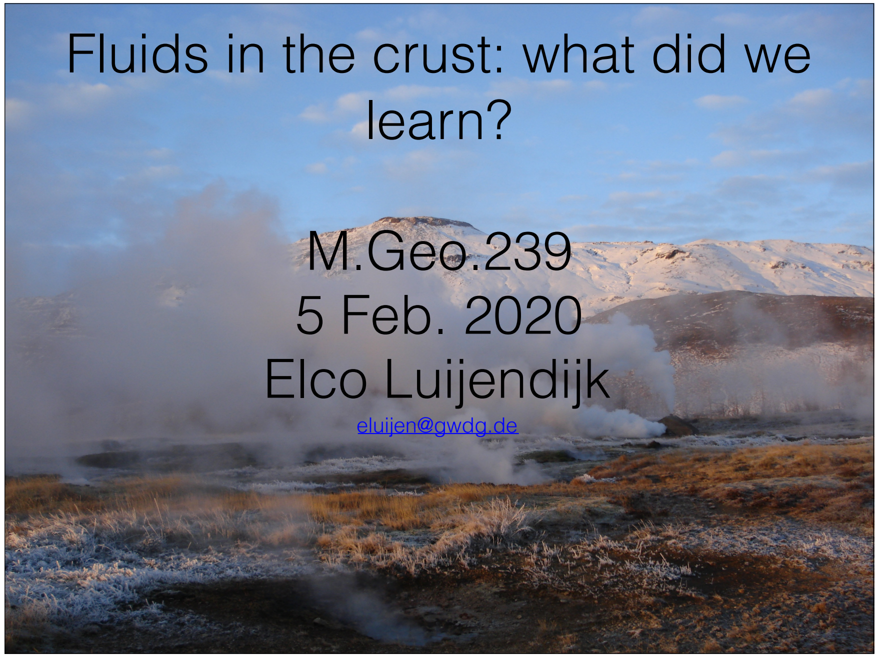

Fluids in the crust: what did we learn?

M.Geo.239
5 Feb. 2020
Elco Luijendijk
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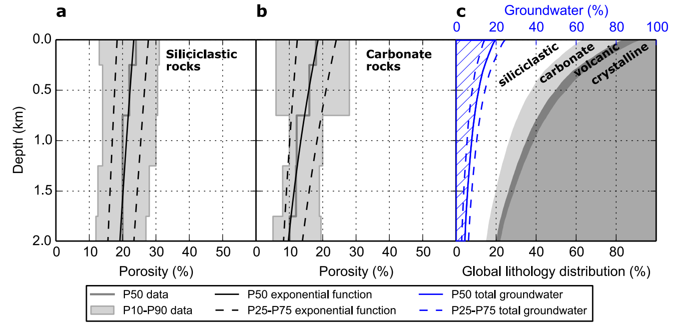
Lecture 2: Groundwater volume in the upper crust

- First order estimate of volume of water in the upper 2 km of the crust = 23 million km^3
- = ~1.5% of the total ocean volume = equal to antarctic ice sheet volume
- = layer of 180 m of water over continental surface
- However, only ~3 m of this layer consists of young water that infiltrated less than 50 yrs ago, most water is much older

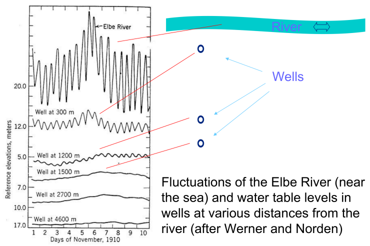


Gleeson et al., Nature Geosc. (2016)

Lecture 3: Diffusion

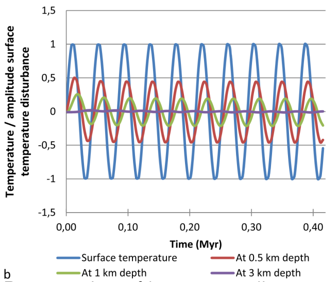
- Fluid flow, heat flow and solute transport are all governed by diffusion laws

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



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

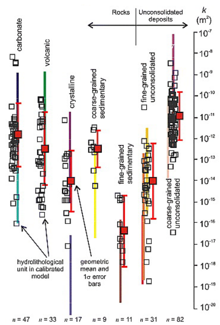
Fluctuations in hydraulic head around the Elbe river
Source: J.Barker, Univ. Southampton

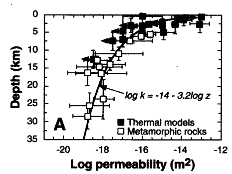


Propagation of long-term climate fluctuations in the subsurface.
ter Voorde et al (2014) NJG

