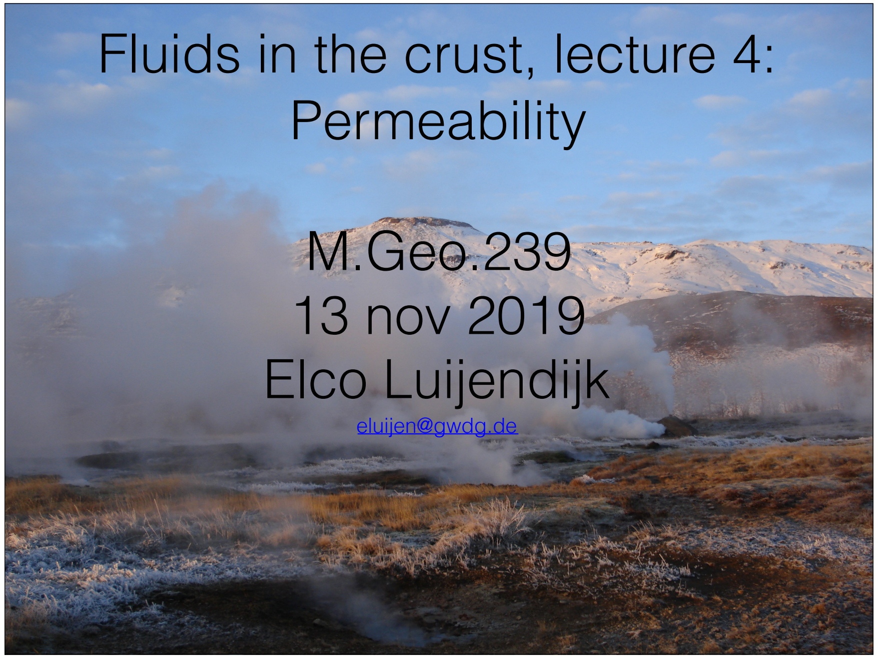

# Fluids in the crust, lecture 4: Permeability

M.Geo.239
13 nov 2019
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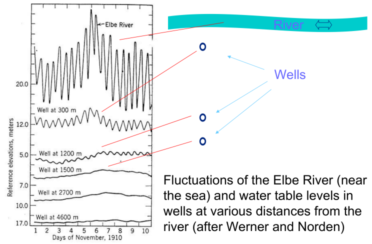
## Last week

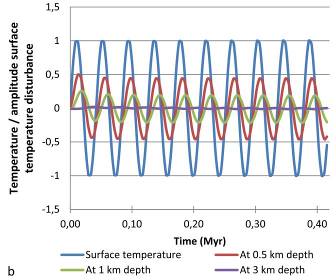
- Fluid flow, heat flow and solute transport in the crust are all governed by diffusion laws:

$$q = K \frac{\partial u}{\partial x}$$




Fluctuations of the Elbe River (near the sea) and water table levels in wells at various distances from the river (after Werner and Norden)

Fluctuations in hydraulic head around the Elbe river
Source: J.Barker, Univ. Southampton




Propagation of long-term climate fluctuations in the subsurface.
ter Voorde et al (2014) NJG



## Today

- Permeability
  - part 1: How do we quantify permeability?
  - part 2: What controls permeability?
    - permeability of porous rocks
    - permeability of fractured rocks
    - permeability at different scales
  - part 3: Crustal permeability



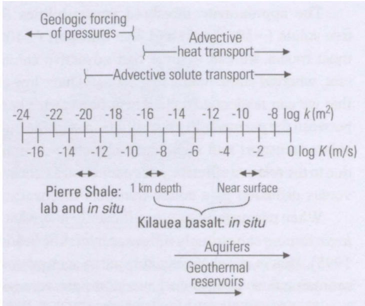
## Why is permeability important?

- Fluid flow is governed by Darcy's law: $q = \frac{\rho g \mathbf{k}}{\mu} \nabla h$

- In words: fluid flux = fluid properties x **permeability** x hydraulic gradient

# Why is permeability important?

- k > ~$10^{-20}$ $m^2$ : solute transport -> facilitates chemical reactions, metamorphism, diagenesis, fault sealing, etc…
- k > $10^{-16}$ $m^2$ : heat transport by fluids: fluid flow changes temperatures in the crust
- k < ~$10^{-17}$ $m^2$ : permeability is low enough to maintain elevated fluid pressures -> causes or facilitates deformation, fracturing
- k > ~$10^{-14}$ $m^2$ : permeability is high enough for extraction of fluids for geothermal energy, hydrocarbons, drinking water

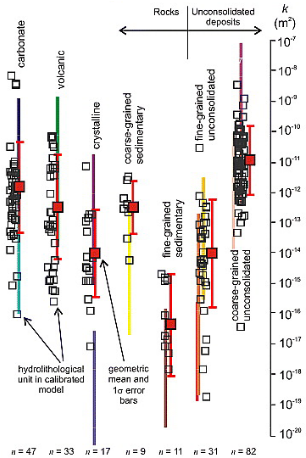



Limiting values of permeability, from Ingebritsen et al (2006) Gw in Geol. Proc.



