Driving forces part 2: density-driven flow

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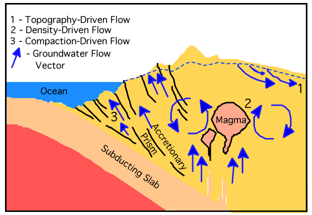
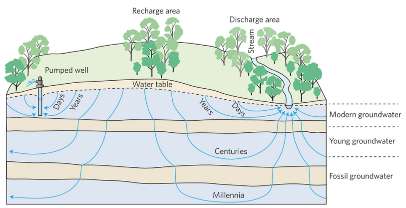
This week: more on the driving forces of fluid flow

- Driving forces, why do crustal fluids flow?
  - ~~Topography-driven flow~~ / Recharge-driven flow
  - **Buoyancy, density-driven flow, free convection**
  - Flow driven by sedimentary or tectonic loading
  - Fluid production or consumption by chemical reactions

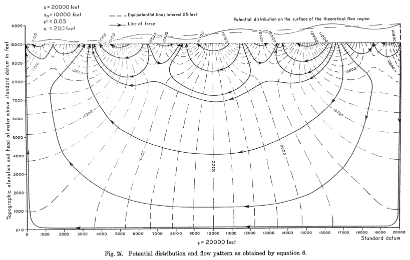


Review: recharge-driven flow

- Topography-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)

Some more physics: transport of heat or solutes by groundwater flow

- So far we have only considered transport of heat or solutes in the subsurface by diffusion
- However, diffusion is not the only process that affects heat or solute concentrations: fluids can transport heat or solutes
- Transport of heat or solutes by fluids is termed advection

$$\rho c \frac{\partial T}{\partial t} = \nabla K \nabla T + W_h$$ Diffusion equation

$$\rho c \frac{\partial T}{\partial t} = \nabla K \nabla T + \rho_f c_f \vec{q}_f \nabla T + W_h$$ Diffusion + advection equation

Some more physics: transport of heat or solutes by groundwater flow

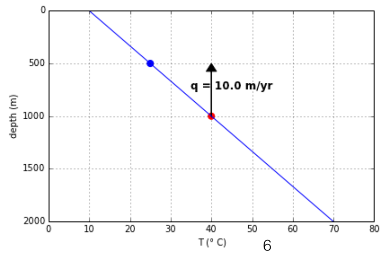
- Heat can also be transported by fluids = advection
- Advection term: $\rho_f c_f q_f \nabla T$
- advection mainly depends on fluid flux (q_f) and temperature gradient (∇T)
- and to a lesser degree on density (ρ_f) and heat capacity (c_f) of the fluid

$$\rho c \frac{\partial T}{\partial t} = \nabla K \nabla T + \rho_f c_f \vec{q}_f \nabla T + W_h$$

Diffusion + advection equation

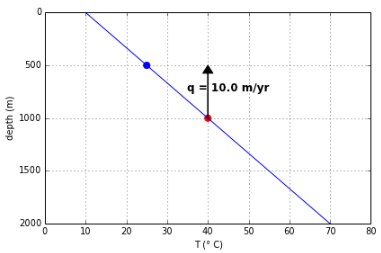
Heat advection: example

- upward advection of heat between 2 points in the subsurface
- geothermal gradient (∇T) of 30 C/km = 0.03 C/m
- upward fluid flux (q) of 10 m/yr
- How much heat is transported upward?
  - heat advection = $\rho_f c_f q_f \nabla T$
  - heat capacity (c) = 4200 J K^{-1} kg^{-1}, density (ρ) = 1000 kg m^{-3}
- Answer: upward heat flux by advection =1000 * 4200 * 10.0 * 0.03 = 1.26×10^6 J/yr



Heat advection: example

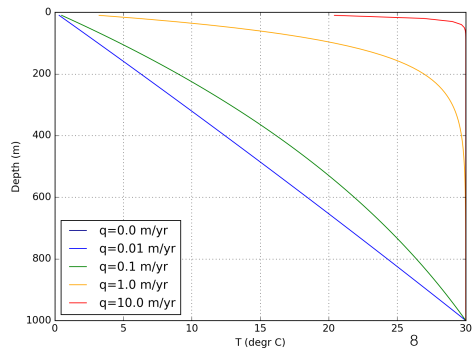
- Use full heat flux equation to estimate advective temperature increase, ignoring diffusion for now…
- point at 500 m gets an amount of heat added to it each year:
  - ρc dT/dt = 1.26 * 10^6 J/yr
- translate to temperature increase using a bulk (rock+fluid) density ρ=2000 kg/m^3 and heat capacity c=1200 J/(K kg):
  - dT/dt = 1.26 * 10^6 / (2000 * 1200) = 0.525 ˚C/yr



$$\rho c \frac{\partial T}{\partial t} = \nabla K \nabla T + \rho_f c_f \vec{q}_f \nabla T + W_h$$