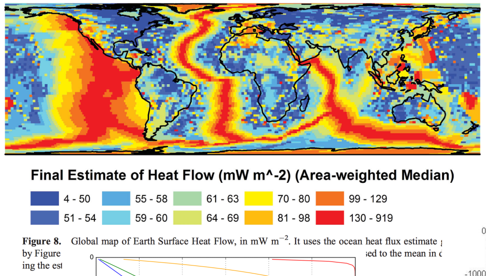
Lecture 4: Permeability

- Quantifying permeability, lab test, pumping tests, calibrating models
- Predicting permeability of sediments (Kozeny-Carman eq) and of fractured rocks (cubic law)
- Permeability, scale and anisotropy
- Permeability of the 'static' crust and the tectonically disturbed crust

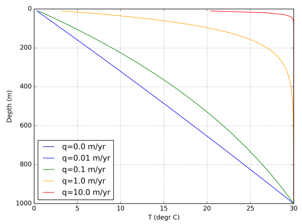




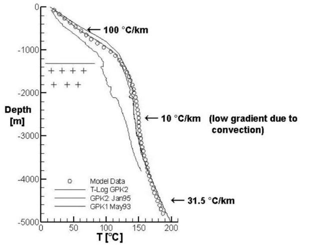
Lecture 6: Crustal heat flow



Global distribution of surface heat flow, Davies (2013) G3



Analytical solution thermal effect of upward fluid flux after Bredehoeft and Papadopulos (1965)

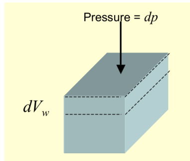


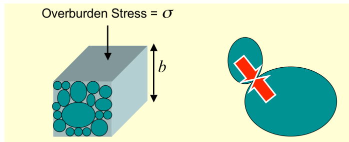
Modeled vs observed temperatures in the upper Rhine Graben near Soulz Kohl et al (2000)

Lecture 7: Specific storage

- In words: specific storage = water released from the reduction of porosity due to compression of rock matrix: dΦ/dh
- + water from the compression or expansion of fluid: $d\rho_f/dh$

$$S_s = \rho g \left(\phi \beta_f + \beta_m\right)$$





Lecture 7: The fluid flow equation

- Ok, we now have one equation for fluid flow with a single unknown (h)
- Different forms of the fluid flow equation:

$$S_s \frac{\partial h}{\partial t} = \nabla \left(\frac{\rho g k}{\mu} \nabla h \right) + W$$

fluid flow eq.,

$$S_s \frac{\partial h}{\partial t} = \nabla \left(K \nabla h \right) + W$$

fluid flow eq., with hydraulic conductivity (K), assumes constant fluid viscosity and density

$$0 = \nabla \left(K \nabla h \right) + W$$

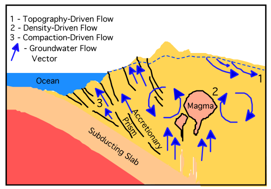
Steady state (no change over time)

$$S_s \frac{\partial h}{\partial x} = \frac{\partial K \frac{\partial h}{\partial x}}{\partial x} + W$$

one-dimensional, with hydraulic conductivity (K)

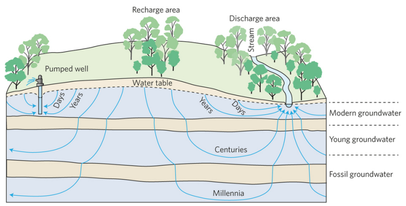
Lecture 8-10: Driving forces of fluid flow

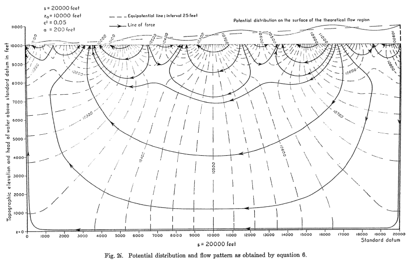
- Driving forces, why do crustal fluids flow?
  - Topography/Recharge-driven flow
  - Buoyancy, density-driven flow, free convection
  - Flow driven by compaction, sedimentary or tectonic loading



Lecture 8: Recharge-driven flow

- Recharge-driven flow: interplay of recharge and groundwater discharge to rivers, lakes, oceans or direct evapotranspiration
- Relief segments flow into local and regional flow systems
- Flow decreases with depth due to layered permeability structure, permeability anisotropy and permeability decrease with depth