# Permeability variability

- However, permeability is highly variable, scale dependent and difficult to quantify
- How do we quantify permeability?
- And can we predict permeability if we have more information on key variables like lithology and porosity, fracture shape and density?






Regional scale permeability, Gleeson et al. (2011)

# Quantifying permeability

- There are many methods to quantify permeability. Each method operates at a different scale
  - Small scale (cm): lab measurements on core sample
  - Intermediate scale (100s m): Pumping test and drill stem tests
  - Large scale (> kms): calibration of numerical models of fluid flow to hydraulic head, temperature or isotope data



# Quantifying permeability: small scale

- Permeameter: A device to measure permeability on small samples. Apply steady or falling hydraulic head at one end of sample and measure outflow at the other end
- Scale: approx 10 cm long, 1 inch (2.5 cm) radius.
- Conceptually very simple, low uncertainty
- However, difficult to measure low-permeability materials (clays, shales, crystalline rocks), even a small leak in the setup can influence the measured permeability
- Typically cannot deal with secondary porosity/ permeability (fractures)

# Quantifying permeability: intermediate scale

- Pumping tests / Drill stem tests (=oil industry equivalent): Test the response in hydraulic head in one or more observation wells to extraction or injection of groundwater through a pumping well
- Area of influence: 100s of m

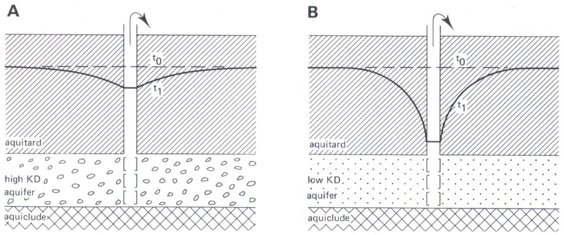



Figure 2.5 Cone of depression at a given time t in:
A) an aquifer of high transmissivity
B) an aquifer of low transmissivity



Example of water table response to pumping in two aquifers, Kruseman & de Ridder (1994)

# Quantifying permeability: intermediate scale

- Pumping test give an effective value of hydraulic conductivity over a larger area, this effective conductivity is the effect of small-scale heterogeneity such as variations in lithology or small fractures
- Calculated transmissivity depends on the choice of equation to interpret the data
- For most methods: pumping tests provide a value of transmissivity. Transmissivity is hydraulic conductivity multiplied by thickness of the formation that is tested

$$\Delta h = \frac{Q}{2\pi K b} ln\left(\frac{r}{R}\right)$$

Steady-state, unconfined aquifer, developed by Günther Thiem (1906)

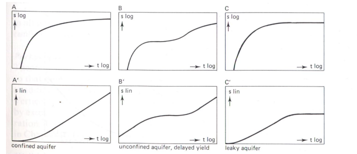


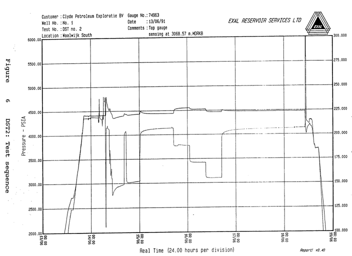

Figure 2.12 Log-log and semi-log plots of the theoretical time-drawdown relationships of unconsolidated aquifers:
Parts A and A': Confined aquifer
Parts B and B': Unconfined aquifer
Parts C and C': Leaky aquifer

Example of water table response to pumping over time, Kruseman & de Ridder (1994)

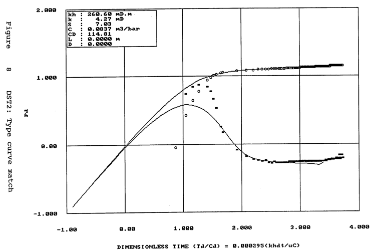


# Quantifying permeability: intermediate scale

- Drill stem test is the oil industry equivalent of the pumping test
- Consist of several cycles of reduction of pressure and pressure recovery
- Temperature and hydrochemical data are often also recorded, often the only source of data on deeper temperatures and fluid chemistry



Change of pressure and temperature over time




Fitting equation for pressure decrease and recovery to observed data. Source: www.nlog.nl