Heat advection

- Thermal effect of fluid flow at vertical fluid fluxes of approx. > 0.03 m/yr
- Compare to flux in average watershed in exercises 1 and 2 of 5 m/yr



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

Buoyancy flow

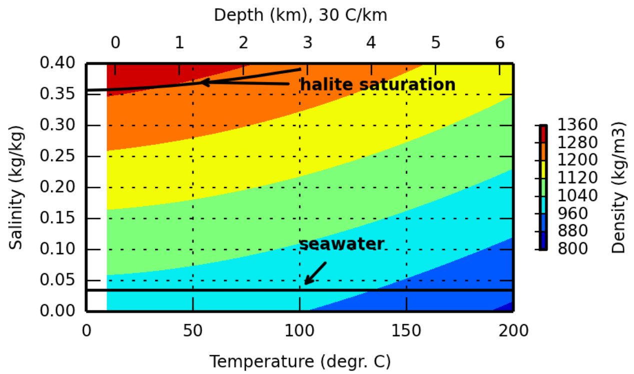
- Fluid flow can transport heat and solutes in the subsurface by advection
- However, differences in temperature and solute concentration can in turn drive fluid flow
- The link between temperature, salinity and fluid flow is density, which is a function of temperature and salinity
- Density affects the buoyancy of fluids

Density and fluid energy potential

- Driving force of fluid flow: energy potential
- Energy potential per weight unit = hydraulic head
- Full equation for energy potential contains density term:
  - fluid energy potential = $\nabla P + \rho g \nabla z$

Fluid density

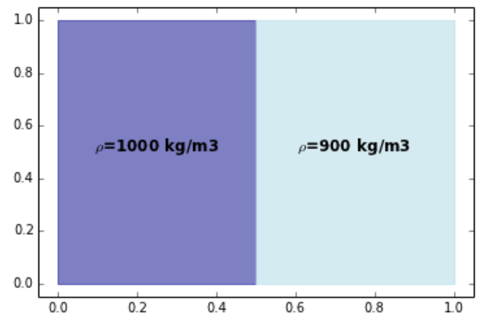
- Fluid density varies with strongly with changes in salinity, and somewhat less strong with changes in temperature:



Relation between fluid density, temperature and salinity (after Batzle and Wang (1992)

Fluid potential example

- Two fluids side by side with contrasting density
- **Question**: Is this stable?

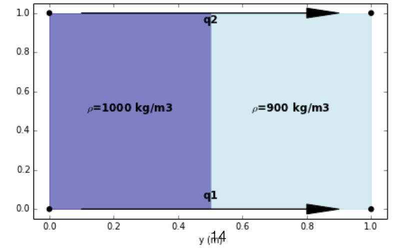


Fluid potential

- We can try to calculate what would happen by calculating the difference in potential energy of the fluid at two points
- If there is a difference, the system will strive to lower potential energy by applying force
- Remember from last week: fluid energy potential per unit mass: $E_t = P/\rho + gz$
- energy potential per unit volume: $E_t = P + \rho gz$ = pressure + density x gravitional acceleration x elevation
- gravitational potential is always directed downwards, new formulation of the difference in fluid energy potential:
  - $\nabla P + \rho g \nabla z$

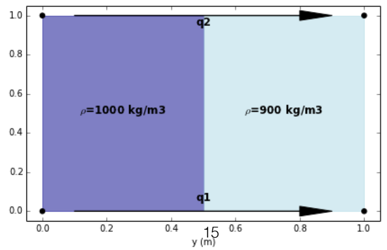
Fluid potential example

- Question: Is this stable? Try to find answer by calculate the fluid potential differences
- bottom left: $P = \rho gh$
  - = 1000 * 9.81 * 1.0 = 10000 Pa
- bottom right: $P = \rho gh$
  - = 900 * 9.81 * 1.0 = 9000 Pa
- difference in fluid energy potential per unit volume = $\nabla P + \rho g \nabla z$
- ∇z is 0 between both points. -> left has a higher potential energy than the right, which results in a force and flow q1 directed to the right



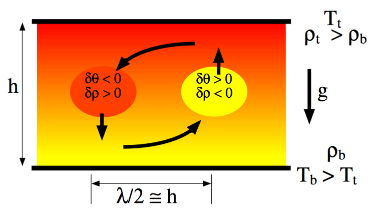
Fluid potential example

- same procedure for potential difference at top:
- ∇P?
  - -> top left = P top right = 0.0 Pa -> no pressure energy
- no elevation difference, $\rho g \nabla z = 0$ -> no gravitational potential too
- no energy potential difference, q2 = 0, no flow at the top
- result: rotational flow, dense water at bottom flows to the right. initially water at the top is static, but as the water at the bottom flows to the right the system will have to adjust by moving water on the top to the left.



