



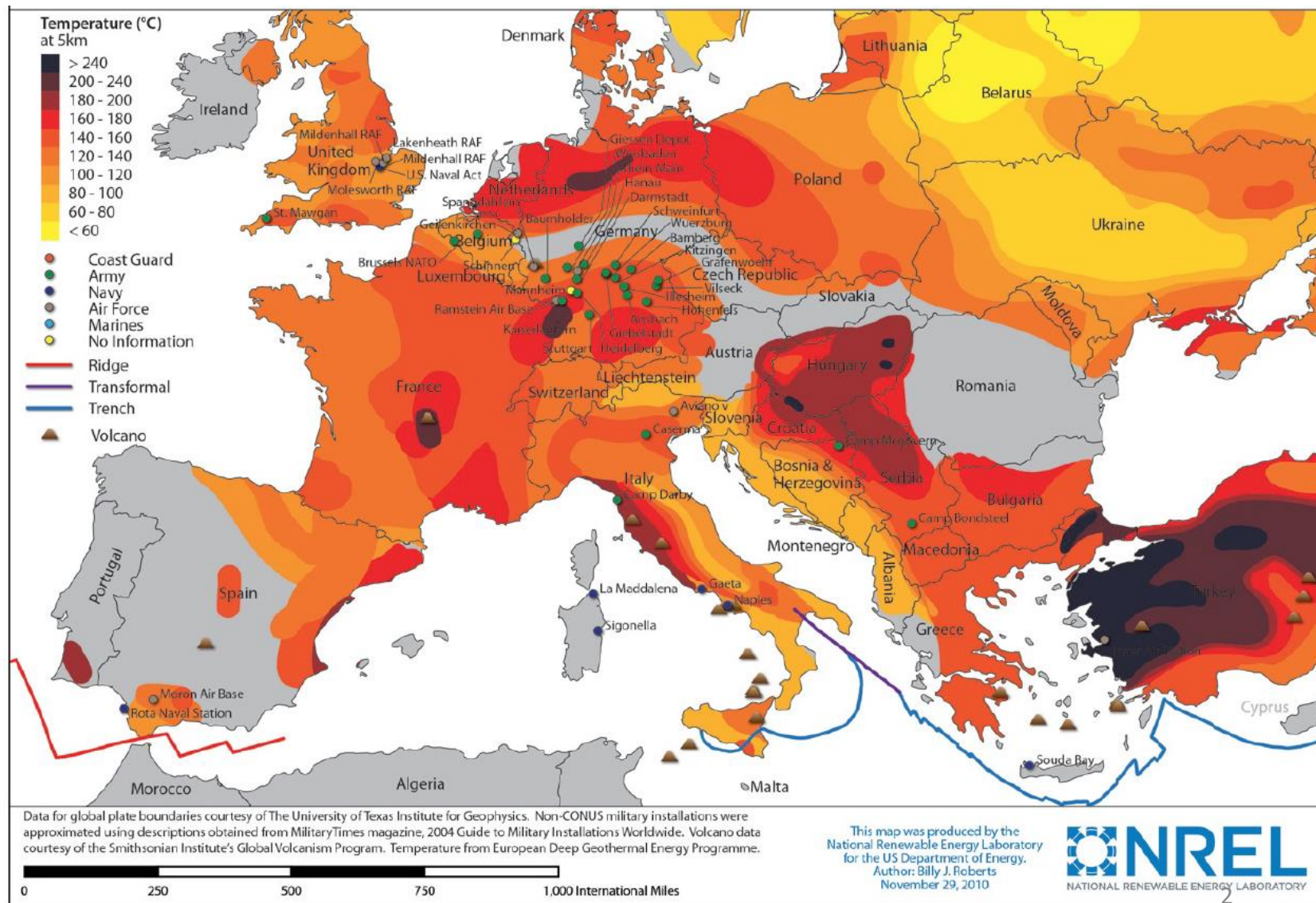
# Geothermal Resource Development

## Hydrology of geothermal systems

# What is geothermal energy?

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

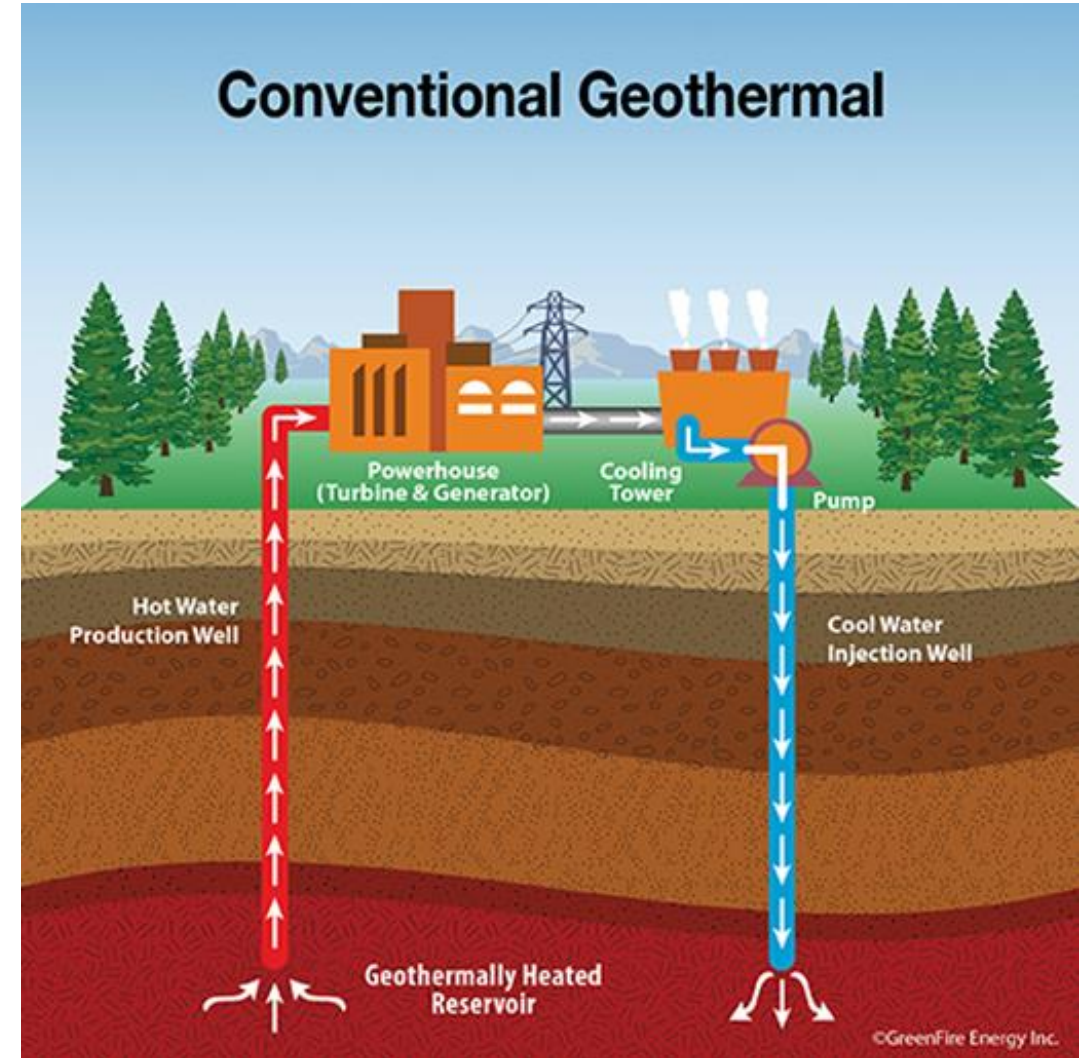
How can we extract that heat?



# Extracting geothermal energy

**Primary resource:**  
Heat

**Resource vector:**  
Water

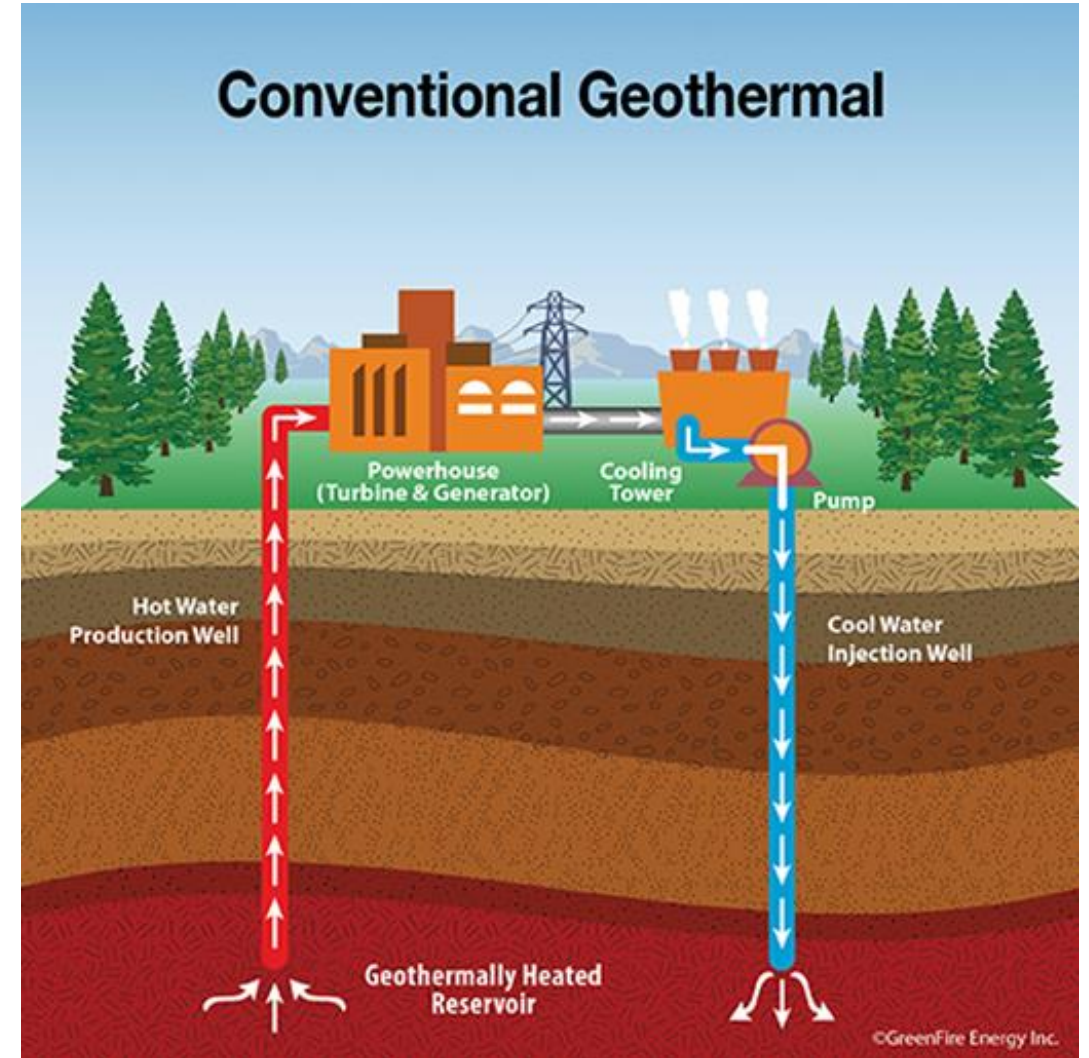


# Extracting geothermal energy

**Primary resource:**  
Heat

**Resource vector:**  
Water

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



# 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:

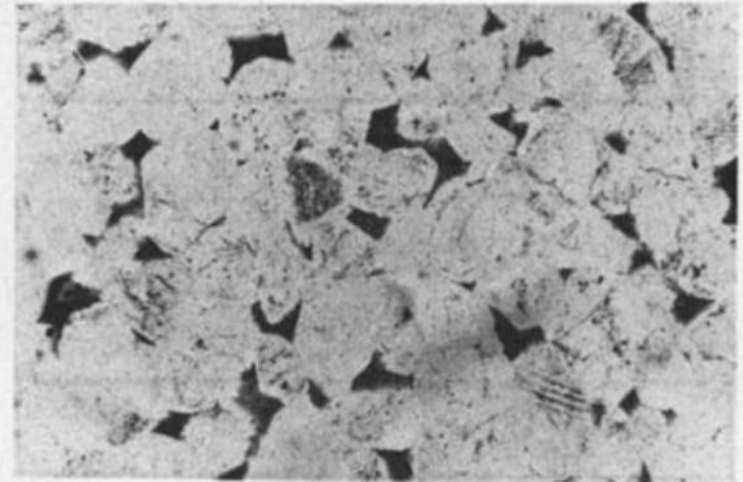
- Fraction of pore space in a material
- Scalar
- Different types of porosity are important for different physical properties:
  - total porosity  $\leftrightarrow$  uniaxial compressive strength
  - **connected porosity  $\leftrightarrow$  permeability**

FONTAINEBLEAU SANDSTONE  
THIN SECTION  
SAMPLES INJECTED WITH RED EPOXY



$\phi = 28\%$

500  $\mu$



$\phi = 6\%$

> 99% QUARTZ CRYSTALS  
GRAIN SIZE  $\approx 250 \mu$

# Porosity

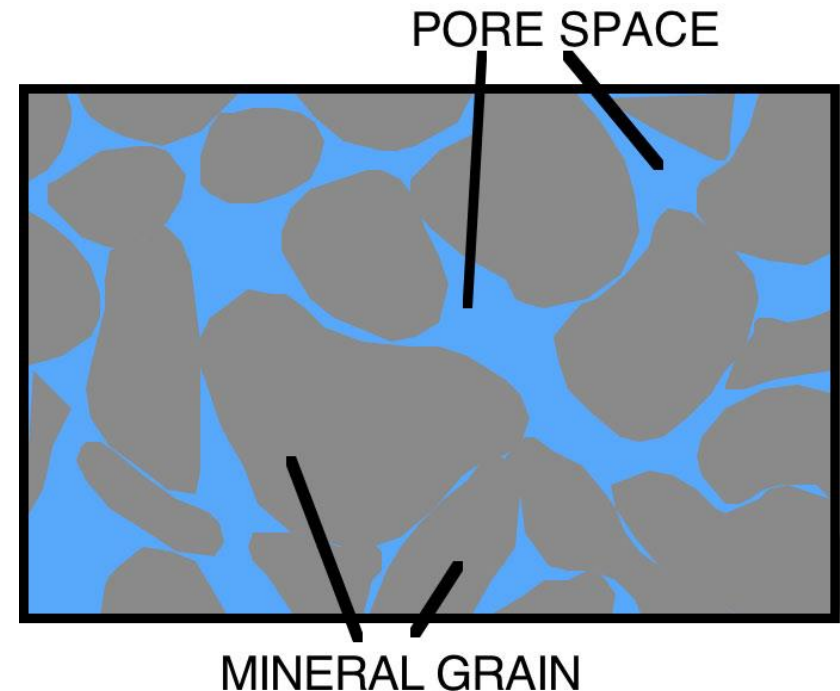
Porosity  $\phi$  is defined as the ratio of pore volume to total volume.