# Quantifying permeability: Large scale

- Large-scale permeability estimate can be obtained by calibrating groundwater models to match observations
- Scale: 100s of m to 10s of kms
- Observations used:
  - Hydraulic head (most common)
  - Groundwater discharge (springs, river base flow, water budgets of lakes)
  - Isotope data on groundwater age ($^{3}H$, $^{14}C$, $^{36}Cl$, etc…)

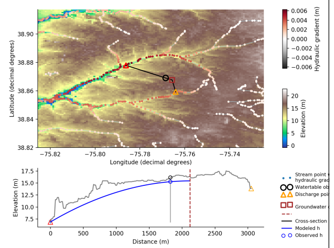
# Quantifying large-scale permeability, examples

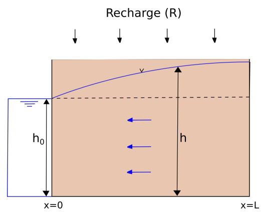
- The 'classical' way to calibrate permeability of the shallow subsurface in groundwater models: adjust permeability until your modelled and observed hydraulic head values in observation wells match
- Works best in for shallow formations: most observation wells are shallow (up to ~100 m), information on deep hydraulic heads is very sparse
- Non-uniqueness problem: Several parameter combinations of permeability, recharge and aquifer thickness all give the same model result (see Exercise 1)



# Quantifying large-scale permeability, examples

- Example of calibrating large-scale transmissivity using large datasets on hydraulic head in observation wells and stream levels
- Using 2D depth-integrated version of Darcy's law: $q = \mathbf{K}\,\mathbf{b}\,\partial h/\partial x$
- Transmissivity = hydraulic conductivity (K) x aquifer thickness (b)
- Note, you can only use groundwater level data to calibrate transmissivity (K x aquifer thickness) because a change in thickness (b) or hydraulic conductivity (K) can result in the same groundwater level (see exercise 1 and 2)
- Recharge is based on regional and global hydrological models (de Graaf et al. 2015) that have been calibrated using river baseflow

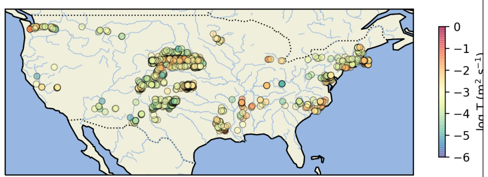


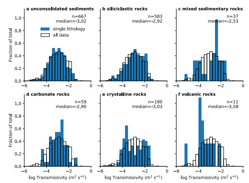





# Quantifying large-scale permeability, examples

- Repeat this 1500 times (using Python):
- Calibrated transmissivity is poorly correlated with mapped bedrock lithology….







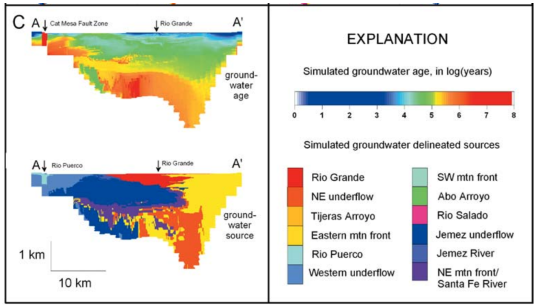
Calibrated values of transmissivity for 2600 hydraulic head data in the continental US

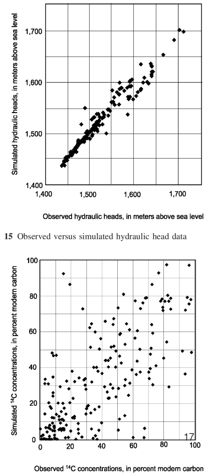
# Quantifying large-scale permeability, examples

- Additional data on groundwater flux or flow velocity can often help to better constrain permeability:
    - groundwater discharge to springs, river base flow, or lakes
    - flow velocity information obtained by studying the age of groundwater (=the time since infiltration) using isotopes like 3H, 14C, 36Cl

# Quantifying large-scale permeability, examples

- Example of matching a groundwater flow model to $^{14}C$ data in the Rio Grande rift, US:



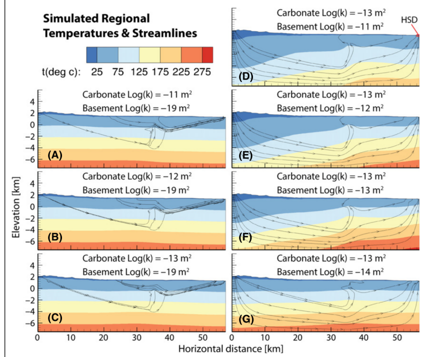




Modelled groundwater age (top left) and comparison modelled and observed hydraulic heads and 14C ages. Sanford et al. (2004) Hydrogeology Jrnl