Free convection

- Density-driven flow can be sustained if there is an external source of energy that affects density (either heat, or addition of solutes by dissolution)
- Convection driven by buoyancy is called free convection
- First discovered in experiments by French physicist Benard in 1900



Explanation of free convection Manneville (2000)

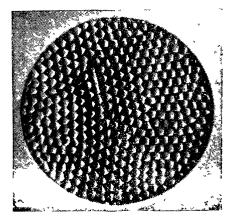


FIG. 4. — Grandeur naturelle. Température : 90°. Épaisseur : 430µ.

View from top on convection cells in material heated from the bottom, original by Benard (1900)

Free convection

Lord Rayleigh

- Theory of what drives free convection completed by Rayleigh in 1916
- Also known for discovery of the Rayleigh wave, and for discovering argon
- The likelihood of convection depends on density difference (Δρ), size of a system (L), permeability (k), and to a lesser degree on viscosity (μ) and solute or thermal diffusion coefficient (D)

$$Ra = \frac{\Delta\rho k g L}{\mu D}$$

- Free convection in porous media (subsurface flow) at Ra>~40
- -> Convection more likely at high temperature gradients, thick homogeneous layers, high permeability

Free convection

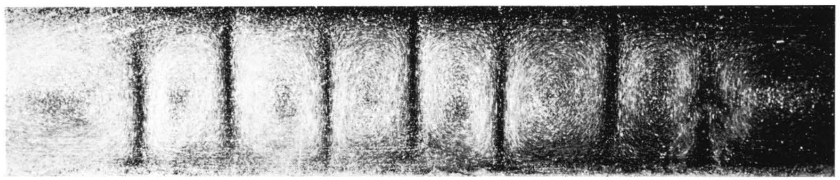
- Theory of what drives free convection completed by Rayleigh in 1916
- Equation for convection driven by temperature gradients (ΔT):

$$Ra = \frac{\eta\rho\Delta T k g L}{\mu D}$$

- New parameter: η = the thermal expansion coefficient (ie how does density change with a change in temperature)
- Free convection in porous media (subsurface flow) at Ra>~40
- Convection mainly depends on layer thickness H (m), permeability k (m^2) and thermal gradient ΔT (˚C)
- -> Convection more likely at high temperature gradients, thick homogeneous layers, high permeability

Free convection in experiments

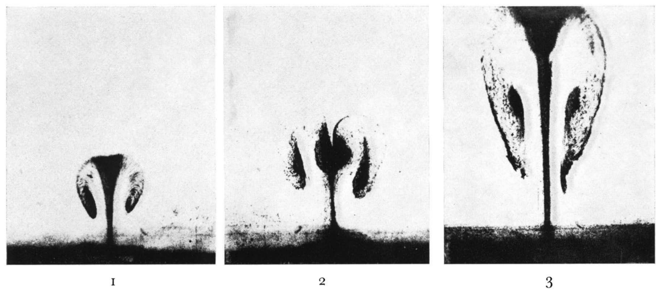
- Density-driven fluid flow organises into convections cells, with upward directed and downward directed limbs
- = self organising nonlinear process
- You can show this nicely in lab experiments:



Fluid convection in a thin strip heated from below, 30 cm x 6 cm, heating at left 10 cm. Elder (1977)

Free convection in experiments

- Spot heating generates a single plume:



Convective motion produced by a small temporary heat source at the base of a fluid layer, Elder (1977)

Free convection in experiments

200 g of butter
200 g of sugar
pinch of salt
7 g of vanilla sugar

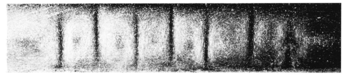
4 eggs
200 g of self-raising flower, sieved
4 tablespoons of cacao
2 tablespoons of sugar

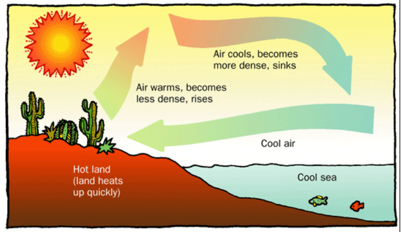
All ingredients must be at room temperature.