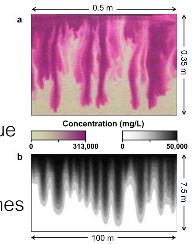


Topography-driven flow, Fan (2015)

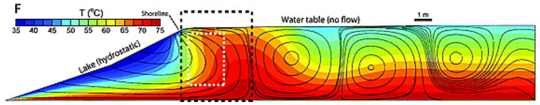
Nested flow systems, Toth (1963)

Lecture 9: Density-driven flow

- free convection = flow driven by buoyancy forces as a result of density differences
- fluid energy potential = ∇P + **ρ**g∇z
- density (ρ) is a function of temperature and salinity
- convection driven by salinity differences: important in coastal regions, salt lakes, around salt diapirs
- thermal convection important in magmatic and volcanic settings due to high temperature gradients and strong density contrasts
- in non-magmatic settings: convection may be important in fault zones



Convection driven by salinity differences



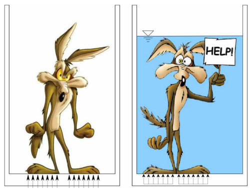
Thermal convection near a volcanic lake

Lecture 10: Compaction-driven flow

- Porosity is a function of effective stress

$$\sigma_e = \sigma - \alpha p$$

- =difference between total stress σ and porewater pressure (p)



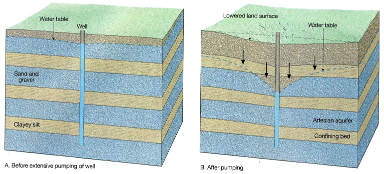


FIGURE 12.8 Before (A) and after (B) extensive pumping of a well. Note in B the lowering of the water-pressure surface, compaction of confining beds between the aquifers, and resulting subsidence of land surface. Arrows indicate the direction of compaction caused by the downward force of gravity, after the opposing water pressure was reduced by excessive withdrawal (discharge) of groundwater from the well.

Lecture 10: Compaction-driven flow

- Porosity change: elastic and inelastic components
- Elastic part is relatively small. Most porosity change is irreversible.
- Porosity mainly a function of mechanical compaction in upper 2-3 km of crust

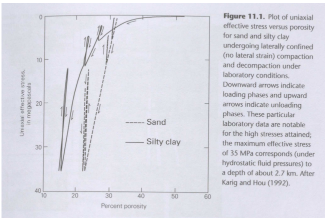
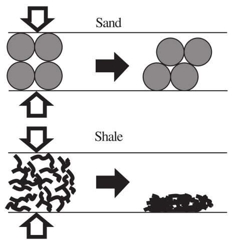


Figure 11.1. Plot of uniaxial effective stress versus porosity for sand and silty clay undergoing laterally confined (no lateral strain) compaction and decompaction under laboratory conditions. Downward arrows indicate loading phases and upward arrows indicate unloading phases. These particular laboratory data are notable for the high stresses attained; the maximum effective stress of 35 MPa corresponds (under hydrostatic fluid pressures) to a depth of about 2.7 km. After Karig and Hou (1992).



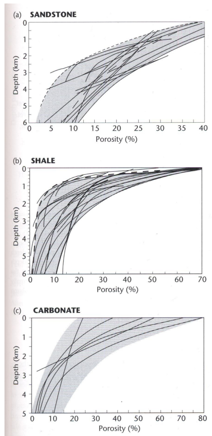
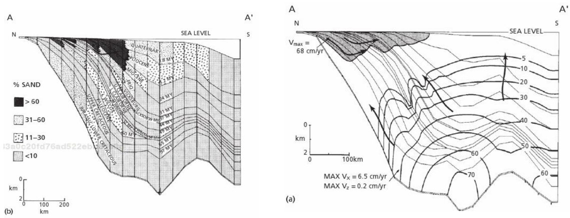
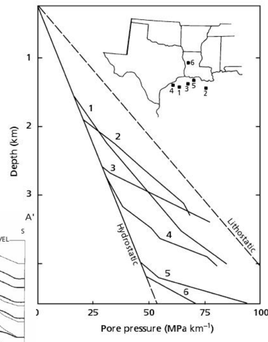


Fig. 9.3 Compilation of porosity–depth curves for sandstones (a), shales (b), and carbonates (c). Sources of datasets in Giles (1997). Note that shales compact early compared to sandstones. The porosity–depth relation for carbonates varies according to grain types and amount of cementation. Reproduced courtesy of Springer.

