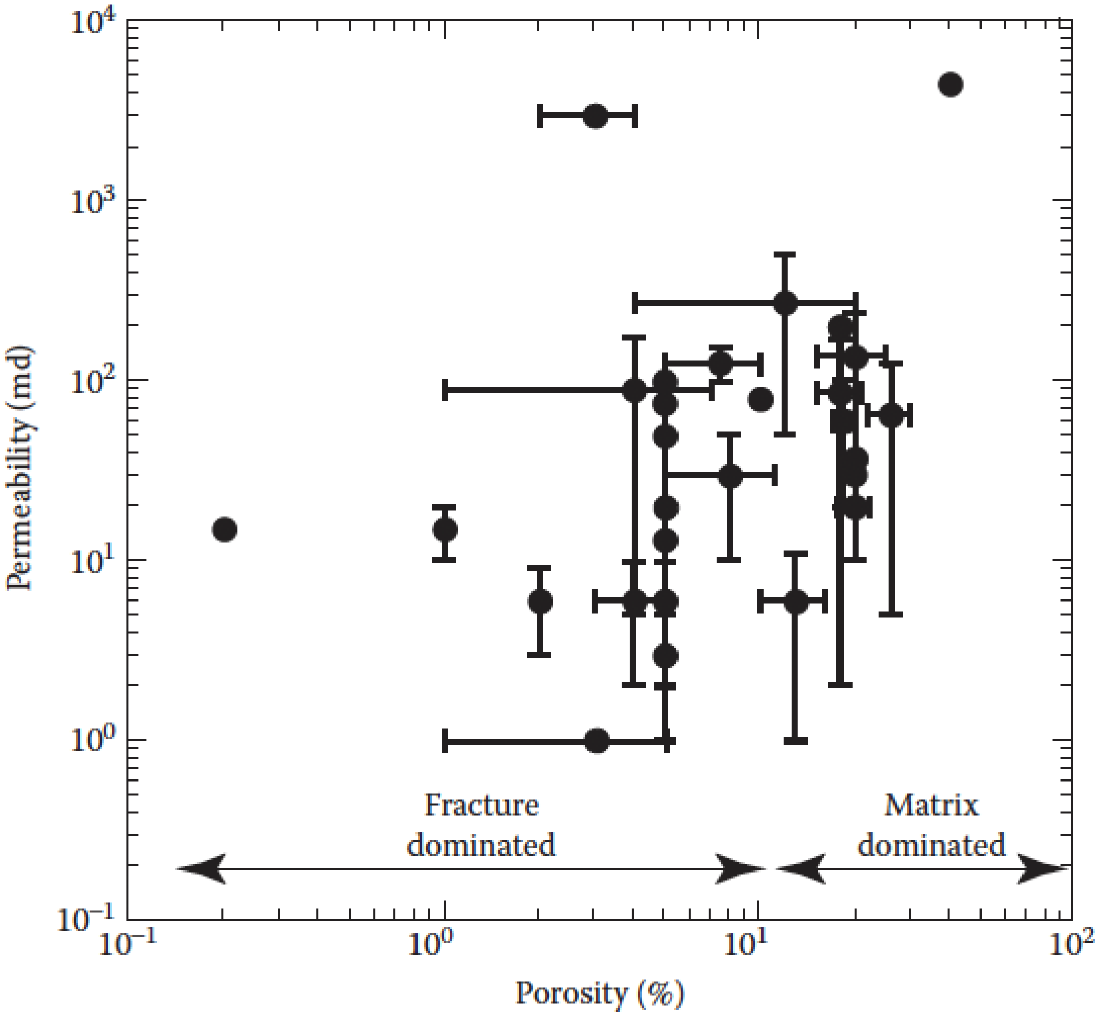
- Porosity and permeability variability in natural systems can span orders of magnitude at a single site.
    - **Practicality:** Extensive exploration programs need to assess for porosity-permeability anisotropies.



Source: Glassley, W. E., *Geothermal Energy*

Key points:

Subsurface fluid flow depends on the characteristics of porosity, including pores and cracks.

Permeability controls the volumetric flow rate that can be accommodated by a system.

Volumetric flow rate controls the rate at which energy can be transferred from to the surface.

Variables controlling flow in porous media include: the extent to which pores are connected, tortuosity, and surface area (geometry) affecting flow.

Variables controlling flow in fracture media include: aperture and number of fractures per rock volume.

Porosity and permeability are affected by lithostatic pressure (i.e., they vary with depth).