Fluid convection cake. Contact me for recipe.
Source: C.J. Wannee (1909) Cookery book of the Amsterdam domestic science school. in PhD thesis Vincent Post (2004)

Free convection in the crust

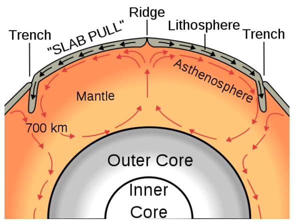
- Convection can be observed in experiments
- And in the atmosphere
- Does fluid convection occur in the subsurface and if yes, where?

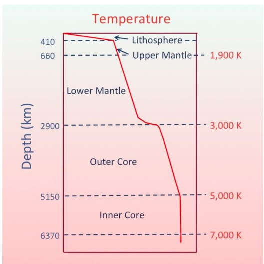




Mantle convection

- Mantle convection: dominant heat transport mechanism in the mantle
- Results in steep geothermal gradient in the mantle compared to lower gradients in the crust: convection is a more efficient heat transport mechanism than conduction
- The exact nature of convection and importance for and interaction with crustal forces (subduction) are still under debate….

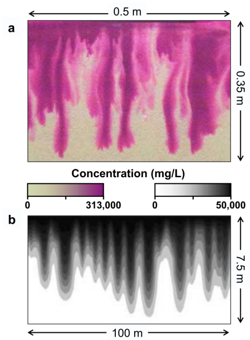




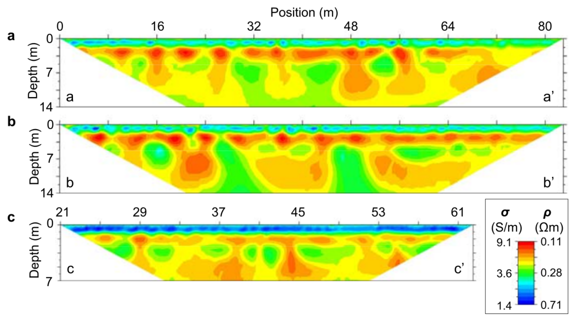
Source: Wikipedia

Convection driven by salinity gradients

- Only direct observation of free-convection of fluids in the subsurface (known to me): convection of saline water beneath a sabkha (salt flat)



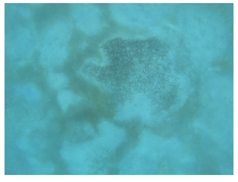
Salt fingers in lab experiments (top) and numerical models (bottom)

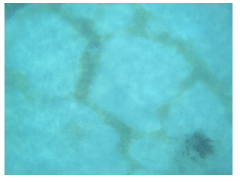


Resistivity profiles underneath a sabkha in Abu Dhabi, Van Dam et al. (2009) red=saline, blue=fresh

Field evidence for convection cells?

- New discovery in july 2019: orange stripes on seafloor at a hydrothermal site in at the coast of Guadeloupe
- Note the similarity in shape with models of convection cells
- Convection related to hydrothermal activity, area hosts many small springs with temperatures of ~90 C
- Color is probably because of diatoms that prefer locations with discharge of hot Si-rich water





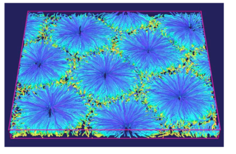
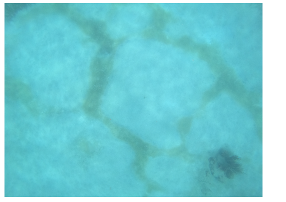


FIG. 1. (Color online) Final streamline plot for the large rectangular system A showing the hexagonal cell pattern; the streamlines are color coded to indicate temperature variation (ranging from red for hot to blue for cold in the color online version).

Photos of seafloor 50 m off the western coast of Guadeloupe depth ~5 m, horizontal scale = 17 m

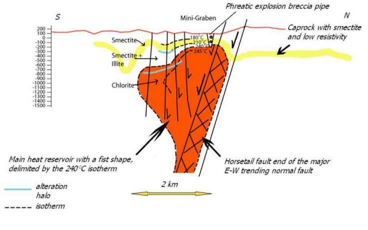
Rapaport et al. (2006) Phys. Rev. E

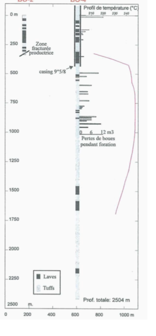
Field evidence for convection cells



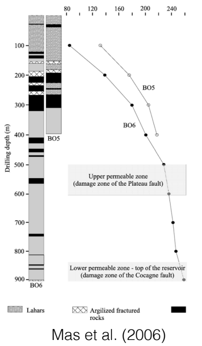
Field evidence for convection cells?