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

$V_p$  → pore volume

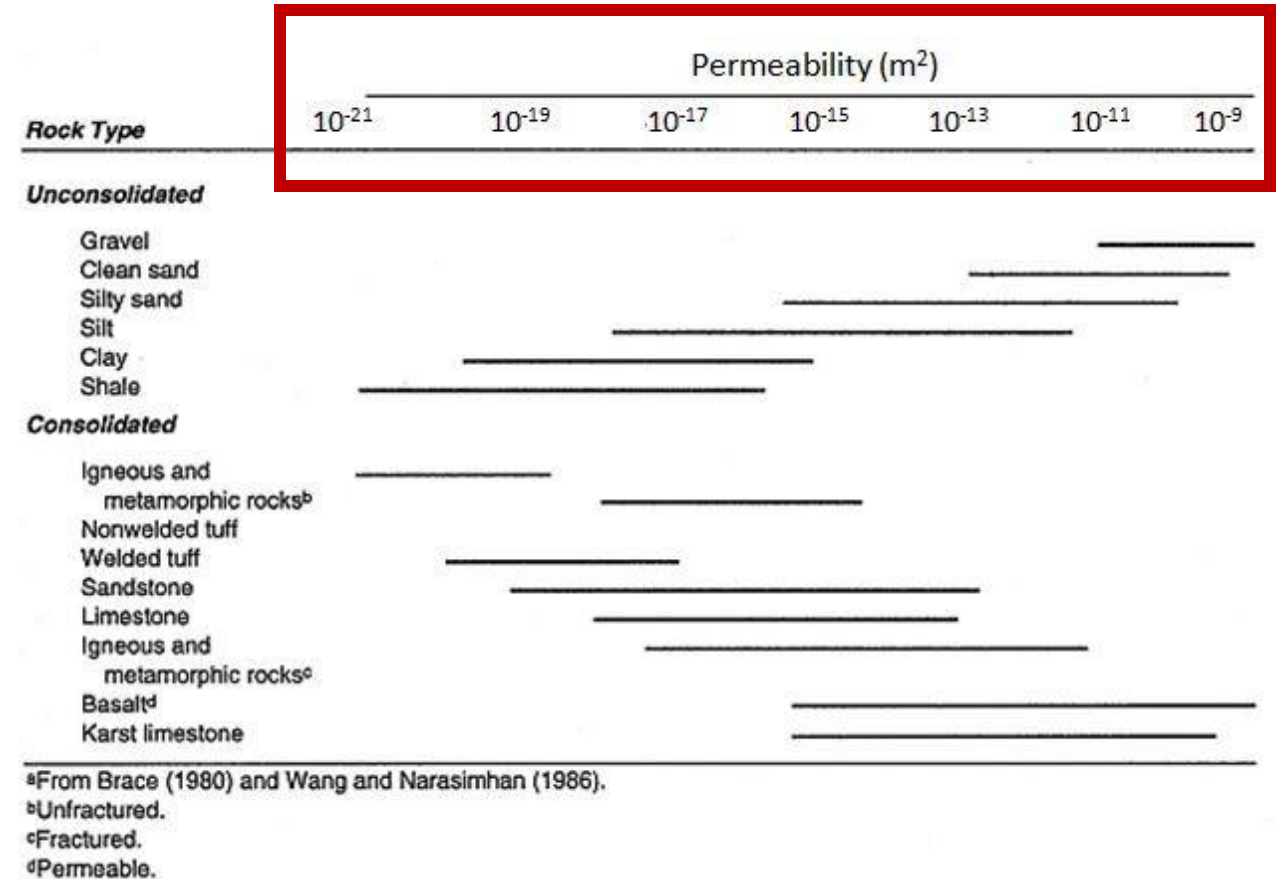
$V_s$  (or  $V_m$ ) → solid (matrix) volume

$V_t$  (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>



A. Kushnir



<https://www.nps.gov/moru/learn/nature/geologicactivity.htm>



<https://www.wordatlas.com/articles/how-are-sedimentary-rocks-formed.html>



A. Kushnir



A. Kushnir

# Components of rock masses



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

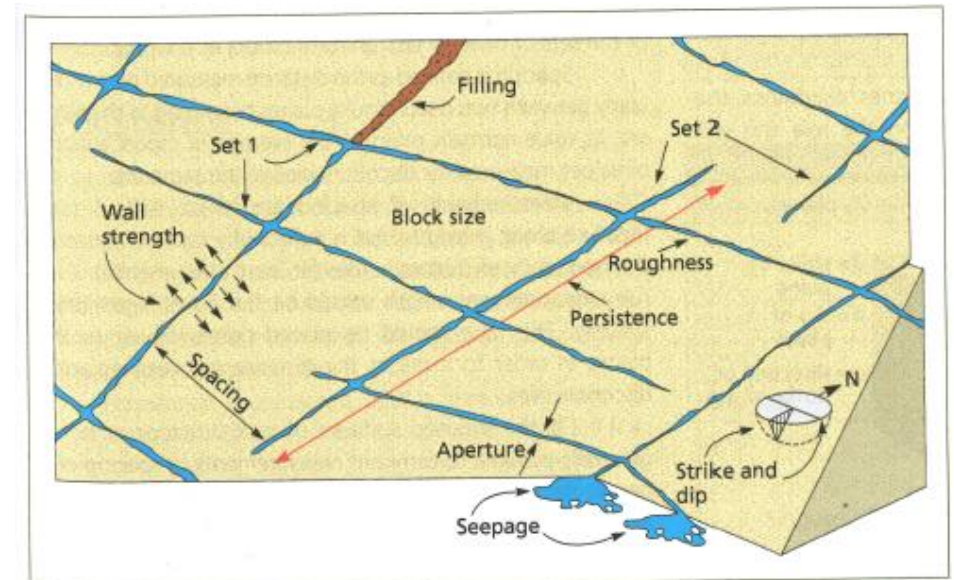


Figure 6.4 Diagram of the geometric properties of discontinuities (Hudson, 1989).

## Matrix porosity and permeability

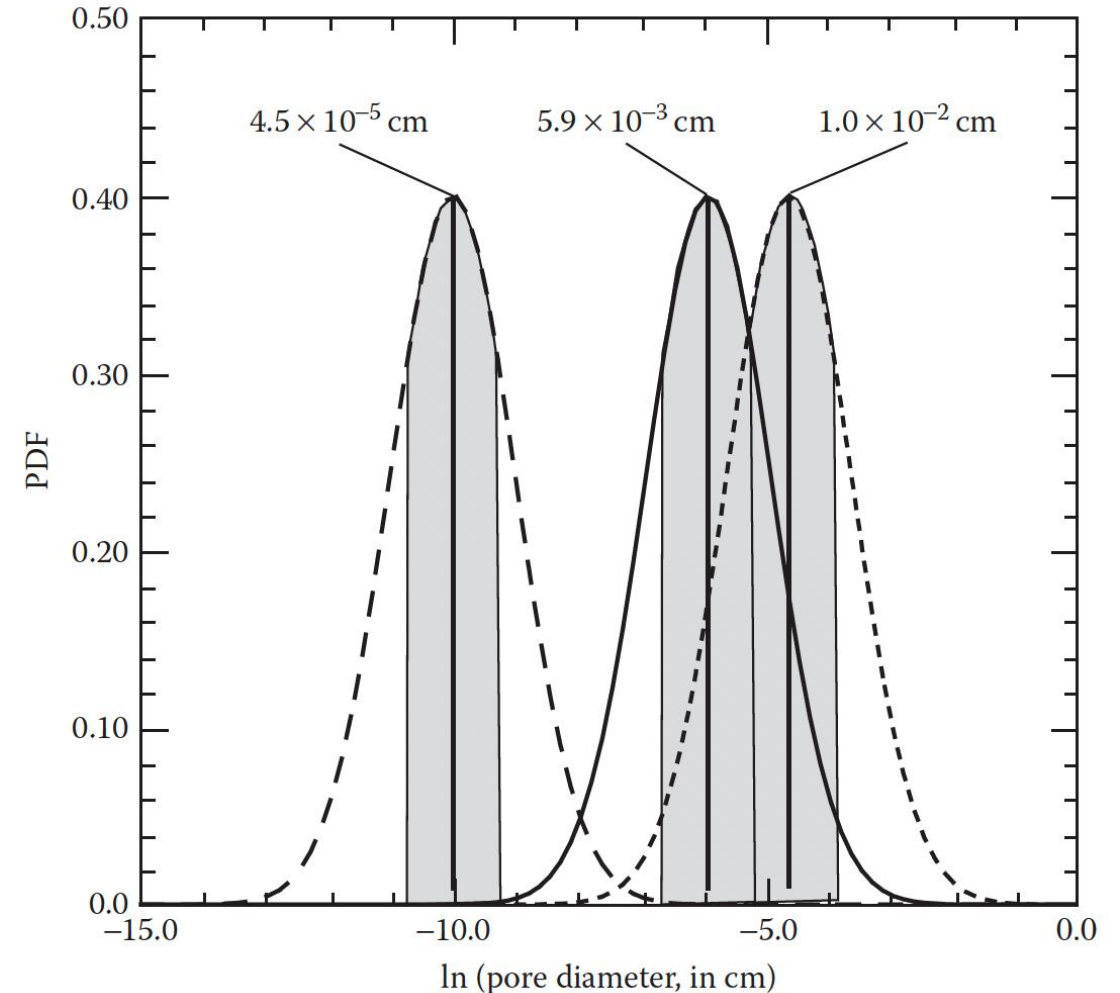
# Matrix porosity

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)

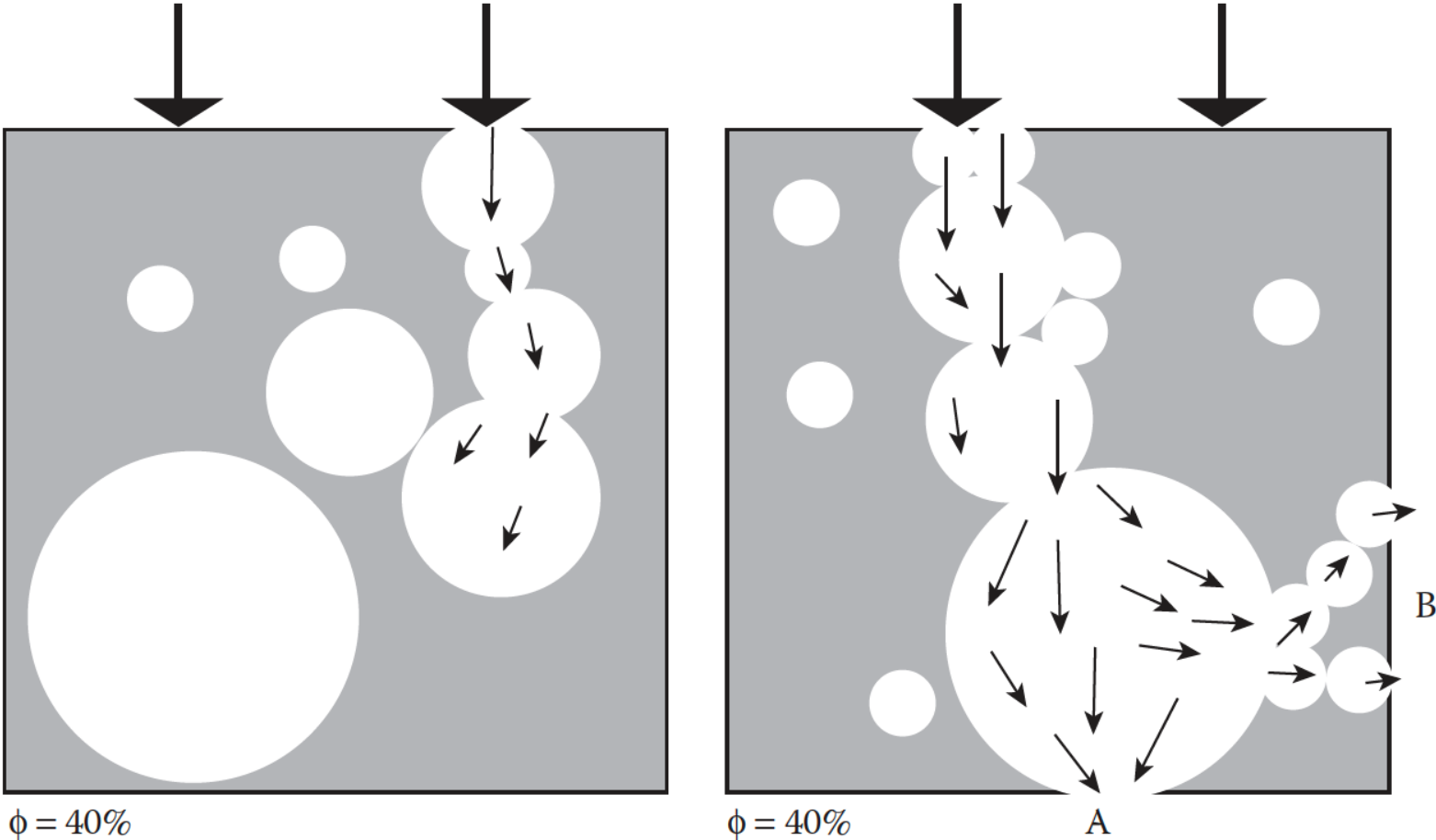
PDFs are mathematical simplifications that we apply to geometrically complex systems

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



# Pore connectivity

Fluids need connected pore spaces through which to flow.