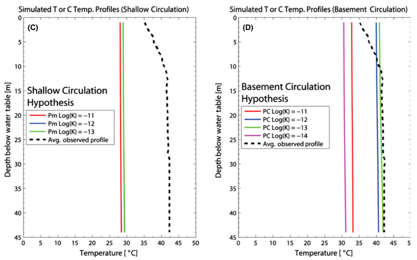


# Quantifying large-scale permeability, examples

- Subsurface or spring temperature data: can often be helpful. However also often suffers from a non-uniqueness problem, many different processes influence temperatures




Basin-scale model of fluid & heat flow in the Rio Grande Rift basin




Modelled vs observed temperatures at a hot spring in the Rio Grande rift for models with different values of permeability (Pepin et al. 2014, Geofluids)



# Summary, part 1:

- Permeability varies 13 orders of magnitude or more, is difficult to quantify, especially for the deep crust / outside areas of interest for drinking water or hydrocarbons
- Permeability is the limiting factor for solute transport and chemical reactions in the crust, heat transport, fluid pressures and deformation
- Quantifying permeability:
  - small scale: Measure permeability in the lab
  - medium scale: Pumping/drill stem tests
  - large scale, calibrate flow models to hydraulic head data, flux data, isotopes / groundwater age, temperature, or more exotically, earthquake swarms and fluid loading effects on seismicity

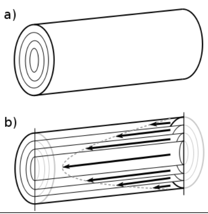


# Part 2a: What controls permeability? Permeability of porous rocks

- Porous rocks: predominantly sedimentary rocks, and volcanic rocks
- Distribution at the surface: ~70% sedimentary, ~7% volcanic (Hartmann & Moosdorf 2012)

# Permeability of porous material

- The best theoretical equation for the permeability of porous material is the so-called Kozeny-Carman equation
- Based on the Hagen-Poseille equation (1838): This is a solution of the Navier-Stokes equations for flow through capillary tubes
- This equation was adjusted by Austrian engineer Kozeny in 1927, to account for tortuous flow paths through connected pore spaces
- Adjusted by south African hydrologist Carman (1937, 1956) to account for variation in pore shapes

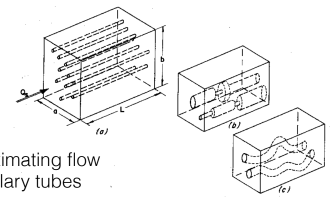



Flow through a capillary tube
source: Wikipedia



# Permeability of porous material

- The Kozeny-Carman equation: $$k = \frac{1}{CS_s^2}\frac{\phi^3}{(1-\phi)^2}$$
- Permeability (k) depends on the specific surface ($S_s$) and porosity ($\phi$) (dimensionless). The ratio between these two determines the frictional forces exerted on the fluid
- $S_s$ = surface area per units of rock volume (=pore space + material) ($m^2$ $m^{-3}$)
- $S_s$ is a function of the grain size distribution, the smaller the grains, the larger the surface area
- The Kozeny-Carman constant (C) depends on particle shape. Appears to be relatively constant in most cases: C=~5

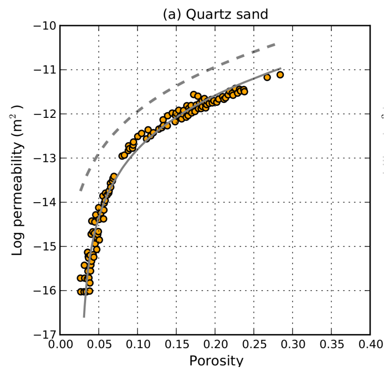



The KC equation is based on approximating flow through pores as a bundle of capillary tubes



# Permeability of sands and silts

- The Kozeny-Carman equation works very well for any granular material (sands, silts)
- Example from a clay-fee sandstone: fit is almost perfect, mean error is 0.2 orders of magnitude
- The fit improves a lot if one assumes that the lower 2.5% of the pore space is not connected. In general this percolation threshold value ranges from 1 to 3 % (Mavko & Nur, 1997, Geophysics)