- Potential convection cells located at an active hydrothermal site
- Extremely high and overturned geothermal gradients indicate a possible relatively recent (ky) system with hot fluid flow along a major fault zone





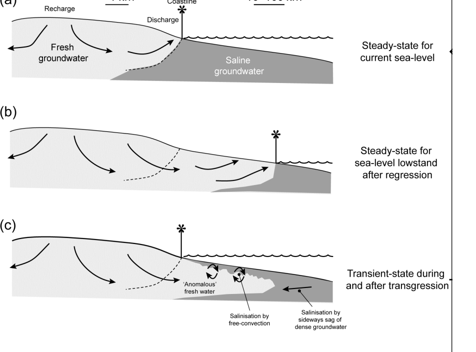
Sanjuan et al. (1999) BRGM report



Mas et al. (2006) jrnl of volc. and geothermal res.

Convection driven by salinity gradients

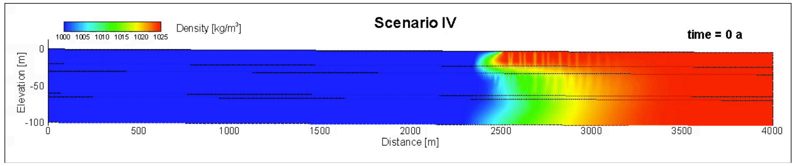
- Convection of saline water can be important in coastal groundwater systems where fresh water and sea water mix
- Over geological timescales: transgression -> seawater over remaining fresh water in inundated aquifers -> density-driven flow



Source: Victor Bense

Convection driven by salinity gradients

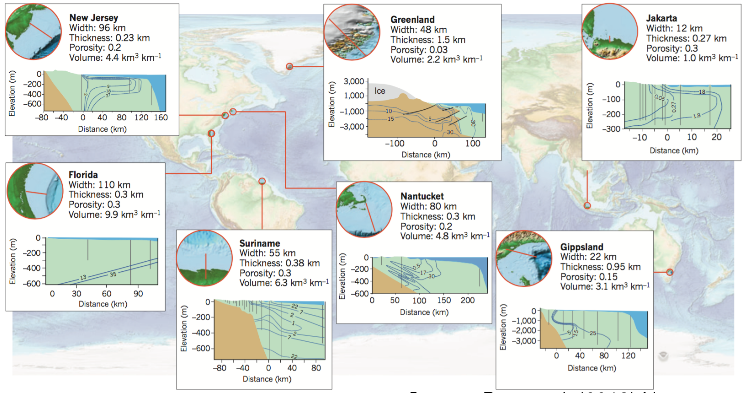
- Density-driven flow by convection of dense saline water into underlying fresh-water aquifer



Modeled salinization coastal plain
during Holocene transgression (Bense, 2015)

Convection driven by salinity gradients

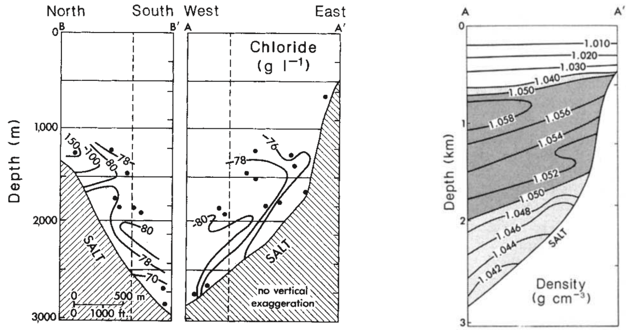
- In several places around the world offshore fresh groundwater is shielded from convective salinisation by low-permeability sediments -> large freshwater occurrences in the coastal shelf



Source: Post et al. (2013) Nature

Convection driven by salinity gradients

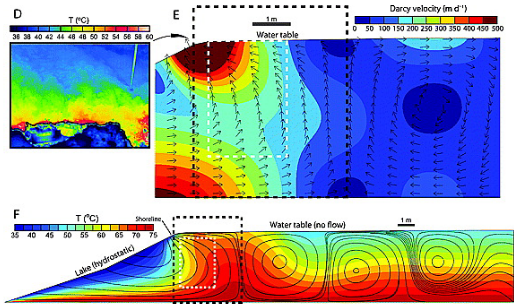
- Convection may be important around salt diapirs: dissolution of salt from diapirs creates strong salinity and density gradients that drive fluid flow



Salinity and density inversion around a salt diapir in the gulf of Mexico, Hanor (1987)

Thermal convection in volcanic settings

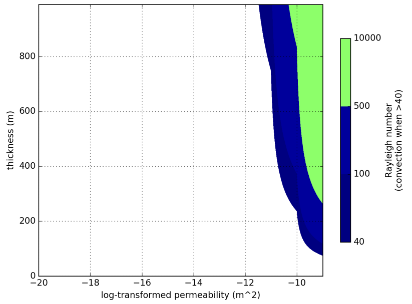
- Convection driven by thermal gradients is very likely in volcanic and magmatic settings due to the very large temperature gradients involved