**Other factors:**

- Tortuosity
- Pore throat size
- Fluid viscosity

# Darcy's Law



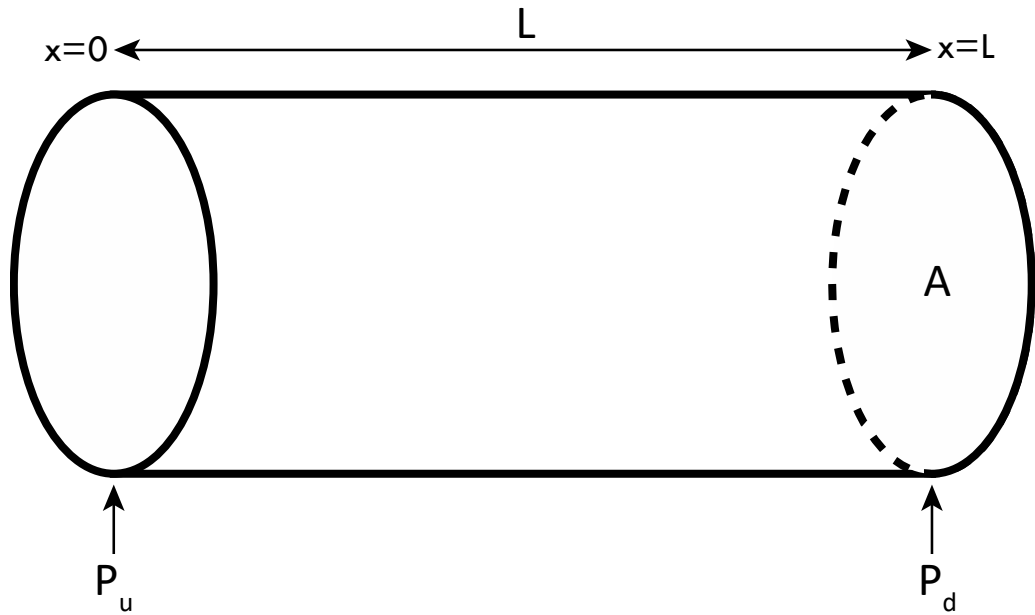
Consider a cylinder of permeable material.

# Darcy's Law



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

# Darcy's Law



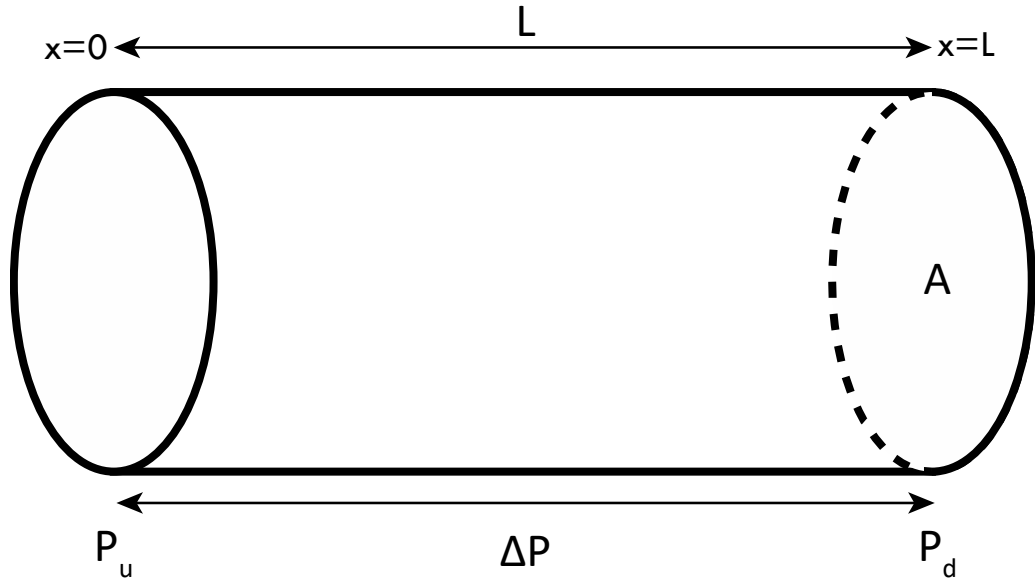
$L$  – length of the sample

$A$  – 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



$L$  – length of the sample

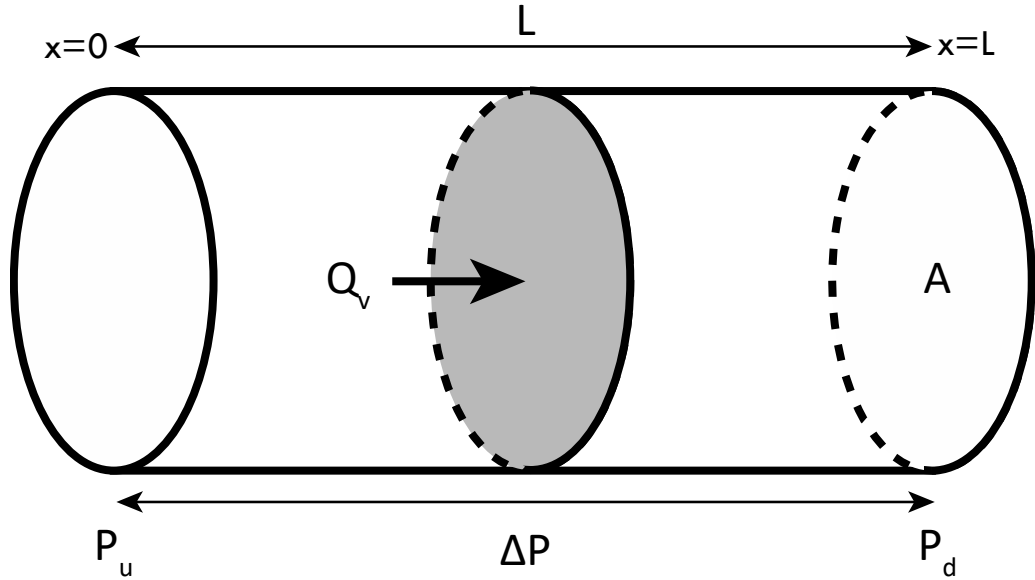
$A$  – cross-sectional area of the sample

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$P_d$  – pore fluid pressure at the outlet of the sample

$$\Delta P = P_u - P_d$$

# 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  
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 $\Delta P = P_u - P_d$

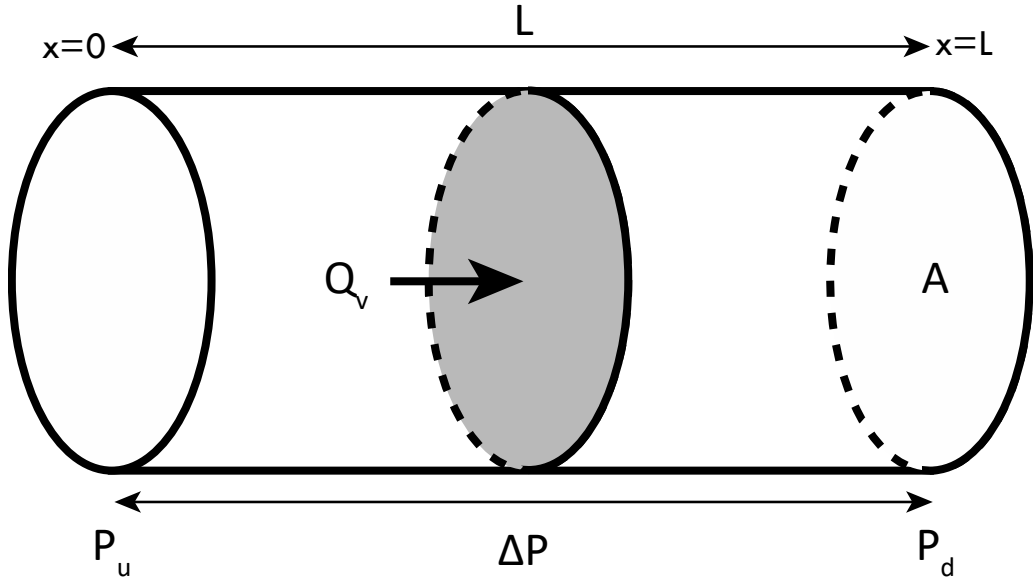
**Darcy's Law:**

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

$Q_v$  is the volumetric flow rate  
 $\mu$  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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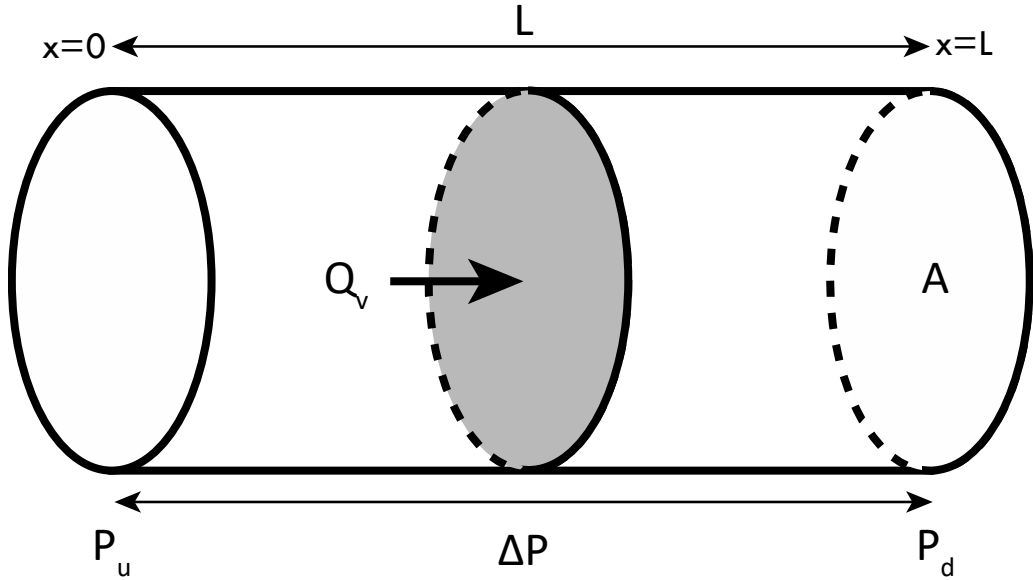
**Darcy's Law:**

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

$Q_v$  is the volumetric flow rate  
 $\mu$  is the viscosity of the pore fluid

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

# 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  
 $\Delta P = P_u - P_d$

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:

$$Q_v = \frac{kA(P_d - P_u)}{\mu L}$$

$Q_v$  is the volumetric flow rate  
 $\mu$  is the viscosity of the pore fluid

**$k$  is the permeability of the material**

# Darcy's Law

Pressure gradient



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

**Where:**

$q$  – flux ( $\text{m}^3/\text{m}^2 \cdot \text{s} = \text{m}/\text{s}$ )

$Q$  – volumetric flow rate ( $\text{m}^3/\text{s}$ )

$A$  – area ( $\text{m}^2$ )

$P$  – pressure (MPa)

$k$  – permeability ( $\text{m}^2$ )

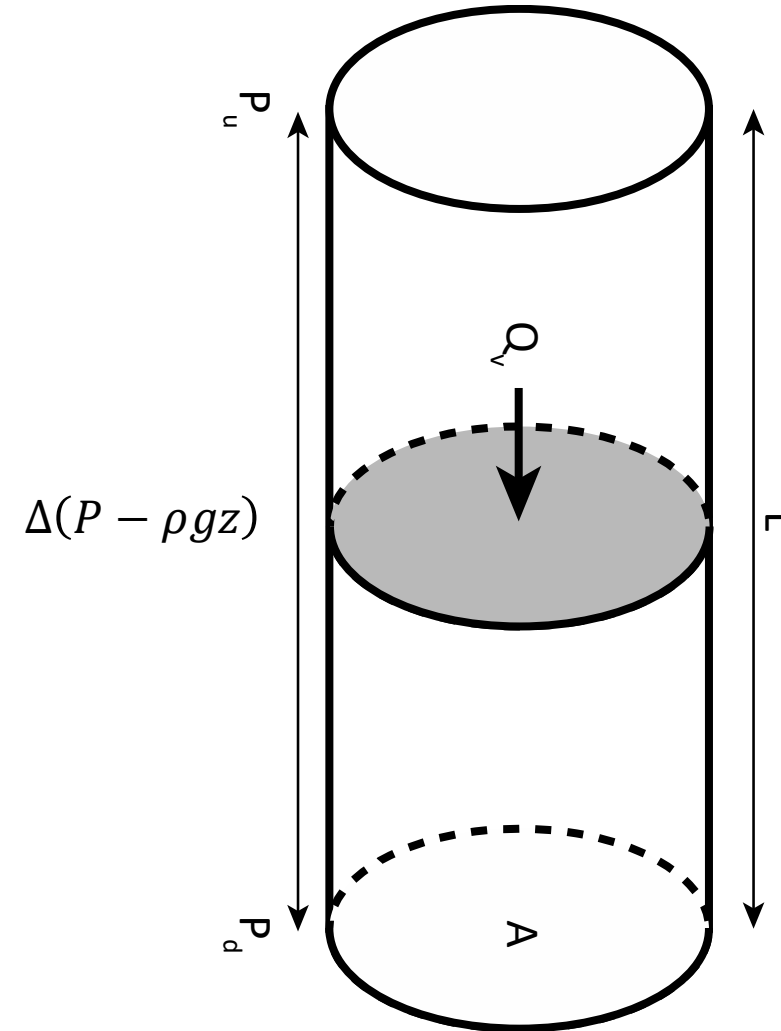
$\Delta L$  – length of the flow regime over the pressure gradient (m)