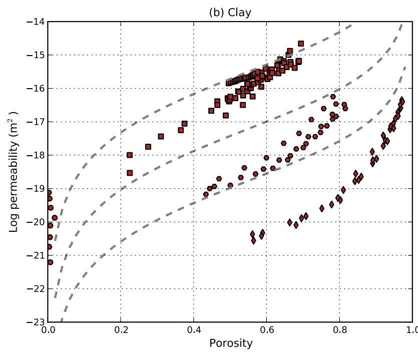



KC equation for a homogeneous sandstone.
Broken line: no percolation threshold
Gray line: KC equation with a percolation threshold
Luijendijk and Gleeson (2015) Geofluids



# Permeability of clays

- However, the permeability of clays is a lot harder to predict. Kozeny-Carman equation strongly overpredicts permeability
- Reasons: platy shape of clay minerals, water bound to clay surface behaves differently.
- Currently there is no good theoretical model of clay permeability (to my knowledge)



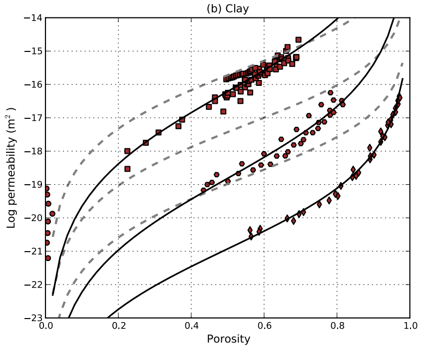

KC equation for the clays kaolinite, illite and smectite (in order of high to low k)
Luijendijk and Gleeson (2015) Geofluids

# Permeability of clays

- Alternative, empirical power law equation predicts k really well

$$k = k_0 v^m$$

- v = void ratio
- = porosity / (1 - porosity)
- k0 and m are empirical parameters that depend on clay type




Power law equation for the clays kaolinite, illite and smectite (in order of high to low k)
Luijendijk and Gleeson (2015) Geofluids



# Permeability of mixed sediments

- Perfectly clay-free sands or silt-free clays are quite rare in the subsurface
- The permeability of any mixture of sand, silt and clays can be predicted with reasonable confidence by taking the geometric mean of the permeability of the sand/silt component and the clay component:

$$\ln(k) = f \ln(k_{clay}) + (1 - f) \ln(k_{sand})$$

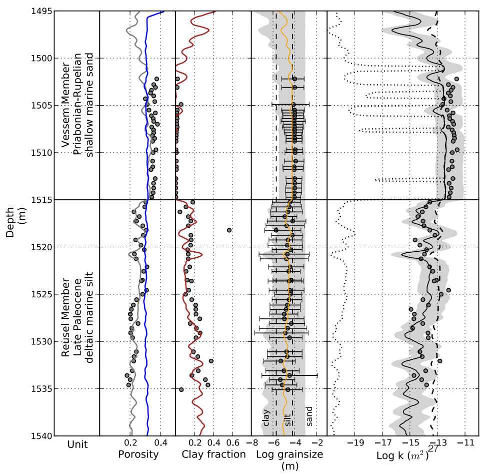
The geometric mean equation for permeability of a mixture of sand/silt and clay. f is the clay fraction



# Permeability of mixed sediments

- Example of calculated vs observed permeability in a 50 m thick formation in the Roer Valley Graben shows a reasonable fit of the geometric mean permeability model:

$$\ln(k) = f \ln(k_{clay}) + (1 - f) \ln(k_{sand})$$

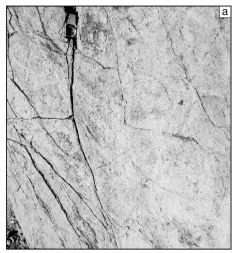



Comparison of observed and calculated permeability, suing the geometric mean model (right hand panel)
Luijendijk and Gleeson (2015)



# Part 2b: What controls permeability? Permeability of fractured rocks

- Most crystalline rocks have a very low 'matrix' permeability
- Most of the fluid flow through these rocks is channeled through fractures
- Can we predict fluid flow through fractured rocks?




Klimczak et al. (2010) HGJ

# Permeability of fractured rocks

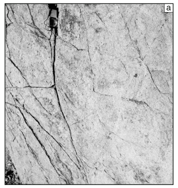
- Cubic law: approximate solution to the Navier-Stokes equations for a open space bounded by two parallel plates with aperture *a* (m):

$$k = \frac{a^2}{12}$$

- For a series of parallel fractures with fracture spacing *B* (m):

$$k = \frac{(2a)^3}{2B\ 12}$$

- Implications: fractured rocks can have very high permeabilities with moderate apertures and fracture spacings:



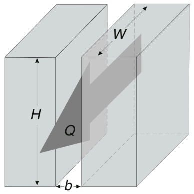




**Fig. 2** Flow (*Q*) between parallel plates with apertures (*b*), plate heights (*H*) and plate lengths (*W*)

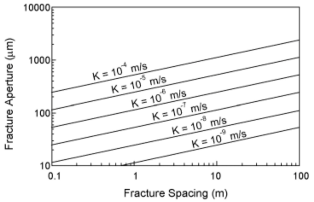



Figure 1.2. Relationship between fracture aperture, fracture spacing and aquifer hydraulic conductivity, for an aquifer consisting of planar, parallel uniform fractures. This figure can be simply derived using Equation 1.6.