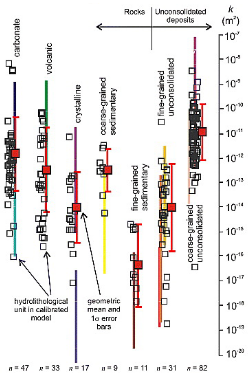
Example of observed temperatures in a volcanic lake (top left)
and modeled thermal convection (Cardenas 2012)

Thermal convection

- Thermal convection in normal geothermal gradients (30 C/km) requires thick permeable formations (coarse-grained sedimentary rocks)



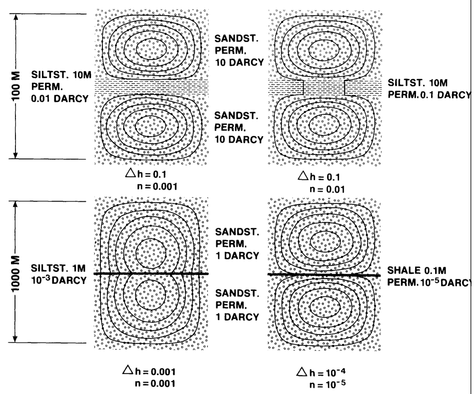
Rayleigh number for geothermal gradients of 30 C/km
Free convection only occurs at high permeabilities



Permeability of various lithologies
Gleeson (2011)

Thermal convection in sedimentary rocks

- However, sedimentary rocks are never homogeneous
- Theoretical analysis shows that even thin (0.1 m) layers of low-permeability material such as clays split convection cells
- Natural rocks consist (mostly) of a continuous alteration of more and less permeable rocks
- This means that there is very little space for convection cells to develop
- Is there any convection in sedimentary rocks at all?



Effect of low-permeability layers
on thermal convection, Bjørlykke (1988)

Thermal convection compared to other driving forces

- Additional limiting factor for convection: the potential gradients and resulting flow velocities tend to be very low compared to topography-driven flow
- -> topography-driven flow will overwhelm convection in many cases

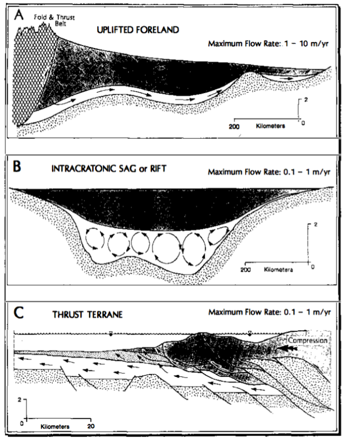
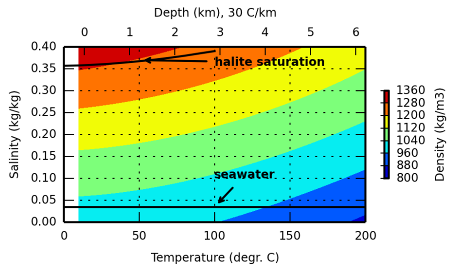


Figure 1 Hydrogeologic and tectonic regimes for continental-scale groundwater flow. Arrows depict general flow directions. (A) Gravity- or topography-driven flow in a foreland basin. (B) Thermally driven free convection in an intracratonic sag or rift basin. (C) Tectonically driven flow in a fold-and-thrust belt. (D) Overpressuring during compaction of a continental margin. (E) Seismic pumping of deep fluids in a rift. (F) Compartmentalization of a basin with no deep regional flow.

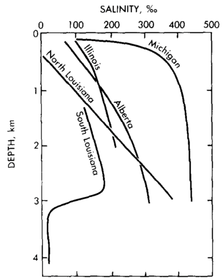
Comparison of different driving forces of basin-scale fluid flow. Garven (1995)

Thermohaline convection?