$\rho$  – fluid density ( $\text{kg}/\text{m}^3$ )

$g$  – acceleration due to gravity ( $\text{m}^2/\text{s}$ )

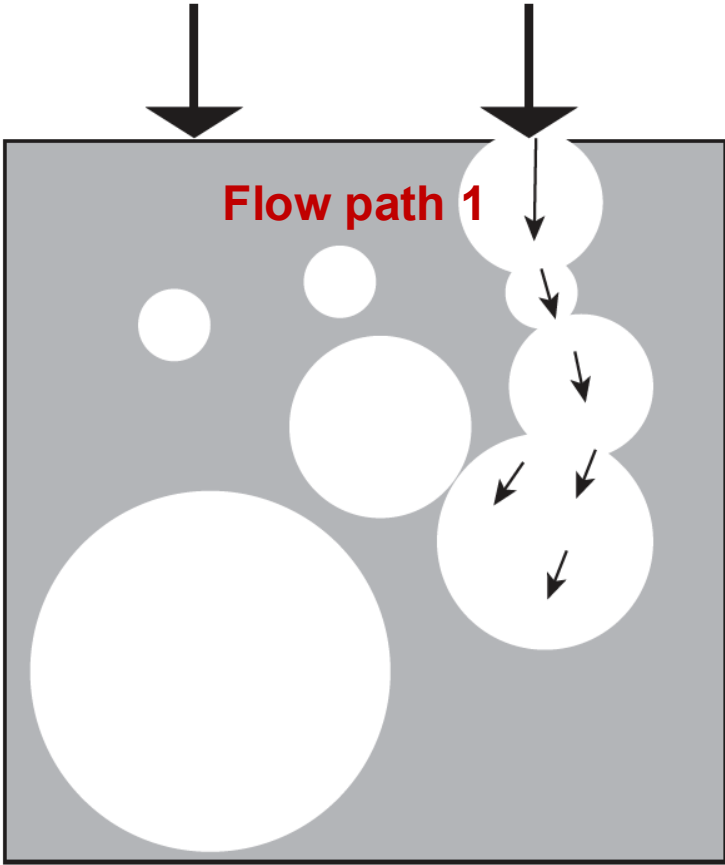
$z$  – vertical distance of the system (m)

$\mu$  – dynamic viscosity ( $\text{kg}/\text{m} \cdot \text{s}$ )

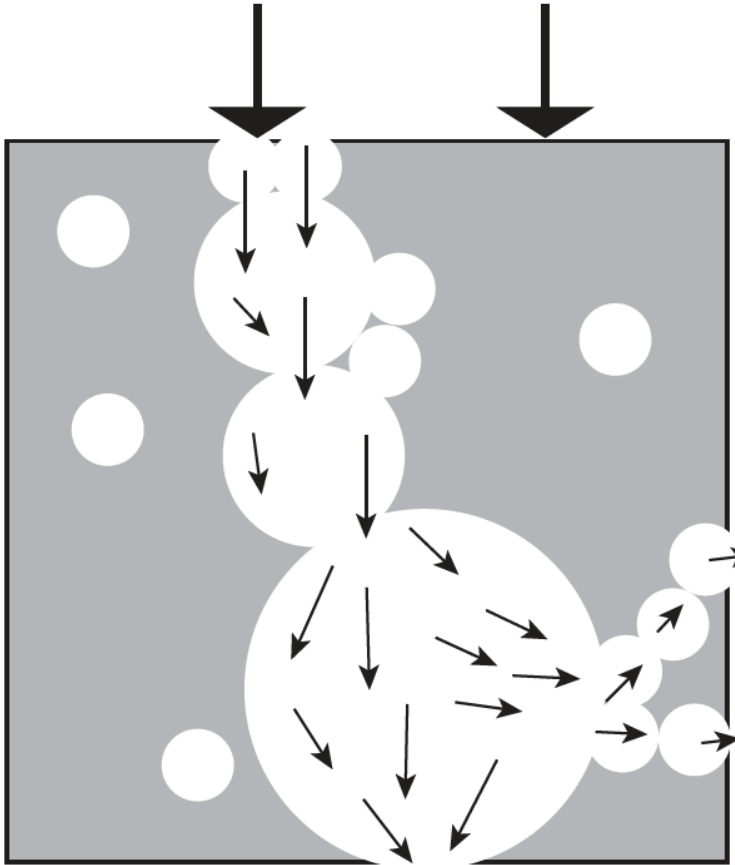


# Permeability

Which flow path is most permeable?



$\phi = 40\%$



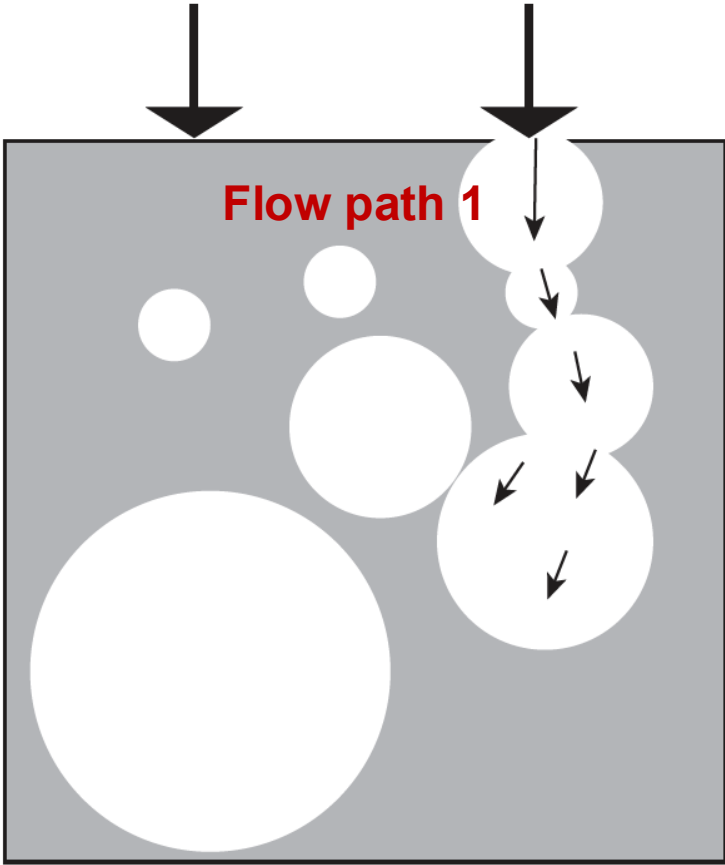
$\phi = 40\%$

**Flow path A**

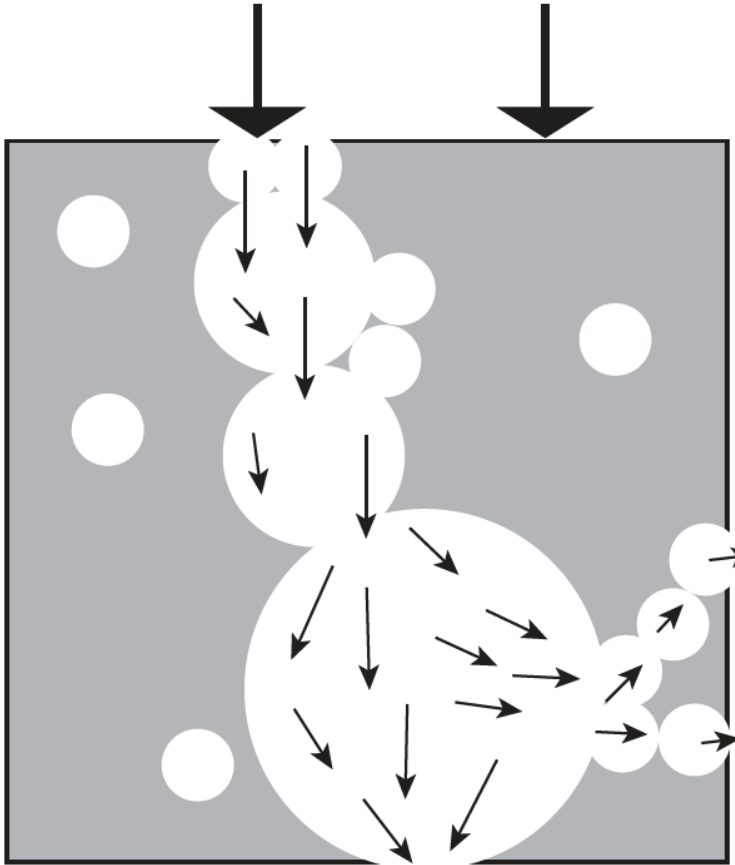
**B Flow path B**

# Permeability

$$k_1 = 0 \text{ m}^2 < k_B < k_A$$



$\phi = 40\%$



$\phi = 40\%$

**Flow path A**

**Flow path B**

# Permeability

- Permeability  $k$  has dimensions of area, or  $m^2$  in SI units.
- But the traditional unit is the Darcy:

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

(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<sup>2</sup>)

$n$  – porosity, as a fraction

$S_A$  – specific surface area of the pore spaces per unit volume of solid (cm<sup>2</sup>/cm<sup>3</sup>)

# Kozeny-Carman Equation

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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<sup>2</sup>)

$n$  – porosity, as a fraction

$S_A$  – specific surface area of the pore spaces per unit volume of solid (cm<sup>2</sup>/cm<sup>3</sup>)

**$T$  – 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

The volume of fluid flowing through a specified cross-sectional area (generally 1m<sup>2</sup> for SI units) 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

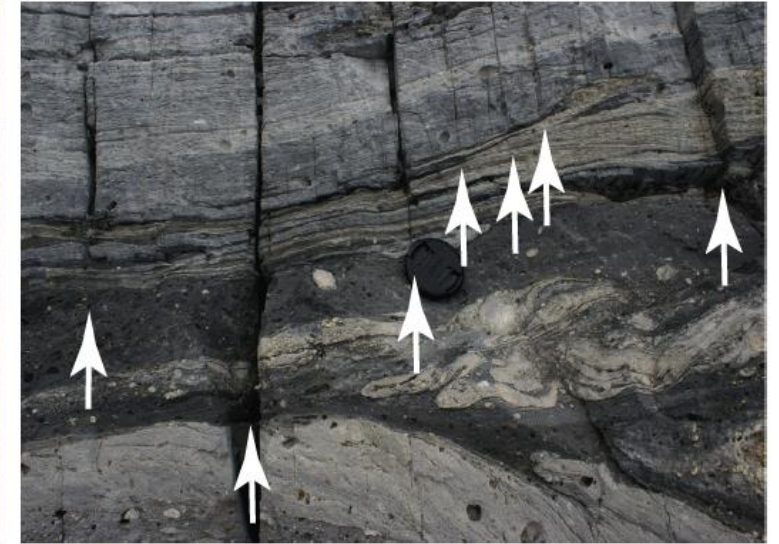
# Fracture permeability

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:**

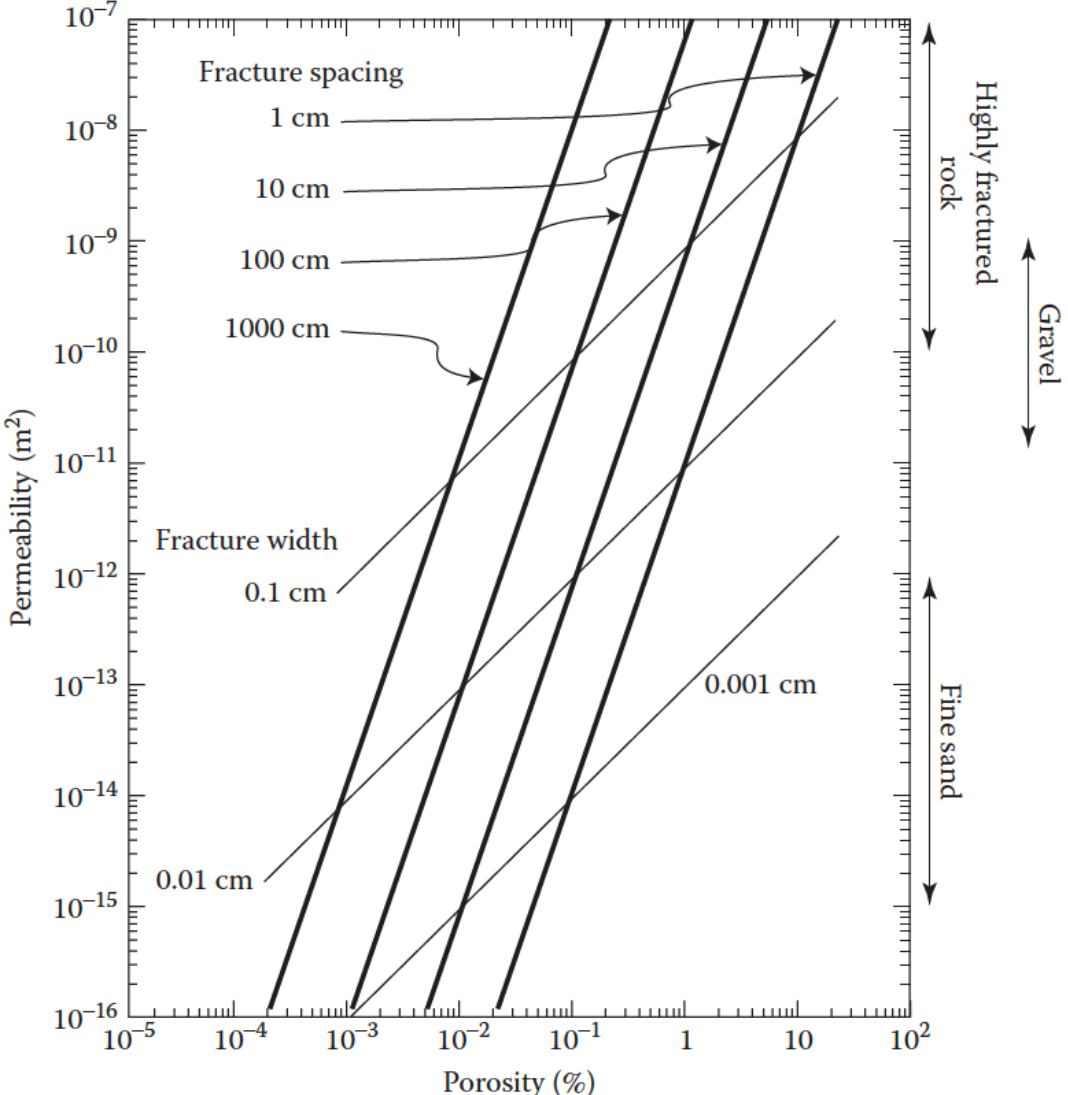
$$K_f = \frac{\rho \times g}{\mu} \times \frac{a^2}{12}$$

$a$  – fracture aperture ( $m$ )

**Permeability of a fracture:**

?