Hydraulic conductivity for a parallel set of fractures
Cook (2003)

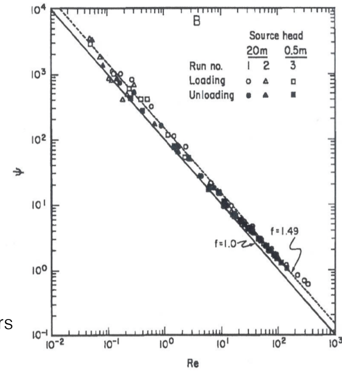


Klimczak et al. (2010) HGJ

# Permeability of fractured rocks

- Fractures do not have a perfectly smooth surface.
- Modification of cubic law by Witherspoon et al. (1980) to account for surface roughness
- f is an empirical factor to account for the additional flow resistance due to surface roughness
- f was found to vary between 1.04 and 1.65 in a large compilation of fracture data

$$k = \frac{a^2}{f\ 12}$$




Modified cubic law and predicted flow parameters through a fracture after landing and unloading experiments, Witherspoon et al. (1980) WRR



# Fracture permeability

- Fracture permeability is strongly dependent on aperture
- However, this is poorly known. Can be measured at the surface, but aperture changes strongly with confining pressure / depth
- In situ measurements are possible, but technically challenging

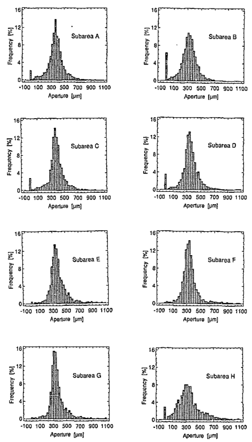


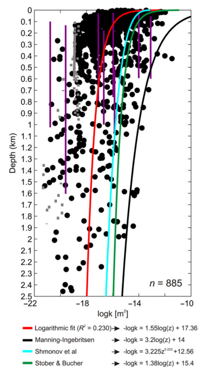

*Figure 12. Well mated fracture in granite (410x190mm). Frequency histogram of apertures. The total number of data is ~30 000 from eight subareas A - H [Paper F].*

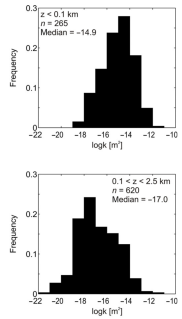
Compilation of fracture apertures in crystalline rocks in Sweden
Hakami (1995) PhD thesis



# Fracture permeability

- Overall the permeability of fractured rocks is highly variable
- Lots of ongoing research on the role of fracture distribution, connectivity, stress
- At a very large scale, there appears to be a change in permeability with depth, with the most permeable fractured rocks at the surface
- Possibly the effect of low confining stress at shallow depths on fracture aperture




Compilation of permeability of crystalline rocks
Ranjram et al. (2015) Geofluids

# Permeability and scale

- Permeability exhibits a scale dependence: tends to increase with the scale of measurement
- Reason?

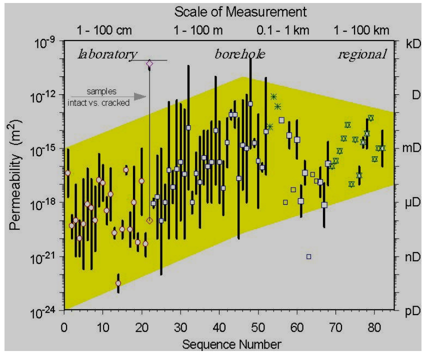


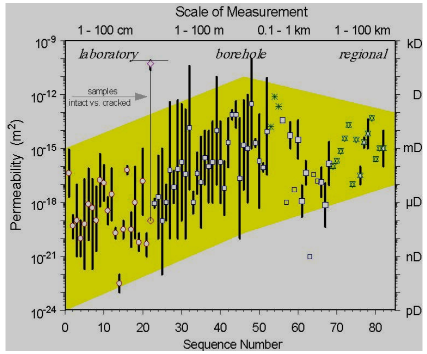

Fig. 1 Range of measured or inferred permeability of basement and metamorphic rocks at 82 locations (Table 1) as a function of the characteristic length scale (circles: laboratory measurements-diamonds: intact and cracked sample (at 22 MPa confining pressure); squares: in situ single and double packer tests, asterisks: tracer tests, stars: indirect methods; updated from Clauser [1992]). Shading suggests a trend for the scale effect of permeability with respect to the characteristic length scale.



source: http://www.geophysik.rwth-aachen.de/Forschung/Petrophysik/rocks/perm.htm

# Permeability and scale

- Permeability exhibits a scale dependence: tends to increase with the scale of measurement
- Reason: permeability is distributed unevenly, regional k dominated by a low number of high permeability conduits like faults or fractures with large aperture and connectivity
- The likelihood of intersecting one of these regional conduits gets higher with increasing scale of measurement

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# Effective permeability at large scales

- For flow parallel to layers, effective k = arithmetic mean

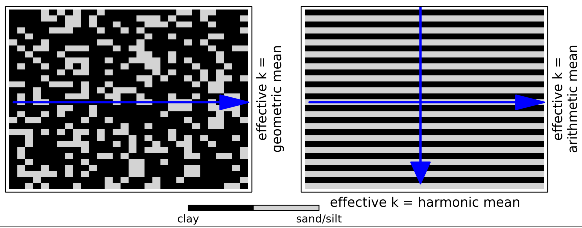
$$k_e = \frac{\sum k \Delta x}{\sum \Delta x}$$

- For flow perpendicular to layers, effective K = harmonic mean

$$k_e = \frac{\sum \Delta x}{\sum \frac{\Delta x}{k}}$$

- For random distribution of lithologies, effective k = geometric mean

$$\ln k_e = \frac{\sum \ln k}{n}$$






# Effective permeability at large scales

- For flow parallel to layers, effective k = arithmetic mean

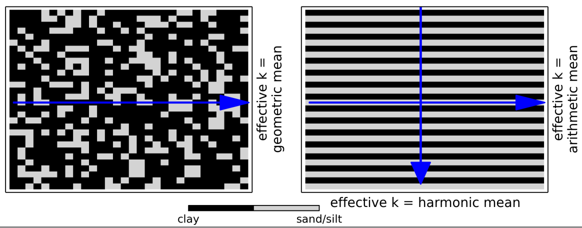
$$k_e = \frac{\sum k \Delta x}{\sum \Delta x}$$ highest k

- For flow perpendicular to layers, effective K = harmonic mean

$$k_e = \frac{\sum \Delta x}{\sum \frac{\Delta x}{k}}$$ lowest k

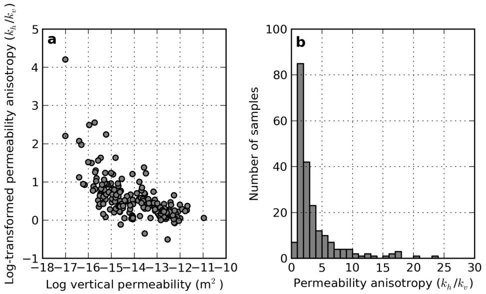
- For random distribution of lithologies, effective k = geometric mean

$$\ln k_e = \frac{\sum \ln k}{n}$$ in between



# Permeability, scale and anisotropy

- This gives rise to anisotropy: the effective horizontal / bedding parallel permeability is usually much higher than the vertical permeability in layered sedimentary rocks
- Permeability is very important in layered sedimentary rocks. ranges from ~1-10 at very small scales to >1000 at large scale
- Anisotropy can even be observed in small core-plug sized samples: apparently even very small scale heterogeneity influences permeability:




Anisotropy ($k_h$ / $k_v$) in a large permeability database of core samples from sedimentary rocks. Luijendijk & Gleeson (2015)



# Summary, part 2:

- Permeability granular material (silts, sands) can be predicted using the Kozeny-Carman equation
- KC equation not valid for clays -> use empirical power law equation
- Good first estimates of permeability of mixed sediments by taking the geometric mean of the granular (sand/silt) and clay components
- Fracture permeability: Cubic law and derivatives provide good first order estimates of permeability of individual fractures. However, aperture and fracture distribution and connectivity very difficult to characterise
- Permeability is scale dependent and dependent on direction, both as a result of heterogeneity
- Effective permeability = harmonic mean for flow perpendicular to layered sequence, arithmetic mean for flow parallel to sequence, and geometric mean for randomly distributed material



# Part 3: Crustal permeability

- Ok, so we know how permeability is measured, and which factors control permeability in porous rocks and fractures
- How does permeability vary in the crust?