- In sedimentary basins, the density effects of increasing temperatures with depth may be cancelled out by the general increase of salinity with depth
- Thermohaline convection is rather unlikely in most cases, even though for some reason it is a popular term in the literature

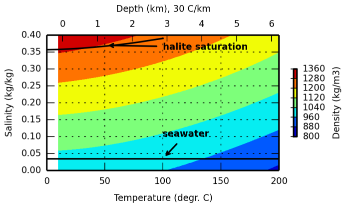


Relation between fluid density, temperature and salinity (after Batzle and Wang (1992)



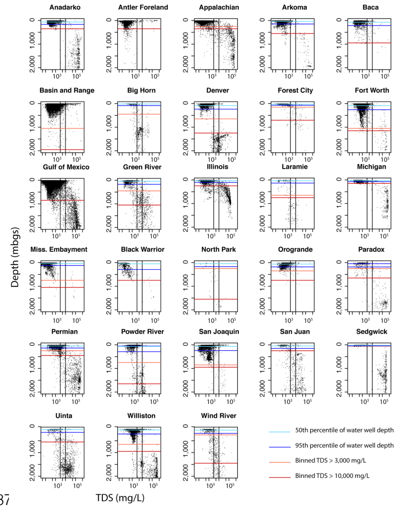
Groundwater salinity in sedimentary basins
Hanor (1979)

Thermohaline convection?



Relation between fluid density, temperature and salinity (after Batzle and Wang (1992)

Compilation of salinity in sedimentary basins in north America,
Ferguson et al. (2018) Env. Res. Letters
TDS = total dissolved solutes. TDS of 3000 mg/L is approximate boundary of fresh and brackish water



Brines in sedimentary basins

- Why is saline water not flushed out of terrestrial sedimentary basins over long timescales?
- Depends on the ratio of topography-driven flow vs bouyancy-driven flow
- High rates of topography-driven flow will tend to push out saline water
- However, if buoyancy forces exceed topography-driven flow the saline water will stay where it is

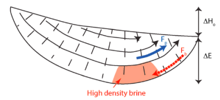


Figure 1. Conceptual model of high density brine trapped where buoyancy forces (F_b) exceed topographic driving forces (F_p) due to lack of ∇H relative to ∇E. The dashed black lines represent freshwater equipotentials, and the solid black lines represent flowpaths for a freshwater system.

Ferguson et al. (2018) GRL

$$\mathrm{DFR} = \left(\frac{\Delta\rho}{\rho_o}\right)\frac{|\nabla E|}{|\nabla H_o|_h}$$

$$H_o = \frac{r}{\rho_o g} + z$$

Equations for the driving force ratio (buoyancy over topographic driving force). ∇E is the gradient of the aquifer. H_0 is equivalent freshwater head using freshwater density ρ_0

Brines in sedimentary basins

- First order calculation of buoyancy vs topographic driving force indicates that in many basins in the western US the topographic driving force is higher, and these basins tend to have relativley low salinities. However in other basins in the gulf coast and eastern US buoyancy exceeds topographic driving forces and saline groundwater is essentially trapped on geological timescales

$$\mathrm{DFR} = \left(\frac{\Delta\rho}{\rho_o}\right)\frac{|\nabla E|}{|\nabla H_o|_h}$$

$$H_o = \frac{r}{\rho_o g} + z$$

Equations for the driving force ratio (buoyancy over topographic driving force). ∇E is the gradient of the aquifer. H_0 is equivalent freshwater head using freshwater density ρ_0

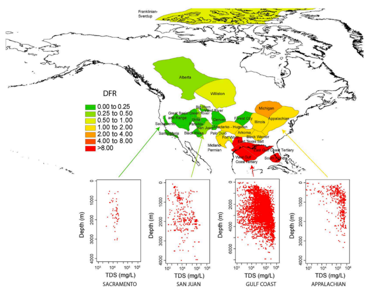
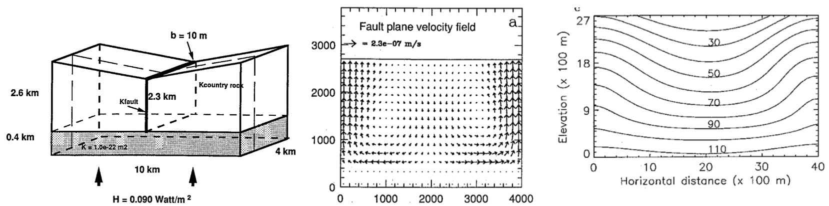


Figure 2. DFR for selected sedimentary basins in North America. Sedimentary basins in western North America are more likely to have been flushed and have lower salinities, similar to those observed in the Sacramento and San Juan basins. Basins in eastern North America tend to have higher DFR are likely to host stagnant brines and have TDS distributions similar to those found in the Gulf Coast and Appalachian basins.