# Fracture aperture matters!



### For a given fracture spacing:

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

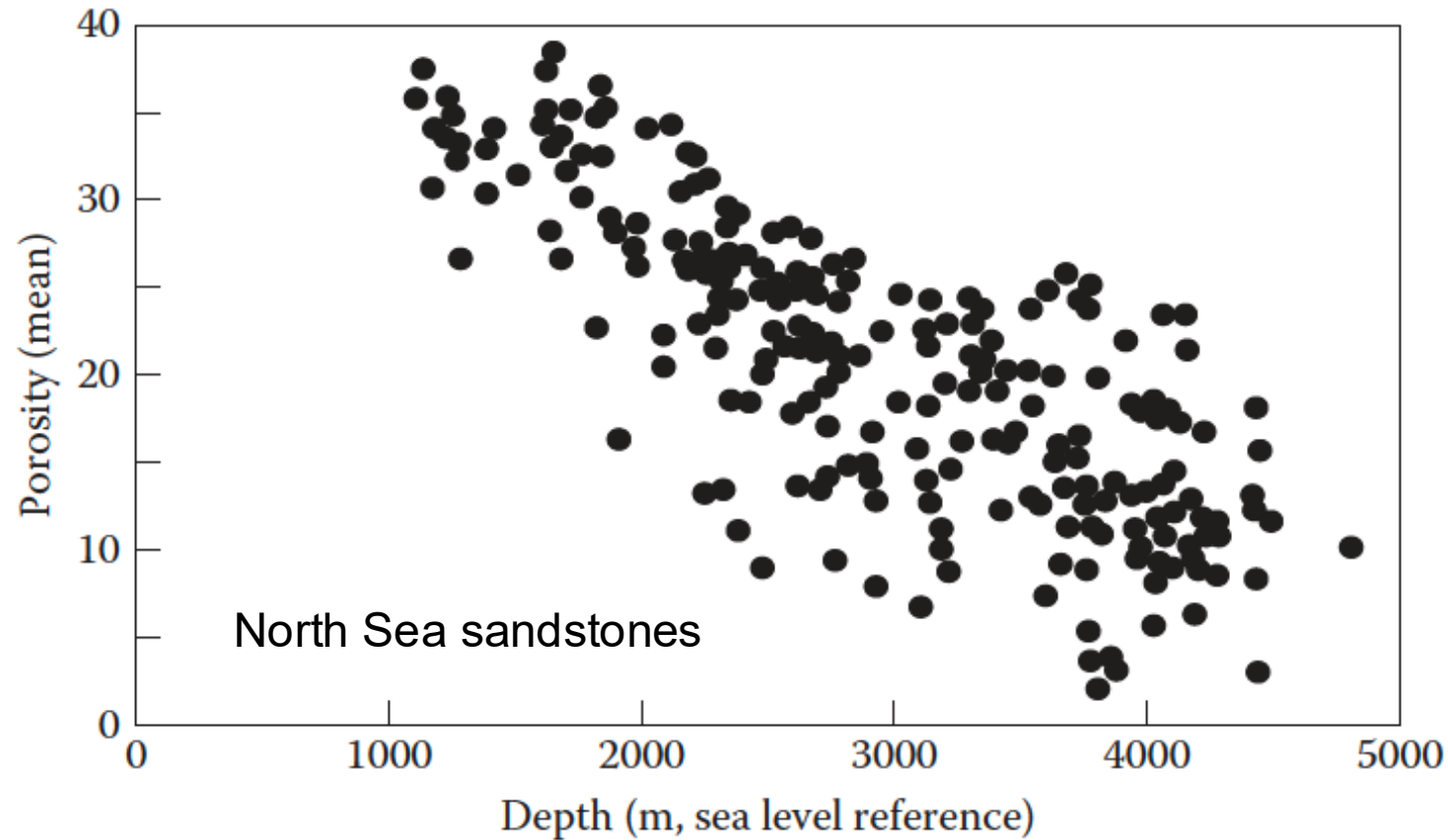
### For a given fracture width:

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

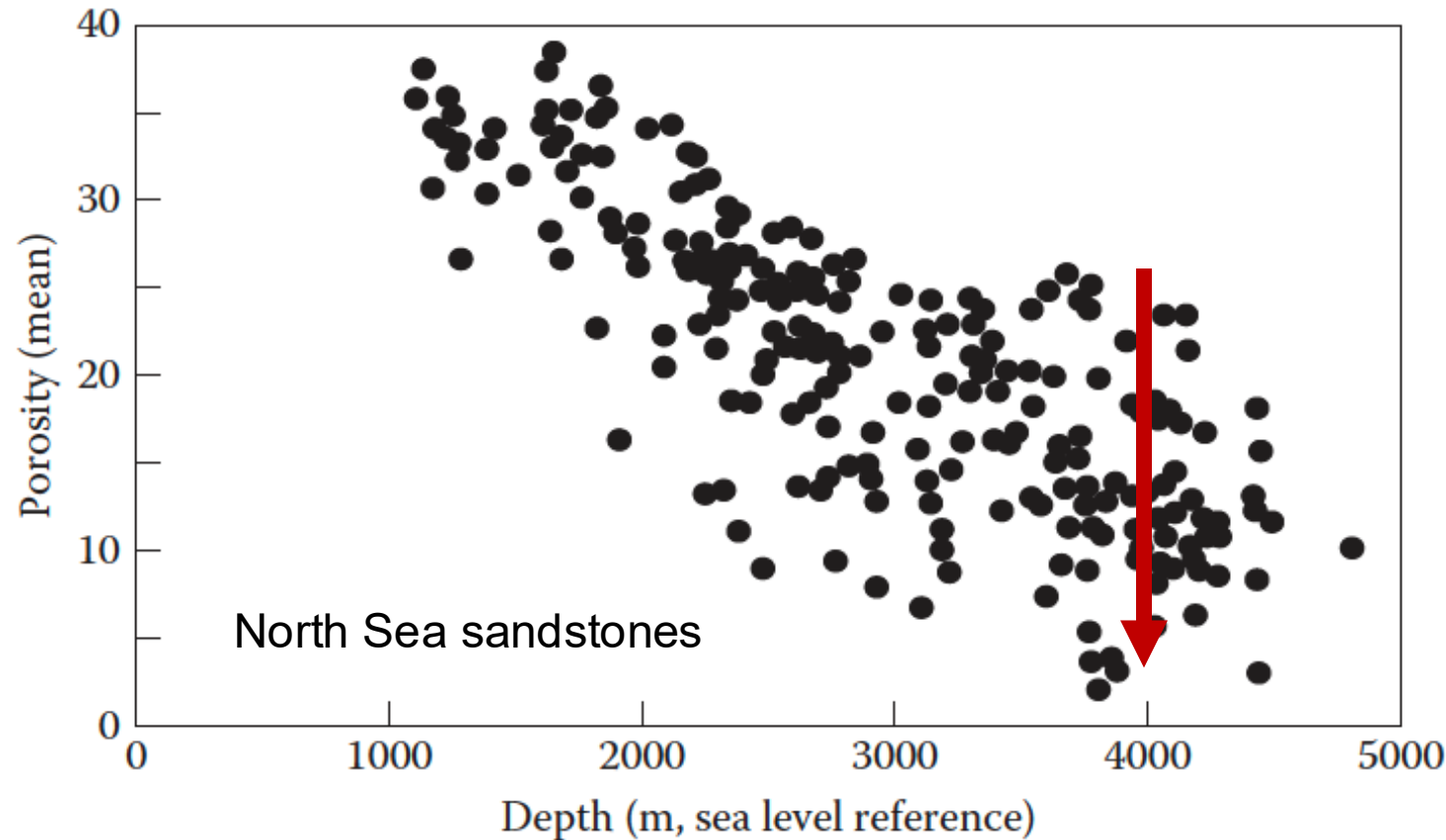
**Permeability is sensitive to fracture aperture.**

Effect of depth

# Porosity and permeability with depth



# 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?**

# 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

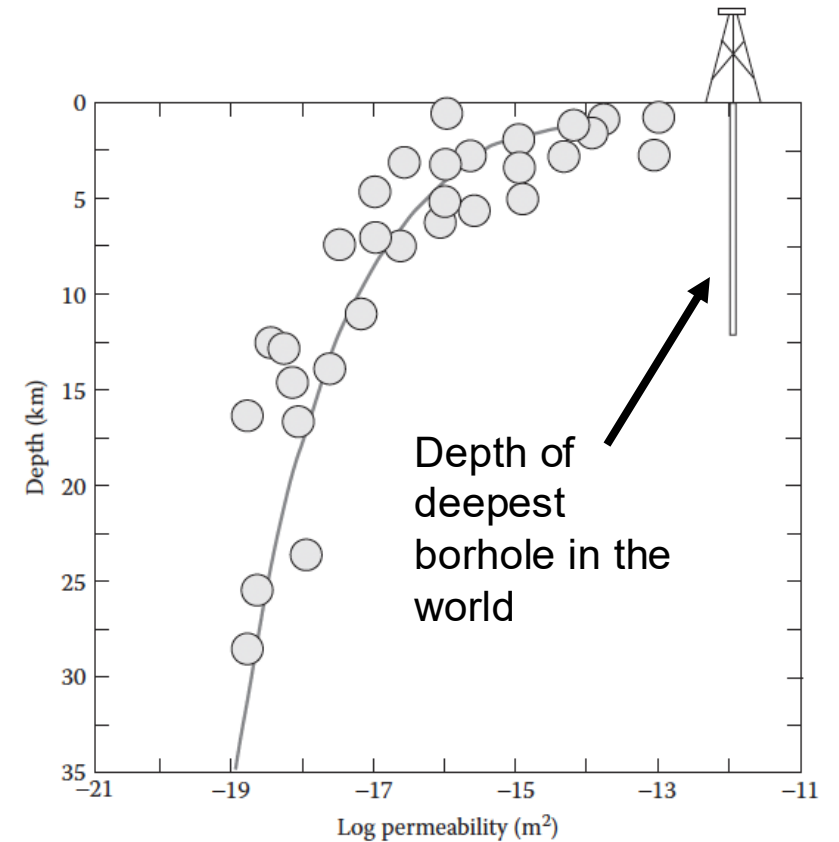
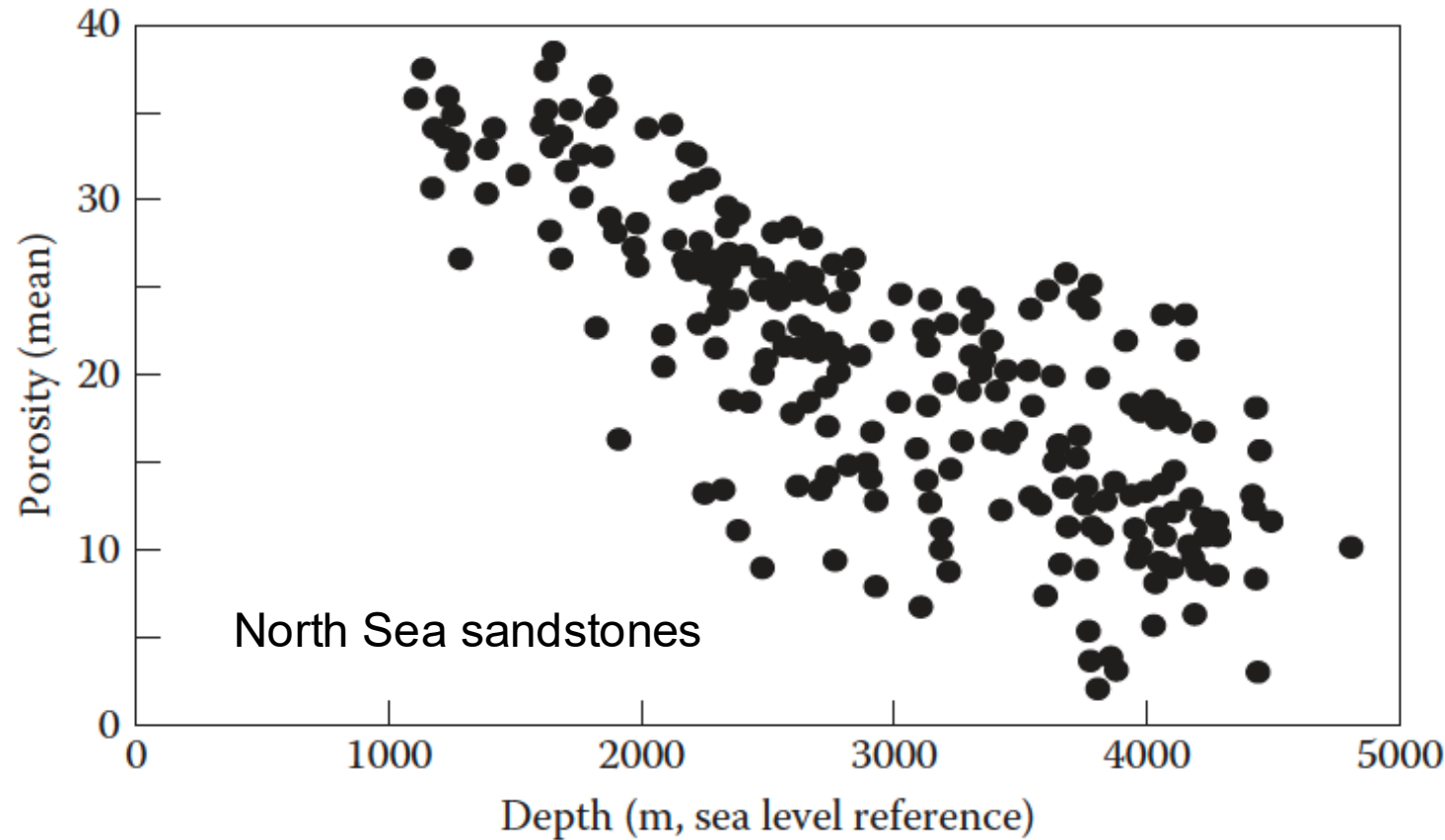
$a_c$  – « conducting » aperture