Lecture 10: Compaction-driven flow

- Compaction very important for generating overpressures
- However, flow velocities and volumes generated by compaction are relatively low, especially compared to recharge-driven flow

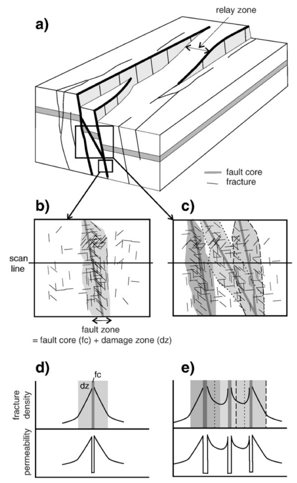




Overpressures and compaction-driven flow in the gulf of Mexico

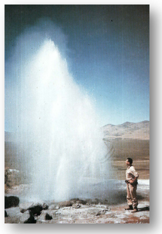
Lecture 11: Faults

- Faults are both conduits and barriers to fluid flow
- High permeability along the fault due to damage zone (consolidated rocks), incorporation of permeable lithologies in the fault plane (unconsolidated rocks)
- Low permeability for flow perpendicular to the fault due to clay smear, cataclasis, formation of clay mineral, cementation

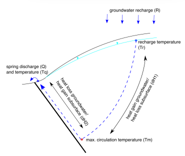


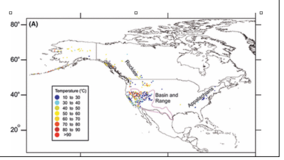
Bense et al. (2013) Earth Sc. Rev.

Lecture 5: Continental hydrothermal systems



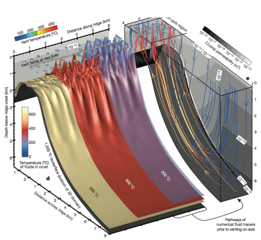
- •Hydrothermale Aktivität in kontinentaler Kruste ist oft an Störungen gebunden
- •Störungszonen weisen eine hohe Permeabilität auf und bieten Fließwege für tiefes Grundwasser
- •Ökonomische Bedeutung: Erzlagerstätten und Energiegewinnung (Geothermie)
- •Wissenschaftliche Bedeutung: Geben einen Einblick in den tiefen Untergrund und Aufschlüsse über beispielsweise:
- •Die Aktivitätsdauer eines hydrothermalen Systems
- •Den Wärmefluss im tiefen Untergrund
- •Die Zirkulationstiefe
- •Den thermischen Fußabdruck einer heißen Quelle, der Einfluss auf Niedrigtemperatur-Thermochronometer haben kann

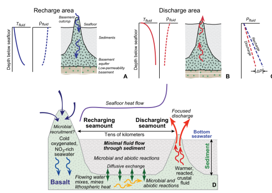


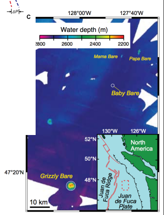


Lecture 12: Seafloor hydrothermal systems

- Focused advective heat transport by fluids facilitates ~30% of the total heat loss in young (<65 Ma) oceanic crust
- Spreading ridges host high temperature systems (>350 ˚C), black smokers. Can be explained by thermal convection, but need a poorly constrained high permeability (k=~10^{-12} m^2)
- Ridge flanks: lower temperature (100-200˚C) vents at widely spaced outcrops of basement rocks between sedimentary cover. Long range (tens of km) fluid flow between seamounts. Can potentially be explained by combination of thermal convection and siphon formation due to difference in convection rate, temperature and density between different seamounts







What to do with the equations?

- The lecture series has introduced a number of equations. However it may not always have been clear what we can use these equations for
- Simple answer: They help us quantify subsurface fluid & heat flow
- Perhaps somewhat obvious: If you know all variables in an equation except one, you can calculate the remaining variable
- Example, Darcy's law:
- If you know K and the hydraulic gradient (dh/dx). For example, if you know the hydraulic head in two wells (h), the distance between these wells (x) and there is data for (or you can estimate) K, then you can calculate q, which is the groundwater flux between the two wells
- Important: Always do a unit check when you work with equations. This helps avoid errors (and increases your grade…). There's also some famous errors with metric to english unit conversion, like a lost Mars orbiter and a Canadian airplane that ran out of fuel too early, both of which could have been avoided with a unit check
- In the case of Darcy's law with q as unknown the unit check is admittedly somewhat simple and results in the correct units for q (m/sec):

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

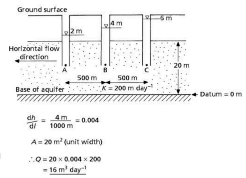
$$q = K\frac{\partial h}{\partial x} = ms^{-1}mm^{-1} = ms^{-1}$$

What to do with the equations?