Ferguson et al. (2018) GRL

Thermal convection along permeable faults

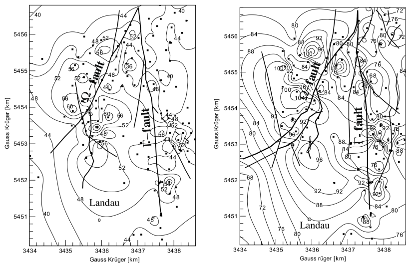
- Thermal convection is more likely to occur in faults
- Faults can provide permeable pathways between deep and shallow fluids -> sufficiently high permeability and temperature gradients to drive convection



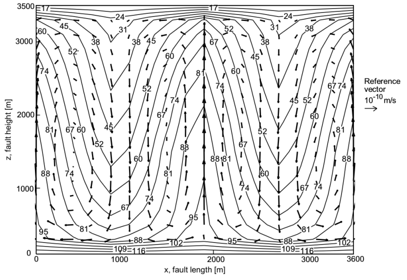
Model experiments of convection in a fault plane, López & Smith (1995)

Thermal convection along permeable faults

- Model example to explain geothermal anomalies in Upper Rhine Graben:



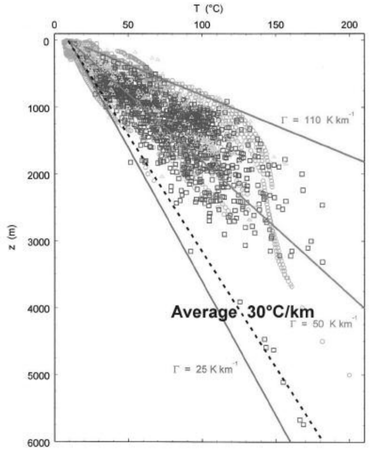
Temperatures in part of the Upper Rhine Graben, Bächler et al (2003)



Modeled convection along a fault plane, Bächler et al (2003)

Thermal convection

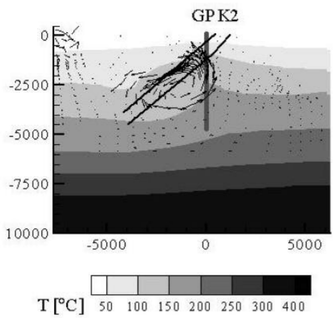
- high thermal gradient in sedimentary rocks
- low geothermal gradients in crystalline basement
- contrast cannot be explained by change in thermal conductivity
- -> thermal convection in crystalline basement?



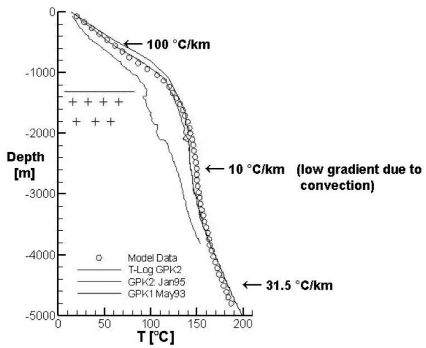
Temperature data Upper Rhine Graben, Munch et al (2005)

Thermal convection

- Free convection in Variscan crystalline basement has a strong effect on geothermal gradients
- Facilitated by high permeability fractured basement rocks, probably caused by tectonic activity



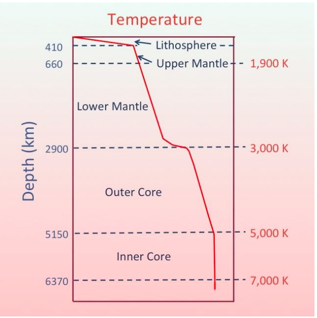
Convection model of the Soulz geothermal site in the URG Kohl et al (2000)



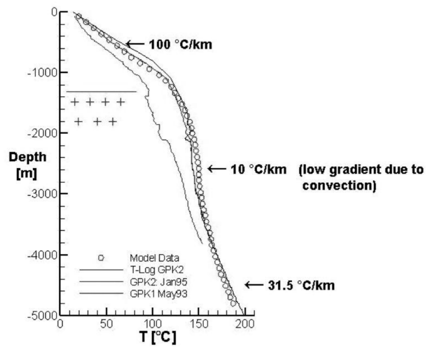
Modeled vs observed temperatures Kohl et al (2000)

Thermal convection

- geothermal signature of convection:



Temperatures in the earth's interior



Temperatures in the Soulz area of the upper Rhine Graben, Kohl et al (2000)

Summary

- Free convection = flow driven by buoyancy forces as a result of density differences
- fluid energy potential = $\nabla P + \boldsymbol{\rho} g \nabla z$
- 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
- importance in sedimentary basins questionable due to influence low permeability sediments
- however, convection along fault planes may be important. Depends crucially on the permeability of faults, see lecture in january
- thermal convection very important in oceanic crust: lecture in january

Next lecture (8 Jan):

- Driving forces, why do crustal fluids flow?
  - Recharge-driven flow
  - Bouyancy-driven flow, free convection
  - **Flow driven by sedimentary or tectonic loading**
  - Fluid production or consumption by chemical reactions