$\nabla P$  – 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

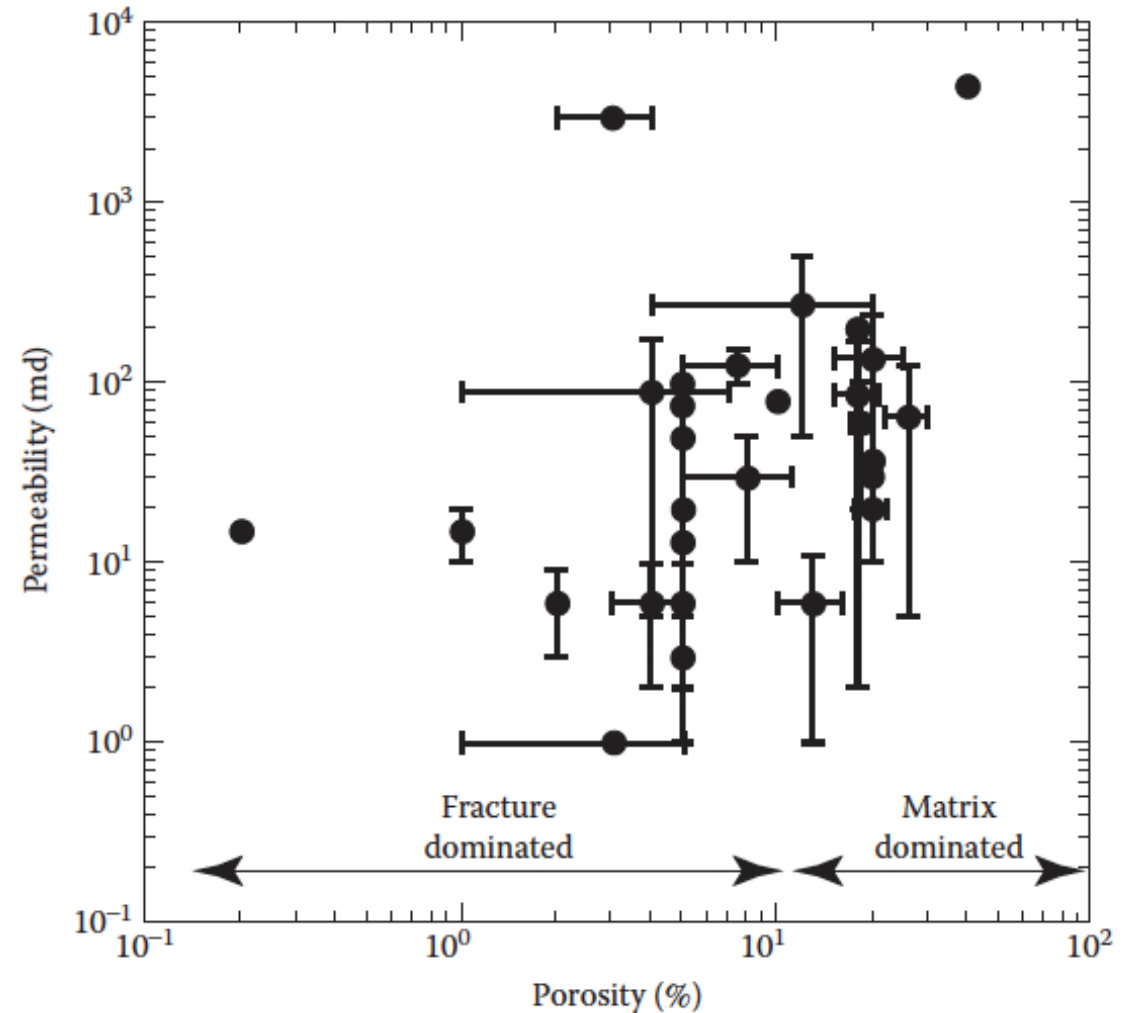


# Hydrological properties of real geothermal systems

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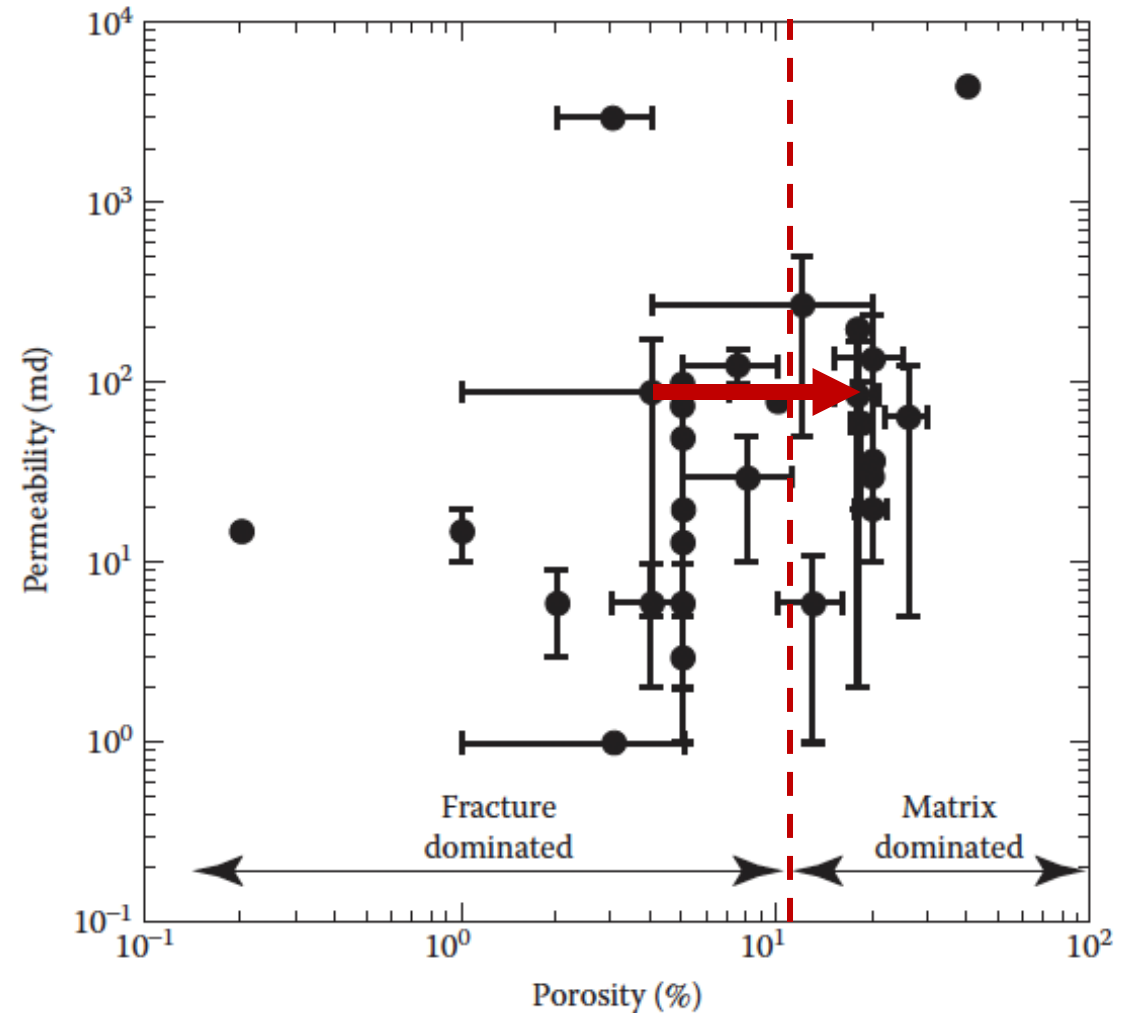
Permeability-porosity ranges for various geothermal systems.

**What are some conclusions that we can draw?**



# 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!







## 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.

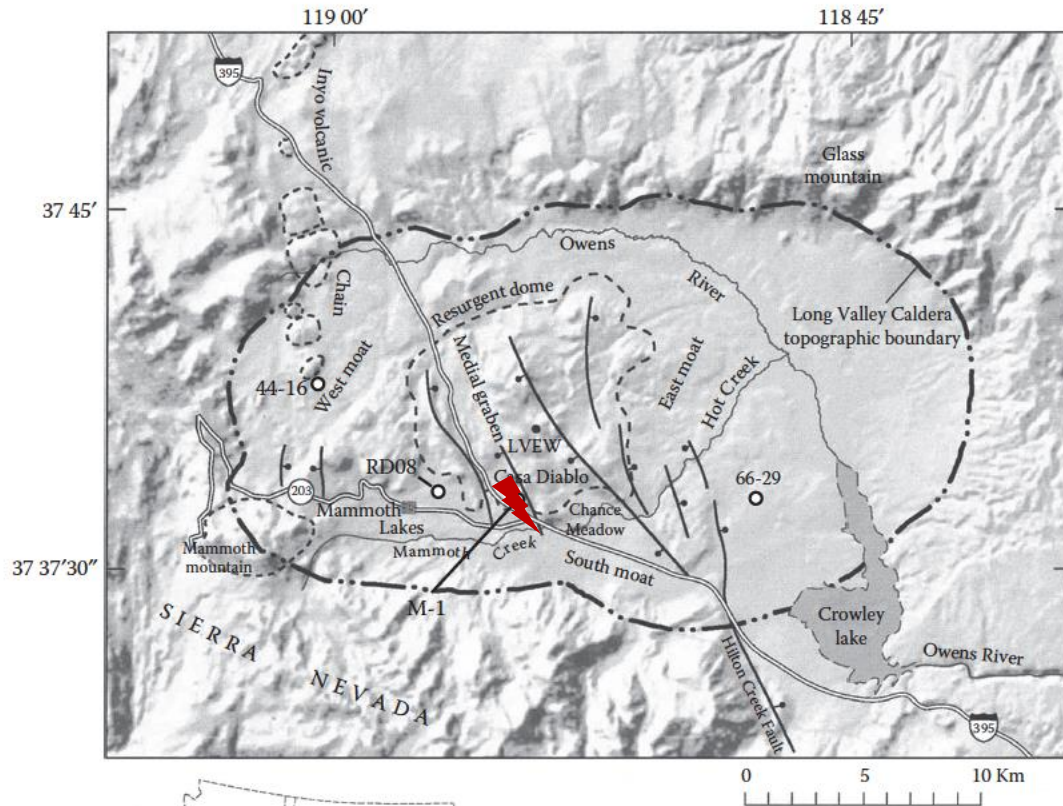
Volumetric flow rate controls the rate at which energy can be transferred from to the surface.

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).

# Long Valley Caldera Case Study

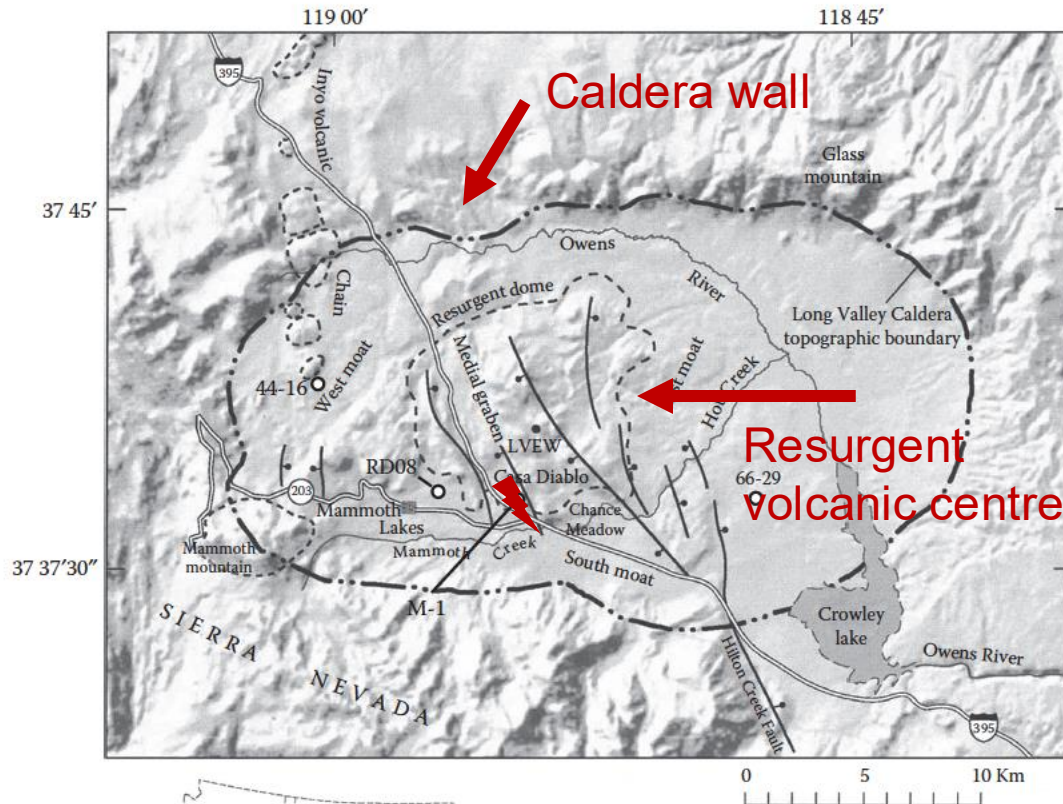


 Casa Diablo power generation facility

## Power production in the Long Valley Caldera

- Site of geothermal power generation since 1985
- Casa Diablo: 40-MWe power plant produces electricity
- Working fluid temperature is 170°C
- Reservoir rocks are both porous and fractured
- Flow rates of about 900 kg/s