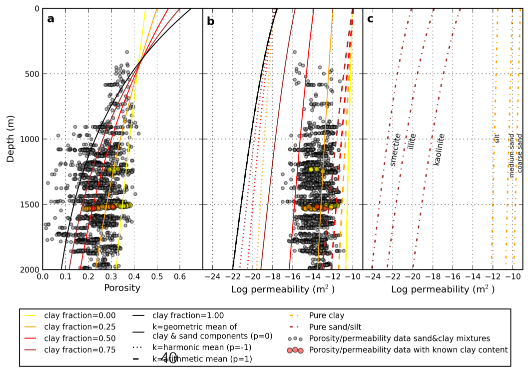


# Permeability of the shallow crust

- Sedimentary basins -> permeability relatively predictable
- Porosity = function of depth and effective stress (will be treated in upcoming lecture)
- Porosity-permeability relations -> using a combination of Kozeny-Carman eq. and empirical power law eq for clays, and the geometric mean of the two for sediment mixtures

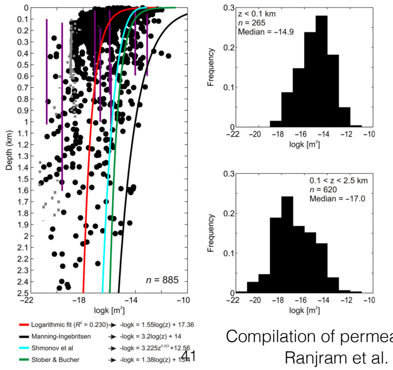
Example of observed permeability of sediments (circles) and theoretical permeability depth curves for sands, silts and clays

Luijendijk and Gleeson, unpublished



# Permeability of the shallow crust

- Fractured rocks: relatively unpredictable, no clear predictive relation with depth, lithology and geological setting
- Highest permeability near surface. Cause uncertain: weathering, unloading of fractures, glacial loading/unloading cycle?

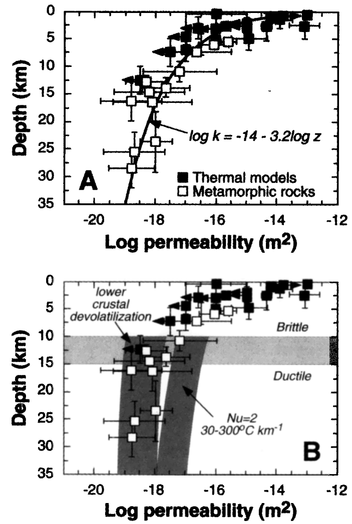


Compilation of permeability of crystalline rocks
Ranjram et al. (2015) Geofluids



# Permeability of the deep crust

- First compilation of permeability of the entire crust by Ingebritsen and Manning in 1999
- Derived from geothermal data (up to 7 km) and estimates of fluid fluxes produced by regional metamorphism
- Permeability decreases strongly with depth. However, there is still significant permeability in the deep crust
- Implication: the deep crust is not impermeable, significant fluid flow throughout the crust
- Even in the ductile part of the crust (below ~12 km)…

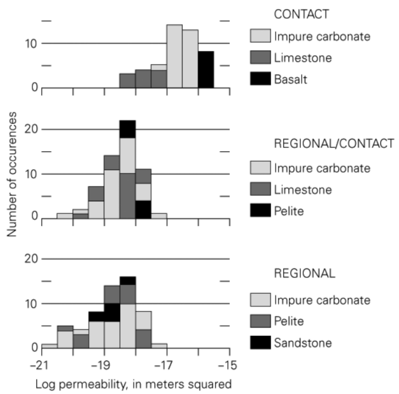





Manning and Ingebritsen (1999) Rev. Geophys.

# Permeability of the deep crust

- Compilation of inferred permeability of metamorphic rocks shows essentially no difference in k between different lithologies
- The reason is that metamorphism destroys pre-existing lithological contrasts that span ~13 orders of magnitude at shallow subsurface
- Much higher k for contact metamorphism. Potentially the results of high thermal gradients, high fluid pressures and resulting deformation (fracturing)




Compilation of permeability metamorphic rocks
Manning and Ingebritsen (1999) Rev. Geophys.



# Summary part 3

- Permeability shallow crust: sediments relatively predictable, fractured rocks not so much
- Deep crust: significant permeability. estimates based on models of metamorphic reactions
- Implications: fluid flux throughout the crust, including the ductile lower crust.

# Next week

- Lecture on terrestrial hydrothermal systems by Sarah Louis
- In two weeks (27 nov): Crustal heat flow, why does it get hot if you travel to the core of the earth?
- Reading material: Section 8.1 of Ingebritsen ea (2006).