- Note that there is also a depth-integrated version of Darcy's law. This calculates the flux though a formation with thickness b
- And you can rewrite this law to a 3D version as well by multiplying with area (A, m2) instead of thickness b (m)
- Other options with Darcy's law: You know the flux (Q), because either the recharge rate (m/s) and the size of the area where recharge takes place (m) are known, or for instance groundwater flow into a river (baseflow) or springs is measured directly. And you know K and b. In this case you can estimate the hydraulic gradient (dh/dx) (dimensionless)
- You can use Darcy's law with hydraulic head values taken from maps (provided they're in the same formation) which provides you with information on lateral flow
- Another option is to use hydraulic head data at different depths from closely spaced wells, this provides information on vertical flow rates

$$Q = Kb\frac{\partial h}{\partial x} = ms^{-1}mmm^{-1}$$
$$= m^2s^{-1}$$

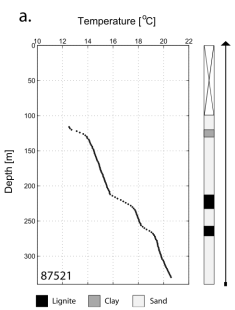
$$\frac{\partial h}{\partial x} = \frac{Q}{Kb} = m^2s^{-1}m^{-1}sm^{-1}$$
$$= \text{dimensionless}$$



What to do with the equations?

- Fourier's law:
- Similar to Darcy's law: If you know the geothermal gradient (dT/dz) and the thermal conductivity (K, W /(m K)) you can estimate heat flow Q (W)
- Or if you know heat flow and K you can calculate geothermal gradient (dt/dz)
- Obvious choices for the geothermal gradient at large scale is the difference between the lithosphere-astenosphere boundary and the surface temperature
- Or at smaller scale, geothermal gradients measured in wells

$$Q = K\frac{\partial T}{\partial z} = Wm^{-1}K^{-1}\ Km^{-1}$$
$$= W$$



What to do with the equations?

- Other equations that are important:
- Compressibility equation: calculate the change in volume (dV, m^3) for a change in pressure (P, Pa)
- See lecture slides for the following equations (and try a unit check on them yourself):
  - Effective stress, hydrostatic fluid & lithostatic pressure. Calculate pressure as a function of fluid or total overburden
  - Athy's law: calculate porosity as a function of depth/effective stress and compressibility
  - Kozeny-Carman equation: Calculate permeability as a function of porosity
  - The effective permeability of a geological unit. Depending on the direction of flow and the structure (layered or random) this is the harmonic, geometric of arithmetic mean of the individual components (sand, clay, etc…)

$$\partial V = \beta V \partial P = Pa^{-1}m^3Pa$$
$$= m^3$$

The exam

- Grading: 1 grade for module
  - Exam LV1: 50% of final grade
  - Exercises (LV2): 50% of final grade
- Exam will consist of 5 questions, of which you can pick 4. In case you answer all 5 of the questions then your grade will be based on the 4 questions with the highest score
- Feel free to ask questions on the study material, I can be found in room 122 or send an email to eluijen@gwdg.de

What to study for the exam?

- Material:
  - Lecture slides
  - Reading material (see syllabus):
    - Chapter 1 and section 8.1, 11.1 and 13.1-13.5 of Ingebritsen et al. (2006)
    - Papers by Cathles, Garven and by Ingebritsen & Gleeson on permeability, with the exception of the part on "Contents of the special issue"
- Exam questions will test your understanding of processes, so no questions on how many hydrothermal springs are there in North America, but more something like "in what type of geological setting do we find most hydrothermal springs in North America? and can you name a reason why there are more springs there?"

What to study for the exam?

- Equations: memorise only the most important ones:
  - Diffusion equations: Darcy's law, Fourier's law (heat flow)
  - Fluid potential and hydraulic head
  - Effective stress
  - hydrostatic stress and lithostatic stress
- Full fluid flow and heat flow equations: you should be able to explain which part does what in each equation, which part of the equation controls the flux, where is the source term, which parameter controls the change of pressure over time etc…
- Same for full storativity equation (compressibility rock and water), Kozeny-Carman eq.
- No need to memorise the derivations, but try to understand broadly what is going on
- Important: when is each equation valid and when is it not? ie. when can one use Darcy's law and in which cases not? (turbulent flow…)
- Key parameters like porosity, permeability, temperature: how do we know these, how important are they (relatively) in determining fluid and/or heat flow, and are they relatively certain or uncertain?
- Good luck!