# Long Valley Caldera Case Study

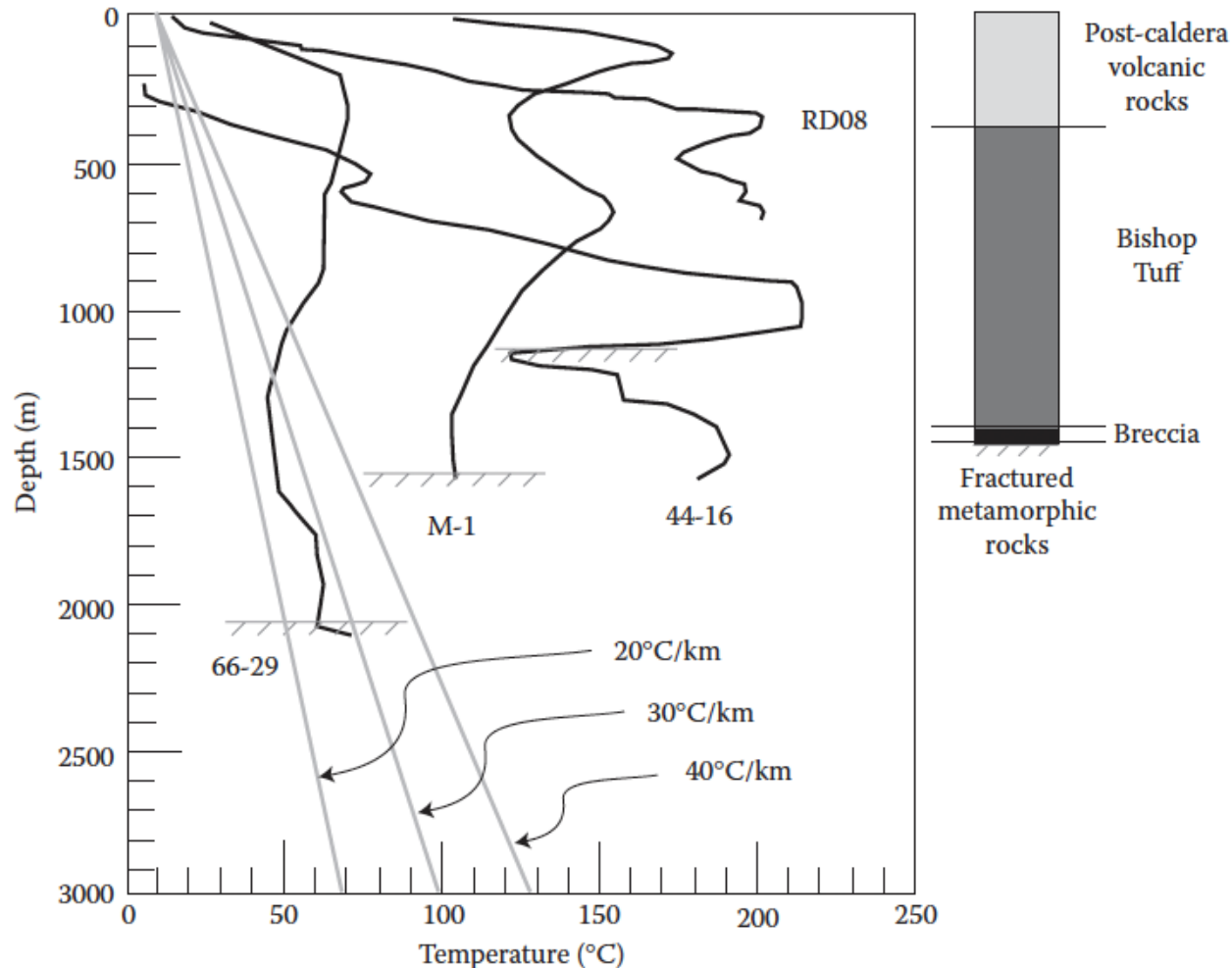


 Casa Diablo power generation facility

## What is the geological context of the Long Valley Caldera?

- Volcanic feature on the boundary of the Sierra Nevada mountain range and the Basin and Range tectonic province
- Began erupting over 3.5 million years ago
- 760 000 years ago, a caldera-forming eruption created the Long Valley Caldera and the Bishop Tuff
- 100 000 years later, a resurgent dome formed
- **Still volcanically active**

# Long Valley Caldera Case Study

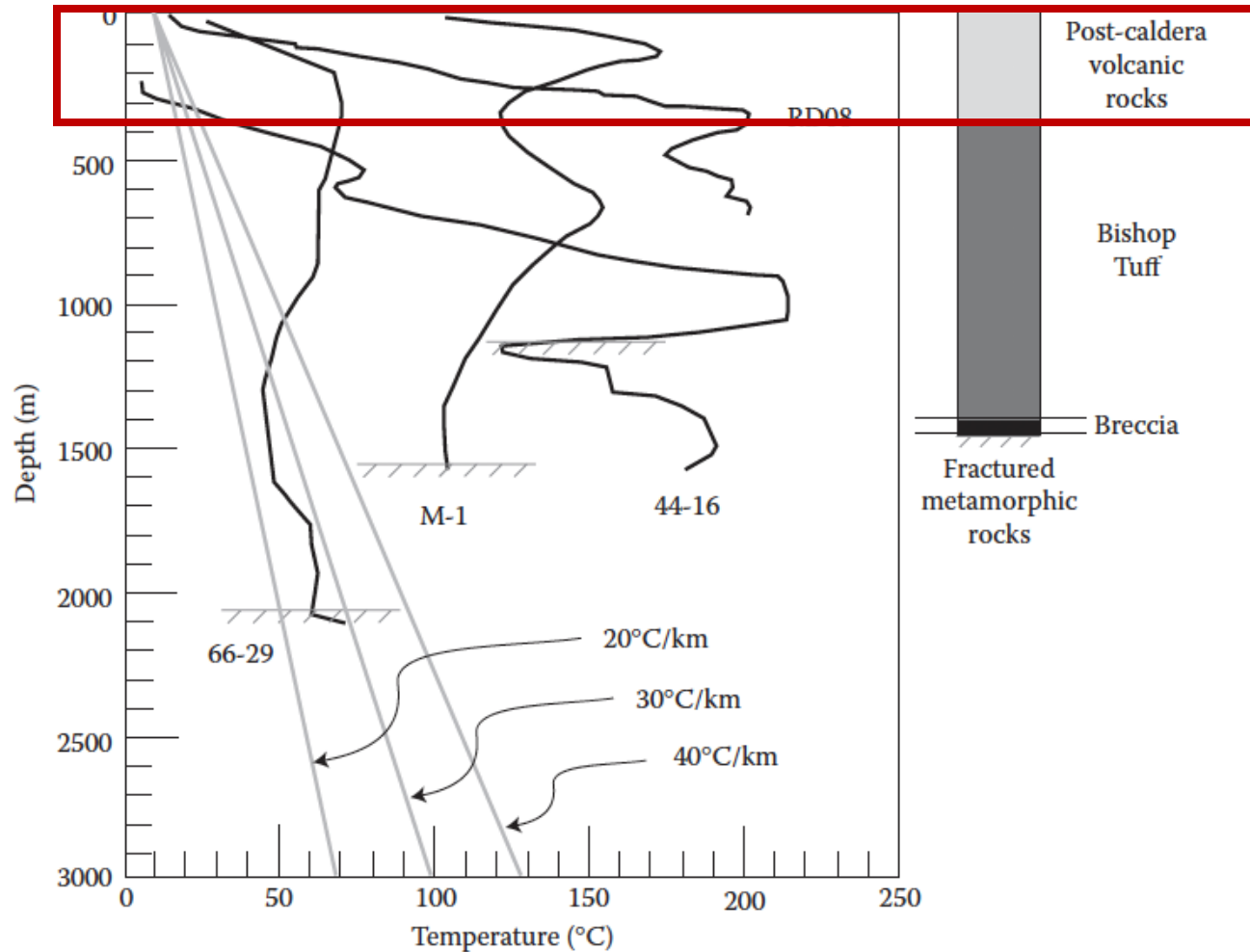


**Dark grey lines:** Temperature profiles down several boreholes in same geological complex as the Casa Diablo power station.

**Light grey lines:** temperature profiles that would be expected from purely conductive heat transport.

**What's going on down the boreholes?**

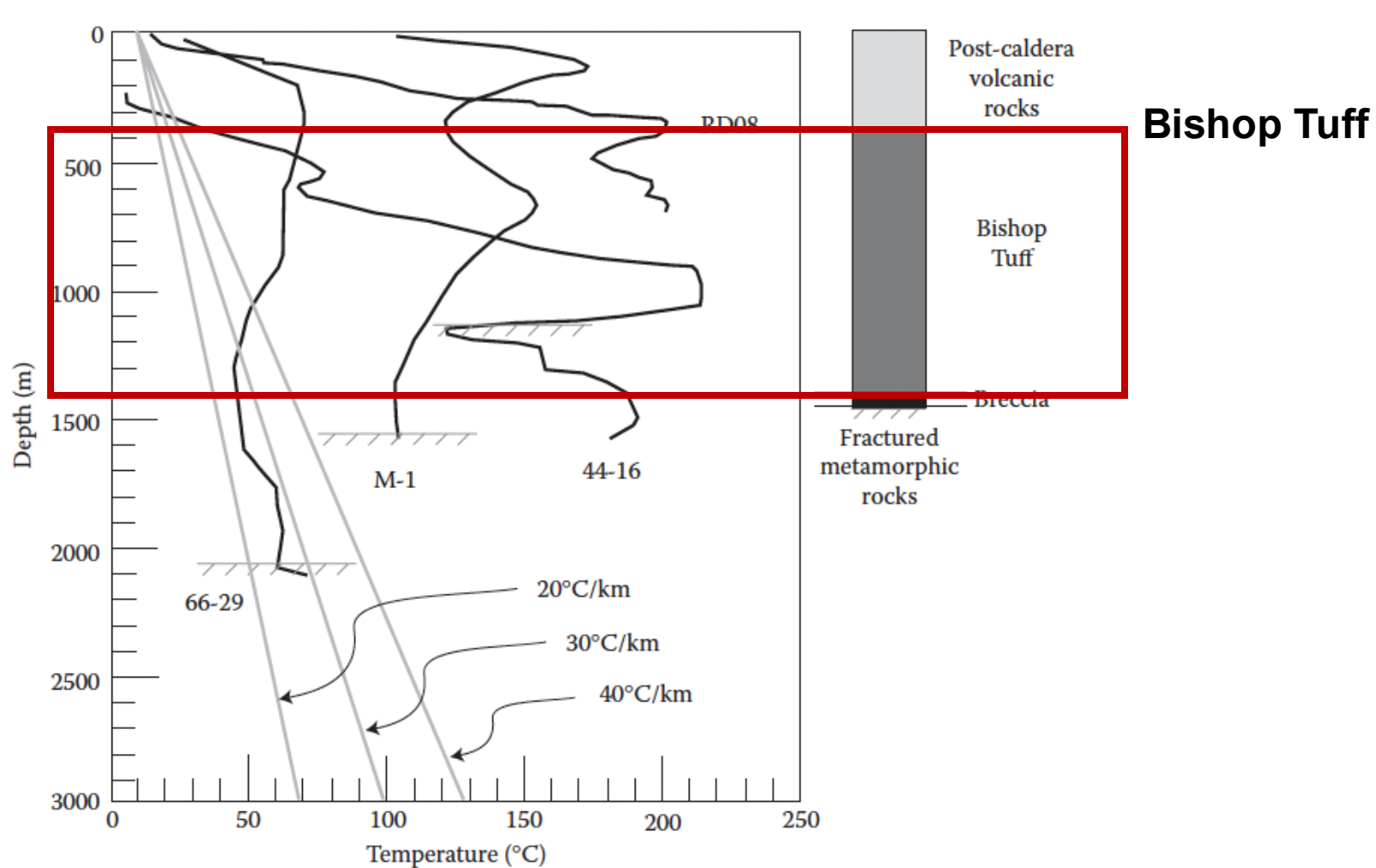
# Long Valley Caldera Case Study



Geology:

Post-caldera volcanic rocks

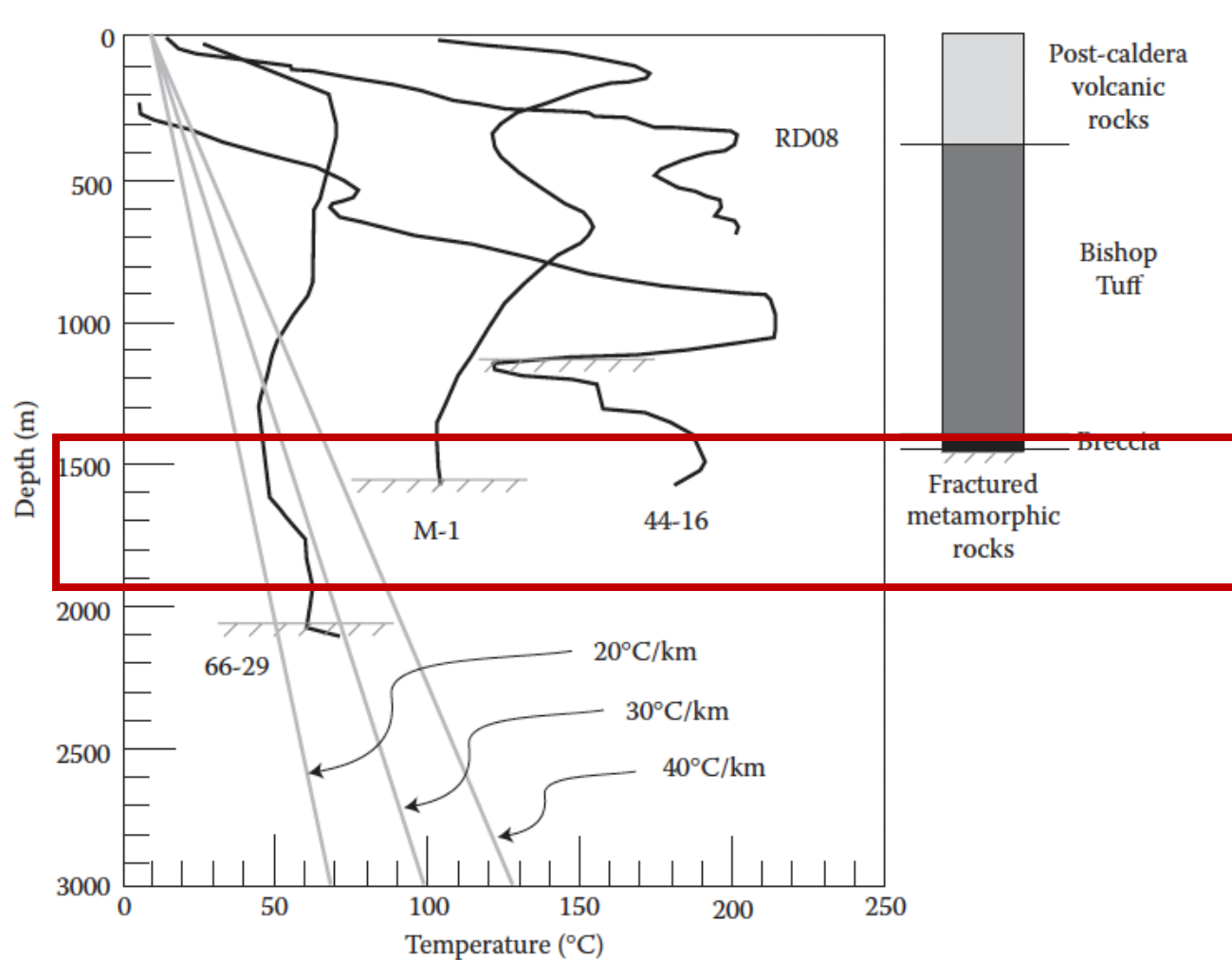
# Long Valley Caldera Case Study



Geology:

Bishop Tuff

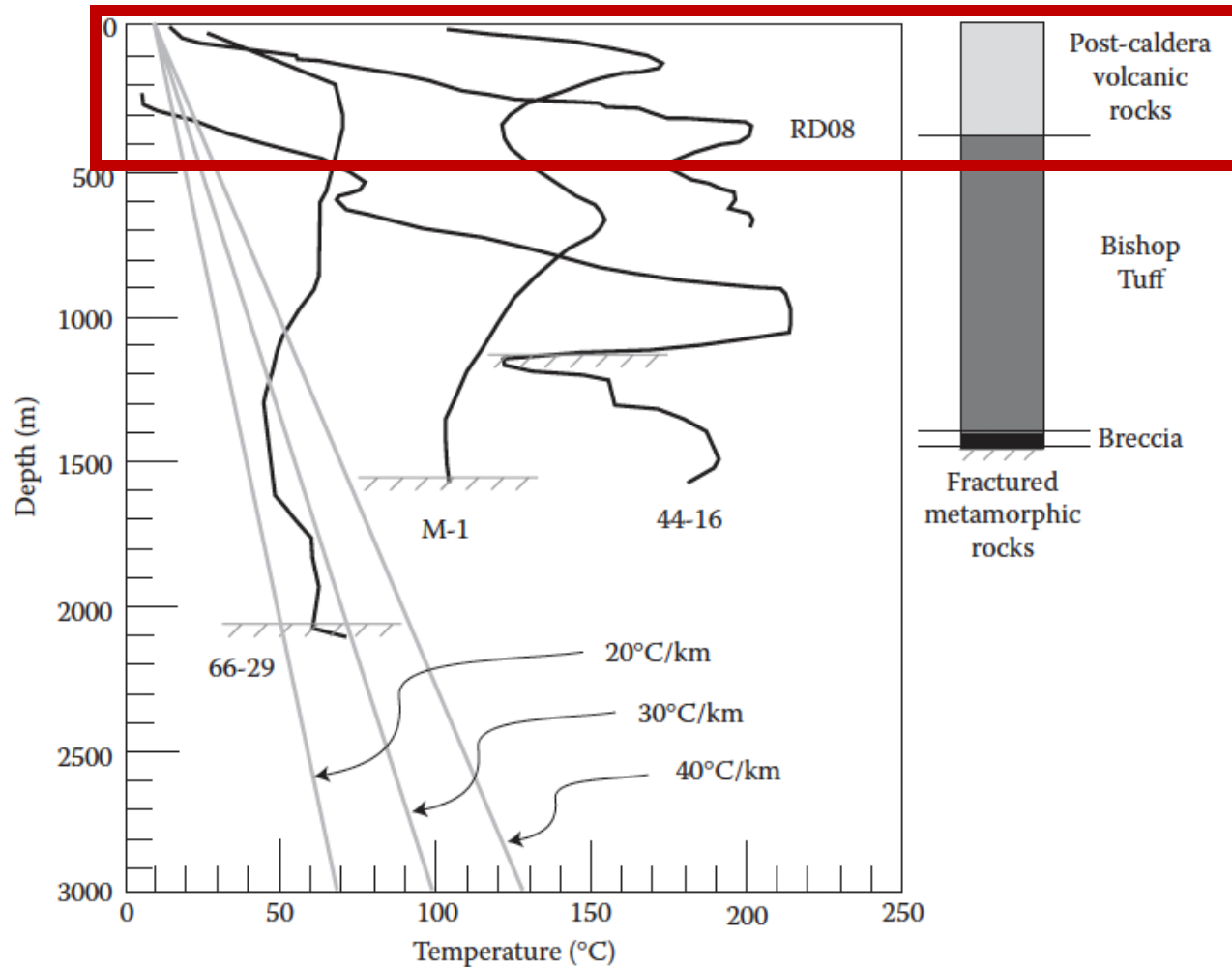
# Long Valley Caldera Case Study



**Geology:**

**Fractured metamorphic rocks**

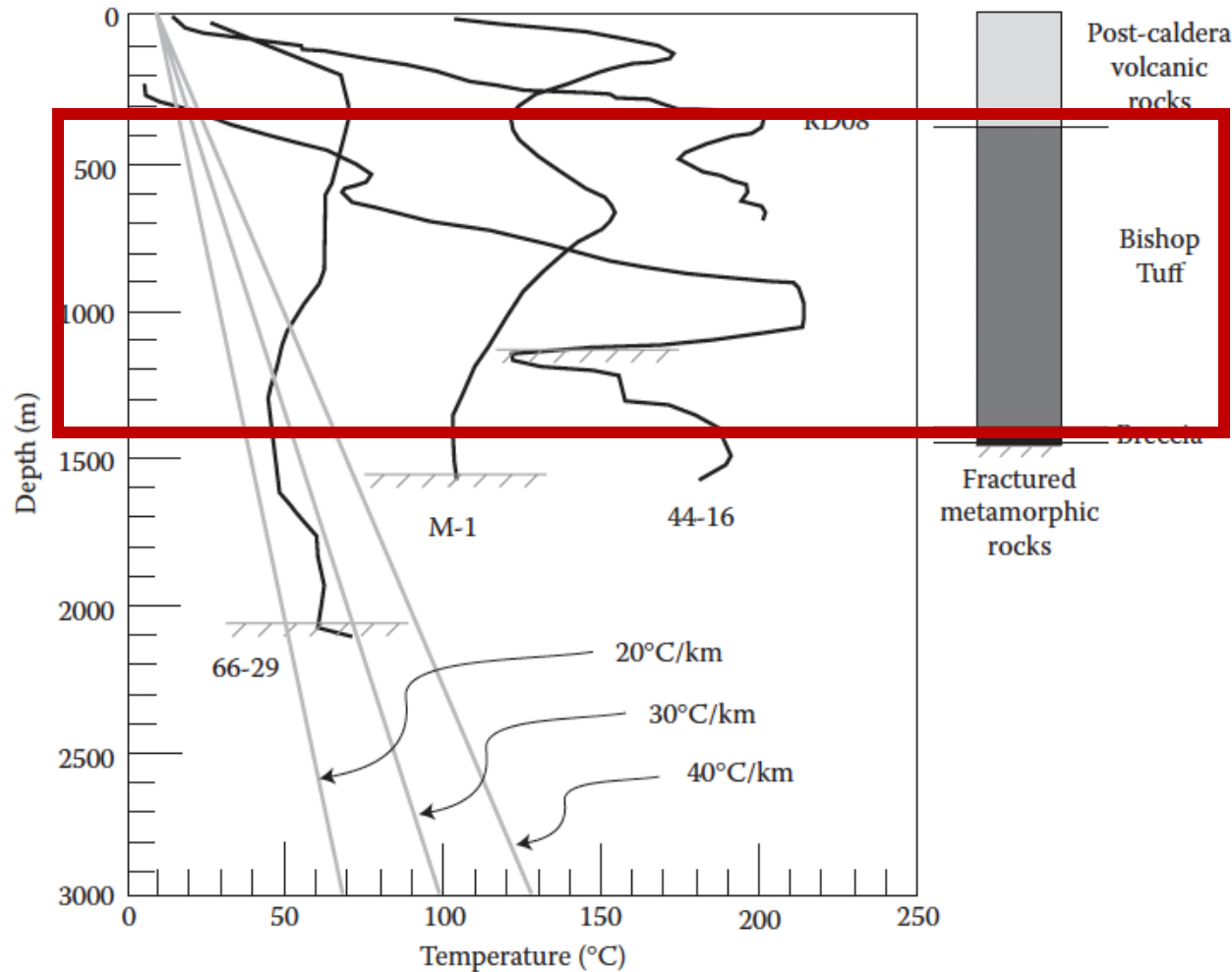
# Long Valley Caldera Case Study



Using geological information, what hypotheses can we make?

What's happening near the surface?

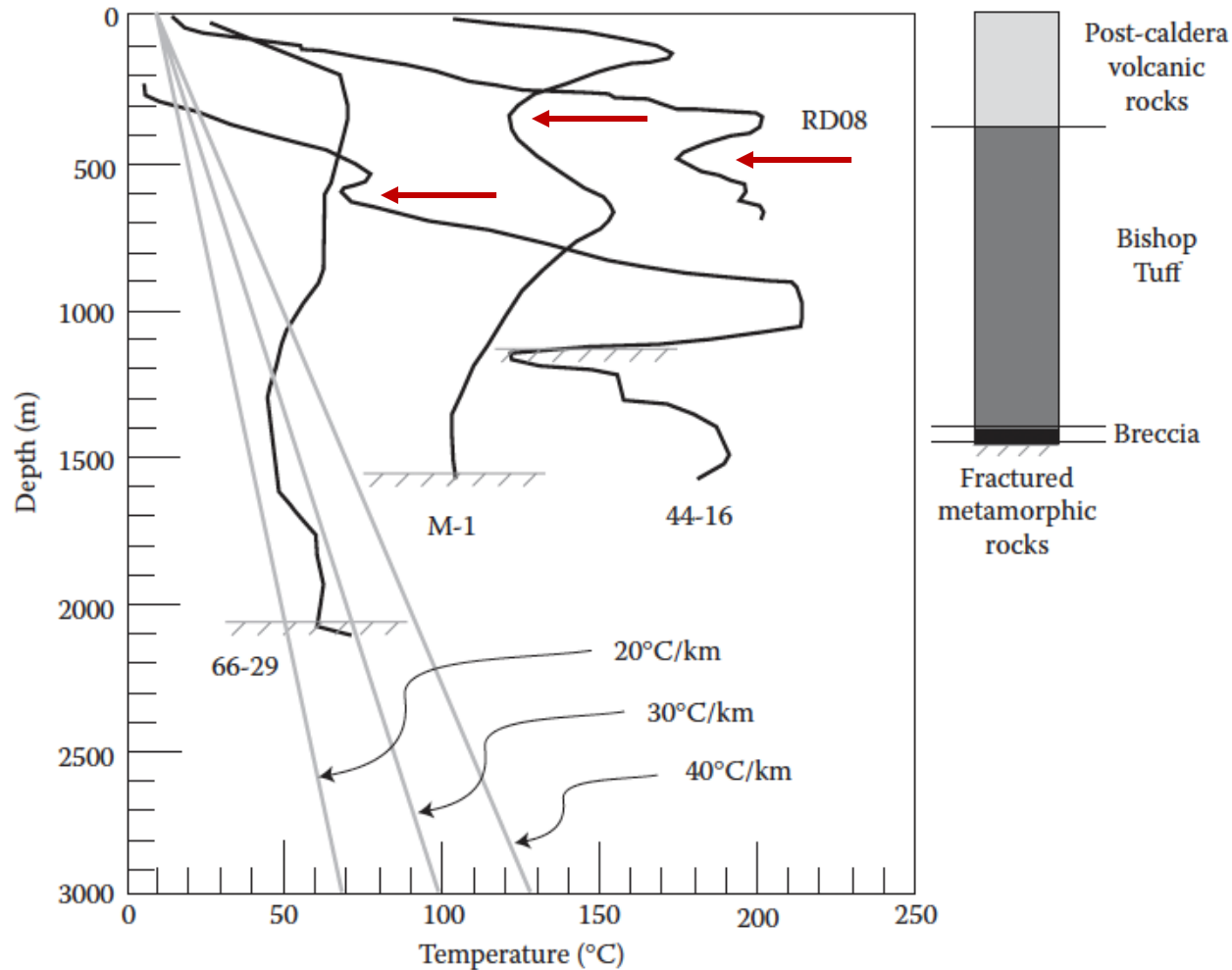
# Long Valley Caldera Case Study



Using geological information, what hypotheses can we make?

What's happening in the Tuff?

# Long Valley Caldera Case Study



Using geological information, what hypotheses can we make?

What about temperature reversals?

# Possible Geological Models:

